Seismic interaction and delayed triggering along the North Anatolian Fault

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[1]   The deformation of northwestern Turkey is the result of the encounter of the westward extrusion of the Anatolian plate with the north-south extension of the Aegean domain. While the North Anatolian Fault localizes the former type of deformation and has been the site of more large earthquakes (9 events of magnitude ≥7) than any other continental fault over the past 100 years, the extension is diffuse and is characterized by spatial clusters of smaller earthquakes and near-continuous activity. We study the evolution of seismicity along the fault and in the clusters neighboring the fault before and after the two large earthquakes of 1999. We observe that the un-ruptured section of the fault and the extension clusters respond very differently to the earthquakes. While significant aftershock activity on the fault segments adjacent to the rupture only occurs at relatively short distance from the rupture (≤30 km), the clusters can be activated at much larger distances (300 km). Remarkably their triggering is not immediate after the earthquake but is delayed in time. Their peak seismic activation may occur weeks or months after the earthquake. This distant and delayed triggering, which is consistent with recent GPS observations, may help resolve some of the previously unexplained characteristics of the 1939–1999 sequence of large earthquakes along the fault.   **Citation:**   Durand, V., M. Bouchon, H. Karabulut, D. Marsan, J. Schmittbuhl, M.-P. Bouin, M. Aktar, and G. Daniel (2010), Seismic interaction and delayed triggering along the North Anatolian Fault, *Geophys. Res. Lett.*, *37*, L18310, doi:10.1029/2010GL044688.

1.   Introduction

[2]   The North Anatolian Fault (NAF) defines the northern boundary of the Anatolian plate and localizes the differential motion between this plate and the Eurasian plate to the north [*Reilinger et al.*, 1997]. In contrast, the strain of the Aegean extension occurs throughout a wide region from western Greece to western Turkey. To understand how these two systems interact, we look at the evolution of seismicity near the NAF since 1971, when a daily catalogue of seismicity, made by the Kandilli Observatory which established and operates the national seismic network, became available. We focus our attention on the section of the NAF which runs from west-central Anatolia to the entrance of the Aegean sea, because of the occurrence within this zone of two large earthquakes in 1999. The first one, the August 17, 1999 *Mw 7.6* Izmit earthquake, ruptured the NAF over a length of 150 km. Three months later, on November 12, 1999, its rupture was extended 40 km eastward by the *Mw 7.2* Düzce earthquake. The triggering of the Düzce earthquake is consistent with a static Coulomb stress increase produced by the Izmit earthquake [*Barka*, 1999].

2.   Extension Clusters and the NAF

[3]   The Kandilli catalog that we use is composed of 27827 events between January 4, 1971 and February 28, 2008, over the studied region ($26 \leq$ lon ≤ 34 and $39.5 \leq$ lat ≤ 42). Its magnitude of completeness over this period is 2.8 (see Text S1 in auxiliary material for details).[1] The errors on the events location are on average 4.3 km (Text S2). The evolution of seismic activity in space and time (Figure 1) shows the presence of two types of activity: the mainshock-aftershocks sequences of the 1999 earthquakes and a few clusters of small events with near-continuous activity. These clusters are located near the cities of Izmit, Yalova, Cerkes and near the western edge of the Marmara sea. Three events out of the eight devastating earthquakes which have ruptured the NAF since 1939 nucleated near one of these clusters: the *Mw 7.6* 1999 Izmit earthquake nucleated near the long-recognized Izmit cluster [*Bariş et al.*, 2002], while both the *Mw 7.6* 1943 and the *Mw 7.3* 1944 earthquakes had their epicenters near the location of the Cerkes cluster [*Dewey*, 1976; *Barka*, 1996]. Although the extension nature of the cluster was not known at the time, its activity was described by *Dewey* (1976) as a region experiencing a high level of moderate seismicity in the 1930's and 40's. This suggests the existence of a link between what we shall term the extension clusters and the NAF.

[4]   The seismicity of northwestern Turkey in the year following the Izmit earthquake is compared in Figure 2a to the seismicity of the previous 10 years. While the pre-Izmit seismicity is quite diffuse except for a nest of activity at the Izmit cluster, the post-Izmit seismicity is more organized. Although part of this organization results from the concentration of activity along or near the Izmit-Düzce rupture, there is also a concentration of the activity in the three clusters identified in Figure 1 and not directly associated

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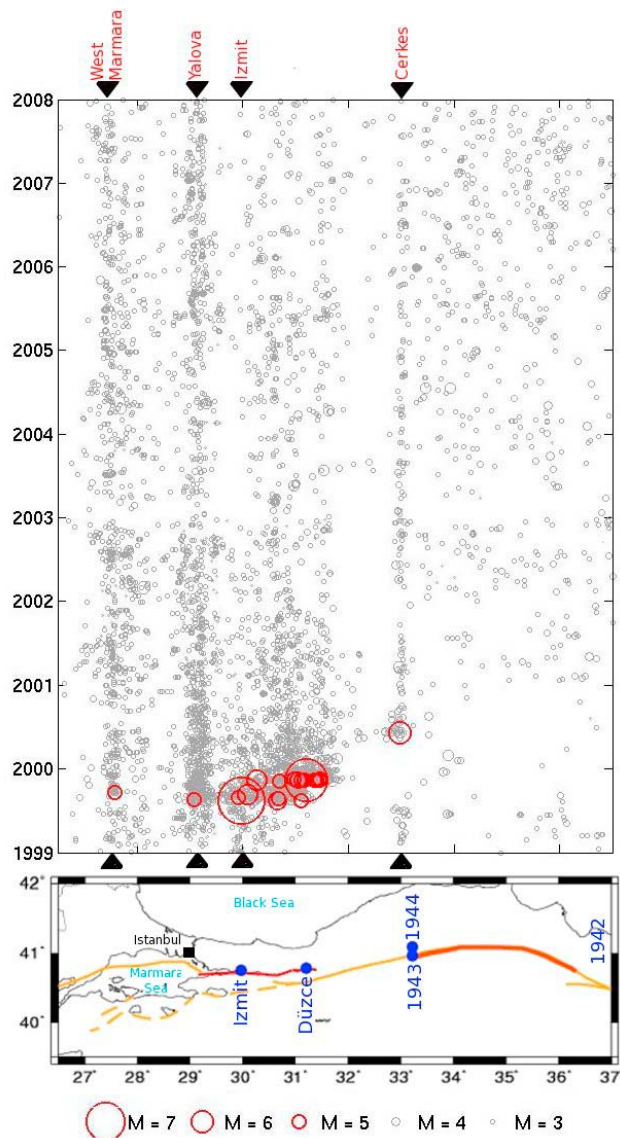
Figure 1. Seismic activity along and near the western and central sections of the NAF as a function of time and longitude with corresponding map. The major clusters (black triangles) and the epicenters of the largest earthquakes (blue) are identified. The main strand of the NAF is in yellow. The 1999 ruptures are in red. The 1943 rupture is in orange.

with the rupture. The Yalova cluster is located just beyond the western end of the Izmit rupture [*Karabulut et al.*, 2002; *Bulut and Aktar*, 2007]. It extends for about 30 km and has its main activity about 10 km south of the NAF. The West Marmara cluster is located at the western edge of the Marmara sea, about 150 km from the Izmit rupture and 300 km from the Düzce rupture. It extends southward from the NAF for about 20 km. The Cerkes cluster lies about 200 km eastward from the Izmit rupture and 150 km from the Düzce rupture.

[5] While no event of magnitude ≥5 had occurred in the region in the 10 years preceding the Izmit earthquake, one event of this magnitude occurred in each cluster in the following year (Figure 2b). The mechanisms of these events [*Aktar and Örgülü*, 2001; *Örgülü and Aktar*, 2001; *Çakir*

and Akoglu, 2008] are predominantly normal faulting with N-S to NNE-SSW extension.

[6] The evolution of the number of events and of the seismic moment released in the three clusters since 1971 (Figure 3a) confirms that the clusters are strongly activated after the 1999 earthquakes. Remarkably, we see that this activation is not immediate but delayed in time relative to the earthquakes (Figure 3b).

[7] The Yalova activation begins slowly and only takes off 2 days after the Izmit earthquake [*Özalaybey et al.*, 2002]. The largest shock (*Mw 5.1*), which occurs in a stress shadow (Figure S1) [*Çakir et al.*, 2003], involves almost pure normal faulting on an east-west trending fault dipping to the north (Figure 2b) [*Örgülü and Aktar*, 2001]. The smaller events have similar mechanisms [*Karabulut et al.*, 2002]. The cluster is also activated, but more weakly, after the distant (150 km) Düzce earthquake with a similar delay of about 2 days [*Daniel et al.*, 2006]. Thus the cluster responds with the same delay to near and remote triggering.

[8] The seismicity of the West Marmara cluster shows a clear activation one month after the Izmit earthquake, and again, more weakly but with a similar delay, after the Düzce earthquake. The largest shock occurred 34 days after Izmit and displays a predominantly normal faulting mechanism with NNE-SSW extension (Figure 2b) [*Aktar and Örgülü*, 2001]. The largest documented earthquake (*Mw 6.4*) in this area occurred in 1935 and has been interpreted as normal faulting on an east-west trending fault [*Nalbant et al.*, 1998].

[9] The activation of the Cerkes cluster is the most delayed in time: It occurs nearly 10 months after Izmit and 7 months after Düzce. The recorded onset of activation begins with a *Mw 6.0* earthquake, which is the only event of magnitude ≥5 to occur in the cluster in almost 50 years (since 1953) [*Dewey*, 1976]. Its epicenter is located 25 km from the NAF [*Taymaz et al.*, 2007; *Çakir and Akoglu*, 2008] and its mechanism (Figure 2b) [*Taymaz et al.*, 2007; *Çakir and Akoglu*, 2008] indicates normal faulting with NNE-SSW extension. Following the earthquake, the cluster becomes the seat of intense seismic activity [*Taymaz et al.*, 2007; *Çakir and Akoglu*, 2008].

3. Discussion

[10] The deformation of northwestern Turkey is the result of the encounter of the westward extrusion of the Anatolian plate and the north-south extension of the Aegean domain. The nucleation of three of the large NAF earthquakes near extensional clusters [*Bariş et al.*, 2002; *Dewey*, 1976] and the activation of these clusters after the 1999 earthquakes show that the two systems interact seismically.

[11] The two systems respond differently to stimulation. While aftershock activity on the un-ruptured section of the NAF after the 1999 earthquakes is limited to short (~30 km long) segments adjacent to the rupture [*Özalaybey et al.*, 2002; *Karabulut et al.*, 2002; *Bulut and Aktar*, 2007; *Görgün et al.*, 2009], as expected from static stress changes, activation of the clusters after the two earthquakes occurs at much larger distance (up to ~300 km). This is well illustrated when comparing the activities of the West Marmara cluster and of the NAF segment in the central Marmara sea (Figure 4). Although the latter is closer to the Izmit rupture than the former, its seismicity rate seems unaffected by the
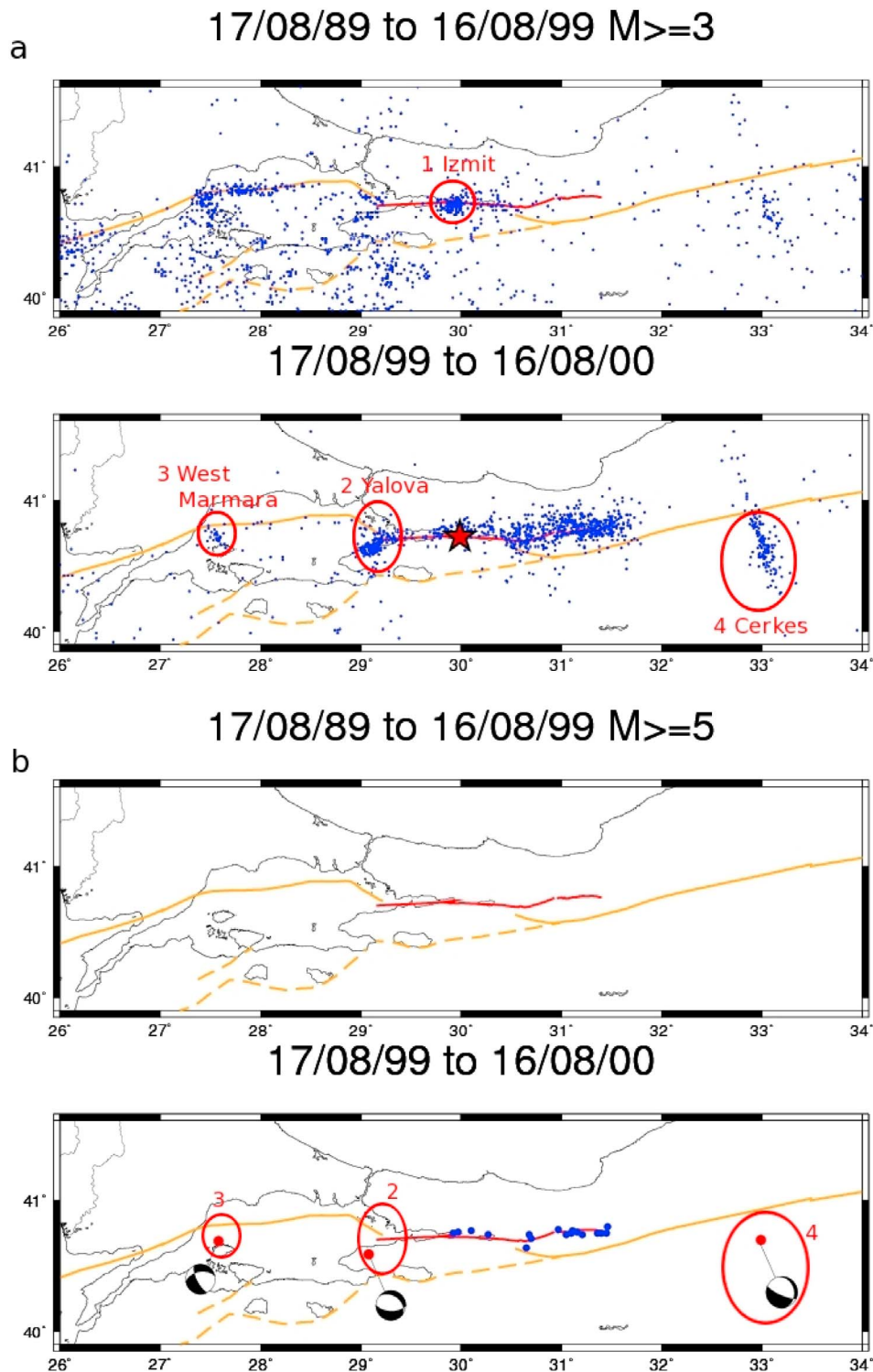
Figure 2. Comparison of the seismicity of northwestern Turkey in the year following the Izmit earthquake with the one of the 10 years before. (a) Events of M ≥ 3. The 4 major extensional clusters are identified. The main strand of the NAF is in solid yellow, the secondary strands in dashed yellow. The 1999 ruptures are in red. The trace of the NAF in the Marmara sea is from *Le Pichon et al.* [2001]. The red star is the Izmit epicenter. (b) Events of M ≥ 5. Events near the Izmit-Düzce rupture are in blue, others in red.

earthquake. The higher sensitivity of extension zones than strike-slip faults to distant earthquakes is consistent with observations elsewhere. Remote triggerings by the Landers, Hector Mine, and Denali earthquakes are uniquely restricted to

extensional areas [*Hill et al.*, 1993; *Gomberg*, 1996; *Gomberg et al.*, 2001; *Hill and Prejean*, 2006]. The Landers case is particularly instructive: although the earthquake widely triggered normal-faulting activity hundreds of kilometers away,
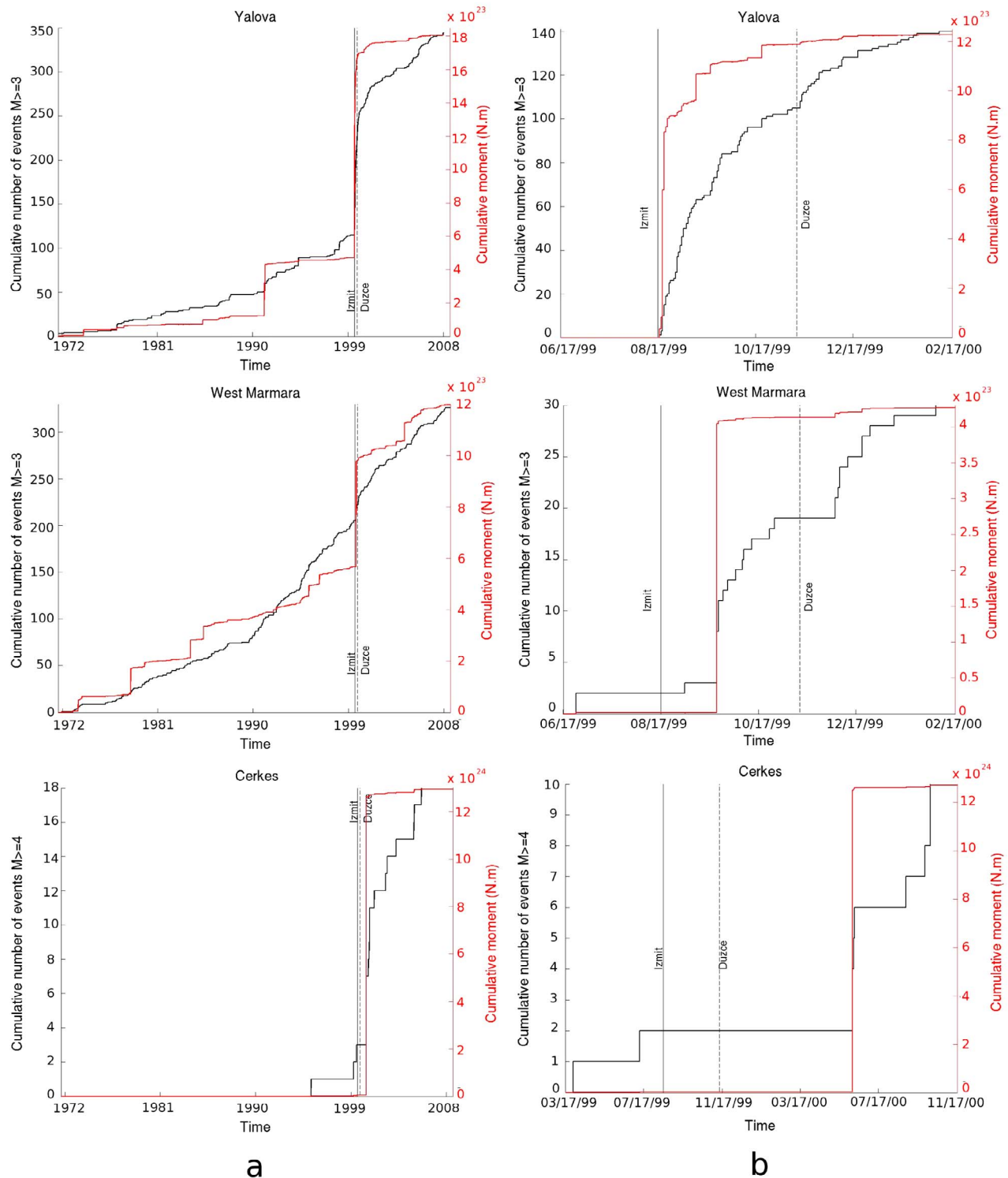
Figure 3. (a) Evolution of the number of events and of the seismic moment of the three clusters. (b) Corresponding zooms of the evolution. (For geographic locations see Table S1 and see Figure S2 for a closer zoom of the evolution of the Yalova cluster).

no significant increase of seismicity was detected on the San Andreas fault, located only ~30 km away from the rupture [*Hill et al.*, 1993] in spite of a static stress increase [*Harris and Simpson*, 1992]. The seismicity rate increase observed in Greece by *Brodsky et al.* [2000] following the Izmit earthquake

also shows that extensional seismicity, which is prevalent there, is sensitive to distant stimulation.

[12] The NAF and the clusters also respond differently in time to stimulation. While the aftershock activity on the two segments of the NAF lying just beyond the ends of rupture begins immediately after the earthquake and then decays
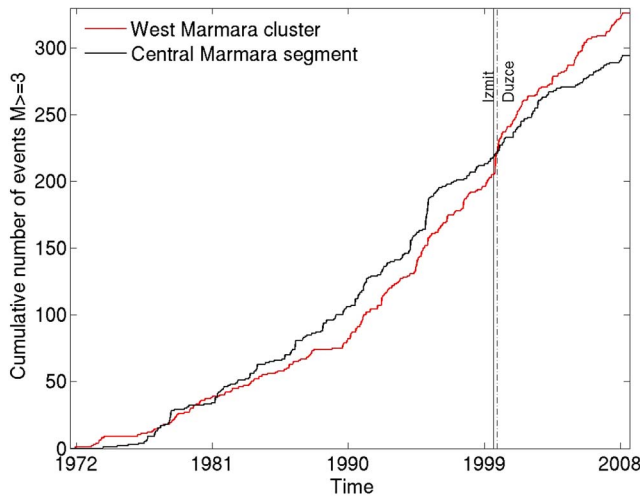
Figure 4. Comparison of the evolution of seismicity on the central Marmara segment of the NAF and in the West Marmara cluster.

rapidly with time [*Örgülü and Aktar*, 2001; *Özalaybey et al.*, 2002], the activation of the clusters is not immediate but delayed in time. This delayed response differs from almost all other reported observations of remote triggering, which show an activation either synchronized with the passage of the seismic waves or occurring soon after. All reported observations of immediate triggering, however, are restricted to small events [*Gomberg et al.*, 2001; *Hill and Prejean*, 2006]. Larger events (M ≥ 2.5) generally occur after some delay. For instance, the largest event remotely triggered by the Denali earthquake occurred 5 days later [*Pankow et al.*, 2004]. The existence and possible widespread of long-delayed triggering has been recently suggested [*Brodsky*, 2009]. The difficulty to link distant events when they occur weeks or months apart may have prevented its earlier recognition [*Hill and Prejean*, 2006].

[13] The long-range delayed activation of the clusters by the large earthquakes of the NAF sheds some light on the key problem in the mechanics of the 1939–1999 sequence [*Dewey*, 1976; *Toksöz et al.*, 1979; *Scholz*, 1990; *Barka*, 1996; *Stein et al.*, 1997]: Why did the *Mw* 7.6 1943 earthquake nucleate so far (280 km, Figure 1) from the termination of the previous rupture? *Stein et al.* [1997] have shown that the westward migration of earthquakes along the NAF is well explained by Coulomb stress except for this event. As the 1943 epicenter was near the Cerkes cluster (Figure 1), a delayed remote activation of the cluster by the 1942 earthquake which had occurred 11 months earlier (the post-Izmit activation occurred after 10 months) would help explain both the location and timing of the 1943 nucleation.

[14] The activation of the extension clusters by the 1999 earthquakes is remarkably consistent with recent analyses of post–Izmit GPS measurements [*Aktug et al.*, 2009; *Ergintav et al.*, 2009; *Hearn et al.*, 2009] which show that, unexpectedly, the earthquakes accelerated the rate of north-south extension over a broad region surrounding the NAF. This extension is particularly large around Yalova [*Hearn et al.*, 2009] and West Marmara [*Aktug et al.*, 2009]. The long duration of the seismic activation observed here also agrees with the GPS-inferred extension which continues for several

years after the earthquakes. These GPS measurements suggest that the activation of the extension is not restricted to the brittle seismogenic crust. The observed delay thus becomes logical as it corresponds to the response of the brittle crust to a deeper process.

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