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EVALUATION OF EARTHQUAKE RECURRENCE ON THE NORTHERN ANATOLIAN FAULT OF ASIA MINOR AND OF TSUNAMI GENERATION IN THE SEA OF MARMARA – Review of the 17 August 1999 Earthquake and Tsunami.

George Pararas-Carayannis

Tsunami Society International

ABSTRACT

The North Anatolian Fault Zone (NAFZ) is the most prominent active fault system in Northwestern Turkey. It is a major fracture that traverses the Northern part of Asia Minor and marks the boundary between the Anatolian tectonic plate and the larger Eurasian continental block, and has been the source of numerous large earthquakes throughout history. The NAFZ splits into three strands at the eastern part of the Marmara Sea. The northern strand passes through Izmit Bay, traverses the Marmara Sea and reaches to the Saros Gulf. The central fault zone passes through Izmit Bay, traverses the Sea of Marmara and reaches the Saros Gulf to the southeast. Earthquakes on this zone involve primarily horizontal ground motions (strike-slip type of faulting). Because of this unstable tectonic system, the area is considered to be as one of the most seismically active zones of the world. In the last hundred years, numerous large earthquakes have also occurred along the NAFZ, in the western part of Turkey. Beginning with an earthquake in 1939, several more quakes - with Richter magnitudes greater than 6.7 - struck in progression along adjacent segments of the great fault. The August 17, 1999 Izmit earthquake was the eleventh of such a series that have broken segments of the NAFZ, in both eastward and westward direction. The epicenter of the 1999 earthquake was near Izmit, as well as the location of previous events. The sequence of historic events indicates that the next destructive tsunamigenic earthquake could occur west of the 1999 event in the Sea of Marmara. The present study incorporates the results of a subsequent 2001 study which uses standardized remote sensing techniques and GIS-methods – based on Digital Elevation Model (DEM) data, and on geo-morph metric parameters that influenced local site conditions in the Sea of Marmara, as determined with Digital elevation data of the Shuttle Radar Topography Mission (SRTM), and with high resolution ASTER-data. With such remote sensing methods, areas that are potentially vulnerable areas in the Sea of Marmara were detected, so that disaster mitigation strategies can be implemented more effectively in the future. Based on such technology, local site conditions, which exacerbated earthquake intensities and collateral disaster destruction in the Marmara Sea region, were identified. Also reviewed by the present study are the similarities of NAFZ with the San Andreas fault in California in the USA, for the formation of an active transform boundary of the strike-slip type, with the two sides moving horizontally and continuously past each other. Finally examined is the tectonic and continuing geodynamic evolution and collision between the Arabian Plate and Eurasia, which places in danger many cities in southeastern Turkey and NorthWest Syria - which is are located on the boundary with the Arabian tectonic plate, as evidenced by the recent disastrous earthquake of 8 February 2023 along the Eastern Anatolian Fault Zone (EAFZ).

Keywords: *1999 Izmit earthquake, tsunami, landslides, Bosporus, Sea of Marmara, Dardanelles, GIS methods, Digital Elevation Model, Shuttle Radar Topography.*

1. INTRODUCTION

On August 17, 1999, a very destructive earthquake on the Northern Anatolian fault struck northwest Turkey and generated a local tsunami within the enclosed Sea of Marmara. Both the earthquake and the tsunami were particularly destructive at Golcuk in the Gulf of Izmit and at other coastal cities in the eastern portion of the Sea of Marmara. The earthquake was also responsible for extensive damage from collateral hazards such as subsidence, landslides, ground liquefaction, soil amplifications, compaction and underwater slumping of unconsolidated sediments. This was the strongest tsunamigenic earthquake to strike Northern Turkey since 1967, and it was recorded by many seismic stations around the world (Pararas-Carayannis, 1999, 1999a, 2000; Yalçiner EtAl, 1999; Altinok EtAl, 1999; Erdik, 2000; Altinok EtAl, 2001; Armijo EtAl. 2002, Taymaz EtAl, 2004; Herbert EtAl, 2005; Soirensen EtAl, 2006; Pararas-Carayannis EtAl, 2011).

Official estimates indicated that about 17,000 people lost their lives and thousands more were injured. However, it is believed that the death toll may have been much higher**.** On 31 August, a strong aftershock killed one person, injured about 166 others and knocked down some of the buildings that were already weakened by the main quake. Surprisingly the aftershocks caused a great deal of damage, which indicated that local conditions, exacerbated earthquake intensities of even weaker events to have secondary collateral destructive impacts. Most of the destruction and deaths resulted from such secondary collateral impacts at locations along coastal area of the Sea of Marmara that were particularly vulnerable because local geologic site conditions, exacerbated earthquake intensities. Therefore, it was determined that there was a need to identify and map such vulnerable sites, based on technology not previously available.

Thus, and as briefly stated in the abstract, the present study incorporated the results of a subsequent study in 2001 which used standardized remote sensing techniques and GIS-methods – based on Digital Elevation Model (DEM) data, and on geomorphometric parameters that influenced local site conditions in the Sea of Marmara, as determined with Digital elevation data of the Shuttle Radar Topography Mission (SRTM), and with high resolution ASTER- data. With such recent remote sensing methods and technology, areas that are potentially vulnerable in the Sea of Marmara were detected, so that disaster mitigation strategies can be implemented more effectively in the future. The use of such methods was documented by the author in collaboration with Professor Theilen-Willige of the University o f Berlin and Professor Wenzel in Austria (Pararas-Carayannis EtAl., 2011). More of these findings are discussed in greater detail in a subsequent section of this report. Figure 1 below is a map of the Sea of Marmara and of the Gulf of Izmit.

Fig. 1. Map of the Sea of Marmara and of the Gulf of Izmit.

The source mechanism and impact of the August 17, 1999 earthquake and tsunami, as well as those of other numerous historical events along the North Anatolian Fault Zone (NAFZ), have been studied extensively and reports have been published by numerous researchers, in addition to the ones mentioned above for events before and after 1999. These included the following: Altinok & Ersoy, 1998; Ansal EtAl., 2004; Barka & Kadinsky-Cade, 1988; Barka, 1992; Crampin & Evans,1986; Erdik, 2000; the Kandilli Observatory and Research Institute; the U.S, National Earthquake Information Center; Heidbach EtAl., 2008; Kuran & Yalciner, 1993; Ross EtAl, 1996; Toksoz EtAl.,1979; Spence (ed 2007). 2007.

1A. Earthquake Epicenter, Origin Time, Magnitude and Aftershocks

The epicenter of the 17 August 1999 earthquake was at 40.702 N, 29.987 E (USGS) near the town of Gölcük on the western segment of the North Anatolian Fault. The earthquake occurred at 00:01:39.80(UTC), 03:01:37 am local time, and its focal depth was shallow at 17 km. (USGS). The Izmit earthquake – as it was named - was measured widely by seismic stations around the world. However, there were small differences in magnitude determinations. The surface wave magnitude was given as 7.8 by the USGS, and its Moment Magnitude was given as Mw=7.4 by the USGS and by the Kandilli Observatory and Earthquake Research Institute (Kandilli). The Duration Magnitude was given as 6.7

(Kandilli), the Body Wave Magnitude as 6.3 (USGS), and as 6.8 (British Geological Survey). The earthquake resulted from right-lateral strike-slip movement on the Northern Anatolian fault, as many other seismic events in the past.

Numerous aftershocks with magnitude above 4 were recorded after the main earthquake. The first of the aftershocks (magnitude of 4.6) occurred 20 minutes later. Several others followed in subsequent days. According to the USGS and Kandilli most of the aftershock activity was confined to the region bounded by 40.5-40.8N and 29.8-30.0E, which covers the area between Izmit and Adapazari to the east of the epicenter (Pararas-Carayannis, 1999). However there was a cluster of aftershocks near Akyazi and Izmit.

Several days later, on 31 August, a strong aftershock killed one person, injured about 166 others and knocked down some of the buildings that were already weakened by the 17 August main quake. According to the USGS and Kandilli most of the aftershock activity was confined to the region bounded by 40.5-40.8N and 29.8-30.0E, which covers the area between Izmit and Adapazari to the east of the epicenter. However there was a cluster of aftershocks near Akyazi and near Izmit. Figure 2 shows the epicenter of the 1999 earthquake and the distribution of the larger aftershocks.

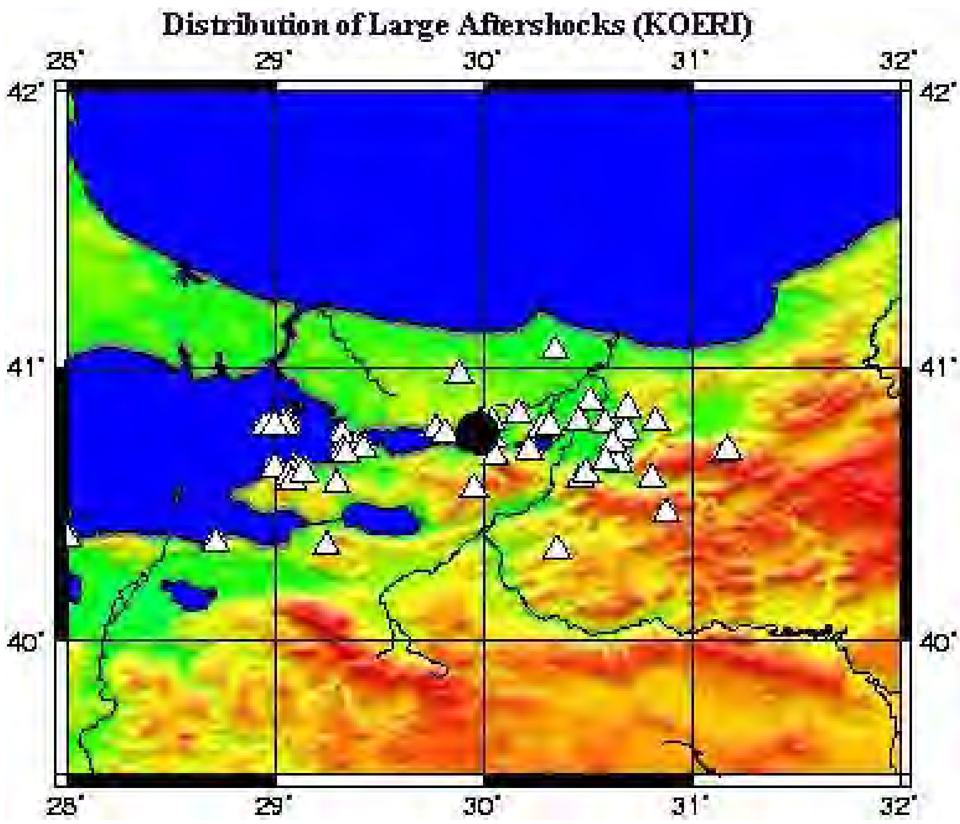

Fig. 2. Epicenter of the 1999 earthquake and distribution of the larger aftershocks

1B. Earthquake Destruction and Death Toll

The early historic record shows that in 1754, an earthquake near Izmit killed about 2,000 people. The earthquake struck a densely populated residential and industrial area, which included the major cities of Istanbul and Izmit. The more recent 17 August 1999 earthquake struck a densely populated residential and industrial area, which included the major cities of Istanbul and Izmit. The quake caused immense destruction to homes, apartment buildings, and oil refineries, to power and communication facilities. According to official reports the earthquake killed thousands of people and injured more than 16,000 others. The exact death toll for this event will never be accurately known as thousands were reported as missing.

Izmit - The earthquake in Izmit also caused immense destruction to homes, apartment buildings, and oil refineries. Many apartment buildings in the poorer section of Izmit collapsed burying thousands. Improper building construction was primarily responsible for the high death toll. Also, a huge fire at Turkey's largest oil refinery outside Izmit, destroyed several storage tanks.

Golcuk - At Golcuk about 500 buildings collapsed leaving about 20,000 people homeless. A Turkish naval base in the port of Golcuk sustained major damage. Reportedly, the collapse of the barracks killed 248 sailors.

2. TECTONIC AND GEODYNAMIC EVOLUTION - INSTABILITY OF THE NORTH ANATOLIAN AND OF THE EAST ANATOLIAN FAULT REGIONS

The source mechanism and impact of the August 17, 1999 earthquake and tsunami, as well as those of other numerous historical events along the North Anatolian Fault Zone (NAFZ), have been studied extensively and reports have been published by numerous researchers (Altinok & Ersoy, 1998; Altinok, et al., 1999, 2001; Armijo, et al. 2002; Ansal et. Al 2004; Barka & Kadinsky-Cade, 1988; Barka, 1992; Crampin & Evans,1986; Erdik, 2000; Kandilli Observatory and Research Institute; the U.S, National Earthquake Information Center; Hebert et.al,, 2005; Heidbach et.al,, 2008, Kuran & Yalciner, 1993; Pararas-Carayannis, 1999, 1999a, 2000; Pararas-Carayannis et.al. 2011; Ross et.al, 1996; Soìrensen, et.al, 2006; Taymaz et.al, 2004; Toksoz et.al 1979, Yalçiner et.al, 1999; Spence (ed 2007). 2007.

The excessive seismicity of this particular region can be explained by current geophysical knowledge of its structural development. The North Anatolian fault is a major fracture that transverses the Northern part of Asia Minor and marks the boundary between the Anatolian tectonic plate and the larger Eurasian continental block (Fig. 3). Because of this unstable tectonic system, the area is considered as one of the most seismically active zones of the world. Turkey is being squeezed sideways to the west as the Arabian plate pushes into the Eurasian plate. The north Anatolian fault forms the edge of this Turkish (Anatolian) crustal block so that destructive earthquakes happen regularly along it as different sections break. The Sea of Marmara is an inland sea separating Asia Minor from Europe. It is 280 km (175 miles) long and almost 80 km (50 miles) wide at its greatest width. On its northeast connects with the Black Sea through the Bosporus Strait. On its southwest end it connects with the Aegean Sea through the Dardanelles (Fig. 3). Although its total area is only 11,350 square km (4,382 square miles), its average depth is about 494 m (1,620 feet), reaching a maximum of 1,355 m (4,446 feet) in the center. The sea was formed as a result of tectonic movements that occurred about 2.5 million years ago, in the Late Pliocene. The region is characterized by frequent earthquakes.

Fig. 3. Tectonic map of the Anatolian Plate bounded by the African, Eurasian and Arabian plates - Modified After Nafi Toksoz of MIT/ERL

The Sea of Marmara is an inland sea separating Asia Minor from Europe. It is 280 km (175 miles) long and almost 80 km (50 miles) wide at its greatest width. On its northeast connects with the Black Sea through the Bosporus Strait. On its southwest end it connects with the Aegean Sea through the Dardanelles. Although its total area is only 11,350 square km (4,382 square miles), its average depth is about 494 m (1,620 feet), reaching a maximum of 1,355 m (4,446 feet) in the center. The sea was formed as a result of tectonic movements that occurred about 2.5 million years ago, in the Late Pliocene. The region is characterized by frequent earthquakes.

The earthquake of August 17, 1999 occurred along the long, East-West trending, great North Anatolian Fault Zone (NAFZ) - known to be the most prominent active fault system in Northwestern Turkey. NAFZ passes through Izmit Bay, traverses the Marmara Sea and reaches the Saros Gulf to the southeast. This great fault system has many similarities to the San Andreas Fault system in California. Earthquakes involve primarily horizontal ground motions (strike-slip type of faulting). Numerous large earthquakes have occurred throughout history. Figure 4 below, shows the epicenter of the 17 August 1999 earthquake and the chronological earthquake activity and sequence of major earthquakes along the Northern Anatolian Fault.

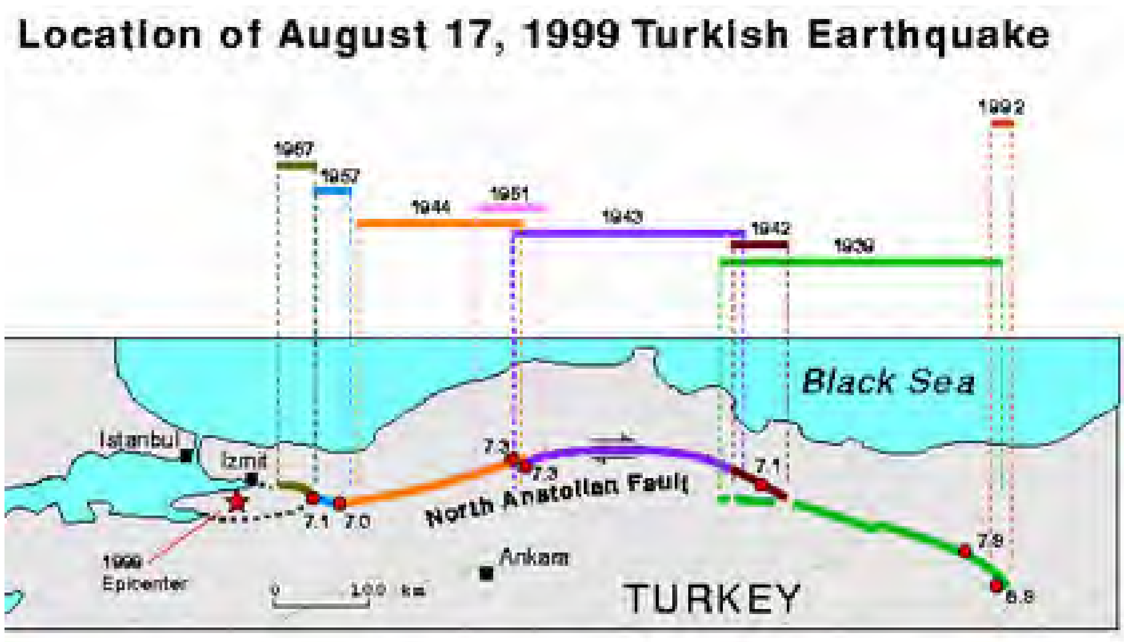

Fig. 4. Epicenter of the 17 August 1999 Earthquake. Historical Seismic Activity Along the Northern Anatolian Fault (Source: Kandilli Observatory and Research Institute)

2A. Earthquake's Surface Rupture and Ground Displacements

As stated, and shown in Figure 5 below, the 17 August 1999 Earthquake occurred along a known seismic gap on the North Anatolian Fault Zone. The earthquake's surface rupture extended for about 100 km east of Golcuk, but did not continue southeast and did not join the rupture of the 1967 earthquake - the last event in this region. Instead, the rupture turned northeast near Akyazi, where a cluster of aftershocks subsequently occurred. Ground displacements of about 1.5 m were measured in this area. Subsequent field studies indicated right lateral ground displacements ranging from 2.5-3 m up to 4 m, with a maximum of 4.2 m east of Lake Sapanca. Ground displacements between Lake Sapanca and the Gulf of Izmit were about 2.60 m. Additionally, there was evidence of about 2 meters subsidence along the north side of the fault's block - which was particularly evident along the coastline at Golcuk, where tsunami waves and major flooding occurred. Such tectonic ground displacements are characteristic of major earthquakes along the North Anatolian Fault and, possibly, have been responsible for tsunami generation in the past.

Fig. 5. Historical Earthquakes and Crustal Movements along the North Anatolian Fault (from Stein et al., 1996)

2B. Historical Earthquakes on the North Anatolian Zone of Turkey

Turkey is seismically very active on both the North Anatolian Fault Zone (NAFZ) and the Eastern Anatolian Fault Zone (EAFZ). The early historic record shows that in 1754, an earthquake near Izmit killed about 2,000 people. In the last hundred years, numerous large earthquakes have occurred along the Northern Anatolian Fault (NAF), on the western part of Turkey. Beginning with an earthquake in 1939, several more quakes - with Richter magnitudes greater than 6.7 struck in progression along adjacent segments of the great NAFZ fault zone. The 17 August 1999 Izmit earthquake was the eleventh of such series that have broken segments of the NAF, in both eastward and westward direction.

There has been an interesting pattern to this seismic activity. Historic seismic records indicate that between 1939 and 1944 there was an active westward trend in seismic activity on the NAF, with a resulting surface rupture of about 600 km. Subsequently, the westward trend of earthquakes slowed down. Figure 6 shows the epicenter of the 17 August 1999 earthquake on the northern strand of the NAF fault in the Sea of Marmara and the Saros Gulf, and its diverging central and southern strands in both the Sea of Marmara and on Turkey's north–west mainland.

Fig. 6. Branching of the NAF fault on its western segment.

Previous earthquakes that occurred in 1957 and 1967 ruptured an additional adjacent 100 km of the NAF, but there was separate activity further west during 1963 and 1964. The 1963 event (Richter magnitude 6.3) in the Sea of Marmara, to the west of Izmit, broke a section of the fault and killed only one person. The last strong earthquake (magnitude 7.1) to strike Northern Turkey occurred in 1967. It killed 173 people.

A long seismic gap separated the location of the 1967 quake and those of the 1963 and 1964 quakes. Quite predictably, the August 17, 1999 earthquake occurred on this gap, where apparently seismic stress had build up. The earthquake filled in the 100 to 150 km long gap, which existed. As early as 1979, numerous scientists had readily identified this gap as a potential site for a future earthquake. A subsequent evaluation in 1997 estimated a 12% statistical probability of an earthquake occurring in the 30-year period, from 1996 to 2026, in this region. Obviously, the statistical probability was underestimated as the earthquake occurred much sooner than statistical studies had anticipated.

Elsewhere in Turkey, a major earthquake (Richter magnitude 7.1) in 1970 near Gediz - about 160 km (100 miles) on the southern strand of NAF killed over 1,000 people. Its aftershocks continued for several years. In 1998, a less severe earthquake on the same southern strand killed 140 people.

2C. Strain and Seismic Gap Release of the North Anatolian Fault by the August 17, 1999 Earthquake. Effects of Seismic Stress Transference into the Aegean Sea.

It appears that most of the seismic strain along this section of the North Anatolian fault was released by the August 17, 1999 earthquake. However, given the measurements of 1.5 meter ground displacements in the Akyazi area, versus the larger displacements elsewhere, it is quite possible that not all of the seismic strain was released by this event and that some future seismic event will release the remaining strain. This may not happen for many years. Also, it appears that there was seismic stress transference to the west on the northern strand of the North Anatolian fault, as several earthquakes occurred subsequently in the Northern Aegean Sea (see Fig. 7).

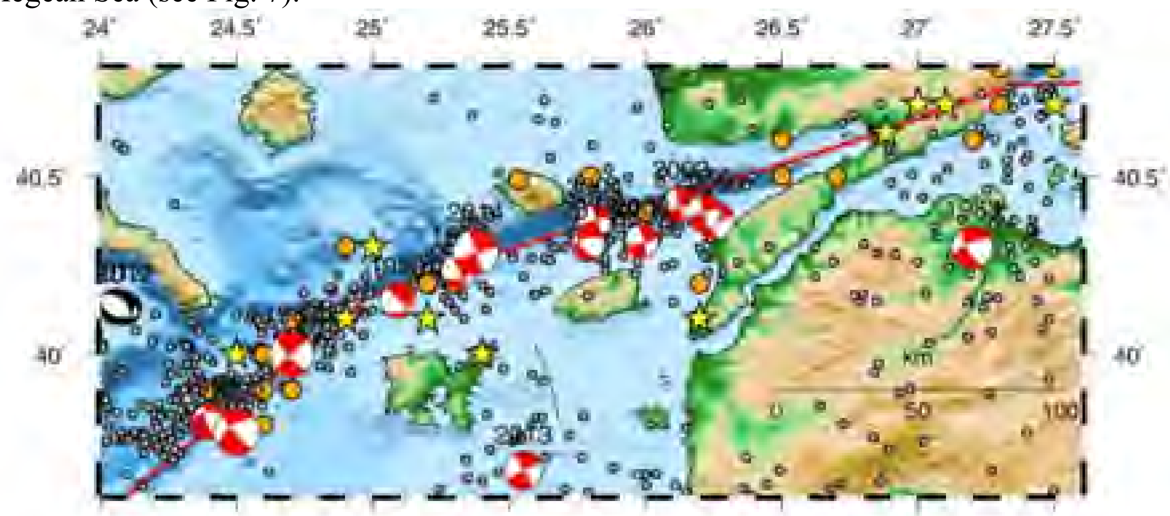

Fig. 7 Earthquakes along the northern strand of North Anatolian fault in the Aegean Sea.

A detailed analysis and measurements of the extension of the North Aegean Fault as it enters into the North Aegean Trough, provided evidence of change from a tectonically controlled simple strike-slip fault deformation, to dextral displacement within the eastern part of the trough and the Gulf of Saros, in the form of oblique en-echelon fractures (McNeil EtAl., 2004)

2D. Counter clockwise crustal block rotation of the Asia Minor Microplate. Effects of Stress Transference on the East Anatolian plate by northward movement and collision of the Arabian Tectonic plate resulting in the 8 February 2023 two earthquakes in Southeast Turkey and Northwest Syria.

Also indicated by the August 17, 1999 earthquake on the North Anatolian Fault are the effects of stress transference along a sinistral NW striking fault separating two sub-basins, which indicates counter clockwise crustal block rotation of the entire tectonic subplate of Asia Minor, as it is pushed northward at 16 mm/year by the Arabian tectonic plate (see Figure 8 below). In fact, based on this continuing collision and resulting stress, a prediction was made as early as 2013, that one or more significant earthquakes were overdue and expected along the East Anatolian plate, which would strike both Southeast Turkey and Northwest Syria (Pararas-Carayannis, 2013) - as indeed they occurred on 6 February 2023.

The counter clockwise rotation of the Asia Minor sub-plate is the result of a continuing geodynamic evolution that began long ago, when the Arabian plate was part of the African plate during much of the Phanerozoic Eon (Paleozoic – Cenozoic) and until the Oligocene Epoch of the Cenozoic Era. Because of the Arabian Plate and Eurasian plate collision, many cities in southeastern Turkey and Northwest Syria - which are along these boundaries - had major earthquakes.

Fig. 8. Collision of the Arabian tectonic plate with the Anatolian plate resulting in Stress Transference and in its counterclockwise rotation.

Figure 9 below shows in greater detail the effects of seismic stress transference along the East Anatolia Fault Zone (EAF) on the North Anatolia Fault Zone NAF by earthquakes such as that of 1999, and of its East-Southeast counterclockwise stress and branching of NAF into the Aegean Archipelago.

Fig. 9. Seismic stress transference on the North Anatolia Fault Zone (NAF) by earthquakes such as that of 1999, and of its East-Southeast counterclockwise stress and branching into the Aegean Archipelago.

2E. Possibility of Near Future Earthquake Recurrence in the Sea of Marmara.

Nearly 24 years have elapsed since the disastrous earthquake of 19 August 1999 on Turkey's North Fault Zone (NFZ) in the Sea of Marmara region. Based on an assessment of seismic stress transference, and the geodynamic complexity of the fault in this western region, it is very possible that not all such stress has been expended, and that another disastrous earthquake could strike and impact more populated areas along the Eastern Sea of Marmara, including Istanbul. Such an earthquake could affect critical structures on both sides of the Bosporus Strait, such as a connecting bridge, or even change the bathymetry of this significant navigable shipping waterway that links the Black Sea with **the** Dardanelles Straight and the Mediterranean Sea.

Another such earthquake on the NSF could reach a magnitude between 7.2 to 7.8, and could have devastating consequences for Turkey even worse than those of the 1999 event and could cause as many as 100,000 deaths. The timing of such an earthquake, however, is impossible to predict, as well as that of another similar to the 7 February 2023 on the East Anatolian fault (EAF). With these two major faults in North Anatolia and East Anatolia, Turkey is one of the most earthquake-prone regions in the world.

2F. Brief Review of Past Work on the 27 August 1999 Earthquake in the Sea of Marmara.

A brief description of the 27 August 1999 earthquake and tsunami in the Gulf of Izmit and elsewhere in the Sea of Marmara was published in 2011 (Pararas-Carayannis Et.Al., 2011). Accordingly, the tsunami was also responsible for extensive damage caused from collateral hazards such as subsidence, landslides, ground liquefaction, soil amplifications, compaction and underwater slumping of unconsolidated sediment.

As stated and although the earthquake involved primarily horizontal ground displacements, slumping and landslides triggered tsunami waves which were particularly damaging in the Gulf of Izmit, perhaps because of convergence and funneling effects. The long duration of the earthquake's ground motions for 45 seconds, the directivity of the surface seismic waves, the proximity of the epicenter to the Sea of Marmara and the Gulf of Izmit, and the overall orientation of the affected area, strongly supported that the tsunami was generated in the Gulf of Izmit, in the eastern portion of the Sea of Marmara. The tsunami waves from this earthquake had an extremely short period of less than a minute, which also supports the premise that the source was localized subsidence of coastal areas and underwater slumping of unconsolidated sediments, rather than larger scale tectonic movements, which involved primarily lateral motions. Figure 10 shows the destruction of buildings due to subsidence, as well as the effect of waves on boats.

An initial recession of the water, which was observed at both sides of Izmit Bay immediately after the quake, was followed by tsunami waves, which had an average run-up of 2.5 m. along the coast. Maximum run-up was 4 m in Golcuk, where there was considerable damage to the naval base facilities. In fact, Golcuk and several coastal areas are now flooded permanently as a result of the tectonic subsidence and landslides. Also, large coastal portions of the town of Degirmendere remained flooded as a result of subsidence - with sea level reaching the second floors of apartment buildings. Similar permanent flooding, but to a lesser extent, occurred also at Karamursel.

3. THE TSUNAMI OF 27 AUGUST 1999 IN THE SEA OF MARMARA

The lesson learned from this event is that tsunamis can occur in any body of water since a variety of mechanisms can generate them. Even earthquakes involving primarily horizontal ground motions (strike-slip type of faulting) can generate tsunamis by triggering slope failures and underwater landslides. Obviously the tsunami risk for the Sea of Marmara needs to be carefully evaluated. Measures must be taken to mitigate the effects of future tsunamis in the area. Better construction and building codes will definitely help.

Numerous large destructive earthquakes and tsunamis have occurred from antiquity to the present in the Ionian Sea, Greece, the Aegean Archipelago, Turkey and the Sea of Marmara - which separates Asia Minor from Europe. Large earthquakes with intensity greater than VIII on the Modified Mercalli scale have caused damaging or disastrous tsunamis - particularly along the Southern Aegean Sea. Most of the destructive tsunamis in the past originated from a region of the Hellenic arc where normal faulting within the southern part of the Anatolian Tectonic Plate (the Aegean plate) is consistent with a NE-SW trending graben along which the Santorin volcanic field has also developed. (Pararas-Carayannis, 1992).

3.1 Assessment of the Tsunami Potential in the Sea of Marmara and the Aegean Archipelago

Numerous large destructive earthquakes and tsunamis have occurred from antiquity to the present in the Ionian Sea, Greece, the Aegean Archipelago, Turkey and the Sea of Marmara - which separates Asia Minor from Europe. Fig.10 below is a photo of the tsunami-like impact of short period waves caused by land subsidence and not of tectonic origin.

Large earthquakes with intensity greater than VIII on the Modified Mercalli scale have caused damaging or disastrous tsunamis - particularly along the Southern Aegean Sea. Most of the destructive tsunamis in the past originated from a region of the Hellenic arc where normal faulting within the southern part of the Anatolian Tectonic Plate (the Aegean plate) is consistent with a NE-SW trending graben along which the Santorin volcanic field has also developed. (Pararas-Carayannis, 1992).

Fig. 10. Damage from the earthquake, tectonic subsidence, ground liquefaction and the tsunami. Ship in the foreground thrown onshore by tsunami wave action. Source: Kandilli Observatory and Research Institute (modified))

To a lesser extent, tsunamis have been also generated along the northeast portion of the Aegean Sea, and the Sea of Marmara. Although most of the earthquakes along the great North Anatolian fault involve primarily horizontal ground displacements - and such tectonic movements do not ordinarily generate tsunamis - some of the earthquakes along the western segment of the fault have triggered major slumps that have generated tsunamis. At least 9 major tsunamis have been reported to have occurred in the Marmara Sea in the past (Kuran and Yalciner, 1993). The most recent tsunami in the Eastern Marmara Sea was associated with the 18 September 1963 earthquake.

Strike-slip ground movement with a very small vertical component; can indeed generate a tsunami in a closed body of water. A combination of disturbances can be triggered by a large magnitude earthquake and several secondary mechanisms for the generation of tsunami waves are possible. Generative causes may include a combination of tectonic movements associated with the earthquake or major sub-aerial or underwater slides. Such secondary phenomena associated with a large earthquake can contribute to the generation of destructive waves particularly in an enclosed body of water like the Sea of Marmara. Tsunami generation will depend on the earthquake's energy release, the proximity of the body of water to the epicenter, the physical rupture along the fault, the propagation path of surface seismic waves, and the magnitude and duration of the dynamic, near-field, strong motions. Earthquake ground motions of high intensity could result in strong ground accelerations and the generation of waves in the immediate area of the earthquake (Pararas-Carayannis, 1999). Ground liquefaction can also trigger landslides, which in turn could generate destructive waves.

CONCLUSIONS

Based on the present analysis, it is believed that earthquakes occurring along the Western portion of the Northern Anatolian fault zone can generate destructive tsunami waves in the Sea of Marmara. A number of grabbens, fault offsets and other structural topo-morphological features at the bottom of the Sea of Marmara indicate that seismic activity and movements of branches of the North Anatolian fault extend under the sea.

Even an earthquake on land or a large aftershock could trigger a landslide in unconsolidated deposits or sediments along the coast. The tsunami danger is more pronounced in the eastern region of the Sea of Marmara and particularly in the Gulf of Izmit. Another significant earthquake further east close to Istanbul and the Bosporus is very possible in the near future and could be extremely destructive and result in great loss of lives. Thus the earthquake and tsunami risk for the Sea of Marmara needs to be carefully reevaluated. Obviously, government authorities will have to do some serious reviews of what measures must be taken to mitigate the effects of future earthquakes and possible tsunamis in the area. Better construction and building codes will definitely help. The potential for tsunami generation in the Sea of Marmara is substantial.

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