**The Seismic Interactions and Spatiotemporal Evolution of Seismicity following
the October 23, 2011 M_w 7.1 Van, Eastern Anatolia, Earthquake**

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Abstract

We studied the mechanisms and spatiotemporal distribution of aftershocks of the M_w 7.1 Van earthquake, in Eastern Turkey. The Van earthquake occurred on an E-W trending thrust fault, in a region under N-S compression due to the convergence of the Arabian plate toward Eurasia. We relocated the seismicity by combining catalogs from two agencies and studied the source mechanisms of the M_w 3.5-5.6 aftershocks using regional body and surface waves. In addition to the aftershocks with thrust mechanism on the mainshock fault, we identified three clusters with strike-slip activity. Two of the clusters are on the left-lateral faults perpendicular to the mainshock fault and are located at the lateral termination of the co-seismic rupture in each direction. Both western and eastern strike-slip clusters were triggered within the first few hours following the mainshock. They were initiated very close to the mainshock rupture plane and propagated away toward the south and north respectively. These two dominantly strike-slip zones are connected to the mainshock fault at a depth of 15 km and possibly determined the lateral extent of the 2011 rupture. This system of two bounding left lateral faults with a thrust fault in between is overall consistent with the N-S convergent tectonic regime in the region. The complex geometry explains unexpected post-seismic motion at a GPS site and can be used to improve the post-seismic slip estimate of the earthquake. The third strike-slip cluster with 17 days delay occurred on an E-W trending right-lateral fault and 40 km on the south of the mainshock. The three activated faults have experienced Coulomb stress increase due to co-seismic rupture. In addition, most of the seismicity has occurred in regions that experienced Coulomb stress increase.

Key Words: Earthquake triggering, Coulomb stress change, Seismotectonics, 2011 Van earthquake; Aftershock studies

1. Introduction

On October 23rd, 2011, the largest instrumentally recorded earthquake occurred in Van, eastern Anatolia. This M_w 7.1, reverse-fault earthquake was felt over a broad area, causing extensive damage in the epicentral region and more than 600 deaths (Kalafat et al., 2013).

The rupture occurred on an E-W trending thrust fault where N-S convergence of the Arabian Plate and the Anatolian microplate takes place (Figure 1). The mechanism of the earthquake was reported by USGS and Global CMT as $255^\circ/50^\circ/73^\circ$ and $246^\circ/38^\circ/60^\circ$, respectively. Similar strike, dip and rake values ($258^\circ/46^\circ/71^\circ$) were reported from InSAR data by Fielding et al. (2013), confirming that the earthquake occurred on an almost E-W trending thrust fault with some left lateral component.

The co-seismic slip model of the mainshock was obtained by using various datasets. Elliott et al. (2013) presented a two-patch slip model that extends 35 km along the strike direction with an average rake of 60° derived from InSAR data, while Konca (2015) and Wang et al. (2015), proposed two patch slip models with rupture lengths of 35 km and 40 km, respectively, from the joint inversion of seismic and geodetic data. Fielding et al. (2013), Feng et al. (2014) and Liu et al. (2015) on the other hand, suggested one-patch slip models with similar rupture lengths. Despite significant differences on the segmentation and peak slip values, most slip models show similar spatial extents of the rupture. Remarkably, the co-seismic finite-fault models of the earthquake show that slip is confined to depths between 10 and 20 km.

Post-seismic deformation model by et al. (2014) shows that the total moment release following the earthquake is 9.8×10^{18} Nm, equivalent to an M_w 6.6 event. Wang et al. (2015) also computed the post-seismic slip during the first three months and came up with total moment release of 2.04×10^{19} Nm, equivalent to an M_w 6.8 earthquake. Both models indicate significant

61 left-lateral slip with some dip-slip motion on the main fault as well as on another splay fault
62 further south, called the Bostaniçi fault (Mackenzie et. al, 2016, Figure 1). Mackenzie et al.
63 (2016) argue that the bifurcation of the thrust fault into a splay fault at a depth of 10 km toward
64 the surface possibly acted as a structural barrier, which led to the lack of shallow slip during the
65 2011 co-seismic rupture.

66 Since the earthquake occurred on a blind fault with co-seismic rupture deeper than 10 km, the
67 aftershock seismicity distribution is crucial to understand the seismogenic structures that cannot
68 be observed at the surface. Previous studies of the seismic activity of 2011 Van earthquake show
69 that the aftershocks following the mainshock in the vicinity of the rupture area mostly have thrust
70 mechanisms. Few aftershocks are reported to have strike-slip mechanisms at the NE and SW
71 termination of the rupture. Utkucu et al. (2013), in their study, observed a strike-slip activity $M_l \geq$
72 5 at the NE end of the rupture during the month following the 2011 earthquake. Aftershocks with
73 magnitudes between 4.8 and 5.3 having strike-slip mechanisms were also reported by Irmak et al.
74 (2012), while Kalafat et al. (2013) argued that most of the aftershocks between M_w 5.1 and M_w 6
75 occurred on thrust faults, independent of their locations.

76 In this study, we analyze the 2011 M_w 7.1 Van earthquake rupture and its interactions with the
77 nearby faults by studying the spatiotemporal distribution of aftershocks and their fault plane
78 solutions. Compared to previous studies, the analysis presented in this study is based on the focal
79 mechanisms of the aftershocks with a lower magnitude threshold and improved aftershock
80 distribution. By using the focal mechanisms and spatiotemporal distribution of the aftershocks,
81 we show that the nearby faults are activated due to stress transfer from the mainshock.

2. Tectonic Setting

The tectonics of Anatolia is driven by the collision of the Eurasian Plate and the Arabian Plate at a rate of 20–30 mm/yr (Reilinger et al., 2006, Figure 1) along the Bitlis Suture Zone in Eastern Anatolia, and N-S back-arc extension along western Anatolia due to Hellenic subduction. The convergence in the east and the extension in the west lead to westward motion and counter-clockwise rotation of the Anatolian Microplate. The collision of Arabia toward Eurasia is partially accommodated by shortening along the Greater and Lesser Caucasus to the north at a rate of 10 mm/yr (Reilinger et al., 1997). Eastern Anatolia Plateau forms the western part of the Turkish-Iranian Plateau (Copley and Jackson, 2006), and in this zone the convergence is accommodated by N-S shortening and westward motion of the Anatolian Microplate due to conjugate strike-slip faults. The shortening across the Eastern Anatolia Plateau is estimated as 10 mm/yr based on GPS measurements (Reilinger et al., 2006).

To the west of Karlıova triple junction (Figure 1), the motion is primarily accommodated by the right-lateral North Anatolian and the left-lateral Eastern Anatolian Fault Zones. To the east of Karlıova triple junction, the motion is accommodated in a more complex fashion within a zone called Bitlis-Zagros Fold and Thrust Belt (BZFTB). As a result of this N-S convergence, the BZFTB is dominated by three types of faulting; NW and NE trending strike-slip, E-W (NNW and ENE) trending reverse faults and N-S trending oblique-slip normal faults (Koçyiğit, 2013). Van fault lies to the north of the Bitlis Suture zone, in a tectonic region characterized by a series of E-W trending thrust faults (Figure 1). To the north of Lake Van, there is an 80 km wide shear zone, namely the Van shear zone, characterized by series of NW-SE trending right lateral faults (Copley and Jackson, 2006) including the Erciş and Çaldıran faults (Figure 1). The total amount of cumulative right lateral slip rate along the Van shear zone is estimated as 10 ± 1 mm/yr by

Reilinger et al. (2006) using a block model, while Copley and Jackson, (2006), estimate a slightly lower rate (8 ± 2 mm).

The 2011 Van earthquake occurred on an E-W trending thrust fault, which is named as Van fault by Emre et al. (2011), or Everek fault by Koçyiğit (2013), located on the north of the BZFTB (Figure 1). Although the geological existence of this fault was known, it was not included in the most recent active fault map of Turkey by the General Directorate of Mineral Research and Exploration (Şaroglu et al. 1992). The slip-rate across the Van fault is unknown due to the lack of dense long-term geodetic observations in the region. However, using the regional GPS data from Reilinger et al. (2006), Elliott et al. (2013) inferred that the slip-rate must be less than 5 mm/yr. Mackenzie et al. (2016) on the other hand, obtained a geological slip-rate of at least 0.5 ± 0.2 mm/yr for the Van fault.

Surface deformation could not be observed in the early field studies following the 2011 earthquake. However, more detailed studies revealed that the surface deformation can be tracked along an ~ 8 km ENE–WSW line before the rupture enters Lake Van (Akyüz et al., 2011; Elliott et al., 2013; Emre et al., 2011) (Figure 1). Using COSMO-SkyMed interferograms, Mackenzie et al. (2016) infers that this small scale surface rupture has formed during the early post-seismic period. Figure 1 shows two-segment surface deformation observed by Mackenzie et al. (2016) along the Van fault and a splay fault further south. Slip distribution models also show that slip is confined to the depths of 8 to 20 km (Konca, 2015; Wang, 2015; Elliott et al., 2013) indicating that the Van fault is a blind thrust fault.

3. Data and Methods

We relocated the aftershocks during the first 3 months following the mainshock using the catalogs of General Directorate of Disaster Affairs of Turkey (AFAD), and Bogazici University,

Kandilli Observatory (KOERI) Regional Earthquake-Tsunami Monitoring Center (BDTIM). For the earthquakes that exist in both catalogs (AFAD and BDTIM), phase readings were merged. The earthquakes that existed only in one of the catalogs were also included in the joint catalog. We revised the phase pickings using the continuous waveforms for the first 3 days (~2000 events). Furthermore, the earthquakes with magnitudes greater than 4.0 were revised using continuous waveforms during the first 3 months. The final merged catalog contains more than 6700 events between 23 October, 2011 and 31 January 2012. A 1-D velocity model was computed using the VELEST inversion code (Kissling et al., 1994). The deviations from 1-D velocity model are accounted in the station corrections. Average location errors are shown in Figure 2. The mean horizontal errors are ~2.0 and ~3.0 km for latitude and longitude, respectively (Figure 2 a-b). The mean of the depth errors is ~4 km but varying significantly between 2.0 and 6 km. The azimuthal gap varies between 90 and 150 for most of the earthquakes (Figure 2d) and the magnitude completeness threshold of the catalog is observed as ~2.7 (Figure 2f).

The locations are further improved using the HYPODD relative location algorithm (Waldhauser and Ellsworth, 2000; Waldhauser, 2001). The relative errors after the double-difference relocation are presented in Figure S1, which indicates that the relative horizontal and depth errors are on the order of a few hundred meters for the majority of the events. A comparison of the AFAD, KOERI, merged and double-difference relocated catalogs (Figure S2) shows the similarities and improvements of the catalogs. The double-difference relocation yields a more compact distribution of aftershocks.

For the moment tensor analysis, we used 25 broad-band seismic stations, 17 of them operated by AFAD and 8 of them operated by BDTIM (Figure 3a inset). 1-D Green's functions were

calculated by employing the frequency-wave number algorithm of Zhu and Rivera (2002) using the crustal velocity structure of Zor et al. (2003), which is obtained from receiver function analysis. Taking into account the tectonic complexity of the region and increasing misfits between the observed and synthetics waveforms at large distances in our preliminary trials, we ignored stations at distances greater than 300 km. The number of stations used for each event varies between 9 and 36. For most of the events around the mainshock area, the number of stations used is between 15 and 25 and the number of waveforms (components) used is between 70 and 125 (Figure S3). We studied 106 earthquakes in the magnitude range M_w 3.6- M_w 5.6 using radial and vertical component of P_{nl} waves and 3-components of surface waves. Band-pass filter was applied between 0.02 Hz and 0.1 Hz for the 35 s P_{nl} window and 0.02-0.08 Hz for the 70 s surface wave window.

In order to invert for the best-fitting focal mechanism solutions, we utilized the generalized Cut and Paste (gCAP) method. This method was developed for double-couple sources by Zhu and Helmberger (1996) and was further extended to full moment tensors by Zhu and Ben-Zion (2013). gCAP is commonly used for studying source mechanisms of moderate to small earthquakes using regional body and surface waves and employs a grid search to obtain the strike, dip and rake angles as well as the moment magnitude (e.g. Tan, et al., 2006; Wei et al., 2012; Zhu and Zhou, 2016). We excluded the non-double couple component and searched only for the best fitting double-couple mechanism and moment magnitude.

We eliminated 32 poorly resolved aftershocks with a variance reduction lower than 50% and were left with 74 aftershocks with a variance reduction higher than 50%. We also searched the best-fitting centroid depths by performing a grid search from 5 to 30 km with 1 km grid spacing. Finally, for 15 of the 74 events, we were able to constrain the centroid depths, which are typically

a few km far from the hypocenter depth obtained using the travel-time inversion. For the rest, we relied on the depth estimates from relocated hypocenters or if they were not relocated (those with $M_w < 4.5$), we used the earthquake catalog from AFAD (Table S1). Three examples of waveform fits and centroid depth grid-search results are shown in Figure S4. The first example on the left panel in Figure S4 shows an event where the centroid depth is well-constrained. For the other two examples shown on the center and the right panel of Figure S4, the centroid depths were not well-constrained, but a stable solution for other source parameters were successfully achieved (For the details on the inversion scheme, see Figure S4 caption).

In order to test the reliability of the mechanisms obtained from regional body and surface waves, we compared the solutions of the relatively larger aftershocks with those that are in the Global CMT catalog. Figure S5 shows the comparison of the 8 focal mechanisms that are common in both databases. We observed that 7 of them have very similar mechanisms and fault orientations. One of 8 earthquakes (event number 4 in Figure S5) has similar thrust mechanism, but the strike angle is significantly different. For this earthquake, the number of stations used is close to the lower limit of the used stations (10 stations), which might have led to a larger uncertainty. Figure S6 shows an example, where the variance reduction is plotted for grid search of strike, dip and rake angles. Although this type of grid search does not yield any statistical uncertainty, it shows that there is a best-fitting region rather than a unique solution which might lead to errors on the order of $\pm 25^\circ$.

4. Aftershock Activity

The spatiotemporal distribution of aftershocks of the October 23rd, 2011, Van earthquake follows a Z-shaped pattern and deviates significantly from a nearly E-W strike direction of the mainshock mechanism (Figure 3a). Significant amount of aftershocks off of the mainshock zone

can be observed at the SW and NE edges of the co-seismic rupture. In addition, the depths of the north-south lineated aftershocks at both edges tend to get shallower at distances further away from the mainshock (Figure 3a).

Figure 3b shows three N-S depth sections of the aftershocks located along three profiles of Figure 3a. The profile at the western edge, A-A', shows that the activity just south of the mainshock rupture zone takes place between the surface and 25 km depth with no apparent dip. A second zone of activity disconnected from the mainshock is clearly observed further south at shallower depths (10-20 km). The profile B-B' crossing the center of the main rupture indicates that the aftershock activity in the mainshock area is in a depth range of 15-25 km. The profile along the eastern edge C-C' shows that the activity gets progressively shallower toward the north from 25 km to 5 km depths. The apparent dip toward the south observed along C-C' profile is inconsistent with the mainshock mechanism, which is a thrust fault dipping north with a dip angle of $\sim 45^\circ$. The location of the transition from the southern dipping seismicity to northern dipping mainshock is indicated by a black arrow in Figure 3a and Figure 3b.

Investigation of the focal mechanisms of the aftershocks shows that, in addition to the thrust mechanisms along the co-seismic rupture, there are three strike-slip clusters (Figure 4a). Two of these strike-slip clusters coincide with the profile A-A' (Figure 3) and the third strike-slip cluster is at the northeast of the rupture area along profile C-C' in Figure 3. In this study, we assign numbers to each of these clusters I, II and III, based on their initiation times after the mainshock, inferred from the focal mechanisms (Figure 4a). It should be noted that a significant portion of the events have oblique mechanisms, including the mainshock which has a rake angle of $\sim 70^\circ$. We classify the earthquakes based on the dominant mechanism inferred from the rake angle δ (e.g., $-45^\circ < \delta < 45^\circ$ would be considered left lateral).

Figure 4b shows the activation times of the aftershocks in each cluster in comparison to the activity of the mainshock zone. The focal mechanism encircled in red in Figure 4a is the first strike-slip earthquake of Cluster I (Box CI). The same event is shown by a red circle in the time-magnitude distribution of Cluster I in Figure 4b. The earliest strike-slip activity started two hours later, at the western tip of the mainshock rupture (Figure 4a-Box CI). Focal mechanisms of the selected events in Cluster I are dominantly strike-slip and they are aligned in the N-S direction, covering a total length of 23 km.

Cluster II is located at the eastern tip of the main fault and extends toward the north (Figure 4a-Box C II). In this region, the aftershocks that occurred during the first 6 hours following the mainshock have thrust mechanisms. However, six hours after the mainshock, the activity extends progressively to shallower depths toward the north and have mostly strike-slip mechanisms (Figure 4a, Cluster II, and Figure 4b). The focal mechanisms and the N-S lineation of the aftershocks in Cluster II indicate that this activity is due to a left lateral N-S trending fault located at the eastern termination of the mainshock rupture. The activity started close to Lake Erçek with 6 hour delay and indicated by the focal mechanism encircled in blue in Figure 4a-Box CII. The activity is deeper in the south where it first initiated and becomes shallower as it extends for 27 km toward north.

The third and the latest initiated activity is located on the southwest of the 2011 event. A cluster of strike-slip earthquakes started with M_w 5.6 earthquake, 17 days after the mainshock (November 9th, 2011) (Figure 4a-Box CIII). The later events in Cluster III are in the magnitude range of M_w 3.6 - M_w 4 and have similar mechanisms as the M_w 5.6 earthquake. These right lateral earthquakes are initiated on the possible continuation of the E-W trending Edremit fault (Ketin, 1977) (Figure 4, Box CIII). This result is consistent with the study of Wang et al. (2015),

who showed that the focal mechanism of the November 9th, 2011, M_w 5.6 event is right-lateral strike-slip with a strike of 259° based on the aftershock locations and the InSAR data.

In addition to thrust mechanism aftershocks along the Van fault and three major strike-slip zones, a few normal mechanism earthquakes were also observed on the hanging wall side, which might be related to the stress release due to co-seismic slip (Figure 4a).

The analysis of aftershock focal mechanisms and their temporal evolution indicates that the 2011, Van earthquake triggered multiple faults in the vicinity of the rupture due to stress transfer. The activation of the first two clusters that are off the mainshock fault shows that they are initiated due to co-seismic stress change of the M_w 7.1 earthquake. The delayed triggering of Cluster III may also be induced by the post-seismic motion during the 17 days following the main shock.

5. Coulomb Stress Changes

The mechanism that explains the temporal delay of the triggered activity remains an open question. However, whether they are consistent with the static stress change caused by the co-seismic slip of the mainshock can be explored by calculating the Coulomb stress change on these proposed faults. Coulomb stress change is the static change of stresses inside the crust which is the summation of change in shear stress Δt_s and normal stress $\Delta \sigma_n$ multiplied by the coefficient of friction, μ (King et al., 1995).

$$\Delta \sigma_f = \Delta t_s + \mu \Delta \sigma_n$$

We computed two types of Coulomb stress changes. First, we computed the stress changes due to co-seismic slip of the mainshock on three proposed faults with given mechanisms. Second, we computed the stress change in the region due to the 2011 event on optimally oriented faults and based on the regional stress of Eastern Anatolia from Sezgin and Pınar (2002).

Here, we constructed three representative faults based on the distribution of seismicity and focal mechanism parameters of the clusters. The location of the representative faults with their strike, dip and rake angles are shown in Figure 5. The fault parameters of these representative faults are computed by adding up the moment tensors of individual earthquakes in the cluster and finding the best-fitting double-couple mechanism from the cumulative moment based on the method described by Jost and Hermann (1989). The selection between main and auxiliary fault planes is based on the spatial distribution of the aftershocks. Presence of the faults related to the Clusters II and III is quite clear. For Cluster I, the spatial distribution and strike angles of the earthquakes are not fully coherent with each other. Despite variations in source parameters, we still consider it as a single cluster since many of these earthquakes have significant left-lateral slip component with a NE-SW striking fault. Therefore, for Cluster I, we computed the average strike-dip-rake angles by summing up the moment tensors of earthquakes larger than M_w 4. We ignored a few earthquakes that are considered as outliers in terms of source parameters. The dip angles of these three faults, which are constructed from cumulative moment tensors, also agree with the depth distribution of seismicity as shown in Figure 3b.

In order to calculate the stress change due to co-seismic slip, we tried using the finite-fault co-seismic slip models of Konca (2015), Shao and Ji (2011) and Elliott et al. (2013). We eventually chose the model of Elliott et al. (2013) due to its compact slip distribution which appears to be more consistent with the activated faults. The calculated Coulomb stress changes on all of the three proposed faults are positive with stress increase of 2 to 5 bars, showing that the co-seismic slip of the Van earthquake contributed to triggering of these faults (Figure 6).

For the Coulomb stress change calculations on optimally oriented faults, we used the regional stress model for eastern Turkey ($\sigma_1 = (350, 0)$, $\sigma_2 = (260, 81)$, $\sigma_3 = (80, 9)$) by Sezgin and

Pinar (2002), which indicates that the compression is in the N–NW direction and the extension is in the E–NE direction. Results show that most of the positive stress change areas coincide with the seismicity on both left-lateral strike-slip faults previously specified as Clusters I and II (Figure 7). It is also noteworthy, with the exception of the seismic activity of Cluster III, most of the seismicity around the co-seismic slip area is in the zones which experienced Coulomb stress increase.

In the region of Cluster III, the regional stress model shows a stress decrease. The maximum stress change for this location is for an E-W trending thrust fault, which would indeed experience a negative Coulomb stress change. However, for a pre-existing right lateral E-W trending strike-slip fault, the stress change is positive, as shown in Figure 8.

The Coulomb stress change calculations show that, the activations of these three proposed faults are consistent with stress transfer from the co-seismic rupture.

6. Discussion

The aftershocks of the 2011 Van earthquake reveal that the mainshock of this earthquake induced activity off the main fault on perpendicular left-lateral faults at the terminations of the co-seismic rupture and on an almost parallel E-W trending right-lateral fault. All of these activities on proposed faults are consistent with Coulomb stress change increase due to the mainshock.

Internal deformation in the Eastern Anatolian region (east of 41.5°E) occurs along the following structures; (1) NNE-SSW and/or NE-SW trending left lateral strike-slip faults in southeast Turkey, (2) NW-SE trending right-lateral strike-slip faults in the northeast, (3) east-

west trending thrusts and folds and (4) N-S trending extension cracks (Arpat et al., 1977; Sengör, 1980; Şaroğlu and Güner, 1981; Şaroğlu, 1985; Barka and Kandinsky-Cade, 1988; Copley and Jackson, 2006). Van area is characterized by E-W trending thrust faults. The area on the north of the Van fault is characterized by multiple NW-SE trending right lateral faults (Copley and Jackson, 2006) (Figure 1).

The aftershocks along the E-W trending main fault are of thrust and oblique thrust mechanism as expected (Irmak et al., 2012; Kalafat et al., 2013; Utkucu et al., 2011) and are possibly related to the post-seismic slip which surrounds the co-seismic slip distribution (Doğan et al., 2014). These predominantly thrust mechanism aftershocks, mostly cover the main fault area between 15 and 25 km depths. The other three clusters on the other hand, are off the main fault and have strike-slip mechanisms at shallower depths (10-20 km).

The two left-lateral faults that initiated their activities during the first day are located at the termination of the co-seismic slip in each direction and possibly cut the main fault. The activity of both zones initiated very close to the mainshock rupture plane and propagated away from the mainshock area to shallower depths. A possible explanation is that these two strike-slip faults are connected to the Van fault and they determined the extent of the co-seismic rupture on the main fault.

The proposed system, in which two left-lateral faults are interconnected by an E-W trending oblique thrust fault, is overall consistent with the N-S shortening in the region. Whether Van fault extends further toward east or west beyond these two left-lateral faults is not clear. However, the observed N-S left-lateral activity at both ends of the co-seismic rupture in the hours following the mainshock is a clear indication that these left lateral faults are connected to Van fault and controlled the lateral extent of the 2011 rupture.

The earthquakes at the southeastern tip of the co-seismic rupture associated with Cluster I reveal a relatively complex pattern. The cumulative seismic moment tensor of this cluster which is obtained by summing up the moment tensor of each event and finding the best DC component, is consistent with left-lateral activity (Figure 5).

On the other hand, the existence of a left-lateral fault at the north-east end of the 2011 rupture is quite clear, due to the consistent N-S lineation of seismicity and mechanisms of the earthquakes in Cluster II. The observation that the seismicity gets shallower toward the north rules out the possibility that the activity in Cluster II is along a tear fault since for a north-dipping fault, a tear fault would imply deeper hypocentral depths of seismicity toward the north.

Van area is characterized by a folding due to the buried Van fault. To the north, Van shear zone is dominated by NW-SE trending right lateral faults. These strike-slip faults have clear surface expression and can be observed at the surface (Mackenzie et al., 2016). However, in the zone of Cluster II, we observe triggering of seismic activity on a N-S trending left-lateral fault with no visible geologic feature. One explanation for the lack of surface expression for this left-lateral fault is that the surface features in the region are only affected by the seismogenic structures of the top 10 km, while deeper tectonic mechanisms are masked (Mackenzie et al., 2016). Since the proposed fault is a blind fault with seismic activity mostly in the 10 to 20 km depth range, it is conceivable that it is not easily detectable from the surface.

Whether this mechanism of left-lateral faults connected by an oblique thrust accommodates tectonically significant motion or not is uncertain; however, there is also evidence that there was significant post-seismic motion on the fault associated with Cluster II (see details below). It is possible that while thrust and right lateral strike-slip faults are more dominant at the uppermost

part of the crust (0-10 km), other mechanisms, such as the one described in this study, exist at mid-crustal depths (>10 km).

The geometry suggested in this study also sheds light on the post-seismic motion which seems to be inconsistent with a single almost E-W thrust fault geometry. Doğan et al. (2014) shows that during the 1.5 year post-seismic period, GPS stations on the hanging wall that are west of Lake Erçek exhibit southward movement as expected (VN05 and VN06 in Figure 3a). On the other hand, station VN08, which is located to the east of Lake Erçek, has moved north (Figure 3a), although it is also on the hanging wall side of the thrust fault. In order to explain this anomalous data, Doğan et al. (2014) introduced a significant curvature to the strike of the main fault and extended the fault further east than the co-seismic slip indicates, so that VN08 station stays on the footwall side. This curvature leading to a more SW-NE striking fault seems to be inconsistent with the strike obtained from co-seismic studies of the earthquake using InSAR (Elliott et al., 2013), GPS and seismic data (Konca et al., 2015). Our study suggests that the northward motion of VN08 can be explained by adding left-lateral motion on the fault at the eastern edge of the co-seismic rupture, associated with Cluster II. Therefore, instead of adding a curvature to the strike of the main fault, one can introduce two left-lateral faults at each end, which would provide a better constrained post-seismic model. The preliminary results obtained from reexamination of the post-seismic motion, using the geometry suggested here, explains the observed post-seismic motion as well as the observed motion at station VN08 (Semih Ergintav, personal communication).

While the first two clusters in the vicinity of the mainshock were triggered during the first 6 hours following the mainshock, Cluster III, which occurred on an independent strike-slip fault, was activated with a delay of 17 days, starting with an M_w 5.6 event. Wang et al. (2015) showed

that this delayed activity can be explained by Coulomb stress increase. We also show that these earthquakes occurred on an E-W right-lateral strike-slip fault which is possibly a continuation of the Edremit fault (Utkucu et al., 2013).

The Coulomb stress modeling for optimally oriented faults based on the regional stress model of Sezgin and Pınar (2002) shows stress increase in the zones of Clusters I and II. In addition, we calculated the stress change on the proposed faults derived from the distribution and mechanism of aftershocks and showed that the stress increased in each of the assumed faults due to co-seismic slip.

The correlation between the distances of the activated faults and their activation delay times is also interesting to note. In most cases, triggering of events $M \geq 2.5$ occurs after some time delay and the amount of delay varies for each cluster (e.g., Durand et al., 2010; Aksarı et al., 2010; Aktar et al., 2007). In this study, the nearby Clusters I and II are triggered within hours, while Cluster III, which is 40 km south of the mainshock, is triggered 17 days later. The post-seismic slip might have also contributed to the triggering of this fault; however, since the current post-seismic models do not consider the geometrical complexity suggested here, we avoided adding their contribution to the Coulomb stress change calculations.

7. Conclusion

By studying the focal mechanisms and the locations of the aftershocks of the 2011 Van earthquake, we illustrated the interaction of the mainshock with the faults in the vicinity. We observed three groups of aftershocks with strike-slip mechanisms and showed that their triggerings are consistent with Coulomb stress transfer due to the mainshock co-seismic slip. The proposed fault geometries and the types of faulting that are triggered due to stress interaction reveal that the Van fault is cut by a N-S striking left-lateral fault at the eastern end. At the

western end of the 2011 rupture, there is distributed seismicity extending toward south with cumulative moment tensor consistent with a NW-SE trending left-lateral fault. These faults have started their activity in the hours following the mainshock and are possibly connected at the lateral termination of the co-seismic rupture at each direction. The proposed geometry will also be useful for improving post-seismic slip models and help explain the anomalous motion observed at a GPS site. The delay time of the activities and their temporal evolution can shed some light on the mechanism of this interaction and requires further exploration.

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Figures and Figure Captions

Figure 1. The map of the study area, Eastern Anatolia, including main tectonic features. Solid black lines indicate the active faults in the region (Emre et al., 2013; Mackenzie et al., 2016). Slip rates of North Anatolian and East Anatolian Faults (Reilinger et al., 2006) are indicated below their names in parentheses. The motion of the Anatolian and Arabian Plates with respect to stable Eurasia are shown by red arrows at a few locations (McCluskey et al., 2000; ArRajehi et al., 2010). The epicenter of the M_w 7.1 2011 earthquake and its largest aftershock are shown with red stars. The surface deformation observed during the post-seismic period of 2011 earthquake are shown by red lines (Mackenzie et al., 2016). Inset shows the study area (red box) on a wider map of Anatolia and surrounding regions. VF: Van Fault; BF: Bostaniçi Fault; GF: Gürpınar Fault; EF: Erciş Fault; CF: Çaldıran Fault SLVF: South Lake Van Fault.

Figure 2. Statistics of the relocated aftershocks during the 3 months after 23 October 2011 Van earthquake; (a) longitude errors; (b) latitude errors; (c) depth errors; (d) azimuthal gap; (e) number of stations used for locating each earthquake; (f) frequency-magnitude distribution.

Figure 3. (a) Map view of aftershock activity during the first 81 days following the mainshock. Each earthquake is shown by a circle scaled by its magnitude and colored based on its hypocenter depth. Three gray strips indicate the locations of depth profiles A-A', B-B and C-C' shown in (b). Black arrow on the profile C-C' corresponds to the intersection of strike-slip fault with the mainshock fault. The rectangular boxes show the edges of the two-segment co-seismic slip model of Elliott et al., (2013) and the red star represents the epicenter. Surface expressions of the Van fault (VF) and The Bostaniçi splay fault (BF) observed during the post-seismic period are indicated by blue lines with triangles indicating the hanging wall side (Mackenzie et al., 2016). White arrows show the GPS displacement vectors recorded at stations VN05, VN06 and VN08 during the 1.5 year post-seismic period (Doğan et al., 2014). Solid black lines show the surface projection of faults that are activated due to mainshock as proposed in this study. The inset shows the broadband seismic stations (BDTIM and AFAD stations denoted by light red and dark red respectively) used for waveform modeling. (b) Depth-sections through A-A', B-B' and C-C' shown in Figure 3a. Aftershocks are represented by red circles scaled in size by magnitude. Black arrow in profile C-C' indicates the intersection of strike-slip fault and the main thrust fault. Solid black lines in profiles A-A' and C-C' indicate the depth profile of faults that are proposed in this study.

Figure 4. (a) Map view of aftershock focal mechanisms obtained in this study. Red star represents the epicenter of the mainshock. Focal mechanisms colored in purple were used to calculate the orientations of the assumed strike-slip faults associated with the three clusters. The remaining source mechanism solutions are in yellow. Black rectangles show the borders of the cluster zones which are numbered based on their initiation time and labeled CI, CII and CIII. Slip contours from Elliott et al. (2013) are also underlain the focal mechanisms. Relocated aftershocks are shown by black circles which are scaled by their moment magnitudes. Focal mechanisms encircled in red and blue indicate the first strike-slip events in Cluster I and Cluster II, respectively. Solid black line inside the box for Cluster III is the surface trace of the Edremit Fault (Ketin, 1977). In Cluster III, November 9th, 2011 M_w 5.6 event is plotted slightly south of the actual hypocenter to uncover other mechanisms in the cluster. The actual location of this earthquake is shown by the red circle. (b) Time evolution of the aftershock activity in Clusters I, II and III (purple circles) in comparison to the time evolution of aftershock activities on the mainshock fault zone (yellow circles). Red and blue circles represent the first modeled strike-slip events inside Cluster I and II, respectively, as shown in map view in Figure 4a.

Figure 5. Focal mechanism solutions used for analyzing the assumed faults which are colored based on depth and scaled in size by magnitude. Solid black lines denote the strikes of the assumed faults. The average strike, dip and rake angles of the clusters are denoted next to each assumed fault. Relocated aftershocks that occurred during the first 81 days are shown by black circles which are scaled by event magnitude. Red star represents the epicenter of the mainshock. CI, CII and CIII denote Clusters I, II and III, respectively. November 9th, 2011 M_w 5.6 event in CIII is plotted slightly south of the actual hypocenter to uncover other mechanisms in the cluster. The actual location of this earthquake is shown by the red circle.

Figure 6. Coulomb stress change calculated on assumed faults and the main fault using the co-seismic slip model of Elliot et al. (2013) using InSAR data. The two-segment co-seismic fault geometry is outlined in green. The slip model from Elliott et al. (2013) is roughened to 6 km by 6 km sub-faults. Blue zones indicate stress decrease while red patches indicate stress increase.

Figure 7. Coulomb stress change due to co-seismic slip (Elliott et al., 2013) for optimally oriented faults based on the regional stress of Sezgin and Pinar (2002) calculated at a depth of 15 km. Relocated aftershocks that occurred during the first 81 days after the mainshock are indicated by black circles that are scaled by event magnitude. Black rectangles labeled CI and CII, indicate Clusters I and II, respectively. Green star represents the epicenter of October 23th, 2011, M_w 7.1 Van earthquake. Direction of the regional stress tensor components are shown at the lower right corner.

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637 **Figure 8.** Coulomb stress change calculated at the depth of 15 km for the source parameters of
 638 the strike-slip fault identified in Cluster III shown in black rectangle. Green star represents the
 639 epicenter of the mainshock. Relocated aftershocks that occurred during the first 81 days after the
 640 mainshock are indicated by black circles that are scaled by event magnitude.