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New Directions in Seismic Hazard Assessment through Focused Earth Observation in the Marmara Supersite

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D7.4

Revisited Historical Earthquake Catalogue: Historical Earthquakes and Earthquake Scenarios from Past to Future Under the Light of Fault Patterns of the Marmara Sea and the Surrounding Areas

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CO	Confidential, only for members of the consortium (including the Commission)	

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Abstract

In this study a three-stage evaluation has been made. In first stage, historical earthquakes were collected from the catalogues and a decision concerning which branch of the North Anatolian Fault is the major fault system with historical data was made. Afterwards, the earthquakes which destroyed at least a settlement were grouped. These earthquakes were grouped on a historical map without faults according to their influence areas by examining different sources. In second stage, three models that differs from each other with some basic terms, were prepared on a database in ArcGIS software. Mw values were calculated for each segment according to segment lengths and seismogenic depths of fault segments.

In third stage, a 1:500000-scale digital geological map of Marmara Region was revised according to the V_s30 data compiled from the literature in the manner of 750x750m grids. Modified Mercalli Intensity (MMI) maps were produced for each segments of each models by using the calculations on these base and fault maps.

In the fourth stage, the 1:25000-scale geological and topographic map of Istanbul was revised according to the V_s30 data of İstanbul Metropolitan Municipality in the manner of 250x250m grids, by reason of the fact that İstanbul is the region where most historical earthquake data have been gathered. The exact locations of the historical constructions in İstanbul have been plotted by using high-resolution satellite images and archaeological maps and then the damages were compared on the basis of these generated maps, fault models and high-resolution MMI maps.

Our approach about the faults that produced earthquakes was invertedly tested and the historical catalogues and MMI maps were locally compared.

Introduction

In order to determine the recurrence intervals of faults from historical earthquakes, the best method is to combine paleoseismological field studies and the specified fault slips of historical earthquakes by the help of fault excavations and morphological properties. An agreeable historical earthquake record should exist to obtain the absolute results, especially for the dating methods, in earthquake excavations. For example, there are 5 months between 1999 Gölcük and 1999 Düzce earthquakes. These two earthquakes generated two fractures close to each other in İzmir Karadere area (Akyüz et al. 2002). If the similar records are observed on the different faults segments in the Marmara Sea and its surrounding areas, then it may be considered as one earthquake along a major fault. Considering data, the great earthquakes which affected the same region in the Marmara Sea and surroundings, repeated at intervals of several months to a few ten years (Yaltırak, 2015). These earthquakes are not aftershocks, all of them are undoubtedly destructive earthquakes. Besides, it is an inevitable issue to use paleo-seismological methods to examine the complex fault structures in the deep sea where the fault excavations are not possible. The Marmara region is one of the precious areas where the longest term settlement and civilization are observed along a fault system. The Marmara Sea and its surrounding area is one of the places, may be the unique one, on the earth which has the detailed earthquake history of 1500 years in the non-instrumental period. There are detailed earthquake catalogues, history books and articles which form an estimate of these earthquakes by using the historical texts (Pınar and Lahn, 1952; Şehsuvarlıoğlu, 1955 ;Ergin et al., 1964; Soysal et al., 1981; Örekli, 1998; Ambraseys and Finkel, 1991; Guidoboni et al., 1994, Ambraseys and Finkel, 1995; Ambraseys and Jackson, 1998; 2000; Zachariadou, 2001; Ambraseys, 2002; Afyoncu and Mete, 2002; Demirkent, 2002;

Ozansoy, 2002; Yıldız, 2002; Karacakaya, 2002; Sancaklı, 2004; Guidoboni and Comanstri, 2005; Ambraseys, 2009; Mazlum, 2011). The Turkish references are mostly disregarded in the international publications, or when considered they might be cited wrongly. This situation causes continuous mistakes in the literature by the researchers who don't examine the original references. Many researchers are not able to distinguish which earthquakes were illustrated on the ordinary engravings. The two examples below might be considered unnecessary. However, so many overlooked details like these examples need to be corrected and when corrected they will provide great contribution to the scientific researches. These two examples below show how the historical earthquake studies might mislead the researchers if the ancient cities in İstanbul and Marmara are not well-known. Example 1: Ambraseys (2009) presents a wooden engraving of the AD 1509 earthquake in his book about the historical earthquakes of Mediterranean. On this engraving, the Fatih Mosque which is supposed to be destroyed in AD 1509 is seen (Ambraseys, 2009, p.429).

Figure 1. a: *Woodprint which is asserted to show 1509 earthquake (Ambraseys, 2009), in this gravure Fatih mosque has two minarets. Fatih mosque was built with small dome and in between 1462-70 by Atik Sinan. After the 1509 earthquake it was rebuilt with big dome and two high minarets near the külliye by Sultan Bayezid II (Şehsuvarlıoğlu, 1955).* ***b:*** *Positions of Fatih mosque and other mosques at the point of view at the same as gravure, some of these mosques was built after 1766 (Some mosques which are seen at gravure but not in photo, remain in between buildings of present day).i*

Also some other mosques are conspicuously observed around this mosque (Figure 1a, colour shaded and numbered). If a curious researcher wonders where this engraving was painted, he/she easily realises that the view is from the Tevfik Sağlam elementary school, at the beginning of the tunnel along the Beyoğlu Refik Saydam Street to the Pera Palace Hotel (Coordinates41.030093N, 28.971324E; view direction: SW). Moreover, when the mosques on the engraving are compared with the recent mosques, it is easy to select the ones built after the AD 1509 and AD 1766 earthquakes. The Fatih Mosque had been repaired by Architect Tahir Agha between AD 1761 and AD 1771. Also Tahir Ağa built a small prayer room for himself in the northern part of the Fatih Mosque, against Balat (Figure 1b). When comparing the photograph and engraving, this engraving indicates the AD 1766 earthquake. The construction of the Fatih Mosque with two minarets and a huge dome started after AD 1509 earthquake in AD 1510 (Şehsuvarlıoğlu, 1955). The mosque which was built firstly by architect Atik Sinan had no minaret and its dome was lower. This characteristic can be seen on a wooden engraving which was made in AD 1493 (Figure 2a). This construction was critically damaged during AD 1509 earthquake (Figure 2b). Example 2: There is another engraving of AD 1556 earthquake in the book written by Ambraseys and Finkel (1995). The damages seen in the engraving give clues about the disaster in the city. However, there is an important deficient in the engraving. Although the construction of the Süleymaniye Mosque had already finished, it doesn't exist in the engraving. In addition to that the damages in the engraving are not identical with the real damages. In fact, another similar engraving made before this one and dated as 14th century shows an undamaged İstanbul. In the engraving which is assumed to show AD 1556 earthquake, the damages of AD 1509 earthquake are seen on the building drawings again (Figure 2). While reading the historical earthquake resources, most of the international researchers pay no attention to the historical drawings that absolutely represent the facts. These two examples are more remarkable ones among several similar examples that indicate how the earthquake data leads to confusion while editing and reading, especially in terms of understanding the reason of the damages. It is possible to obtain information about the effects of the historical earthquakes by comparing the mentioned damages with the dates of the building repairs. For example 06.01.1489/90 Gölcük earthquake is almost an unknown earthquake in the literature (Ambraseys, 2009). It was recorded as İstanbul Earthquake. It devastated a church located in Avcılar surrounding and a trivial damage was observed in the ancient İstanbul area. That earthquake actually caused a quite big damage in Gölcük. Although only the collapsed buildings in Avcılar and Gölcük are mentioned in the earthquake records, it has the same effect area as the 17th of August 1999 earthquake. Beginning with the AD 1453 conquest of İstanbul, the great amount of Muslim population in Gölcük, İzmit and İznik migrated, these settlements became almost empty and lost their significance (Uzunçarşılı, 1999-2003). When considering the Cretaceous limestones as the basement of the northern part of the İzmit Gulf, the reason of the low damage during August 1999 earthquakes can be easily understood. The population of the settlements, geology of the regions, regional immigration and military activities should be carefully examined in the analysis of historical records. In some cases, there might be lack of data about the earthquakes in a region or the settlements may have been abandoned completely after an earthquake. These issues should be also taken into account. Sometimes a city might be completely destroyed after an earthquake. As an example, Hellenopolis, which was situated on the Hersek Delta and renamed by Constantine after her mother's death around AD 330, was heavily damaged by the AD 553 earthquake and almost completely destroyed by the AD 740 earthquake. The ruins are still observed on the Hersek Delta and along the eastern coast. The examples above are only a few problems while examining the earthquakes. In this context, the historical earthquake literature of Marmara Region presents valuable information only if it can be analysed carefully. The historical earthquakes examined in this study can answer many questions. The studies that compare historical earthquakes with the Marmara Sea fault system and present a projection about next earthquake(s) should also explain where and when the historical earthquakes occurred. Very few researches exist in the earth sciences literature and the historical earthquake publications are not examined in detail. The studies that give random references spark a debate about the historical earthquakes and their periods, and cause the perplexity when the researchers try to refer them.

In this study, all of the 16th century earthquakes have been revised and a new approach regarding which of these earthquakes had happened on the fault segments of Marmara Sea was suggested. The continuities of the earthquakes which were felt and/or caused damage in the cities around the Marmara Sea between 4th and 20th centuries have been compiled from the earthquake records and catalogues. (Pınar and Lahn, 1952; Şehsuvarlıoğlı, 1955; Engin et al., 1967; Guidoboni et al., 1994; Ambraseys and Finkel, 1995; Ambraseys and Jackson, 1998, 2000; Zachariadou, 2001; Guidoboni and Comanstri, 2005; Ambraseys, 2009).

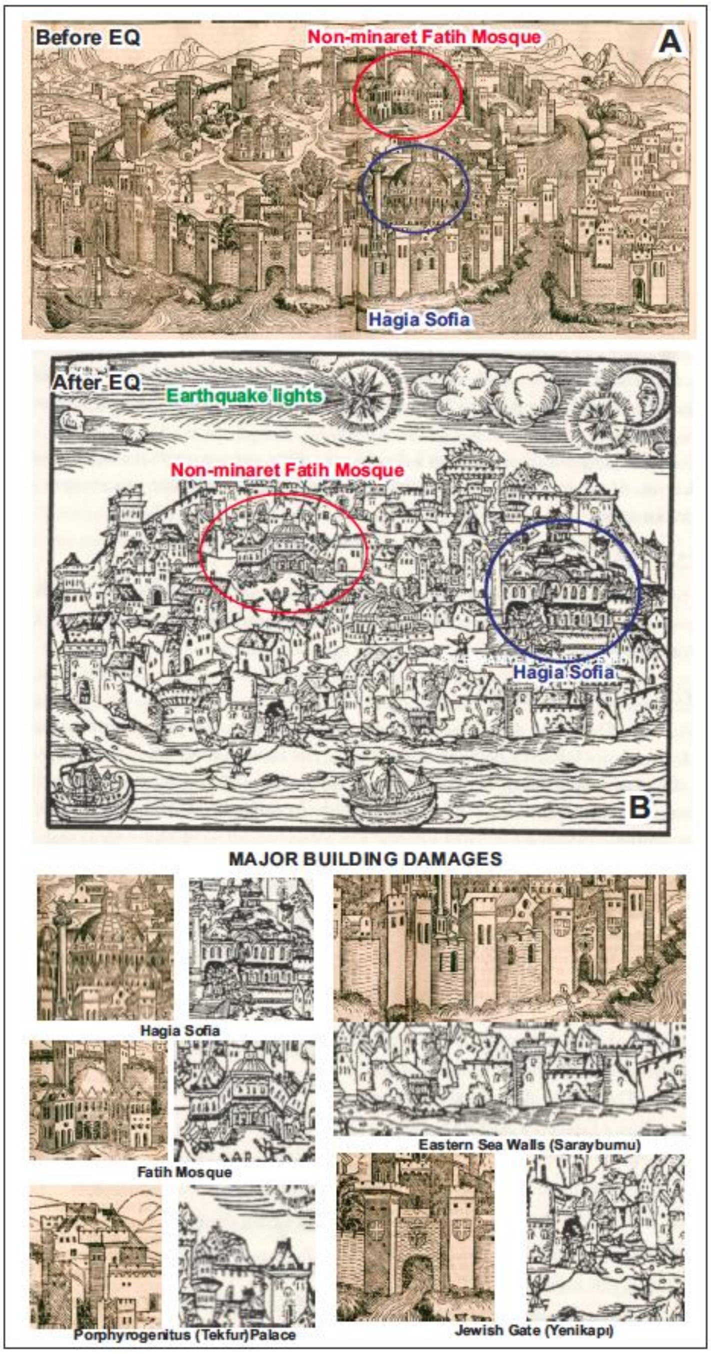


Figure 2. *There are crucial data in between gravure which is asserted by Ambraseys and Finkel (1995) to show AD 1556 earthquake (a) and same characteristics another gravure which is dated 1493 (b) (Schedel, 1493) for the comparison of earthquake damages. The most important damages at the Fatih mosque, Tekfur Palace and Hagia Sophia. Süleymaniye mosque was built between in 1551-1557 but it isn't in this gravures. Especially Fatih mosque was rebuilt in 1510 with two minarets. This gravure shows 1509 earthquake because the important clue is Fatih mosque has small dome without minarets built by Atik Sinan.*

Materials and Methods

In this study we present the generating of the Modified Mercalli Intensity maps of the great earthquakes in Marmara region for the past 1500 years which are assessed in this article. MTA 1:500.000 scaled digital geological maps are used to generate the Modified Mercalli Intensity (MMI) maps. We assign the shear-wave velocity values to the geological units according to their physical condition and lithological characteristics by using the Turkish Seismic Code soil and site classifications (Kalkan and Gülkan, 2004a). After that, we digitize the active faults of the Marmara region according to Armijo et al. (2005), Pichon et al. (2001) and Yaltırak (2002). The calculation and modelling of the MMI maps are made by using each active fault maps. Previous studies were evaluated for calculation of the g acceleration and MMI values such as for the attenuation relationships of Boore et al. (1993), Boore et al (1997), Akkar and Boomer (2010), Kalkan and Gülkan (2004a) and Ulusay et al. (2004) and for the MMI values Wald et al. (1999), Arioglu et al. (2001), Tselentis and Danciu (2008), Faenza and Michelini (2010) and Bilal and Askan (2010). In this study we used the Boore et al. (1993 and 1997) attenuation equation for calculations of the g acceleration because the other equations don't work for the far distances or generate huge errors in the important areas. In order to calculate the MMI values we used the PGA-MMI equation of Bilal and Askan (2010). ESRI ArcGIS 10.2 was used for all calculations to generate the value of an individual cell. The MMI data sets produced in ArcGIS 10.2 utilized to generate the images by using the Generic Mapping Tool (GMT).

Historical Earthquakes and Marmara Faults

Classifying Historical Earthquakes as felt by all or destructives

Considering the historical earthquake literature of Marmara region, there are two types of earthquakes. First-type is the earthquakes that cause to panic and are felt in a few centres but causes no reported damage. Second-type earthquakes, which devastate at least one settlement and cause damages in two or three settlements, lead to death, physical injury and epidemic illness. When examining the Marmara earthquakes during the past hundred years, the magnitudes of first-type earthquakes are between 5 and 6.9. There are 20 earthquake records in the sea from Saros Gulf to İzmit Gulf. Three earthquakes in Marmara Region that cause wide destruction and deaths are 1912 Mürefte Şarköy, 1953 □Yenice Gönen and 1999 Gölcük earthquakes. In Marmara Sea, the fault system is divided into three branches (Yaltırak, 2002).

When considering the historical earthquake records in the influence areas of these branches, there are 287 earthquakes in the ancient cities related to northern branch of North Anatolian Fault, which extends from İzmit Gulf to Saros Gulf, between A.D. 450 and 1912 (Appendix 1). Only 37 of these earthquakes damaged more than one settlement. There are 10 earthquake records along the middle branch which extends from İznik Lake to Gemlik and Bandırma gulfs and continues in the Biga Peninsula to Bababurnu (Appendix 2). These earthquakes only effected the ancient cities and the periodicity cannot be determined due to the deficiency of records. 123 Kyzikos, 368 İznik (Nikea), 460 Kyzikos, 1065 İznik (Nikea), 1737 Biga and 1855 Gemlik earthquakes are the unique earthquakes that cause destructions along this branch. The southern branch starts at the south of Bursa, in the Yenişehir Plain and continues through the south of Bursa, Manyas and Yenice-Gönen plains. Along this line, there are 22 recorded historical earthquakes

(Appendix 3). All these earthquake records belong to Ottoman Empire. Only the Bursa earthquakes have destructive damage records.

There is a significant relationship between the numerical distribution of historical earthquakes and GPS velocities that inform about the activities of recent fault branches. 329 recorded earthquakes in the Marmara region exist in literature. %86 of these earthquakes occurred on the northern branch, %7 occurred on the southern branch and %9 occurred on the middle branch. The distribution of GPS velocities in the area (23 mm/year) is %82 on the northern branch (18 mm/year), %13 on the southern branch (3 mm/year) and %9 on the middle branch (2 mm/year). As clearly seen, the relative distributions of the number of historical earthquakes and GPS vectors are similar. In this case, it is clearly understood that the most of the earthquakes had happened on the northern branch of the North Anatolian Fault Zone and these data can be used for the earthquake periodicity.

How is determined which earthquake on which fault ?

The earthquakes on the northern branch is a moot point because of the fact that the earthquake-generating parts are located in the sea. The best approach is to suggest the closest fault segment to the locations affected by earthquake. The best bet is to study on a historical map that show the cities in the catalogues (Figure 3). The first order of business is to write the destructive earthquake dates on the devastated cities and provide groups. In this study, all the earthquakes in the literature had been determined individually and the influence areas were marked in the map below (Figure 3). This type of grouping presents an amazing view. 38 destructive earthquakes from Saros Gulf to İzmit represent a distribution like that: Saros Gulf: 4, Gaziköy-Gelibolu: 6, Western Marmara: 6, Middle Marmara, 6: Eastern Marmara: 3, Southern Marmara 6, İzmit Bay: 7 including the 1999 earthquake (Figure 3). The vertical distance between the coast settlements, located from İzmit Gulf to Saros Gulf, and the major axis along the trenches of the Marmara Sea is 61 kilometres. When considering the east-west distribution of the earthquakes that affect these settlements, 37 earthquakes are grouped in 7 regions and the earthquakes migrate towards west (Figure 4). According to the influence areas, these earthquakes were classified as; Izmit Bay (A), Southern Marmara: Yalova-Tekirdağ (B), Eastern Marmara (C), Middle Marmara: Western Istanbul-Silivri (D), Western Marmara: Tekirdağ-Silivri-Bandırma (E), Gaziköy-Gölcük (F), Saros-Kavak (G) (Table1). Only three of them (Segment B) are defined as Southern Marmara Earthquakes and they have the widest influence areas (Figure 3, 4 and Table 1).

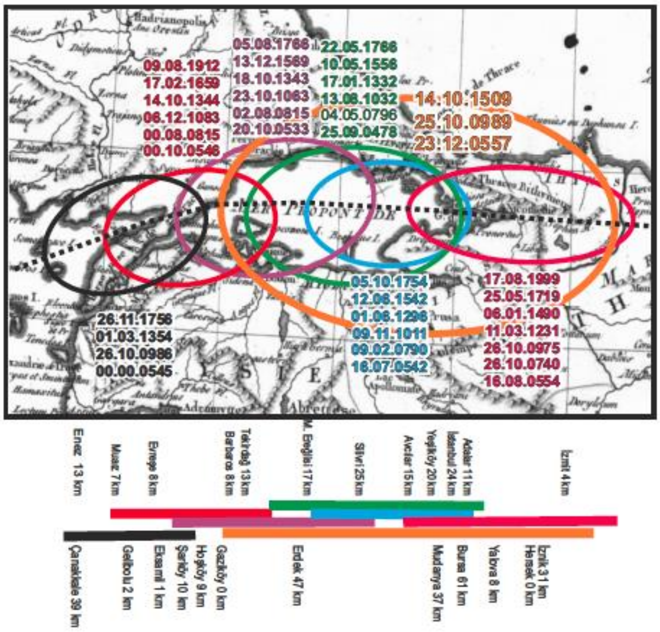


Figure 3. *Distribution of the historical earthquakes that destroy more than one settlement along the northern branch of North Anatolian Fault Zone. The earthquakes caused severe damage based on İstanbul are defined at the green, blue, and orange areas. Ellipses were drawn by considering the settlements affected by earthquakes. Colourful lines at the lower part of the image show the distance of the settlement at east-west route and active part of the segment which is in the middle of the Marmara Sea. Historical earthquakes were collected from catalogues at the appendix.*

The most remarkable side of the historical earthquakes is the intersection of the regional historical earthquake groups (Figure 4). This means that some settlements can be damaged, even destroyed two or three times by the earthquakes that occur one after another in very short time periods (such as 1999 Earthquakes). The distribution of the historical earthquakes in the Marmara Sea without a fault map and the time relationships are clearly seen when drawing small circles (Figure 3). Although some of the earthquakes occurred in the western side of Marmara region are reputed to migrate eastward, this is a famous illusion. If we have a feeling that a motion is going to an opposite direction instead of a direction, the reason is the phase shifting. The longer periodicity of the F and G ellipses compared to the middle part (Figure 4) causes these shifts. Within this framework, the term of periodicity is a problem that should be examined not only for a group but also for each segment.

As seen in Figure 4, each earthquake ellipses indicate the earthquakes that are individually periodic, have influence areas overlapping with the adjacent areas (Figure 3 and 4) and migrate westward continuously. The intersection of earthquake influence area and the sequent earthquakes have been known since 1939 along North Anatolian Fault. During the field studies, it was observed that the decreasing slip rates towards the end of the segments overlapped during 1999 Gölcük and Düzce earthquakes (Akyüz et al., 2002). The most interesting part of the figure above is that the periodicity of each earthquake ellipse and its influence area are different from each other, and among them, only earthquakes of group B can damage 3 or more settlements and its periodicity is 2 times bigger than the others. The most valuable information to be obtained from this situation is that the earthquakes can display the segments, periodicities and triggering along a fault zone without a fault model. As seen on the table prepared to understand the earthquake periodicity (Table 1), each ellipse has an individual periodicity. In most of the studies about the historical earthquakes, the earthquake periodicity of İstanbul conflicts with the periodicity of the fault segment. Considering the 15 destructive earthquakes in İstanbul (B, C and D ellipses), only three earthquakes with a 450-year periodicity were fatal earthquakes in the last 1600 years. The periodicity of the others is 250 years. These 15 earthquakes indicate that the recent fault maps cannot explain how the destructive earthquakes frequently occur along a line of 150 km in Marmara region.

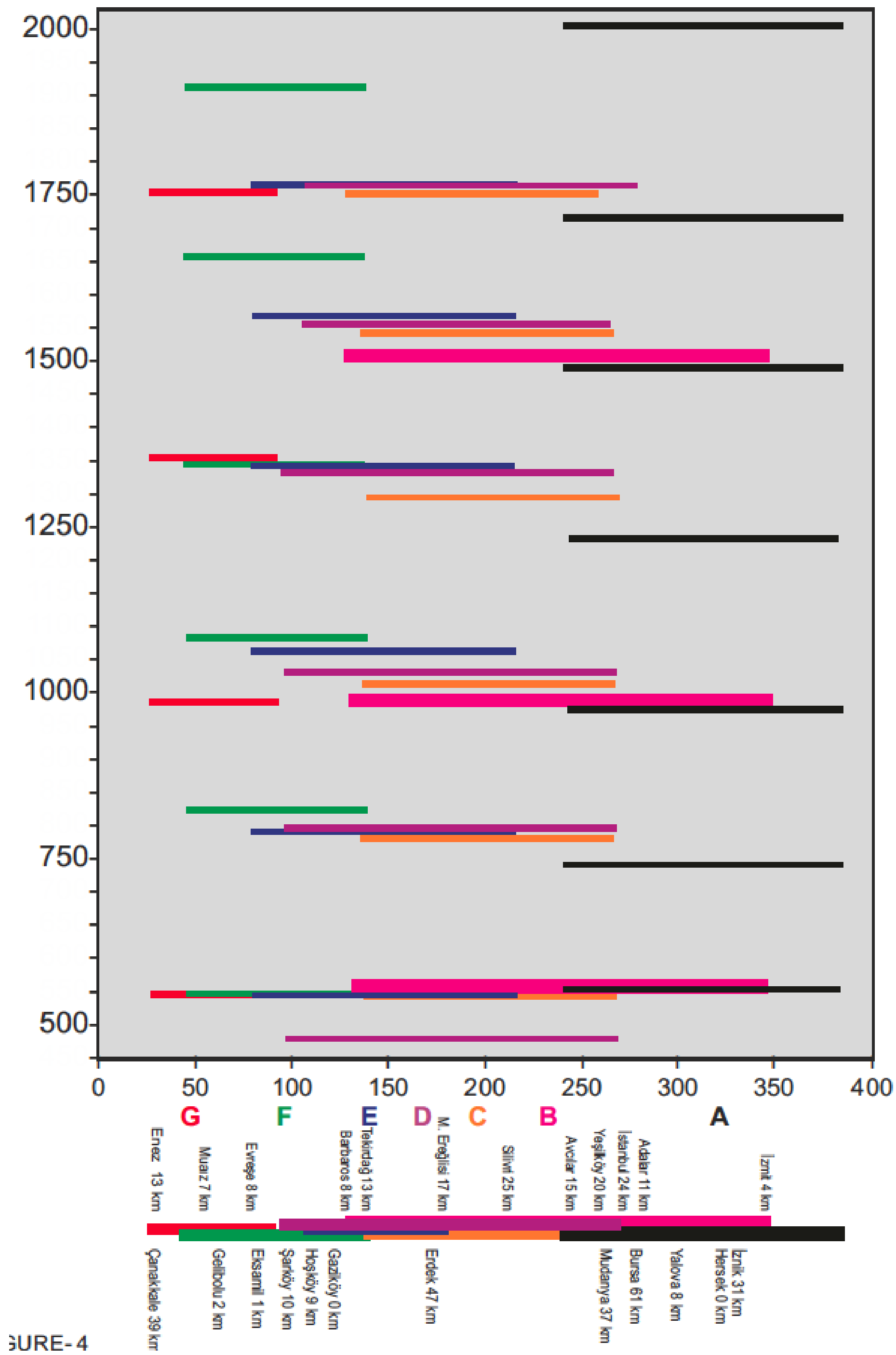


Figure 4. *Regional distribution and migration of destructive earthquakes along a line detected on the area where Marmara earthquakes were assumed to occur on the northern branch of the North Anatolian Fault*

Table 1. *Historical destructed earthquakes separation and periods of the Marmara Region*

EQ CLUSTER CLUSTER NAME	SAROZ GELİBOLU G	GELİBOLU GAZİKÖY F	TEKİRDAĞ MARMARA ISLAND E	MARMARA EREĞLİSİ TEKİRDAĞ SİLİVRİ D	İSTANBUL DOĞUSU SİLİVRİ C	TEKİRDAĞ İSTANBUL İZMİT B	GULF OF İZMİT A
EQ YEAR	22xx	22xx	20xx	20xx	20xx	20xx	17 08 1999
CONTINUUM	259	103	249	249	261	506	280
EQ YEAR		09 08 1912	05 08 1766	22 05 1766	05 10 1754		25 05 1719
CONTINUUM		253	197	210	212		229
EQ YEAR	26.11.1756	17 02 1659	13 12 1569	10 05 1556	12 06 1542	14 10 1509	06.01.1490
CONTINUUM	402	315	225	224	246		259
EQ YEAR	01 03 1354	14 10 1344	18 10 1343	17 01 1332	01 06 1296		11.03.1231
CONTINUUM	368	261	281	300	285	520	256
EQ YEAR		6 12 1083	23 10 1063	13 08 1032	09 11 1011	25 10 989	26 10 975
CONTINUUM		258	273	236	231		235
EQ YEAR	26 10 986	05 05 824	09 02 790	04 05 796	17 03 780		26 10 740
CONTINUUM	441	278	247	318	238	432	187
EQ YEAR	00 00 545	00 00 546	06 09 543	25 09 478	16 07 542	23 12 557	15 08 553
REPETATION AVARAGE	*403±42 yr Deviation%10*	*278±41yr Deviation %14*	*244±40 yr Deviation %16*	*257±40 yr Deviation %15*	*242±40 yr Deviation %16*	*476±44 yr Deviation %10*	*249±30 yr Deviation %12*

Fault Maps (Models) and Historical Earthquake Clusters

The fault maps in the Marmara Sea studies can be divided into three groups. In this study, three different group of fault maps have been examined in ArcGIS 10 database to create a scenario by using the recent topographic and bathymetric data. The first of these groups is single fault model (Okay et al. 2000; Le Pichon et al., 2001; Imren et al., 2001), second is pull-apart basin model by Armijo et al. (2001 and 2003) and third is negative flower structure in the form of horsetail (Yaltırak, 2002). There are 4 main segments in the first system. These segments differ by their lengths. According to Le Pichon et al. (2001) and Imren et al. (2001), İzmit segment is 140 km (A), Western Marmara-Princes Islands Fault is 160 km (B+C+D+E) and Gazik□y-Saros segment is 120 km (F+G) along the northern branch of North Anatolian Fault (Figure 5). According to Armijo et al. (2003), İzmit segment is 140 km (A), Princes Islands Fault is 40 km (B), Western Marmara Fault is 70 km (C+D) and Gaziköy-Saros segment is 150 km (E+F+G) (Figure 6). According to the active fault map produced from the shallow seismic studies, Yaltırak (2002) suggested that the models have more complicated faults and there is a segmentation composed of strike-slip faults in the form of horsetail. In accordance with this segmentation, İzmit segment is 120 km (A), Eastern Marmara Fault is 97 km(B), western side of the eastern ridge is 34 km (C), northern fault of middle ridge is 65 km (D), Western Marmara Fault is 80 km (E), Ganos Fault is 56 km (F) and Eastern Saros Fault is 48 km (G) (Figure 7).

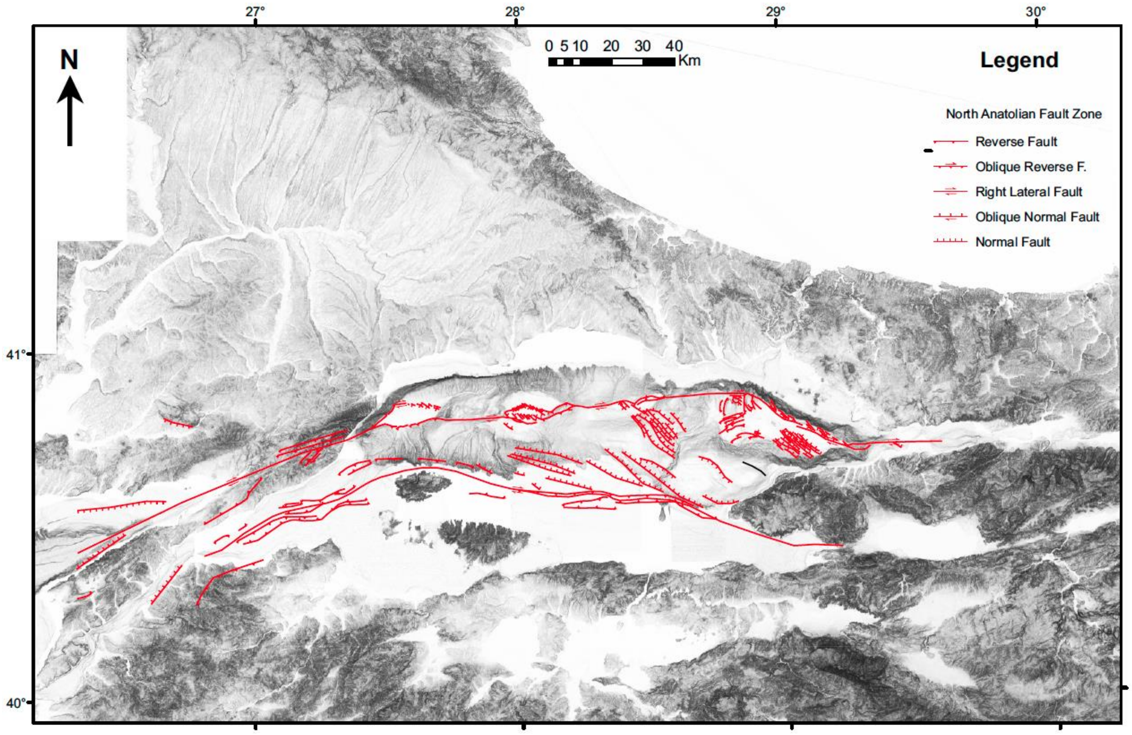


***Figure 5**. Single Marmara Fault Pattern (Le Pichon et al 2001)*

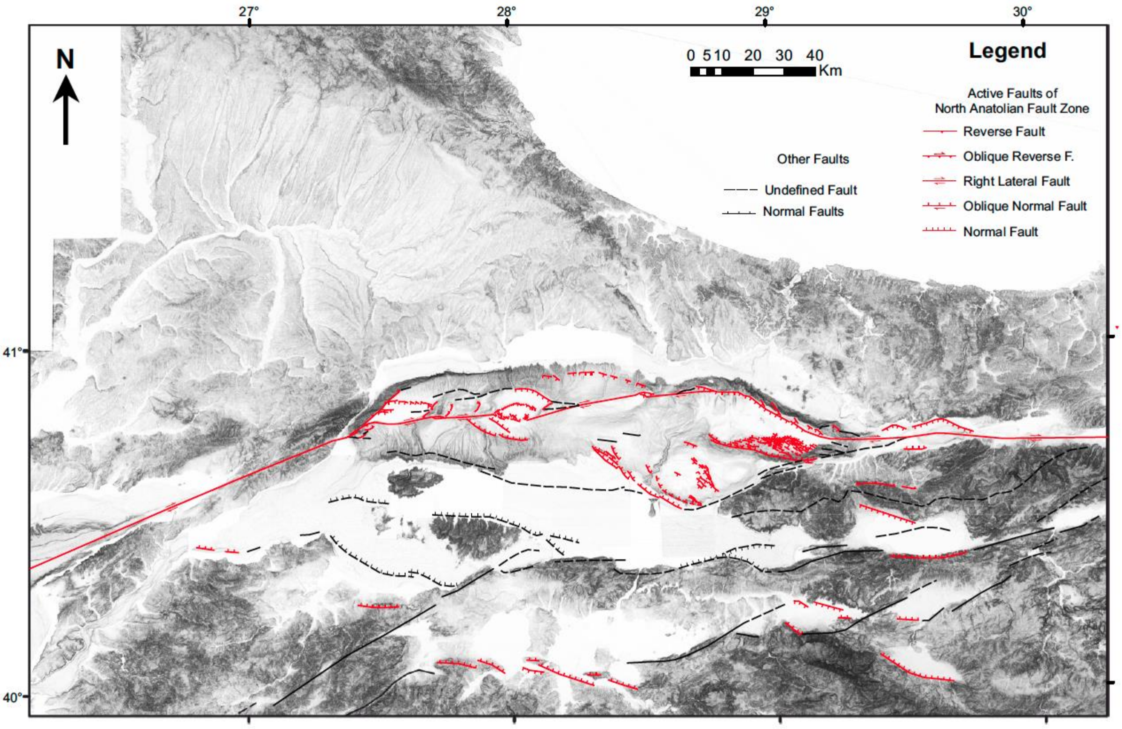


Figure 6. *Pull-Apart Marmara Fault Pattern (Armijo et al. 2002;2005)*

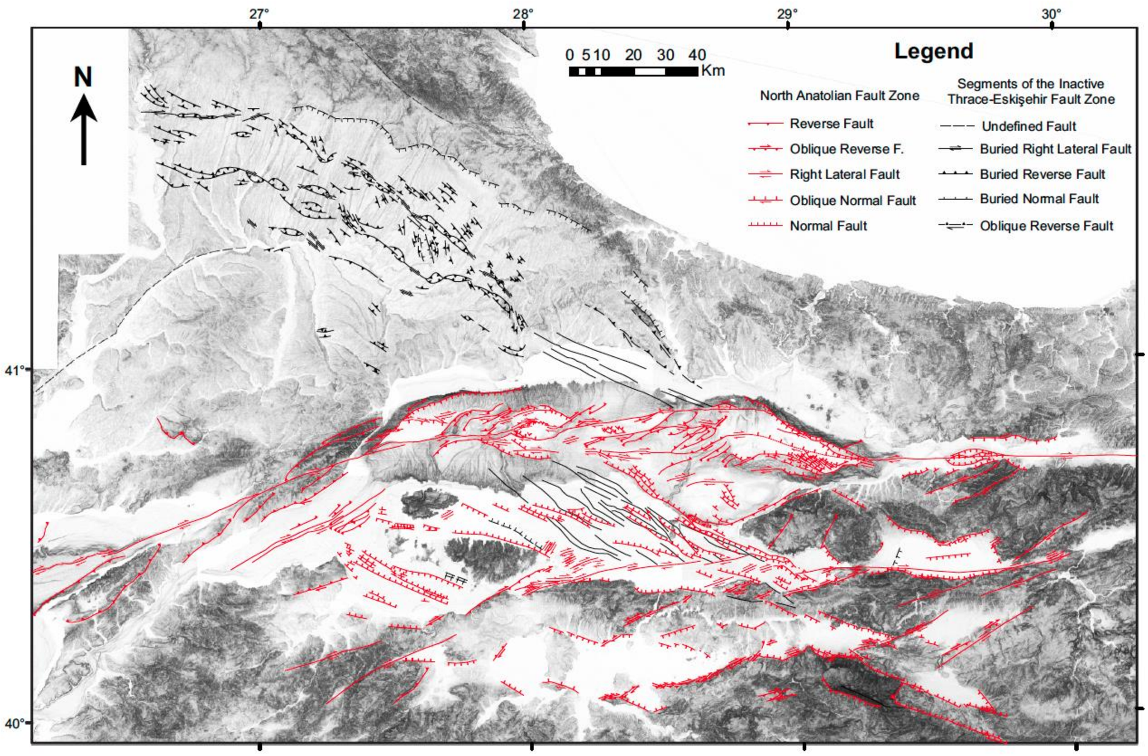


Figure 7. *Horsetail Structure Marmara Fault Pattern (Yaltırak, 2002; 2015)*

The derivatives of these three main models were published and all were examined by using historical earthquake scenarios. It is possible to divide the historical earthquakes into the segments of these three models considering the influence areas and identify the magnitudes of historical earthquakes for each. Under this circumstances, the all of the 38 destructive earthquakes should be compatible with a fault model and so it will be easy to interpret the periodicity and magnitude of the earthquakes in the future.

In this study, when grouping these earthquakes according to each model individually, it is seen that 21 destructive earthquakes occurred on a fault in the single fault model (Figure 8A). There is a time difference of a few years or a few months between these earthquakes. Therefore, all the earthquakes cannot be destructive (Table 2). Only the 8 of 21 earthquakes might be destructive and also it would be impossible for 13 earthquakes to be destructive. The method used here is the moment magnitude calculation by considering the fault lengths, total slip rates per year and depth of seismogenic zone. The similar situation is observed in the fault segmentation model (Figure 8B) of Armijo et al. (2001, 2003) (Table 3). When taking into consideration of this model, the recorded destructive earthquakes, such as 1766 earthquake, are not destructive. In this case, it is a doubt that the destructive earthquakes have short-time periodicity and damage the same region. In addition to that considering both the single fault model and pull-apart model, the earthquakes that damage an unique region according to only one of these models require to examine the all fault models in the literature. The historical earthquakes groups are in accordant with the fault segmentation model of Yaltırak (2002) (Figure 8C, Table 4). The segments and historical earthquake groups overlap and these earthquakes verify the earthquake magnitudes calculated by using the total accumulation.

Table 2. *Single Fault segments (Okay et al., 2000; Le Pichon et al., 2001; İmren et al., 2001) and historical earthquake scenarios magnitudes. Red colour sows destructed earthquakes*

Main Marmara Fault (B+C+D+E)

EQ	L (m)	W (m)	displacement D	M0	Mw
478	208000	12000		0	#NUM!
542	208000	12000	1,152	8,63E+19	7,29
543	208000	12000	0,018	1,35E+18	6,08
557	208000	12000	0,252	1,89E+19	6,85
780	208000	12000	4,014	3,01E+20	7,65
790	208000	12000	0,18	1,35E+19	6,75
796	208000	12000	0,108	8,09E+18	6,60
989	208000	12000	3,474	2,6E+20	7,61
1011	208000	12000	0,396	2,97E+19	6,98
1032	208000	12000	0,378	2,83E+19	6,96
1063	208000	12000	0,558	4,18E+19	7,08
1296	208000	12000	4,194	3,14E+20	7,66
1332	208000	12000	0,648	4,85E+19	7,12
1344	208000	12000	0,198	1,48E+19	6,78
1509	208000	12000	2,988	2,24E+20	7,56
1542	208000	12000	0,594	4,45E+19	7,09
1556	208000	12000	0,252	1,89E+19	6,85
1569	208000	12000	0,234	1,75E+19	6,82
1754	208000	12000	3,33	2,49E+20	7,59
1766	208000	12000	0,216	1,62E+19	6,80
1766	208000	12000	0,018	1,35E+18	6,08
Ganos (F+G)					
824	182000	15000	5,022	4,11E+20	7,74
986	182000	15000	2,916	2,39E+20	7,58
1083	182000	15000	1,746	1,43E+20	7,43
1344	182000	15000	4,698	3,85E+20	7,72
1354	182000	15000	0,18	1,47E+19	6,77
1659	182000	15000	5,49	4,5E+20	7,76
1756	182000	15000	1,746	1,43E+20	7,43
1912	182000	15000	2,808	2,3E+20	7,54

Table 3. *Pull-Apart Fault segments (Armijo et al., 2002 and 2005) and historical earthquake scenarios magnitudes. Red colour sows destructed earthquakes*

C+D						E+F+G					
EQ	L (m)	W (m)	Displacement D (m)	M0	Mw	EQ	L (m)	W (m)	Displacement D (m)	M0	Mw
1766	60000	12000	0.22	4.75E+18	6.45	1912	140000	15000	2.77	1.75E+20	7.49
1754	60000	12000	3.76	8.12E+19	7.27	1766	140000	15000	0.19	1.2E+19	6.72
1556	60000	12000	0.26	5.62E+18	6.50	1756	140000	15000	1.83	1.15E+20	7.37
1542	60000	12000	3.9	8.42E+19	7.28	1659	140000	15000	1.7	1.07E+20	7.35
1332	60000	12000	0.19	4.1E+18	6.41	1569	140000	15000	4.08	2.57E+20	7.61
1296	60000	12000	5.56	1.2E+20	7.39	1354	140000	15000	0.19	1.2E+19	6.72
1032	60000	12000	0.2	4.32E+18	6.42	1344	140000	15000	0.001	6.3E+16	5.20
1011	60000	12000	4.08	8.81E+19	7.30	1343	140000	15000	4.95	3.12E+20	7.66
796	60000	12000	0.3	6.48E+18	6.54	1083	140000	15000	0.38	2.39E+19	6.92
780	60000	12000	4.55	9.83E+19	7.33	1063	140000	15000	1.43	9.01E+19	7.30
542	60000	12000	1.26	2.72E+19	6.96	986	140000	15000	1.84	1.16E+20	7.38
478	60000	12000	0			824	140000	15000	0.64	4.03E+19	7.07
						790	140000	15000	4.63	2.92E+20	7.64
						546	140000	15000	0.019	1.2E+18	6.05
						545	140000	15000	0.38	2.39E+19	6.92

Table 4. *Horsetail Structure Fault segments (Yaltirak, 2002 and 2015) and historical earthquake scenarios magnitudes.*

G SAROZ F. 52 Km. Yr I meter I Mw	F GANOS F. 60 Km. Yr I meter I Mw	E WESTERN MARMARA F. 74 Km. Yr I meter I Mw	D MID RIDGE NORTH FAULT 93 Km. Yr I meter I Mw	C EASTERN RIDGE NORTHERN F. 42 Km. Yr I meter I Mw	B EASTERN MARMARA F. 110 Km. Yr I meter I Mw	A GÖLCÜK FAULT 100 Km. Yr I meter I Mw
2015	2015	2015	2015	2015	2015	17.08.1999
259 I 4.6 I 7.29	103 I 1.8 I 7.01	249 I 4.5 I 7.33	249 I 4.5 I 7.40	261 I 4.6 I 7.15	506 I 9 I 7.65	280 I 5 I 7.45
26.11.1756	09.08.1912	05.08.1766	22.05.1766	05.10.1754		25.05.1719
	253 I 4.5 I 7.27	197 I 3.5 I 7.26	210 I 3.8 I 7.35	212 I 3.8 I 7.12		229 I 4.1 I 7.39
402 I 7.2 I 7.42	17.02.1659	13.12.1569	10.05.1556	12.06.1542	14.10.1509	06.01.1490
	315 I 7.2 I 7.41	225 I 4 I 7.30	224 I 4 I 7.37	246 I 4.4I 7.16		259 I 4.6I 7.43
01.03.1354	14.10.1344	18.10.1343	17.01.1332	01.06.1296	520 I 9.3 I 7.66	11.03.1231
	261 I 4.6 I 7.28	281 I 5 I 7.36	300 I 5.4 I 7.45	285 I5.1 I 7.21		256 I 4.8 I 7.44
368 I 6.6 I 7.39	06.12.1083	23.10.1063	13.08.1032	09.11.1011	25.10.0989	26.10.0975
	258 I 5 I 7.30	273 I 4.9 I 7.36	236 I 4.3 I 7.38	231 I 4.2 I 7.15		235 I 4.2I 7.40
26.10.0986	05.05.0824	09.02.0790	04.05.0796	17.03.0780	432 I 7.7 I 7.6	26.10.0740
441 I 7.9 I 7.45	278 I 5 I 7.30	247 I 4.5 I 7.33	318 I 4.5 I 7.40	238 I 4.3 I 7.16		187 I 3.3 I 7.33
00.00.0545	04.08.0546	06.09.0543	25.09.0478	16.07.0542	23.12.0557	15.08.0553

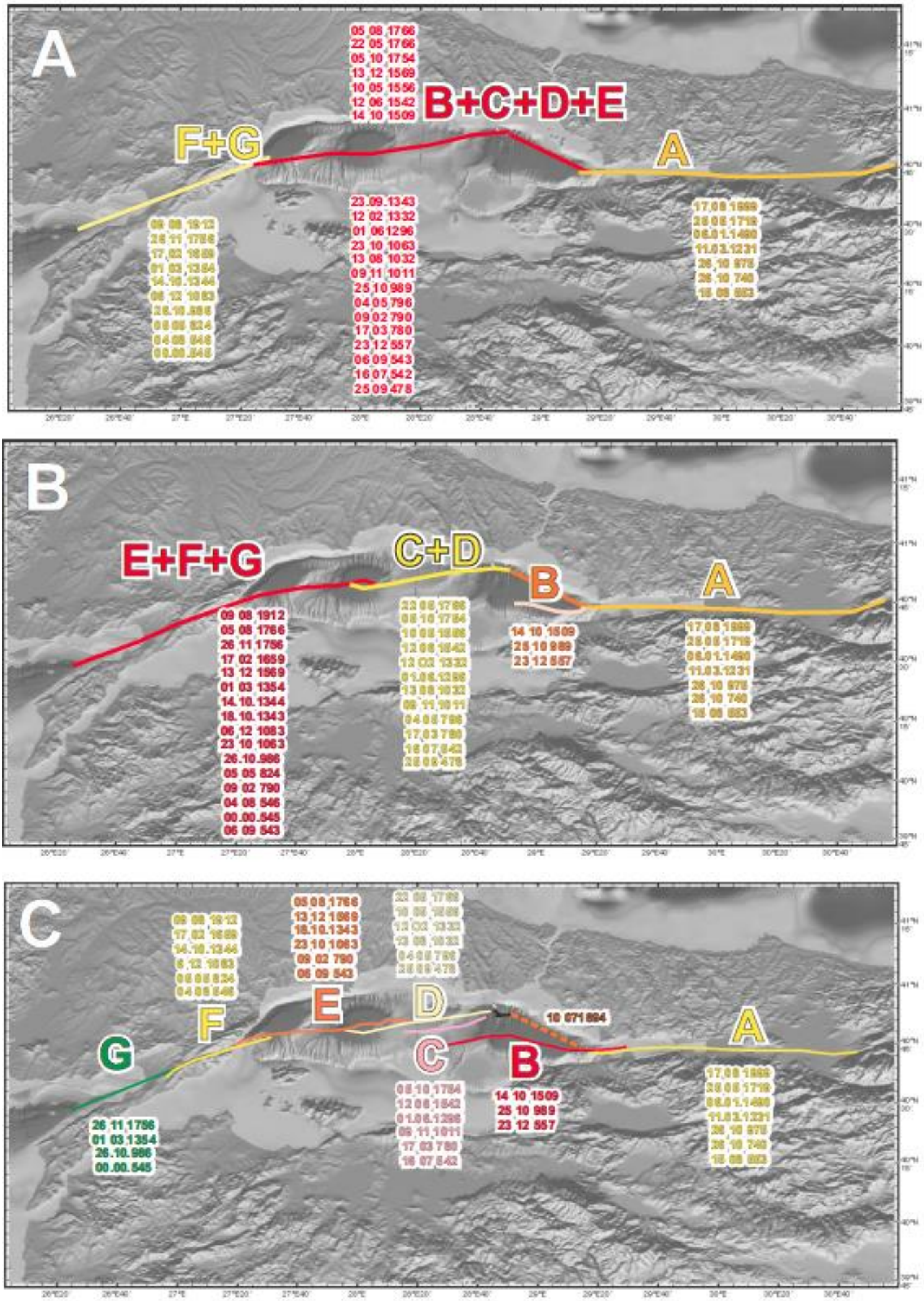


Figure 8. A: *Single Fault Model Historical Earthquake Clusters,* ***B*** *Pull-Apart Fault Model Historical Earthquake Clusters,* ***C:*** *Horsetail Structure Marmara Fault Pattern Historical Earthquake Clusters*

Historical Earthquake Scenarios

It is possible to generate three groups of scenario for 38 destructive earthquakes which are thought to be occurred along the northern branch of the North Anatolian Fault in the Marmara region. These scenarios were prepared as two different resolutions. The regional scenarios were prepared related to the ground properties of the Marmara Sea and surrounding area and V_s30 values are designated for 750x750m grids (Figure 9). The other scenario was prepared for the historical İstanbul peninsula. 250x250m grids were generated by using 1:25000-scale digital elevation model, geological map and V_s30 values measured by İstanbul Metropolitan Municipality (Figure 10) (İstanbul Metropolitan Municipality, 2007). The damages of 38 earthquakes were compared with the intensity values obtained from the scenarios. Thus the historical damage can compare with the scenarios created from magnitude calculations related to fault patterns. For this purpose, the important historical constructions of İstanbul added to the maps and a list was presented as appendix (Appendix 4).

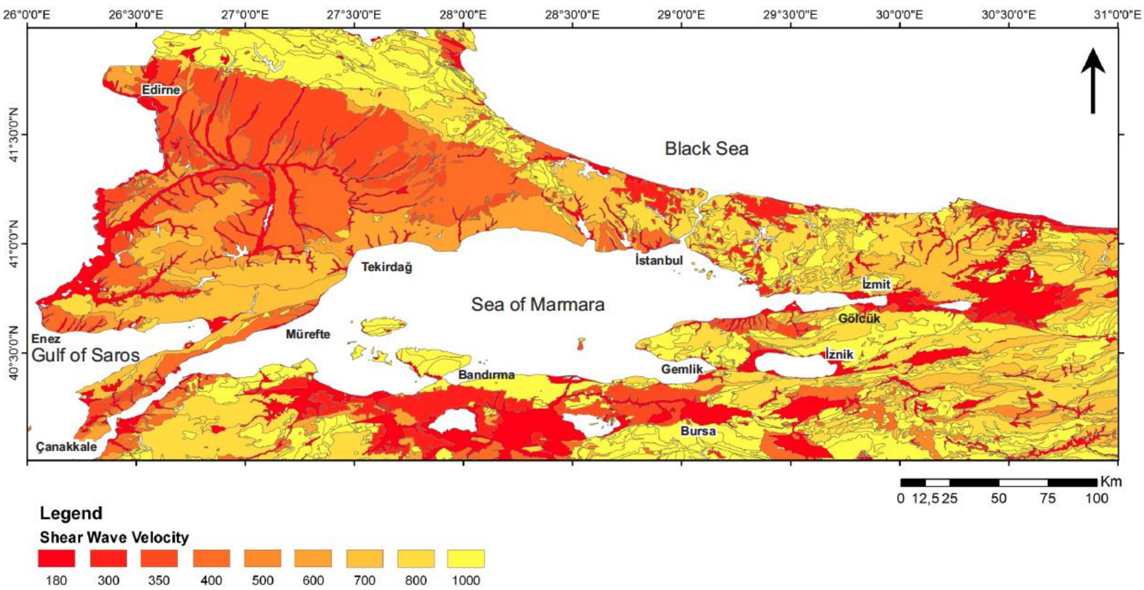


Figure 9. *Marmara region Vs 30 map from calculated lithological formations. Base map from MTA 1/500000 scale geological map.*

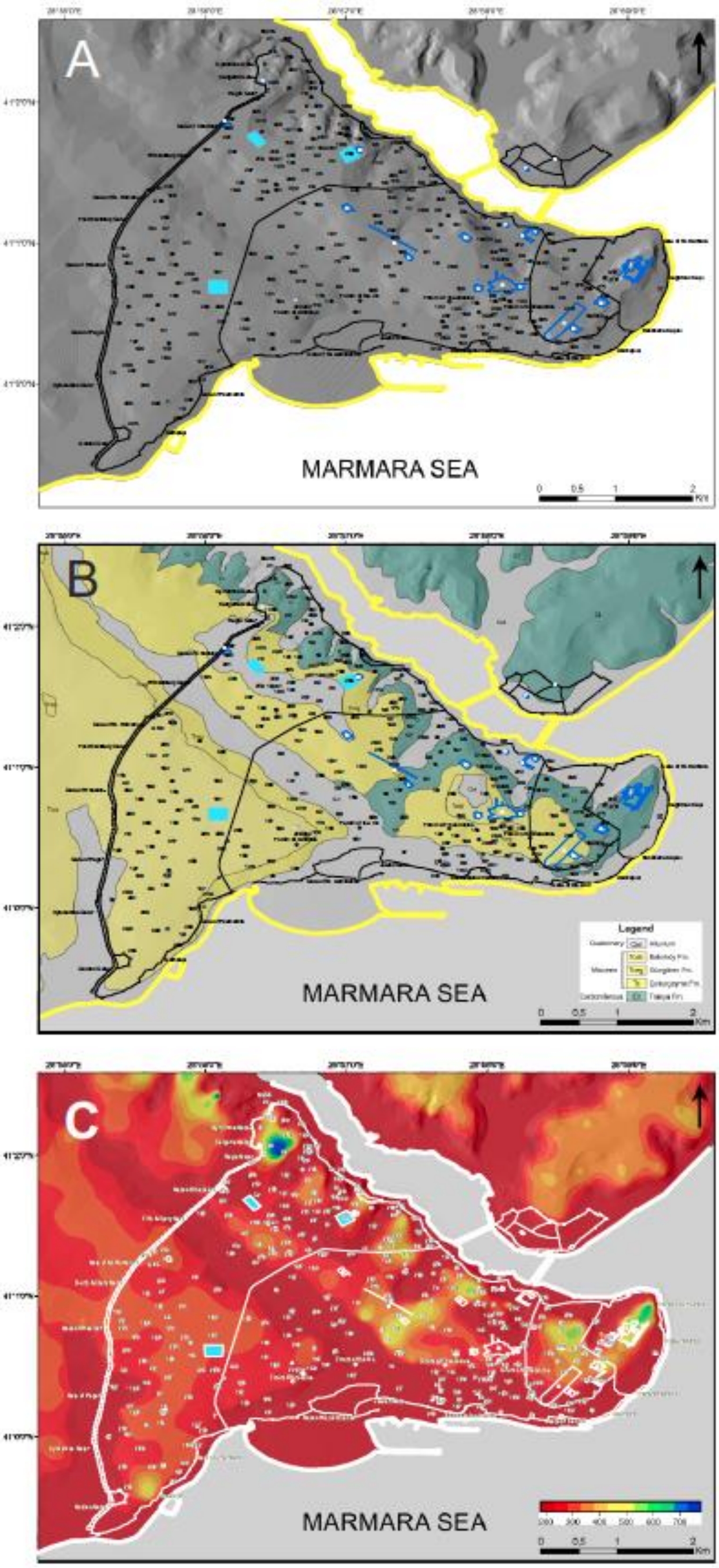


Figure 10. *Historical city plan (a) Geological map of historical peninsula (b) Vs30 map of the city (IBB, 2007)*

Marmara Region EQ Scenarios

The characteristics and lengths of the faults in Marmara Sea show differences from study to study. Therefore, three models were generated for each segment by using the geological properties and historical earthquakes. There is no earthquake suggestion for the segment A except of Yaltırak (2015). The researchers whose models will be examined (Okay et al., 2000; Le Pichon et al., 2001; İmren et al., 2001; Armijo et al., 2001, 2003) have no suggestion about the historical earthquakes. There are only trench studies on the fault causing the 17th August 1999 Earthquake. Yaltırak (2015) suggested a view base on earthquake catalogues and history books in the matter of the earthquake periodicity on this segment. According to Yaltırak (2015), 553, 740, 976, 1231, 1490 and 1999 earthquakes occurred along the segment A since 5th century. There are very few data about 1231 and 1490 earthquakes in the literature. Dikbaş and Akyüz (2010) indicate an earthquake between 1200 and 1300. This is probably the 1231 earthquake. Also, Dikbaş and Akyüz (2010) assert that they have discovered the 989 earthquake. But it is reported in the historical sources that this 10 earthquake was effective from İzmit to Tekirdağ and the most damage was observed in İstanbul (Appendix 1). This area is quite similar to the area affected by 1509 earthquake and bigger than the damage area of 1999 earthquake. This earthquake is most probably the 976 earthquake which is mentioned in the limited number of Turkish sources and affected İstanbul, İzmit and Southern Marmara (Sakin, 2002). 1509 earthquake is also suggested as another earthquake. Considering the similarity of the damage area of 9th January 1489/90 earthquake with 1999 earthquake, this earthquake is most probably another lesser known 1498 earthquake (Sakin, 2002; Sancaklı, 2004). In the period the earthquake occurred, the great majority of the people in Gölcük and İzmit had migrated to İstanbul because of the conquest of

İstanbul. Therefore, both two settlements became smaller and lost their importance. With reference to GPS models, the accumulation on the İzmit segment is around 18-19 mm/year (Ergintay et al., 2014). Accordingly, the slip rates and magnitudes calculated on this segment (Table 4) show similarity to the recent. The MMI maps are in accordance with the historical earthquakes for our scenario (Table 4, Figure 11). Also, a MMI map was generated in order to compare the 1999 İzmit earthquake with today. The periodicity of this segment is 240±30 years and the magnitude of the earthquakes occured along this segment is approximately Mw 7.39±0.06 (Table 4).

Table 4. *Horsetail Structure Fault segments (Yaltirak, 2002 and 2015) and historical earthquake scenarios magnitudes.*

G SAROZ F. 52 Km. Yr I meter I Mw	F GANOS F. 60 Km. Yr I meter I Mw	E WESTERN MARMARA F. 74 Km. Yr I meter I Mw	D MID RIDGE NORTH FAULT 93 Km. Yr I meter I Mw	C EASTERN RIDGE NORTHERN F. 42 Km. Yr I meter I Mw	B EASTERN MARMARA F. 110 Km. Yr I meter I Mw	A GÖLCÜK FAULT 100 Km. Yr I meter I Mw
2015	2015	2015	2015	2015	2015	17.08.1999
259 I 4.6 I 7.29	103 I 1.8 I 7.01	249 I 4.5 I 7.33	249 I 4.5 I 7.40	261 I 4.6 I 7.15	506 I 9 I 7.65	280 I 5 I 7.45
26.11.1756	09.08.1912	05.08.1766	22.05.1766	05.10.1754		25.05.1719
	253 I 4.5 I 7.27	197 I 3.5 I 7.26	210 I 3.8 I 7.35	212 I 3.8 I 7.12		229 I 4.1 I 7.39
402 I 7.2 I 7.42	17.02.1659	13.12.1569	10.05.1556	12.06.1542	14.10.1509	06.01.1490
	315 I 7.2 I 7.41	225 I 4 I 7.30	224 I 4 I 7.37	246 I 4.4I 7.16		259 I 4.6I 7.43
01.03.1354	14.10.1344	18.10.1343	17.01.1332	01.06.1296	520 I 9.3 I 7.66	11.03.1231
	261 I 4.6 I 7.28	281 I 5 I 7.36	300 I 5.4 I 7.45	285 I5.1 I 7.21		256 I 4.8 I 7.44
368 I 6.6 I 7.39	06.12.1083	23.10.1063	13.08.1032	09.11.1011	25.10.0989	26.10.0975
	258 I 5 I 7.30	273 I 4.9 I 7.36	236 I 4.3 I 7.38	231 I 4.2 I 7.15		235 I 4.2I 7.40
26.10.0986	05.05.0824	09.02.0790	04.05.0796	17.03.0780	432 I 7.7 I 7.6	26.10.0740
441 I 7.9 I 7.45	278 I 5 I 7.30	247 I 4.5 I 7.33	318 I 4.5 I 7.40	238 I 4.3 I 7.16		187 I 3.3 I 7.33
00.00.0545	04.08.0546	06.09.0543	25.09.0478	16.07.0542	23.12.0557	15.08.0553

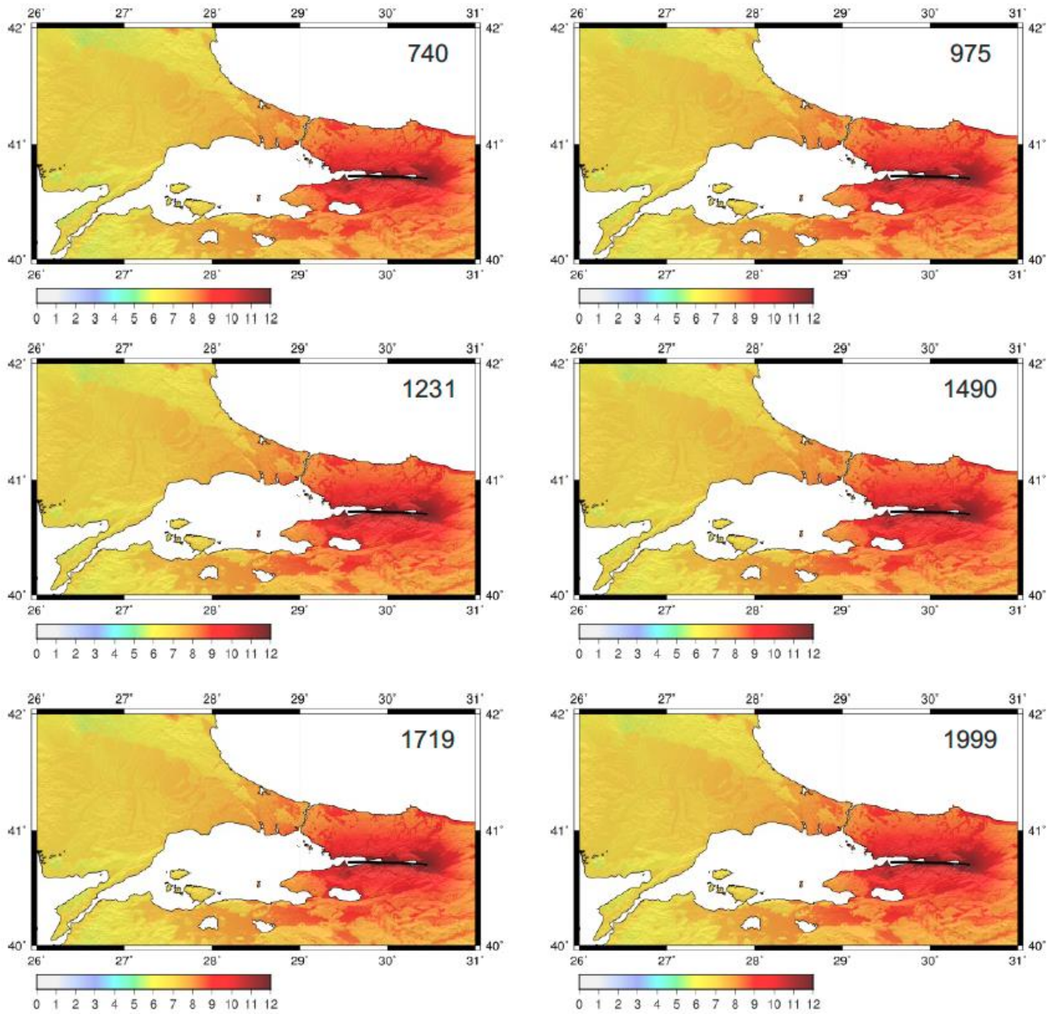


Figure 11. *Historical intensity map of the İzmit Segment.*

Single Fault Structure (Le Pichon et al., 2001)

According to single fault model, the fault ruptured till Prince Islands Fault in 1999 Izmit Earthquake (Le Pichon et al., 2001). The authors suggest that the 1509 earthquake occurred on the western side of this segment as a unique fault and the following earthquake will be occurred in the same way. Then, the historical earthquake clusters B+C+D+E (see Figure 3, 4 and 8a) are the influence area of this segment (Figure 5 and 8a). In that study, there are 21 earthquakes that caused damaged more than one settlement in the literature. The MMI maps of these earthquakes indicate that the influence areas of these earthquakes are not compatible with the historical data (Figure 12 and 13). Only five earthquakes (780, 989, 1296, 1509, 1754 earthquakes) have a magnitude of >Mw 7.6 in the Marmara region (Table 2). In this case, the total accumulation calculated from the average GPS velocities show that the magnitudes of 557, 1032, 1556 and 1766 earthquakes are smaller than Mw 7 (Table 2). When examining the single fault model, only 5 of the 21 earthquakes could be destructive. Especially when considering the damage of 1754 earthquake in İstanbul, the two earthquakes in 1766 are not effective. However, the first earthquake of 1766 has higher intensity than 1754 earthquake (Appendix 1). If this segment ruptured in 1754 and caused damages between İstanbul and Marmara Ereğlisi, the magnitudes of 1766-1 and 1766-2 earthquakes should be Mw 6.8 and 6.08, respectively. Under the circumstances, it is not possible to make reference to any period of the single fault model and also the historical damage data would be 65% debatable. The accumulation along this segment is 18 mm/year. The segment ruptured between 209 and 307 as seen on the graph (Figure 14). The records of the destructive earthquakes should be examined (see Appendix 1). Another segment drawn by using single fault model is Ganos Fault. According to the scenario models generated by using the lengths of segment in the publications, three earthquakes occurred in western Marmara is bigger than Mw 7.7 (Table 2 and Figure 15). And also one of the most destructive earthquakes, 1354 earthquake must have the magnitude of Mw 6.7. Especially, the magnitude of Mw 7.54 calculated for 1912 earthquake is inconsistent with its damage on a wide area (Figure 15). In the first fault model, Main Marmara Fault cannot explain the historical earthquakes.

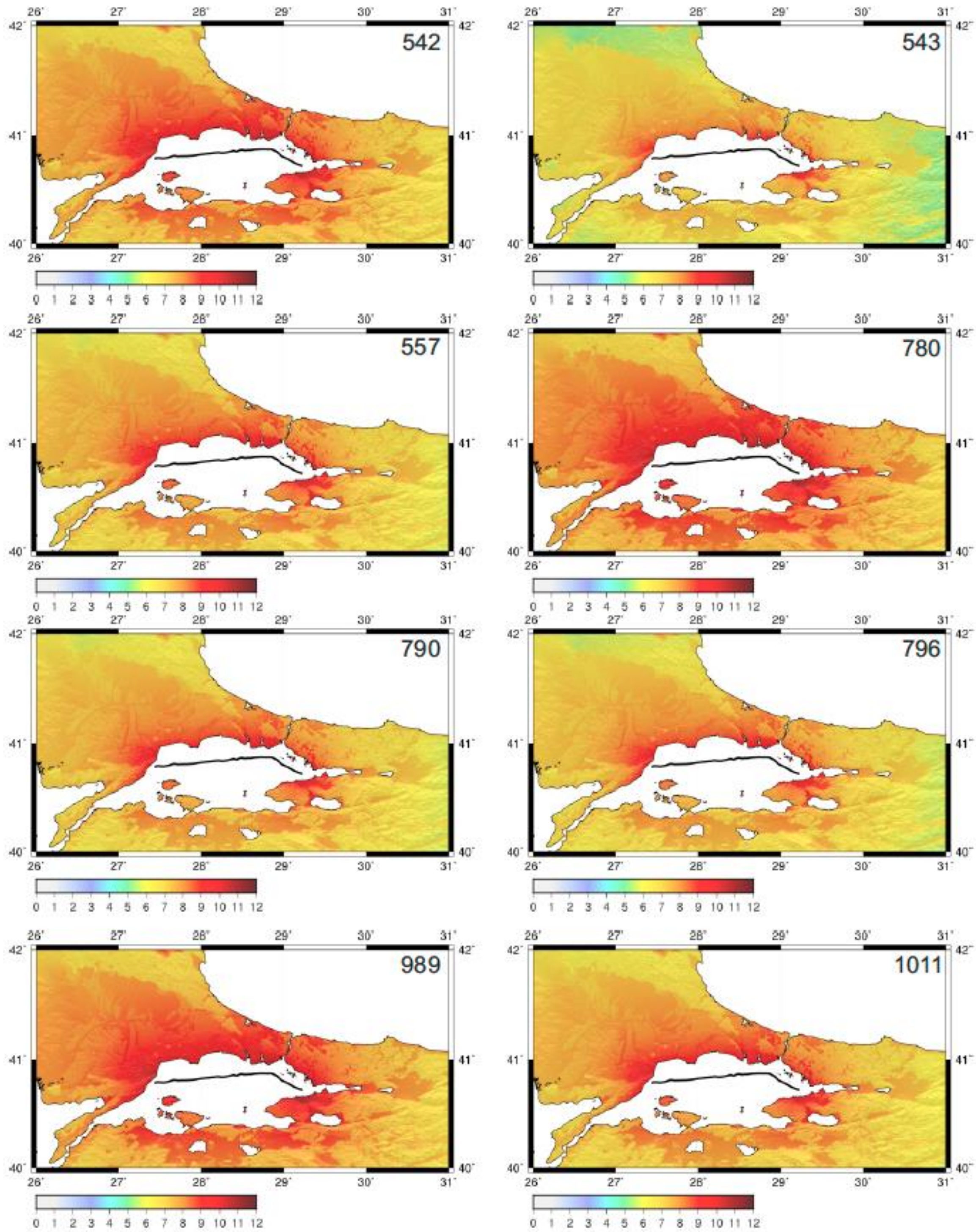


Figure 12. *Historical intensity map scenarios of the Main Marmara Fault (Segment B+C+D+E :542-1011).*

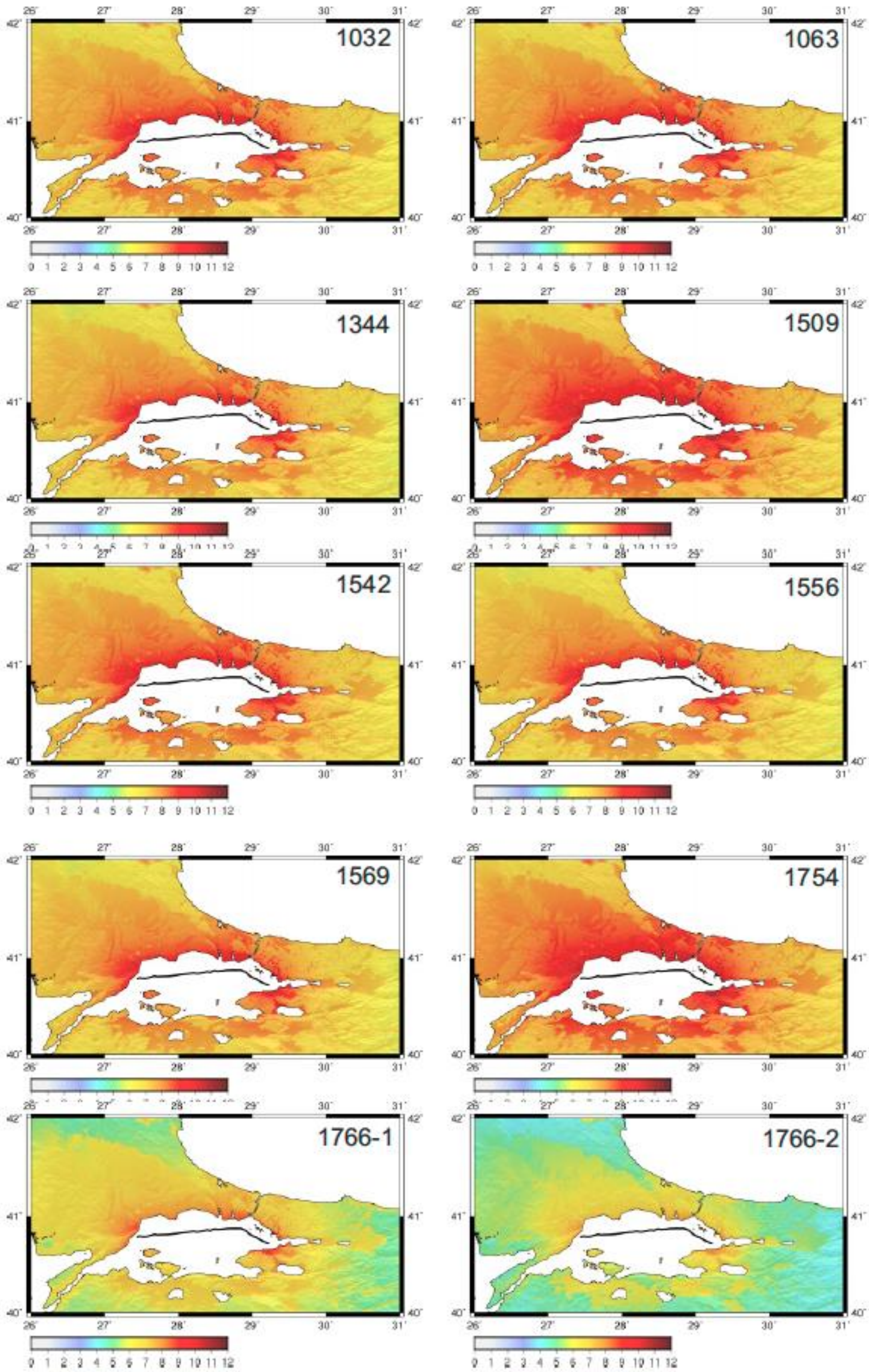


Figure 13. *Historical Intensity map scenarios of the Main Marmara Fault (Segment B+C+D+E 1036-1766).*

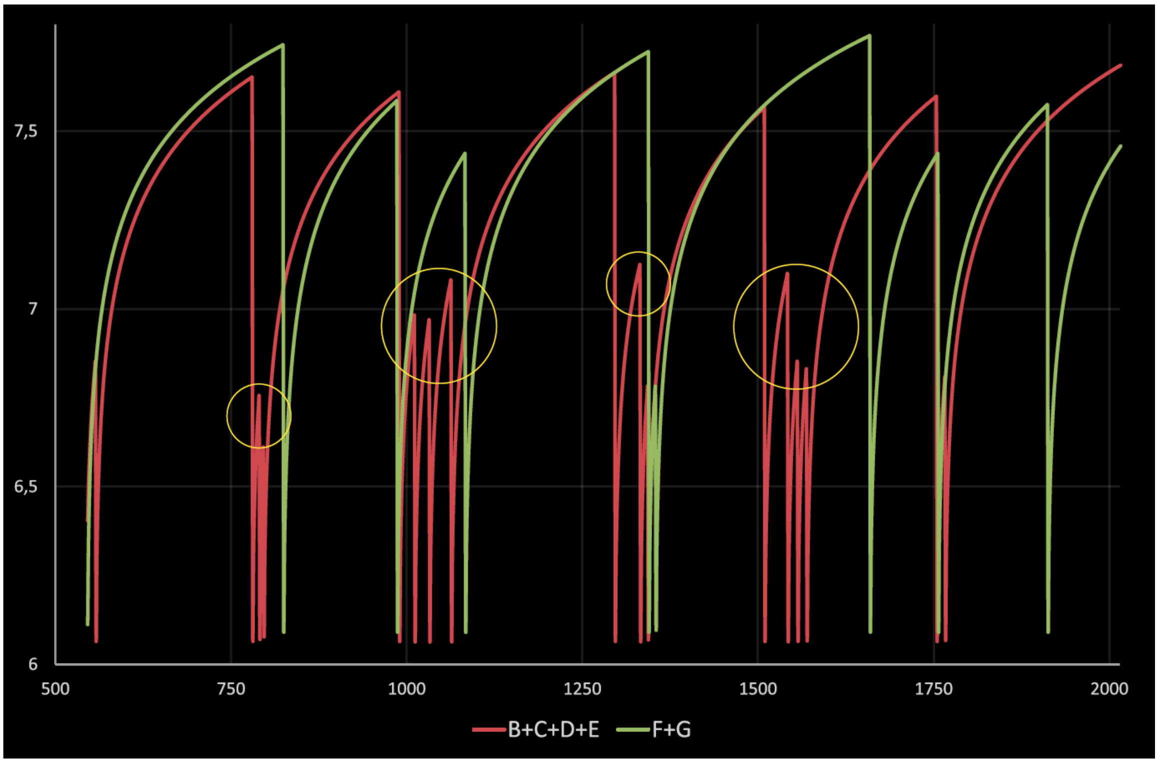


Figure 14. *Calculated historical magnitudes and periods on the single fault model. Yellow circle shows small magnitude earthquakes, but historical data was important damages on the region.*

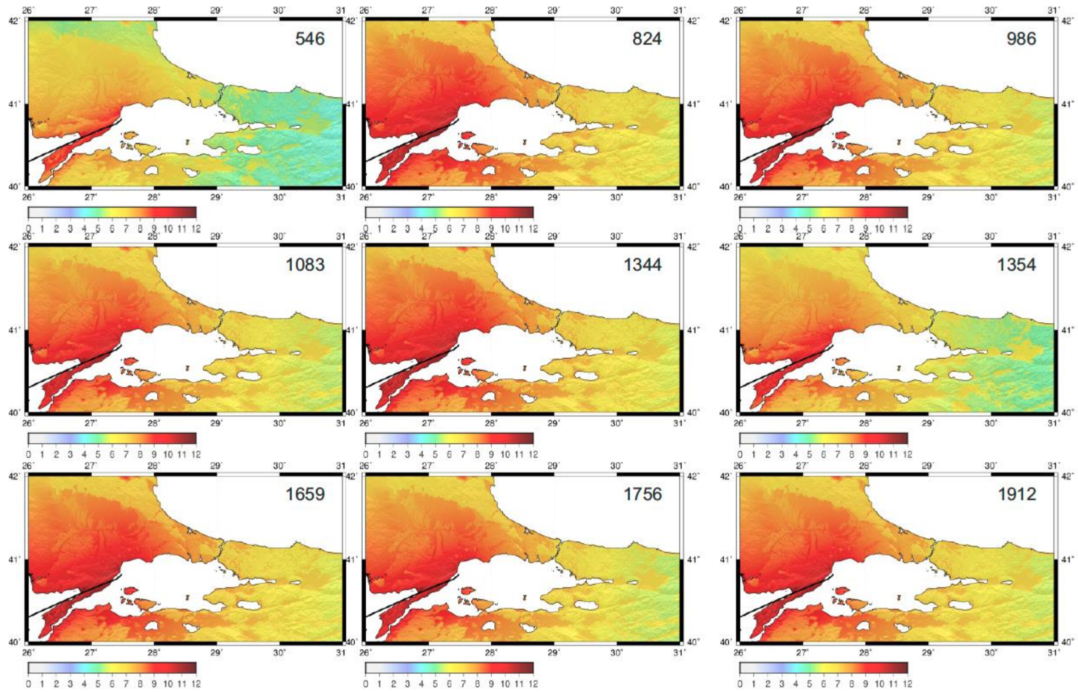


Figure 15. *Historical intensity map scenarios of the Ganos Fault (Segment F+G; Le Pichon et al. 2001)*

Pull-Apart Structure (Armijo et al. 2001; 2004)

Armijo et al. (2001; 2004) mentions that the Marmara Sea is composed of pull-apart basins and the right-lateral faults in the sea are divided into segments in the form of step-over geometry (Figure 6). The authors discuss the seismicity of the Princes Island Fault, Middle Marmara Fault and Ganos Fault in this model. According to the authors, 557, 989 and 1509 earthquakes occurred along the Princes Island Fault shown as segment B. If the 557 earthquake is considered as a starter, the magnitudes of the 989 and 1509 earthquakes should be Mw 7.4. However, when examining the influence area of these earthquakes, the damage records between the İzmit Gulf and western Marmara are not compatible with these magnitudes. This is also seen on the MMI map (Figure 16). In regard to the historical earthquake groups (Figure 3 and 8b), 542, 796, 1032, 1322, 1556, 1766 earthquakes along the C+D segments cannot be destructive in the Marmara region (Table 3). Although these earthquakes are destructive in İstanbul, the magnitudes are smaller than Mw 7. It is clearly seen on the MMI maps that these earthquakes cannot be destructive around the Marmara (Figure 17 and 18). The model about the 1754 earthquake show that this earthquake should be destructive especially in the northern Marmara, but 1766 earthquake shouldn't. At this stage, they are conflict with the historical data (Figure 18). Armijo et al. (2004) suggests that 1912 earthquake occurred along a segment extends from Saros Gulf to middle Marmara (Ganos Fault) (Figure 6). Here there are 15 destructive earthquakes (Figure 3, 4 and 8c). It is obvious that these earthquakes should be along a segment. However, with reference to our calculation, 545, 546, 1083, 1344, 1354 and 1766 earthquakes cannot be destructive (Figure 3 and 8c). Especially, considering the 1344, 1354 and 1766 earthquakes as destructive (Appendix 1), this segment shouldn't be a fault and shouldn't rupture at once (Table 3). The MMI map along this segment is not compatible with the historical data (Appendix 1, Figure 17 and 18).

The time-dependent earthquake periodicity of the Marmara Fault System related to three segments does not exist in the pull-apart model, except Princes Island Fault. C+D and E+F+G segments represent aperiodic behaviour (Figure 21). The conformity between the fault model suggested by Armijo et al. (2004) and the damages in the historical catalogues is 54%. In such a case, 12 of 26 earthquakes are not in concordance with the historical data.

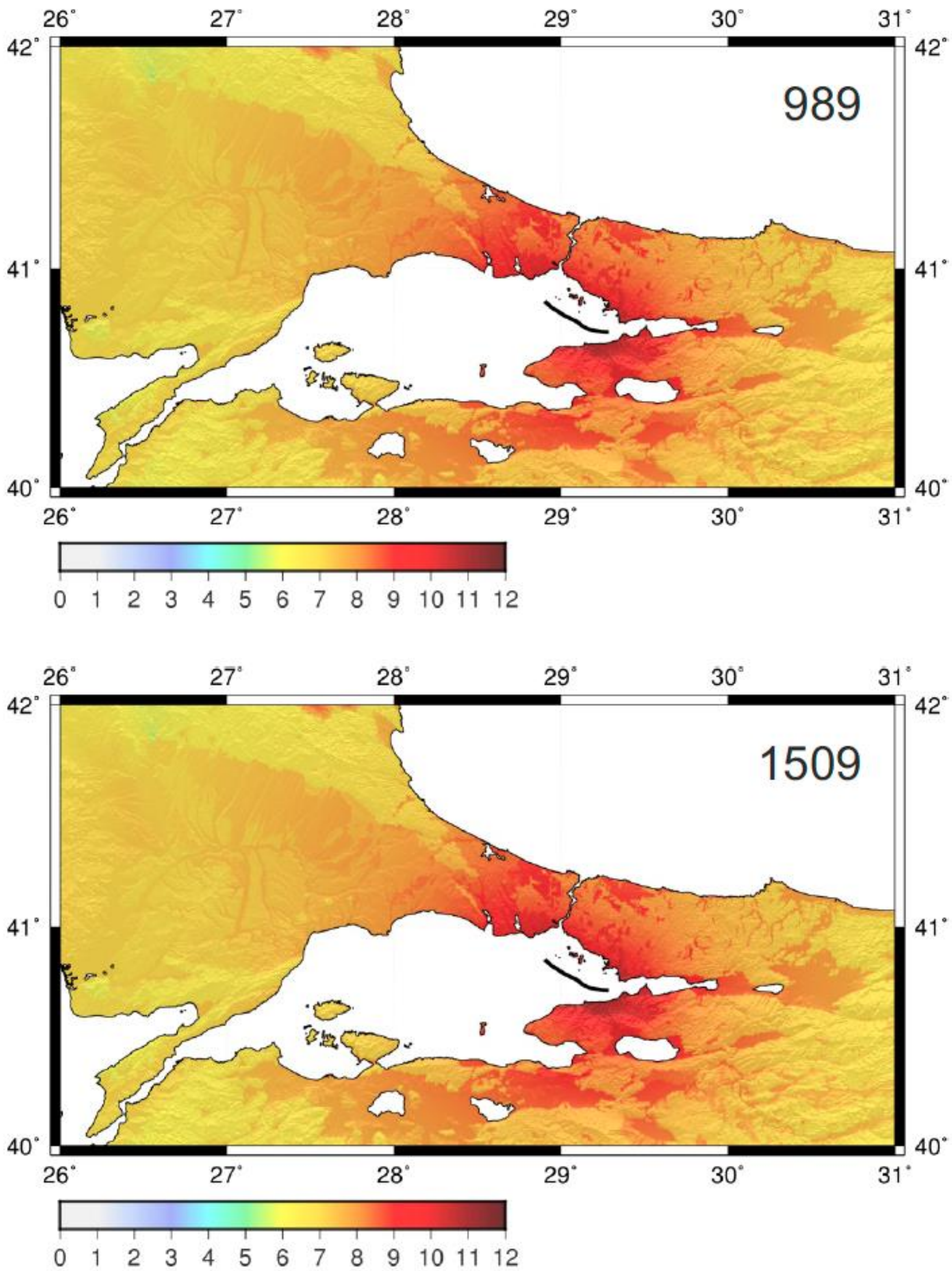


Figure 16. *Historical intensity map scenarios of the Adalar Fault (Segment B Armijo et al. 2002; 2005).*

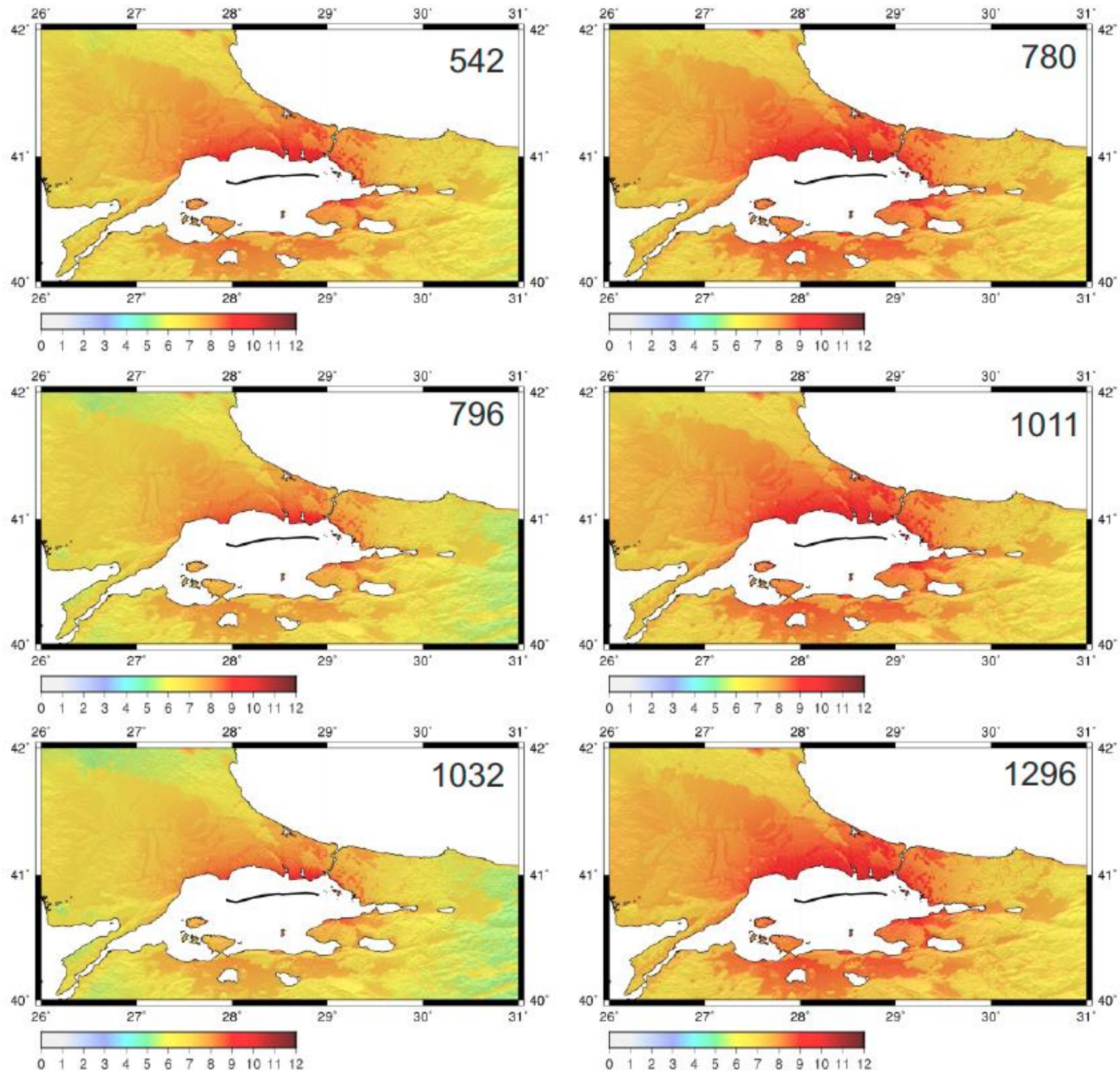


Figure 17. *Historical intensity map scenarios of the Middle Marmara Fault (Armijo et al. 2002; 2005; Segment C+D:5 42-1296).*

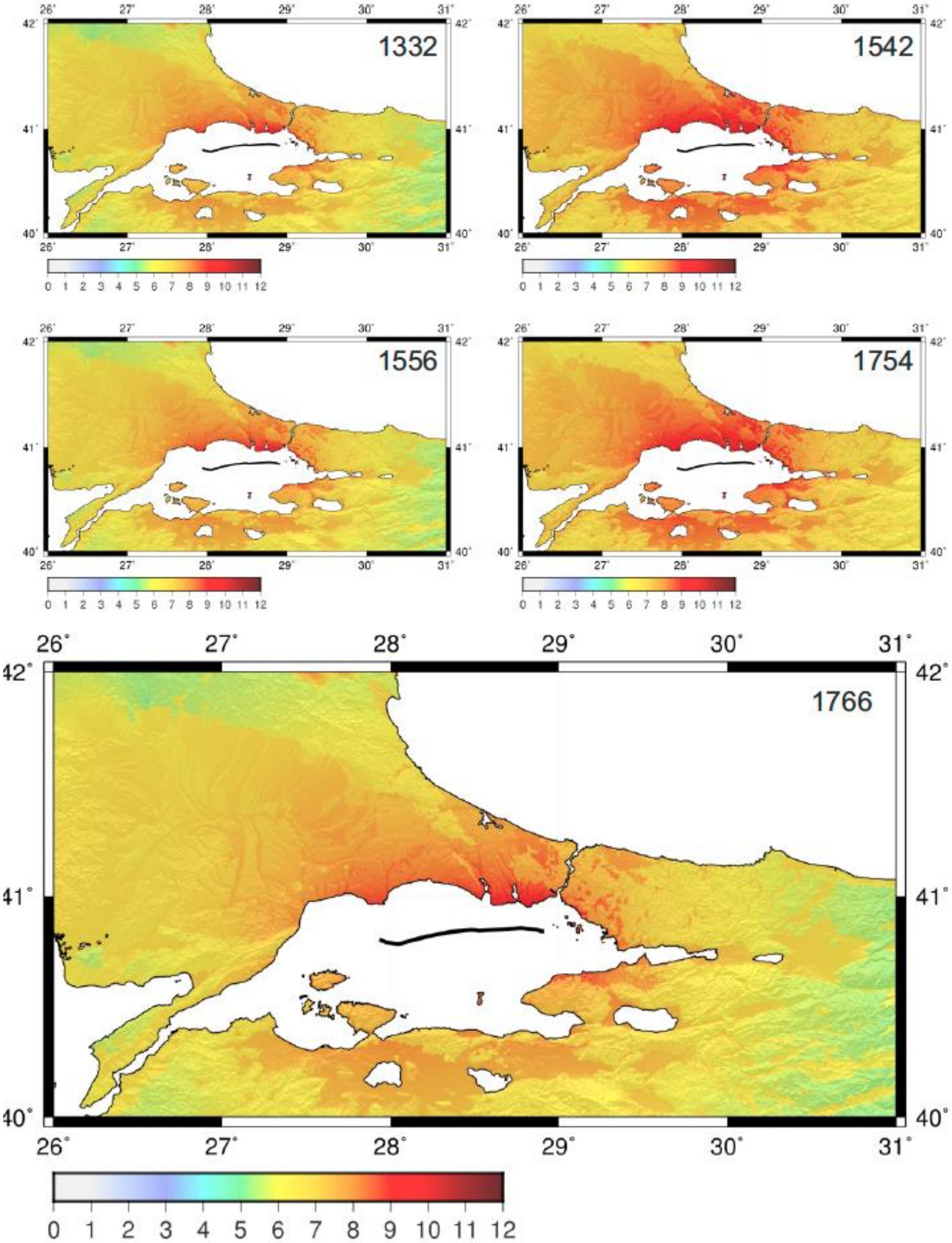


Figure 18. *Historical intensity map scenarios of the Middle Marmara Fault (Armijo et al. 2002; 2005; Segment C+D: 1332-1766-1).*

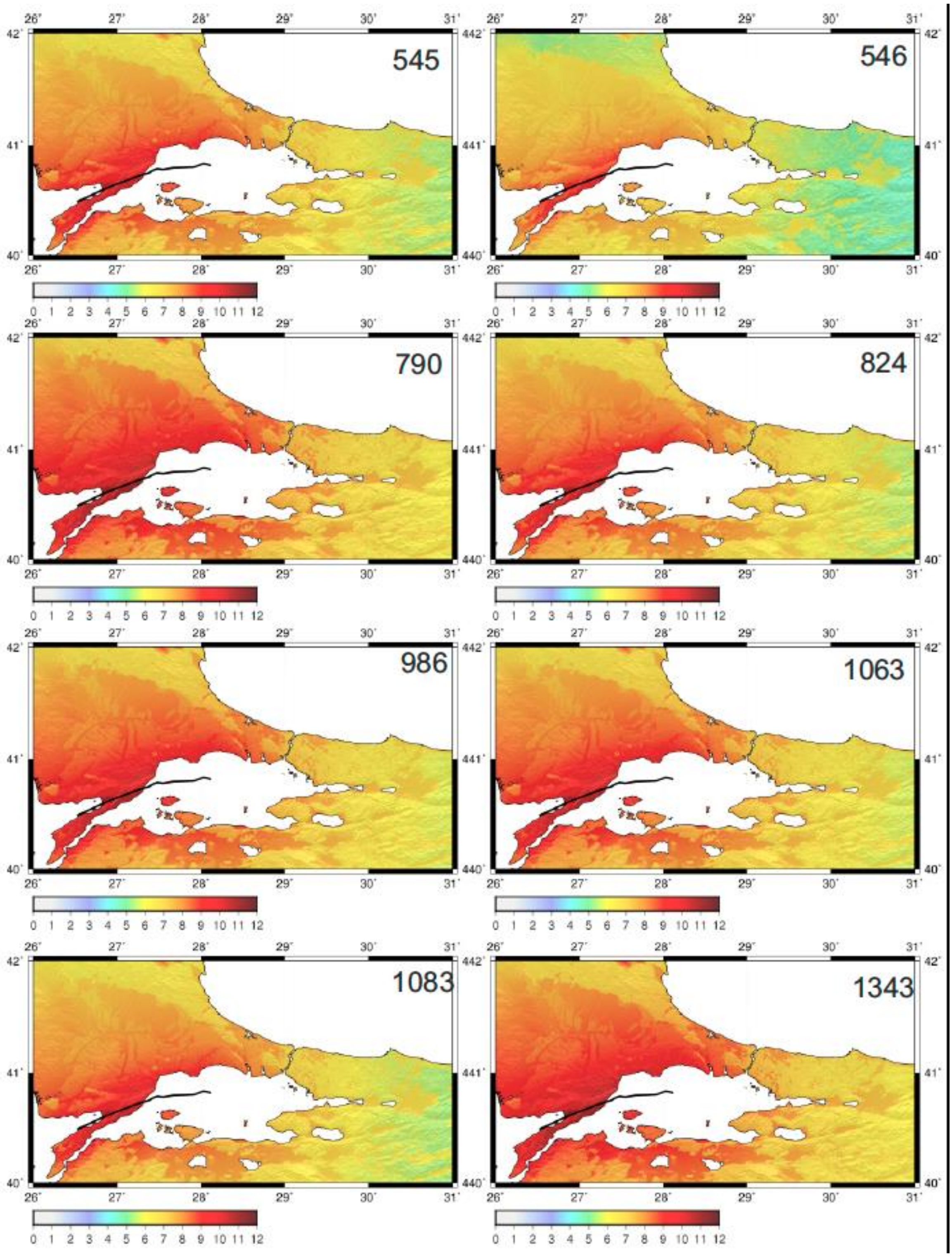


Figure 19. *Historical intensity map scenarios of the Ganos Fault (Armijo et al. 2002; 2005; Segment C+D :543-1343).*

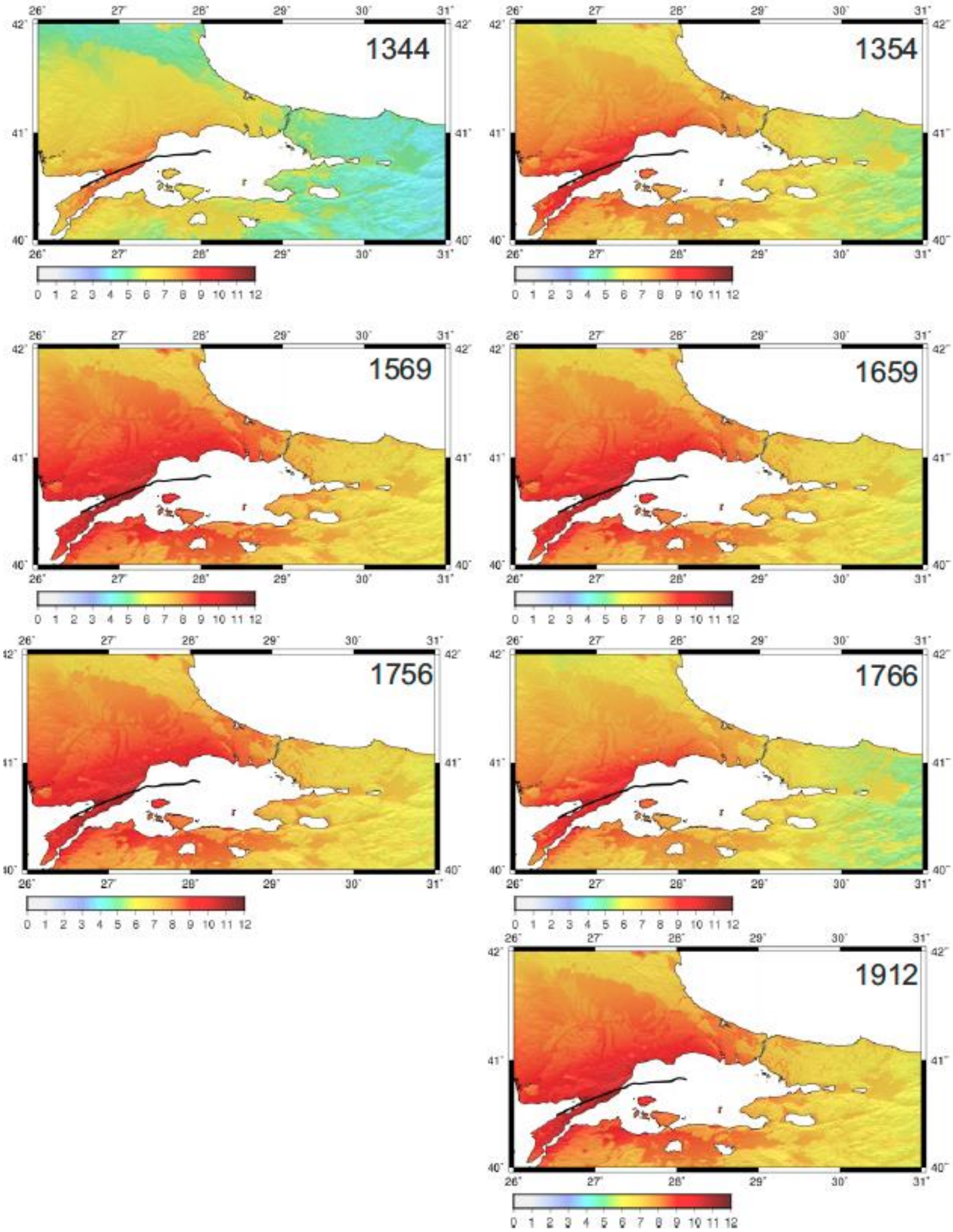


Figure 20. *Historical intensity map scenarios of the Ganos Fault (Armijo et al. 2002; 2005 ; Segment C+D; 1344-1912).*

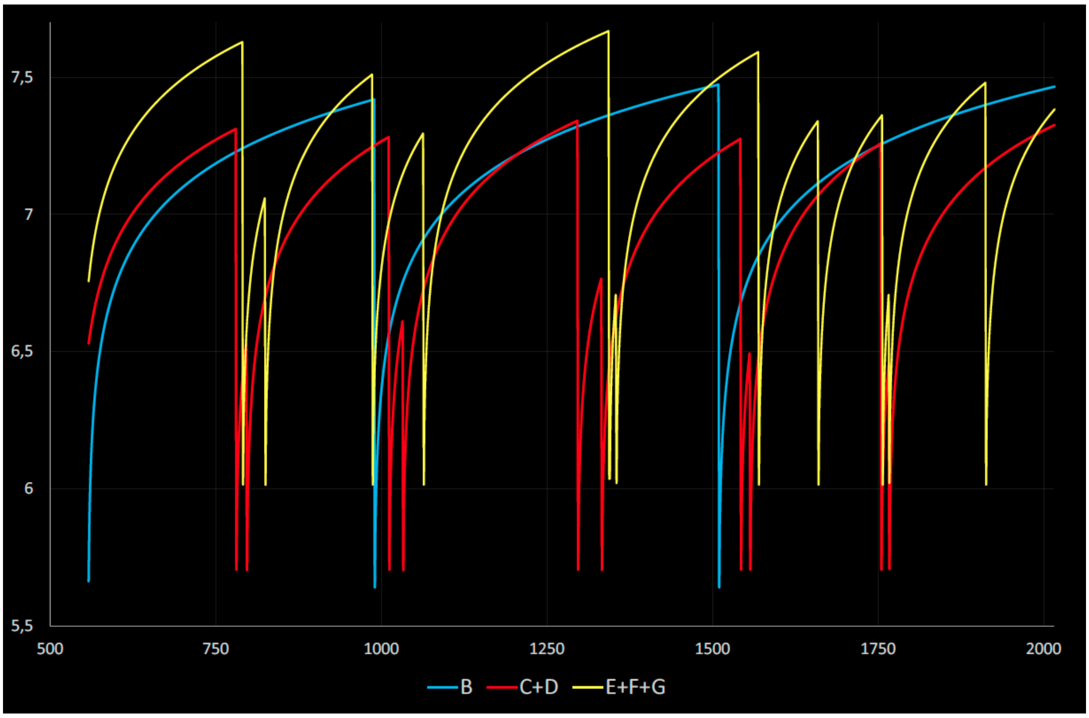


Figure 21. *Calculated historical magnitudes and periods on the pull-apart fault model. Ganos Segment earthquakes bigger than Middle Marmara Segment earthquakes. Historical data didn't support these magnitudes. Ganos Fault works aperiodic, but trench studies show periodicity.*

Horsetail Structure (Yaltırak 2002, 2015)

The earthquakes are grouped based on the influence areas (Figure 3 and Table 1) in the 7 regions along the axis of the Marmara Sea. These groups were gathered by Yaltırak (2015) on the 7 fault segments and surroundings between Saros Gulf and İzmit. altırak (2015) calculates the historical magnitudes of these faults by using the accumulation of 18 mm/year according to the properties of the faults on the map and seismic profiles (Table 4). Similar earthquakes with 10-15% deviations occur along each segment (Table 1 and 4). Under these circumstances, each branch should have a periodicity (Figure 22). The scenarios created by using all earthquakes along each segment is majorly in concordance with the damages in the historical data. However, some of the earthquakes don't exist in the catalogues and are uninformative because of the migrations, wars and unimportant settlements. The magnitude and MMI map scenarios of the earthquakes occurred around İzmit (Table 4 and Figure 11) clearly show that İzmit Gulf-oriented earthquakes are periodic. Another remarkable point is that the calculated magnitude and slip rate between 1719 and 1999 earthquakes are compatible with the instrumental measurements and field studies of 1999 earthquake (Örgülü and Aktar, 2001; Barka et al., 2002).

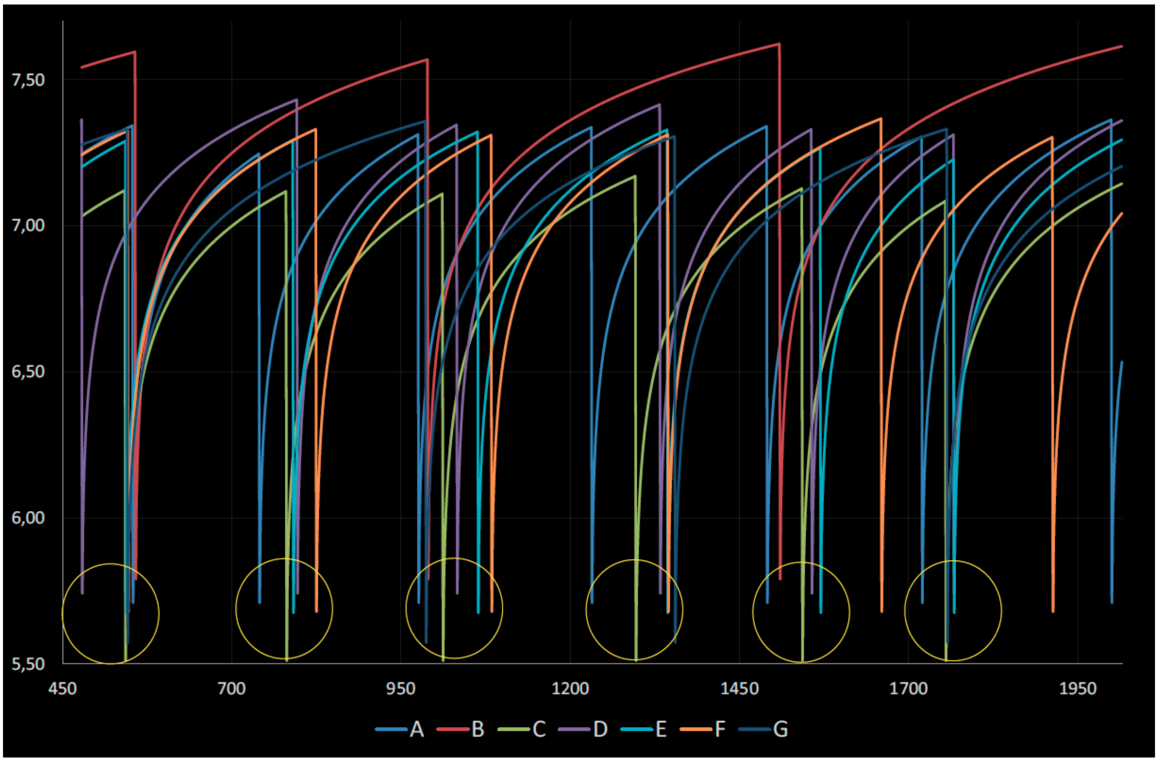


Figure 22. *Calculated historical magnitudes and periods on the horsetail structure fault model (Yaltirak 2002 and 2015). 7 segment shows periodicity surrounding of the Marmara Sea and Historical data correlation.*

In this study, there are 7 horsetail-shaped fault structures in the Marmara and surrounding area related to the scenario that determines the relationship between the historical earthquake distribution and fault model (Yaltırak, 2015). These faults are superimposed and work as flip-flop. The segment B in the eastern Marmara is an arc-shaped fault that is parallel to the southern part of Çınarcık, transtensional at the east and transpressional at the west (Figure 7). The earthquakes occurred along this segment affect the western part of Marmara and İzmit Gulf. These earthquakes are 557, 989 and 1509 earthquakes. When considering the damage area of these earthquakes in the Marmara region (see Appendix 1), they are compatible with the MMI maps. The scenario area intersects with the damages of the 1509 earthquakes revised by Ambraseys (2005) (Figure 24). The magnitudes of the 989 and 1509 earthquakes are calculated as Mw 7.6 and Mw 7.66, respectively (Table 4).

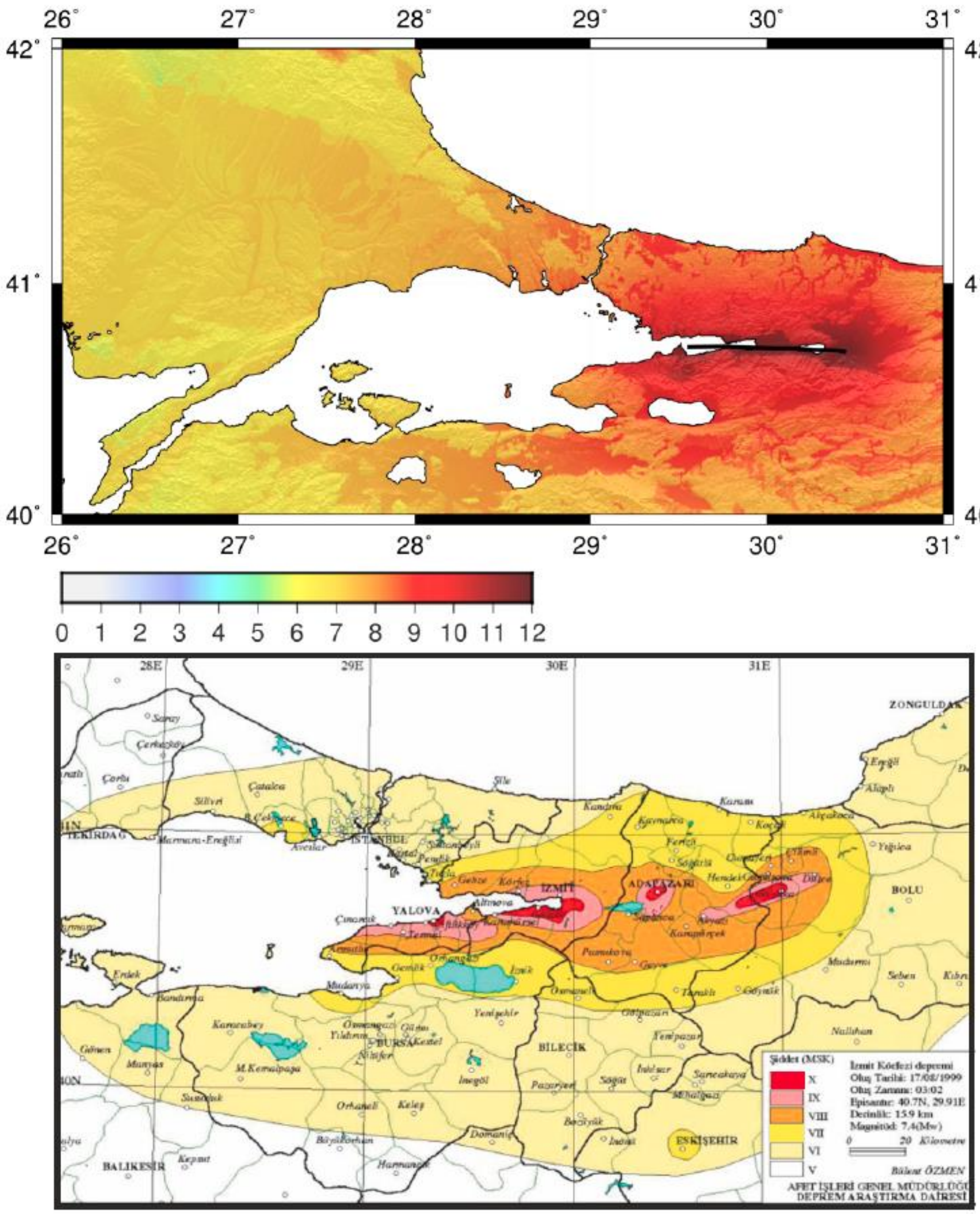


Figure 23. *ArcGIS-based intensity scenarios of the 1999 August earthquake and field-base intensity map of the gulf of İzmit.*

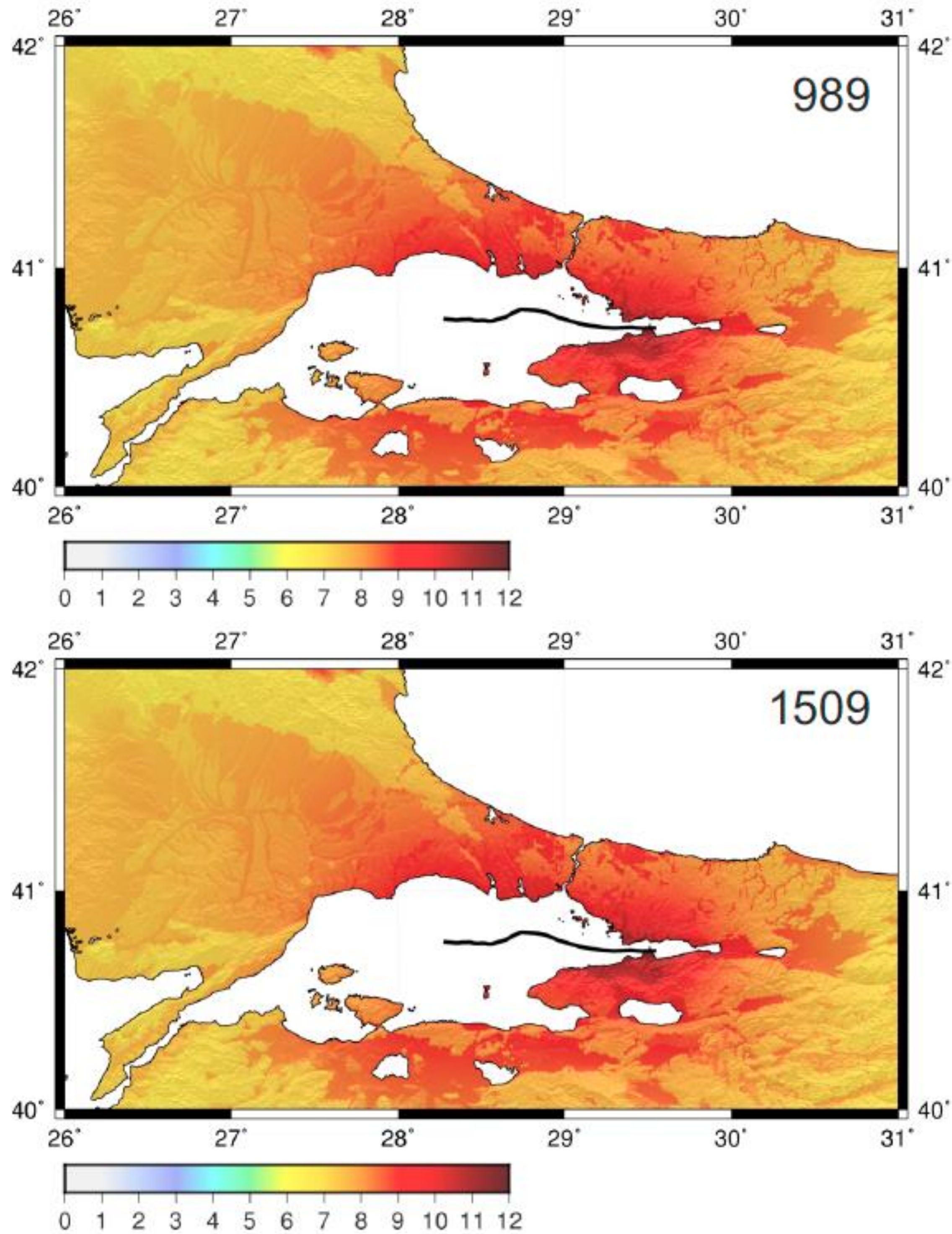


Figure 24. *Historical intensity map scenarios of the Segment B 989 and 1509 earthquakes (Yaltirak 2002; 2015).*

The segment is determined by Yaltırak (2015) as a 2 km-long segment that cuts the eastern Marmara ridge (Figure 7 and 8c). It is suggested that 542, 780, 1011, 1296, 1542 and 1754 earthquakes occurred along this segment. The scenario for this segment and the historical earthquake areas are well-matched (Appendix 1 and Figure 25). Especially, there is more information about the 1754 earthquake (Appendix 1, Ambraseys and Finkel, 1995). The damage area of this earthquake and the damage area of İstanbul surrounding is nearly same. The average magnitude is Mw 7.1□0.05 (Table 4).

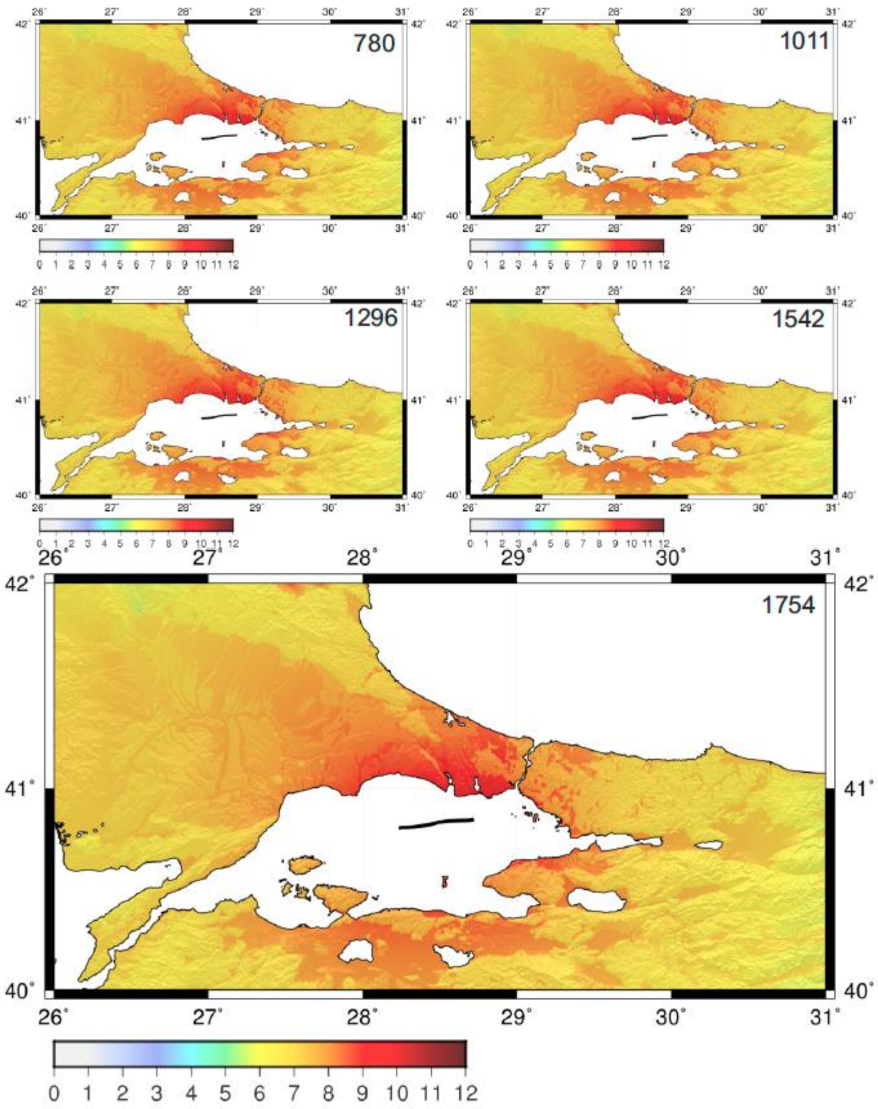


Figure 25. *Historical intensity map scenarios of the Segment C; 780, 1011, 1296, 1542 and 1754 earthquakes (Yaltirak 2002; 2015).*

The segment D has a length of about 93 km (Figure 7 and□8c). Yaltırak (2015) suggests the 478, 796, 1032, 1332, 1556 and 1766 earthquakes along this segment. The magnitude and MMI maps produced by using the fault map indicate the earthquakes with similar magnitudes (Table 4). The average magnitude is Mw 7.4□0.05 (Table 4). The damage area compatible with the historical catalogue and data is observed on the MMI scenarios (Figure 24). The damage area of the first 1766 earthquake is in conformity with the scenario (Appendix 1 and Figure 26). The segment E is situated in the western Marmara and has a length of 74 km (Figure 7 and 8c). The earthquakes along this segment are 543, 790, 1063, 1343, 1569 and 1766-2 earthquake (Figure 3 and 8c). The calculations give the average magnitude as Mw 7.31□0.05. When examining the 1766-2 earthquake occurred on this segment (Appendix 1 and Figure 25), the influence area of this earthquake in the western Marmara is similar. The studies suggesting that this earthquake occurred on the Ganos Fault extend the damage area to Mürefte and Şarköy (Rockwell et al., 2001; Altunel et al., 2004; Armijo et al., 2004; Megrouhi et al., 2012). Even though the Ganos Fault doesn’t rupture, the settlements situated on the southern block of the Ganos Fault (Appendix 1) that is composed of the loose Miocene formations (Yaltırak, 1996; Yaltırak and Alpar, 2002) might be affected from the earthquakes (Figure 27). The 1766-2 earthquake model, suggested by Armijo et al. (2004) and accepted by the other researchers, is based only on a 16th century earthquake discovered as a result of a fault excavation in the Saros Gulf (Rockwell et al., 2001). However, they don’t consider the report of Ambraseys and Finkel (1995) which present the damages as a result of the destructive 1756 earthquake in the area and on the Evre□e □astle situated close to this trench at the east of Saros Gulf. The 1343 earthquake should be evaluated in the same way (Figure 27).

The segment F is also known as the Ganos Fault. The magnitude of the earthquakes along this 60-km-long segment is Mw 7.35±0.06 (Table 4: 546, 824, 1083, 1344, 1659, 1912 earthquakes). The damage area is in keeping with the historical data on the model (Figure 28 and Appendix 1). According to the slip rates and paleoseismologic data, the total slip rate of four earthquakes is 21 meter (Meghraoui et al., 2012). The MMI and magnitude models are compatible with the paleoseismologic ages suggested by Meghraoui et al. (2012), historical earthquakes (1083, 1344, 1659, 1912) and probable slip rates (total 21.3 m) in reference to 18 mm/year (Table 4).

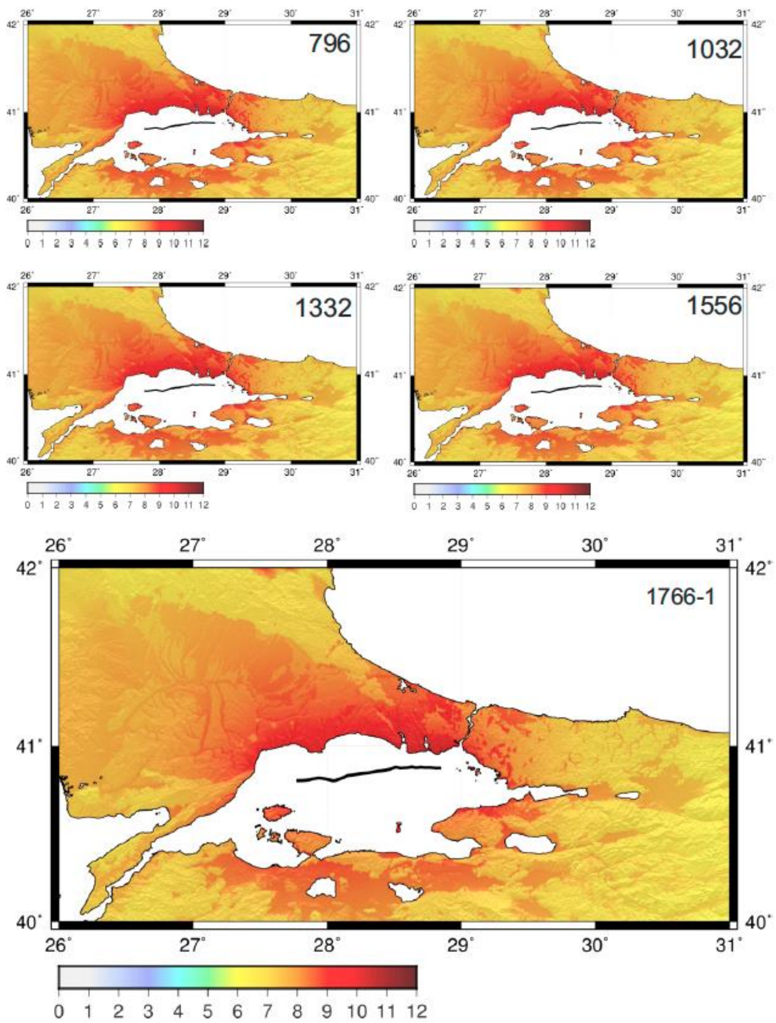


Figure 26. *Historical intensity map scenarios of the Segment D; 796, 1032, 1332, 1556 and 1766-1 earthquakes (Yaltirak 2002; 2015).*

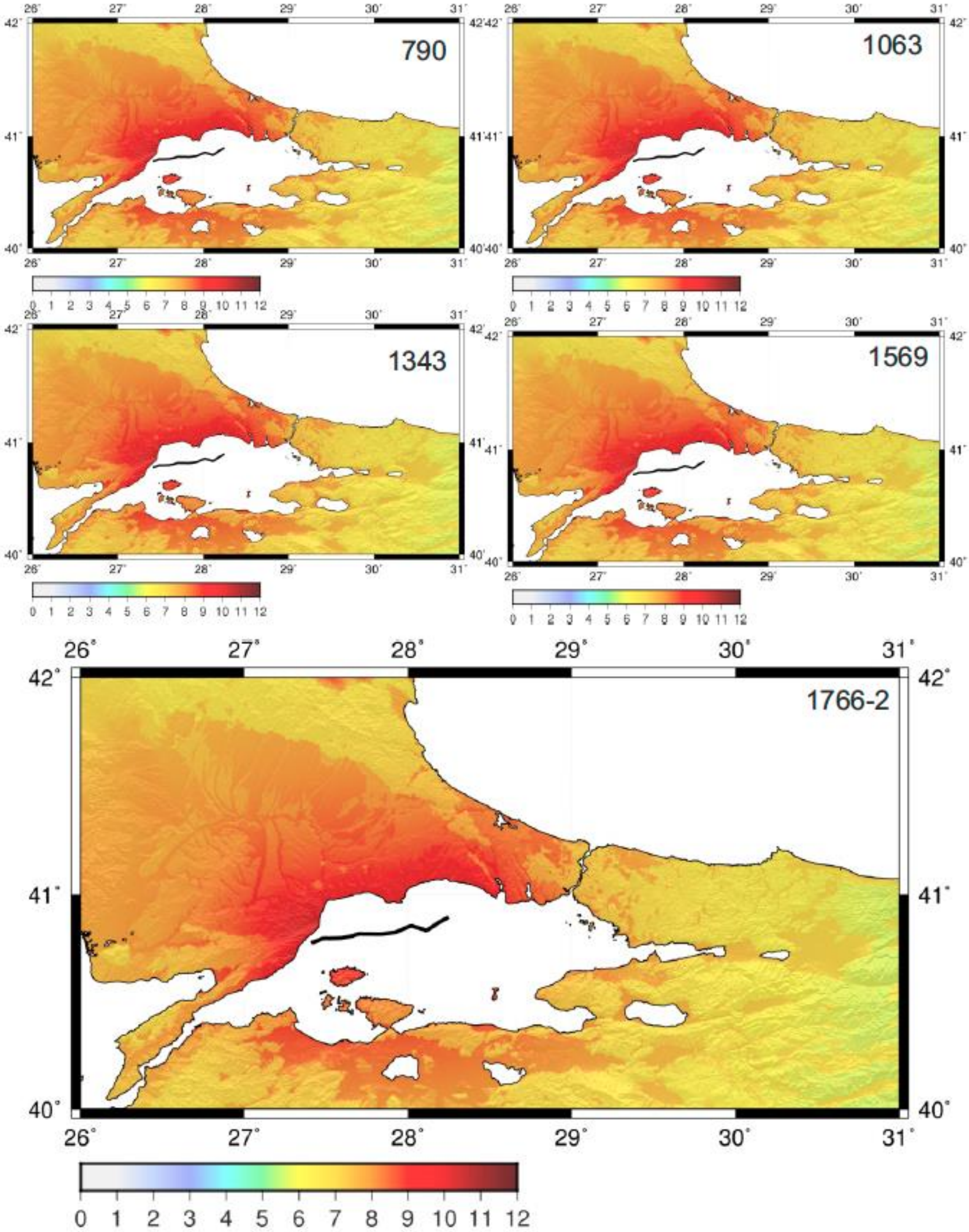


Figure 27. *Historical intensity map scenarios of the Segment E; 790, 1063, 1343, 1569 and 1766-2 earthquakes (Yaltirak 2002; 2015).*

The segment G is a 52-km-long segment between Evreşe Plain and Saros Shelf (Figure 7 and 8c). The 545, 986, 1354 and 1756 earthquakes exist on this segment. According to the scenario and model, the magnitude of the earthquakes is Mw 7.42 0.03. The damage area intersects with well-known 1354 earthquake that was especially effective on the Ganos Fault and surrounding area. Also 1344 earthquake effects the same area. The influence area of the 1659 and 1756 earthquakes and the influence area of 1756 and 1766-2 earthquakes are same. Accordingly, these areas on the segment F overlap in the MMI scenarios (Figure 27, 28 and 29). The similarity of Gelibolu and Ganos damages that were caused by the earthquakes occurred on the E, F and G segments is related to the ground properties of the Ganos Fault. Therefore, most of the geoscientist couldn’t correlate these earthquakes with the segmentation.

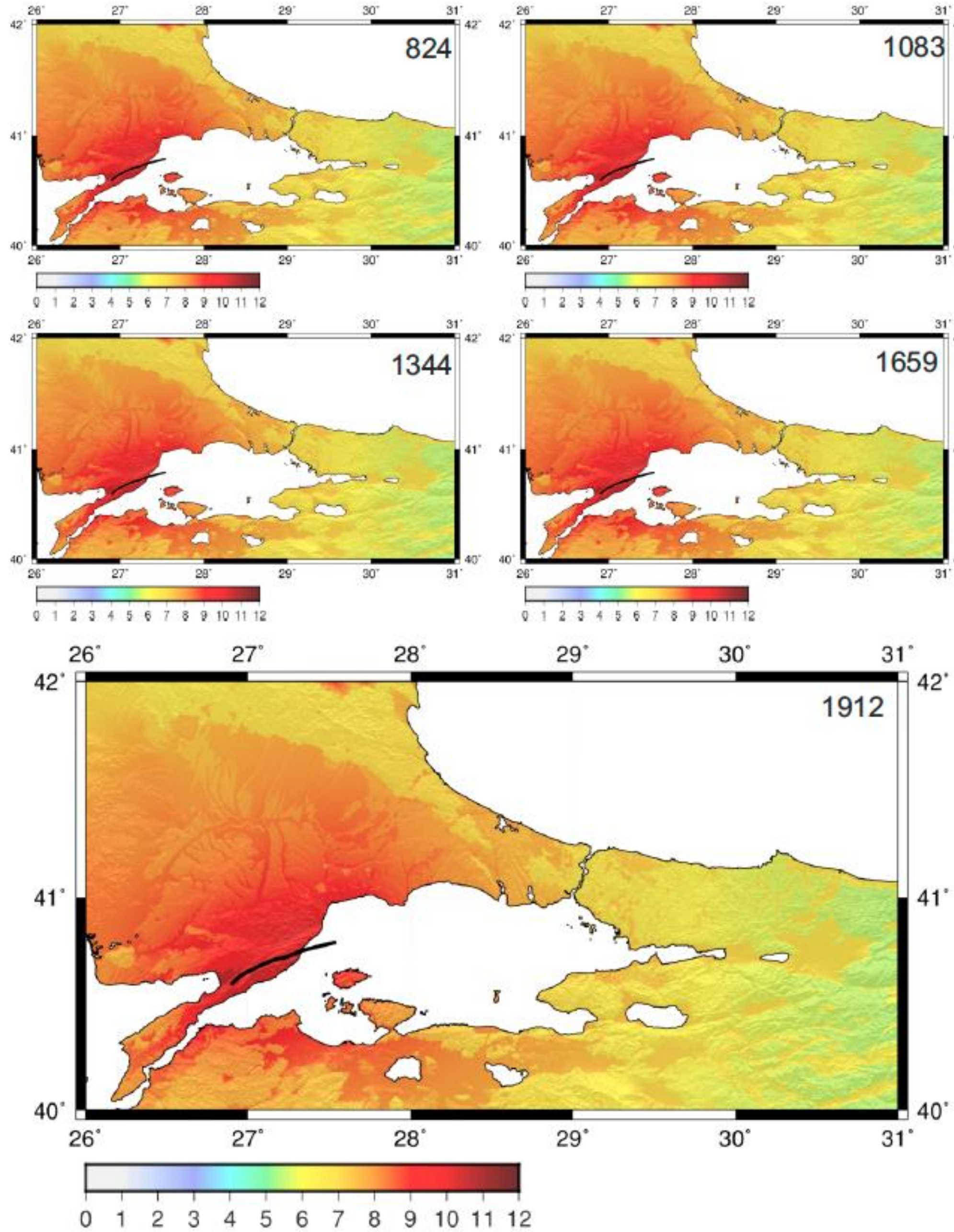


Figure 28. *Historical intensity map scenarios of the Segment F; 824, 1083, 1344, 1659 and 1912 earthquakes (Yaltirak 2002; 2015).*

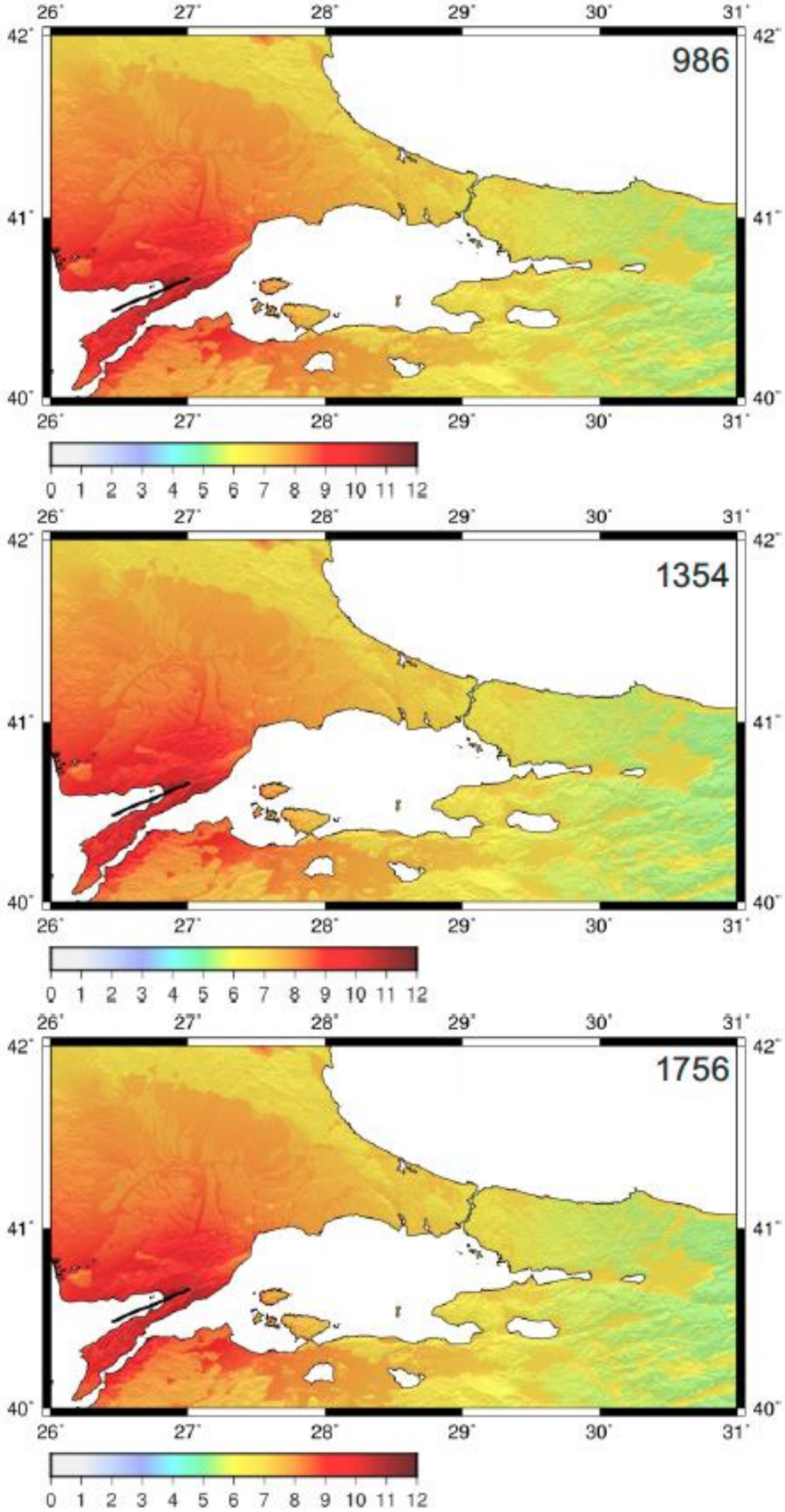


Figure 29. *Historical intensity map scenarios of the Segment C; 986, 1354, and 1756 earthquakes (Yaltirak 2002; 2015).*

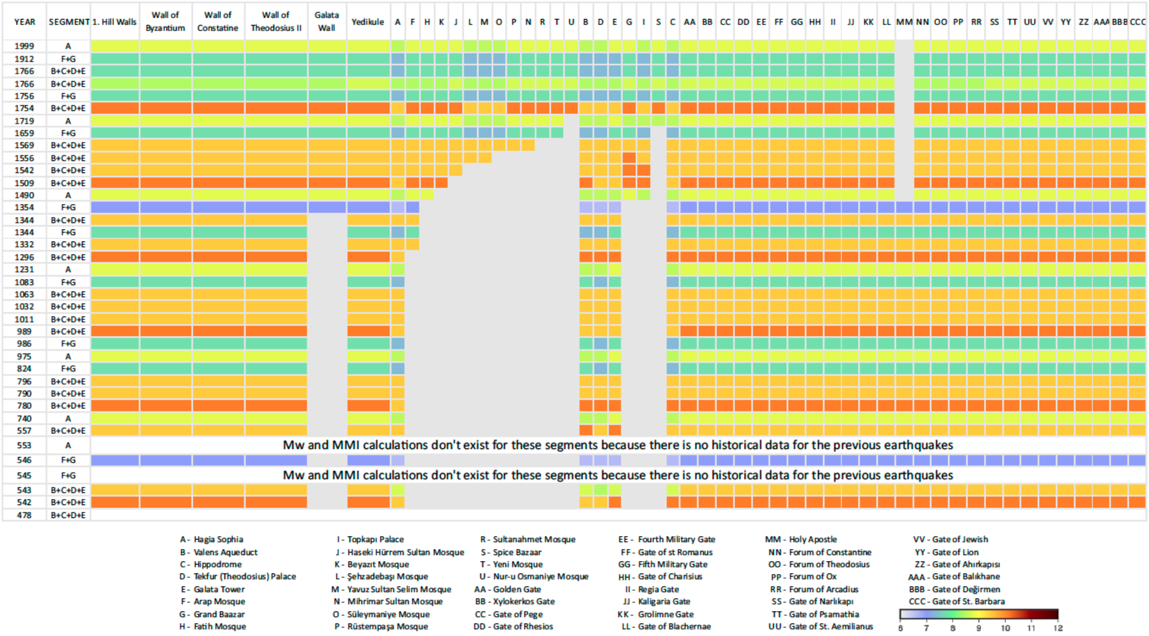
Historical Istanbul Base Scenarios

38 earthquakes along the northern branch of Marmara Region have important effect in ancient İstanbul. In the historical records, some of these earthquakes have been recorded as 'Istanbul Earthquake' because of limited information obtained from the earthquake area, but either they did not cause damage or they cause damage in the areas close to the fault. Among all ancient cities in the Marmara region, only 1600-year record of İstanbul is reliable. The most important reason of that is that Istanbul was the capital city of both Byzantium and Ottoman Empire. It is an important stage to understand how the historical buildings were affected while interpreting the historical earthquakes. At this point, the intensity scenarios of the earthquakes have been applied for the city by taking account the damage records of historical buildings, the ground geology and V_s30 values (Figure 10). The 1/10000 scale intensity maps of the calculated earthquakes of the three models were generated for the effects of the Marmara earthquakes in İstanbul, all the historical constructions have been marked on this map and presented as a list (Appendix 1, 4, 5, 6 and 7).

There is no significant consistency between the historical earthquake damage records and scenarios which were applied to each segments in the single fault model (Le Pichon et al., 2001). (compare, Table 5 and Appendix 1, 4 and 5). Especially there is no similarity between the effects of the 543, 557, 790, 796, 1011, 1032, 1063, 1344, 1542, 1556, 1569, 1766-1, 1766-2 earthquakes on the constructions in İstanbul (Table 5 and Appendix 1, 4 and 5) and historical records. The intensity of these earthquakes might be smaller than Mw 8. However, the historical data mentions heavy destructions. The 542, 780, 989, 1296, 1509 and 1754 earthquakes are the most effective earthquakes in the model and they should be the intensity of 9-10 in Mercalli Scale. Whereas, among these earthquakes only 989 and 1509 are the most destructive ones. It is expected that they should be at least 11 in Mercalli Scale. Although both historical data and scenario model give similar results, the destructive earthquakes still remain unexplained.

According to pull-apart model (Armijo et al., 2001; 2004), especially the segment (C+D) in the middle Marmara recommended by researchers has almost no effect on İstanbul (Table 6 and Appendix 1, 4 and 6). The intensity of the earthquakes suggested for Princes Island Fault cannot exceed 9 in Mercalli scale. The 542, 1011, 1032, 1296, 1332, 1542, 1556, 1766-1 earthquakes are clearly irrelevant with historical data. The effect of the 989 and 1509 earthquakes occurred on the segment B is not more than 10 in Mercalli Scale. In the horsetail fault system (Yaltırak 2002, 2015), three segments close to İstanbul which are consistent with regional calculations about effectively produce earthquakes and effect on historical peninsula with historical data (Appendix 1, 4, 7 and Table 7). The effects of the 780, 790, 989, 1011, 1032, 1063, 1296, 1332, 1509, 1556, 1754, 1766-1 earthquakes on the area where the constructions are situated is more appropriate than other two models. It can be clearly understood that Istanbul had been affected from 10 to 11 in Mercalli Scale (Appendix 1, 4, 7 and Table 7).

Table 5. *Calculated intensity for Single Fault patterns Marmara Earthquakes on the old city*

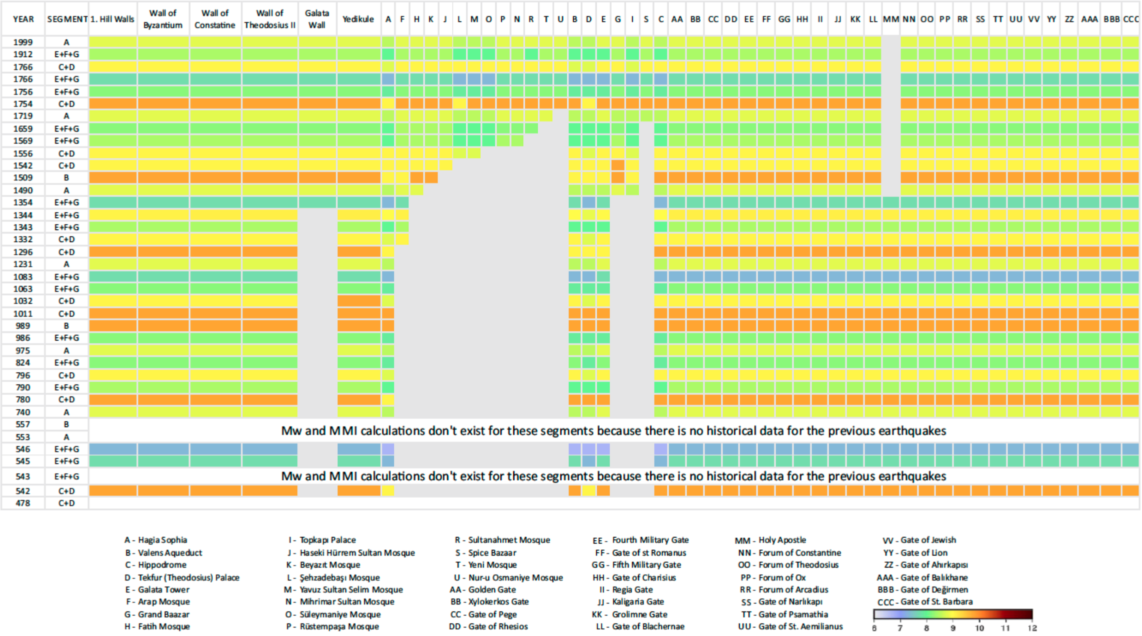


Results

New catalogue (Appendix 1), which was generated by cross checking from different sources for historical earthquakes in the literature, and the exact locations of the earthquakes which are mentioned in this work were obtained. There is a chance to test the other fault models which are different versions of main model and not mentioned in here, with historical earthquakes from new catalogue. No researcher has been examined the historical earthquake in detail until now. The historical data that conflict with the fault models are likely to be ignored. In this case, even if the historical earthquakes exist in catalogues, they cannot be used randomly. The biggest problem is that the assertive fault models are likely to be generated by ignoring some data and using the data that can prove the researcher’s approach. It is possible to compare the historical earthquakes according to the segment lengths in the different studies. The earthquake distributions of Le Pichon et al. (2001), Imren et al. (2001) and Armijo et al. (2001; 2003) are seen on Figure 8a and 8b. If the historical sequence of the earthquakes around the western Marmara segment and the fault maps are accepted as correct, most of the historical earthquakes wouldn't have occurred. For example, Armijo et al. (2003) has a scenario which is based on historical data for exact location of an earthquake in the future. The historical earthquakes and fault patterns suggested by the researchers indicate that the historical earthquakes don't have a regular periodicity as seen on Figure 3b and only a small amount of these earthquakes can be destructive. If the previous earthquake before 1912 earthquake occurred in 1756 or 1766, the question should be asked: How did the accumulation which caused a displacement of 4.5 m during 1912 earthquake happen in the past 145-156 years (Altınok et al., 2003; Altunel et al., 2004). In this case, the slip rate of the North Anatolian Fault should be 30 mm/year. Similarly, if 1719 İzmit and 1754 eastern Marmara earthquakes caused heavy damage, how could the first earthquake of 1766 be too destructive on the same segment? These examples display that Armijo et al. (2003) did not mapped most of the seismogenic structures. Same examples might be given in Figure 8b for Le Pichon et al. (2001) and İmren et al. (2001) as well. The models including 3 and 4 segments contradict with Marmara earthquake history.

On the other hand, the compatibility between the segmentation on the map of Yaltırak (2002) (Figure 8c) and the earthquake distributions on the Figures 3 and 4 is remarkable. Each destructive historical earthquake in the Marmara Sea can be explained by moment magnitude calculation for each segments according to their seismogenic depth, length and 18 mm/year accumulation (Table 4).

Table 6. *Calculated intensity for Pull-apart Fault patterns Marmara Earthquakes on the old city*



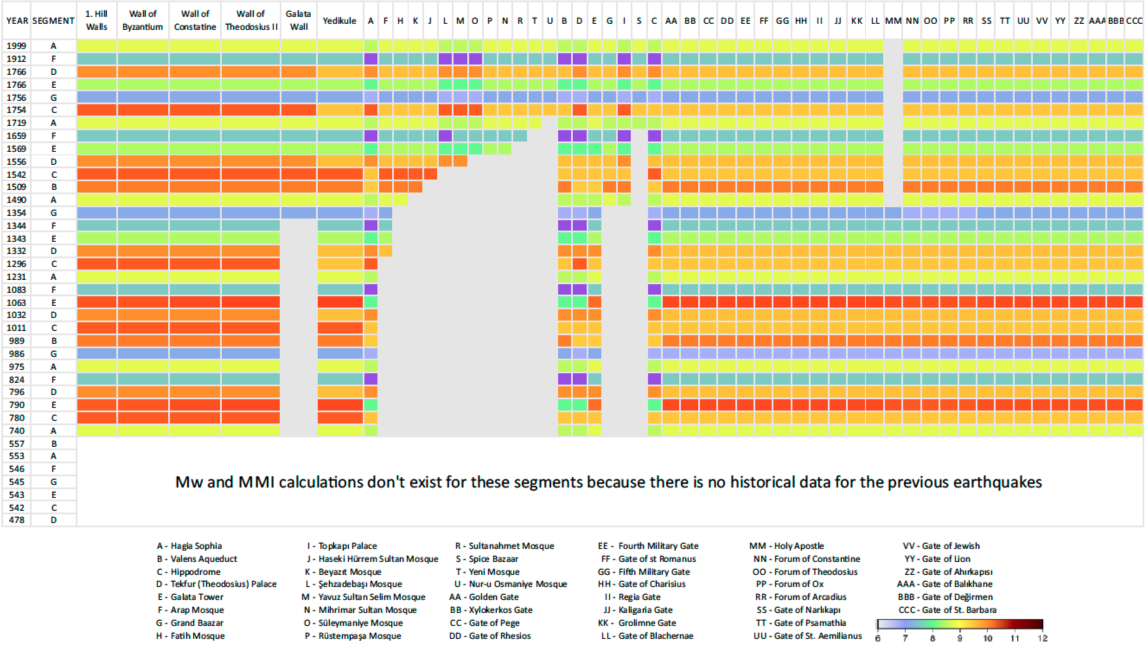
According to the results that we gain after examining the relation between historical earthquakes and fault patterns,

- Each segment has its own periodicity and these are A: 249±30, B:476±44, C:242±40, D: 257±40, E: 244±40, F: 278±41, G: 403±42years.
- Even if the fault segments are short, long periods cause A: Mw 7.43±0.05, B: Mw 7.65±0.05, C: Mw 7.20±0.05, D: Mw 7.31±0.05, E: Mw 7.3±0.05, F: Mw 7.28±0.05, G: Mw 7.37±0.05
- Three earthquakes occur in segment B has a periodicity of 500 years by reason of the fact that this fault is a fault with thrust component between eastern Marmara ridge and İzmit Gulf. An arc-shaped shear zone developed in the southern part of the eastern Marmara ridge, a pressure ridge was formed in the eastern Marmara when the fault was propagating from here to

the northern faults. The possible relationship between the magnitude of three great effective earthquakes in the Marmara region and the segment B where the earthquakes with long periodicity occur on revealed in this study. The magnitudes of the 14.10.1509, 25.10.989, 23.12.557 earthquakes that completely effect the Hagia Sophia and historical walls are around Mw. 7.65.

- According to our explanation compatible with historical earthquakes and fault patterns, on the 4 segments in the Marmara region the earthquakes with the magnitudes of B: Mw 7.65, C: Mw 7.19, D: Mw 7.28, E: Mw 7.34 could occur.
- The propagation of the faults from east to west can be easily observed from this perspective (Figure 30). All the segments from İzmit to Saros ruptured in a sequence between 47 and 246. Most of the studies include the fault patterns inconsistent with the historical earthquakes. In the Marmara region the number of the recorded historical earthquakes are 280. 37 of these 280 earthquakes cause the fatal damage in the cities. Not considering these earthquakes is a big problem in the scientific researches.
- Our results and approaches could be wrong, if all of the historical records were fiction. The complicated results which were originated in the deep sea trenches with high slopes may cause the misleading opinions because of the limited data obtained during the studies in the Marmara Sea.
- Not being able to map the faults from the seismic profiles and the scenarios including simplified fault models lead to the contradictory results with the historical earthquakes.

Table 7. *Calculated intensity for Horsetail Fault patterns Marmara Earthquakes on the old city*



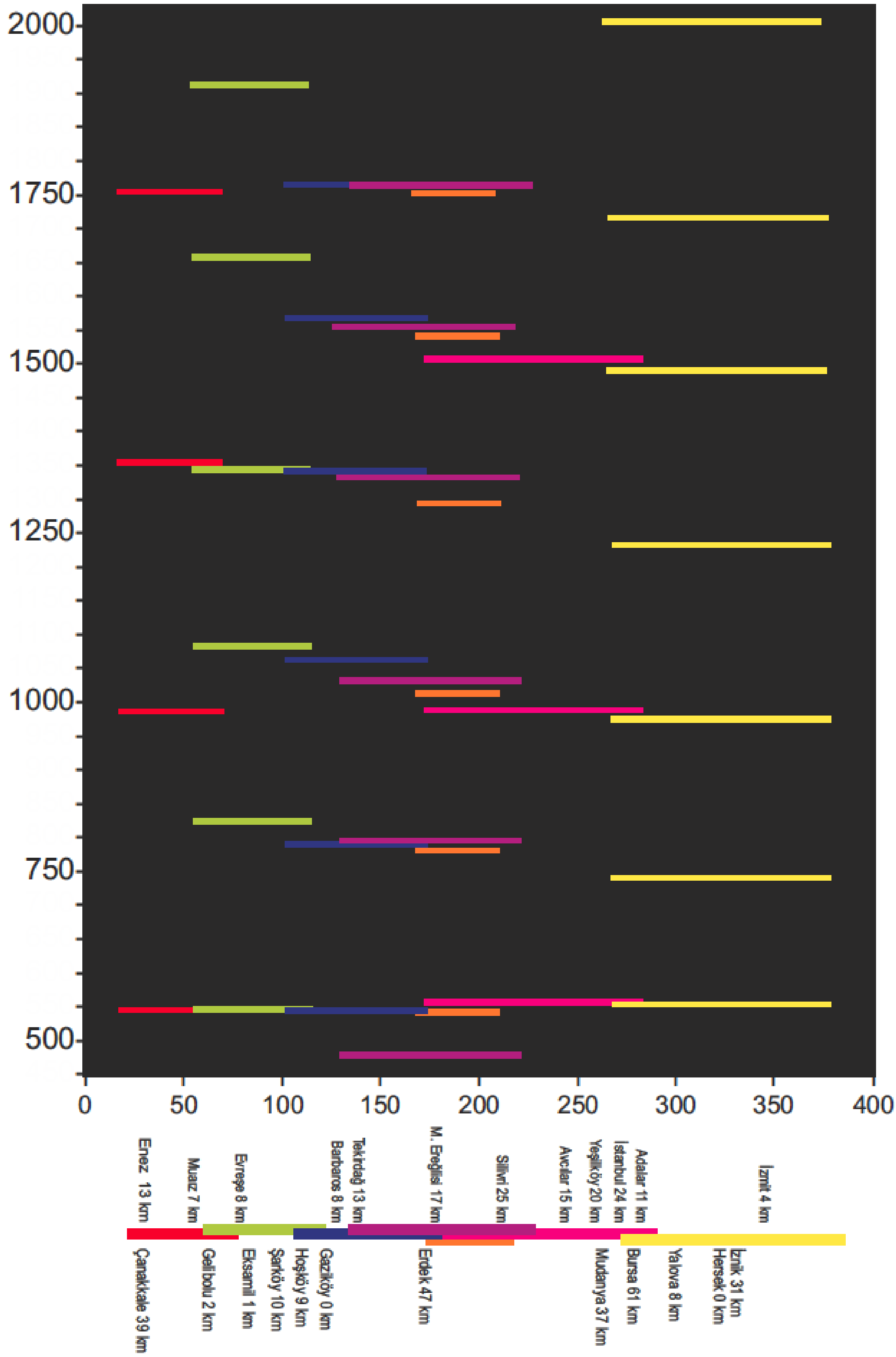


Figure 30. *Time depended western migration Marmara fault segments (Yaltirak, 2015)*

References

Afyoncu, E., and Mete, Z., 2002. 1766 Istanbul Earthquakes and efects on the social life. Seminar of the Natural Disaster and earthquakes surrounding of the Historical Anatolia, University of Istanbul, Faculty of Literature, History Reseach Center. İstanbul, □5-92.

Akkar, S. and Bommer, J., 2010. Empirical Equations for the Prediction of PGA, PGV, and Spectral Accelerations in Europe, the Mediterranean Region, and the Middle East. Seismological Research Letters 81, 2, 195-206.

Akyüz, H.S., Hartleb, R., Barka, A., Altunel, E., Sunal, G., Meyer, B., Armijo, R., 2002. Surface rupture and slip distribution of the November 12, 1999 Düzce earthquake (M□7.1), North Anatolian Fault, Bolu Turkey. Bull. Seism. Soc. Amer., 92 (1): 61-66.

Altınok, Y., Alpar, B., Yaltırak, C., 2003. Şarköy-Mürefte 1912 Earthquake's Tsunami, Extension of the Associated Faulting in the Marmara Sea, Turkey. J. Seismology, 7, 329-346.

Altunel, E., Meghraoui, M., Akyüz, H.S., Dikbaş, A., 2004. Characteristics of the 1912 co-seismic rupture along the North Anatolian Fault Zone (Turkey): implications for the expected Marmara earthquake, Terra Nova, 16, 198-204.

Ambraseys N., 2002, The seismic activity of the Marmara Sea region during the last 2000 years, Bull. Seism. Soc. Am., vol.92, pp.1-18

Ambraseys N.N. and Finkel C., 1987a Seismicity of Turkey and neighbouring regions 1899-1915, Annal. Geophys., 5B, 701-726

Ambraseys N.N. and Finkel C., 1987b. The Saros-Marmara earthquake of 9 August 1912, J. Earthq. Eng. Struct. Dynamics, 15, 189-211

Ambraseys N.N. and Finkel C., 1990. The Marmara Sea earthquake of 1509, Terra, 2, 167-174

Ambraseys, N.N., 2002. Seismic sea-waves in the Marmara Sea region during the last 20 centuries. Jour. of Seismology 6(4): 571-578.

Ambraseys, N.N. and Finkel, C., 1991. Long term seismicity of the Istanbul and of the Marmara Sea region, 1991, Terra Nova, 3, 527-539.

Ambraseys, N.N. and Finkel, C.F. 1995 The seismicity of Turkey and adjacent areas: a historical review, 1500-1800. Eren Yayıncılık ve Kitapçılık Ltd. Şti., İstanbul.

Ambraseys, N.N. and Jackson, J. A., 2000, Seismicity of the Sea of Marmara (Turkey) since 1500. Geophysics J. Int., 141, F1-F6

Arioglu, E., B. Arioglu, and Girgin, C., 2001. Assessment of the Eastern Marmara earthquake in terms of acceleration values, Beton Prefabrikasyon, 57-58, 5-15 (in Turkish).

Armijo R., Meyer B., Navarro S., King G., Barka A., 2002. Asymmetric slip partitioning in the Sea of Marmara pull-apart: a clue to propagation processes of the north Anatolian Fault?, Terra Nova, 14, 80-86.

Armijo R., et al. 2005. Submarine fault scarps in the Sea of Marmara pull-apart (North Anatolian Fault): implications for seismic hazard in Istanbul, Geochem. Geophys. Geosyst., 6, Q06009, doi:DOI.

Bakır, M., 2005. Depremlerin oluş nedenlerine ilişkin Bizans teorileri, İTÜ Dergisi, 2,1,3-9.

Belivet, M. 2008. Bizans ve Osmanlı ilişkileri (Byzantins et Ottomans: relations, interaction, succession) Alkim Yayınları, İstanbul

Bilal, M. and Askan, A., 2014). Relationships between Felt Intesity and Recorded Ground-Motion Parameters for Turkey, Bulletin of the Seismological Society

Boore, D.M., Joyner W.B., and Fumal, T.E., 1993. Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report, U.S. Geol. Surv. Open-File Rept. 93-509, 72p.

Boore, D.M., Joyner, W.B., and Fumal, T.E., 1997. Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work, Seismological Research Letters, Volume 68, No 1, p 128-153

Çelebi, K. 2009. Tarih-i Konstantiniyye ve Kayasire, Gençlik Kitabevi, İstanbul

Demirkent, I., 2002. IV-XI Century Istanbul Earthquakes from Byzantion source, Seminar of the Natural Disaster and earthquakes surrounding of the Historical Anatolia, University of Istanbul, Faculty of Literature, History Reseach Center. İstanbul, 51-66.

Dikbaş, A. and Akyüz, H.S., 2010. KAF zonu üzerinde İzmit-Sapanca Gölü segmentinin fay morfolojisi ve paleosismolojisi. İTÜ Dergisi/d, cilt 9, sayı 3, 1□1-152.

Ebersolt, ., 2005. Bizans İstanbulu ve Doğu Seyyahları, Pera Orient Yayınları İstanbul

Ergin, K., Güçlü, U. and Uz, Z. 1967. Türkiye ve civarının deprem katoloğu. İTÜ. Maden Fak., Arz Fiziği Enstitüsü yayınları, No: 24, 169s

Faenza, L., and A. Michelini, 2010. Regression analysis of MCS intensity and ground motion parameters in Italy and its application in ShakeMap, Geophys. J. Int. 180, 1138-1152

Finkel, C., 2007. Osmanlı, Tima□ İstanbul.

Grelot, □., 2008. İstanbul Seyahatnamesi. Pera Orient Yayınları, İstanbul.

Guidoboni, E. and A. Comastri 2005. Catalogue of Earthquakes and Tsunamis in the Mediterranean area from the 11th to the 15th Century. Instituto Nazionale di Geofisica e Vulcanologia - SGA, Bologna, pp 1037, ISBN 88-85213-10-3.

Guidoboni, E., Comastri, A. ve Traina, G., 1994. Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th century, Institute Nazionale di Geofisica, Rome.

Hammer, V. 1968. Osmanlı İmparatorluğu Tarihi (Empire History of Ottoman) İstanbul.

İmren, C., Le Pichon, X,, Rangin, C., Demirbağ, E., Ecevitoğlu, B., Görür, N. (2001) The North Anatolian Fault within the Sea of Marmara: a new evaluation based on multichannel seismic and multibeam data. Earth Planet Sci Lett 186:143-158

Kalkan, E., Gülkan, P., 200□, Site-Dependent Spectra Derived from Ground Motion Records in Turkey, Eartquake Spectra, Volume 20, No 4, 1111-1138.

Karacakaya, R., 2002. The 1912 Mürefte-Şarköy Earthquake. Seminar of the Natural Disaster and earthquakes surrounding of the Historical Anatolia, University of Istanbul, Faculty of Literature, History Reseach Center. İstanbul, 1-28.

Le Pichon, X., Şengör, AMC., Demirbağ, E., Rangin, C., İmren, C., Armijo, R., Görür, N., Çağatay, N., Mercier de Lepinay, B., Meyer, B., Saatçiler, R., Tok, B. (2001) The active main Marmara Fault. Earth Planet Sci Lett 192:595-616

Mazlum, D., 2011. 1766 İstanbul depremi Belgeleri ışığında yapı onarımları. İstanbul Araştırmaları Enstitüsü. 310p

Meghraoui, M., Aksoy, M.E., Akyüz, H.S., Ferry, M., Dikbaş, A., Altunel, E. 2012. Paleoseismology of the North Anatolian Fault at Güzelköy (Ganos segment, Turkey): Size and recurrence time of earthquake ruptures west of the Sea of Marmara. 3G.13,4,1-26.

Oeser, E., 1992. Historical Earthquake Theories from Aristotle to Kant, in Gutdeutsch, R., Grünthal, G. ve Musson, R., eds. Historical Erathquake in Europe, Vienna.

Okay, A. I., Kaşlılar-Özcan, A., İmren, C., Boztepe-Güney, A., Demirbağ, E., Kuşçu, İ. 2000, Active faults and evolving strike slip basins in the Marmara Sea, northwest Turkey: a multichannel seismic reflection study. Tectonophysics, 321, 189-218.

Ozansoy, E., 2002. Istanbul Earthquakes (1200-1453) from Byzantion source. Seminar of the Natural Disaster and earthquakes surrounding of the Historical Anatolia, University of Istanbul, Faculty of Literature, History Reseach Center. İstanbul, 1-28.

Pınar, N. and Lahn, E. 1952.Türkiye Depremleri İzahlı Katalogu, T.C. Bayındırlık Bakanlığı Yayınları, Seri:□6, Sayı:□3, Ankara

Rockwell, T., Barka, A., Dawson, T., Akyüz, H.S., Thorup, K., 2001. Paleoseismology of the Gazikoy-Saros segment of the North Anatolia fault, northwestern Turkey: Comparison of the historical and paleoseismic records, implications of regional seismic hazard, and models of earthquake recurrence. Journal of Seismology, 5, 433-448.

Sakin, O., 2002. Tarihsel Kaynaklarına Göre İstanbul Depremleri, Kitabevi, İstanbul, 170 p.

Sancaklı, N., 200□. Marmara Bölgesi Depremleri (M□ □27-MS 1912) Kabataş Yayınevi, İstanbul, 216 p.

Schedel, H.,1493. Die Schedelsche Weltchronik, Nurmberg. https://upload.wikimedia.org/wikipedia/commons/5/5f/Constantinople%2C_woodcut_from_Schedel%27s_Weltchronik_%281493%29.png

Soysal, H., Sipahioğlu, S., Kol□ak, D., Altınok, □. 19□1, Türkiye ve □evresinin tarihsel deprem katoloğu, TÜBİTAK proje no: TBAG341

Şehsuvarlıoğlu, H. Y., 1955. Asırlar Boyunca İstanbul,□Cumhuriyet Yayınları, 253 s.

Tselentis, G., and L. Danciu, 2008. Empirical relationships between modified Mercalli intensity and engineering ground-motion parameters in Greece, Bull. Seismol. Soc. Am. 98, no 4, 1863-1875.

Ulusay, R., Tuncay, E., Sonmez, H., Gokceoglu, C., 2004. An attenuation relationship based on Turkish strong motion data and iso-acceleration maps of Turkey, Engineering Geology, 74, 265-291

Uzunçarşılı, İ.H., 1996-2003 Osmanlı Tarihi,8 Cilt, TTK yayınları

Ürekli, F., 1998. 1894 İstanbul Depremi, İstanbul Araştırmaları, 5,□7-80.

Wald, D. J., V. Quitoriano, T. H. Heaton, and H. Kanamori, 1999. Relationships between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California, Earthq. Spectra 15, 3, 557□564.

Wald, D. J., V. Quitoriano, T. H. Heaton, H. Kanamori, C. W. Scrivner, and B. C. Worden, 1999. TriNet □ShakeMaps□rapid generation of peak ground-motion and intensity maps for earthquakes in southern California, Earthq. Spectra 15, 3, 537-556

Yaltırak, C., 2002. Tectonic evolution of the Marmara Sea and its surroundings. Mar. Geol. 190, 1/2, 493-530.

Yaltırak, C., 2015. Marmara Denizi ve Çevresinde tarihsel depremlerin yerleri ve anlamı. İTÜ Vakfı dergisi, 67, 51-58.

Yıldız, M., 2002. 1□55 Bursa Earthquakes. Seminar of the Natural Disaster and earthquakes surrounding of the Historical Anatolia, University of Istanbul, Faculty of Literature, History Reseach Center. İstanbul, 119-140.

Zachariadou, E. 2001, Osmanlı İmparatorluğu’nda Doğal Afetler, Tarih Vakfı Yurt Yayınları, ISBN: 975-333-150-9 313.