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Planar Seismic Source Characterization Models Developed for Probabilistic Seismic Hazard Assessment of Istanbul

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Abstract. This contribution provides an updated planar seismic source characterization (SSC) model to be used in the probabilistic seismic hazard assessment (PSHA) for Istanbul. It defines planar rupture systems for the four main segments of North Anatolian Fault Zone (NAFZ) that are critical for the PSHA of Istanbul: segments covering the rupture zones of 1999 Kocaeli and Düzce earthquakes, Central Marmara, and Ganos/Saros segments. In each rupture system, the source geometry is defined in terms of fault length, fault width, fault plane attitude, and segmentation points. Activity rates and the magnitude recurrence models for each rupture system are established by considering geological and geodetic constraints and are tested based on the observed seismicity that associated with the rupture system. Uncertainty in the SSC model parameters (e.g. b-value, maximum magnitude, weights of the rupture scenarios) is considered in the logic tree. To acknowledge the effect of earthquakes that are not associated with the defined rupture systems on the hazard, a background zone is introduced and the seismicity rates in the background zone are calculated using smoothed-seismicity approach. The state-of-the-art SSC model presented here is the first fully-documented and ready-to-use fault-based SSC model developed for the PSHA of Istanbul.

1 Introduction

North Anatolian Fault Zone (NAFZ), one of the most active fault systems in the world, extends for more than 1500 kilometers along Northern Turkey (Figure 1b). NAFZ was ruptured progressively by eight large and destructive earthquakes (M_w>6.7) in the last century. Earthquakes that occurred between 1939 and 1967 had ruptured approximately 900 kilometers of a uniform trace in the east, whereas the 1999 Kocaeli and Düzce Earthquakes ruptured a total fault span of approximately 200 kilometers where the NAFZ is divided into a number of branches in the west. Northern strand of NAFZ is submerged beneath the Marmara Sea to the west of the 1999 Kocaeli Earthquake rupture zone, introducing major uncertainties to segment location, continuity, and earthquake recurrence (Figure 1a). In 2004, Parsons collected a catalog of large magnitude (M>7) earthquakes occurred around the Marmara Sea for the time period of A.D. 1500 - 2000. Based on the rupture zones of these large magnitude events, four main segments for the northern strand of NAFZ around Marmara Sea were proposed by Parsons (2004): (1) Ganos segment that combines the rupture zones of August 1776 and 1912 earthquakes, (2) Prince Island's segment that includes the rupture zones of 1509 and May 1766 earthquakes, (3) Izmit Segment defined for the

rupture zones of 1719 and 1999 earthquakes, and (4) Çınarcık Segment defined for M~7 floating earthquakes. Parsons (2004) noted that the 10 May 1556 (Ms=7.1), 2 September 1754 (M = 7.0), and 10 July 1894 (M = 7.0) earthquakes were located in the Çınarcık basin or on mapped normal faults in the southern parts of Marmara Sea. These events were not allocated to the other segments in order not to violate the inter-event time calculations, although they could have occurred on

5   the northern strand of NAFZ.

The fault segmentation model proposed by Erdik et al. (2004) was similar to the segmentation model proposed by Parsons (2004) in terms of the fault geometry; however, smaller segments were preferred. Erdik et al. (2004) noted that "*the Main Marmara fault cuts through Çınarcık, Central and Tekirdağ basins, follows the northern margin of the basin when going through the Çınarcık trough in the northwesterly direction, makes a westwards kink around south of Yeşilköy until it reaches*

10   *the 1912 Murefte–Şarköy rupture*". All of these fault lines were interpreted as separate fault segments in the segmentation model. Erdik et al. (2004) considered multi-segment ruptures by assigning lower probabilities to "*cascading ruptures*". Based on the rupture zones of previous large magnitude events, multi-segment ruptures involving the segments in connection with the 1999 Kocaeli Earthquake and 1509 earthquakes were included in the rupture forecast. Even though multi-segment ruptures were considered, the relative probabilities of the multi-segment ruptures vs. single-segment ruptures were not

15   systematically defined in Erdik et al. (2004). This seismic source model was updated for the Earthquake Hazard Assessment for Istanbul Project by OYO (2007). The fundamental differences between the Erdik et al. (2004) and OYO-2007 models are: (1) small segments around Marmara Sea used in Erdik et al. (2004) model were combined to form bigger segments in OYO-2007 model; (2) fault segments that represent the floating earthquakes were defined. The segmentation model used in OYO-2007 source characterization is very similar to the segmentation model proposed by Parsons (2004).

20   The fault segmentation model used by Kalkan et al. (2009) includes significant differences in terms of the fault geometry with the Erdik et al. (2004) model, even though both studies used the active fault maps of Şaroğlu et al. (1992) for inland faults and the fault segmentation model from Le Pichon et al. (2003) and Armijo et al. (2005) for the segments beneath the Sea of Marmara. On the other hand, the magnitude recurrence models used by Erdik et al. (2004), in OYO-2007 model, and by Kalkan et al. (2009) were rather similar. In all of these studies, linear fault segments were modeled (fully or partially) by

25   the characteristic model proposed by Schwartz and Coppersmith (1984); therefore, only large magnitude events were associated with the fault segments. Additionally, a background source representing the small-to-moderate magnitude earthquakes (earthquakes between 5 and 6.5-7 depending on the study) were added to the source model and the earthquake recurrence of the background source was modeled using a double-truncated exponential magnitude distribution model. Either the Poisson (Erdik et al., 2004; Kalkan et al., 2009) or time dependent renewal (Brownian Passage Time Model,

30   Ellsworth et al., 1999) model (Erdik et al. 2004) was preferred to model the earthquake recurrence rates for linear segments; whereas the Poisson distribution was used to model the recurrence rates of the background source in these studies.

Recently proposed SSC models for the western segments of NAFZ (Gülerce and Ocak, 2013 and Murru et al., 2016) are more complicated in terms of the segmentation models, magnitude recurrence relations, and estimation of the activity rates.

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In Gülerce and Ocak (2013) SSC model, length of segments and the segmentation points were determined and incorporated with the help of available fault maps and traced source lines on the satellite images from recent available information. Planar fault segments were defined and a composite magnitude distribution model (Youngs and Coppersmith, 1985) was used for all seismic sources in the region to properly represent the characteristic behavior of NAFZ without an additional background

5 zone. Unfortunately, the seismic source model proposed by Gülerce and Ocak (2013) cannot be directly implemented in the PSHA for Istanbul since the model does not include the fault segments on the west of 1999 Kocaeli Earthquake rupture zone. Geometry of the fault segments defined in Murru et al. (2016) is generally similar to the Erdik et al. (2004) model; however, the complete set of parameters required for a fault-based PSHA analysis (e.g. slip rates, fault widths, rupture models and rates, parameter uncertainties, etc.) was provided in Murru et al. (2016).

10 The objective of this study is to provide an updated and properly documented fault-based SSC model to be used in the PSHA studies in Istanbul. A significant portion of the tectonic database is acquired from the Updated Active Fault Maps of Turkey that was published by General Directorate of Mineral Research and Exploration (Emre et al., 2013) (accessed through http://www.mta.gov.tr/v3.0/hizmetler/yenilenmis-diri-fay-haritalari). The 1/250.000 scale Çanakkale (NK 35-10b), Bandırma (NK 35-11b), Bursa (NK 35-12), Adapazarı (NK 36-13), Bolu (NK 36-14), and Istanbul (NK 35-9) sheets of

15 Updated Active Fault Maps of Turkey were accessed and digitized. The seismological database is taken from the Integrated and Homogeneous Turkish Earthquake Catalog published by Kandilli Observatory and Earthquake Research Institute (Kalafat et al., 2011). Seismotectonic information related to the active faults and the fault systems that are available in these databases and in the current scientific literature are used in combination with the segmentation models proposed by Gülerce and Ocak (2013) and Murru et al. (2016) to define the rupture systems. Fault segments, rupture sources, rupture scenarios

20 and fault rupture models are determined using the terminology given in Working Group of California Earthquake Probabilities (WGCEP-2003) report and multi-segment rupture scenarios are considered in a systematic manner. Events in the seismological database are attributed to the rupture systems and the logic tree weights for the rupture scenarios are determined by comparing the accumulated seismic energy due to the geological constraints (rupture dimensions and slip rate) with the seismic-moment release due to associated seismicity. Different than the previous efforts, the PSHA inputs (e.g.

25 coordinates of the fault segments, logic tree branches and corresponding weights) are properly documented; therefore, the SSC model presented here can be directly implemented in the future site-specific PSHA studies in Istanbul.

2 Fault Models, Rupture Systems, and Partitioning of Slip Rates

The SSC model consists of one background source (defined in Section 5) and four distinct (non-overlapping) rupture systems that are defined by considering the rupture zones of previous large magnitude earthquakes. We note that all sub-

30 segments in the defined rupture systems are assumed to be near vertical with right-lateral slip as suggested by geological, seismological, and GPS data.

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2.1 Izmit and Düzce Rupture Systems:

Location, geometry and slip distribution of the rupture zones of 1999 Kocaeli and Düzce earthquakes has been studied extensively after these events (e.g. Barka et al., 2002; Langridge et al., 2002; Akyüz et al., 2002). The surface rupture of the 1999 Kocaeli earthquake extended for almost 165 km and 4 distinct segments were ruptured (Hersek Segment, Gölcük-

5   Karamürsel-Izmit Segment, Sapanca-Akyazı Segment, and Karadere Segment as in Barka et al., 2002). The coseismic fault was terminated at the western end of the rupture, very near to the eastern side of the Marmara Sea (Ergintav et al., 2014). The northern strand of NAFZ that delimits the boundary between the Marmara Sea and Çınarcık Block did not rupture during 1999 Kocaeli Earthquake (Segment 3 in Figure 1a). Mert et al. (2016) argued that the northern strand of NAFZ is observed as a single continuous fault strand along Izmit Bay and at its entrance to the sea southeast of Istanbul. We included

10   the North Çınarcık segment (Segment 3) in the Izmit rupture system since it's one of the faults that developed in response to the bending of the main strand of the NAFZ towards NW (Prince Islands Fault-PIF) and its motion must be controlled by the motion of the Izmit Segment. Similarly, South Çınarcık Segment is not included in the analysis which is developed in response to transtension resulted from the Northern Çınarcık segment (Segment 3) as a dip-slip fault. Therefore, the Izmit rupture system proposed here consists of five (Hersek-Gölcük, Izmit, Sapanca-Akyazı, Karadare and North Çınarcık) sub-

15   segments. Düzce Earthquake produced 40-km-long surface rupture zone; however, there is a 4-km releasing step-over around Eften Lake (Akyüz et al. 2002). Therefore, a 2-segment model (Segments D1 and D2) is established for the rupture zone of the Düzce earthquake (Figure 1a). The segments, segment lengths, and mean characteristic magnitudes for the Izmit and Düzce rupture systems are given in Table 1. Mean characteristic magnitudes for each segment are calculated by the magnitude-rupture area relationship proposed by Wells and Coppersmith (1994) for strike-slip faults.

20   Past studies based on GPS measurements and field research performed for the region (McClusky et al. 2000; Meade et al., 2002; Reilinger et al., 2006) showed that the total annual slip rate on NAFZ is approximately 25 mm/year. However, the seismic moment accumulating on NAFZ is shared by parallel fault strands; therefore, slip rates should be participated among individual segments. Moreover, these studies suggested that more than 80% of the annual slip rate is accommodated along the northern branch. On this branch, the segments that formed the west and central parts of Izmit rupture system (Segments 3,

25   2_1, 2_2 and 2_3 in Figure 1a) share the total slip rate of 25 mm/year with Geyve-Iznik Fault. The slip rate of 19 mm/year is assigned to these segments of the northern strand and 6 mm/year is assigned to Geyve-Iznik Fault based on the values proposed by Stein et al. (1997) with slight modifications due to catalogue seismicity.

Similarly, the total slip rate of 25 mm/year is distributed over the eastern segment of NAFZ Southern Strand (Segment 1 in Figure 1a) and the segments of Düzce Rupture System (D1 and D2). Since the contribution of Düzce Fault to the total slip is

30   around 33% to 50% (Ayhan et al. 2001), the slip rate of 15 mm/year is assigned to NAF_S1 (Abant) Segment and 10 mm/year is assigned to D1 and D2 segments. For consistency, same slip rate (10 mm/year) is assigned to the segments of İzmit rupture system that are connected to the Düzce fault (Segment 1). It is notable that the segment geometry given in

Gülerce and Ocak (2013) SSC model is modified according to Emre et al. (2013) for this study, however, slip rate participation model remained unchanged.

2.2 Ganos/Saros Rupture System:

The ENE-WSW trending Ganos Fault is the fault segment at the westernmost section of NAFZ that generated the 9 August
5   1912 Mürefte (Ganos) earthquake. Magnitude of this earthquake was estimated from historical catalogues and field observations as $M_s = 7.3 \pm 0.3$ (by Ambraseys and Jackson, 2000) and M_w=7.4 (by Altunel et al., 2004), respectively (Aksoy et al., 2010). A second large event was occurred on 13 September 1912 (M_s=6.8 ± 0.35 and estimated the seismic moment as 2.19×10^{19} Nm as given in Ambraseys and Jackson, 2000). Ambraseys and Jackson (2000) suggested a 37-km-long co-seismic rupture for this large second shock. Aksoy et al. (2010) used the duration of the recorded waveforms to estimate the
10 rupture lengths of 1912 events: assuming the rupture width as 15-20 km, estimated values were 130 ± 15 km and 110 ± 30 km for August 9 and September 13 events, respectively. According to Aksoy et al. (2010), co-seismic surface ruptures were visible along the 45 km on-land section of this segment. Supporting the estimations based on waveforms by aerial photographs, satellite imagery, digital elevation models, bathymetry, and field measurements; Aksoy et al. (2010) proposed 120 ± 30 km-long fault rupture for the August 9, 1912 event.

15 Murru et al. (2016) defined two segments covering the 120 ± 30 km long fault rupture of the 1912 Ganos Earthquake: a 74 km-long segment that includes the on-land section and a 46 km-long off-shore segment (Segments 6 and 7 in Figure 1a). The maximum seismogenic depth of these segments was assumed to be 15 km on the basis of the locking depth suggested by mechanical best fit modelling of GPS data (Flerit et al., 2003) and by the depth extent of instrumental seismicity (Gürbüz et al., 2000; Özalaybey et al., 2002; Örgülü and Aktar, 2001; Pınar et al., 2003). A similar segmentation model is adopted in
20 this study by implementing minor changes in the sub-segment lengths as shown in Table 1. The slip rate proposed in the segmentation model of Murru et al. (2016) is directly adopted for the Ganos sub-segment, whereas the slip rate partitioned in between the North Saros and South Saros sub-segments in Murru et al. (2016) is concentrated over the North Saros sub-segment. This is because the southern segment is developed in response to transtension exerted by the curvilinear trace of northern segment (Okay et al., 2004), a mechanism somewhat similar to northern and southern Çınarcık segments proposed
25 above. The slip rate assigned to the Ganos and Saros sub-segments is consistent with the recent GPS velocity profiles given in Ergintav et al. (2014).

2.3 Central Marmara Rupture System:

The northern strand of the NAFZ forms a major transtensional NW-SE right bend under the Sea of Marmara at the Çınarcık trough (Murru et al., 2016). The fault trace follows the northern margin of the Marmara Sea and connects the complex
30 Central Marmara and Tekirdağ pull-apart basins, before merging into the NE-SW striking Ganos fault on land (Wong et al., 1995; Okay et al., 1999; Armijo et al. 2002; Le Pichon et al., 2001; Yaltirak, 2002; McNeill et al., 2004; Murru et al., 2016).

Building the segmentation model for the off-shore segments of NAFZ (also known as the Central Marmara Fault-CMF) is especially difficult because the fault traces are not directly observable (Aksu et al., 2000; Imren et al., 2001; Le Pichon et al., 2001; Armijo et al., 2002, 2005; Pondard et al., 2007). Murru et al. (2016) noted that the segments under Marmara Sea are bounded by geometric fault complexities and discontinuities (e.g., jogs and fault bends) that act as barriers to rupture propagation (Segall and Pollard, 1980; Barka and Kadinsky-Cade, 1988; Wesnousky, 1988; Lettis et al., 2002; An, 1997) and proposed two separate segments for CMF.

We adopted the fault geometry and the segments proposed by Murru et al. (2016) to build the 2-segments Central Marmara rupture system (see Figure 1a for details). As mentioned by Murru et al. (2016), this model is consistent with the segmentation model proposed by Armijo et al. (2002) and in good agreement with the observed Marmara Sea basin morphology and geology (Flerit et al., 2003; Muller and Aydin, 2005; Carton et al., 2007; Pondard et al., 2007). The slip rates adopted for Central and West Marmara sub-segments (19 mm/year) is consistent with the neighbouring sub-segments of the Izmit and Ganos/Saros rupture systems. Ergintav et al. (2014) noted that the PIF segment (Segment 4) is actively accumulating strain and has not experienced a large event since 1766, making it the most likely segment to generate a $M > 7$ earthquake, and hence the most imminent seismic hazard to Istanbul and other cities around the Sea of Marmara. Even if lower geodetic slip rate estimates for this segment is available in the literature (Hergert and Heidbach, 2010), the slip rate of 19 mm/year representing the upper bound of these estimates is adopted for Segment 4.

3 Instrumental Earthquake Catalogue and Activity Rates of Earthquakes

Catalog of earthquakes documenting the available knowledge of past seismicity within the site region is a key component of the seismic source characterization for the hazard analysis. A very detailed review of the historical earthquakes and their rupture zones around the Marmara Sea region was documented by Parsons (2004). These earthquakes and the extension of their rupture zones are directly utilized in this study to define the sub-segments, rupture systems, and to calculate the mean characteristic magnitude values. The Integrated and Homogeneous Turkish Earthquake Catalog published by KOERI (Kalafat et al., 2011) including the events with $M_w > 4$ that occurred between 1900 and 2010 is employed to represent the instrumental seismicity in the region. It is notable that areal source zones (or poligons) are not utilized in the SSC model to estimate the activity rates; therefore, the maximum magnitude estimates and the PSHA results are not solely dependent on the collected catalogue.

Collected catalogue includes the moment magnitude estimations for all instrumental events and this magnitude scale is consistent with the magnitude scale used in the current ground motion prediction equations (GMPEs). The mainshock-aftershock classification of catalog (de-clustering) is performed and the aftershocks are removed from the dataset using the Reasenberg (1985) methodology in the ZMAP software package (Wiemer, 2001). Reasenberg (1985) algorithm assumes a

dynamically modeled (spatial and temporal) interaction zone centered on each earthquake. Earthquakes occurring within the interaction zone of a prior earthquake are considered as aftershocks.

Catalog completeness analysis for different magnitude ranges is performed in order to achieve the catalogue completeness levels used in calculating the magnitude recurrence parameters. Cumulative rates of earthquakes larger than specific

5 magnitude levels are plotted vs. years in order to examine the completeness of catalog as shown in Figure 2. For different cut-off magnitudes, the breaking points for the linear trends in the cumulative rate of events are examined and a significant breaking point is observed to be at 52 years from the end of the catalogue for magnitudes smaller than 4.5 and 5.0. Therefore, the catalog was assumed to be complete for 52 years for $M_w \leq 4.5$ and $M_w \leq 5.0$, respectively. Although the larger magnitude plots in Figure 2 suffer from the lack of data due to the truncation of the catalog, the catalog is assumed to

10 be complete for the greater magnitudes for the whole-time span (110 years).

The magnitude-frequency relationship developed for each rupture system and the background zone is explained in the next section. Only one of the magnitude-frequency relationship parameters, the slope of the cumulative rate of events (as known as the b-value), is calculated based on the instrumental catalogue. We delineated three different zones for estimating the b-value, considering the temporal and spatial variability of this parameter as shown in Figure 1c. Zone 1 includes the

15 Ganos/Saros and Central Marmara rupture systems, Zone 2 covers the Izmit and Düzce rupture systems, and Zone 3 is a larger area that includes both Zone 1 and 2. For each zone, the b-value is estimated using the maximum likelihood method provided in ZMAP software package. Figure 3 (a-c) shows the completeness magnitudes and the b-values for Zones 1, 2, and 3. Analysis results show that the b-value varies in between 0.68 and 0.74 for different rupture systems given in the previous section; whereas, the b-value for the large area covering whole system is equal to 0.76.

20 Additionally, the b-values for each zone are estimated using the modified maximum likelihood method (Weichert, 1980) that takes into account the completeness of the catalog for different magnitude bins. The b-values calculated by Weichert (1980) method is approximately 5% higher than the maximum likelihood estimations of ZMAP for Zones 1 and 2, but for the larger zone (Zone 3), estimated b-values are almost the same in both methods (Table 2). To acknowledge the uncertainty in the b-value estimations, 30% weight is assigned to the zone-specific b-value calculated by ZMAP and the zone-specific b-value

25 calculated using Weichert (1980) method each, and 40% weight is given to the regional b-value since the number of data in this zone is larger and the estimated b-value is statistically more stable. Finally, the b-value for the background zone (limits shown in Figure 5) is calculated as 0.81 by removing the earthquakes within the buffer zones. Uncertainty in the b-value of background zone is determined using the method proposed by Shi and Bolt (1982) and included in the logic tree (Table 2).

4 Magnitude Recurrence Models – Seismic Moments

30 Seismic sources generate varied sizes of earthquakes and magnitude distribution models describe the relative rate of these small, moderate and large earthquakes. The basic and the most common magnitude recurrence relation is the exponential

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model proposed by Gutenberg and Richter (1944). Since there is a maximum magnitude that the source can produce and a minimum magnitude for engineering interest, the G-R distribution is usually truncated at both ends and renormalized so that it integrates to unity. The truncated exponential distribution function is given in Eq. (1):

$$f_m^{TE}(M) = \frac{\beta \exp\left(-\beta(M - M_{min})\right)}{1 - \exp\left(-\beta(M_{max} - M_{min})\right)} \tag{1}$$

where $\beta = ln(10) \times b - value$, M_{min} is the minimum magnitude, and M_{max} is the maximum magnitude. Youngs and
5 Coppersmith (1985) proposed that the truncated exponential distribution is suitable for large regions or regions with multiple faults but in most cases does not work well for fault zones. Instead, individual faults may tend to rupture at what have been termed as *"characteristic"* size events and the alternative magnitude distribution for this case is the characteristic model proposed by Schwartz and Coppersmith (1984). In characteristic probability distribution function (PDF), once a fault begins to rupture in large earthquakes, it tends to rupture the entire fault segment and produce similar size earthquakes due to the
10 geometry of the fault. It is notable that the characteristic model does not consider the small-to-moderate magnitude earthquakes on a fault. A third model was proposed by Youngs and Coppersmith in 1985 that combines the truncated exponential and characteristic magnitude distributions as shown in Eq. (2) and (3):

$$f_m^{YC}(M) = \begin{cases} \dfrac{1}{1+c_2} \times \dfrac{\beta \exp\left(-\beta(\bar{M}_{char}-M_{min}-1.25)\right)}{1- \exp\left(-\beta(\bar{M}_{char}-M_{min}-0.25)\right)} & \text{for } \bar{M}_{char}-0.25<M\leq\bar{M}_{char}+0.25 \\[3mm] \dfrac{1}{1+c_2} \times \dfrac{\beta \exp\left(-\beta(M-M_{min})\right)}{1- \exp\left(-\beta(\bar{M}_{char}-M_{min}-0.25)\right)} & \text{for } M_{min}<M\leq\bar{M}_{char}-0.25 \end{cases} \tag{2}$$

where,

$$c_2 = \frac{0.5\beta \exp\left(-\beta(\bar{M}_{char} - M_{min} - 1.25)\right)}{1 - \exp\left(-\beta(M_{char} - M_{min} - 0.25)\right)} \tag{3}$$

and M_{char} is the characteristic earthquake magnitude. Coupling the truncated exponential magnitude PDF with seismic
15 sources defined by planar fault geometries results in unrealistically high rates for small-to-moderate magnitude events (Hecker et al., 2013), especially in the close vicinity of NAFZ (Gülerce and Vakilinezhad, 2015). Therefore, the composite magnitude PDF proposed by Youngs and Coppersmith (1985) is utilized to represent the relative rates of small, moderate and large magnitude earthquakes related to the rupture systems defined in this study.

The rupture systems presented in Section 2 includes more than one sub-segment. We adopted the terminology of WGCEP
20 (2003) and defined the rupture source as a fault sub-segment or a combination of multiple adjacent fault sub-segments that may rupture and produce an earthquake in the future. For Düzce, Central Marmara, and Ganos/Saros rupture systems with two sub-segments (as A and B), three different rupture sources can be defined; single segment sources (A and B) and a two-sub-segment source (A+B). Any possible combination of rupture sources that describes the complete rupture of the system is defined as the rupture scenario. Two rupture scenarios for these rupture systems are; (1) rupture of the two sub-segments

individually and (2) rupture of the two sub-segments together. The rupture model includes the weighted combination of rupture scenarios of the rupture system. Five segments defined for Izmit rupture systems form a rupture model with 15 rupture sources and 16 rupture scenarios (Table 5). The minimum magnitude (M_{min}) is set to M_w=4.0 for all rupture sources considering the completeness magnitude. Mean characteristic magnitudes for each rupture source are calculated by the

5 relationship proposed by Wells and Coppersmith (1994) and are listed in Table 6. The upper bound for the magnitude PDF (M_{max}) is determined by adding 0.25 and 0.5 magnitude units to M_{char} for each source in each logic tree branch (Table 6).

Magnitude PDF only represents the relative rate of different magnitude earthquakes. In order to calculate the absolute rate of events, the activity rate $N(M_{min})$ defined as the rate of earthquakes above the minimum magnitude, should be used. For areal sources, $N(M_{min})$ may be calculated by using the seismicity within the defined area. For planar fault sources, the activity rate

10 is defined by the balance between the accumulated and released seismic moments as shown in Eq. (4). The accumulated seismic moment is a function of the annual slip rate (S) in cm/years, area of the fault (A in cm^2) and the shear modulus of the crust (μ in dyne/cm^2).

$$N(M_{min})= \frac{\mu AS}{\int_{M_{min}}^{M_{max}} f_m(M_w)10^{1.5M_w+16.05}dM} \tag{4}$$

Ultimately the magnitude distribution and the activity rate are used to calculate the magnitude recurrence relation, N(M), as shown in Eq. (5).

$$N(M) = N(M_{min}) \int_{M_{min}}^{M_{max}} f_m(M_w)\, dM \tag{5}$$

15 The magnitude recurrence relation given in Eq. (5) and the accuracy of the model parameters such as the b-value or M_{max} shall be tested by the relative frequency of the seismicity associated with the source in the moment-balanced PSHA procedure. Therefore, a weight is assigned to each rupture scenario and the cumulative rates of events attributed to that particular rupture system are plotted along with the weighted average of the rupture scenarios to calibrate the assigned weights and to evaluate the balance of the accumulated and released seismic moment. The "*moment-balancing*" graphs for

20 Izmit, Düzce, Central Marmara, and Ganos/Saros rupture systems are provided in Figure 4. In these plots, the black dots stand for the cumulative annual rates of earthquakes and the error bars represent the uncertainty introduced by unequal periods of observation for different magnitudes (Weichert, 1980). The best fit between the cumulative annual rate of events and the weighted average of rupture scenarios (red dashed lines) is established by modifying the weights of the rupture scenarios. In Figure 4, the scenarios that are separated by plus signs in the legend are the scenarios with multiple rupture

25 sources. When multiple segments rupture together, these scenarios are separated by a comma sign in the legend. For example, the "S4, S5" line in Figure 4(c) represents the scenario where S4 and S5 sub-segments are ruptured individually. This scenario brings in relatively higher rates for small-to-moderate earthquakes when compared to the S4+S5 scenario which represents the rupture of these two segments together to produce a larger event. In each moment balancing plot, relatively higher weights are assigned to the rupture scenarios that combine the individual (single-segment) rupture sources

based on the assumption that single-segment ruptures are more likely than multiple-segment ruptures. The weights assigned to each rupture scenario are given in Table 4 and these values are adopted in the logic tree.

5 Background Zone – Smoothed Seismicity

A background source zone of diffused seismicity is utilized to characterize the seismicity that is not associated with the rupture systems described in the previous sections. This additional background source zone represents the seismicity associated with the mapped active faults on the south of Marmara Sea (yellow fault lines in Figure 1a) and the interpretation that even in areas where active faults or distinctive zones of seismicity are not observed, earthquakes can still occur. Figure 1c shows that the spatial distribution of the earthquakes (outside the buffer zones around the rupture systems) is not homogeneous; density of the events increases significantly around the Geyve-Iznik Fault Zone. Therefore, defining an areal source zone with homogeneous seismicity distribution would result in the overestimation of the seismic hazard in Istanbul. Instead, the background source is modelled as a source of gridded seismicity where the earthquakes are represented as point or planar fault sources at the centers of evenly spaced grid cells (0.05 degree spacing). The truncated exponential magnitude distribution (Eq. 1) is selected to represent the relative frequency of the different magnitude events for this source. In the magnitude recurrence model, spatially uniform M_{max} and b-values and spatially variable a-values, or seismicity rates, are defined. The minimum magnitude (M_{min}) is again set to M_w=4.0 and the b-value is taken as 0.81. The a-value for each grid cell was calculated from the maximum likelihood method of Weichert (1980), based on events with magnitudes of 4.0 and larger. The gridded a-values were then smoothed by using an isotropic Gaussian kernel with a correlation distance of 10 km (Frankel, 1995). The smoothed-seismicity rates overlying the earthquakes outside the buffer zones are presented in Figure 5. Tabulated values of the grid cell coordinates and the seismicity rates are provided in the Electronic Supplement 2.

The M_{max} distribution of the background zone is developed by taking into account the lack of evidence for surface faulting in the city of Istanbul. So far, no active fault has been reported from the near vicinity of the study area. Similarly, the MTA Active Fault Maps (Emre et al., 2013) do not contain any active fault in the northern part of the NAFZ between Izmit and Tekirdağ. In this regard, the M_{max} distribution is defined such that there is reasonable likelihood that the M_{max} earthquake will not produce surface faulting (see Table 4). The focal mechanisms of the background source should reflect the tectonic style of the parent region, therefore, a weighted combination of strike-slip (SS, 75%), normal (N, 20%), and reverse (R, 5%), motion with weights that sum to 1 is assigned to this source (Table 3). A uniform distribution of focal depths between the surface and 18 km depth is utilized.

6 Conclusions

This manuscript presents the details of the SSC model proposed for the PSHA studies in Istanbul. When compared to the previous SSC models developed for this region, significant improvements in the proposed model can be listed as follows: (1)

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planar seismic sources that accounts for the most current tectonic information (e.g. updated fault maps) are built, (2) the multi-segment rupture scenarios are systematically utilized in the rupture forecast, (3) buffer zones around the rupture systems are defined to associate the small, moderate, and large magnitude events with the rupture systems, (4) activity rates for the planar rupture systems are calculated using the geological and geodedic constraints (e.g. slip rate and fault geometry),

5   (5) balance of the accumulated and released seismic moment is considered in building the magnitude recurrence model, and (6) associated earthquakes are used to test the suitability of the magnitude recurrence model with the instrumental seismicity. Even though the rupture systems develop in this study accounts for the relative rates of small, moderate, and large magnitude events that can occur on the faults, a background source is defined to represent the small-to-moderate magnitude earthquakes that may take place anywhere in the vicinity of Istanbul and Marmara Sea. Properties of the rupture systems, background

10   source and the logic tree associated with both of these components are fully documented through Tables 1-6. Additionally, coordinates of the fault segments and smoothed seismicity rates are provided in the Electronic Supplements 1-2. Therefore, proposed SSC model can be directly implemented to any of the available PSHA software for the site-specific PSHA analysis in Istanbul.

We would like to emphasise that the SSC model presented here is different than the models proposed by Gülerce and Ocak

15   (2013) and Murru et al. (2016): difference in the fault geometry is minor but the differences in the magnitude recurrence models and the time dependent probabilities of earthquakes are more significant. Proposed model does not utilize the time-dependent hazard methodologies; however, we believe that the ongoing research on the paleoseismic recurrence periods will provide a substantial contribution in the PSHA practice of Turkey and eventually will lead to a change the hazard estimates.

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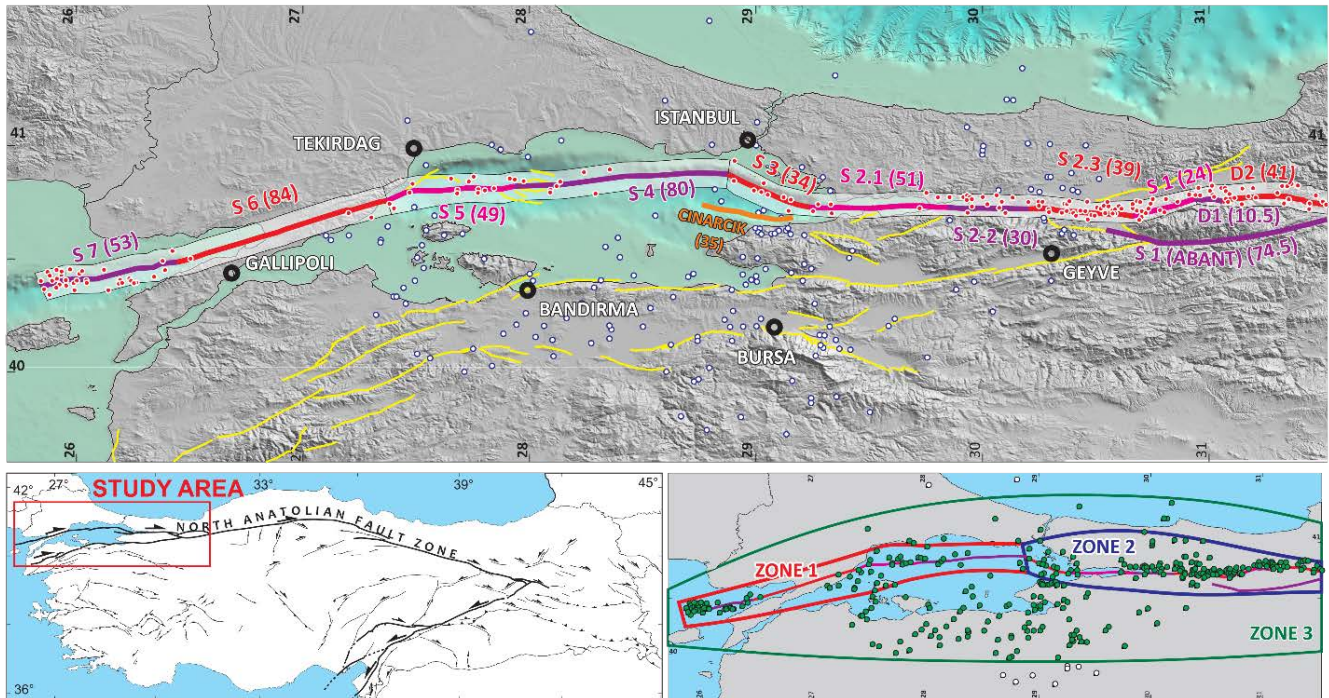
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Figure 1: (a) Major branches of North Anatolian Fault Zone, defined rupture systems and the instrumental seismicity (M_w>4) in the study area. The buffer zones used for source-to-epicenter matching are shown around the rupture systems. (b) Simplified active tectonic scheme of Turkey (modified from Emre et al., 2013). Thick lines are North Anatolian and East Anatolian fault zones, thin lines are other active faults. (c) Distribution of the declustered seismicity used to calculate the b-values. Zone 1, Zone 2 and Zone 3 are the polygons utilized for calculating the b-values.
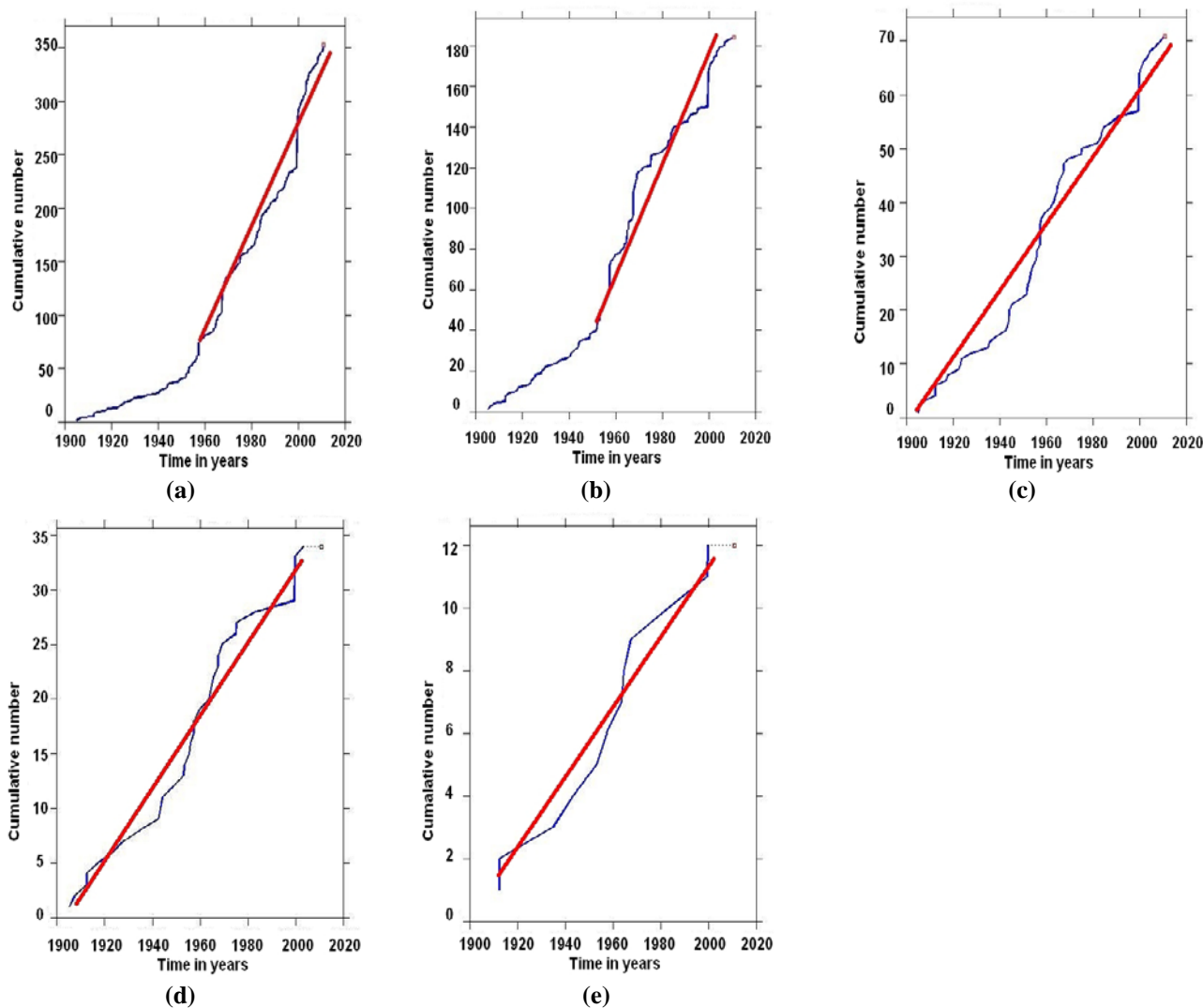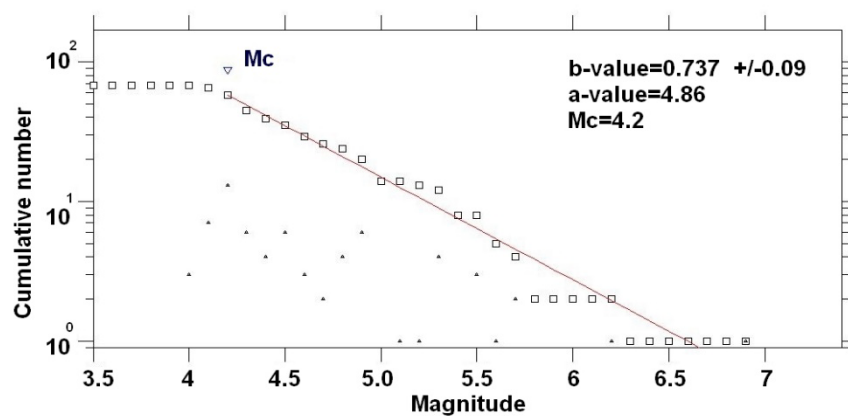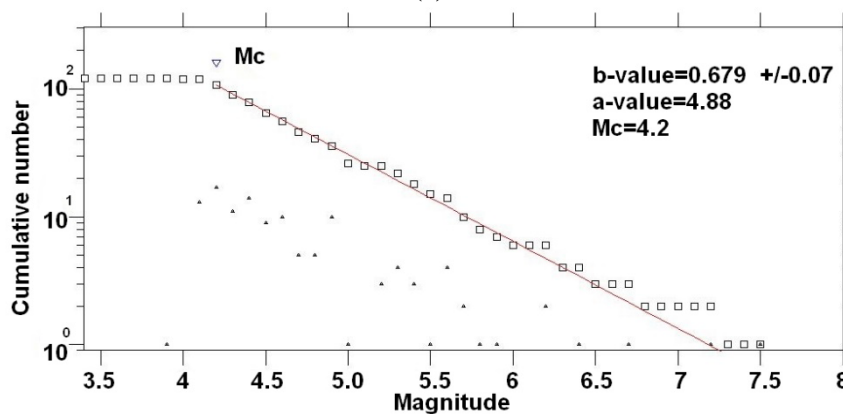
Figure 2: The catalogue completeness analysis for the instrumental earthquake catalogue showing the cumulative number of events for (a) Mw ≥4.0, (b) Mw ≥4.5, (c) Mw ≥5.0, (d) Mw ≥5.5, and (e) Mw ≥6.0.

5

(a)

(b)
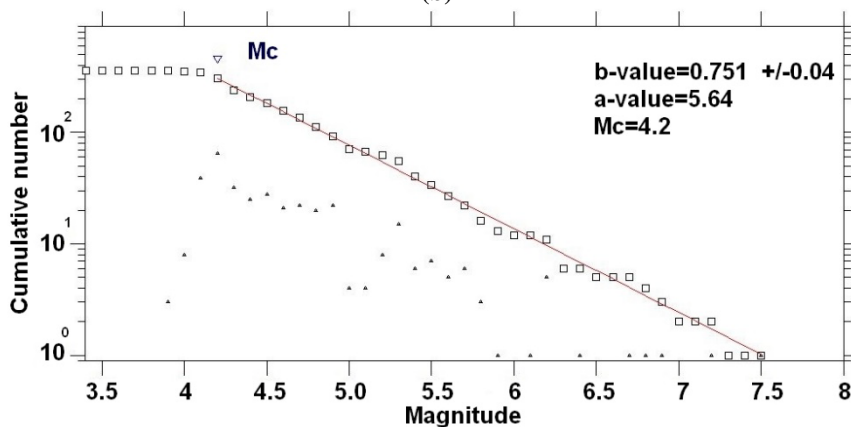
(c)

Figure 3: Estimated magnitude recurrence parameters for (a) Zone 1, (b) Zone 2, and (c) Zone 3.
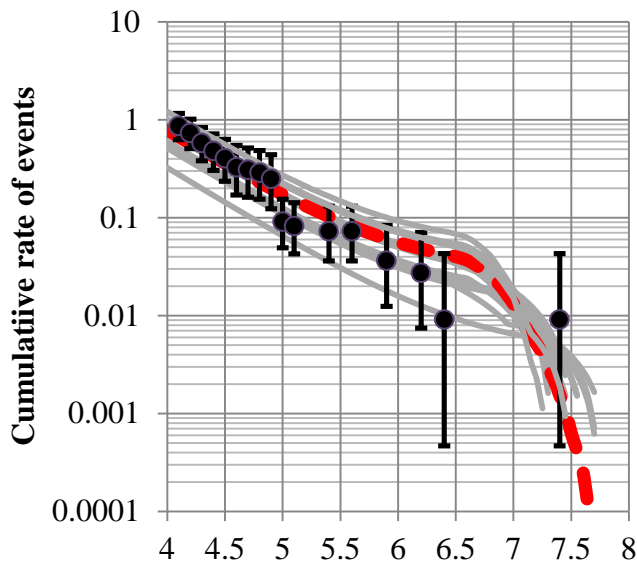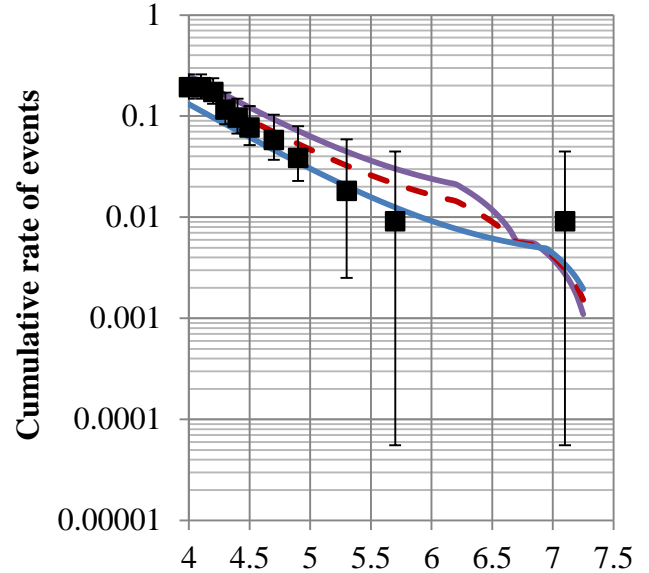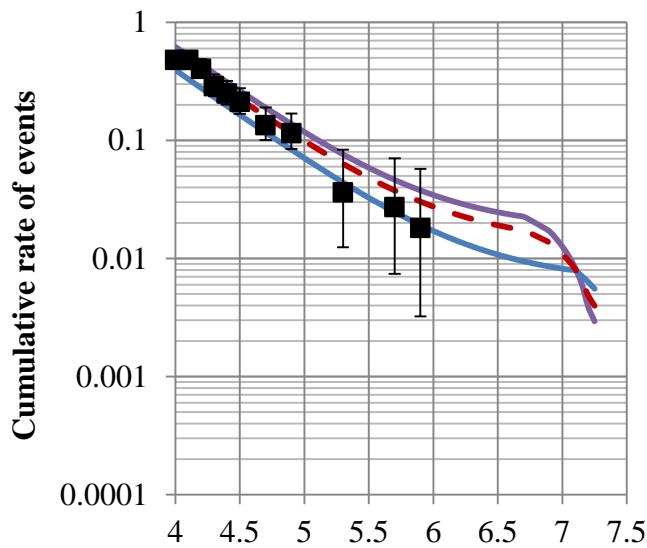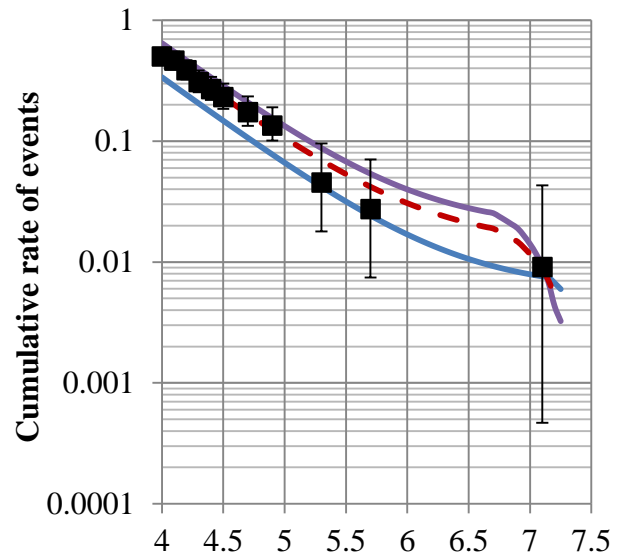
Figure 4: Cumulative rate of events of the magnitude recurrence model and associated events (showing the balance of the accumulated and released seismic moment) for (a) Izmit, (b) Düzce, (c) Central Marmara, and (d) Ganos/Saros rupture systems. In each figure, black points represent the earthquakes associated with the rupture system and red broken line is the weighted 5 **average of the magnitude recurrence model for the rupture system.**
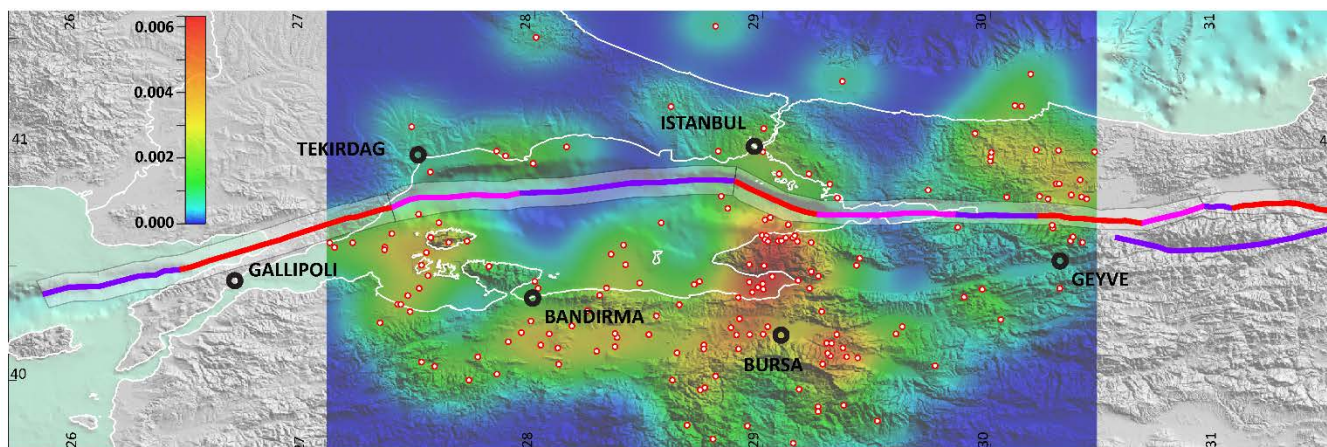
Figure 5: Spatial distribution of the activity rates in the smoothed seismicity source.

5   **Table 1: The fault segments and rupture systems included in the SSC model.**

Rupture System	Segment No	Segment Name	Length (km)	Width (km)	Slip Rate (mm/yr)	Characteristic Earthquake (M_{char})
Izmit	3	Çınarcık	34.6	18	19	6.83
Izmit	2_1	Hersek- Gölcük	51.6	18	19	7.01
Izmit	2_2	İzmit	30.2	18	19	6.77
Izmit	2_3	Sapanca – Akyazı	39.1	18	10	6.88
Izmit	1	Karadere	24.7	18	10	6.68
Düzce	D1	Düzce_1	10.5	25	10	6.45
Düzce	D2	Düzce_2	41	25	10	7.05
Ganos/Saros	6	Ganos	84	15	19	7.14
Ganos/Saros	7	Saros	53	15	19	6.94
Central	4	Central Marmara	80	15	19	7.12
Central	5	West Marmara	49	15	19	6.90

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Table 2: b-values estimated using different methods and corresponding weights in the logic tree.

Source Zone	Maximum likelihood estimation by ZMAP (Zone-specific)		Maximum likelihood estimation by Weichert (1980) (Zone-specific)		Regional Value	
	b-value	weight	b-value	weight	b-value	weight
Düzce Rupture System	0.68	0.3	0.72	0.3	0.76	0.4
Izmit Rupture System	0.68	0.3	0.72	0.3	0.76	0.4
Central Marmara Rupture System	0.74	0.3	0.78	0.3	0.76	0.4
Ganos/Saros Rupture System	0.74	0.3	0.78	0.3	0.76	0.4
	Maximum likelihood estimation by Weichert (1980) (Mean - 2σ)		Maximum likelihood estimation by Weichert (1980) (Mean)		Maximum likelihood estimation by Weichert (1980) (Mean + 2σ)	
Background Zone	b-value	weight	b-value	weight	b-value	weight
	0.714	0.20	0.81	0.60	0.906	0.20

Table 3: Logic tree for style of faulting

	Style of faulting		
Weights	Normal	Strike Slip	Reverse
150km radius background zone	0.20	0.75	0.05
All rupture systems of NAFZ	-	1.00	-

Table 4: Logic tree representing epistemic uncertainty in rupture scenario weights

Rupture System	Rupture type	Included sub-segment no	Weight
Düzce Rupture System	Single segment ruptures	D1, D2	0.5
	2-segment ruptures	D1+D2	0.5
Central Marmara Rupture System	Single segment ruptures	4,5	0.6
	2-segment ruptures	4+5	0.4
Ganos/Saros Rupture System	Single segment ruptures	6,7	0.6
	2-segment ruptures	6+7	0.4
Izmit Rupture System	Table 5		

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Table 5: Rupture sources and rupture scenarios utilized for the Izmit rupture system*

	3	2_1	2_2	2_3	1	3+2_1	2_1+2_2	2_2+2_3	2_3+1	3+2_1+2_2	2_1+2_2+2_3	2_2+2_3+2_4	3+2_1+2_2+2_3	2_1+2_2+2_3+1	3+2_1+2_2+2_3+1	*Rupture Scenario*	*Weight*
3, 2_1, 2_2, 2_3, 1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0.20
3+2_1 ,2_2, 2_3, 1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	2	0.07
3, 2_1+2_2, 2_3 ,1	1	0	0	1	1	0	1	0	0	0	0	0	0	0	0	3	0.07
3, 2_1, 2_2+2_3, 1	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	4	0.07
3, 2_1, 2_2, 2_3+1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	5	0.07
3+2_1+2_2, 2_3, 1	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	6	0.05
3, 2_1+2_2+2_3 ,1	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	7	0.05
3, 2_1, 2_2+2_3+1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	8	0.05
3+2_1+2_2+2_3, 1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	9	0.05
3, 2_1+2_2+2_3+1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	10	0.03
3+2_1, 2_2+2_3, 1	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	11	0.03
3, 2_1+2_2, 2_3+1	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	12	0.03
3+2_1+2_2, 2_3+1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	13	0.03
3+2_1, 2_2+2_3+1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	14	0.03
3+2_1, 2_2, 2_3+1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	15	0.03
3+2_1+2_2+2_3+1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	16	0.14
Rupture Source No	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*		

*Note: Rows show the rupture scenarios and the columns show the rupture sources. 1 and 0 in a cell indicate that the particular rupture source is included or excluded in the rupture scenario, respectively. Scenario weights are given in the last column. For sub-segments 3, 2_1, 2_2, 2_3, and 1, please refer to Figure 1b.

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Table 6: Logic tree representing epistemic uncertainty in maximum magnitudes

Rupture System	Rupture Source	Source Width (km)	Source Length (km)	Mean Characteristic Magnitude (WC94)	M_{max} 1 (Weight = 0.5)	M_{max} 2 (Weight =0.25)	M_{max} 3 (Weight = 0.25)
Düzce	D1	25	10.5	6.45	6.45	6.70	6.95
Düzce	D2	25	41	7.05	7.05	7.30	7.55
Düzce	D1+D2	25	51.5	7.15	7.15	7.40	7.65
Central Marmara	S4	15	80	7.12	7.12	7.37	7.62
Central Marmara	S5	15	49.2	6.91	6.91	7.16	7.41
Central Marmara	S4+S5	15	129.2	7.33	7.33	7.58	7.83
Ganos / Saros	S6	15	84	7.14	7.14	7.39	7.64
Ganos / Saros	S7	15	53	6.94	6.94	7.19	7.44
Ganos / Saros	S6+S7	15	137	7.36	7.36	7.61	7.86
Izmit	3	18	34.6	6.83	6.83	7.08	7.33
Izmit	2_1	18	51.6	7.01	7.01	7.26	7.51
Izmit	2_2	18	30.2	6.77	6.77	7.02	7.27
Izmit	2_3	18	39.1	6.88	6.88	7.13	7.38
Izmit	1	18	24.7	6.68	6.68	6.93	7.18
Izmit	3+2_1	18	86.2	7.23	7.23	7.48	7.73
Izmit	2_1+2_2	18	81.8	7.21	7.21	7.46	7.71
Izmit	2_2+2_3	18	69.3	7.14	7.14	7.39	7.64
Izmit	2_3+1	18	63.8	7.10	7.10	7.35	7.60
Izmit	3+2_1+2_2	18	116.4	7.37	7.37	7.62	7.87
Izmit	2_1+2_2+2_3	18	120.9	7.38	7.38	7.63	7.88
Izmit	2_2+2_3+1	18	94	7.27	7.27	7.52	7.77
Izmit	3+2_1+2_2+2_3	18	155.5	7.50	7.50	7.75	8.00
Izmit	2_1+2_2+2_3+1	18	145.6	7.47	7.47	7.72	7.97
Izmit	3+2_1+2_2+2_3+1	18	180.2	7.56	7.56	7.81	8.06
Background	-	18	-	-	6.5	6.4	6.6