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## Link between Coulomb stress changes and seismic activation in the eastern Marmara sea after the 1999, Izmit (Turkey), earthquake

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[1] We investigate the effect of dynamic and static stress changes produced by the 1999 Izmit earthquake, on four preexisting seismic clusters located in the eastern Marmara sea, beyond the western termination of the earthquake rupture. These four clusters show long-lasting modifications in their seismicity rate. We observe that these seismic activity variations are related to stress changes. Dynamic stress pulses activate strike-slip faulting instantaneously, but in the absence of a concomitant static Coulomb stress increase, this activation is short lived. Indeed, a large dynamic stress combined with a negative static Coulomb stress may result in an immediate activation followed by the occurrence of a seismicity shadow. In contrast, the activation of extensional clusters begins slowly and takes a few days to fully develop. It is also remarkably long lasting and does not follow a classical Omori decay. More than 10 years after the earthquake, the extensional clusters located near the termination of the rupture, where static stress and pressure changes were high, are still activated.

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### 1. Introduction

[2] It is now well established that stress changes induced by large earthquakes can affect seismicity at close and far distances [Das and Scholz, 1981; Stein and Lisowski, 1983; Reasenber and Simpson, 1992; Hill et al., 1993; Anderson et al., 1994; Bodin and Gomberg, 1994; King et al., 1994; Harris, 1998; Brodsky et al., 2000; Gomberg et al., 2001, 2004; Marsan, 2003; Prejean et al., 2004; Steacy et al., 2005; Daniel et al., 2006; Hill and Prejean, 2007] and may trigger or modify the timing of future earthquakes in the region [Harris and Simpson, 1992; Stein et al, 1992, Stein, 1999; Nalbant et al, 1998; Toda et al., 1998; Cocco et al, 2000]. On the North Anatolian Fault (NAF), a combination of static Coulomb stress increases

on neighboring fault segments [Stein et al., 1997], and long-range dynamic stress excitation of extensional seismic clusters [Durand et al., 2010] explains the migration of large ruptures along this major plate boundary [Toksöz et al., 1979]. However, an understanding of the deformation mechanisms which are set in action by permanent or transient stress changes is lacking and requires more detailed observations. The aim of this study is to add a set of observations based on the long-term monitoring of seismicity in the eastern Marmara sea, a region which was strongly shaken by the 1999 Mw 7.6 Izmit earthquake. This region is of particular interest because of the possible nucleation there of the next large earthquake in the NAF sequence.

[3] Previous calculations of static stress increase on faults in this region after the Izmit earthquake have been performed by Parsons et al. [2000] to infer probabilistic seismic risk for Istanbul and by Çakir et al. [2003a]. In the present study, we investigate the link between stress and seismicity changes and we try to separate the roles of static and dynamic stimulations.

### 2. Faults and Seismicity in the Region

[4] The Izmit earthquake occurred on 17 August 1999 and ruptured the east-west running North Anatolian Fault bilaterally over a length of about 150 km [Barka et al., 2002; Çakir et al., 2003b]. Nearly 3 months later, on 12 November, the Mw 7.2 Düzce earthquake extended the rupture 40 km eastward. To the west, the rupture ended in

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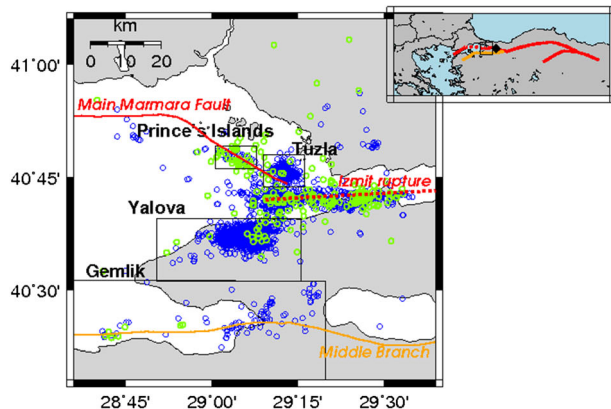
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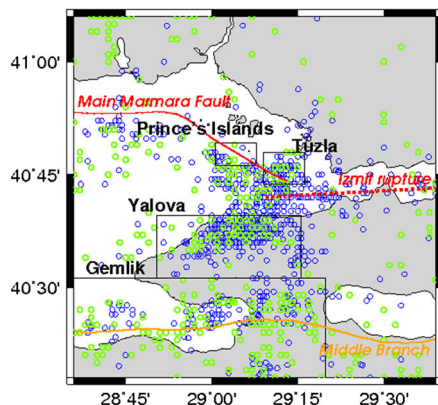
the Çınarcık basin, where the main branch of the NAF abruptly changes direction and is referred to as the Main Marmara Fault (MMF) [Le Pichon *et al.*, 2001]. The seismic activity in the eastern Marmara sea following the earthquake is depicted in Figure 1a. This figure displays seismic events which occurred between August 17 and November 5, 1999 when many seismic stations were deployed in the region [Karabulut *et al.* 2011]. We shall use the corresponding relocated catalog for this period and the national catalog of the Kandilli Observatory and Earthquake Research Institute (KOERI) (Figure 1b) for the decade before and after the earthquake to study the evolution of activity in the region and to investigate its relation to stress changes. Besides the

concentration of seismicity along the earthquake rupture, the post-Izmit activity clusters in a few areas: The Princes Islands zone of the MMF, the area off the Tuzla peninsula just north of the termination of the Izmit rupture, the Yalova region to the southwest of the rupture termination, and further south, the Gemlik region around the Middle Branch of the NAF. This activity takes place in two major types of seismic events: strike-slip events which are associated with the NAF system, and normal faulting events associated with the Aegean extension (see Supplementary Figure S1). A cutoff magnitude is utilized to select the earthquakes used in the following analysis. We selected  $M \geq 2.8$  for the Tuzla and Yalova areas and  $M \geq 3.0$  for the Princes Islands and Gemlik zones. These cutoff magnitudes were chosen after computing the frequency-magnitude curves for each zone and insuring that they follow a Gutenberg-Richter law (see Supplementary Figure S3 for details). Except for Princes Islands, where the limited number of earthquakes (only 31 events of magnitude above or equal to 3.0) prevented it, we observed no significant deviation from a Gutenberg-Richter law down to cutoff magnitude, for separate time intervals (1 January 1989 to 16 August 1999, 17 August 1999 to 31 December 2001, 01 January 2002 to 17 August 2009) for each zone (see Supplementary Figure S3).

**A** Relocated seismicity 08/17/1999-11/05/1999



**B** Kandilli catalog 01/01/1989-08/17/2009

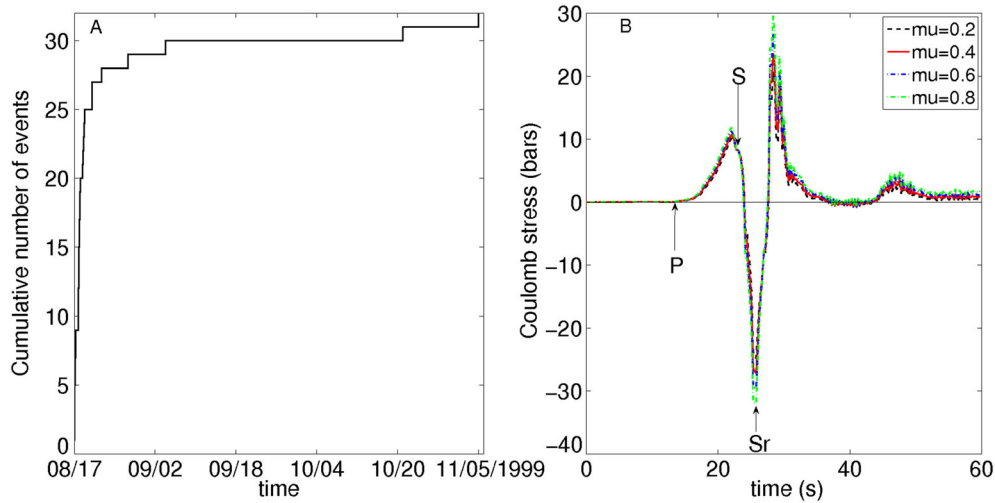


**Figure 1.** Maps of seismic activity in the eastern Marmara Sea. The inset shows the location of the studied area (square) and of the Izmit earthquake epicenter (diamond). The main branch of the NAF is in red (Izmit rupture in dotted line, Main Marmara Fault in continuous line). The less active Middle Branch of the NAF is in yellow. The boxes show the extent of the zones over which the cumulative numbers of events are displayed. (a) Relocated catalog (used to plot the cumulative number of events in the Princes Islands zone) from 17 August 1999 to 11 May 1999, without any condition on magnitude. Events during the day following the Izmit earthquake are in green. (b) KOERI catalog (used for the Tuzla, Yalova, and Gemlik areas) over the period from 1989 to 2009, for the events of magnitude  $\geq 2.8$ . Events during the 10 years preceding the Izmit earthquake are in green. The scale is the same for the two maps.

### 3. Observations

#### 3.1. Princes Islands

[5] The Princes Islands cluster is located on the Main Marmara Fault, the continuation of the main branch of the NAF in the Marmara sea (Figure 1). Only the relocated data are used here, since the unrelocated (Kandilli) catalog does not allow to select earthquakes in this case (see Figure 1). As a consequence, we could not estimate the rate of earthquakes in this cluster prior to the Izmit main shock. The evolution of seismic activity in this cluster is shown in Figure 2a. It is characterized by a strong immediate activation followed by a rapid extinction of the activity: The parameter  $p$  of the Omori-Utsu law is equal to 2 (see Supplementary Figure S4), which is considerably higher than its usual value. Indeed, some of the largest early aftershocks of the earthquake occurred in this cluster [Örgülü and Aktar, 2001; Özalaybey *et al.*, 2002]. These events have almost pure strike-slip mechanism with a nodal plane oriented along the fault direction [Örgülü and Aktar, 2001; Özalaybey *et al.*, 2002]. The Coulomb stress produced by the earthquake on the MMF at the center of this cluster and near its average depth of 10 km (Table 1) is shown in Figure 2b. The stress is calculated using the fault model inferred for the earthquake [Bouchon *et al.*, 2002] and the discrete wave number method [Bouchon, 1981; Cotton and Coutant, 1997]. A friction coefficient of 0.6, consistent with laboratory experiments [Scholz, 1998], is assumed. Other values (0.2 to 0.8) were also tested. The influence of this coefficient is very limited (Figure 2b). While the static Coulomb stress increase is relatively small (a little over 1 bar), the positive peak of the dynamic Coulomb stress reaches about 28 bars, a value typical of what is often observed for earthquake stress drops. In view of Figures 2a and 2b, we interpret the immediate and strong activation of this short segment of the NAF as triggered by the high



**Figure 2.** (a) Cumulative number of events on the Princes Islands segment of the Main Marmara Fault from 17 August to 5 November 1999, using the relocated catalog. (b) Coulomb stress calculated in the middle of this segment (for the receiver coordinates and configuration, see Table 1) as a function of time since the start of the rupture. Four different friction coefficients are considered ( $\mu=0.2$ ,  $\mu=0.4$ ,  $\mu=0.6$ , and  $\mu=0.8$ ). Theoretical arrival times of P and S waves are indicated. Sr is the S wave associated with the rupture front.

dynamic stress pulse radiated by the earthquake. Likewise, we attribute its rapid extinction to the low level of the permanent Coulomb stress increase. These observations support the view that static stress changes and transient deformations have different timescales as has been proposed [e.g., Marsan, 2003; Voisin *et al.*, 2004].

### 3.2. Gemlik (Middle Branch)

[6] Seismicity on and around the Middle Branch of the NAF is clearly activated by the Izmit earthquake near the place where the Middle Branch enters the Marmara sea (Figure 1). The length of the fault segment which is activated is relatively long and extends over about 50 km. Background seismic activity in the region shows that this zone encompasses both strike-slip and normal faulting events [Karabulut *et al.*, 2011]. Normal faulting events dominate onshore, whereas strike-slip events tend to occur offshore. The activation is immediate offshore where the strike-slip regime dominates, while it takes a few days to develop onshore, reaching its peak there about a week after the earthquake (Figure 1a). The activation lasts for several months and is followed by an almost total extinction which lasts for nearly 2 years (Figure 3a).

[7] We compute the rate of background earthquakes prior to and posterior to the Izmit earthquake. Background earthquakes are those events that remain after declustering

so that their rate can be directly interpreted as a forcing rate alone in the absence of earthquake interactions. We here compute the background rate using the simple approach of Hainzl *et al.* [2006], which is appropriate at these long time scales. The total seismicity rate of the cluster is given by

$$\lambda(t) = \mu + v_{int}(t) + v_{ext}(t) \quad (1)$$

with  $\lambda(t)$  the total rate,  $\mu$  the rate due to tectonic loading,  $v_{int}(t)$  the seismicity generated by the events within the cluster and  $v_{ext}(t)$  the seismicity in the cluster produced by earthquakes exterior to the cluster. This computation removes the seismicity generated by the events of the cluster. We have computed the seismicity rate before the Izmit earthquake due to the tectonic loading, and the seismicity rate after the earthquake, including both the effect of the tectonic loading and the influence of the Izmit earthquake. The difference between the two illustrates the influence of the Izmit earthquake and shows that the background rate after the Izmit earthquake ( $0.0070 \pm 0.0015$  events per day) is nearly half of the one before ( $0.0130 \pm 0.0019$  events per day).

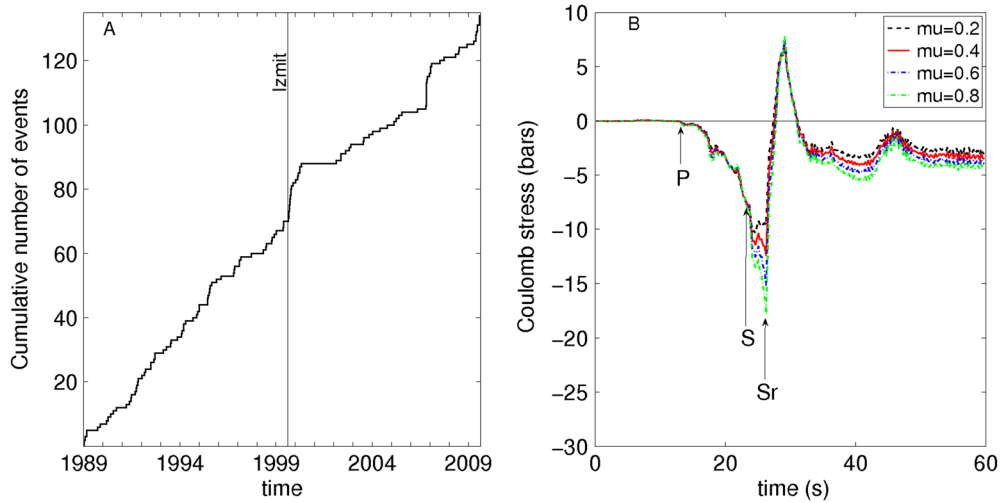
[8] The Coulomb stress calculated for a fault orientation and mechanism representative of the Middle Branch of the NAF (Table 1, Figure 3b) reaches a positive dynamic value of about 8 bars but has a negative static value of  $4 \pm 0.5$  bars (depending on the value of the friction coefficient). Nearly similar values are obtained for the normal faulting events geometry. Thus, like what is observed on the Princes Islands segment of the MMF, the dynamic stress seems to control the seismicity at short time range (immediate activation), whereas the static stress could control its long time range evolution (decrease of seismic rate and seismicity shadow). The migration of seismicity from offshore to onshore after a few days suggests a rapid decrease of the strike-slip activity, as observed along the MMF, and a slow decrease of normal-fault activity. The emergence of quiescence after

**Table 1.** Parameters Used for The Stress Calculation in Each Cluster<sup>a</sup>

Cluster name	Lon (deg.)	Lat (deg.)	Depth (km)	Strike (deg.)	Dip (deg.)	Rake (deg.)
Princes Islands	29.07	40.79	10	113	90	0
Gemlik	29.16	40.43	10	90	90	0
Yalova	29.10	40.63	10	300	60	90
Tuzla	29.19	40.76	10	155	70	90

<sup>a</sup>Strike is given from north.





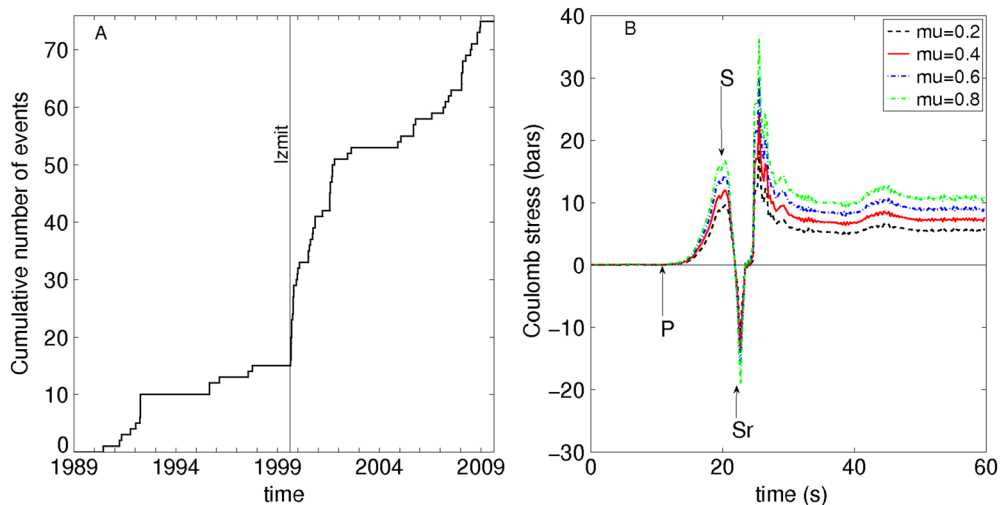
**Figure 3.** (a) Cumulative number of events in the Gemlik region for the decade before and the decade after the earthquake. The jump in the cumulative number during the year 2007 is due to a  $M=5.2$  earthquake. We consider only the events of magnitude larger than 3. (b) Coulomb stress calculated in the middle of the Gemlik cluster (for the receiver coordinates and configuration, see Table 1) for four different friction coefficients ( $\mu=0.2$ ,  $\mu=0.4$ ,  $\mu=0.6$ , and  $\mu=0.8$ ). As in Figure 2b, arrival times of P and S waves are indicated.

a period of triggered activity has been observed elsewhere [e.g., Marsan, 2003; Ma *et al.*, 2005; Marsan and Nalbant, 2005; Daniel *et al.*, 2008]. Like in the present case, these observations show short-term triggering followed by long term quiescence, suggesting the existence of two distinct interaction regimes, a first one caused by the destabilization of active faults by travelling seismic waves, and a second one due to the remaining static stress perturbation [Marsan and Nalbant, 2005].

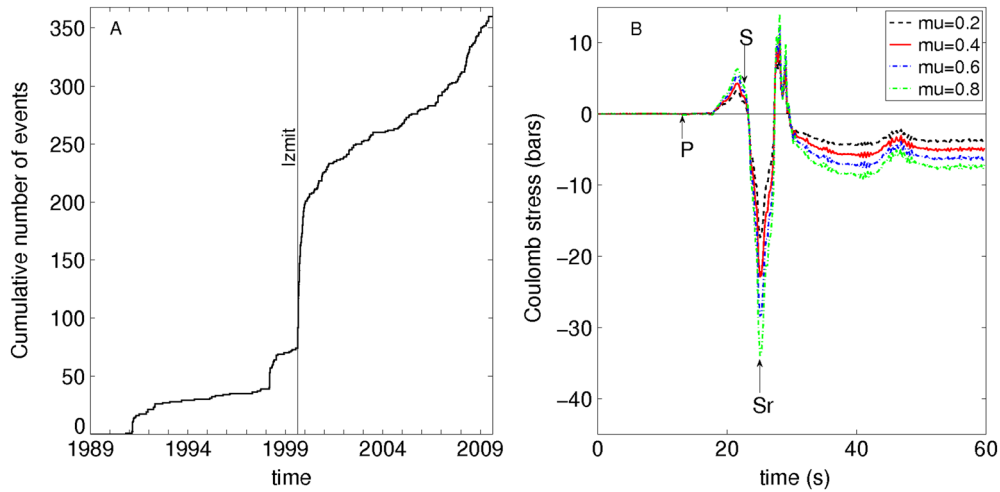
### 3.3. Tuzla Cluster

[9] This cluster is of particular interest because it lays near the junction of the Izmit rupture with the Main Marmara Fault. If static Coulomb stress increase alone were to

determine the nucleation site of the next large earthquake on the NAF, it is logically where it would happen. Most of the events in this cluster have normal faulting mechanisms and are located between depths of 5 and 10 km [Karabulut *et al.*, 2002]. The evolution of seismicity (Figure 4a) shows a strong activation following the earthquake. Like for the normal faulting events around the Middle Branch of the NAF, this activation was not immediate but built up slowly over several days and reached its peak about a week after the earthquake [Durand *et al.*, 2010]. This slow onset suggests that fluids could be responsible for the activation of seismicity. This activation does not appear limited in time, as 10 years after the earthquake the background activity (0.0064 events per day) is still higher than what it was before



**Figure 4.** (a) Cumulative number of events in the Tuzla cluster for the decade before and the decade after the earthquake. We consider the events of magnitude larger than 2.8. (b) Coulomb stress calculated in the middle of the Tuzla cluster (for the receiver coordinates and configuration, see Table 1) for four different friction coefficients ( $\mu=0.2$ ,  $\mu=0.4$ ,  $\mu=0.6$ , and  $\mu=0.8$ ).



**Figure 5.** (a) Cumulative number of events in the Yalova cluster for the decade before and the decade after the earthquake. We consider the events of magnitude larger than 2.8. (b) Coulomb stress calculated in the middle of the Yalova cluster (for the receiver coordinates and configuration, see Table 1) for four different friction coefficients ( $\mu=0.2$ ,  $\mu=0.4$ ,  $\mu=0.6$ , and  $\mu=0.8$ ).

(0.0017 events per day). The normal faults in this area underwent a peak dynamic Coulomb stress of about 30 bars during the earthquake and have had a permanent Coulomb stress increase of nearly  $9 \pm 2$  bars ever since (Figure 4b), depending on the value of the friction coefficient.

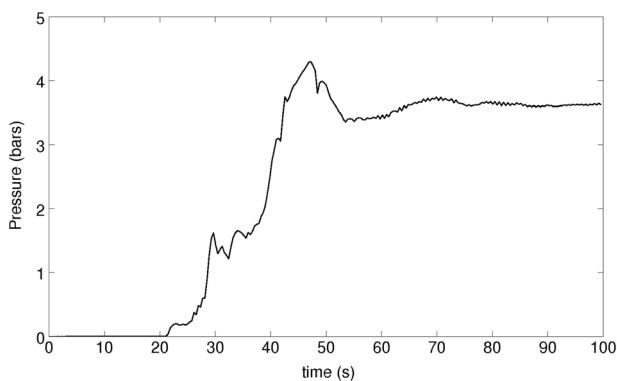
### 3.4. Yalova Cluster

[10] This cluster is a long-recognized nest of seismicity located southwest of the termination of the Izmit rupture. It covers an area about 20 km across which is well known for its geothermal springs. It was strongly activated by the Izmit earthquake and is made up of normal faulting events on north-dipping east-west trending faults [Karabulut *et al.*, 2002; Özalaybey *et al.*, 2002; Bulut and Aktar, 2007]. Like for the other normal faulting events in the region, the seismic activity was not immediate but built up slowly over a few days [Daniel *et al.*, 2006; Durand *et al.*, 2010]. As shown in Figure 5a, 10 years after the earthquake, the background rate (0.0250 events per day) is still considerably higher than what it was before (0.0061 events per day). The Coulomb calculation shows a large negative static value

( $-6 \pm 1$  bars) on the normal faults in the area (Figure 5b), while the positive peak of the dynamic stress is relatively small. Thus, the strong activation of long duration which is observed is not related to Coulomb stress. A calculation of the pressure produced by the earthquake at the center of the cluster (Figure 6), which is equal to one third of the negative trace of the stress tensor, shows that the area underwent a permanent compression of about 3.6 bars. The reaction of the fluid-filled fractured area to this high pressure increase seems the logical mechanism of the activation.

## 4. Discussion

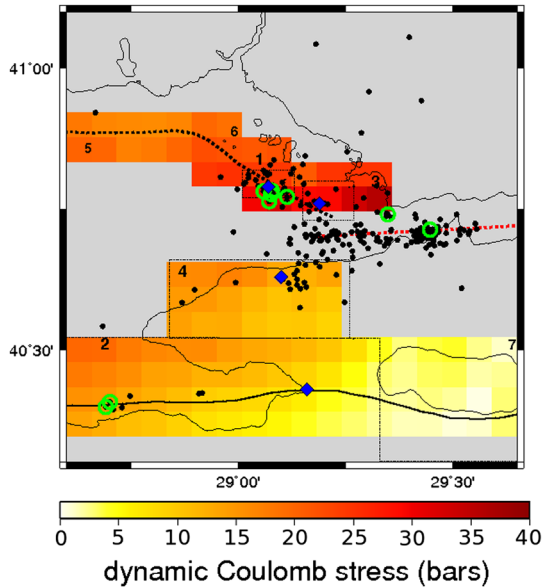
[11] To gain more insight into the link between stress and seismicity, we calculate the spatial variation of the Coulomb stress in the eastern Marmara sea. To do so, we separate the different tectonic regimes of the region into six zones, which cover the areas where known faults or seismic activity are present (Table 2). In each zone, we consider the predominant fault orientation and mechanism associated with the seismicity and evaluate the corresponding Coulomb stress at a grid of points located at 5 km interval and 10 km depth. The resulting map of the positive peak of the dynamic Coulomb stress is presented in Figure 7. The events which occurred in the day following the earthquake are superposed on the stress map. We notice that some areas that



**Figure 6.** Pressure (trace of the stress tensor) at the Yalova cluster (the configuration of the receiver is the same as in Figure 5b).

**Table 2.** Parameters Used for the Calculation of Stresses in Each Area

Zone	Lon. min. (deg.)	Lon. max. (deg.)	Lat. min. (deg.)	Lat. max. (deg.)	Strike (deg.)	Dip (deg.)	Rake (deg.)
1	29.01	29.13	40.77	40.82	113	90	0
2	28.16	29.33	40.27	40.52	90	90	0
3	29.15	29.27	40.73	40.80	155	70	90
4	28.84	29.26	40.52	40.66	300	60	90
5	28.60	28.89	40.83	40.93	105	78	0
6	28.89	29.01	40.77	40.93	113	90	0
7	29.33	29.70	40.27	40.52	90	90	0

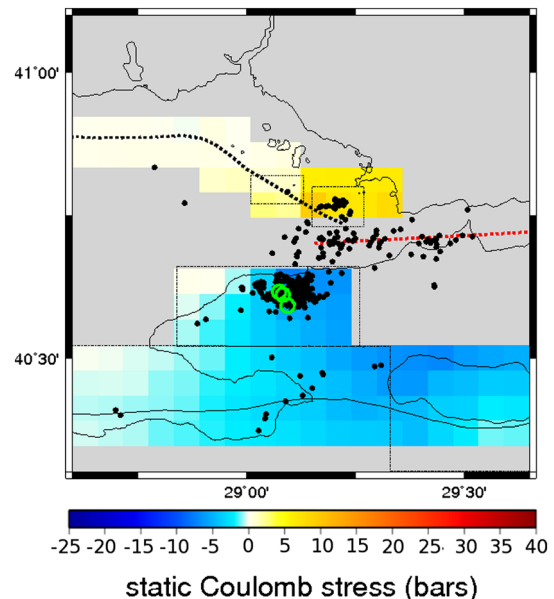


**Figure 7.** Map of the peak (positive) dynamic Coulomb stress calculated in each zone of interest. The receiver configurations in each zone is given in Table 2. Black dots denote the events of  $M \geq 2.8$  in the day after the earthquake. Green circles show the  $M \geq 4$  events, for the same period. Blue diamonds indicate the locations where the Coulomb stress time histories of Figures 2b–5b are calculated. The dotted lines show the traces of the Izmit rupture and the Main Marmara Fault. The continuous line is the Middle Branch of the NAF. The dashed boxes show the extent of the zones over which the cumulative numbers of events are displayed.

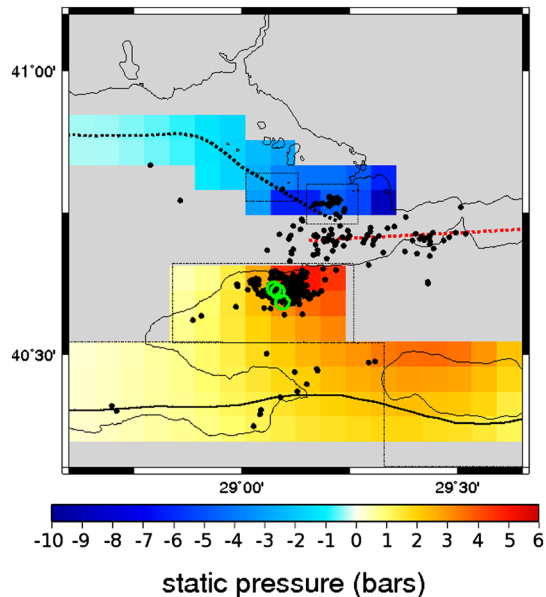
presumably underwent high dynamic stress are not activated. These are areas of low background seismicity. The largest events in the region on the day following the earthquake are associated with the two branches of the NAF: the Princes Islands segment of the MMF, and the Gemlik Bay segment of the Middle Branch of the NAF. These events are located in areas where the dynamic Coulomb stress is particularly high. On the Middle Branch, the seismicity is only observed on the offshore segment where the dynamic stress is the highest. The inland segment, closer to the Izmit rupture but where the dynamic stress is significantly lower seems devoid of activity. This suggests that the activation along the Middle Branch is controlled by the directivity of the Izmit rupture, as has been observed elsewhere [Gomberg *et al.*, 2001, 2003]. A similar calculation done for a normal faulting mechanism in this zone instead of a strike-slip one is presented in Supplementary Figure S6. It shows a lower value of the dynamic stress in this zone. This indicates that the dynamic Coulomb stress around the Middle Branch is more likely to have triggered strike-slip rather than normal-faulting events, in agreement with what is observed on the day after the earthquake.

[12] The map of static Coulomb stress is presented in Figure 8. Its value is inferred from the level of the stress time history 100 s after the start of the earthquake. As seen in Figures 2b–5b, the stress has by then reached its permanent value. The seismicity which occurred between 1 October

(6 weeks after the earthquake) and 5 November 1999 is superposed on the map. Most of the seismic activity which occurs away from the Izmit rupture is now associated with normal-faulting events. To the north of the rupture termination, the Tuzla cluster location correlates with an area of large static stress. In contrast, activity on the Princes Islands section of the MMF where the static stress is low (about 1 bar) is now almost extinct. To the south, seismic activity has picked up in the inland and coastal area around Gemlik, where normal faulting dominates but has largely decreased on the offshore segment of the Middle Branch of the NAF. The rapid decrease of strike-slip activity there and in Princes Islands correlates with negative or low values of the static Coulomb stress on the associated strike-slip faults. The strongest activation in the weeks and months following the earthquake occurs in the Yalova cluster. This activation is in the form of normal faulting events and, like the activation of normal faulting events in the Gemlik area (Supplementary Figure S7), it corresponds to a zone of decrease in static Coulomb stress. The main reason for the negative static Coulomb stress at Yalova and Gemlik is that these zones are put under compression after the Izmit earthquake. This has the effect of increasing the normal stress (in absolute value) across faults and, in the absence of fluids, would increase friction. The two areas, and more particularly Yalova, have been known since antiquity for their geothermal springs which are present throughout the region [Eisonlohr, 1997]. This indicates the widespread presence of crustal fluids circulating in this highly fractured region. The map showing the static pressurization of the region produced by the earthquake is presented in Figure 9. The large permanent compression undergone by the Yalova region resulted in a large long-lasting increase of its seismic activity



**Figure 8.** Map of the static Coulomb stress changes calculated in each zone of interest. These values are inferred from the amplitude of the stress time histories 100 s after the start of the earthquake. The seismicity represented is the activity between 1 October and 5 November 1999. The symbols are the same as in Figure 7.



**Figure 9.** Map of the static pressure calculated in each zone of interest. These values are inferred from the amplitude of the pressure time histories 100 s after the start of the earthquake. The seismicity represented is the activity between 1 October and 5 November 1999. The symbols are the same as in Figure 7.

(Figure 5a), which is still being felt more than 10 years before the earthquake.

[13] The parallel observations of seismicity and stress in the eastern Marmara sea following the Izmit earthquake help shed some light on how stress changes affect seismicity. As emphasized elsewhere (Dewey, [1976]; Karabulut *et al.*, [2011]), the interest of the region is that it combines in the same place intense strike-slip deformation and intense extension. In spite of this apparent complexity, what we observe is surprisingly simple and seems physically logical:

[14] 1. The strike-slip events are immediately activated after the earthquake. They occur on two sections of the NAF (the MMF and the Middle Branch) which underwent high dynamic Coulomb stress and small or negative static Coulomb stress. Thus, their activation seems triggered by the dynamic stress.

[15] 2. This strike-slip activity decays very rapidly. The short duration of the dynamic stress excitation that these areas underwent compared to the sustained excitation that static stress would procure seems consistent with a rapid extinction of the activity as observed elsewhere [Gomberg *et al.*, 2001] and reproduced experimentally [Belardinelli *et al.*, 2003].

[16] 3. Intense normal faulting activity seems triggered by the static deformation of a crustal volume where the presence of fluids is widespread. Beeler *et al.* [2000] and Cocco and Rice [2002] have shown that fluids can decrease the effective normal stress enough to trigger failure while Hill and Prejean [2007] suggest that fluid-driven deformations are sufficient to trigger events. For the Yalova and Gemlik regions, pressure increase seems to have been the triggering factor. In Tuzla where the presence of crustal fluids is less documented, static Coulomb stress increase or permanent volume dilatation or a combination of both were possible triggers.

[17] 4. The normal faulting activity begins slowly and builds up over a few days. Because this activation involves fluid circulation in a large crustal volume, the presence of a period during which the activity builds up and extends spatially [Karabulut *et al.*, 2011] seems to be expected. Nur and Booker [1972] have shown that the redistribution of the pore pressure by fluid flow can lead to a decrease of the strength of faults and delayed rupture.

[18] 5. Once started, the normal faulting activity lasts for a long time. In Yalova and Tuzla, the seismicity is still considerably higher more than 10 years after the earthquake than what it was before. In Gemlik, where the permanent deformation is smaller, the activation lasted for about 10 months.

[19] Combined with other studies, the observations that we have reported show the variety and richness of the seismic triggering mechanisms involved. Transient or static Coulomb stress increases can both activate the same seismogenic structure. Which one dominates in a given case is necessarily a function of the distance to the source of the excitation. For instance, 3 months after the Izmit earthquake, the Yalova cluster was slightly activated by the Düzce earthquake nearly 200 km away, making dynamic stress the likely triggering excitation at that time [Daniel *et al.*, 2006].

[20] The present observations reinforce the differences which have been previously observed between the response of extensional zones and strike-slip faults [Hill and Prejean, 2007; Durand *et al.*, 2010]. The remarkable sensitivity of extensional clusters to stress excitation, which is often seen by the long range triggering of these clusters, is shown here by the very long duration of their activation. Their delayed response shows that the strain changes induced by the earthquake initiate physical processes which take some time to fully develop [Gomberg, 1996; Freed, 2005; Hill and Prejean, 2007]. The peak of activation occurs here after a few days, providing an order for the time constant of the processes involved.

[21] The present observations also confirm the limited time efficiency of dynamic triggering previously reported [e.g., Marsan, 2003; Voisin *et al.*, 2004]. This characteristic which is displayed here for strike-slip faulting does not, however, apply to extensional clusters for which fluids may be the triggering agent [Durand *et al.*, 2010].

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