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Usefulness of Coulomb Static Stress Changes in Earthquake Hazard Studies: An Example from the Lake Van Area, Eastern Turkey

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Abstract

It has been globally documented over different tectonic environments that Coulomb static stress changes caused by a mainshock can promote or demote stresses along the neighboring faults and thus triggers or delays following seismicity. In the present study Coulomb stress changes of the earthquakes in the Lake Van area are calculated using available data and the likely source faults. The calculated stress change maps demonstrate that the large earthquakes in the Lake Area are mostly stressed by the preceding earthquakes, suggesting earthquake rupture interactions. It is further suggested that Coulomb stress maps could be used for constraining the likely locations of the future large earthquakes and in the earthquake hazard mitigation studies.

Key words: The Lake Van area, Eastern Turkey, Coulomb stress changes, earthquake interactions, 23 October 2011 Van earthquake

1. Introduction

Coulomb static stress perturbations caused by a mainshock can increase or decrease stresses along the neighboring faults and thus triggers or delays following aftershocks and mainshocks along them. Spatial correlations between mainshock coseismic stress changes and aftershock occurrences have been globally documented over different tectonic environments [1, 2, 3, 4, 5, 6, 7]. Tiny stress increases can bolster occurrence of aftershocks (or increase seismicity rates) while a few aftershocks occur (or seismicity rate decreases) in the area of stress drops or stress shadows [8, 9]. This puts forwards usage of Coulomb stress changes modelling as a tool for understanding of earthquake interactions and earthquake hazard mitigation purposes.

This study is aimed to investigate earthquake stress interactions in the Lake Van Area, Eastern Turkey, using the all available data related to seismicity and the source faults**.** Further results are to be presented following Utkucu et al [6] who modeled Coulomb static stress changes before and after the October 23, 2011 Van earthquake.

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Northward movement of the Arabian plate with respect to the Anatolian plate is the main cause behind the tectonics of the eastern Anatolian block (Figure 1) [10, 11]. The convergence results in a continent-continent collision along a suture zone known as Bitlis Thrust Zone (BTZ) [12]. Main tectonic features of Lake Van Area are the BTZ lying immediate south of Lake Van (Figures 1 and 2) and a number of dextral and sinistral faults. Dextral Karayazı Fault, Tutak Fault, Erciş Fault Zone, Hasantimur Fault and Çaldıran Fault Zone and sinistral Malazgirt, Süphan and Çakırbey faults are the members of the distributed strike-slip faulting lying close to Lake Van (Figures 1 and 2) [13, 14, 15, 16, 17].

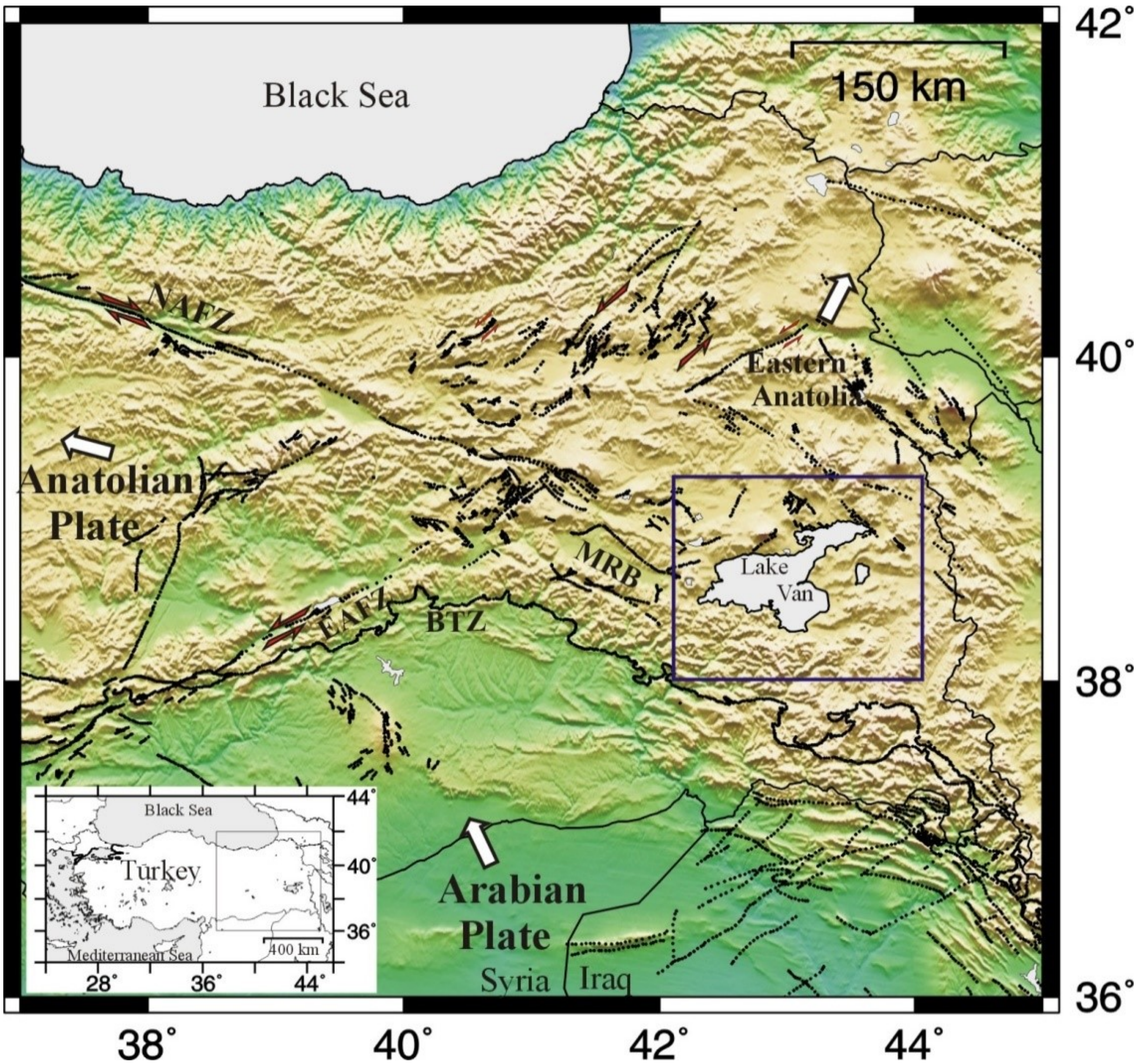

Figure 1. Major tectonic elements of eastern Anatolia. Large rectangle encloses the map areas shown in Figures 2, 3 and 4 and large arrows indicate relative plate motions. Extent of faults and relative plate motions are from Reilinger et al [11] and MTA [17], respectively. *NAFZ* North Anatolian Fault Zone, *EAFZ* East Anatolian Fault Zone, *BTZ* Bitlis Thrust Zone, *MRB* Muş Ramp Basin.

The active tectonics features of the Lake Van area mentioned above have caused dense seismic activity in both historical and instrumental periods [18, 19, 20, 21, 22]. Epicentral distribution of the damaging earthquakes after the 7 April 1646 Van earthquake and before 1860 and the M ≥ 5.0 earthquakes after 1860 to the occurrence of the 2011 Van earthquake is shown in Figure 2.

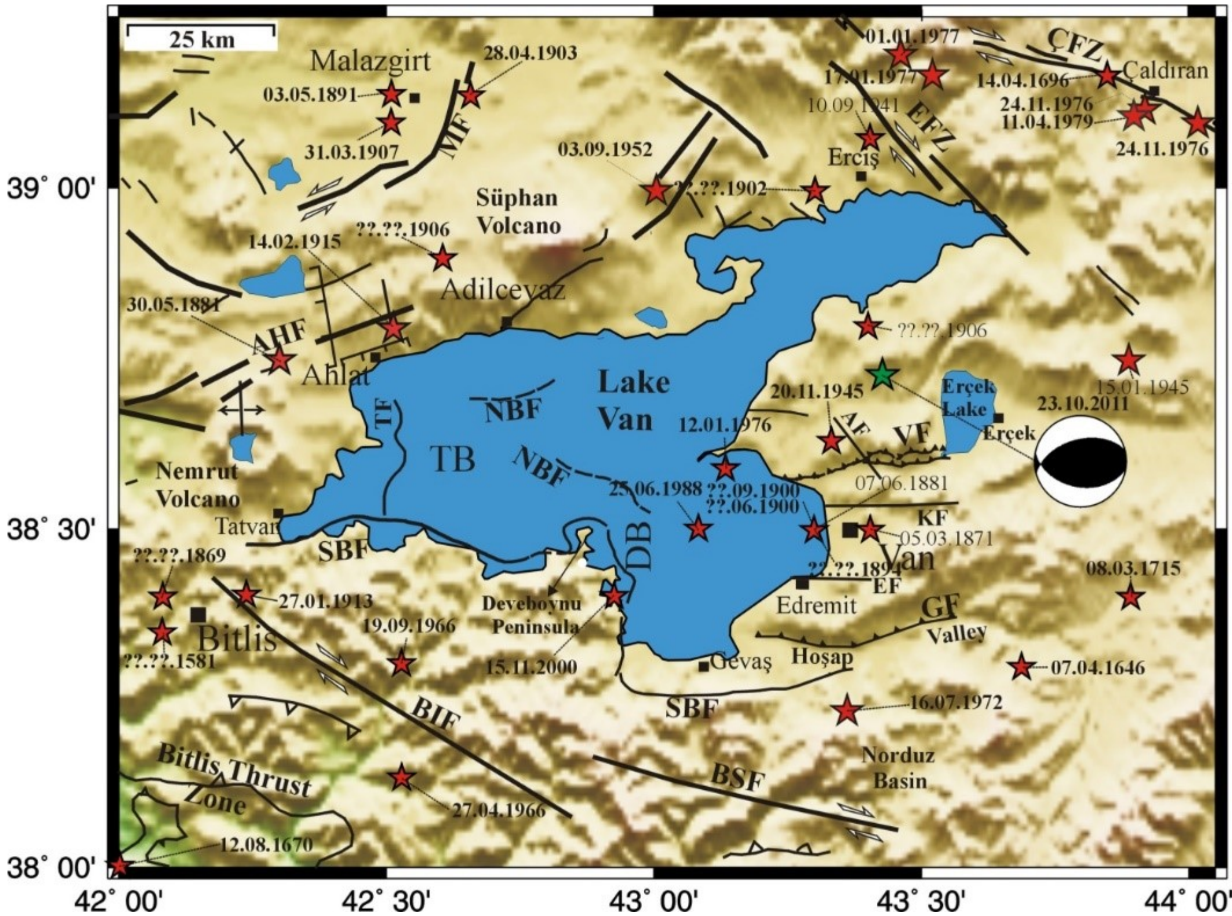

Figure 2. Local tectonic features and epicentral distribution of significant earthquakes (red and green stars) for the Lake Van area. Van. Extent of faults is from Koçyiğit et al [15], MTA [17] and Degens et al [23]. The black-white beach ball represents focal mechanism of the 23 October 2011 Van earthquake by USCS-NEIC. *NBF* Northern Boundary Fault, *SBF* Southern Boundary fault, *EFZ* Erciş Fault Zone, *ÇFZ* Çaldıran Fault Zone, *MF* Malazgirt Fault, *BIF* Bitlis Fault, *BSF* Bahçesaray Fault, *AHF* Ahlat Fault, *EF* Edremit Fault, *KF* Kalecik Fault, *AF* Alabayır Fault, *DB* Deveboynu Basin, *TB* Tatvan Basin, *VF* Van Fault, *GF* Gürpınar Fault.

2. Coulomb Stress Changes Analysis

The Coulomb failure stress changes are calculated over the fault plane of the earthquake interested by taking account its strike, dip and rake angles in the stress calculations. Coulomb failure stress change ($\Delta\sigma_f$) can be simply written as

$$\Delta\sigma_f = \Delta\tau + \mu' \Delta\sigma_n \quad (1)$$

where $\Delta\tau$ and $\Delta\sigma_n$ represent the changes in the shear and the normal stresses over the target fault plane, respectively. Here, μ' is the apparent coefficient of the friction [24], which includes the unknown effect of pore fluid pressure. Stein [25] indicated that μ' varies in the range 0.2-0.8 and we have used $\mu' = 0.4$ in the study. Earthquake ruptures are assumed as rectangular dislocation surfaces in an elastic half-space having Young's modulus of $8x10^5$ bar and Poisson's ratio of 0.25 and the stress calculations are based on the coseismic elastic dislocation modelling of the earthquakes [26]. The calculations are implemented using Coulomb 3.2 software [27, 28].

Only M ≥ 6.0 earthquakes, with the exception of the 2000 Gevaş earthquake (M_W = 5.6), after the 1646 Van earthquake have been used in the Coulomb stress change modeling (Table 2).

Table 1. Fault parameters of the earthquakes used for the Coulomb stress change modelling in the Lake Van area (after Utkucu et al [6]). S1 and S2 stand for first and second segment of the earthquake rupture under interest.

Date	Lat. (°)	Lon. (°)	*Magnitude*	Strike (°)		Dip (°)	Rake (°)	Fault length (km)	Fault width (km)	Slip (m)
07.04.1646	38.30	43.70	M_S 6.7		265	50	73	38[1]	23.50	1.7[1]
12.08.1670	38.00	42.00	M_S 6.7		303	85	175	38	18.07	1.4[1]
14.04.1696	-	-	M_S 6.8	S1	105	85	176	42	24	UT02
				S2	117	85	176	36	24	
08.03.1715	38.40	43.90	M_S 6.6		255	50	73	35	30	UT13
30.05.1881	38.75	42.30	M_S 6.3		250	85	5	21[1]	10.04	0.5[1]
03.05.1891	39.15	42.50	M_S 6.0		250	85	5	21[1]	10.04	0.5[1]
28.04.1903	39.14	42.65	M_S 7.0	S1	204	85	5	20	18.07	1.5[1]
				S2	251	85	5	21	18.07	
10.09.1941	39.07	43.40	M_S 6.0		145	85	175	14[1]	10.04	0.3[1]
24.11.1976	39.10	44.02	M_S 7.3	S1	105	85	176	36	24	UT02
				S2	117	85	176	42	24	
15.11.2000	38.40	42.92	M_W 5.7		228	40	37	9[1]	5	0.32-0.24
23.10.2011	38.73	43.43	M_W 7.1		255	50	73	35	30	UT13

[1]Fault lengths and slip values are determined from the empirical relations of [29]. UT02= [30], UT13= [31]

The rupture parameters (strike, dip, rake and slip values of the faulting) for the earthquakes in the instrumental periods are taken from the published studies [30, 31]. As for the rupture parameters and source faults of the historical earthquakes following methodology is used. First, much likely source faults are assigned by assessing damage descriptions in the historical sources and the strike values are measured from the active fault map [15, 17], (Figures 2 and 3). If the fault type is strike slip then the dip angle is in the range 80°-90° while the rake angle is in the range ±170° - 180° and 0° - ±10° for the dextral and sinistral faults, respectively. The empirical relationships of Wells and Coppersmith [29] are used to define the rupture length and slip amplitude of the historical earthquakes by assuming homogeneous fault slip. The seismogenic thickness starting from the earth's surface and is assumed as 20 km for all earthquakes. The stress changes are calculated at a depth of 9 km, which almost corresponds to half the seismogenic thickness in the Lake Van area.

3. Results

The map view of the calculated stress patterns before the 2011 Van earthquake are shown in Figures 3 and 4. The stress changes due to the 1646 Van earthquake is resolved onto the 2011 Van earthquake's rupture plane requires a stress shadow over the 2011 Van earthquake rupture plane (Figure 3a). Therefore the stress changes are mapped from the earthquakes occurred after the 1715 Van earthquake (Figure 3b). Effect of the 2011 Van earthquake on the both Çaldıran Fault's segments are shown in Figure 3c and 3d. Figure 4 reflects the stress interactions among the background earthquakes of the 2011 Van earthquake. Both in Figures 3 and 4, enhancement and reduction in the stresses are represented with red and blue colors, respectively.

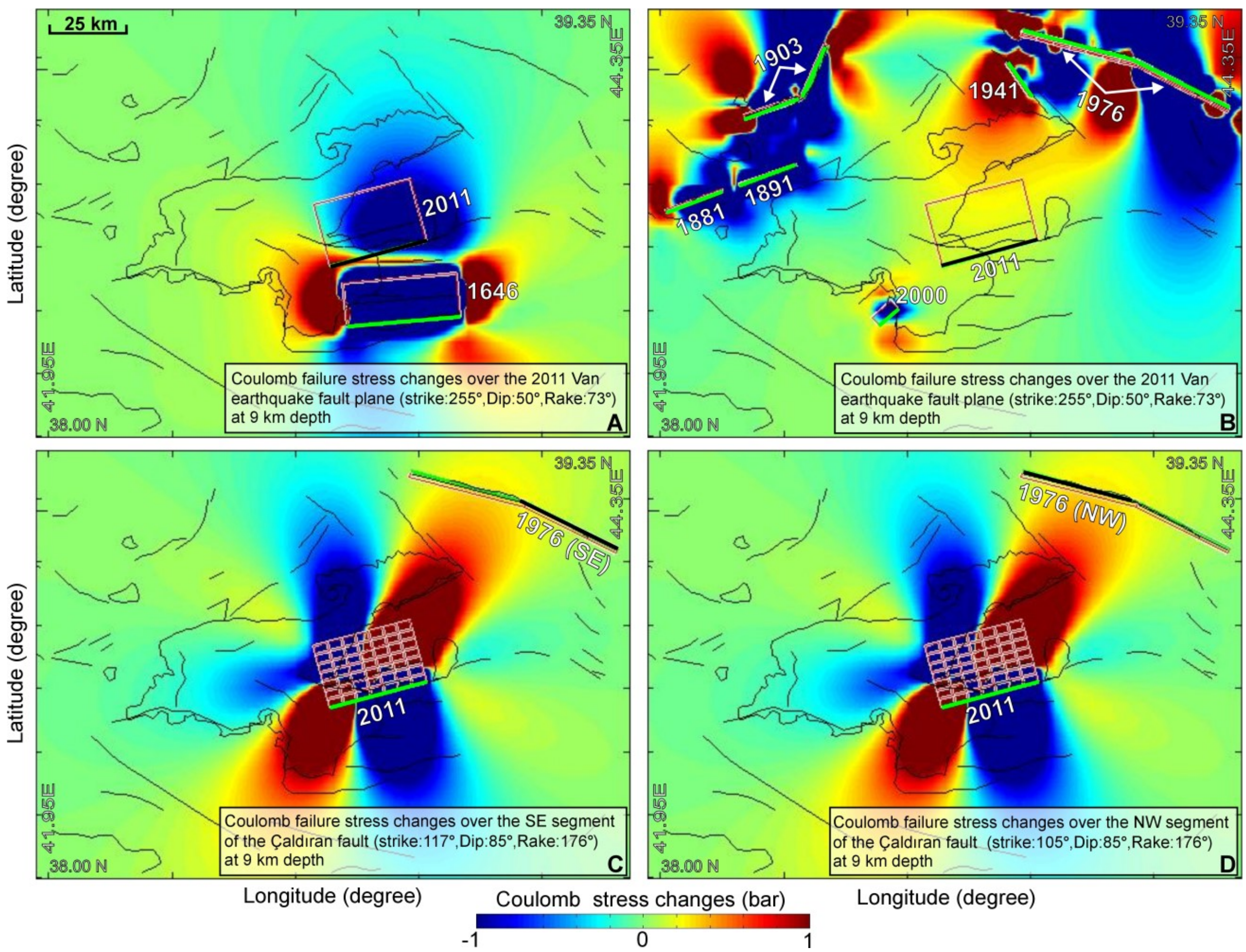

Figure 3. (a) The stress changes caused by the 7 April 1646 Van earthquake alone and (b) by the earthquakes after the 1715 Van earthquake calculated over the 2011 Van earthquake's fault. The stress changes of the 2011 Van earthquake alone resolved onto the (c) SE and (d) NW segments of the Çaldıran Fault that produced 1976 Çaldıran earthquake.

4. Discussion

Figure 3a indicates that the strong stress shadow over the rupture plane of the 2011 Van earthquake caused by the 1646 Van earthquake could not be overwhelmed by the earthquakes after the 1646 Van earthquake (Figure 3b). Indeed, Figure 3b suggests that the 2011 Van earthquake's rupture plane has been coseismically stressed after the occurrence of the 1715 Van earthquake. However the stress increase after the 1715 Van earthquake has not been enough to overcome the stress decrease due to the 1646 Van earthquake alone. Figure 4b suggests that the stress increase was mostly or completely caused by the 1976 Çaldıran earthquake rupture. Therefore it could be said that the 1646 Van and 1976 Çaldıran earthquakes are dominating earthquake ruptures to effect the 2011 Van earthquake rupture plane by means of coseismic stress changes from the background seismicity under interest. As apparent from Figures 3c and 3d, the coseismic stress changes due to 2011 Van earthquake alone have promoted stresses over the SE and NW segments of the 1976 Çaldıran earthquake rupture, respectively. Fortunately, the rupture of the Çaldıran Fault is relatively new and the stress increase caused by the 2011 Van earthquake is not currently a serious problem by means of an occurrence of large earthquake, with magnitude comparable to the 1976 Çaldıran earthquake, in the near future.

As for the coseismic stress interactions of the earthquakes in the background of the 2011 Van earthquake, firstly situation of the fault producing 1881 earthquake is investigated. Figure 4a shows that the 1881 earthquake fault is stressed by the earthquakes in its background. The 1670 earthquake is determined to be main cause of the stress increase. Notice that the 1891 earthquake fault remains in the stress shadow. However, when the stress changes of the 1881 earthquake are also taken into account southwestern part of the 1891 earthquake fault seems to be exposed stress increase of the 1881 earthquake rupture (Figure 4b). In Figures 4c and 4d, the stress changes are projected onto the northern and southern segment of the 1903 Malazgirt earthquake rupture, respectively. Though Figure 4c indicates tiny stress decrease for the northern segment, the southern segment is exposed to the tiny stress increase caused by the 1891 earthquake rupture, as seen from Figure 4d. As for the 1941 Erciş earthquake, it is not stressed by neither all of the earthquakes in its background nor the 1903 Malazgirt earthquake alone (Figures 4e and 4f). Rather the 1941 Erciş earthquake rupture remains in the stress shadow of the previous earthquakes. In order to have an idea about the future earthquake hazard, stress condition of the Nazik Lake Fault is also investigated using the all earthquakes in the Lake Van area. Figure 4g indicates that SE part of the fault is strongly stressed by the background earthquakes while the Figure 4h indicates that the 1903 Malazgirt earthquake rupture is the main cause of the stress increase. In spite of the stress increase it is difficult to interpret its earthquake potential because there is no information about what is the earthquake recurrence interval along the fault and when did the last earthquake take place.

Conclusions

Coulomb stress changes of the earthquakes in the Lake Van area are calculated using available data and the likely source faults. It is shown that the large earthquakes in the Lake Area have been interacted with each other and most of the future earthquakes was stressed by the preceding earthquakes. This put forward usage of the Coulomb stress maps in interpreting the future earthquake hazard and its reduction.

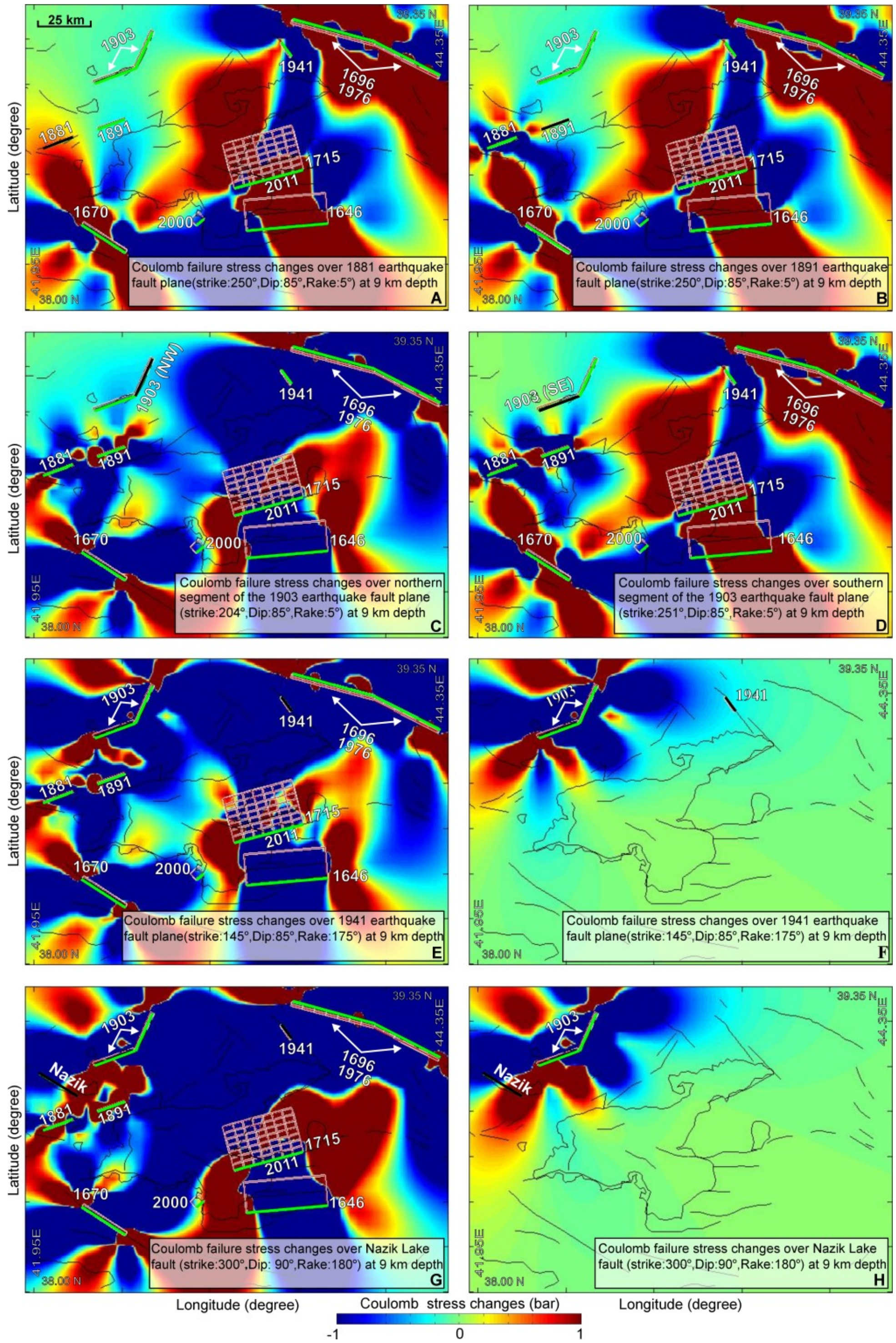

Figure 4. Maps of Coulomb stress changes related with the background earthquakes of the 23 October 2011 Van earthquake in the Lake Van area. The stress changes are estimated from the earthquakes that occurred before the target earthquake fault ruptures. The targets are (a) the 1881, (b) 1891 (c) NW and (d) SE segments of the 1903 Malazgirt, (e) and (f) 1941 Erciş earthquakes. In (g) and (h) the target is Nazik Lake Fault. Note that in (f) and (h), the stress changes are computed using only the 1903 Malazgirt earthquake rupture as a source.

References

[1] Toda, S., and Stein, R., “Toggling of seismicity by the 1997 Kagoshima earthquake couplet: A demonstration of time-dependent stress transfer”, J. Geophys. Res., 108(B12), 2567, 2003, doi:10.1029/2003JB002527.
[2] Steacy ,S., Marsan, D., Nalbant, SS., McCloskey, J., Nostro, C., Scotti, O., and Baumont, D., “Onto what planes should Coulomb stress perturbations be resolved?”, *J. Geophys. Res.*, 110, B05S15, 2005, doi:10.1029/2004JB003356.
[3] Raju, PS., Gahalaut, VK., Ravi, KM., “Phodong (Sikkim) earthquake of 14 February 2006 and its aftershocks-Coulomb stress analysis”, J Geodyn 46:63–67, 2008.
[4] Lasocki, S., Karakostas, VG., Papadimitriou, EE., “Assessing the role of stress transfer on aftershock locations”, J Geophys Res 114: B11304, 2009, https://doi.org/10.1029/2008JB006022
[5] Sato T, Hiratsuka S, Mori J., “Coulomb stress change for the normal fault aftershocks triggered near the Japan trench by the 2011 Mw 9.0 Tohoku-Oki earthquake”, Earth Planets Space 64:1239–1243, 2012
[6] Utkucu, M., Durmuş, H., Yalçın, H., Budakoğlu, E., Işık, E., “Coulomb static stress changes before and after the 23 October 2011 Van, Eastern Turkey, earthquake (M_W 7.1): Implications for the earthquake hazard mitigation”, *Natural Hazards and Earth System Sciences*, 13 (7), 1889-1902, 2013.
[7] Kassaras, I., Kapetanidis, V., Karakonstantis, A., Kaviris, G., Papadimitriou, P., Voulgaris, N., Makropoulos, K., Popandopoulos, G., Moshou, A., “The April-June 2007 Trichonis Lake earthquake swarm (W. Greece): new implications toward the causative fault zone”, J. Geodyn. 73, 60–80, 2014
[8] Stein, R.S. “Earthquake Conversations”, Scientific American, Vol. 288, No. 1, pp. 72-79, 2003.
[9] S. Toda, RS. Stein, GC. Beroza, D. Marsan, “Aftershocks halted by static stress shadows” Nat. Geosci., 5, pp. 410-413, 2012
[10] McClusky, S., et al., “GPS constraints on plate kinematics and dynamics in the Eastern Mediterranean and Caucasus”, *J. Geophys. Res.*, 105, 5695-5719, 2000
[11] Reilinger, R., et al., “GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions”, *J. Geophys. Res.,* 111, B05411, 2006, doi:10.1029/2005JB004051
[12] Şengör, AMC., Özeren, S., Genç, T., and Zor, E., “East Anatolian high plateau as a mantle-supported, north-south shortened domal structure”, *Geophys. Res. Lett*., 30(24), 8045, 2003, doi:10.1029/2003GL017858.
[13] Barka, A. and Kadinsky-Cade, K. “Strike-slip fault geometry in Turkey and its influence on earthquake activity”, *Tectonics*, 7, 663-684, 1988
[14] Adıyaman, Ö., Chorowicz, J., and Köse, O., “Relationships between volcanic patterns and neotectonics in Eastern Anatolia from analysis of satellite images and DEM”, *J. Volcanol. Geoth. Res.,* 85, 17–32, 1998[15] Koçyiğit, A., Deveci, Ş., and Kaplan, M., “Van Depremleri Raporu (23 Ekim-30 Kasım 2011)”*,* Aktif Tektonik ve Deprem Araştırma Laboratuvarı*,* Orta Doğu Teknik Üniversitesi, Ankara, Türkiye, 22 pp., 2011
[16] AFAD Van Depremi (23 Ekim 2011) Raporu, T.C. Başbakanlık Afet ve Acil Durum Yönetimi Deprem Dairesi Başkanlığı, Ankara, Türkiye, 100 pp., 2011
[17] MTA, “Maden Tektik Arama (MTA) Türkiye Yenilenmiş Diri Fay Haritası”, 2012. http://www.mta.gov.tr/v2.0/default.php?id=yeni_diri_fay_haritalari-goruntule,

[18] Ergin, K., Güçlü, U. ve Uz, Z., "Türkiye ve civarının deprem kataloğu", İTÜ yayınları, No: 24, 1967
[19] Ambraseys, N. N. and Finkel, C., "The Seismicity of Turkey and Adjacent Areas: A Historical Review", 1500-1800, *Eren Publication*, İstanbul, ISBN 975-7622-38-9, 240 pp., 1995
[20] Kalafat, D., Güneş, Y., Kara, M., Deniz, P., Kekovalı, K., Kuleli, S. H., Gülen, L., Yılmazer, M., and Özel, N, "A revised and extended earthquake catalogue for Turkey since 1900(M≥4.0)", Boğaziçi University, Kandilli Rasathanesi ve Deprem Araştırma Enstitüsü, Bebek-İstanbul, 553 pp., 2007
[21] Ambraseys, N., "Earthquakes in the Mediterranean and Middle East: A Multidisciplinary Study of Seismicity up to 1900", Cambridge University Press, 947 pp., 2009, ISBN 978-0-521-87292-8
[22] Albini, P., Demircioglu, M. B., Locati, M., Rovida, A., Sesetyan, K., Stucchi, M., and Vigano, D., "In search of the predecessors of the 2011 Van (Turkey) Earthquake", *Seismol. Res. Lett.*, 83, 5, 2012, doi: 10 .1785/0220110146
[23] Degens, E.T. and Kurtman F. (eds.), "The Geology of Lake Van" Miner. Res. Explor. Inst. Turkey, Ankara, 158 pp., and plates, Publ. No. 169, 1978
[24] Harris, R. A. "Introduction to special section: Stress triggers, stress shadows, and implification for seismic hazard", *J. Geophys. Res*., 103, 24347-24358, 1998
[25] Stein, R.S. "The Role of Stress in the Earthquake Occurrence", Nature, 402, 605-609, 1999
[26] Okada, Y., "Internal deformation due to shear and tensile faults in a half-space", B. Seismol. Soc. Am., 82, 1018-1040, 1992
[27] Lin, J. and Stein, R.S., "Stress triggering in thrust and subduction earthquakes and stress interaction between the southern San Andreas and nearby thrust and strike-slip faults", *J Geophys Res* 109, B02303, 2004, doi:10.1029/2003JB002607
[28] Toda, S., Stein, R., Richards-Dinger, K., Bozkurt, S., "Forecasting the evolution of seismicity in southern California: Animations built on earthquake stress transfer", *J Geophys Res* B05S16, 2005, doi:10.1029/2004JB003415
[29] Wells, D. L. and Coppersmith K. J., "New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement", *B. Seismol. Soc. Am.,* 84(4), 974-1002, 1994
[30] Utkucu, M., Pınar, A., Alptekin, Ö. "24 Kasım 1976 Çaldıran Depremi (Ms=7.3) İçin Telesismik P Dalga Şekillerinden Ters Çözümünden Elde Edilen Kırılma Modeli", *İstanbul Üniv. Müh. Fak. Yerbilimleri Dergisi*, 15(2), 25-36, 2002
[31] Utkucu, M., "23 October 2011 Van, Eastern Anatolia, earthquake (MW 7.1) and seismotectonics of Lake Van Area", *J. Seismol*, 17:783-805, 2013, doi: 10.1007/s10950-012-9354-z