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Synchronization of small-scale seismic clusters reveals large-scale plate deformation

Hayrullah Karabulut[1], Michel Bouchon[2] and Jean Schmittbuhl[3*]

Abstract

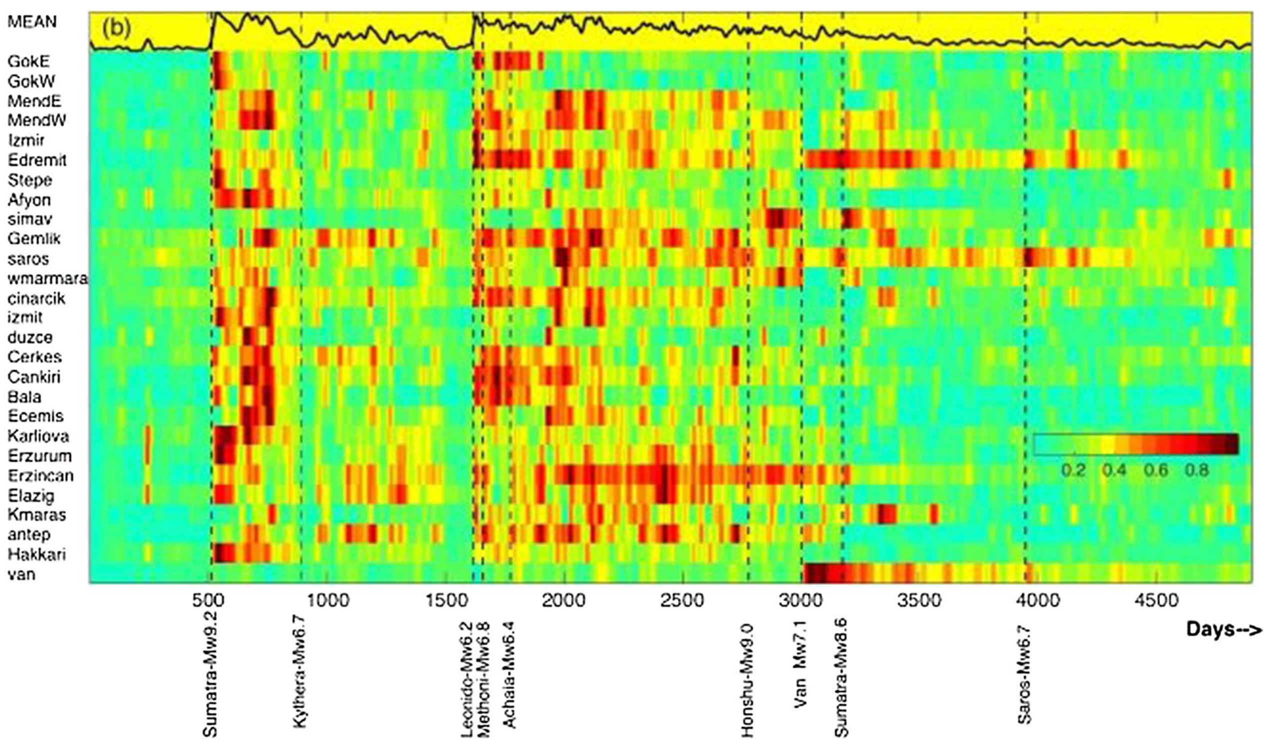
It has long been observed that periods of intense seismic activity in a region alternate with periods of relative quiescence, but establishing whether or not this intermittency is driven by broad-scale physical processes occurring in the Earth, remains a challenge. Here, we address this question of long-range triggering by a large-scale analysis of evolution of the seismicity between 2003 and 2017 in the Anatolia region. Two multi-year periods of synchronous high seismicity rate in 27 seismicity clusters across the Anatolian plate are evidenced before a relatively uniform quiescence period. We argue that two remote tectonic processes are important for the timing of these activities: the 2004 M9.2 Sumatra earthquake and the 2008–2011 episode of slab rollback/deformation in the Hellenic subduction, even if a clear causal mechanism is still lacking.

Keywords: Anatolian seismicity, Earthquake triggering, Seismicity rate, Plate deformation

*Correspondence: Jean.Schmittbuhl@unistra.fr

[3] EOST/ITES, Centre National de la Recherche Scientifique and Université de Strasbourg, 5 Rue Descartes, 67084 Strasbourg, France
Full list of author information is available at the end of the article

Graphical Abstract



Main text

Introduction

Sited at the intersection of three major plate boundaries, Turkey is one of the most active seismic areas in the world. In the past century, 12 earthquakes of magnitude between 7 and 8 have occurred there, with devastating consequences. Located along the only unbroken segment in the past century of the ~1400-km-long North Anatolian Fault, the Marmara Sea with the city of Istanbul on its shore is thought to be one of the most exposed areas in the world to a major earthquake in coming decades. Besides large earthquakes, small and moderate seismic activity is intense throughout Turkey. This activity has been extensively studied in recent years, particularly in and around the Marmara Sea (Karabulut et al. 2011; Bohnhoff et al. 2013; Durand et al. 2013; Schmittbuhl et al. 2016) in the hope of deciphering the tectonic loading occurring there and detecting possible signs of preparation of the next rupture.

In this study, we analyze the history of 27 seismic clusters distributed all over the Anatolian plate and their relative evolutions in time to evidence possible synchronization at the scale of the tectonic plate, over 15 years. We first describe the seismicity catalogs that have been considered and the methodology that has been introduced to assess the seismicity rate over time and space at the scale of the Anatolian plate. In the result section, we show that two major tectonic events are synchronous to the timing of the global pattern of the seismicity evolution: one is the 2004 Mw9.2 Sumatra earthquake which coincides with an increase of the seismic activity throughout Anatolia for about a year and the other one is an episode of slab slow-slip/rollback in the Hellenic subduction which lasted from 2008 to 2011. In the discussion section, the implications of these observations are formulated in terms of long-lasting triggering (~1 year) of seismic waves from large distant earthquakes and deformation rate that is much slower than seismic wave propagation but still faster than viscous deformation (~1 day to cover the whole Anatolian plate).

Data and methods

We use for this study the seismicity catalogs of the Kandilli Observatory and Earthquake Research Institute (KOERI). The map of seismic activity between 1998 and 2017 is presented in Fig. 1. One long recognized characteristic of this seismicity is its organization in numerous

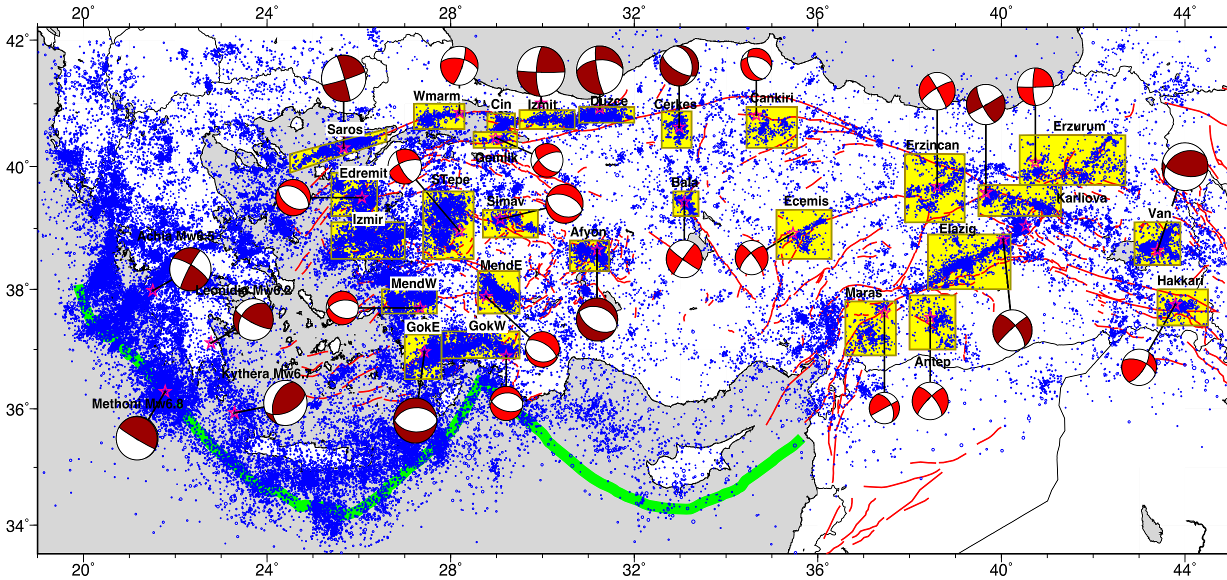


Fig. 1 Seismicity map between 1998 and 2017. Earthquake locations are from the catalogs of Kandilli Observatory and Earthquake Research Institute and the National Observatory of Athens. Boxes outline regions where the clusters of seismicity are considered in the analysis and named with the closest geographical location (see also Supporting Information). The beach balls show the mechanisms of the earthquakes between 1998 and 2017 with the largest magnitude (in dark red color, Mw > = 6.0) in each cluster (CMT Catalog). The red lines show the major active faults (Emre et al. 2018) and the green ones the Hellenic trench

clusters (Dewey, 1976). We selected 27 active seismic clusters that we consider as most significant and representative of the seismicity distributed over the Anatolian plate. We used several criteria to form and select these seismicity clusters. Most of the clusters are geographically isolated and defined within rectangular cells. When seismicity is diffuse, we used the fault geometry to adjust the centroid of these cells which confine the clusters. The seismic events with hypocentral depths less than 20 km are retained in each cluster. The selected clusters contain at least one Mw4.5 + event during the study period. The main features of these 27 clusters are detailed in the supplemental information file. Additional file 1: Text S1 and Fig S1 show the magnitude distribution of each cluster and provide estimates of their completeness magnitude (typically Mc = 2.9).

In western Anatolia, the density of clusters is the largest, in particular along the Aegean coast of Turkey. Most of the focal mechanisms of these clusters display nearly north–south extension, indicative of the stretching of the upper crust. In northwestern Anatolia, from Saros to Düzce, and in eastern Anatolia, most clusters are associated with the long strike-slip, North and East Anatolian Faults or their branches. Near the south-eastern border in the Van region, the tectonic regime becomes compressive and thrust faulting is observed. In most of the clusters, activity is nearly continuous in time and consists of small-to-moderate events.

We study here the evolution of seismicity throughout Turkey between 2003 and 2017 to take advantage of the network improvements after the two large earthquakes of 1999 (Izmit and Düzce) and to avoid, to a large part, the influence of these two earthquakes. In the period studied, four earthquakes with magnitude larger than 6 occurred in Turkey or at its borders: the May 1 2003 Mw 6.3 Bingöl, the March 8 2010 Mw 6.1 Elazığ, the October 23 2011 Mw 7.1 Van, and the May 24 2014 Mw 6.9 Saros earthquakes. Two events (Bingöl and Elazığ) were on the East Anatolian fault, one (Saros) was on the Aegean Sea segment of the North Anatolian fault, and the largest one (Van) was a thrust event near the eastern border of Turkey.

We computed the time evolution of cumulative number of earthquakes with magnitudes greater than the completeness magnitude (see Additional file 1: Text S2 and Fig S1 of the supplemental information file for details). We also calculated the seismicity rates from the number of earthquakes per day and smoothed them by convolving with a Gaussian function (see Additional file 1: Text S3 and Fig S2 of the supplemental information file for details). The time series of cumulative number of earthquakes for the 27 clusters are normalized by the maximum value of each cluster, i.e., the total number of earthquakes in a given cluster (details of the procedure for the Simav cluster are given in Additional file 1: Fig S3 of the supplemental information file). To enhance the coherent signals of the daily seismicity time series of the clusters, we applied Singular Value Decomposition (see Additional file 1: Text S4 and Figs S4–S6 of the supplemental information file for details).

Results

The evolution of seismic activity of the clusters from 2003 to 2017 is shown in Fig. 2a and b, respectively, as the cumulated number of earthquakes and the seismicity rate. The striking feature of Fig. 2b is the similarity of the long-term behavior of the cluster activities despite their broad distribution over the whole Anatolian plate. From the western Aegean coast to Caucasus and from the Black Sea in the north to the Mediterranean coast in the south, the evolutions of activity of most of the clusters present global similarities and two main periods of high activity emerge as shown by the averaged evolution of the seismicity rates over all the clusters (black line in the yellow box of Fig. 2b). The first period is starting late 2004 and last more than 1 year, and the second is starting in 2008 and decreasing slowly up to 2016. It suggests that a large-scale (~2000 km) synchronization of the seismicity rates of nearly all the clusters exist over long periods (more than 1 year).

To check that the latter observation was not related to the KOERI network evolution, we compared the catalogs from KOERI, AFAD and ISC (Additional file 1: Fig S7). The ISC catalog is basically a combination of AFAD and KOERI catalogs. Its magnitude completeness is rather high (>3) as the small events are not reported to ISC. The AFAD catalog is heterogeneous in time. Until 2007, the coverage of the seismic stations was poor and the completeness magnitude was high. The completeness of AFAD catalog reached that of KOERI catalog (~2.9) in ~2012. We compared the cumulative seismicity and the seismicity rate of the 27 clusters using the three catalogs between 2006 and 2017 (Additional file 1: Fig S7a–c). The results did not show significant differences supporting the conclusion that observations were not depending on the seismic network. Moreover, the relative quiescence before 2007 and after 2014, are also consistent with the observations of Durand et al. (2013) in Greece which evidence similar regional trends and similar local jumps of seismicity activity between 2008 and 2009.

We search for major events that could be related to these two periods of high activity. We found that the onset of the first period coincides with the occurrence of the Mw9.2 Sumatra earthquake on December 26, 2004. We also found that the second period which is longer (more than 4 years) started with the episode of slip/rollback of the Hellenic slab which begins by a rupture of the deep slab in January 2008 and continued for about 3 years (Durand et al. 2014).

If both coincidences are clear, the triggering mechanisms for a long-term seismic activity rise are not known. In order to shed light on the possible mechanisms, we investigate in more detail the evolution of the cluster activities around the beginning of these two major periods. Fig. 3a shows the activity evolution after the Sumatra earthquake. Compared to the annual period before 2004, the activity is increased simultaneously several folds in most of the 27 clusters and remains high for about a year. The microearthquake activity is triggered at several stations in Anatolia following the 2004 Mw9.2 Sumatra earthquake and lasted several days after the passage of the large amplitudes (see Additional file 1: Fig S8). While dynamic triggering by passing seismic waves is well documented (Freed 2005), such a long duration of activation if produced by a large distant earthquake, has not been reported before. Moreover, several clusters are located along strike-slip and thrust faults, while most previous observations of long-distance activation are restricted to normal faulting in extensional tectonic settings (Hill and Prejean 2007; Gomberg et al. 2004; Freed 2005; Velasco et al. 2008). The timing of the peak activation differs from cluster to cluster and is occurring up to several months after the passage of the seismic waves. Such delays imply that the triggering mechanism of seismicity is not directly related to the passage of the waves but to subsequent and intermediate physical processes which last several months and which are themselves initiated by the shaking of the waves. They also suggest that long-distance triggering is more common than presently thought as the existence of an extended delay between two distant events usually renders their eventual link impossible to establish.

The observation of seismic activation throughout Anatolia after the giant 2004 earthquake is a very long-distance activation, but such long-distance activation has been reported previously as for the 1992 Landers earthquake (Hill et al. 1993; Gomberg et al. 2001) or the 2007 Sumatra earthquake (Mendoza et al. 2016). Worldwide activation of seismicity has also been reported after the 11 April 2012 $M=8.6$ East Indian Ocean earthquake (Pollitz et al. 2012). It is of interest to observe that the orientation of Eastern Anatolia is in an azimuth close to the strike of the Sumatra subduction. Eastern Anatolia is also where activation is the strongest (Additional file 1: Fig S8 for the Hakkari cluster). The unilateral propagation of the 2004 rupture to the northwest implies that the seismic energy radiated by the earthquake was strongly focused in the direction of Eastern Anatolia. The maximum dynamic stress changes due to the passage of surface waves at several stations in Anatolia is estimated to be in a range of 6–17 kPa (Aiken et al. 2013). The calculated dynamic stress change is similar (10–20 kPa) from

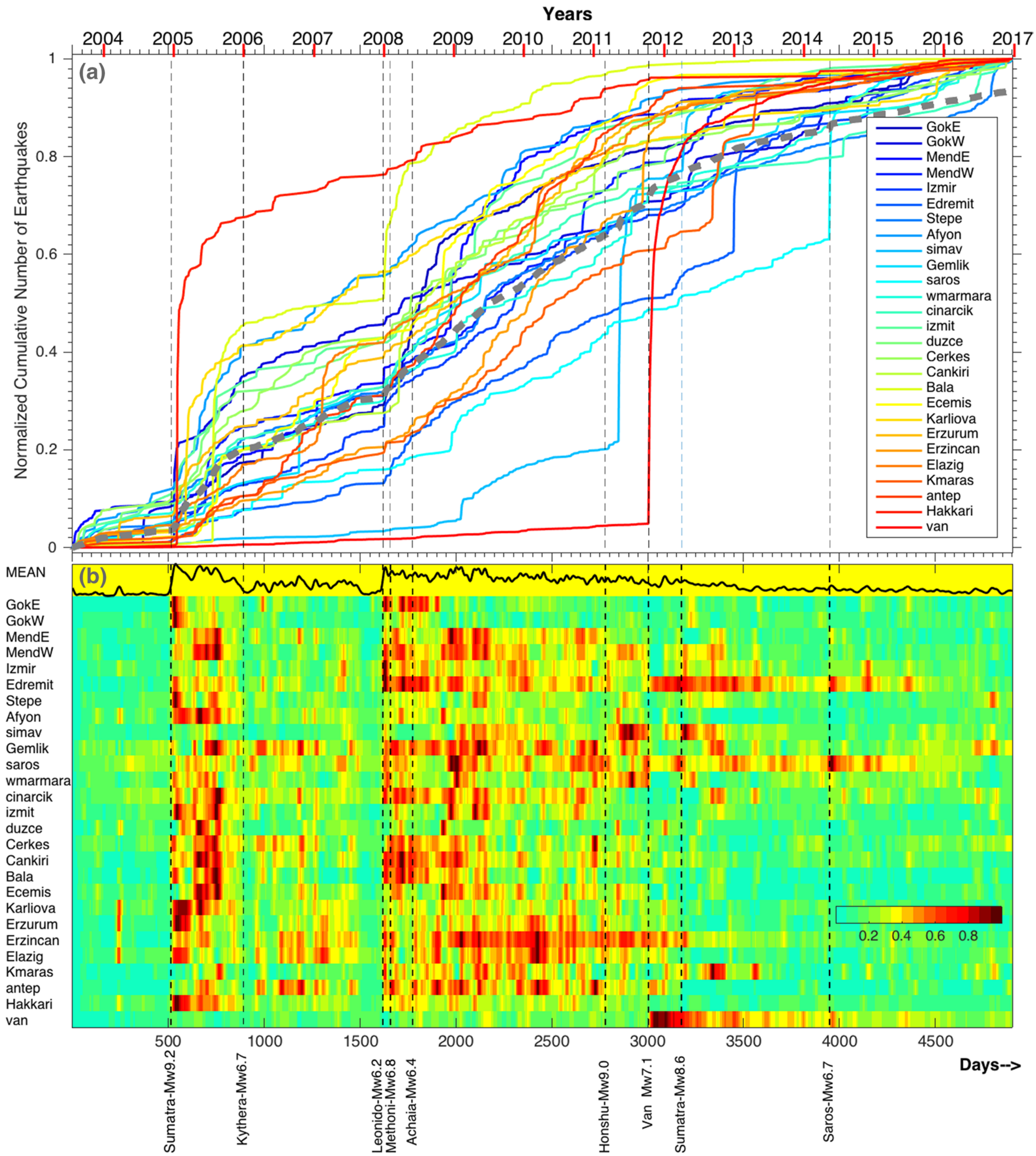


Fig. 2 Evolution of activity in the seismic clusters outlined in Fig. 1. **a** Cumulative number of earthquakes in each cluster. Time is measured from August 2003 and each curve is normalized to its final value. The dashed lines show the occurrence times of the large earthquakes discussed in the text. The gray dashed line shows the average of all clusters. The legend indicates the names of the clusters (see Fig. 1 for their locations). **b** Seismicity rates in each cluster. The upper black trace is the mean of the rates for all clusters. The names of the clusters are displayed on the left. The time series are displayed at increasing longitudes. The color scale shown on the lower right corner refers to the normalized cumulative number of earthquakes

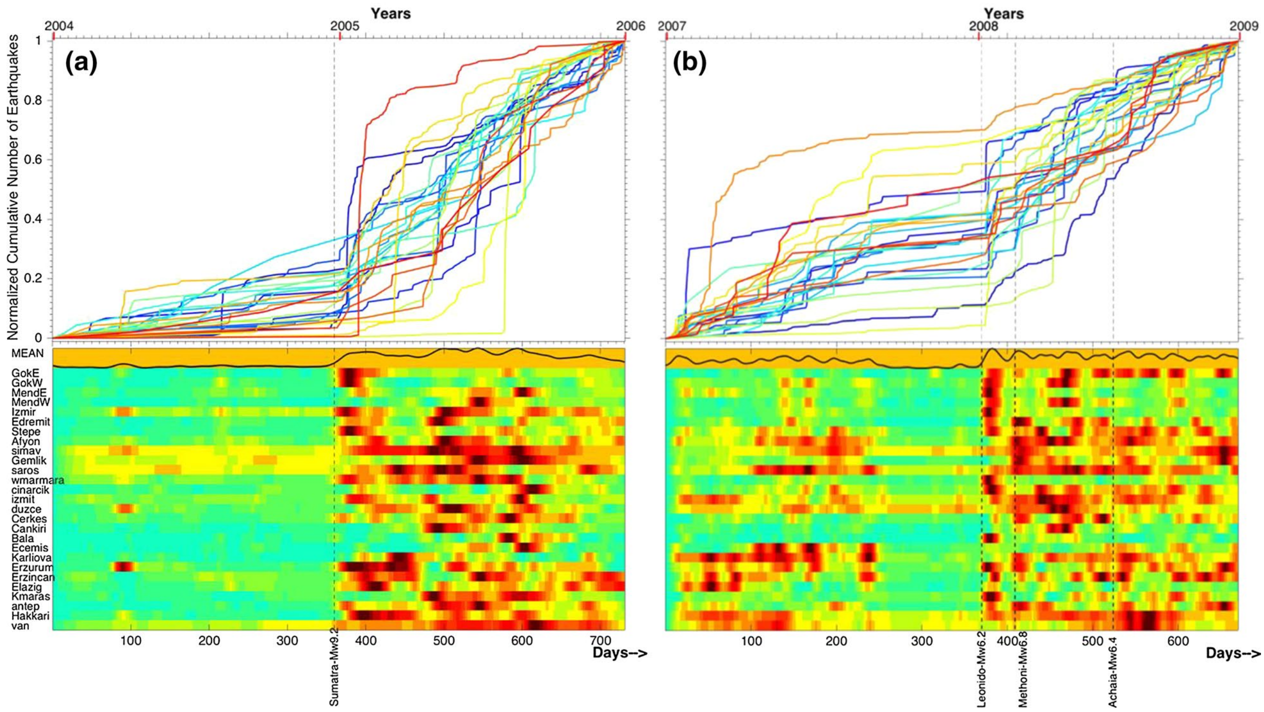


Fig. 3 Close-up views of Fig. 2. **a** One year before Sumatra Mw9.2 earthquake and 1 year after. **b** One year before Leonidio Mw6.2 earthquake (deep slab break) and 1 year after. The clusters are plotted in the same order as in Fig. 2

the teleseismically triggered tremors (Aiken et al. 2015, and references therein).

The second strong seismic activation begins in January 2008 at nearly all the clusters (Fig. 3b). We point out that this increase of seismic activity actually begins after an unusual event in the Hellenic subduction on January 6, 2008. This event, known as the Leonidio earthquake, is the largest earthquake deeper than 70 km in the Hellenic subduction since the beginning of the current Greek catalog in 1964. Its magnitude is, however, moderate (Mw6.2), indicating that direct dynamic triggering by seismic waves is unlikely. This is confirmed by the observation that 2 years earlier, on January 8 2006, an earthquake of higher magnitude (M6.7 Kythera) located nearby at a depth of 50 km did not generate any increase of activity in the clusters (Fig. 2). While the mechanism of the 2006 event was a lateral compression of the slab, thought to result from the amphitheater shape of the Hellenic subduction (Kiratzi and Papazachos 1995), the 2008 earthquake was a slab-pull event, pulling the upper part of the slab away from the overriding plate (Zahradnik et al. 2008; Kiratzi and Benetatos 2008). This earthquake initiated an episode of slab slip and rollback, mostly aseismic, which lasted for ~ 3 years and spread over more than 500 km (Durand et al. 2014). Forty days after this deep slab break, the largest subduction earthquake (Roumelioti et al. 2009) (Feb 14 2008, Mw 6.8 Methoni) since 1964 occurred directly up-dip from it, while in the following months what has been called a storm of earthquakes spread throughout Greece (Papadopoulos et al. 2009; Durand et al. 2014). Fig. 3b shows that the activation of the clusters begins sharply and in a remarkably synchronized manner, a few days after the deep slab rupture of 6 January 2008, well before the occurrence of the subduction earthquake of 14 February 2008. Notably, this activation is strongest in the Western Anatolia clusters (Additional file 1: Fig S10).

Discussion

What is observed in Anatolia illustrates the long-distance triggering of seismic activity produced by large earthquakes (Hill et al. 2007; Freed 2005; Hill et al. 1993; Pollitz et al. 2012; Mendoza et al. 2016; Johnson and Burgmann 2016). What is unprecedented are the scale, nature, and duration of the activation: the activity appears as triggered across the entire Anatolian plate, regardless of the fault mechanism involved (normal faulting, strike-slip, thrust), with no observation of propagation, and lasts for months or years. While shaking induced by seismic waves appears to be at the initiation of the activation, intermediate mechanisms responsible for long-term triggering are clearly involved like slow aseismic deformation, i.e., deformation on a time scale much larger than seismic events but faster than the long-term strain rate of the plate (Kreemer et al. 2014).

The long duration of intense seismic activation throughout Eastern Turkey which follows the 2004 Sumatra earthquake shows that shaking induced by seismic waves from a distant earthquake can also activate long-term dynamic processes far away. Such long-term processes might involve crustal fluids and probably deep ductile material (Bouchon et al. 2022). The similar duration of the activation at many distant clusters indicates that the deformation processes are broad scale, possibly extending to the uppermost mantle.

We also argue that the acceleration of the Hellenic subduction rollback in 2008 with respect to the long-term kinematic of the Anatolian plate (Pérouse et al. 2012; Kreemer et al. 2014), which follows the January 2008 slab break, introduced a significant perturbation on the state of stress of the Anatolian plate. From Durand et al. (2014), we can estimate the strain rate perturbation to be of the order of 20 nstrain/year, which has to be compared to the long-term strain rate (~ 100 nstrain/year) (Pérouse et al. 2012). Following this scenario, this stretching enhancement of the plate appears to induce an increase of the level of crustal seismic activity throughout the plate. What is unexpected is the rapidity with which the perturbation of the deformation of the slab is transmitted to the overriding plate and spreads to the plate interior and to the whole plate. Within a few days, the slab rollback acceleration increased the deformation of the crust in Eastern Anatolia 2000 km away from the subduction. What is observed is the near-instantaneous (a few days) response of the Anatolian plate through stretching, to the rollback of the plunging African slab. This response is both too rapid and with no spatial spreading, to involve ductile or viscous material and suggests the existence of a continuous quasi-rigid connection (i.e., pulse-like propagation) between the slab undergoing rollback and the Anatolian crust where the clusters are located.

It is also question of interest to assess the impact of the 1999 Mw7.4 Izmit and Mw 7.2 Düzce earthquakes which were two major events that might have strong impact on the behavior of the seismic clusters in particular through viscoelastic relaxation. To address this impact, we present in Additional file 1: Fig S11 the same analysis as shown in Fig. 2 but starting in 1998 instead of 2004. It shows the temporal evolution of the 27 clusters during the following years of the Izmit and Düzce earthquakes. From Additional file 1: Fig S11, we see that changes in the seismicity rates are limited both in space and time to the clusters around Marmara Sea, decelerating in 2004, before the 2004 Sumatra earthquake. Subsequently, we concluded that the viscoelastic relaxation mechanism related to the 1999 Izmit earthquake was different from the mechanisms involved during the periods following the 2004 Sumatra earthquake or the Hellenic sequence.

The activation of the clusters during these two episodes (2004 and 2008) shows, however, differences in the magnitude of the triggered events. While the 2004 episode consists of a large number of small and moderate-magnitude earthquakes, the 2008 episode generates mostly small-magnitude events (Additional file 1: Fig S12). This is possibly related to the property of the trigger source. Indeed, the 2004 Sumatra earthquake triggered oscillations with wavelengths at the scale of lithospheric thickness and longer (see Additional file 1: Fig S13). On the other hand, the 2008 Hellenic slab episode is a slow stretching of the brittle crust produced by the slab rollback. The long duration of the activation associated with the episode of slab rollback (~ 3 years) corresponds to the duration of this episode measured by GPS stations close to the Hellenic subduction (Durand et al. 2014). On the other hand, the duration of activity produced by the 2004 Sumatra earthquake is remarkably long (~ 1 year) in comparison to the short duration of the excitation (~ 1 day), pointing to deep physical processes, in scale with the long wavelengths involved. Indeed, one may wonder if the strong shaking of the Sumatra earthquake of Eastern Anatolia affected the timing of the devastating 2011 Mw7.1 Van earthquake which hit this region 7 years later. The evolution of seismic activity in the two easternmost clusters—Van and Hakkari—is interesting in this respect: in the months following the 2004 Sumatra earthquake, the largest earthquake in over 20 years occurs in Hakkari (Mw5.4) on Jan 25, 2005 while activity in the neighboring region of Van (about 100 km away), slowly increases up to Oct 2011 (Fig. 3a). This increase becomes significant ~ 4 months after the shaking and from then on activity will stay high with a slight acceleration in the 7 years leading to the earthquake (Additional file 1: Fig S14). Whether the Sumatra earthquake advanced the clock of the Van earthquake is a possibility. The long delay would be consistent with the lack of observations of rapid long-distance triggering of thrust events (Hill et al. 2007).

A complementary view of the process involved is provided by declustering the seismic catalog (Fig. 4). This analysis removes the seismic events which display the statistical characteristics of aftershocks of larger events and keeps only the events thought to be primary events. The earthquake time series are processed to separate the factors contributing to seismicity rate changes: stress changes generated coseismically by main shocks and also postseismic relaxation. Declustering amounts to removal of coseismic and postseismic effects, with the aim of reducing the temporal dependence of the

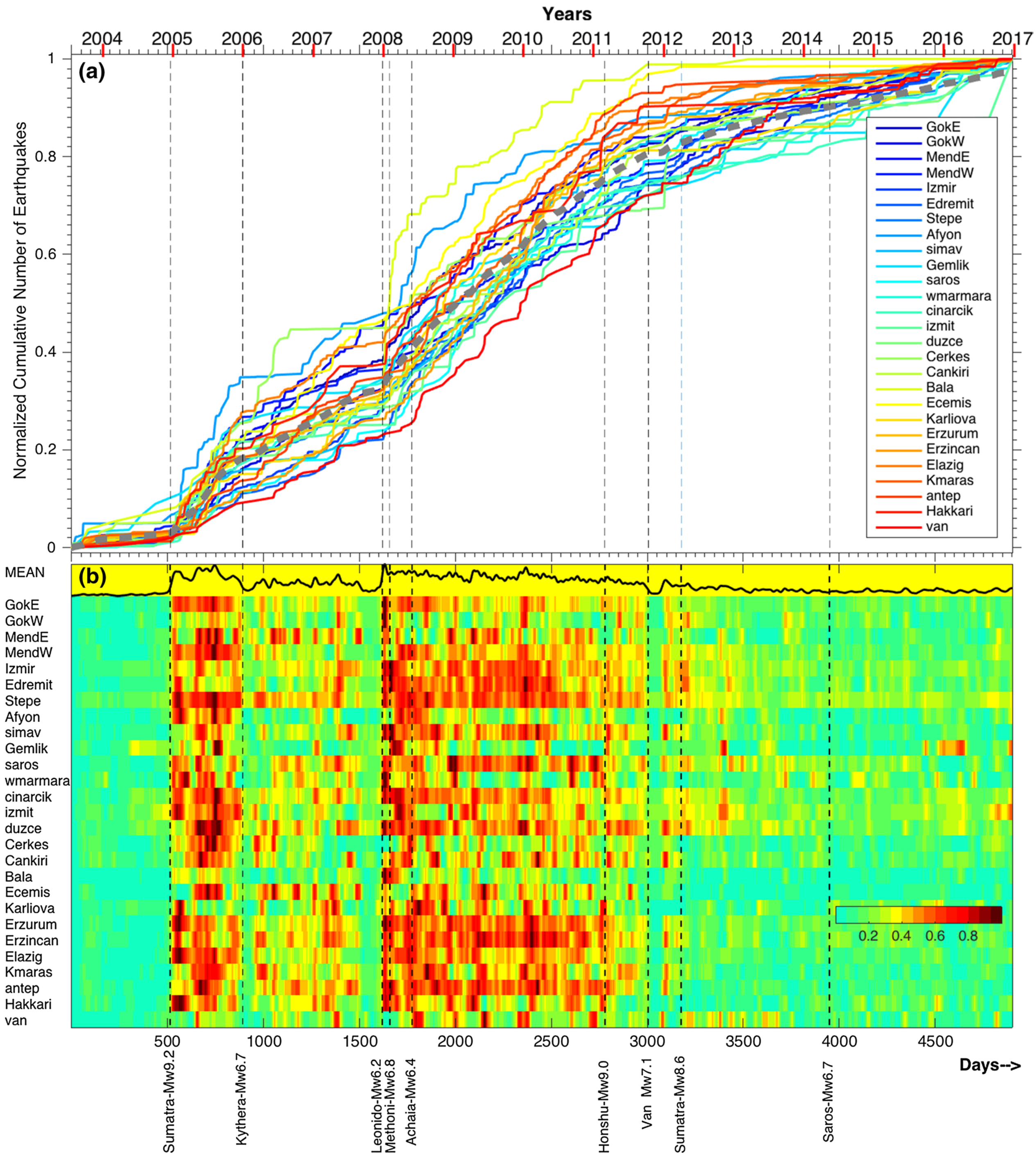


Fig. 4 **a** Evolution of cumulative number of earthquakes declustered using ETAS model of the seismic clusters shown in Fig. 1. Time is measured from August 2003 and each curve is normalized to its final value. The gray dashed line shows the average of all clusters. The black dashed lines show the occurrence times of giant earthquakes worldwide and of large regional earthquakes. The legend indicates the names of the clusters displayed in Fig. 1. **b** Seismicity rates of the clusters displayed in **a**. The upper black trace is the mean of the rates. The color scale shown on the lower right corner refers to the normalized cumulative number of earthquakes

remaining, i.e., "background" earthquakes. The declustering method we used, is a modified form of Zhuang et al. (2002, 2004), which is based on a space–time Epidemic-Type Aftershock Sequence (ETAS) model (Ogata 1998). The method was initially designed to estimate a spatially non-uniform, but temporally constant, background rate. Marsan et al. (2017) modified it to explore the possible non-stationarity of the background seismicity, in order to detect long-term changes. It models earthquake occurrences using the number of earthquakes per unit time and unit area λ(x, y, t) defined as the sum of two contributions: $\lambda(x, y, t) = \mu(x, y, t) + \nu(x, y, t)$, in which ν accounts for triggering by previous earthquakes, and μ is the activity that would occur in the absence of any such interactions, i.e., the background rate. Triggering by previous earthquakes occurring at {x, y, t} is modeled as the product of the Omori–Utsu law with a power law spatial density. The parameters we used in this study are similar to Marsan et al. (2017). Additional file 1: Fig S4b shows the effect of declustering for a single cluster and Fig. 4 shows the declustering of the seismicity for all clusters presented in Fig. 1. What is then obtained represents the background seismic activity. The evolution of this background in the clusters of Anatolia is presented in Fig. 4. The most noticeable observation is the similarity of the temporal evolutions of this background activity throughout Anatolia (i.e., see similarities between Figs. 2b and 4b). As introduced before, the year-long activation in 2005–2006 following the 2004 Sumatra earthquake and the 2008–2011 activation accompanying the slab plunge/rollback are displayed at nearly all the clusters. The slowing down of the activity after 2012 is also concomitant throughout Anatolia.

Conclusion

Our observations suggest that there can be a long delay between the occurrence of the triggering process and the occurrence of a large earthquake, even if its nucleation process began at this time. While smaller seismicity gets triggered very early on, even beginning during the shaking itself, it seems to take months or years to trigger a large earthquake, suggesting that its nucleation is the result of a long process. Further studies are needed to propose physical models of these observations.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40623-022-01725-z.

Additional file 1: Text S1. Normalized cumulative distributions of the magnitude and 9 magnitude completeness of each seismic cluster. **Text S2.** Cumulative Seismicity. **Text S3.** Seismicity Rates. **Text S4.** Singular Value Decomposition. **Figure S1**. Normalized cumulative distributions of the magnitude of earthquakes 75 for each cluster using the same color coding as in Fig.2. Magnitude completeness 76 of the clusters for 4 different time windows a) 2003 – 2008 (Mc=2.9) b) 2003 – 77 2017 (Mc=2.7) c) 2004 – 2006 (Mc=2.9) d) 2007-2017 (Mc=2.7). **Figure S2**. Gaussian smoothing function. **Figure S3.** Processing steps for the seismicity time series. (a) Cumulative 88 number of earthquakes (blue) and daily seismic activity (red) for the Simav 89 cluster (b) after declustering. All plots are normalized by their maximum values. 90 The daily seismic activity is smoothed using the Gaussian function of Figure S2. **Figure S4.** Singular values of the matrix constructed from daily seismicity time series of the clusters. They are normalized by the first singular value. **Figure S5-1.** Top: Cumulative seismicity time series of 27 clusters. Bottom: Reconstructed daily seismicity rates using only the first singular value. **Figure S5-2.** Top: Cumulative seismicity time series of 27 clusters. Bottom: Reconstructed daily seismicity rates using only 3 largest singular values. **Figure S6.** Top : a) Cumulative seismicity time series of 27 clusters. Bottom: b) Reconstructed time series after removing largest 12 singular values. **Figure S7.** Comparison of the cumulative seismicity of 27 clusters and the seismicity rates from 2006 to 2017 using a) Kandilli Observatory and earthquake Research Institute (KOERI) (https://koeri.boun.edu.tr/) b) Disaster and Emergency Management Authority of Turkey (AFAD) (https://deprem.afad.gov.tr/) and c) International Seismological Center (ISC) (http://www.isc.ac.uk/) catalogs. **Figure S8.** Top: The locations of the seismic stations of which the continuous recordings are displayed in the following figures. Middle: 24 hour recordings of NS components of 5 seismic stations (red) and filtered with 1-9Hz bandpass filter (blue). Notice the occurrence of several moderate seismic events at the selected stations in addition to smaller events. Bottom: 6 days long NS component recording of DALT station (red) and filtered with 1-9Hz bandpass filter (blue). Beneath is the spectrogram of the seismic trace. The traces are normalized by maximum values and saturated for small-magnitude events. The seismic activity is not confined to the passage of seismic waves due to Sumatra earthquake. **Figure S9.** Cumulative number of events of selected clusters in central and eastern Anatolia for the time period of 2004 Sumatra Mw9.2 earthquake (see Figure 1 for the locations of the clusters). **Figure S10.** Cumulative number of events of selected clusters in the western Anatolia for time period of Hellenic subduction earthquakes (see Figure 1 for the locations of the western clusters). **Figure S11.** The diagram shows cumulative seismicity of 27 clusters (a) and the seismicity rate color coded for all clusters as in Figure 2 but from 1998 to 2017 (b). The occurrence times of giant earthquakes worldwide and of large regional earthquakes are shown. The color scale is shown on the lower right corner. **Figure S12.** Cumulative number of earthquakes in Anatolia between 36.80N-41.00N latitudes and 25.5E-44.0E longitudes (includes all clusters in Figure 1) for varying lower magnitude cut-offs between 2.8 ('ml28' blue curve) and 5.8 ('ml58' red curve). The displayed time period is starting 4 years after the 1999 Izmit earthquake and ending with the occurrence of 2011 Van earthquake. The red curve (5.8 magnitude threshold) is showing a sharp increase during the 2004 episode and a plateau during the 2008 episode. On the contrary, the blue curve (2.8 magnitude threshold) exhibits a similar increase between both periods. **Figure S13.** Broadband N-S component recordings of 2004 Sumatra earthquake at seismic stations shown on top of the traces. The traces are normalized by maximum values (see the map in Figure A8 for station locations.). The period of large amplitude S wave exceeds 100sec. **Figure S14.** Evolution of the cumulative number of events of the clusters in the two easternmost clusters of Anatolia (see Figure 1 for the locations of the clusters).

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Author contributions

HK contributed to the original draft preparation, methodology, data analysis and visualization. MB and JS contributed to the conceptualization of this study, validation, writing, reviewing, and editing. All authors read and approved the final manuscript.

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Availability of data and materials
Catalog data used in this study are publicly available at the webpage of the KOERI: http://www.koeri.boun.edu.tr/sismo/zeqdb/, AFAD: https://deprem.afad.gov.tr/ and ISC: http://www.isc.ac.uk/.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Department of Geophysics, Kandilli Observatory and Earthquake Research Institute, BoğaziçiUniversity, 34684 Istanbul, Cengelköy, Turkey. [2]Centre National de la Recherche Scientifique and Université Joseph Fourier, Grenoble, ISTerre, BP 53, 38041 Grenoble, France. [3]EOST/ITES, Centre National de la Recherche Scientifique and Université de Strasbourg, 5 Rue Descartes, 67084 Strasbourg, France.

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