Turkish Journal of Earth Sciences (Turkish J. Earth Sci.), **Vol. 12**, 2003, pp. 91-103. *Copyright ©TÜBİTAK*

Coulomb Stress Interactions and the 1999 Marmara Earthquakes

ZİYADİN ÇAKIR[1], AYKUT A. BARKA[2] & EMRE EVREN[2]

[1] İstanbul Technical University, Faculty of Mines, Department of Geological Engineering,
Ayazağa, TR-80626 İstanbul, Turkey (e-mail: cakirz@itu.edu.tr)
[2] İstanbul Technical University, Institute of Eurasian Earth Sciences, Ayazağa, TR-80626 İstanbul, Turkey

Abstract: The effects of previous earthquakes on the 1999 İzmit and Düzce earthquakes, the influence of the İzmit earthquake on the Düzce earthquake, and the seismic hazard in the Marmara region are investigated using Coulomb failure stress. Calculation of the Coulomb stress changes using the fault parameters deduced from the modelling of the coseismic Synthetic Aperture Radar Interferometry (InSAR) and GPS data shows that the İzmit earthquake occurred where the Coulomb stress was increased by the previous events. Despite the stress decrease on the Düzce Fault due to the events before 1999, the Düzce earthquake appears to have been triggered by the high increase in the static Coulomb stress transferred by the İzmit earthquake. The Düzce and the previous earthquakes increased the static stress in western and eastern Marmara by over 5 bars. Calculation of secular stress loading based on the modelling of interseismic GPS measurements shows that stress accumulation along the northern branch of the North Anatolian Fault Zone is 0.37 bars per year. Thus, a stress increase of 5 bars corresponds to an increase normally accumulated in 12–13 years by secular loading due to continuous plate motion. In other words, the previous earthquakes brought forward the next earthquake in the Sea of Marmara by 12 years. The faults in this region therefore pose a serious seismic hazard, particularly for İstanbul.

Key Words: 1999 Marmara earthquakes, Coulomb stress, earthquake hazard

Coulomb Gerilme Etkileşimleri ve 1999 Marmara Depremleri

Özet: Bu çalışmada, Coulomb gerilme yöntemi kullanılarak, 1999 yılı öncesinde Marmara bölgesinde oluşan büyük depremlerin 17 Ağustos 1999 İzmit ve 12 Kasım 1999 Düzce depremlerini nasıl etkilediği, İzmit depreminin Düzce depremine olan etkisi ve günümüzde Marmara bölgesindeki deprem tehlikesi araştırıldı. InSAR ve GPS verileriyle bulunan fay parametrelerinin kullanıldığı Coulomb gerilim hesaplamaları İzmit depreminin, önceki depremlerden kaynaklanan statik gerilme artışının oluştuğu bir alanda meydana geldiğini göstermektedir. 1999 yılı öncesi depremlerin Düzce Fayı üzerindeki gerilimi azaltmasına rağmen, Düzce depreminin İzmit depreminden kaynaklanan yüksek gerilim artışı nedeniyle tetiklendiği sonucu bulunmaktadır. Düzce ve öncesinde oluşan depremler batı ve doğu Marmara bölgesindeki gerilmeyi 5 bar'ın üzerinde arttırmıştır. İntersismik GPS gözlemlerine dayalı modellerden elde edilen Coulomb hesaplamalarından, KAFZ'nun kuzey kolu üzerinde yıllık gerilim miktarının 0.37 bar civarında olduğu ortaya çıkmaktadır. Dolayısı ile 5 bar'lık gerilme artışı normalde 12–13 yılda birikmektedir. Diğer bir deyişle, önceki depremler Marmara Denizi'nde meydana gelecek bir depremi 12–13 yıl öne almıştır. Dolayısı ile Marmara Denizi altındaki faylar özellikle İstanbul için ciddi bir deprem potansiyeli oluşturmaktadır.

Anahtar Sözcükler: 1999 Marmara depremleri, Coulomb gerilimi, deprem tehlikesi

Introduction

The 17 August 1999 (Mw=7.4) İzmit and 12 November 1999 (Mw=7.2) Düzce earthquakes occurred in eastern Marmara, causing an extensive destruction in a heavily industrialised and populated region of Turkey (Barka *et al.* 2002; Akyüz *et al.* 2002; Hartleb *et al.* 2002) (Figure 1). The İzmit earthquake was not a surprise because the site has long been identified as a seismic gap (Toksöz *et al.* 1979, 1999). Taking into account the space-time migration of the earthquakes along the North Anatolian Fault Zone (NAFZ) in the 19th and 20th centuries, Toksöz *et al.* (1979) pointed out that the portion of the NAFZ (29°–30° E) in İzmit Bay area posed a seismic hazard associated with an earthquake of magnitude 6 or greater.

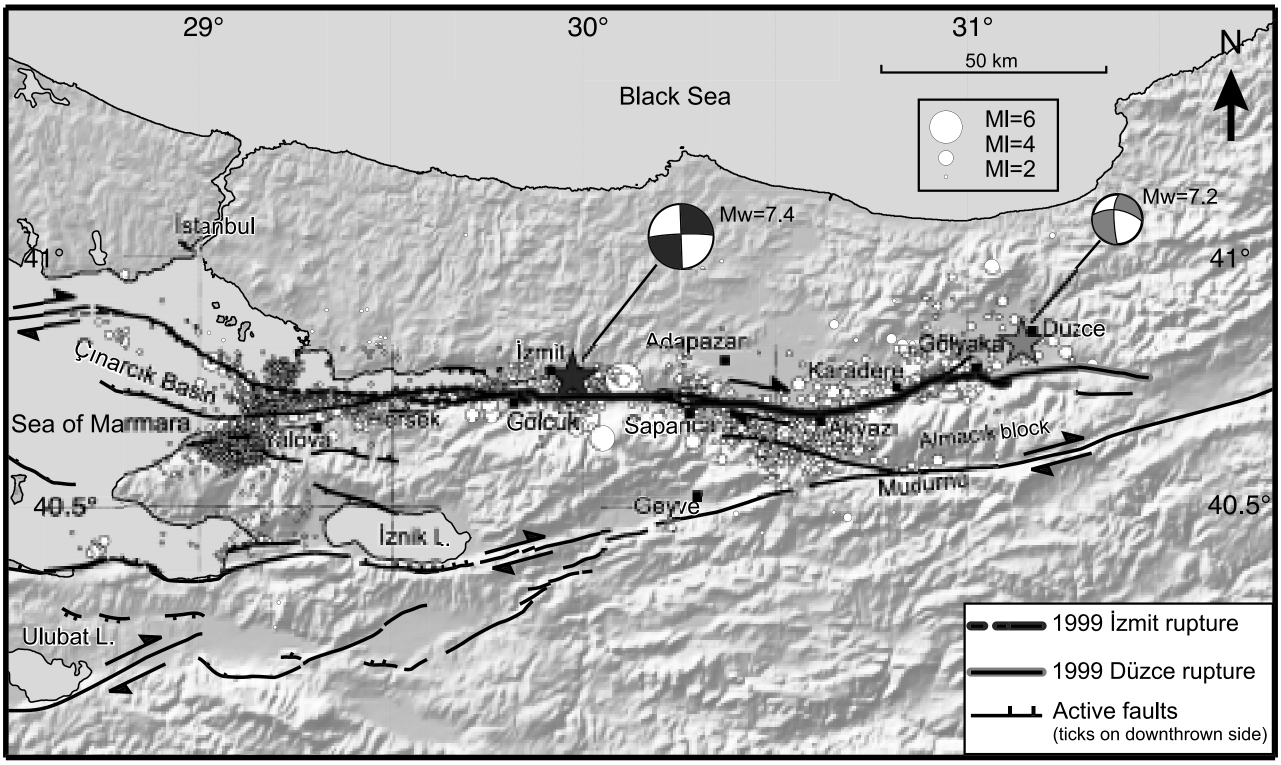

Figure 1. Active faults and the 1999 İzmit and Düzce earthquake breaks in the Marmara region. Aftershocks are from Özalaybey *et al.* (2002).

Recently, before the İzmit earthquake, the progressive failure of the NAFZ, particularly during the last century, has also been interpreted in terms of Coulomb stress interaction (i.e. triggering due to increases in Coulomb stress) (Stein *et al.* 1997; Nalbant *et al.* 1998). Coulomb analysis of the westward migrating earthquake sequence since the 1939 Erzincan event (Stein *et al.* 1997), and analysis of historical earthquakes in the Marmara region (Nalbant *et al.* 1998) also showed that the Gulf of İzmit was subject to the threat of an earthquake. The Düzce earthquake was also expected by Barka (1999), who, after the İzmit earthquake, taking into account the earthquake sequence of the 20th century and its slip distribution along the NAFZ around the Almacık block (Figure 1), concluded that not only the area to the western end of the İzmit rupture but also the Düzce Fault to the east might break in the near future.

In recent years, the analysis of Coulomb stress changes due to coseismic dislocation has been widely applied to investigate the variation in failure stresses on known faults (Harris & Simpson 1992; Stein *et al.* 1992, 1994, 1997; King *et al.* 1994; Hubert *et al.* 1996; Harris 1998; Nalbant *et al.* 1998; Toda *et al.* 1998; Hubert-Ferrari *et al.* 2000; King & Cocco 2000). These studies show that earthquakes cause static stress changes on neighbouring faults that may delay, hasten or trigger subsequent earthquakes. Therefore, the determination of stress changes is important in seismic hazard assessments.

After the 1999 earthquakes, one or two earthquakes as great or greater than the İzmit earthquake (Mw=7.4) are now expected to occur within the submarine fault system that extends west of the İzmit Fault under the Sea of Marmara, adjacent to İstanbul (Barka 1999; Hubert-Ferrari *et al.* 2000; Parsons *et al.* 2000; Ambraseys 2001; King *et al.* 2001; Atakan *et al.* 2002). Coulomb analysis of the 1999 Marmara earthquakes has been performed previously by several researchers (Hubert-Ferrari *et al.* 2000; Parsons *et al.* 2000; Papadimitriou *et al.* 2001; Pınar *et al.* 2001). However, different researchers have used different fault parameters, and hence have found varying results. In this study, the fault geometry and slip distribution used in the Coulomb stress calculations are those obtained directly from InSAR and

GPS modelling. As they explain the geodetic data very accurately (Çakır 2003), maps of stress changes determined using them are thought to better represent the actual stress distribution. Here, the Coulomb stress changes due to four large earthquakes are calculated to map the static stress distribution on both the İzmit rupture plane and its surrounding regions prior to the İzmit event. Then the stress changes caused by the İzmit event on the Düzce rupture and the stress changes around the Sea of Marmara are investigated.

Method

When an earthquake occurs, it changes the state of stress on nearby faults. In order to estimate the state of stress, the Coulomb failure stress is calculated using elastic dislocations on rectangular planes in a homogeneous and isotropic half-space following Okada (1985). The change in Coulomb stress $\Delta\sigma\phi$ is given by

$$\Delta\sigma\phi = \Delta\tau - \mu' \Delta\sigma\nu \qquad (1)$$

where $\Delta\tau$ is the change in shear stress (positive in the direction of slip) and $\Delta\sigma\phi$ is the change in effective normal stress (positive in compression) on target faults. μ' is the effective coefficient of friction with a range 0.0–0.8 (King *et al.* 1994). Here, the effective friction coefficient is assumed to be 0.4 in all calculations. A μ' of 0.4 minimises the calculation error caused by the uncertainty in μ' to ± 25% (King *et al.* 1994). Failure is facilitated on specified or optimally oriented faults when the Coulomb failure stress, $\sigma\phi$, rises. Unless specified, the optimal fault orientation is defined by the given regional stress field (Anderson 1951).

The accuracy of the Coulomb stress changes due to an earthquake depends mainly on the accuracy of the source parameters of that earthquake (i.e. the location and geometry of the fault rupture, and the amount and sense of slip distribution). The more accurate the source parameters the more reliable results, and thus interpretations can be made. A reliable estimate of the slip distribution and fault geometry is therefore very important for stress transfer calculations. Small differences in slip distribution and fault geometry can lead to significant perturbations in the Coulomb failure stress. Further details of the technique can be found in King *et al.* (1994).

Coulomb Stress Field Prior to the 1999 İzmit Earthquake

The Coulomb stress field caused by four large earthquakes that occurred on the northern branch of the NAFZ in northwestern Turkey prior to the 1999 İzmit earthquake is shown in Figure 2a. The stress increase due to continuous loading of the NAFZ (secular stress) is not taken into account because the history of previous earthquakes on all faults is not known. The total stress accumulation cannot be deduced because it is not known very well which historical earthquake broke which portion of the fault system, particularly in the Sea of Marmara region. The four earthquakes are the Ms=7.4 1912 Ganos, Ms=7.3 1944 Gerede, Ms=7.0 1957 Abant and Ms=7.1 1967 Mudurnu earthquakes. Some smaller events, such as the 1935 west Marmara (Ms=6.4), 1943 Hendek (Ms=6.4), and 1963 east Marmara (Ms=6.4) earthquakes, are not taken into account because their fault parameters (in particular the location) are poorly known and their contribution to the İzmit earthquake is thought to be insignificant. One of these small earthquakes, however, is thought by King *et al.* (2001) to control the propagation of the İzmit rupture. The İzmit rupture terminated about 30 km west of Hersek. According to King *et al.* (2001), the reason why the rupture stopped there is that the western termination of the rupture is located in a stress shadow induced by the Ms=6.4 1963 east Marmara earthquake. However, the exact location of this event is a matter of debate (Nalbant *et al.* 1998). Seismic focal mechanism solutions indicate that it is a normal faulting event, but as the location of the event could not be resolved very well it is not known whether the event occurred on the north-dipping or south-dipping boundary fault of the Çınarcık Basin. All the modelled earthquakes produced surface break and were mapped in the field (Ergin 1969; Ambraseys & Zatopek 1969; Barka 1996; Ambraseys & Jackson 1998; Barka & Kadinsky-Cade 1988; Altunel *et al.* 2000a, b). Thus, their locations and surface slip distributions are well known. Moment magnitudes calculated from the source parameters used in Coulomb modelling are consistent with seismological estimates.

The Coulomb stress distribution on optimally oriented strike-slip faults shown in Figure 2a indicates that the faults in the Sea of Marmara region are stressed by the previous earthquakes at two locations: the İzmit region in the east and the Marmara region in the west. The stress

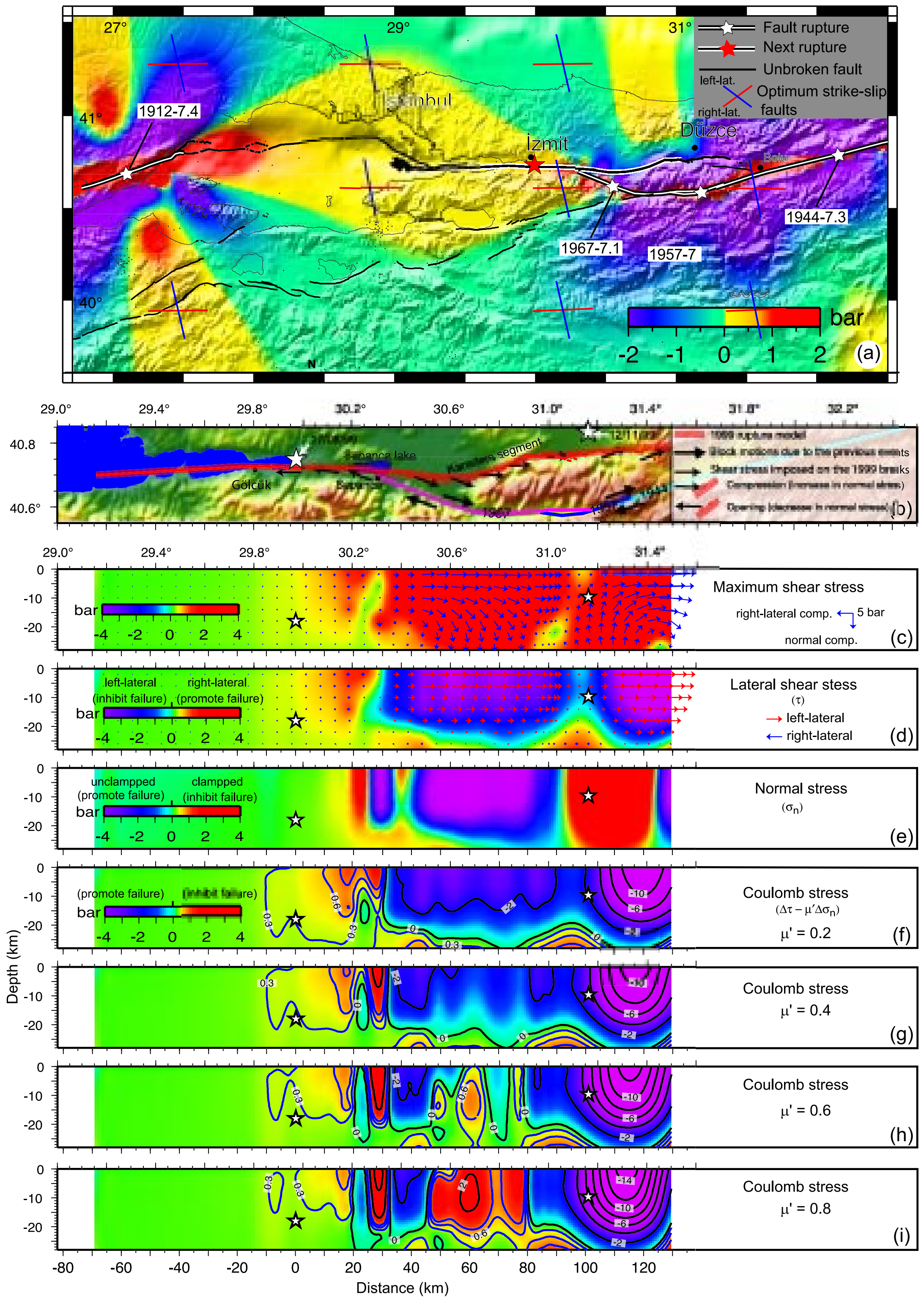

Figure 2. Coulomb stress changes prior to the 1999 İzmit earthquake due to previous events. **(a)** Coulomb stress changes on optimally oriented strike-slip faults (sampled at 10-km depth). **(b)** Shaded topographic map with 1999 breaks. Arrows show block motions due to previous earthquakes. **(c-i)** Resolved stresses on the Düzce and İzmit ruptures.

increase in the epicentral area of the upcoming 1999 İzmit earthquake is about 0.3 bars. On the other hand, the Düzce area is located in a stress shadow.

The trend and type of the optimum faults are set indirectly by accepting a regional stress field in which the maximum and minimum stresses are horizontal with a compression axis (150 bars) trending N30°W. This definition results in a set of two conjugate strike-slip faults of optimal orientation at each calculation point, one being left lateral and the other right lateral (Figure 2a). The right lateral set of faults trends E–W, consistent with the overall trend of the NAFZ in the region. Therefore, the stress change along the fault shown in Figure 2a is not a real representation of the stress change along the entire fault as the fault strike deviates from its general E–W trend. Consequently, instead of calculating the Coulomb stress change on optimally oriented faults, stress changes resolved on the İzmit and Düzce ruptures themselves are calculated. Stress change at the centre of each fault patch used in InSAR modelling is calculated and then all the values found are interpolated. The advantage of this method is that the spatial distribution of the resolved stress on the entire rupture can be visualised and thus the variation in stress can be seen in 2D (Figures 2c–i).

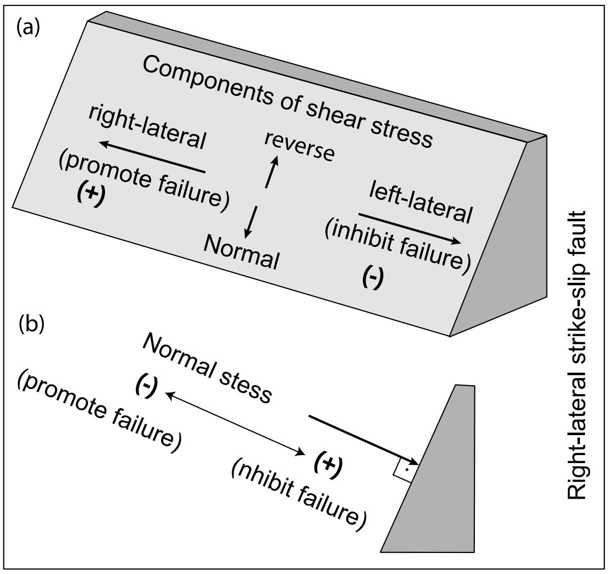

Figure 3. Block diagram illustrating the convention used here for the sign and sense of the shear and normal stresses.

The shear stress imposed on the 1999 İzmit and Düzce ruptures due to previous earthquakes (i.e. 1912, 1944, 1957 and 1967) is shown in Figure 2c (for simplicity the Düzce rupture is assumed to be vertical here). The sense and magnitude of the shear stress on the 1999 rupture surface varies both along the strike and with depth. This is because the geometric relationship between the previous ruptures and the 1999 rupture varies from place to place. As the strike of the 1999 rupture and its location with respect to the previous ruptures varies, a variety of fault kinematics are promoted by the block motion induced by the previous earthquakes (Figures 2b & 3). Because the 1967 Adapazarı rupture strikes at an angle to the İzmit rupture and its western termination is located in the vicinity of the town of Sapanca, mostly left-lateral strike-slip with normal and reverse components is encouraged to the east of Sapanca, whereas only right-lateral strike-slip with a reverse component is promoted to the west of Sapanca (Figures 2c & d). While the shear stress being right-lateral (promote failure) or left-lateral (inhibit failure) depends on whether the 1999 ruptures are located to the west or east of the western end of the 1967 rupture, the shear stress being reverse or normal and hence the normal stress being compressive (clamping effect [inhibit failure]) or dilatational (unclamping effect [promote failure]) depends on the angle between the 1999 ruptures and the previous ones (Figures 2b, c & e). The distribution of the Coulomb stress can be divided into two distinct parts: (1) the west Sapanca section, on which stress is entirely increased; and (2) the east Sapanca section, on which stress is mostly reduced (Figure 2f). A lobe of high stress increase reaching 2.5 bars occurs in the vicinity of Sapanca, mostly due to the edge effect. Except for this part, the increase in Coulomb stress along the rupture is quite low (<1 bar). It is about 0.3 bars around the İzmit hypocentre. However, if the calculations are made using different values of μ', the distribution and the amount of the Coulomb stress change along the rupture surface will differ. When μ' is increased the Coulomb stress around the hypocentre decreases. On the other hand, with increasing values of μ' the Coulomb stress change along the Karadere segment and south of Adapazarı becomes higher and higher and becomes positive (red) as a result of the high normal stress decrease there (Figures 2f–i). In contrast to the Karadere segment, with increasing values of μ' the Coulomb stress decrease along the Düzce rupture becomes lower and lower, revealing the segmentation of the NAFZ due to the difference between the strike of the Karadere and Düzce faults. Therefore, the clear difference between the Karadere and Düzce segments revealed in the distribution of the Coulomb stress change with increasing μ' may have been one of the factors that prevented the Düzce Fault from breaking simultaneously with the İzmit earthquake.

With any coefficient of friction value, it is clear that the İzmit earthquake nucleated in an area of enhanced stress (Figures 2f–i). If μ' is assumed to be 0.4 or smaller, its rupture also propagated towards the east into the stress shadow. Thus, if that is a reasonable value for μ', then the stress shadow in this region did not stop the rupture (although it might have hindered it). Propagation of the earthquake ruptures into the stress shadow is not paradoxical and can occur as observed in the case of the 2000 Hector Mine earthquake after the 1992 Landers event (Fred & Lin 2001; Pollitz & Sacks 2002).

Calculation of secular stress loading based on the modelling of interseismic GPS measurements (McClusky *et al.* 2000) shows that stress accumulation along the northern branch of the NAFZ is 0.37 bars per year (Figure 4), which is consistent with King *et al.* (2001), who suggest a 0.4-bar increase per year. Accordingly, ~0.3 bars of stress increase induced by the previous events at the hypocentre of the İzmit event is loaded by the continuous plate motion in about a year. Thus, the İzmit earthquake is weakly promoted by the previous

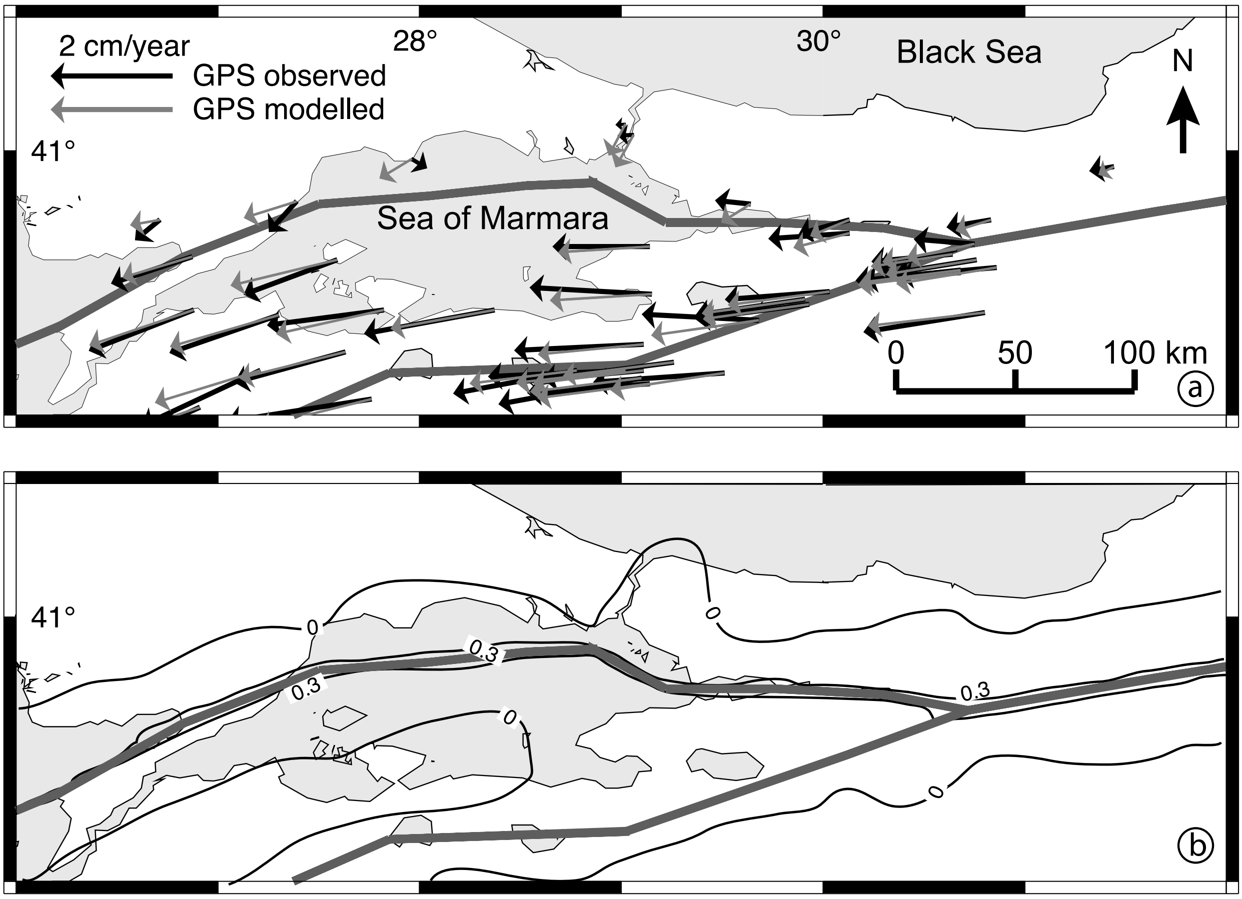

Figure 4. Stress accumulation induced by loading due to continuous plate motions in the Sea of Marmara region. (a) Modelling GPS measurements (McClusky *et al.* 2000) showing the motion of the Anatolian block relative to the erosion plate. Thick grey lines are the North Anatolian Fault Zone that bounds the two plates. Faults are assumed to be locked at 15-km depth, below which plate motion is continuous at a slip rate of 3 cm per year on the northern branch and about 0.8 cm per year on the southern branch of the NAF. (b) Annual stress loading at 10-km depth derived from the model in (a), which is about 0.37 bars per year on the northern strand.

earthquakes. One of the reasons for this low stress increase is the trend of the 1967 rupture. Because it trends in the NW–SE direction (Figure 2a), the Coulomb stress increase caused by this event is not significant on the E–W-trending faults. In addition, the slip on this rupture is assumed to be pure strike-slip, consistent with field observations. If, however, the event is in fact associated with some oblique normal component, then the Coulomb stress increase will be higher.

Coulomb Stress Changes Induced by the İzmit Event and Its Effect on the Düzce Earthquake

There have been several Coulomb models of the İzmit earthquake published by different researchers. Although they are roughly the same, there are some significant differences in the distribution and amount of static stress changes between the models. The differences arise mainly from the different rupture geometry and slip distribution of the earthquake used in the calculations. As a result, seismic hazard analysis based on each model will be different. Therefore, here the fault parameters of the İzmit earthquake used in the Coulomb stress calculations come directly from the modelling results of the geodetic data. As they explain the InSAR and GPS observations within the resolution uncertainties of the geodetic data set, maps of the Coulomb stress changes using such sources are more reliable.

The distribution of the Coulomb stress changes on optimum strike-slip faults calculated in this study are shown in Figure 5a. The aftershocks are mostly located in regions of stress increase on optimally oriented strike-slip faults and thus they are most likely to be triggered due to the Coulomb stress transfer. It is interesting to see that although Coulomb stress increased by well over 4 bars in the Düzce region, seismic activity was very low there prior to the Düzce earthquake.

The Coulomb stress changes resolved on the Düzce rupture due to previous events, including the İzmit earthquakes, are shown in Figure 5d. Based on InSAR and GPS modelling, the rupture is assumed to be associated with multiple faults (Çakır *et al.* 2003). The shear stress on the rupture caused by the 1944, 1957 and 1967 events is left lateral (inhibit failure) and the normal stress, which is about 2 bars around the hypocentre of the upcoming Düzce earthquake, is mostly compressive (inhibit failure). Therefore, these events do not promote seismic activity on this fault as it is a right-lateral fault and the normal stress is high (Figure 5d1). The Coulomb stress decrease due to previous events around the hypocentre of the upcoming Düzce earthquake is 1–2 bars before the 1999 İzmit earthquake. In contrast to the previous events, the İzmit earthquake imposes right-lateral shear on the Düzce rupture and increases the Coulomb stress around the Düzce hypocentre 4–6 bars (Figure 5d2). Therefore, the İzmit earthquake removes the Düzce Fault from the stress shadow and promotes the Düzce earthquake (Figure 5d3).

Coulomb Stress Field around the Sea of Marmara after the Düzce Earthquake

The Coulomb stress change around the Marmara region after the Düzce and previous earthquakes is shown in Figure 5c. There are three regions of enhanced stress: Bolu, west Marmara and east Marmara.

The area of enhanced stress to the east of the Düzce rupture remains because of the 12–15-km-long gap between the 1944 rupture and the eastern termination of the Düzce rupture. The Düzce Fault splays from the southern branch of the NAFZ in a complex stepover, within which several intervening short faults accommodate the transfer of slip between the northern (i.e. Düzce Fault) and southern branches. Detailed palaeoseismological studies (Altunel *et al.* 2000a, b; Barka *et al.* 2001; Hitchcock *et al.* 2003) suggest that this area should not be considered a potential seismic gap that could produce events larger than magnitude 6.

The submarine fault system in the Sea of Marmara is stressed from both edges in the east and west by over 5 bars. In order to reveal the distribution of the Coulomb stress change on the main Çınarcık Fault in the east, first a 34-km-long fault with 2 x 2 km patches to a depth of 20 km (170 patches in total) is formed and then the Coulomb stress change on each fault patch due to the İzmit and previous earthquakes is calculated (Figure 6). The location and geometry (dipping 85°SW) of the fault are constrained by the high-resolution bathymetry data and deep seismic profiles (Le Pichon *et al.* 2001; Armijo *et al.* 2002; Singh *et al.* 2002). As shown in Figure 6, the Coulomb stress change is maximum (over 5 bars) close to the end of the İzmit rupture and decreases westwards and downwards. The shear stress induced by previous earthquakes (mostly the İzmit event) on the main

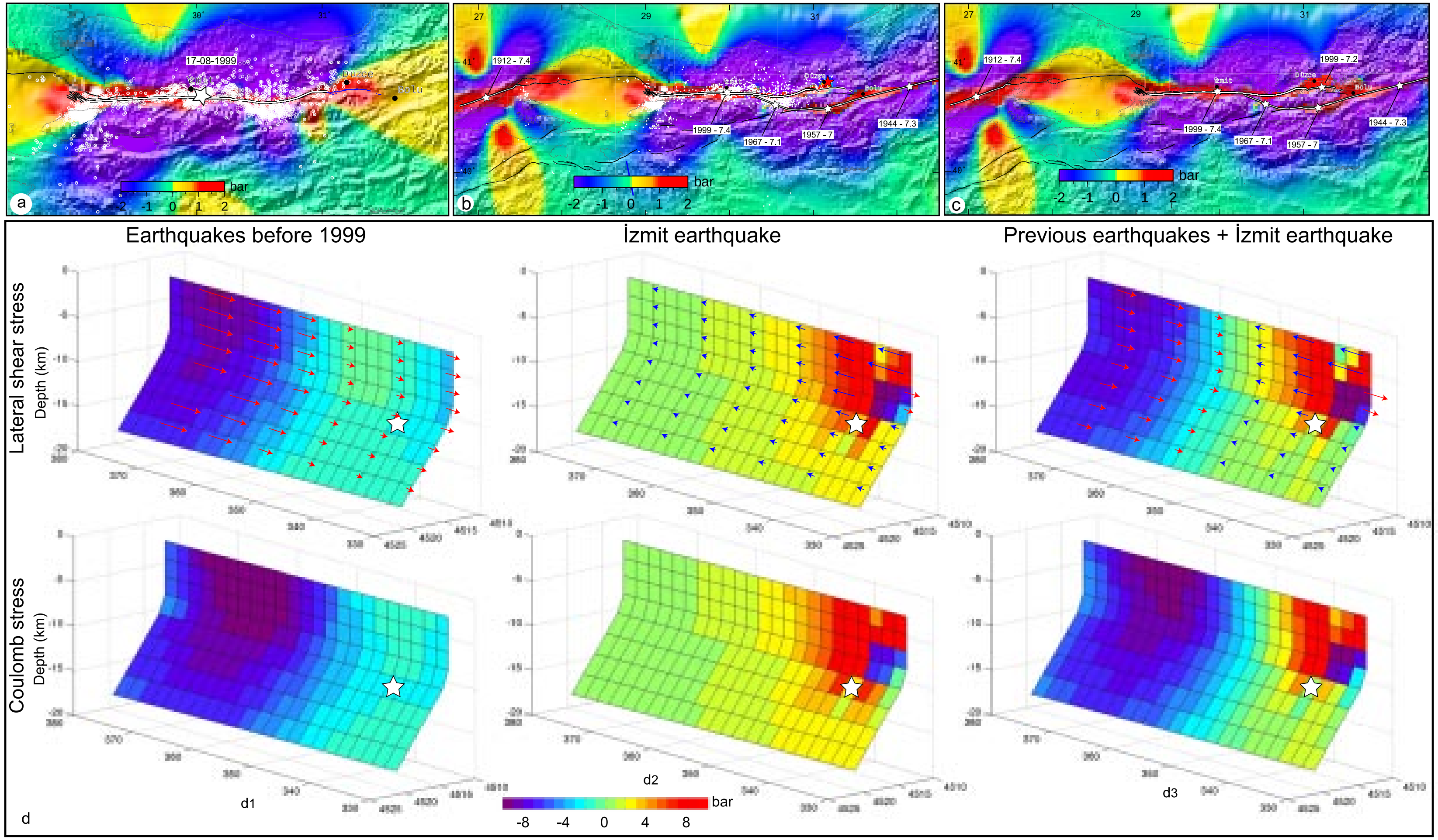

Figure 5. (a) Coulomb stress changes caused by the 1999 İzmit earthquake. (b) Coulomb stress field prior to the 1999 Düzce earthquake. (c) Coulomb stress field in the Marmara region after the Düzce earthquake. (d) Resolved stress on the Düzce rupture induced by the previous earthquake.

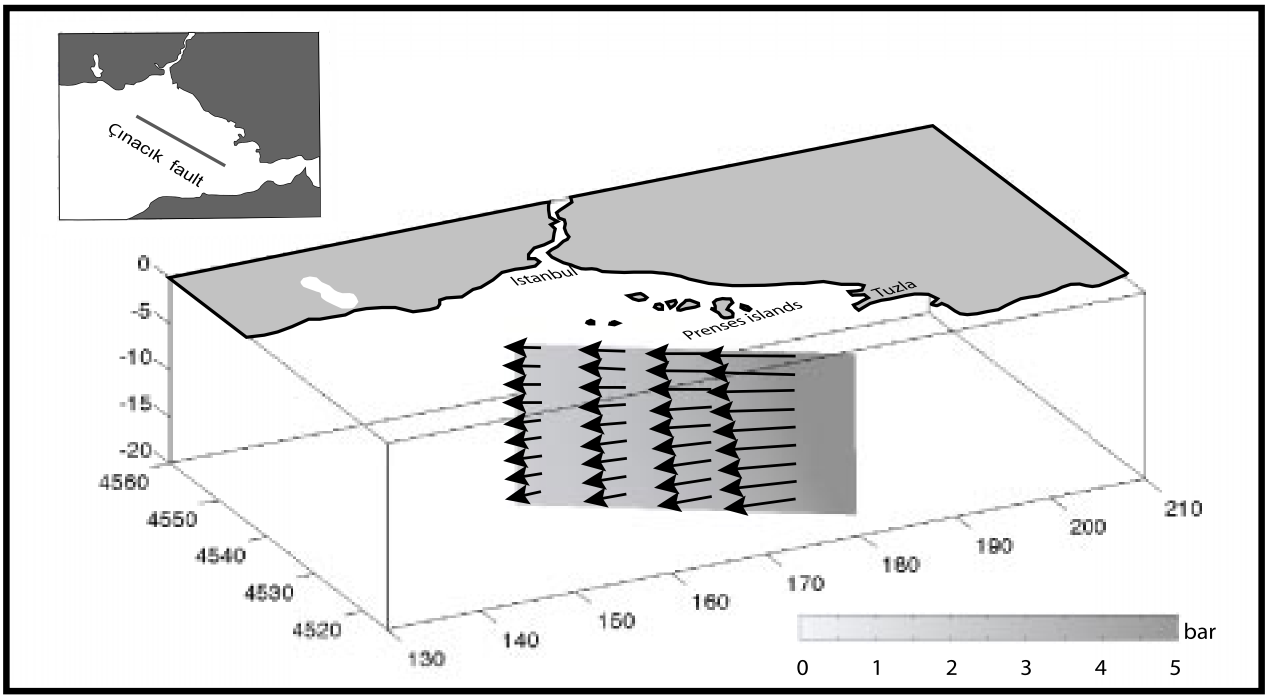

Figure 6. Coulomb stress changes on the main Çınarcık fault due to previous earthquakes. Arrows indicate the sense (right-lateral) and magnitude of the maximum shear stress.

Çınarcık Fault is dominantly strike-slip with a minor normal component (Figure 6). Therefore, the strike-slip aftershocks that have occurred along this fault (Özalaybey *et al.* 2002) were most likely triggered by transient stress changes induced by the İzmit earthquake and thus they do not necessarily confirm the long-term kinematics of this fault.

Figure 5c assumes that the rupture of the 1912 Ganos earthquake terminated in the Tekirdağ Basin. If, however, it continues further east, then the area of stress increase will be shifted eastward, in which case the stress transfer onto the central part of the NAFZ and onto the Çınarcık Fault will be much higher.

Results and Discussion

At present, the Sea of Marmara region is located in an area of enhanced stress increase due to large earthquakes (Ms > 7) since the 1912 Ganos event (Figure 5c). The 1912 and 1999 events, in particular, increased the static stress over 5 bars on the submarine fault system in the east and west, respectively. A stress increase of 5 bars corresponds to an increase normally accumulated in about 12 years by secular loading due to continuous plate motion. In other words, the previous earthquakes brought forward the next earthquake in the Sea of Marmara by 12 years. The faults in this region therefore pose a serious seismic hazard, particularly for İstanbul, where over 12 million people live.

Although it is under debate (Le Pichon *et al.* 2001), detailed studies by Armijo *et al.* (2002) based on the high resolution bathymetry data and deep seismic profiles suggest that the NAFZ in the Sea of Marmara is fragmented into three segments of about 140 km in total length. If this is the case, as only one or two neighbouring segments may break, the three segments may break at once in the future as well. In the latter case, the empiric formula between the rupture length (L) and the earthquake magnitude (Mw) (Mw= 4.95 + 1.2 logL) (Wells & Coppersmith 1994; Anderson *et al.* 1996) suggests that the earthquake should be around 7.5. If, however, the 1912 Ganos rupture extends to the central basin, then the length of the NAFZ that poses a seismic risk for the Marmara region and thus the magnitude of the future earthquake will be smaller (~80 km). If one or two segments simultaneously break, then the question is whether the future earthquake will occur in the eastern or western Marmara region. Considering the westward migration of earthquakes since the 1939 Erzincan event, one can suggest that the earthquake will likely occur in the eastern Marmara region. However, the history of the large earthquakes that occurred in the Sea of Marmara must be known better to answer this question with confidence. Historical records on the past earthquakes give clues about which earthquake broke which fault (Ambraseys & Finkel 1991; Ambraseys 2001), but they are inadequate. Submarine studies on the Marmara faults by a CNRS-TÜBİTAK (French-Turkish) cooperation are planned to reveal the history of the earthquakes in this region.

In Coulomb-based seismic hazard studies, if available, well-constrained source parameters should be used. The locations of aftershocks after an earthquake can be better predicted by using better source parameters of that earthquake. However, Coulomb models that predict the location of aftershocks fairly well do not necessarily suggest that they represent the actual distribution of stress change. For example, dismissing the segment west of Hersek deduced from geodetic data (Reilinger *et al.* 2000; Armijo *et al.* 2000; Wright *et al.* 2001), Pınar *et al.* (2001) prefer a much shorter coseismic rupture for the İzmit earthquake because their Coulomb model with such a short rupture predicts the aftershocks, particularly those around Yalova, better than the model with a longer fault rupture that continues west of Hersek. When discussing the location of aftershocks in relation to the Coulomb stress changes, what is commonly forgotten and thus not taken into account is the kinematics of the aftershocks. The distribution of the Coulomb stress changes on different types of optimal faults (i.e. strike-slip, normal and thrust) will vary. Therefore, if for example the changes in Coulomb stress are calculated for optimally oriented strike-slip faults, there may be no relation between the changes in stress and the location of the normal faulting aftershocks. For example, focal mechanism solutions of the aftershocks in the Yalova region show that most of them are purely normal faulting events (Özalaybey *et al.* 2000; Örgülü & Aktar 2001; Pınar *et al.* 2001). Thus, in order to suggest whether these earthquakes were triggered by Coulomb stress transfer or not, one should calculate the Coulomb stress changes on optimally oriented normal faults, not optimally oriented strike-slip faults as suggested by Pınar *et al.* (2001).

Thus, care must be taken when evaluating the fault parameters of an earthquake on the basis of the correlation between the aftershock distribution and Coulomb stress changes. After all, not all the aftershocks are directly related to the Coulomb stress increase as some other factors such as dynamic stresses, fluid movements, viscoelastic relaxation of the lower crust or upper mantle, after-slip and complex fault systems probably play a role in the locations of the aftershocks. The Yalova cluster appears to be a good example of induced seismic activity unrelated to static stress increase. The cluster falls mostly in the stress shadow when the Coulomb stress changes are calculated on optimally oriented normal faults. Therefore, seismicity in Yalova could not be related to Coulomb stress increase. This of course assumes that the source parameters obtained through InSAR and GPS inversions are correct. Dynamic stress triggering is thought to be a possible explanation of this seismic activity (Özalaybey, pers. comm. 2002).

In both the İzmit and Düzce cases, there is no correlation between the distribution of Coulomb stress changes and the distribution of coseismic slip or between the maximum Coulomb stress increase and the location of the hypocentre. It is clear that the adjoining İzmit earthquake definitely promoted the 12 November Düzce earthquake by raising the static stress on the Düzce rupture over 5 bars, but coseismic stress changes alone cannot satisfactorily explain the 3-month delay between the Düzce and İzmit earthquakes. In addition to coseismic stress change, Hearn *et al.* (2002) found that post-seismic deformation following the İzmit earthquake (Ergintav *et al.* 2002) contributed substantially to the Coulomb stress change on the Düzce rupture.

Acknowledgements

We thank R. Stein and S. Toda for organising and giving the Coulomb course and for the Coulomb 2.0 software. Süleyman Nalbant greatly improved the early version of this manuscript. Financial support from CNRS and TÜBİTAK is gratefully acknowledged.

References

Altunel, E., Barka, A.A. & Akyüz, H.S. 2000a. Slip distribution along the 1912 Mürefte-Şarköy earthquake, North Anatolian Fault, western Marmara. *In*: Barka, A.A. Kozaci, O., Akyüz, S. & Altunel, E. (eds), *The 1999 İzmit and Düzce Earthquakes: Preliminary Results.* İstanbul Technical University Publication, 341–349.

Altunel, E., Barka, A.A., Çakir, Z., Kozaci, Ö., Hitchcock, C., Helms, J., Bachuber, J. & Lettis, W. 2000b. What goes on at the eastern termination of the November 12, 1999 Düzce earthquake, M=7.2, North Anatolian Fault, Turkey. *American Geophysical Union Fall Meeting, California, USA, Abstracts*, p. F816.

Akyüz, H.S., Hartleb, R., Barka, A.A., Altunel, E., Sunal, G., Meyer, B. & Armijo, R. 2002. Surface rupture and slip distribution of the 12 November 1999 Düzce earthquake (M 7.1), North Anatolian Fault, Bolu, Turkey. *Bulletin of the Seismological Society of America* **92**, 61–66.

Ambraseys, N.N. 2001. The earthquake of 10 July 1894 in the Gulf of İzmit (Turkey) and its relation to the earthquake of 17 August 1999. *Journal of Seismology* **5**, 117–128.

Ambraseys, N.N. & Finkel, C. 1991. Long-term seismicity of İstanbul and of the Sea of Marmara region. *Terra Nova* **3**, 527–539.

Ambraseys, N.N. & Jackson, J.A. 1998. Faulting associated with historical and recent earthquakes in the Eastern Mediterranean region. *Geophysical Journal International* **133**, 390–406.

Ambraseys, N.N. & Zatopek, A. 1969. The Mudurnu Valley, west Anatolia, Turkey, earthquake of 22 July 1967. *Bulletin of the Seismological Society of America* **59**, 521–589.

Anderson, E.M. 1951. *The Dynamics of Faulting and Dyke Formation with Application to Britain.* Oliver & Boyd, Edinburgh.

Anderson, J.G., Wesnousky, S.G. & Stirling M.W. 1996. Earthquake size as a function of fault slip rate. *Bulletin of the Seismological Society of America* **86**, 683–690.

Armijo, R., Meyer, B., Barka, A.A., de Chabalier, J.B., Hubert, A. & Çakir, Z. 2000. The fault breaks of the 1999 earthquakes in Turkey and the tectonic evolution of the Sea of Marmara: a summary. *In*: Barka, A.A., Kozaci, O., Akyüz, S. & Altunel, E. (eds), *The 1999 İzmit and Düzce Earthquakes: Preliminary Results.* İstanbul Technical University Publication, 55–62.

Armijo, R., Meyer, B., Navarro, S., King, G.C.P. & Barka, A.A. 2002. Asymmetric slip partitioning in the Sea of Marmara pull-apart: a clue to propagation processes of the North Anatolian Fault. *Terra Nova* **14**, 80–86.

Atakan, K., Ojeda, A., Meghraoui, M., Barka, A.A., Erdik, M. & Bodare, A. 2002. Seismic hazard in İstanbul following the 17 August and 12 November 1999 Düzce earthquakes. *Bulletin of the Seismological Society of America* **92**, 466–482.

Barka, A.A. 1996. Slip distribution along the North Anatolian Fault associated with the large earthquakes of the period 1939–1967. *Bulletin of the Seismological Society of America* **86**, 1238–1254.

Barka, A.A. 1999. The 17 August 1999 İzmit earthquake. *Science* **285**, 1858–1859.

Barka, A.A. & Kadinsky-Cade, K. 1988. Strike-slip fault geometry in Turkey and its influence on earthquake activity. *Tectonics* **7**, 663–684.

Barka, A.A., Altunel, E., Akyüz, S., Çakir, Z., Kozaci, O., Lettis, W., Bachhuber, J., Hitchcock, C. & Helms, J. 2001. Seismic activity and fault segmentation of the NAF in the Bolu Mountain: relationship between the November 12, 1999 and the February 1, 1944 earthquakes. *EUG XI Meeting, Abstracts, Strasbourg, France*, p. 295.

Barka, A.A., Akyüz, S.H., Altunel, E., Sunal, G., Çakir, Z., Dikbaş, A., Yerli, B., Armijo, R., Meyer, B., de Chabalier, J.B., Rockwell, T., Dolan, J.R., Hartleb, R., Dawson, T., Christofferson, S., Tucker, A., Fumal, T., Langridge, R., Stenner, H., Lettis, W., Bachhuber, J. & Page, W. 2002. The surface rupture and slip distribution of the 17 August 1999 İzmit earthquake M=7.4, North Anatolian Fault. *Bulletin of the Seismological Society of America* **92**, 43–60.

Çakir, Z. 2003. *Analysis of the Crustal Deformation Caused by the 1999 İzmit and Düzce Earthquakes using Synthetic Aperture Radar Interferometry.* PhD thesis, İstanbul Technical University [unpublished].

Çakir, Z., Barka, A., de Chabalier, J .B., Armijo, R. & Meyer, B. 2003. Kinematics of the November 12, 1999 (Mw=7.2) Düzce earthquake deduced from SAR interferometry. *Turkish Journal of Earth Sciences* **12**, 105–118.

Ergin, K. 1969. 22 Temmuz 1967 Adapazarı-Mudurnusuyu Vadisi Depremi Üzerine İncelemeler [The study of the 22 July 1967 Adapazarı-Mudurnusuyu Valley earthquake]. *İstanbul Teknik Üniversitesi Arz Fiziği Enstitüsü Yayınları,* **27** [in Turkish with English abstract].

Ergintav, S., Bürgmann, R., McClusky, S., Çakmak, R., Reilinger, R.E., Lenk, O., Barka, A.A. & Özener, H. 2002. Postseismic deformation near the İzmit earthquake (17 August 1999, M=7.5) rupture zone. *Bulletin of the Seismological Society of America* **92**, 194–207.

Fred, A.M. & Lin, J. 2001. Delay triggering of the 1999 Hector Mine earthquake by viscoelastic stress transfer. *Nature* **411**, 180–183.

Harris, R.A. 1998. Stress triggers, stress shadows and implications for seismic hazards, *Journal of Geophysical Research* **103**, 24347–24358.

Harris, R.A. & Simpson, R.W. 1992. Changes in static stress on southern California faults after the 1992 Landers earthquake. *Nature* **360**, 251–254.

Hartleb, R.D., Dolan, J.F., Akyüz, H.S., Dawson, T.E., Tucker, A.Z., Yerli, B., Rockwell, T.K., Toraman, E., Çakir, Z., Dikbaş, A. & Altunel, E. 2002. Surface rupture and slip distribution along the Karadere segment of the 17 August 1999 İzmit and the western section of the 12 November 1999 Düzce, Turkey, earthquakes. *Bulletin of the Seismological Society of America* **92**, 67–78.

Hearn, E.H., Bürgmann, R. & Reilinger, R.E. 2002. Dynamics of İzmit earthquake postseismic deformation and loading of the Düzce earthquake hypocenter. *Bulletin of the Seismological Society of America* **92**, 172–193.

Hitchcock, C., Altunel, E., Barka, A.A., Bachhuber, J., Lettis, W., Kozaci, Ö., Helms, J. & Lindvall, S. 2003. Timing of Late Holocene earthquakes on the eastern Düzce Fault and implications for slip transfer between the southern and northern strands of the North Anatolian Fault System, Bolu, Turkey. *Turkish Journal of Earth Sciences* **12**, 119–136.

Hubert, A., King, G.C.P., Armijo, A., Meyer, B. & Papanastassiou, D. 1996. Fault re-activation, stress interaction and rupture propagation of the 1981 Corinth earthquake sequence. *Earth and Planetary Science Letters* **142**, 573–585.

Hubert-Ferrari, A., Barka, A.A., Jacques, E., Nalbant, S.S., Meyer, B., Armijo, R., Tapponnier, P. & King, G.C.P. 2000. Seismic hazard in the Marmara Sea following the 17 August 1999 İzmit earthquake. *Nature* **404**, 269–273.

King, G.C.P. & Cocco, M. 2000. Fault interaction by elastic stress changes: new clues from earthquake sequences. *Advances in Geophysics* **44**, 1–38.

King, G.C.P., Stein, R.S. & Lin, J. 1994. Static stress changes and the triggering of earthquakes. *Bulletin of the Seismological Society of America* **84**, 935–953.

King, G.C.P., Hubert-Ferrari, A., Nalbant, S.S., Meyer, B., Armijo, R. & Bowman, D. 2001. Coulomb interactions and the 17 August 1999 İzmit, Turkey earthquake. *C. R. Academi Science Paris, Sciences de la Terre et des Planets* **333**, 557–570.

Le Pichon, X., Şengör, A.M.C., Demirbağ, E., Rangin, C., İmren, C., Armijo, R., Görür, N., Çağatay, N., de Lepinay, B.M., Meyer, B., Saatçilar, R. & Tok, B. 2001. The active main Marmara Fault. *Earth and Planetary Science Letters* **192**, 595–616.

McClusky, S.C., Balassanian, S., Barka, A.A., Ergintav, S., Georgiev, I., Gürkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidse, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadaria, M., Ouzounis, A., Paradisissis, D., Peter, Y., Prilepin, M., Reilinger, R.E., Şanli, I., Seeger, H., Teableb, A., Toksöz, N. & Veis, G. 2000. Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. *Journal of Geophysical Research* **105**, 5695–5719.

Nalbant, S.S., Hubert, A. & King, G.C.P. 1998. Stress coupling between earthquakes in northwest Turkey and the North Aegean Sea. *Journal of Geophysical Research* **103**, 24469–24486.

Okada, Y. 1985. Surface deformation due to shear and tensile faults in a half-space. *Bulletin of the Seismological Society of America* **75**, 1135–1154.

Örgülü, G. & Aktar, M. 2001. Regional moment tensor inversion for strong aftershocks of the August 17, İzmit earthquake (Mw=7.4). *Geophysical Research Letters* **28**, 371–374.

Özalaybey, S., Aktar, M., Ergin, M., Karabulut, H., Bouchon, M., Tapirdamaz, C., & Yörük, A. 2000. Aftershock Studies Following Recent Earthquakes in Turkey. *XXVII General Assembly of the European Seismological Commission (ESC), Lisbon University, Lisbon, Portugal, September 10–15*, p. 31.

Özalaybey, S., Ergin, M., Aktar, M., Tapirdamaz, C., Biçmen, F. & Yörük, A. 2002. The 1999 İzmit earthquake sequence in Turkey: seismological and tectonic aspects. *Bulletin of the Seismological Society of America* **92**, 376–386.

Papadimitriou, E.E., Karakostas, V.G. & Papazachos, B.C. 2001. Rupture zones in the area of the 17.08.99 İzmit (NW Turkey) large earthquake (Mw 7.4) and stress changes caused by its generation. *Journal of Seismology* **5**, 269–276.

Parsons, T., Shinji, T., Stein, R.S., Barka, A. & Dieterich, J.A. 2000. Heightened odds of large earthquakes near İstanbul: an interaction-based probability calculation. *Science* **228**, 661–665.

Pinar, A., Honkura, Y. & Kuge, K. 2001. Seismic activity triggered by the 1999 İzmit earthquake and its implications for the assessment of future seismic risk. *Geophysical Journal International* **146**, F1–F7.

Pollitz, F.F. & Sacks, I.S. 2002. Stress triggering of the 1999 Hector Mine earthquake by transient deformation following the 1992 Landers earthquake. *Bulletin of the Seismological Society of America* **92**, 1487–1496.

Reilinger, R.E., Ergintav, S., Bürgmann, R., McClusky, S., Lenk, O., Barka, A.A., Gürkan, O., Hearn E.H., Feigl, K.L., Çakmak, R., Aktuğ, B., Özener, H. & Toksöz, M.N. 2000. Coseismic and postseismic fault slip for the 17 August 1999 M=7.5, İzmit, Turkey earthquake. *Science* **289**, 1519–1524.

Singh, S., Hirn, A., Voogd, B., Vigner., A., Bazin, S., Charvis., P., Gelil L., Saatçiler, R., Taymaz, T., Özalaybey, S., Çetin, S., Ocakçioğlu, N., Ricolleau, A. & Karakoç, F. 2002. 3D geometry of the North Anatolian Fault System in the Çınarcık Basin: Preliminary results. *1st International Symposium of the Faculty of Mines (İTÜ) on Earth Sciences and Engineering, 16–18th May 2002, İstanbul, Turkey, Abstracts,* p. 11.

Stein, R.S., King, G.C.P. & Lin, J. 1992. Change in failure stress on the southern San Andreas fault system caused by the 1992 magnitude=7.2 Landers earthquake. *Science* **258**, 1328–1332.

Stein, R.S., King, G.C.P. & Lin, J. 1994. Stress triggering of the 1994 M=6.7 Northridge, California earthquake by its predecessors. *Science* **256**, 1432–1435.

Stein, R.S., Barka, A.A. & Dieterich, J.H. 1997. Progressive failure on the North Anatolian Fault since 1939 by earthquake stress triggering. *Geophysical Journal International* **128**, 594–604.

Toda, S., Stein, R.S., Reasenberg, P.A. & Dieterich, J.H. 1998. Stress transferred by the M_W=6.9 Kobe, Japan, shock: Effect on aftershocks and future earthquake probabilities. *Journal of Geophysical Research* **103**, 24543–24565.

TOKSÖZ, M.N., SHAKAL, A.F. & MICHAEL, A.J. 1979. Space-time migration of earthquakes along the North Anatolian Fault Zone and seismic gaps. *Pure and Applied Geophysics* 117, 1258–1270.

TOKSÖZ, M.N., REILINGER, R.E., DOLL, C.G., BARKA, A.A. & YALÇIN, N. 1999. İzmit (Turkey) earthquake of the 17 August 1999: first report, *Seismological Research Letters* 70, 669–679.

WELLS, D.L. & COPPERSMITH, K.J. 1994. New empirical relationships among magnitude, rupture, length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America* 84, 974–1002.

WRIGHT, T.J., FIELDING, E.J. & PARSONS, B.E. 2001. Triggered slip: observations of the 17 August 1999 İzmit earthquake using radar interferometry. *Geophysical Research Letters* 28, 1079–1082.

Received 06 August 2003; revised typescript accepted 05 February 2003