Failure stress change caused by the 1992 Erzincan earthquake (Ms = 6.8)

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Abstract. We calculated Coulomb failure stress change caused by the March 13, 1992 Erzincan, Turkey, earthquake, and explored the relationship between failure stress and the aftershock distribution which includes the Püllümlü earthquake (Ms = 5.8) that occurred two days later. One of the most significant features of the Erzincan earthquake was the location of aftershocks, which did not correspond with either the eastern segment of the North Anatolian fault zone or the Ovacık fault. This feature can be explained by mapping the failure stress due to the Erzincan earthquake. The map revealed that there is a significant correlation between the aftershock distribution and the area where static stress was raised by 20.3 bar. The 1992 Erzincan earthquake raised the Coulomb failure stress about 1.4 bar at the site of the Püllümlü event. This stress rise and optimum orientation of the Püllümlü fault favored its occurrence.

Introduction

A severe earthquake in the eastern part of the North Anatolian fault zone (NAFZ), south west of the city of Erzincan in Turkey occurred on 13 March 1992, causing loss of life (over 600 casualties) and widespread damage. Beside a few local tectonic fractures, no clear surface breaks were observed (Barka, 1992). Thus, it was suggested that the fault lies under approximately 1.5-2 km thick sedimentary Erzincan basin (Fuenzalida et al., 1995). In this region the NAFZ has three segments; S-1, S-2 and S-3 (Fig. 1). Even though there is no clear surface break, there is no doubt that the main shock was on the S-2 segment of the NAFZ (Fuenzalida et al., 1995), because an earthquake of this magnitude with a right lateral movement parallel to the NAFZ in the area could only be produced by the NAFZ. Two days later, a large aftershock (Ms = 5.8) occurred about 40 km southeast of Erzincan near the town of Püllümlü. The epicenters of the Erzincan and Püllümlü earthquakes, relocated by Bernard et al. (1995), are shown in Figure 1.

Waveform inversion showed that the faulting mechanism of the Erzincan earthquake was almost pure right-lateral strike-slip in a good agreement with slip on the NAFZ (Evirdogan, 1992; Barka and Evirdogan, 1993, Fuenzalida et al., 1995). But waveform inversion for the Püllümlü earthquake showed both thrust and left lateral strike-slip components (Fig. 1) (Fuenzalida et al., 1995).

As can be seen from the aftershock distribution (Fig. 1), most of the aftershocks are located SE of the Erzincan basin and south of the S-3 segment, and also located on NE side of the S-2 segment. The S-3 segment last ruptured in 1784 (Ambrosey and Zatopek, 1968, Barka et al., 1988). The question here is why the rupture terminated in the town of Püllümlü instead of a previously known segment (S-3) of the NAFZ (Fuenzalida et al., 1995). In this study we investigate: a) why most of the aftershocks have occurred south west of the Erzincan basin but not on the previously broken S-3 segment (Fig. 1); b) if there is any correspondence between the areas where aftershocks are located and where Coulomb stress was raised; c) the Erzincan earthquake's effect on other nearby faults (i.e. S-1, S-3 segments, Ovacık fault and the northeast Anatolian fault (NEAF)).

We employ the same algorithm as Stein et al. (1992) and King et al. (1991), and examine triggering conditions. The approach is similar to that of Das and Scholz (1981), Stein and Lisowski (1983), Houghnet et al. (1989), Heasehnberg and Simpson (1992), Harris and Simpson (1992), and Jaume and Sykes (1992). The M=7.4 1992 Landers earthquake in California provided seismologists with an excellent opportunity to calculate static stress change induced by an earthquake and test its effect on other nearby faults. Three groups of scientists (Stein et al., 1992; Harris and Simpson, 1997; Jaume and Sykes, 1997) studied the Landers earthquake using the Coulomb criteria and predicted that the earthquake while relieving about 85 bars of stress on the fault, also added about 5 bars to a segment of the San Andreas fault near San Bernardino. Stein et al. (1992) concluded that the largest event, the Big Bear earthquake, that occurred near the Landers epicenter 3 hours 26 minutes later, was triggered by the Landers earthquake by raising the failure stress about 3 bars. These three groups also underlined that an earthquake can advance or delay the movement of a fault near the epicenter by increasing or decreasing the static stress. Harris et al. (1995) also indicated that, by studying 55 earthquakes that have occurred in southern California, changes in static stress on neighboring faults due to an earthquake may delay, hasten or even trigger subsequent earthquakes. They emphasized, in addition, that after a damaging earthquake in southern California, Coulomb failure stress modeling could be used in a 1.5-year period in terms of its influence on other faults. After this period, damaging earthquakes are equally likely to
rupture loaded and relaxed faults. Stein et al. (1994) calculated the failure stress generated by the 1994 M=6.7 Northridge earthquake and its predecessors. They showed the Coulomb stress transfer between the earthquakes, and the correspondence between areas with increased stress and aftershock distribution. Bennett et al. (1995) studied the slip distribution of the 1992 Joshua Tree earthquake by using geodetic and GPS data, and calculated Coulomb failure stress. They also noted the good correspondence between failure stress and aftershock distributions. The studies mentioned above and the others (i.e. Simpson and Reasenberg, 1994; Pollitz and Saacke, 1995) have shown that the Coulomb failure stress calculation is useful tool for studying subsequent earthquake interactions.

Method

The method used in this study was introduced by Stein et al. (1992), and the sensitivity of parameters tested by King et al. (1994). Here, we will briefly outline the method. There are a number of failure criteria which have been used in the literature to explain failure of rocks under stress conditions. The Coulomb criteria formulates the failure of rocks under laboratory conditions. This criteria also seems to explain failures in the earth (Jaeger and Cook, 1971). Based on the Coulomb criteria, the change in Coulomb failure stress, acting on a plane in the crust is defined by

\[ \Delta \sigma_c = \Delta \sigma_n + \mu (\Delta \sigma_s - \Delta P), \]

(1)

where \( \Delta \sigma_n \) and \( \Delta \sigma_s \) are the normal (positive tensile) and shear stress changes respectively, \( \mu \) is the coefficient of friction. \( \Delta P \) represents change of pore fluid pressure. If \( \Delta P \) is taken to scale with \( \Delta \sigma_n \) with a proportionality or Skempton's coefficient \( B \), then equation (1) may be rewritten

\[ \Delta \sigma_c = \Delta \sigma_n + \mu' (\Delta \sigma_s), \]

(2)

where \( \mu' \) is the effective coefficient of friction defined as (1-B) (Stein et al., 1992), and varies between 0.0 and 0.75 (Stein et al., 1992; 1994), also acceptable values for B generally range from 0 to 1. When Coulomb stress, \( \sigma_c \) equals or exceeds inherent shear strength of the rock, failure occurs. Pore fluid pressure acts to reduce the normal stress. The sign of \( \Delta \sigma_c \) only effects the direction of sliding, so its sign should be chosen appropriately. The failure stress and the optimum slip planes calculations were made for the values 0.1, 0.2, 0.4 and 0.75 of the \( \mu' \), and it was found that 0.2 was the most suitable for the study area.

The maximum changes in Coulomb failure stress occur on planes optimally oriented for failure (Stein et al., 1992), and thus most of the aftershocks might be expected to occur on small faults around the master fault which are optimally oriented for slip. The orientation of optimum failure planes is controlled by both the earthquake stress change and the existing regional stress (Stein et al., 1992; King et al., 1994). The direction of the regional stress also effects the distribution of failure stress around the master fault (King et al., 1994). The maximum change in Coulomb failure stress occurs when the \( \beta \), an angle between the failure plane and maximum principal stress is

\[ \tan 2\beta = \pm 1/4\mu'. \]

(3)

Total stresses are calculated by using a three-dimensional boundary element technique (Gomberg and Ellis, 1993, 1994) which includes the formulation of Okada (1992) for dislocation in an elastic half space. In this method, the surface of a fault can be represented by a rectangular area, and can be divided into subareas equally. The slip values can be assigned to these subareas in order to calculate the immediate response of the crust to the earthquake.

Input Data

Waveform inversion for the 1992 Erzincan earthquake resulted a complex source indicating multiple fracturing with a total seismic moment of \( 1.2 \times 10^{22} \) dyne-cm (Finar et al., 1994; Fuenzalida et al., 1995). Major energy release was due to a fault 30 km in length aligned along the NAFZ. Thus, we modeled the 1992 Erzincan earthquake by a fault 30 km in length and 12 km in width 1.5 km below the surface with a dip angle 63° SW (Fuenzalida et al., 1995). Bennett et al., (1995) modeled the 1992 Erzincan earthquake GPS data by using dislocations in an elastic half-space. We employed the slip magnitudes from the GPS modeling of Bennett et al. (1995) for the Erzincan earthquake, since no surface ruptures were observed. The amount of right-lateral slip along the rupture zone from NW to SE are 107.5, 143.3 and 90.1 cm respectively for 10 km sublengths of our 30 km long fault model. From the mechanical model derived by Fuenzalida et al. (1995) for the study area and information gathered from waveform inversion, we used a model fault of 8 x 8 km in size striking 233° SW and dipping 61° NW 1 km below the surface is used for simulation of the Puliirtur event. From waveform inversion a moment magnitude of 7.01 \( \pm 0.5 \times 10^{22} \) dyne-cm was calculated for the Puliirtur earthquake (Fuenzalida et al., 1998). By using an empirical moment magnitude relation (Acharya, 1979), we calculated a slip amount of 36.5 cm for this earthquake. Considering the thrust nature of the event, slip amount of 30.5 cm and 20 cm are assigned in the modeling for up dip and left lateral directions respectively.
Coulomb failure stress changes at a depth of 7 km caused by the Erzinçan and Pülümür earthquakes with the aftershocks occurring between 4 April and 10 April 1992 are shown in Figure 3. Most of the aftershocks occurred in regions where the stress is increased by ≥ 0.3 bar as a result of the main shock and the following Pülümür aftershock. A few aftershocks occurred in areas where the stress was reduced (Fig. 3).

The failure stress decrease along the 1992 rupture zone is related to the lack of detailed slip information. A more detailed description of the fault geometry would undoubtedly cause local stress areas near to the plain. The aftershocks, which occurred along the 1992 rupture zone, therefore, do not correspond with failure stress distribution of Figure 3. There is a 0.3 bar stress increase to east of S-3 segment of the NAFZ, where a few aftershocks are located. The eastern part of the NAFZ has a slip rate of 1–1.5 cm/year (Oral, 1994), and the S-3 segment last ruptured in 1784 (Ambroseys, 1975). Thus, it has an accumulated slip deficit of 211–312 cm, assuming a 75 km length and a 12 km width, corresponding to a single earthquake of M (moment magnitude) = 7.1. The Coulomb stress increased by 0.3 bar at the western end of the S-3 segment where some of the aftershocks occurred. In this area discontinuous surface breaks were observed after the Erzinçan earthquake (Barka, 1992). This stress increase could have caused these slight movements. The Ovacik basin, along part of the Ovacik fault, coincides with 0.3 bar stress increase. A few aftershocks are located in this area. There were no aftershocks along the NW part of the S-2 segment, because S-1 segment of the NAFZ broke in the 1939 Erzinçan earthquake (M=8.0) when the maximum slip was about 7.5 m (Barka, 1992). As a result of this slip, stress on S-1 was released and several centuries are required to re-establish high stress levels. A 1 bar stress increase is consequently too small to cause any seismic activity on this segment (Fig. 1 and 3). Some parts of the NEAF also showed an increase of Coulomb stress with no concentration of aftershocks.

**Results and Discussion**

The Coulomb stress change distribution on optimally oriented slip planes at a depth of 7 km due to the 1992 Erzinçan earthquake is shown in Figure 2. Calculated optimum left and right-lateral planes after the Erzinçan earthquake are also shown in Figure 2. In Figure 3 the azimuth of the aftershock cluster where the Pülümür earthquake occurred and the azimuth of the left lateral optimum plane is consistent. Although the Pülümür earthquake mainly had a thrust component, its azimuthal direction appears to be approximately parallel to left-lateral optimum plane direction (Fig. 2 and 3), which makes it favorable for failure. By knowing the orientation of the Pülümür fault from the focal mechanism solution of Fuenzalida et al. (1995), we calculated the Coulomb failure stress on the fault. We found that the stress was increased as much as 1.4 bars at the hypocentral depth (h = 4.1) of the Pülümür earthquake. Even though this stress loading is small, it seems that such changes can readily trigger a fault near to failure (King et al., 1994).

![Figure 2. Map views of calculated Coulomb failure stress changes associated with the 13 March 1992 Erzinçan earthquake of Ms=6.8. The Coulomb failure stress increase at the future Pülümür site is 1.4 bar. Note the correspondence between the geometry of optimum left lateral failure plane (white lines) and of Pülümür fault. White lines of the crosses on the map represent left-lateral optimum planes while blacks represent right-lateral ones. Stress is sampled at 7 km depth.](image)

![Figure 3. Map showing the aftershock activity and the Coulomb failure stress change caused by the Erzinçan and Pülümür earthquakes. Note the good correlation of aftershock activity with the areas where the failure stress was increased. Stress is sampled at 7 km depth.](image)
Conclusions

The Coulomb failure stress increase distribution caused by the 1992 Erzincan earthquake was calculated and mapped. This mapping revealed that the Erzincan earthquake increased the Coulomb failure stress as much as 1.4 bars in the Pültümür area and assisted with the triggering of the Pültümür earthquake of 15 March 1992. Summing the Coulomb stress changes for both the Erzincan and Pültümür earthquakes showed that most of the aftershocks occurred in regions where the failure stress was raised by $\geq 0.3$ bar, and very a few occurred where the failure stress dropped. Due to the change of the azimuthal geometry of S-2 and S-3 segments from 122° to 108° the failure stress increase only affected the western end of S-3 segment (about 0.3 bar) where some aftershocks were located. Therefore, rupture did not continue on the S-3 segment. The Ovacik fault, in the Ovacik basin coincides with a 0.3 bar stress increase, in which a few aftershocks were also located. The Coulomb stress increased on some parts of S-1 segment of the NAFZ and the NEAF. They have not reactivated, presumably because accumulated seismic energy had been released by previous seismic activity (i.e., 1939 Erzincan and 1939 Tercan earthquakes).

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