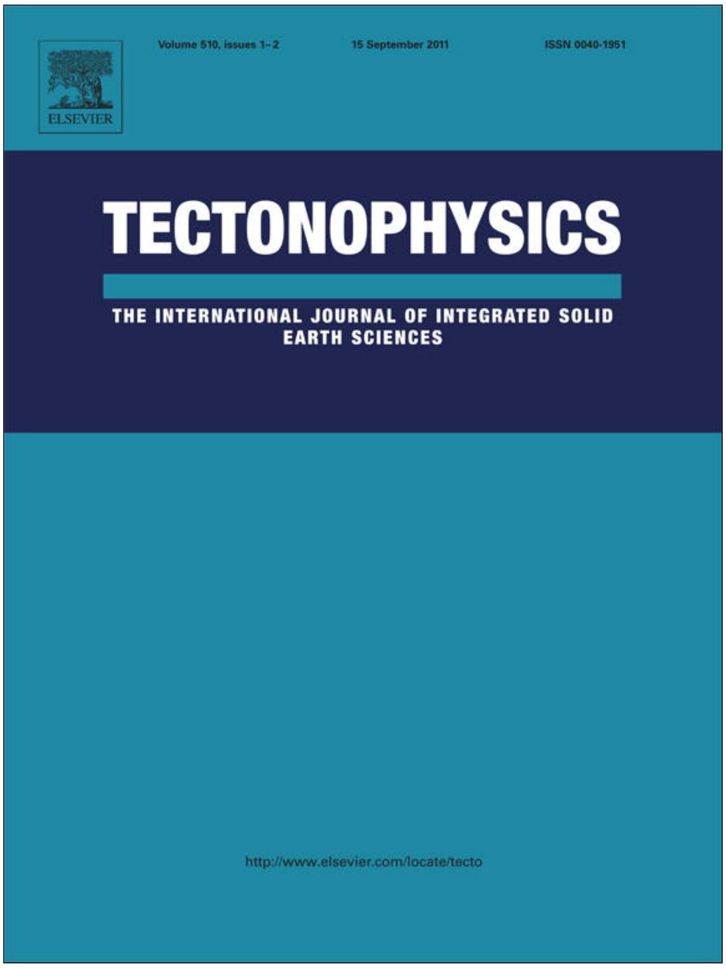
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Review Article

Evolution of the seismicity in the eastern Marmara Sea a decade before and after the 17 August 1999 Izmit earthquake

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ABSTRACT

We review the long term evolution of seismicity in the eastern Marmara Sea over a decade, before and after the 1999 Mw 7.6 Izmit earthquake. We analyze large scale space-time variations of seismicity in the region and illustrate the impact of the recent large strike-slip earthquakes on the background activity composed of distinct pre-existing seismic clusters. Two types of aftershocks activity are observed: the first type of enhancement is on strike-slip fault segments (Izmit Fault, Princes Island section of the Main Marmara Fault, Gemlik Fault) immediately following the main shock and related to Coulomb stress transfer; the second type of enhancement is attached to extensional clusters (Yalova, Tuzla) with a few days delay in the onset of strong activation, probably related to pore pressure increase. We observe a fast decay of the activity on strike-slip segments and slower evolution of seismic clusters with extensional features. Two years after the Izmit earthquake, seismic activity returned to the pre-earthquake pattern with most of the activity occurring within extensional clusters. It appears that the influence of the last large strike-slip event on the spatial seismicity distribution in the eastern Marmara Sea is less significant than the effect of the long term regional extension.

Contents

1. Introduction

The Marmara Sea region is presently a major seismic gap along the North Anatolian Fault (NAF). The region is located at the western termination of a unique sequence of large earthquakes (M>7) initiated by the 1939 Mw 7.9 Erzincan earthquake and propagated westwards over 1000 km (Şengör et al., 2005; Stein et al., 1997; Toksöz et al., 1979). Latest in this series, the August 17, 1999 Mw 7.6 Izmit earthquake ruptured a 150 km long segment of the North Anatolian Fault (NAF) (Barka, 2002). Rupture started below the city of Izmit and propagated bilaterally along the fault (Toksoz et al., 1999). In the west, rupture terminated in the Çınarcık basin of the Marmara Sea where the NAF changes orientation with a complex transition zone (Le Pichon et al., 2001) (Fig. 1). Three months later, on

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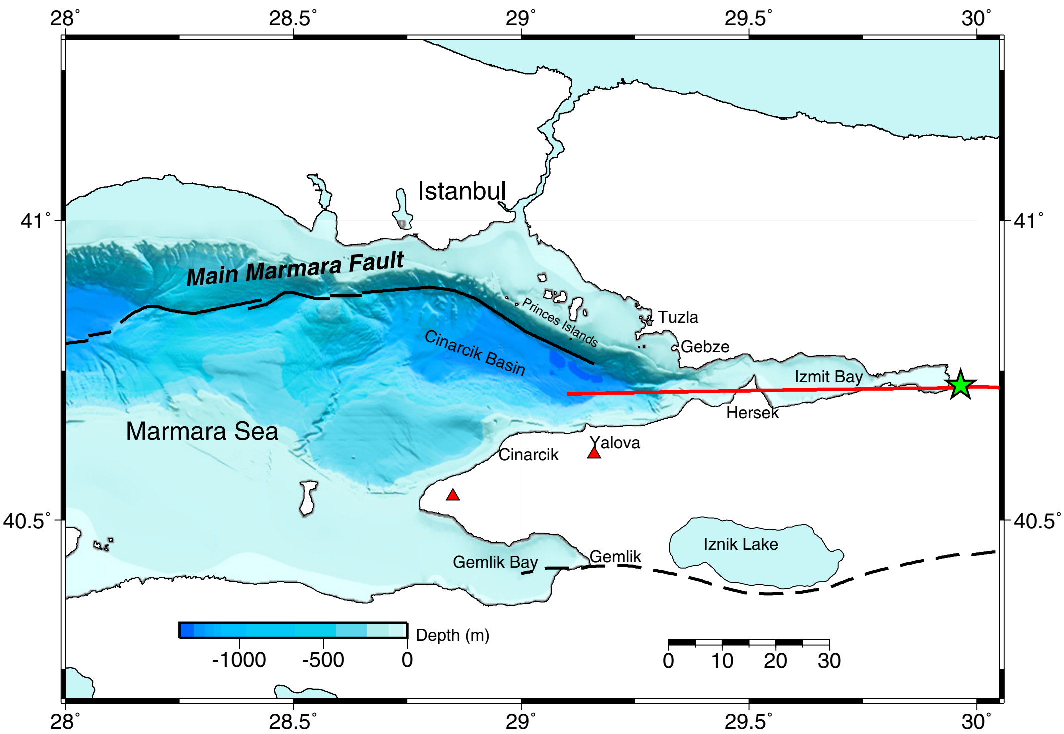

Fig. 1. Map of the eastern Marmara Sea (bathymetry data from Le Pichon et al. (2001). Continuous black lines show the Main Marmara Fault (MMF) from Le Pichon et al. (2001). Dashed line corresponds to the middle Branch (Gemlik Fault). Thick red line shows estimated surface rupture geometry of the 1999 Izmit earthquake from the aftershock locations. The green star indicates the Izmit epicenter. Red triangles show the location of thermal springs in the Armutlu peninsula.

November 12, 1999, the Düzce (Mw 7.2) earthquake was initiated near the eastern end of the Izmit rupture (Bouin et al., 2004).

Among the numerous observations accumulated on this major plate boundary, the remarkable westward migration of large earthquakes since 1939 suggests that the NAF obeys at large scale a simple deterministic evolution despite a rich history and a complex fault system at local scale. It is a strong motivation for expressing and formulating simple laws that are expected to rule the behavior of this major plate boundary from the nucleation of major events to the large scale interactions of the seismic activity. As examples of these rules, one might cite the duality of the rupture propagation (sub and super-shear) and its link with the geometry of the fault and the distribution of aftershocks (Bouchon and Karabulut, 2008; Bouchon et al., 2010) or the recent discovery of an extended nucleation phase for the Izmit earthquake that couples aseismic slip and dynamic rupture (Bouchon et al., 2011).

Large continental earthquakes do not only release stress on the ruptured segments of the fault but they also change the state of stress on unruptured segments of the same and nearby faults. Stress changes are not limited to the proximity of the hosting fault. The influence of viscoelastic relaxation in the lower crust and upper mantle is felt at distances far greater than the fault length while the transient fields from large earthquakes are known to trigger faults at large distances even with long time delays (Freed, 2005). Monitoring of seismic activity at various scales following large earthquakes provides critical information for improved understanding of the earthquake process and hazard assessment.

A central question therefore concerns the triggering mechanisms of a large earthquake: Is initiation of earthquakes on the NAF mostly influenced by lateral stress transfer as suggested by Stein et al. (1997) or by pre-existing local seismic clusters, as suggested by Dewey (1976)? It may also be a combination of the two with very long range of interactions between large earthquakes and local clusters through deep coupling (Durand et al., 2010).

The analysis of the seismicity in the Çınarcık basin appears of central importance for addressing the proposed question on the transition to the next major event in the Marmara region. Previous studies in the area have either focused on the spatial distribution of the activity in specific time periods (Barış et al., 2002; Bulut et al., 2009; Gürbüz et al., 2000; Karabulut et al., 2002; Özalaybey et al., 2002; Sato et al., 2004) or on analysis of long term observations at more regional scale with lower spatial resolution (Dewey, 1976; Durand et al., 2010). Particular studies on the NAF pointed out the importance of the seismic activity before and after large earthquakes (Dewey, 1976; Durand et al., 2010). Dewey (1976) indicated that large ruptures begin in regions with small and moderate earthquakes and then propagate into sections of the fault with lower level of seismicity. Similarly, Durand et al. (2010) showed triggering of seismic activity at large distances following the Izmit and Düzce earthquakes, and the existence of mechanical interaction between the NAF and the extension clusters.

Here we review the long term evolution of seismicity in the eastern Marmara Sea, 10 years before the Izmit earthquake to present (10 years later). We build spatio-temporal distributions of the pre-Izmit background seismicity, the post-Izmit aftershock sequence, two transitional periods (2001–2003 and 2005–2007), and the most recent period (2008–2010). We pay special attention to seismic clusters that occurred off the main strike slip faults in the aftershock zone of Izmit earthquake. We compare qualitatively the present activity with both the pre-Izmit seismicity and the aftershock sequence in relation to tectonic processes.

2. Data

We based our analysis on two types of seismicity catalogs (Table 1). The first type has been obtained from the permanent network of Kandilli Observatory and Earthquake Research Institute (KOERI) and is continuous from 1992 to 2009. Catalogs of the second type contain data from several sources with varying accuracy and resolution (Table 1). The latter type is not continuous and rather devoted to a spatial analysis of the seismicity.

Table 1
Origin of the seismic data and summary on the statistics of the event locations.

Period	Network	Location error (km)	Magnitude completeness
1992–2009	KOERI[a]	~5.0	3.0
1990–17 Aug. 1999	KOERI[a], IZINET	~5.0	3.0
17 Aug. 1999	KOERI[a], IPGS[b], Tubitak	~4.0	3.0
18 Aug. 1999	KOERI, IPGS, Tubitak	~3.0	2.2
19 Aug.–12 Nov. 1999	KOERI, IPGS, LGIT[c], Tubitak	~1.5	2.2
2001–2003	KOERI, Tubitak	~2.0	1.5
2005–2007	CINNET[d], KOERI	~2.0	1.7
2008–2010	CINNET, KOERI	~1.2	1.0

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[d] Çınarcık Network, a local network around the Çınarcık Basin operated since 2007.

The spatial coverage of the seismic stations since 17 August 1999 to present is uniform neither in time nor in space as shown in Fig. 2. As a result, the seismicity catalogs for the different time periods have varying magnitude thresholds and completenesses (see Table 1 and Fig. 3). We presented in Fig. 3 the Gutenberg–Richter distribution for each catalog and their respective magnitude thresholds. The KOERI and the pre-Izmit catalogs have the same magnitude completeness of the order of M~3. The aftershock period (17/08/99-12/11/99) which has the largest number of events, shows a slightly lower magnitude threshold (M~2.2). The three 2-year catalogs during the post Izmit period (2001–2003, 2005–2007, 2008–2010) show a similar number of events for each period (*i.e.* same overall seismicity rate) with a significantly lower magnitude threshold: M~1.5 compare to the pre-Izmit catalog or the aftershock catalog.

The seismicity before the Izmit earthquake was compiled from the networks of KOERI and IZINET (Üçer et al., 1985). The station distribution was sparse. Average location error (~5km) and magnitude completeness (~3) were high. As the digital waveform data were not available no attempts were made to improve locations. Datasets covering the Izmit aftershock sequence come from several temporary deployments (Karabulut et al., 2002; Özalaybey et al., 2002; Polat et al., 2002) and the permanent network of KOERI (Fig. 2).

The early stage (first day) of the activity was not accurately monitored since the station coverage was relatively poor. Besides KOERI, two networks (IPGS and IZINET) were operational during the initial phase of the activity. We took a step to improve the locations using the stations of the IPGS network and reduced magnitude threshold in particular along the Princess Island (PI) section of the MMF. Multiplets were searched within the database using cross-correlation of the waveforms but less than 5% of the events showed similarities. The majority of the multiplets are located in Tuzla and Yalova regions. We therefore did not attempt to improve the locations using relative location techniques (*e.g.* hypoDD) and located the events only by Hypoinverse location code (Klein, 1989). A 1-D velocity model was obtained (Table 2) using Velest inversion code (Kissling et al., 1994). The velocity model estimated here is similar to the velocity model of Karabulut et al. (2002) with improved data set. The deviations from 1-D velocity model are accounted in the station corrections. 2-D or 3-D velocity model could be implemented for further improvement of the locations (Becel et al., 2009). The average location errors for the first day are ~4.0 km. The station coverage in the region improved significantly during the following days. Both magnitude threshold and average location errors are reduced to 2.2 and 1.5 km, respectively. The final catalog covers the aftershock period up to the occurrence of the Düzce earthquake (November 12, 1999) with more than ~3500 aftershocks located on the western part of the epicenter. Magnitudes are duration magnitudes before the Izmit earthquake and local magnitudes after this event.

The database containing the 2001–2003 period was obtained from the networks of TUBITAK-MRC and KOERI. A large number of temporary stations deployed during the Izmit aftershock sequence were still operational in this period. Therefore both location errors (~2km) and magnitude completeness (~1.5) were satisfactory. The third database covers the period of 2005–2006 and is obtained from the KOERI network. The station coverage was rather poor and the magnitude threshold was high. We however relocated the events initially located by KOERI. The average horizontal errors are now less than 3 km and the magnitude completeness is ~1.7.

The KOERI network was significantly improved after 2006 both in instrumentation and station coverage. However, we took a step to further improve the location accuracies and also reduce the magnitude threshold. A network of 6 three component stations around the Çınarcık basin was installed in 2008 (CINNET). As a result we are able to reduce the location errors within the network to

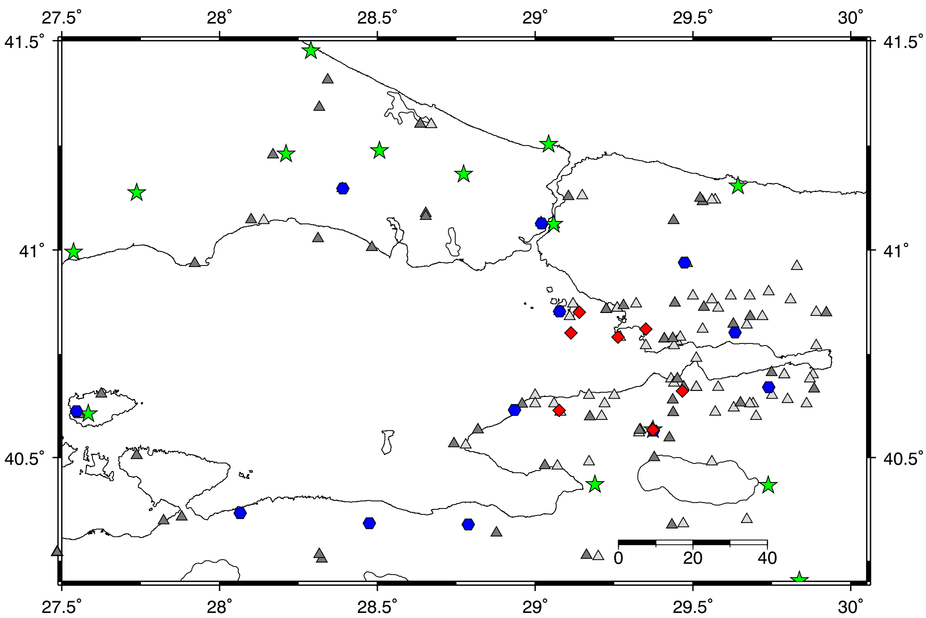

Fig. 2. Map of seismic stations in the eastern Marmara region. Gray triangles show the locations of the stations operated after 17 August 1999 Izmit Earthquake. Red diamonds are CINNET stations installed in 2008. Blue hexagons correspond to temporary IPGS stations installed before the Izmit earthquake. Green stars are the locations of the permanent KOERI stations installed between 2006 and 2008.

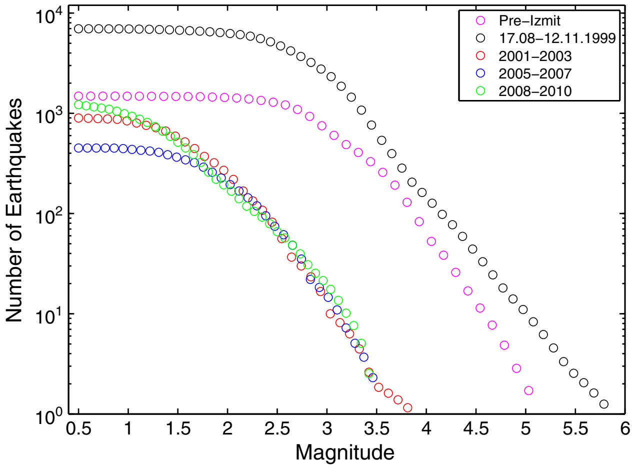

Fig. 3. Cumulative number of earthquakes *versus* magnitude for the time periods in this study. The continuous catalog (1992–2009) from the permanent KOERI network has the same features (*e.g.* magnitude completeness) as the plotted pre-Izmit catalog.

~1.2 km and the magnitude completeness to ~1.0. Such improvements on the data quality allowed us to monitor the finer details of the activity. Clusters related to quarry blasts were removed from the catalogs by simply checking if all events of a cluster occurred during daytime. However it is likely that isolated events of quarry blasts are still present in the database.

Fault plane solutions of the large aftershocks of the Izmit earthquake were compiled from previous studies (Karabulut et al., 2002; Örgülü & Aktar, 2001; Özalaybey et al., 2002). We used the first motion polarities to determine focal mechanisms for the period 2001–2009 with M_l>3.7. The aftershocks with at least 20 first-motion polarities were selected for the focal mechanism determination (Table 3). Lower-hemisphere fault plane solutions of single events were determined from first-motion data using a grid-search algorithm and tools introduced by Reasenberg and Oppenheimer (1985).

3. Results

We present two types of analysis of the seismic activity. The first one comes from the continuous catalog between 1992 and 2009. Time evolution of seismicity is presented at a regional scale: From the western edge of the Marmara Sea to the eastern termination of Düzce rupture along the NAF (Fig. 4). The second analysis focuses on the spatial distribution of seismicity within selected time periods (Figs. 5 and 6).

Table 2
Velocity model for the location of the earthquakes.

Depth(km)	Vp(km/s)	Vs(km/s)
0.0	3.00	1.90
1.0	5.60	3.15
2.0	5.70	3.21
3.0	5.80	3.26
4.0	5.90	3.41
5.0	5.95	3.42
6.0	6.05	3.44
8.0	6.10	3.48
10.0	6.15	3.56
12.0	6.20	3.59
14.0	6.25	3.61
15.0	6.30	3.63
20.0	6.40	3.66
22.0	6.50	3.78
25.0	6.70	3.85
32.0	8.00	4.65

Table 3
First motion focal mechanism solutions of the earthquakes between 2000 and 2009.

Year	MMDY	HRMN	Lat (°)	Lon (°)	Depth (km)	M_l	Strike (°)	Dip (°)	Rake (°)
2000	0707	0115	40.861	29.310	6.7	4.8	175.0	85.0	−10.0
2001	0116	0333	40.937	29.148	13.3	4.4	178.0	88.0	0.0
2001	0324	1307	40.860	28.878	8.5	4.1	117.0	80.0	17.0
2003	0919	0051	40.857	29.312	7.8	3.1	170.0	76.0	−22.0
2004	0929	1542	40.798	29.044	11	4.1	230.5	48.44	48.1
2006	1024	1400	40.403	29.001	8.1	5.2	153.3	60.5	−42.4
2008	0312	1853	40.607	29.040	14.8	4.7	356.0	71.3	−23.9
2008	0709	0454	40.421	28.732	8.0	3.5	159.2	46.9	−14.5
2008	1005	0604	40.598	29.014	8.7	3.8	136.0	52.8	−64.6
2008	1022	0100	40.726	29.175	4.1	4.0	355.3	54.6	−29.8
2009	1021	2216	40.854	28.823	7.7	3.7	195.8	79.0	8.7

3.1. Large scale space-time evolution

The long term activity is presented in Fig. 4 both as a cumulative map of the activity (*i.e.* no time evolution) and a space-time diagram where all the activity is projected along an east-west line. Both diagrams of Fig. 4 show that distributions are homogeneous neither in space nor in time. We introduce four geographical zones: Izmit area (IZ), eastern Marmara cluster (EM) (3 sub-regions with similar longitudinal coordinates are separated: Gemlik Bay (GB), Yalova-Çınarcık area (Y-Ç) and Tuzla-Central basin area), western Marmara (WM) and the Düzce area (DZ). Apart from the Düzce area, a higher level activity is observed consistently through time within these regions and defines three main clusters along the NAF in the Marmara Sea area. In time, a two year period (1999–2001) of high activity clearly emerges after the Izmit–Dżce earthquakes and corresponds to the aftershock period.

One striking observation is the significant decrease of activity in the Izmit cluster after 2001. During the years before the Izmit earthquake, local seismicity has been studied in detail during the Turkish Dilatancy Projects (Crampin et al., 1985; Evans et al., 1987) and later by Barış et al. (2002). Complementary, shear wave splitting measurements indicated coherent splitting directions with respect to fault plane solutions and regional stress directions (Crampin et al., 1985; Evans et al., 1987). Microearthquake activity in the epicentral region of Izmit earthquake was already interpreted as precursory seismic activity. However, a clear anomalous behavior is not apparent in the seismicity evolution prior to the August 17, 1999 (Fig. 4) even though, precursory events were detected one hour before the main shock at the epicentral region (Bouchon et al., 2011; Özalaybey et al., 2002). Two years after the Izmit earthquake, activity near the Izmit epicenter almost disappeared while activities in the Y-Ç, GB as well as WM are remarkably persistent throughout time. A relative increase of the most recent activity in the Eastern Marmara (EM) cluster is noticeable but might be related to the improvement of the seismic network. Whether these activities have similar signatures as the pre-Izmit activity at the epicenter region is not clear and has to be studied in more detail.

3.2. Time-lapse distribution of seismic activity

The spatial distribution of seismicity in the eastern Marmara Sea over 20 years, before and after the Izmit earthquake is shown in Figs. 5 and 6. The seismicity between 1990 and August 17, 1999 is diffuse and does not seem to be localized along well-defined seismogenic structures (Fig. 5a). The major part of this activity, however, is concentrated in four broad zones: 1) In the south, a continuous east-west band of seismicity follows the Middle Branch of the NAF from Iznik Lake through Gemlik Bay; 2) Inland, between Yalova and Çınarcık, a broad cluster of activity is present; 3) The south-central part of the Çınarcık basin is the seat of scattered seismic activity; 4) A small nest of seismicity occurs off-shore from the Tuzla peninsula.

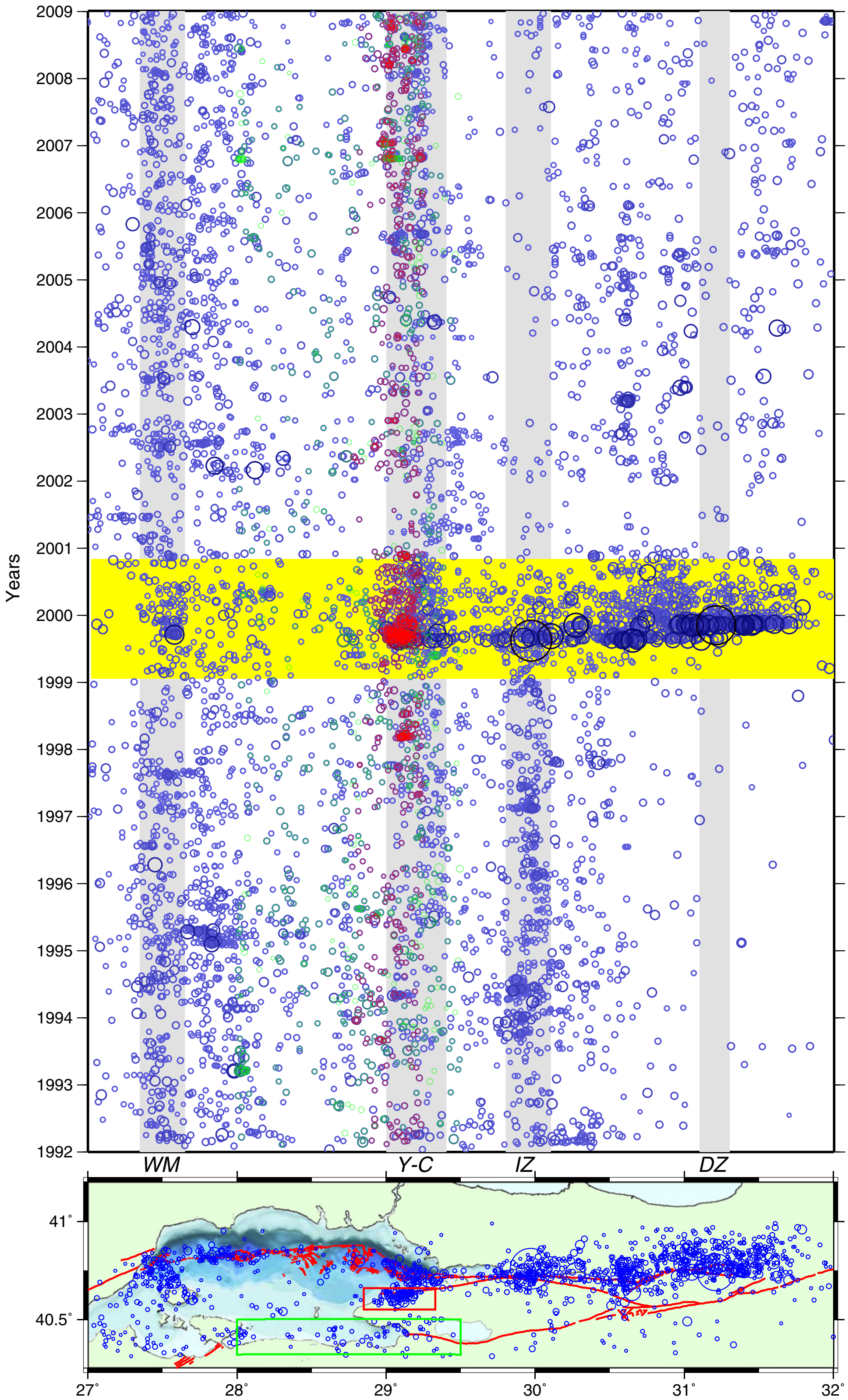

Fig. 4. Spatio-temporal evolution of seismicity in the Marmara region (KOERI catalog). The seismicity covers a period between 1992 and 2009 with magnitudes greater than 2.5. Top: space-time evolution. Yellow bar indicates the activity approximatively two years before and after the Izmit and Düzce earthquakes. Gray bars show the seismic activity in four zones of interest: west Marmara region (WM), east Marmara region (EM) mostly due to the Yalova-Çınarcık cluster (Y-Ç), the Izmit epicenter region (IZ) and the Düzce region (DZ). Bottom: seismicity map. Water depth color code is the same as in Fig. 1. Fault lines are from Le Pichon et al. (2001). The red box defines the region of Y-Ç cluster whose activity is plotted in red in the top sub-figure. The green box defines the region of the Gemlik fault. Activity in the latter region is plotted in green in the top sub-figure.

Remarkably, the pre-Izmit seismicity in the eastern Marmara Sea carries almost no information related to the main strand of the NAF which runs through the Izmit Bay and along the northern slope of the Çınarcık basin (Fig. 1). This is in contrast with the east-west alignment of seismicity that extends westward from Iznik Lake and follows the Middle Branch of the NAF to the Gemlik Bay.

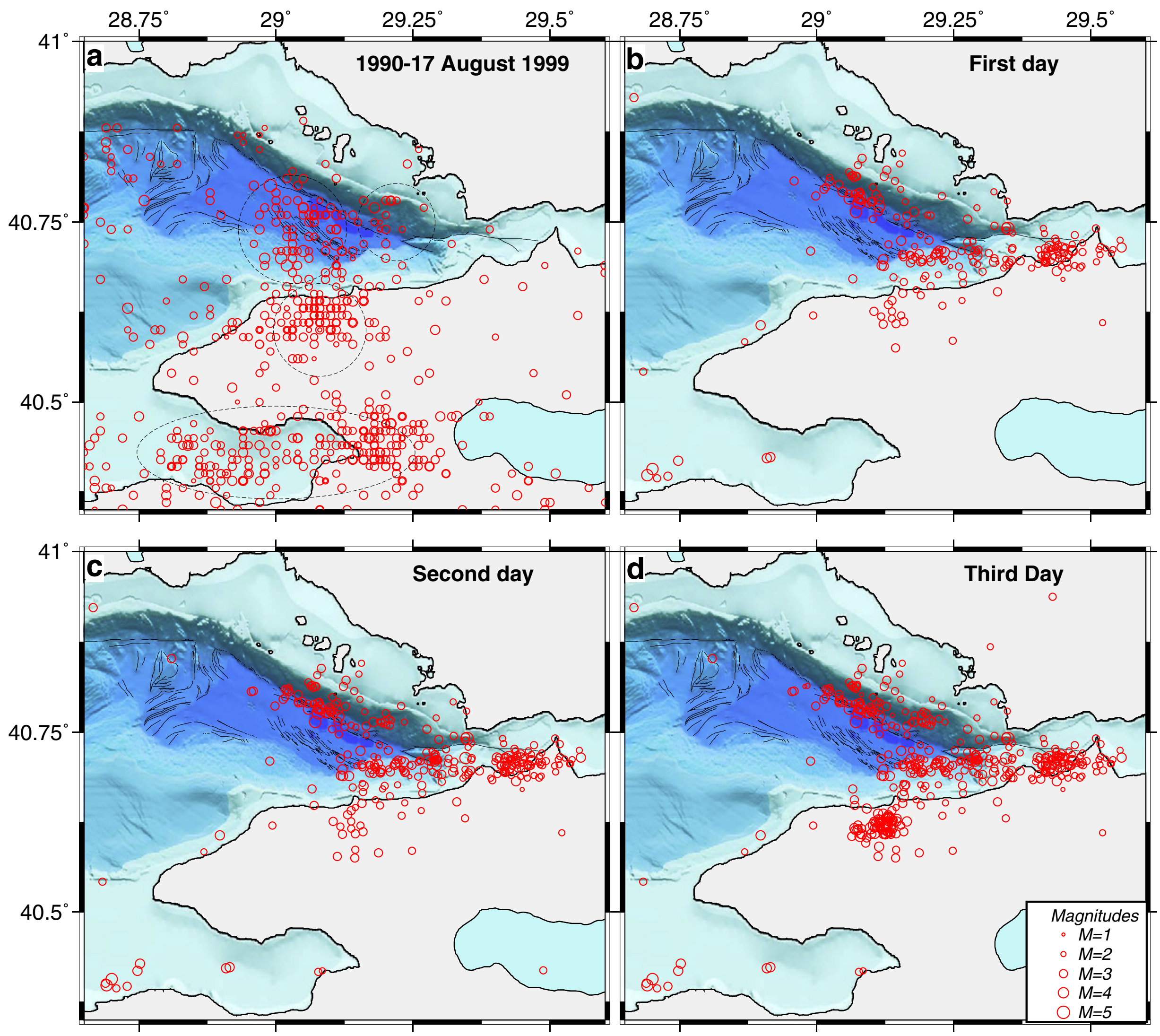

Fig. 5. Evolution of seismicity in the eastern Marmara Sea: a) 10 years before the 1999 Izmit Earthquake, b) one day, c) two days and d) three days of cumulative seismic activity after the main shock. Water depth color code is the same as in Fig. 1. Fault lines are from Le Pichon et al. (2001).

The August 17, 1999 Izmit earthquake ruptured a ~70 km long segment of the NAF to the west of the epicenter. The overall distribution of the immediate seismicity is remarkably complementary to that of the pre-Izmit earthquake (Fig. 5b). The aftershocks during the first day clearly mark the spatial extent of the rupture in the Çınarcık basin, where it terminates at ~30 km westward from the Hersek Peninsula. A nearly E–W linear band of seismicity follows the rupture under the Izmit Bay and the entrance of the Marmara Sea. The activity during the first day is also strong along the Princess Island section of the MMF. To the south few aftershocks occurred immediately after the earthquake in the Gemlik Bay along the middle branch of the NAF (Gemlik fault) at large distance from the Izmit fault. On the contrary the pre-Izmit clusters in Yalova-Çınarcık (Y-Ç) and Tuzla are not or weakly activated on the first day (Fig. 7) despite their short distance to the fault. It is of interest to note that activity was triggered quicker on the Gemlik fault than in the Y-Ç cluster despite a larger distance along the same direction.

On the second and third days (Fig. 5c–d), the clusters of Y-Ç and Tuzla are activated. These clusters are not associated directly with any major fault but are located in the close vicinity of the rupture. By the time of the Düzce earthquake (November 12, 1999), the Y-Ç cluster has become the most energetic aftershock zone of the earthquake (Fig. 6a). In the north-west, most of the aftershock activity on the PI section that occurred during the first few day, decreased rapidly in the following days (Fig. 7).

To explain the enhancement of the seismic activity in the zones of interest, we analyze the stress transfer induced by the main shock. The computation includes not only the static stress transfer (Parsons et al., 2000) but also the dynamic stress transfer and uses the source model of the Izmit earthquake obtained from the inversion of the near-fault seismic records (Bouchon et al., 2002). The orientation of the faults on which the stress is inferred corresponds to the prevalent earthquake mechanism of the area (Table 4). The stress tensor is computed at a depth of 10 km using the discrete wavenumber method (Bouchon, 1981). Coulomb stresses are calculated using a friction coefficient of 0.4 on the faults of Tuzla, Yalova-Çınarcık, Princess Island and Gemlik (Fig. 8) using fault orientations given in Table 4.

The dynamic Coulomb stress on the Princess Island section of the MMF reaches a maximum of ~21 bars while the static stress is small (~1 bar), which may explain the almost instantaneous triggering of the activity in the area and its subsequent rapid extinction. In Yalova, the onset of strong activity occurs after a delay of two days and stays very high for at least 4 months (Fig. 7). This area underwent a static Coulomb stress decrease (~5 bars) but a large pressure increase

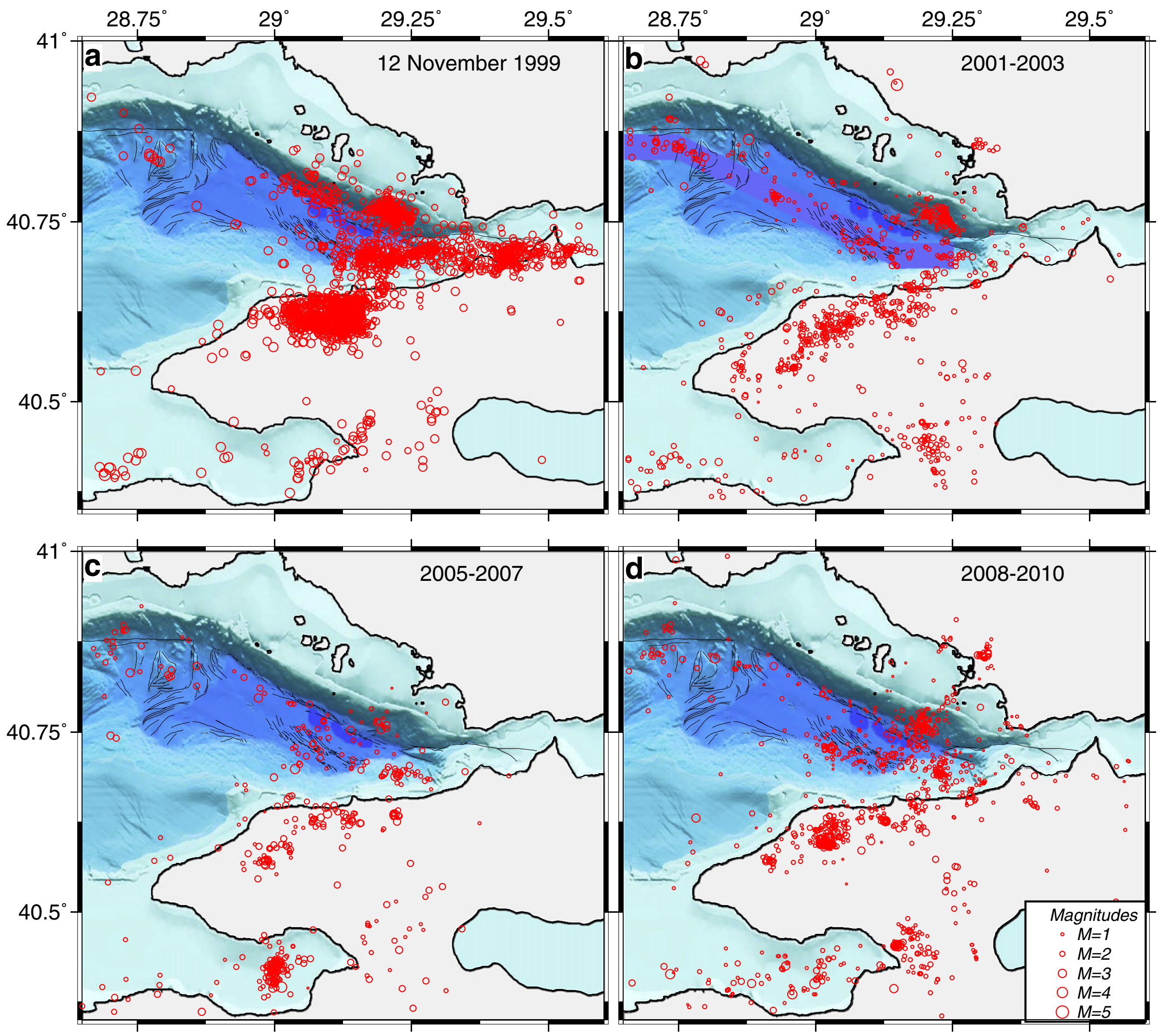

Fig. 6. Evolution of seismicity in the eastern Marmara sea in periods of 3 years after the 1999 Izmit Earthquake: a) 3 months of cumulative seismic activity after the main shock; b) 2001–2003, c) 2005–2007, d) 2008–2010. Water depth color code is the same as in Fig. 1. Fault lines are from Le Pichon et al. (2001).

(~10 bars) following the earthquake. Therefore the activation is likely related to fluids present in this well-known hydrothermal area. Fig. 9 compares distance dependency of the static pressure and dynamic stress on faults in Yalova region. It is clear that the pressure is higher close to the fault but decreases rapidly with distance. This may explain why the activity was initiated in the cluster at the closest location of the rupture termination. Although the Y-Ç region contains a network of fractures so that dynamic triggering of seismic activity might occur at any of these weakness zones, the activity started in a small confined zone and expanded throughout the area. In Tuzla, the intense long lasting activation is consistent with the large increase (~9 bars) in static Coulomb stress, but the dynamic stress is also large (~20 bars). The Tuzla cluster is also activated with approximately 2 day delay similarly to the Y-Ç cluster. In the Gemlik Bay, the dynamic Coulomb stress reaches ~6 bars while the static stress is not favorable. Therefore the activity there, soon after the main shock, is likely to be dynamically triggered.

Fig. 6b–d shows the long term return to the background activity over the last 10 years. Significant changes are apparent on the distribution of seismicity over the period. In the Gemlik region, the activity is continuous but alternates between inland and off-shore with episodic changes in the seismicity. An earthquake of magnitude 5.2 and several with magnitudes greater than 4 occurred there during 2006–2007. Focal mechanisms of the earthquakes in the region contain extensional and right-lateral strike-slip components (Fig. 10).

The gradual evolution of seismicity in the Y-Ç continues from the end of observational period of 1999 activity to the present. The activity evolves from a massive cluster of 1999 aftershock period to a long streak along the coast (N60°) with a reduced and sparse activity. The activity is localized in space in a few sub-clusters but also clustered in time.

In the north, the most striking observation is the vanishing of the activity along the MMF. Between 1999 and 2001, the activity shifts from the Princess Island section of the MMF, to a sub-parallel geometry extending near-continuously from the termination of the Izmit rupture to the north-western edge of the Çınarcık basin. After 2003, seismicity in the northern part of the basin decreases significantly while it stays high in the eastern Çınarcık basin.

In the south-central part of the basin, activity clusters near and beyond the termination of the 1999 rupture in the area of the pre-Izmit cluster (Fig. 6c–d). Compared to 1999, the activity has moved westwards by about 20 km in the prolongation of the Izmit rupture (Fig. 6d). This suggests that during the 10 years following the earthquake, the Izmit rupture has been slowly progressing westward.

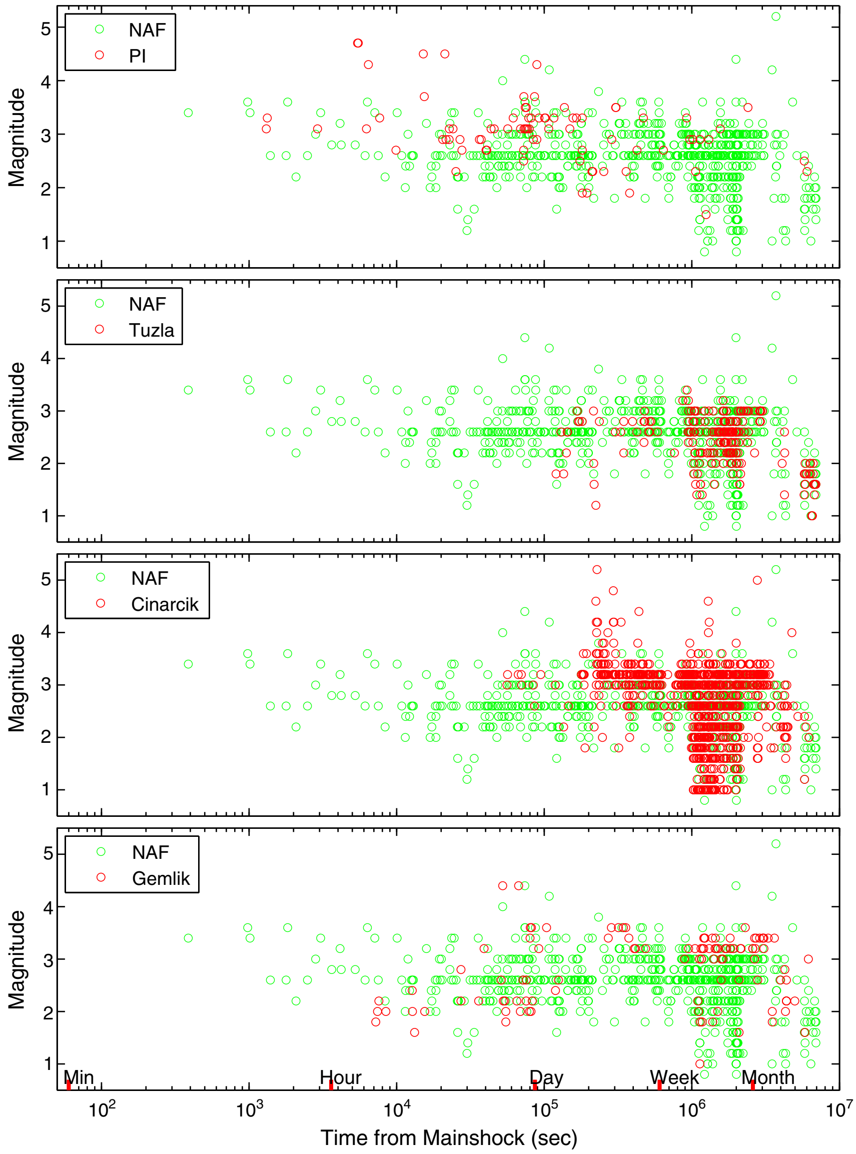

Fig. 7. Time-magnitude distribution of 1999 August 17 Mw = 7.6 Izmit aftershocks. Only events located on the west of the Hersek Peninsula are displayed (NAF).

On the contrary, in Tuzla region, the activity is maintained over the 10 years.

4. Discussion and conclusions

Observations presented in this work capture the critical stages (*i.e.* pre and post-rupture stages) of a seismic cycle in a region of critical importance for the next large earthquake and provide information on the mechanisms of seismic interactions. Two tectonic systems are known to exist in the region: one attached to the major strike-slip fault (NAF) and the second related to regional extension. These two systems strongly interact through time (Fraser et al., 2010; Şengör et al., 2005).

The present study shows the near-absence of seismicity along the main branch of the NAF in the eastern Marmara sea in the 10 years preceding the Izmit earthquake. Indeed the fault segment which extends from the Izmit bay to the southeast of the Çınarcık basin, is not associated with any significant seismic activity. Similarly the Main Marmara Fault segment along the northern edge of the basin, shows no significant seismic activity. The pre-Izmit seismicity is rather concentrated within the clusters associated with regional extension. The absence of events along the trace of the MMF in the eastern Marmara Sea before the main shock suggests that this segment was locked throughout the seismogenic zone prior to the earthquake.

Following the main shock, seismic activity is enhanced within the pre-existing seismic clusters. The Yalova cluster grew laterally from its initiation to the western termination of the rupture. The Tuzla cluster kept its persistent activity and geometry throughout time. A slow progression of the activity from the western termination of the

Table 4
Parameters of the receiver faults for the stress transfer computation of Fig. 8.

Location	Strike(°)	Dip(°)	Rake(°)	Lat(°)	Lon(°)
Princess Islands (MMF)	23	80	0	29.07	40.79
Tuzla	65	70	−90	29.19	40.76
Yalova	180	60	−90	29.10	40.63
Gemlik	0	90	0	29.00	40.40

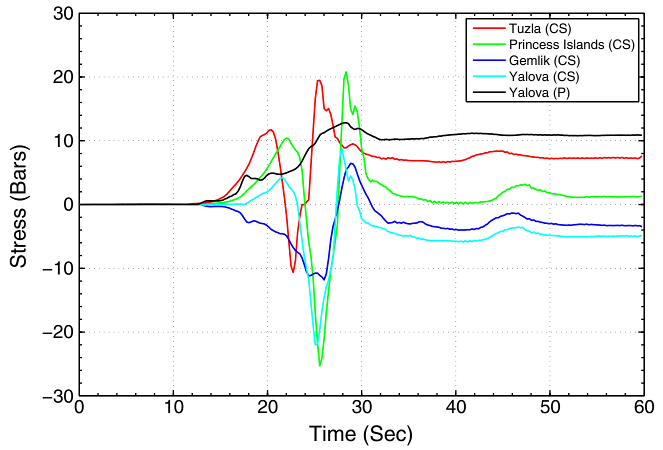

Fig. 8. Stress evolution at the Tuzla, Princess Island, Yalova-Çınarcık and Gemlik clusters calculated by the discrete wavenumber method (Bouchon, 1981). Time is defined from the onset of the main shock. We use the source model of the Izmit earthquake obtained from the inversion of the near-fault records (Bouchon et al., 2002) to compute the dynamical evolution of local stress tensors. From the orientation of the fault given by the local prevalent earthquake mechanism (Table 4) we inferred normal (σ) and shear (τ) stresses and Coulomb stress (CS) as: $CS = \tau - \mu\sigma$. A coefficient of friction $\mu = 0.4$ is used. Pressure (P) is computed from the trace of the stress tensor, independently of the fault orientation. Static stresses are estimated from plateaux at long time (around 60 s).

Izmit rupture towards the center of the basin (where a pre-Izmit cluster was identified, see Fig. 5a) is observed in the years following the Izmit earthquake. Except for its much finer resolution and detail, the general pattern of seismicity in and around the eastern Marmara Sea, 10 years after the Izmit earthquake bears strong resemblance to the pre-Izmit pattern.

Stress transfers are however significant. Seismic activity (including the largest aftershocks) has been triggered along the PI section of the MMF in the hours following the earthquake (Örgülü & Aktar, 2001; Özalaybey et al., 2002) (Fig. 7). This indicates that the segment was highly loaded by the regional stress field and early aftershocks are the result of significant Coulomb stress transfer. Moreover, as the effect of the Coulomb stress died off, the activity strongly diminished. One possible explanation for a limited impact of the stress load from the Izmit rupture, is that the local orientation of the MMF with respect to the regional stress field direction was not favorable for the segment to

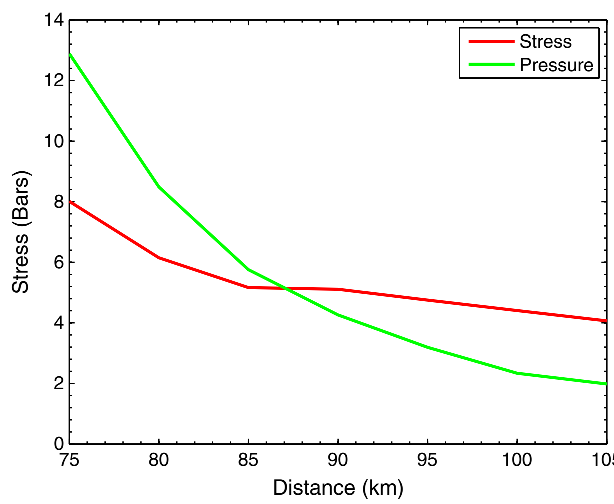

Fig. 9. Evolution of static pressure in green, and maximum dynamic stress in red, with distance to Izmit epicenter at the Yalova cluster location.

break. Indeed regional crustal stress orientations obtained from fault plane solutions are varying between N145E and N118E (Bohnhoff et al., 2005; Gürbüz et al., 2000; Pınar et al., 2001). Crampin et al. (1985) also obtained the principal stress direction from shear wave splitting measurements as N100E in the epicenter area of the Izmit earthquake. If the misorientation argument of the MMF is valid then a segment with more favorable geometry is expected be activated. This is consistent with the recognizable shift of the seismic activity from the PI section of the MMF to the south along the long axis of the Çınarcık basin between 2001 and 2003 (Fig. 6b). However this activity does not appear during the period of 2008–2010. Between 2008 and 2010 many events occur along the western extension of the 1999 rupture which is more east-west oriented. This latest alignment of the activity is actually following the fault lines mapped by Le Pichon et al. (2001). It is worthwhile to mention that gas emissions are also found above this region (Geli et al., 2008). The observed activity could be related to methane gas emissions in the shallow sedimentary column as a result of the recent seismic activity.

Aside from the Tuzla cluster, the rest of the seismicity during the latest period is weaker and more diffuse. The most significant change over the last period occurred in the Y-Ç cluster. From the activation of the cluster (~2 days after the rupture) to the time of the Düzce earthquake, the size of the cluster gradually increased. As indicated by several authors (Daniel et al., 2006; Özalaybey et al., 2002), the preferred mechanism for the initiation of this activity is stress triggering in a critically sensitive region known for its intense hydrothermal activity (Eisonlohr, 1996). Fault plane solutions and field observations also suggest the presence of a highly fractured crust in an extensional context. Seismicity on the cross sections defines a plane dipping to the north with approximately 55° which is consistent with the majority of the focal mechanisms (Fig. 10). A gradual evolution of seismicity in the Y-Ç is on-going from the end of 1999 to the present. The activity extended into a larger area with a decreasing rate during 2001–2003 and finally reached the background seismicity level in 2005–2007. The recent presence of small size clusters is consistent with a highly fractured crust with strong stress heterogeneities.

Both the Y-Ç and Tuzla clusters were activated with approximately two day delay. Both clusters are located very close to strike slip segments of the NAF and are extensional in nature (Karabulut et al., 2002). The Tuzla cluster is located in the vicinity of the change of orientation of the NAF and in an area where relatively large landslides were observed from bathymetry (Fig. 1). Indeed, in this region, the slope of the northern escarpment of the Çınarcık basin is steep (but not the steepest in the area of the Tuzla cluster) and past earthquakes may have triggered landslides. Moreover strikes of fault plane solutions of events within the Tuzla cluster after the Izmit earthquake indicate approximately 15–20° deviation from the orientation of the MMF (Fig. 10). The geometry of MMF and PI section suggests that Tuzla cluster is a result of a local transtension basin.

The initiation of the Y-Ç is located close to the western termination of the Izmit rupture. An intense seismic activity started in this cluster with several events with magnitudes greater than 4, two days after the main shock following a slowly progressing seismic activity (Fig. 7). Transient stress transfer and static pressure increase are likely responsible for this activity rise.

The continuous activity in Gemlik Bay is also interesting and needs to be monitored more carefully. The middle branch of the North Anatolian Fault which runs from the east, enters the Marmara sea at the town of Gemlik (Kuşçu et al., 2009). Seismic activity was observed just after the Izmit earthquake but was not very energetic.

Even though the distance from the rupture was much larger than for the Y-Ç and Tuzla clusters, the activity was triggered much earlier (see Fig. 7). This suggests that the Gemlik segment responded to a dynamic stress transfer in a way similar to the PI segment (see Fig. 8) and confirms that Y-Ç cluster is not sensitive to dynamical stress transfer.

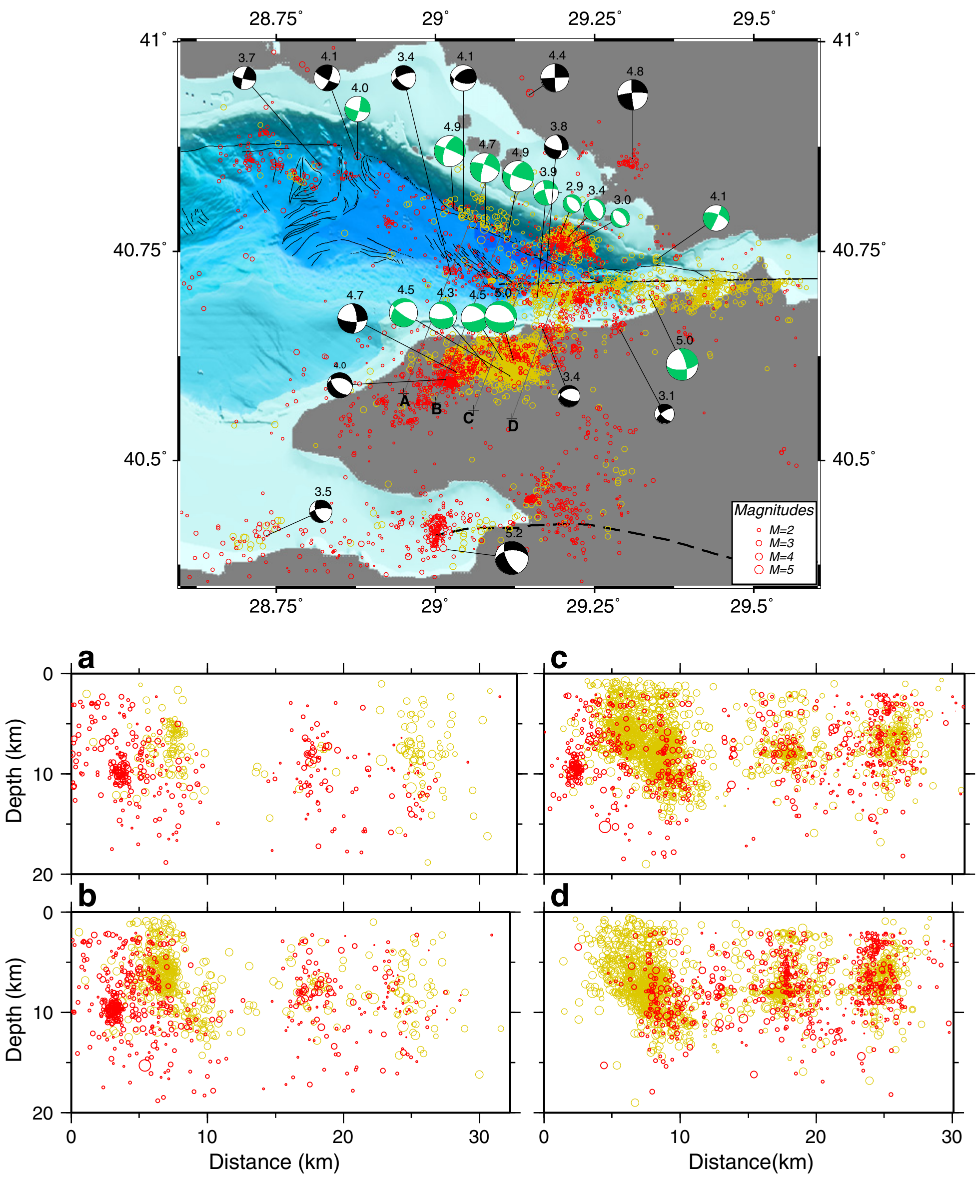

Fig. 10. Seismicity in the Çınarcık basin since 17 August 1999 (yellow: 17 August 1999–12 November 1999, red: 2001–2010). Water depth color code is the same as in Fig. 1. Fault lines are from sLe Pichon et al. (2001). Focal mechanisms of the largest aftershocks for the Izmit rupture are in green (Karabulut et al., 2002; Örgülü & Aktar, 2001; Özalaybey et al., 2002) and first motion focal mechanisms for large events of the 2001–2010 period are in black. Below: depth sections along SW-NE profiles shown with gray lines (A, B, C, D) ordered from left to right.

Both SAR and GPS data indicated significant afterslip in the eastern Marmara (Çakır et al., 2003; Hearn et al., 2009). Besides the fast afterslip observed few months after the rupture, the GPS data indicated that significant viscoelastic relaxation in the Çınarcık basin took place during the period 2001–2003 (Hearn et al., 2009). The GPS observations indicate a shallow locking depth along a profile crossing Princess Islands and Y-Ç (Ergintav et al., 2009). These observations may be related to creeping along this section of the fault. Multiplets observed in this cluster may be the indication of creeping.

In conclusion, activity of clusters is shown to be maintained on the long term and even developed (*e.g.* Tuzla cluster) despite a complete dying out of the NAF seismicity in the region. We conclude that the influence of the stress transfer from the Izmit earthquake on the regional pattern of the activity appears to be marginal. However, the Izmit earthquake had a strong influence on the enhancement of the activity of the existing clusters, even at very large distances (Durand et al., 2010). The exact impact of these long term clusters, in particular the most active ones at present, on the nucleation of the next major event has to be now monitored carefully.

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