Synchronization of Small Scale Seismic Clusters Reveal Large Scale Plate Deformation

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Abstract

It has long been observed that periods of intense seismic activity in a region alternate with periods of relative quiescence, but establishing whether this is the expected result of purely random fluctuations or is due to some broad-scale physical processes occurring in the Earth is a challenge. We present here compelling observations which show that periods of high seismicity rate and periods of quiescence are synchronized throughout the Anatolian plate. These observations are based on the remarkably similar evolution of the numerous seismic clusters between 2003 and 2017 in Anatolia. Two outside clocks set the timing of these activities, the 2004 M9.2 Sumatra earthquake and the 2008-2011 episode of slab rollback/deformation in the Hellenic subduction. The observed high seismicity rate in the plate which began with the Sumatra earthquake and lasted for about 7 years has been replaced by a relatively uniform quiescence period.

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It has long been observed that periods of intense seismic activity in a region alternate with periods of relative quiescence, but establishing whether this is the expected result of purely random fluctuations or is due to some broad-scale physical processes occurring in the Earth is a challenge. We present here compelling observations which show that periods of high seismicity rate and periods of quiescence are synchronized throughout the Anatolian plate. These observations are based on the remarkably similar evolution of the numerous seismic clusters between 2003 and 2017 in Anatolia. Two outside clocks set the timing of these activities, the 2004 M9.2 Sumatra earthquake and the 2008-2011 episode of slab rollback/deformation in the Hellenic subduction. The observed high seismicity rate in the plate which began with the Sumatra earthquake and lasted for about 7 years has been replaced by a relatively uniform quiescence period.

Sited at the meeting place 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 ~1400km-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.

We use the seismicity catalogs of the Kandilli Observatory and Earthquake Research Institute. 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 clusters (Dewey, 1976). In western Anatolia, the density of clusters is the largest, in particular along the Aegean coast of Turkey. Most of the 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 branchings. 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 Elazig, the October 23 2011 Mw 7.1 Van, and the May 24 2014 Mw 6.9 Saros earthquakes. Two events (Bingöl and Elazig) 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 2.9, which is the largest completeness magnitude of the catalog over this period (Fig. S1). We also calculated the seismicity rate from the number of earthquakes per day using a Gaussian operator over a time span of 60 days (see Supplementary Information for details). The evolution of seismic activity of the clusters from 2003 to 2017 is shown in Figs. 2a-b, respectively as the cumulated number or the seismicity rate. The striking feature is the synchronization of the seismicity rates of nearly all the clusters. From the western Aegean coast to Caucasus and from the Black Sea in the north to the Mediterranean coast in the south, the general evolution of activity of most of the clusters is surprisingly similar. Considering the duration (more than 1 year) and the scale (~2000km) of the activity, two major periods of activity emerge from the figure and enhanced by the evolution of the mean of the rates for all clusters as the black line at the top of Fig 2b. The first one is of about one year and its onset coincides with the occurrence of the Mw9.2 2004 Sumatra earthquake. The other one is the episode of slip/rollback of the Hellenic slab which begins by a rupture of the deep slab in January 2008 and will continue for about 3 years (Durand et al., 2014).

We now investigate in more detail the evolution of the clusters activity around the onset of these two major periods. Activity after the Sumatra earthquake is increased several folds in most of the 27 clusters for about a year (Fig. 3a). Such a long duration of activation produced by seismic waves from a distant earthquake has not been reported before. Also surprising is the fact that several clusters are located along strike-slip and thrust faults, while most previous observations of long distance activation are restricted to normal faulting (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 also a surprise as it may occur several months after the passage of the seismic waves. Such delays imply that physical processes lasting several months are initiated by the shaking of the waves. They also suggest that long distance triggering is more common than presently thought as the presence 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 not in itself a surprise. Such long distance activations have been reported since the first such observations were made after the 1992 Landers earthquake (Hill et al., 1993; Gomberg et al. 2001). Worldwide activation of seismicity has also been reported after one M8.6 earthquake (Pollitz et al., 2012). The orientation of Eastern Anatolia, where activation is the strongest (Fig. S6) relatively to the earthquake in an azimuth close to the strike of the Sumatra subduction and the unilateral propagation of the 2004 rupture to the northwest imply that the seismic energy radiated by the earthquake was strongly focused in the direction where Eastern Anatolia lies. This provides a logical explanation for the activation. What are surprising are the intensity of this activation, its widespread extent throughout Anatolia, and its year-long duration.

The second strong seismic activation begins in January 2008. (Fig. 3b). At nearly all the clusters the increase of seismic activity starts after an unusual event occurred in the Hellenic subduction on January 6. This event, known as the Leonidio earthquake, is the largest earthquake deeper than 70km in the Hellenic subduction since the beginning of the current Greek catalog in 1964. Its magnitude is however moderate (Mw6.2), indicating that dynamic triggering by its seismic waves is unlikely. This is confirmed by the observation that two years earlier, on January 8 2006, an earthquake of higher magnitude (M6.7 Kythera) located nearby at a depth of 50km 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, 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 et al. 2008). This earthquake initiated an episode of slab slip and rollback, mostly aseismic, which lasted for ~3 years) Pollitz et al. 2012). 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 remarkable synchronization a few days after the deep January 6 slab break, well before the occurrence of the subduction earthquake on February 14. As logically expected, this activation is strongest at the clusters of Western Anatolia (Fig. S7).

What is observed in Anatolia remarkably illustrates the long distance triggering of seismic activity produced by some large earthquakes (Hill et al., 2007; Freed, 2005; Hill et al., 1993; Pollitz et al., 2012). What is unprecedented are the scale, nature, and duration of the activation: Activity is triggered throughout the Anatolian plate regardless of the mechanism involved (normal faulting, strike-slip, thrust), lasts for months or years, and is related to aseismic deformation. While shaking induced by seismic waves is clearly the triggering mechanism of the activation produced by the Sumatra earthquake, a new type of mechanism involving the aseismic deformation of the slab is observed in 2008: The acceleration of slab rollback which follows the January slab break pulls with it the Anatolian plate. The plate becomes stretched. This stretching increases the level of crustal seismic activity throughout the plate. What is astonishing is the rapidity with which 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 deforms the crust in Eastern Anatolia 2000km away from the subduction. What is observed is the near-instantaneous response of the Anatolian plate through stretching, to the rollback of the plunging African slab. This response is far too rapid to involve ductile or viscous material and requires the existence of a continuous rigid connection between the slab undergoing rollback and the Anatolian crust where the clusters are located.

The reported observations have important implications. 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 activate long term dynamic processes far away. Such long term processes must involve crustal fluids and probably deep ductile material. The similar duration of the activation at many distant clusters indicates that the deformation processes are broad scale, possibly extending to the uppermost mantle.

The activation of the clusters during these two episodes (2004 and 2008) also shows differences in the magnitude of the triggered events (Fig. S5). While the 2004 Sumatra earthquake triggers a relatively large number of moderate size earthquakes, the 2008 episode generates smaller magnitude seismic activity. The 2004 episode is initiated by shaking with wavelengths at the scale of lithospheric thickness and longer. On the other hand, the 2008 episode seems the response of the 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 Sumatra shaking of Eastern Anatolia affected the timing of the devastating 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 Sumatra the largest earthquake in over 20 years occurs in Hakkari (Mw5.4) while activity around Van slowly increases (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 (Fig. S8). 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. What is then obtained represents the background seismic activity. Temporal variations of this background are logically related to variations in the state of strain of the seismogenic crust. The evolution of this background in the clusters of Anatolia is presented in Fig 4. The most striking observation is the similarity of the temporal evolutions of this background activity throughout Anatolia. 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.

As the example of the Van earthquake that is discussed above suggests (and other observations also suggest, even if a proof of the causality escapes us because of the time delay involved between the excitation and the response), there can be a long delay between the occurrence of the triggering process and the occurrence of a large earthquake, even if we somewhat realize that its nucleation process began at this time. This is indeed very interesting: 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.

Acknowledgments

We are grateful to the network operators, Kandilli Observatory and Earthquake Research Institute (Turkey) and National Observatory of Athens (Greece) providing seismicity catalogs. Catalog data used in this study are publically available at the webpage of the KOERI and NOA (KOERI, http://www.koeri.boun.edu.tr/sismo/zeqdb/; NOA, http://www.gein.noa.gr/en/seismicity/earthquake-catalogs

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Figures

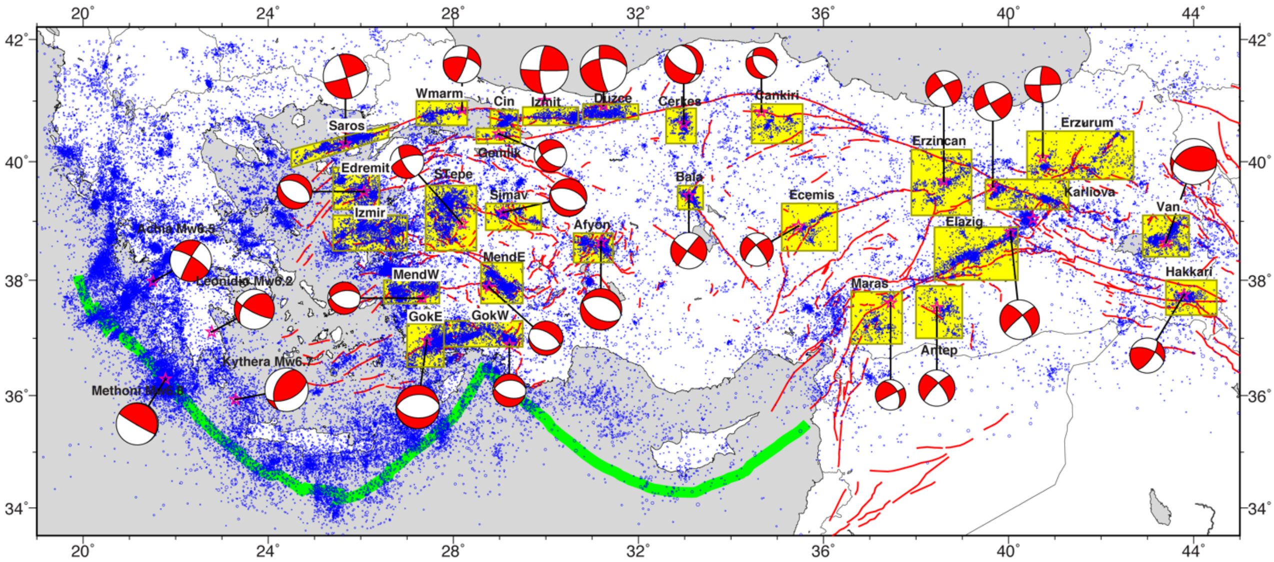
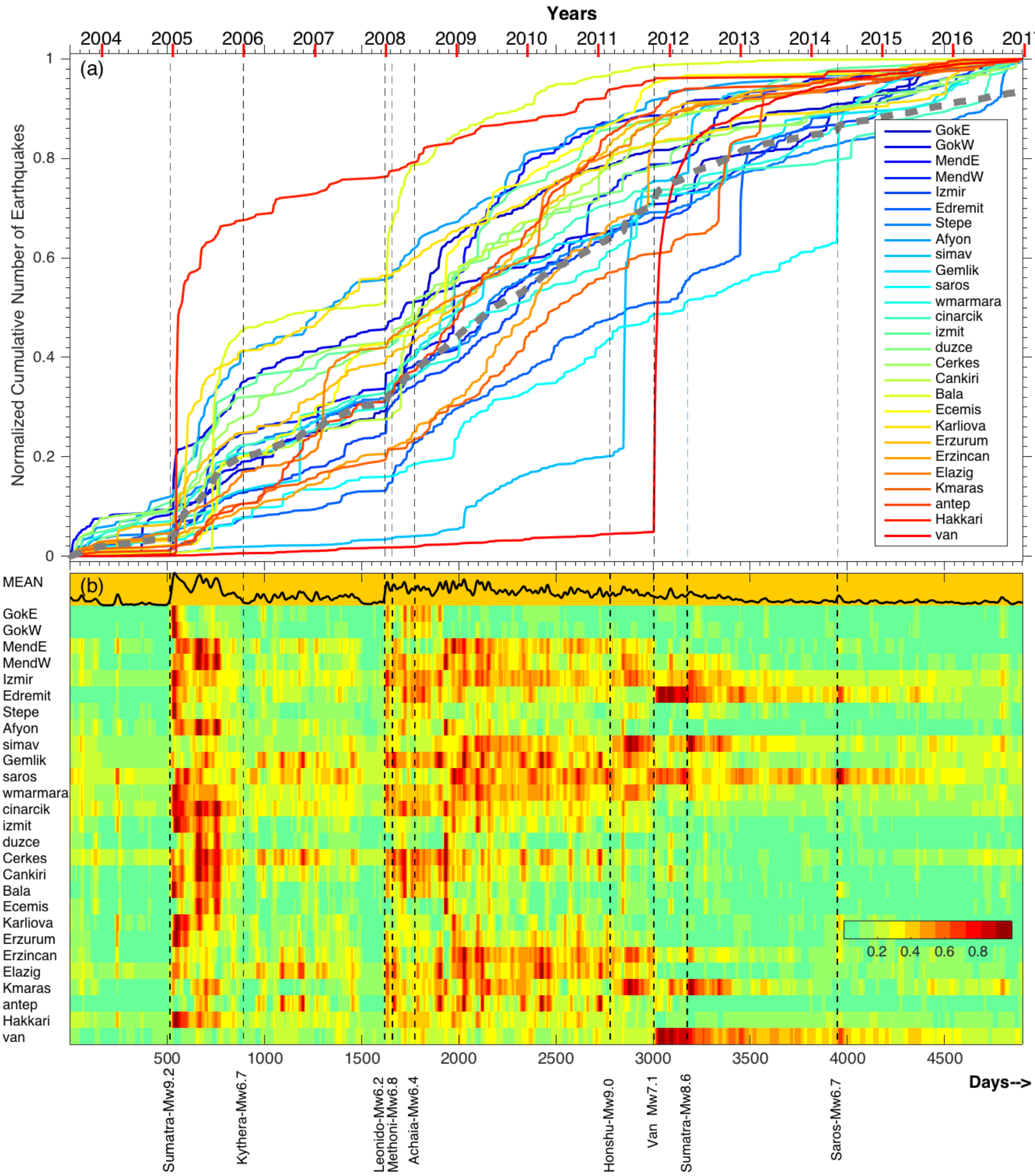


Figure 1: Seismicity between 1998 and 2017 (from the catalogs of Kandilli Observatory and Earthquake Research Institute and the National Observatory of Athens). Boxes outline regions where the clusters of seismicity are considered in the analysis and named with the closest geographical location (see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



Years
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
(a)
Normalized Cumulative Number of Earthquakes
GokE
GokW
MendE
MendW
Izmir
Edremit
Stepe
Afyon
simav
Gemlik
saros
wmarmara
cinarcik
izmit
duzce
Cerkes
Cankiri
Bala
Ecemis
Karliova
Erzurum
Erzincan
Elazig
Kmaras
antep
Hakkari
van
(b)
MEAN
0.2 0.4 0.6 0.8
500
1000
1500
2000
2500
3000
3500
4000
4500
Days-->
Sumatra-Mw9.2
Kythera-Mw6.7
Leonido-Mw6.2
Methoni-Mw6.8
Achaia-Mw6.4
Honshu-Mw9.0
Van Mw7.1
Sumatra-Mw8.6
Saros-Mw6.7

Figure 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 colorscale is shown on the lower right corner.

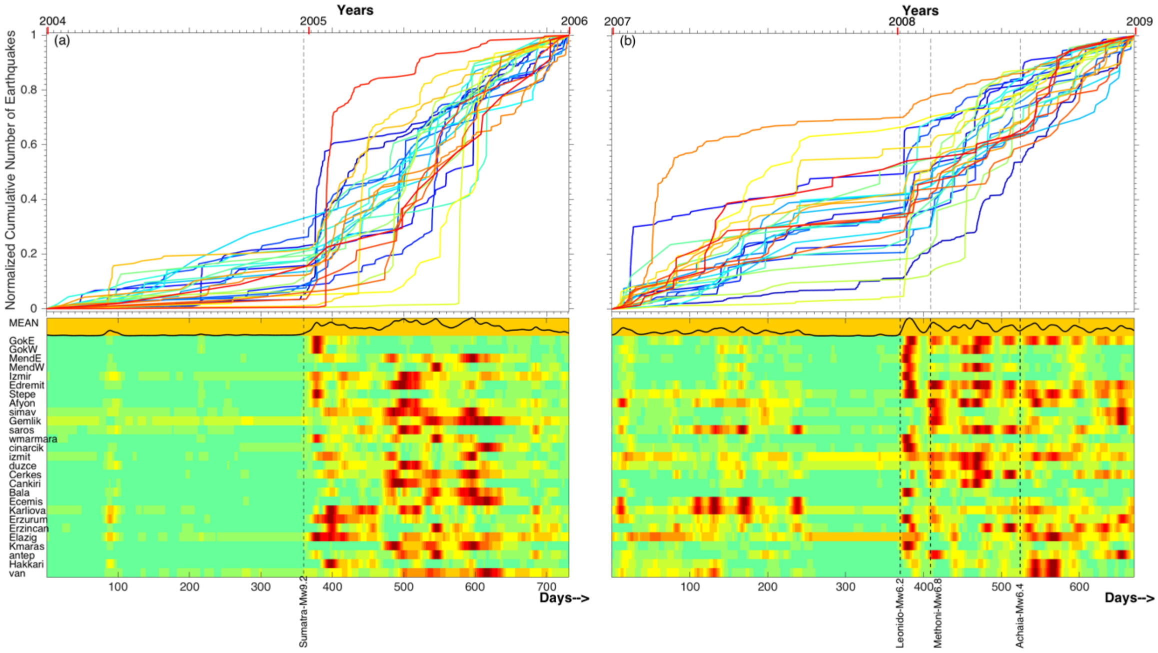
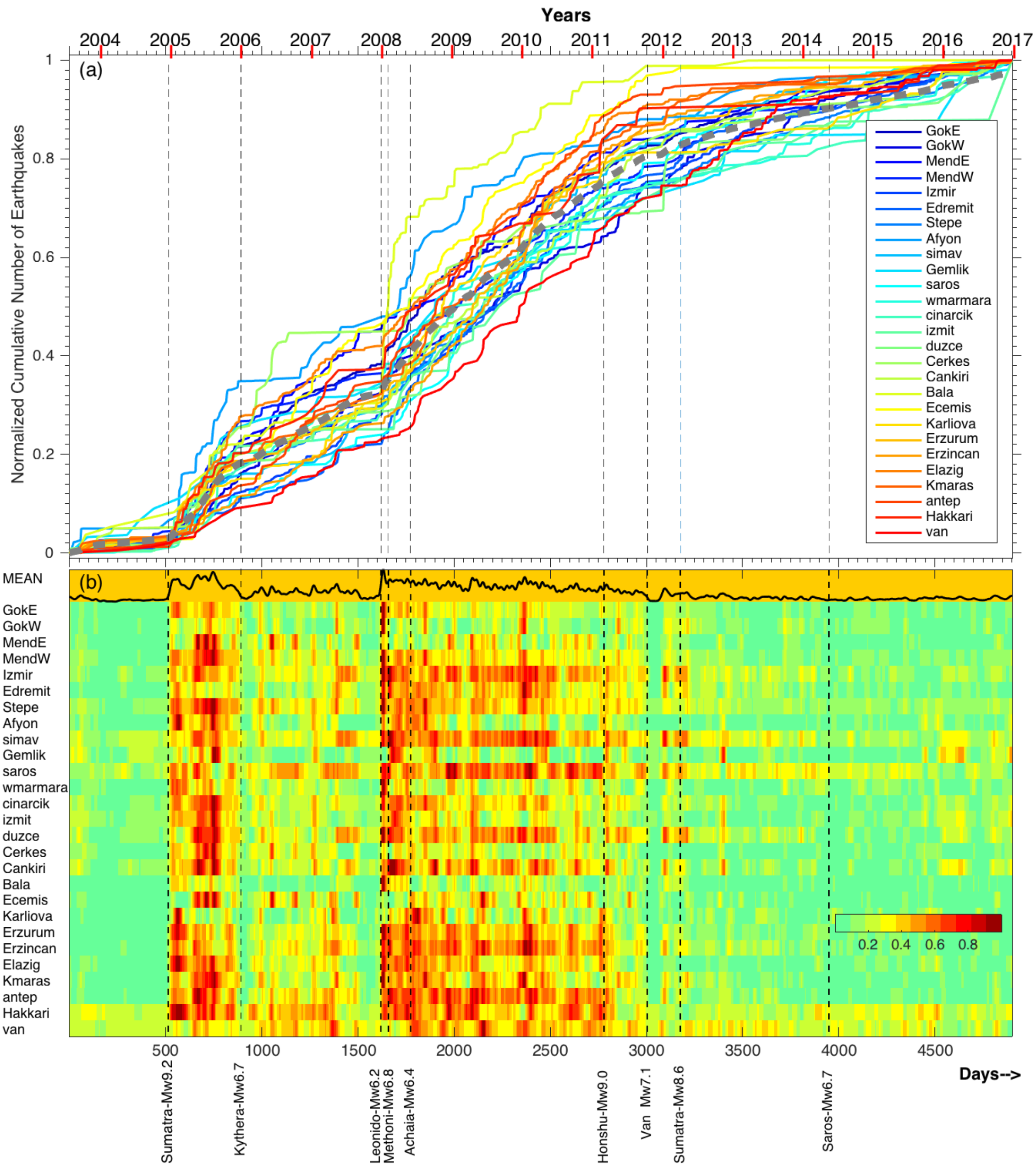


Figure 3: Close up views of Fig. 2. a) one year before Sumatra Mw9.2 earthquake and one year after. b) one year before Leonidio Mw6.2 earthquake (deep slab break) and one year after. The clusters are plotted in the same order as in Fig. 2.



Years
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
(a)
Normalized Cumulative Number of Earthquakes
0 0.2 0.4 0.6 0.8 1
GokE
GokW
MendE
MendW
Izmir
Edremit
Stepe
Afyon
simav
Gemlik
saros
wmarmara
cinarcik
izmit
duzce
Cerkes
Cankiri
Bala
Ecemis
Karliova
Erzurum
Erzincan
Elazig
Kmaras
antep
Hakkari
van
(b)
MEAN
0.2 0.4 0.6 0.8
500 1000 1500 2000 2500 3000 3500 4000 4500
Days-->
Sumatra-Mw9.2
Kythera-Mw6.7
Leonido-Mw6.2
Methoni-Mw6.8
Achaia-Mw6.4
Honshu-Mw9.0
Van Mw7.1
Sumatra-Mw8.6
Saros-Mw6.7

Figure 4: a, Evolution of cumulative number of earthquakes declustered using ETAS model of the seismic clusters shown in Figure 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 Figure 1. b, Seismicity rates of the clusters displayed in (a). The upper black trace is the mean of the rates. The colorscale is shown on the lower right corner.

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Supplementary Information

Magnitude Completeness

The magnitude completeness is computed as 2.9 based on the completeness analysis through time (Fig. S1). Figure S1 shows the normalized cumulative number of earthquakes vs magnitude for the clusters displayed in Figure 1. We used 0.1 bin size and %25 overlapping windows. Completeness is changing through time and the lowest is between 2011 and 2017 when the seismic network was significantly improved.

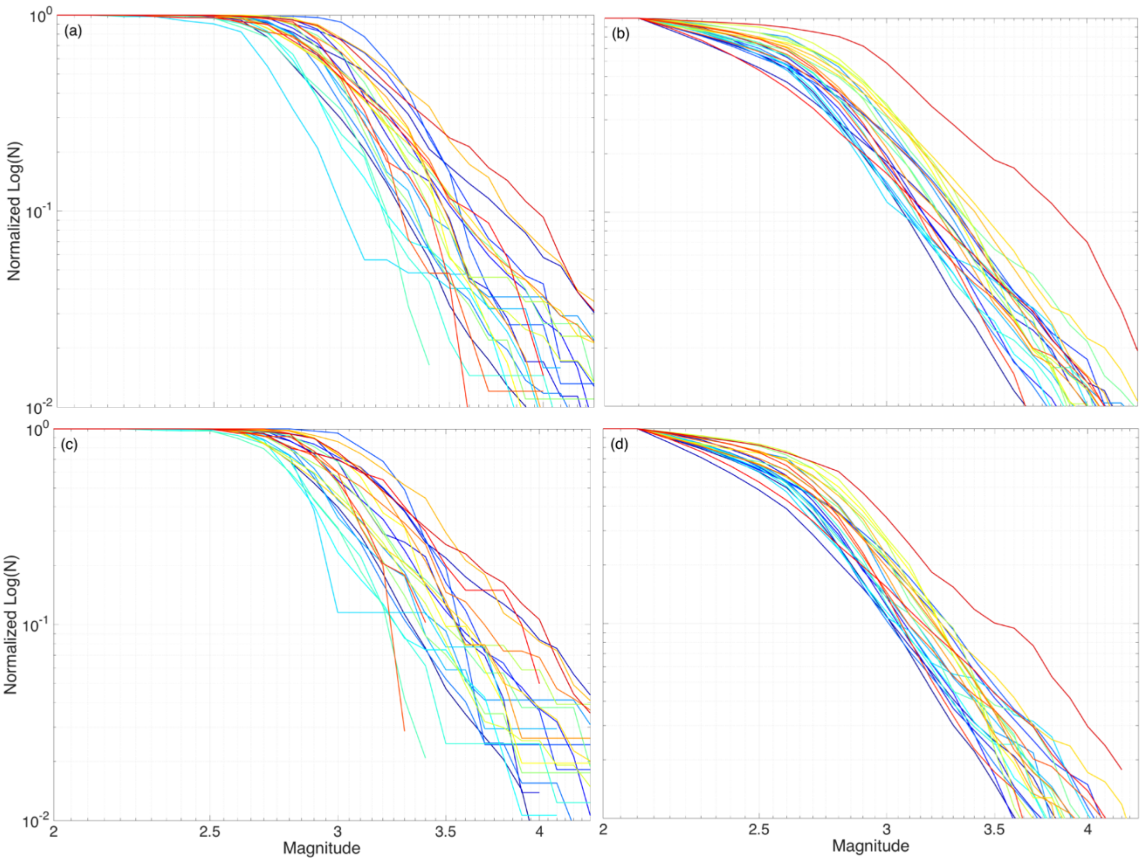

Figure S1 : Normalized cumulative distributions of the magnitude of earthquakes for each cluster using the same color coding as in Fig.2. Magnitude completeness of the clusters for 4 different time windows a) 2003 – 2008 (Mc=2.9) b) 2003 – 2017 (Mc=2.7) c) 2004 – 2006 (Mc=2.9) d) 2007-2017 (Mc=2.7) .

Cumulative Seismicity

The cumulative number of earthquakes with magnitutes greater than 2.9 is computed in each cluster displayed in Figure 1. The traces are interpolated in time using nearest neighboors in order to have a uniform sampling. We present in Figure S2a the cumulative seismicity for the period from 1998 to 2017 as the completeness was significantly higher before 1998 (>3.2) (Figure S2). The influence of 1999 Izmit and Duzce earthquakes (coseismic and postseismic) has been dominant on the clusters close to the Marmara region and lasted for several years. To analyze the interactions between seismic clusters over the whole Anatolian plate, we used the time period from August 2003 (4 years after Izmit earthquake) to 2017, when activity is spread over all clusters.

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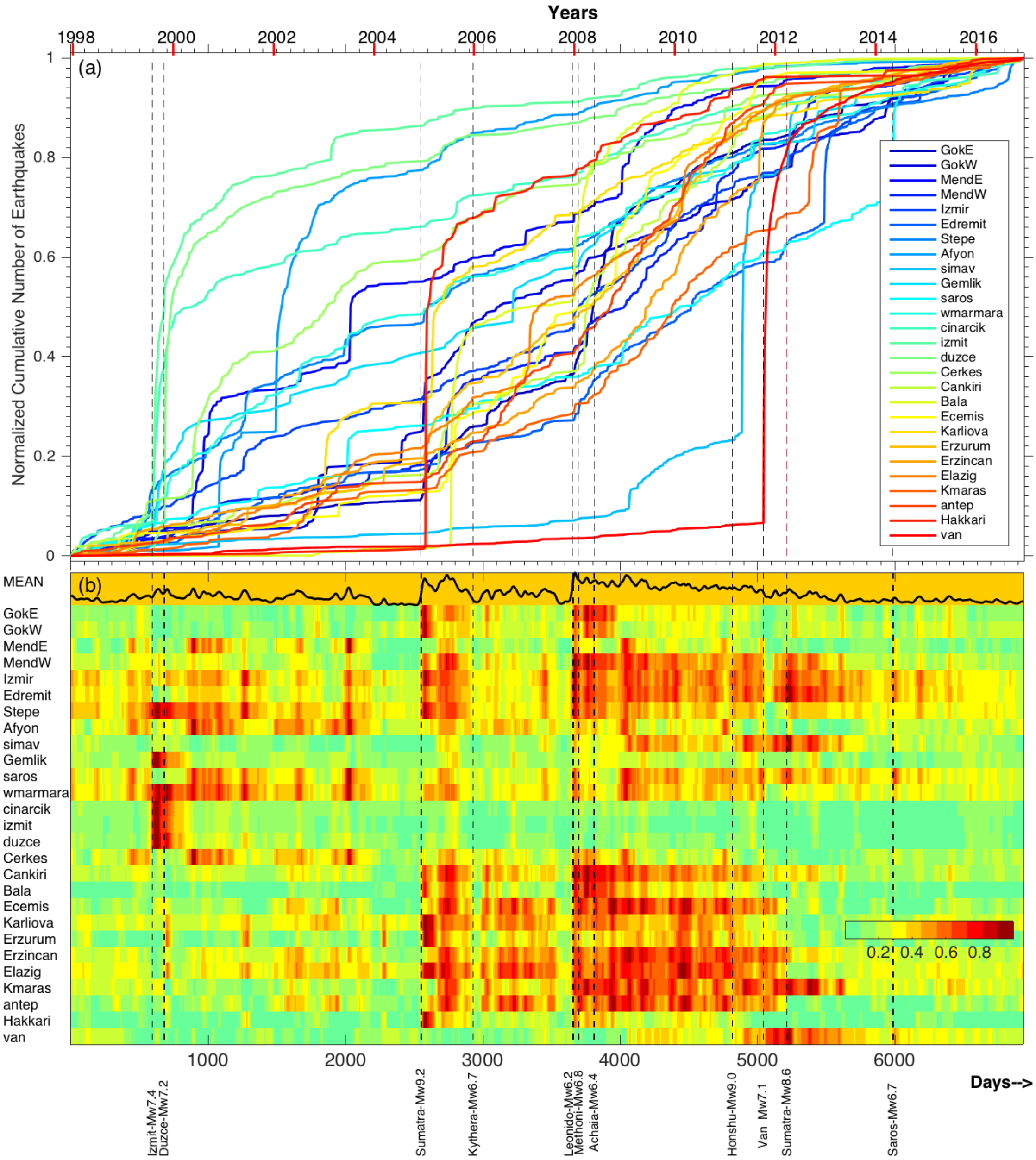

Figure S2: a) Evolution of cumulative number of events in the seismic clusters shown in Figure 1. Time is measured from 1998 and each curve is normalized to its final value. b) The occurrence times of giant earthquakes worldwide and of large regional earthquakes are shown. The colorscale is shown on the lower right corner.

Seismicity Rates

The daily seismicity rates in each cluster are computed by convolving the time series from the number of earthquakes for each day by a Gaussian function as in Figure S3. The temporal resolution of the rates depends on the length of the Gaussian operator. An example of the cumulative and rate of the seismicity for a cluster is displayed in Figure S4. The time series of each cluster are put into a single matrix and singular value decomposition is applied. The displayed traces correspond to the first 8 eigenvalues and corresponding eigenvectors and thus eliminate the majority of the uncorrelated part of the signals (Figure S4b).

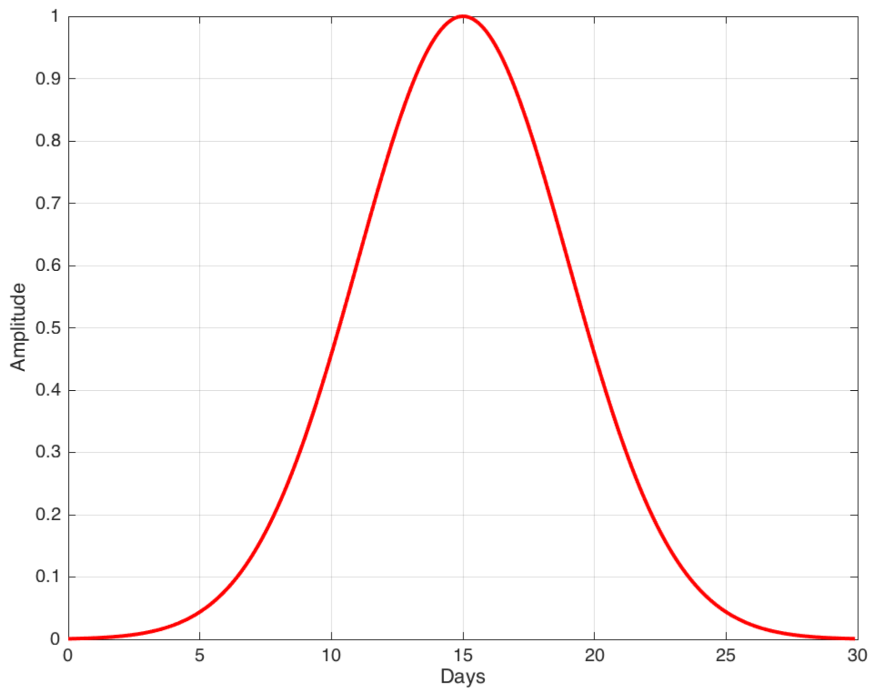

Figure S3 : Gaussian smoothing operator

Declustering of the Catalog

The earthquake time series are processed to separate the factors contributing to seismicity rate changes: stress changes generated coseismically by main shocks and also due to postseismic relaxation. Declustering amounts to such a removal of coseismic and postseismic effects, with the aim of reducing the temporal dependence of the remaining, i.e., “background,” earthquakes (Helmstetter et al., 2003; Marsan, 2003) . FigureS4b shows the effect of declustering of a single cluster and Figure 4 shows the declustering of the seismicity in Figure 1.

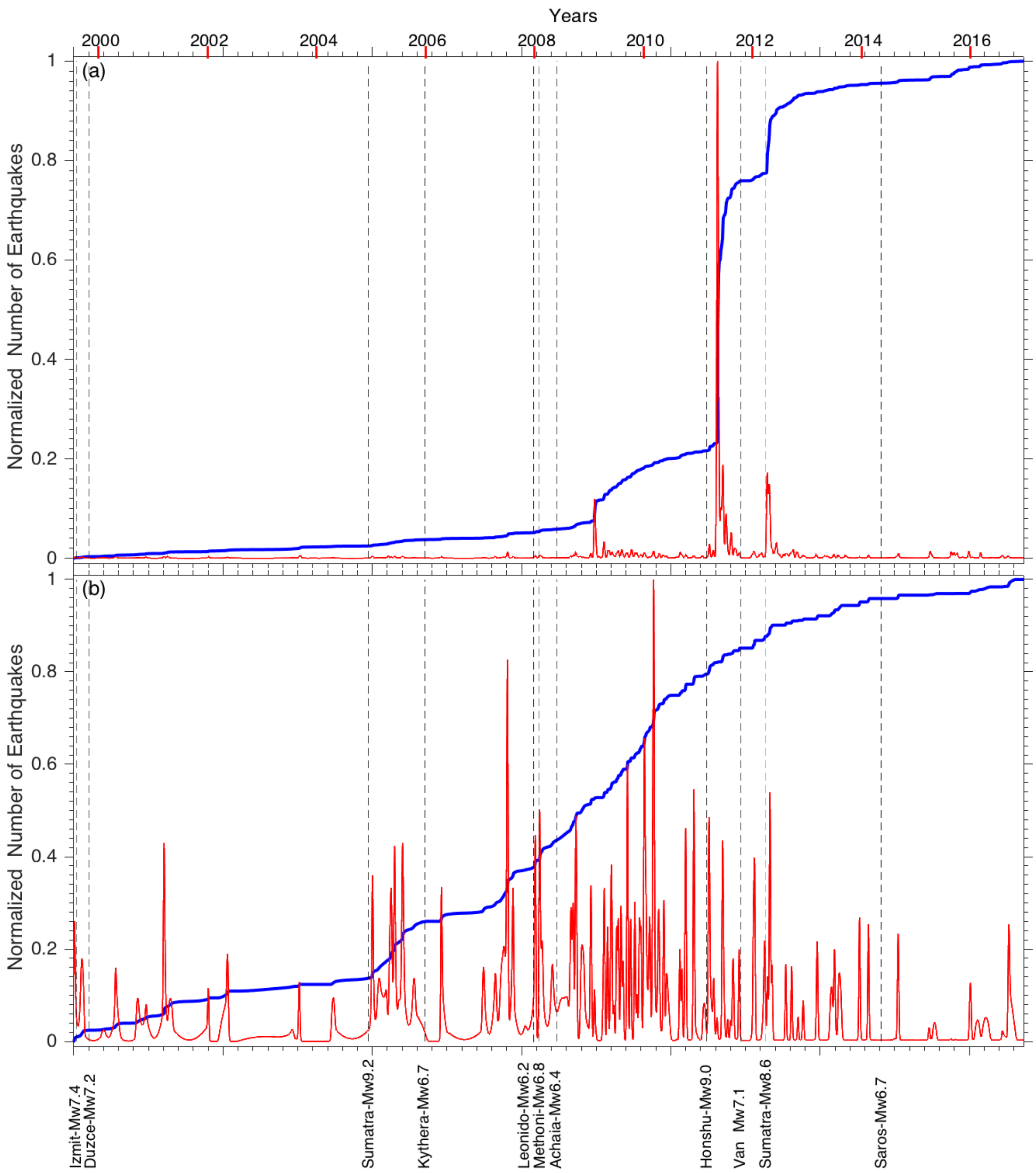

Figure S4 : (a) Cumulative number of earthquakes and seismicity rate for the Simav cluster (b) after declustering.

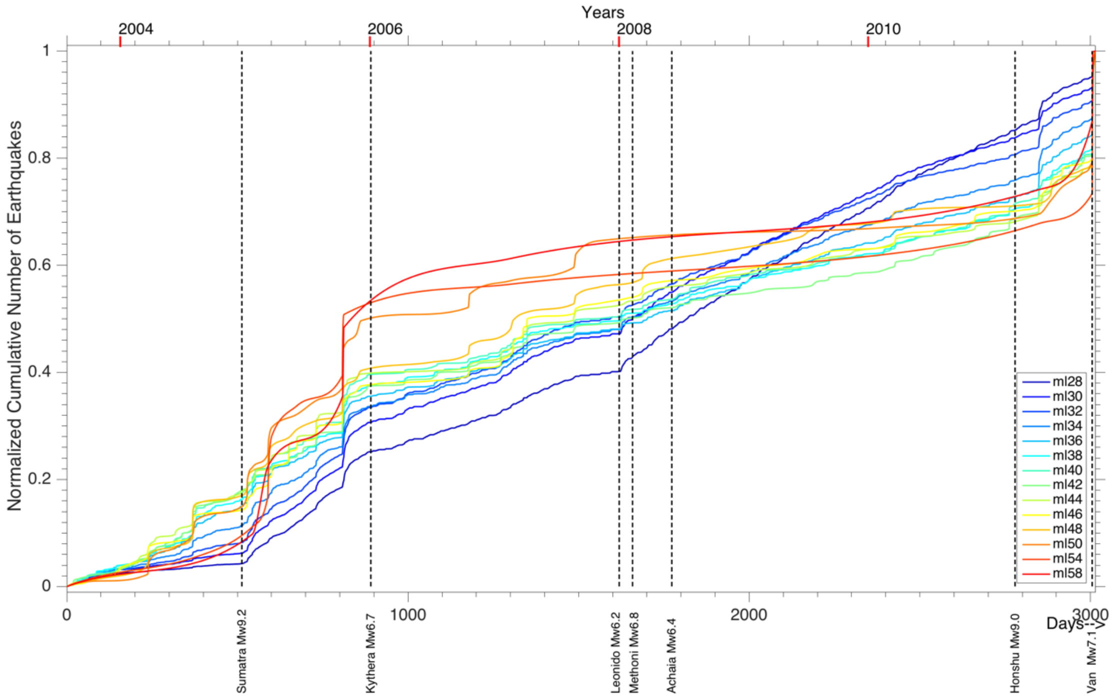

Figure S5: Cumulative number of earthquakes in Anatolia between 36.80N-41.00N latitudes and 25.5E-44.0E longitudes (includes all clusters in Figure 1) for varying lower magnitude cut-offs between 2.8 and 5.8. We limit the display to the occurrence of 2011 Van earthquake.

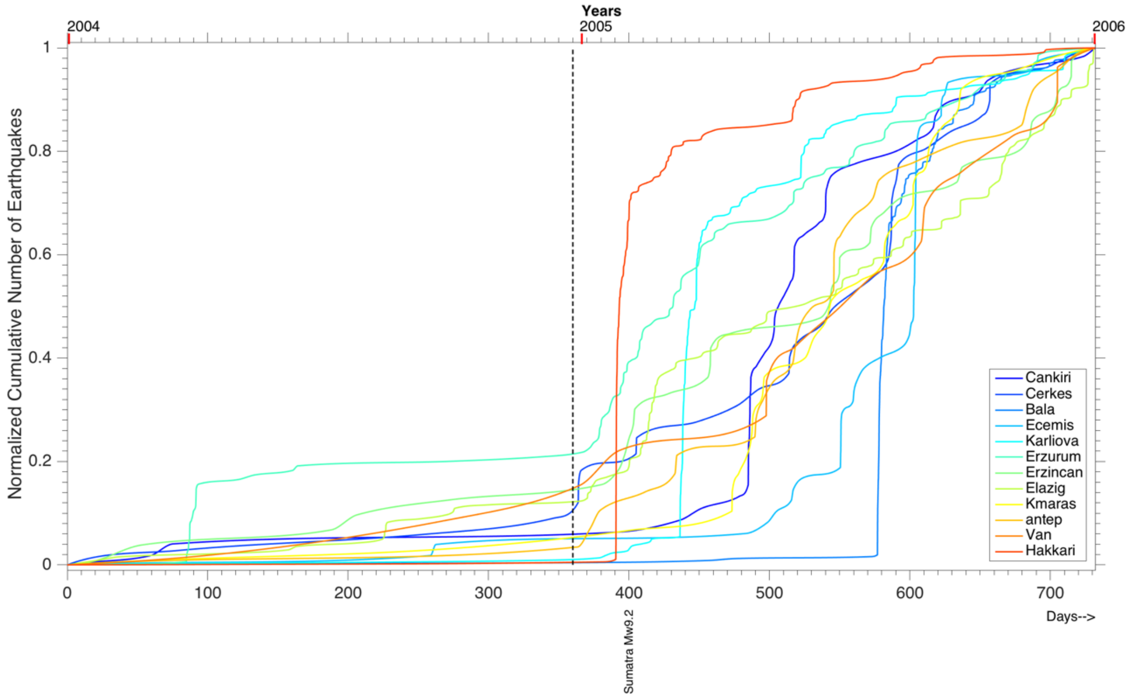

Figure S6: Cumulative number of events of selected clusters in central and eastern Anatolia for the time period of 2004 Sumatra Mw9.2 earthquake (See Figure 1 for the locations of the clusters).

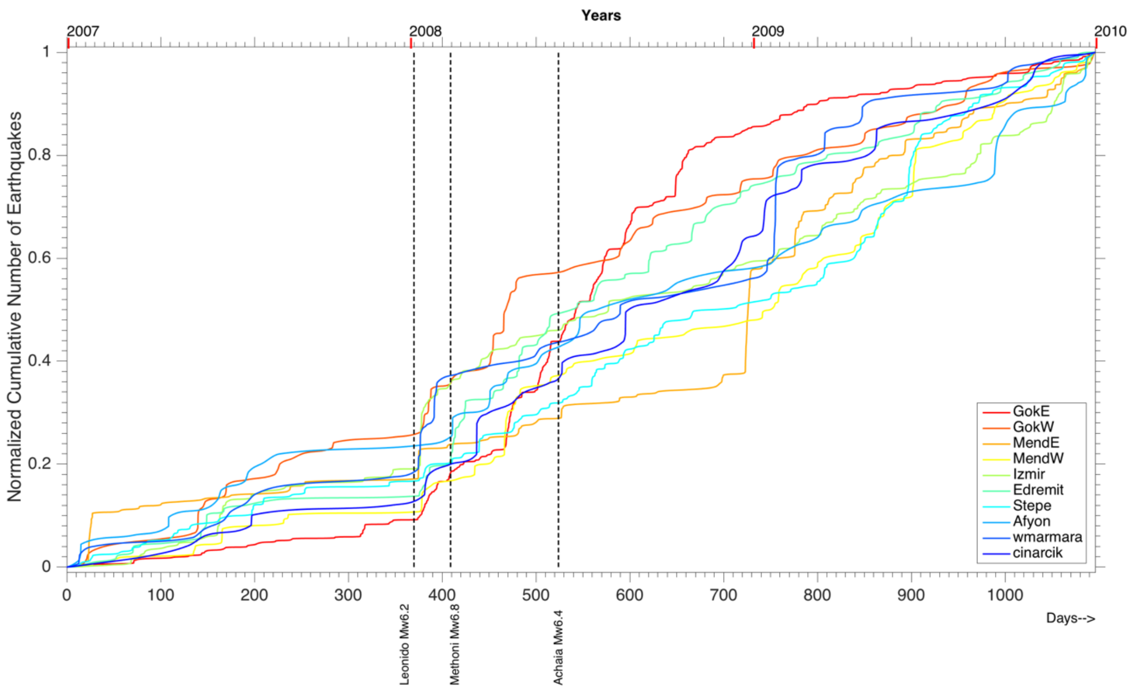

Figure S7: Cumulative number of events of selected clusters in the western Anatolia for time period of Hellenic subduction earthquakes (See Figure 1 for the locations of the western clusters).

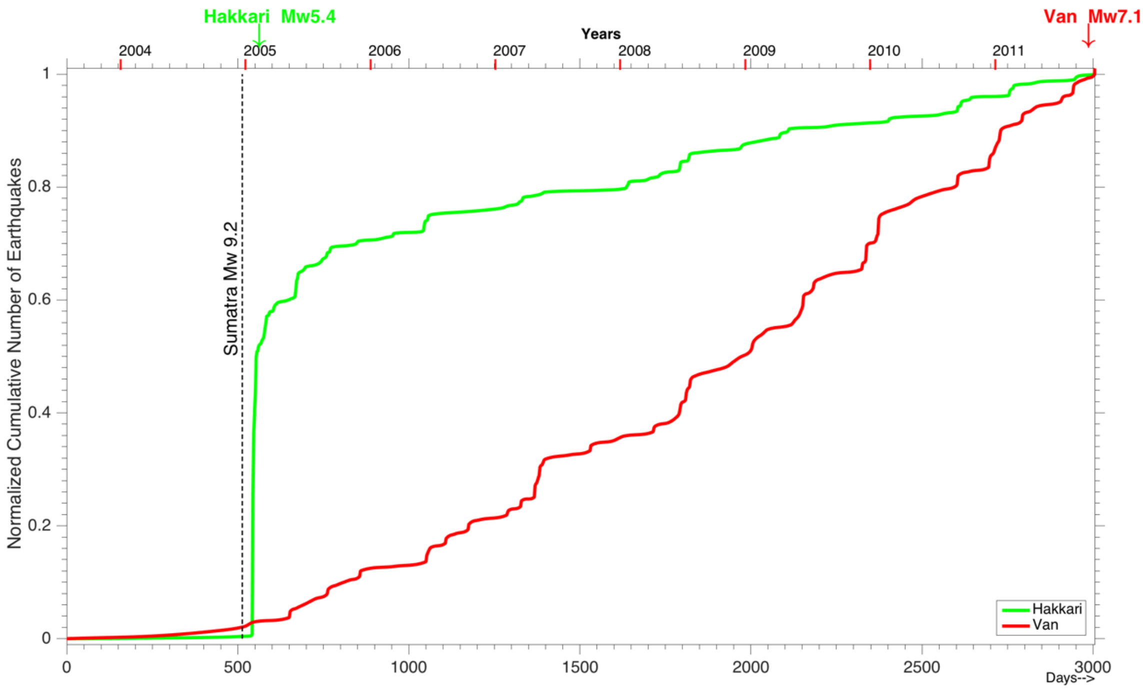

Figure S8: Evolution of the cumulative number of events of the clusters in the two easternmost clusters of Anatolia (See Figure 1 for the locations of the clusters)