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Submarine earthquakes in South-West Anatolia until the 18th century and their probable seismic sources

Güney-Batı Anadolu'da 18. yüzyıla kadar olan denizaltı depremleri ve olası kaynakları

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Murat Ersen AKSOY[1,*]

[1]*Muğla Sıtkı Koçman Üniversitesi, Mühendislik Fakültesi, 48000, Muğla, Türkiye*

ABSTRACT

Submarine earthquakes in South West Anatolia's offshore region are a major threat to the coastal settlements therein. Many cities on Turkish and Greek territory suffered from earthquakes through historical time. The social and economic impact of these events have been documented in several historical earthquake catalogues. This article provides an analysis for the historical earthquakes from B.C. 2000 until the 18th century for the offshore region of SW Anatolia (Muğla Province). The summary consists of 17 earthquakes with intensities ranging from VII to X. A significant gap of earthquakes exists between the 6th and the 15th century (883 years). Available damage records concentrate on Rhodos and Kos island, with little information for the surrounding coastal region. Nevertheless, the historical and present day seismicity shows that the islands and coasts in SW Anatolia have experienced several destructive earthquakes between magnitudes of M_w 6 to 8. This fact should be taken into account in seismic hazard assessments and mitigation efforts for the area.

Keywords: Submarine earthquake, Seismic source, fault, Aegean, Mediterranean

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* (corresponding author)
E-mail: ersenma@mu.edu.tr

ÖZET

Güney Batı Anadolu'nun deniz açıklarında meydana gelen denizaltı depremleri bölgedeki yerleşimler için bir tehdit oluşturmaktadır. Türkiye ve Yunanistan sınırlarında yer alan yerleşimler, tarih boyunca birçok yıkıcı depreme maruz kalmıştır. Bu depremlerin sosyo-ekonomik etkilerine tarihsel deprem kataloglarında yer verilmiştir. Bu çalışma, M.Ö. 2000 ile 18. yüzyıla kadar, güney batı Anadolu'nun (Muğla bölgesi) deniz açıklarında meydana gelen depremlerini incelemektedir. Buna göre, bölgede 17 adet yıkıcı deprem belirlenmiştir. Depremlerin şiddeti 7 ile 10 arasında değişmektedir. Tarihsel kataloglarda, 6. ila 15. yüzyıl arasında 883 yıllık bir deprem kaydı eksikliği belirlenmiştir. Mevcut hasar bilgileri ise genellikle Rodos ve Kos çevresinde odaklanmakta ve çevre kıyı yerleşimleri için çok az bilgi sunmaktadır. Yine de tarihsel ve güncel deprem kayıtları güney batı Anadolu kıyıları ve açıklarındaki adalarda büyüklükleri M_w 6 ila 8 arasında değişen yıkıcı depremlerin meydana geldiğini göstermektedir. Bu durum bölgede yürütülecek deprem tehlikesi belirleme ve azaltma çalışmalarında dikkate alınmalıdır.

Anahtar sözcükler: Denizaltı depremi, Deprem kaynağı, fay, Ege, Akdeniz

1. INTRODUCTION

Submarine earthquakes and related mass-movements are noteworthy geo-hazards for coastal settlements and related infrastructure. Offshore earthquakes above a certain magnitude cause significant damage to such areas. The Aegean and Mediterranean coasts of south-west Anatolia (Muğla Province) have suffered from such earthquakes throughout history. This paper aims to summarize the historical seismicity of submarine earthquake from B.C. 2000 until the 18th century in the Muğla Province and discuss their potential sources.

1.1. Tectonic Setting

SW Anatolia is part of the Anatolian platelet, which is bounded by two large strike-slip plate boundary faults (Figure 1); the North Anatolian Fault (NAF) and the East Anatolian Fault (EAF). Anatolia moves westwards at a rate of 20 mm/yr. due to the convergence of the Eurasian, African and Arabian plates (Reilinger *et al*., 2006). The African plate subducts northward below the Anatolian plate along the Aegean and Cyprean arcs (Bozkurt, 2001 and references therein). The Aegean arc is Europe's seismically most active area and the source of several destructive earthquakes throughout history (Ambraseys, 2009).

The main seismic sources in the region are the Pliny-, Strabo- and Rhodos transform faults, Fethiye Burdur Fault Zone, Gökova fault, (Yolsal-Çevikbilen and Taymaz, 2012; Papazachos, 1999).

2. MATERIAL AND METHOD

Several catalogues exist for the historical seismicity of the Mediterranean and Aegean region (Ambraseys, 2009; Soloviyev *et al*., 2000; Pınar and Lahn 1952; Tan *et al*., 2008; Guidoboni *et al*., 1994, Guidoboni and Komatsi, 2005; Soysal *et al*., 1981). The work of Ambraseys (2009), is a multidisciplinary analysis of the seismicity of the entire Mediterranean area and the Middle East, covering the earthquake activity from of the last 4000 years. Guidoboni *et al*., (1994) is a catalogue for the Mediterranean region covering the time-span from B.C. 760 to AD 10th c. The seismicity post AD 10th c. until the 15th c. has been summarized in Guidoboni and Comastri (2005). The historical seismicity of Turkey

has been revised by Tan *et al*., (2008) where earthquakes since B.C. 2000 are available. Below is a summary and a discussion of historical earthquakes for south-west Anatolia coastal area. Particular emphasizes were given to shocks that were likely caused by offshore seismic sources.

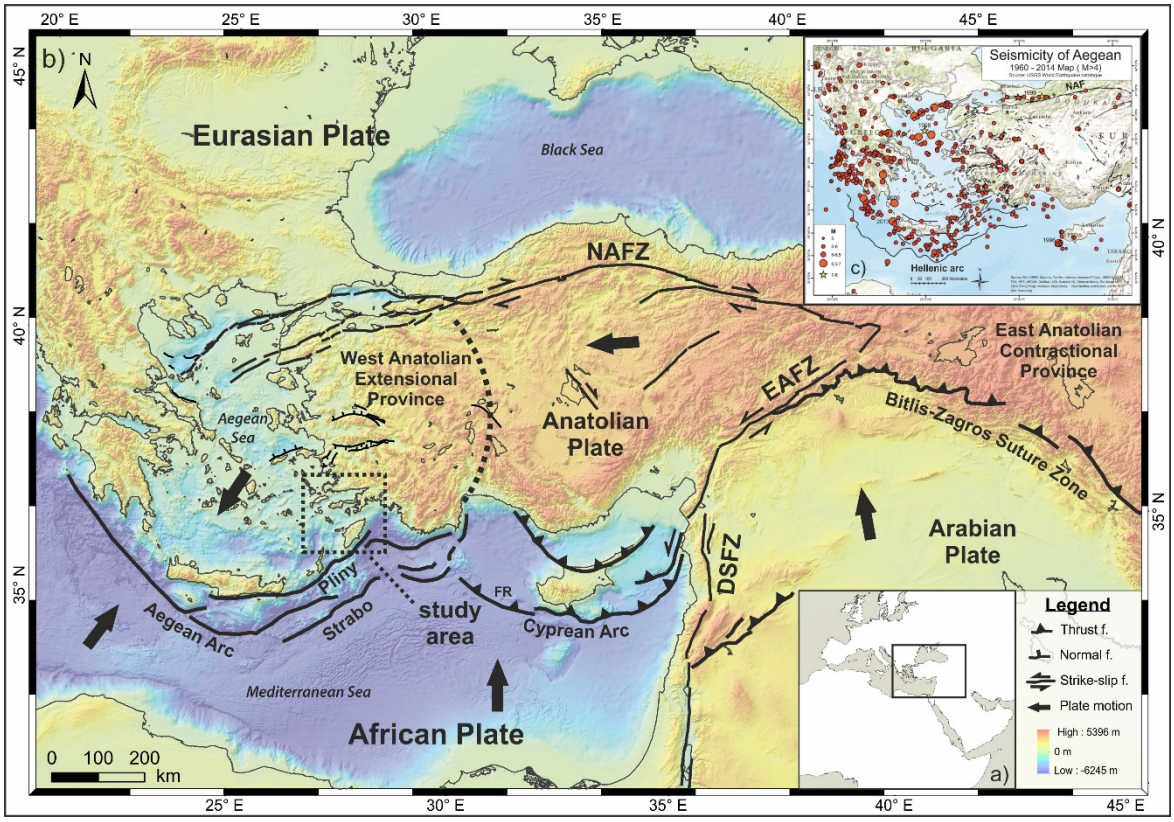

Figure 1. The Anatolian plate lies within the convergence zone between Eurasia and Africa (a, b). The collision of the Arabian plate with Anatolia causes a westward escape tectonism, together with a subduction along the Aegean and Cyprian arcs, Anatolia experiences a clockwise rotation. The complex tectonic setting of SW Anatolia (dashed box) causes earthquakes of different order of magnitude. In the figure the digital elevation and bathymetry model is SRTM30PLUS (Becker et al. (2009), faults are from Yolsal-Çevikbilen and Taymaz (2012), the seismicity in "b" is from USGS (2014) World earthquake catalogue.

3. RESULTS

3.1. Historical Seismicity

B.C. 412-411 Kos:

The record corresponds to the island of Kos and was described as an event that totally destroyed Kos. Following the earthquake the city was sacked by the Spartan commander. Villagers describe the earthquake as the severest event in living memory (Ambraseys, 2009; Guidoboni *et al*., 1994).

B.C. 227 Rhodes, Caria, Lycia:

This is a large earthquake that has been reported mainly in Rhodes. Damage of the Colossus of Helios (Rhodos; one of the seven wonders of the World) has been

reported by several contemporary accounts. Besides, many cities of Caria and Lycia region are mentioned to have suffered damage (Guidoboni *et al*., 1994; Ambraseys, 2009). According to Strabo the earthquake destroyed the lighthouse-statue of Collosus of Rhodos, the fortress and landing pier. Ships were destroyed too (Soloviev *et al*., 2000). This is most likely an offshore earthquake within the Hellenic arc and is accompanied by a tsunami.

B.C. 199-198 Dodecanese, Rhodes, Caria:
This is an earthquake in the Aegean Sea that hit Dodecanese, Rhodes and other cities of Minor Asia (Anatolia). Walls and towers collapsed in Rhodes-Camirus. Similarly, damage of walls was reported in Panamara, a city close to Yatağan – Bağyaka (Guidoboni *et al*., 1994; Ambraseys 2009, Soloviev *et al*., 2000). Ambraseys (2009) notes that despite existing records fall into the same time period, it is difficult to attribute references to one single shock.

B.C. 24 Kos:
An earthquake hit the Kos island causing extensive destruction. The city was completely re-build (Ambraseys, 2009). Guidoboni *et al*. (1994) reports this event to B.C. 27 when Laodicea (Denizli), Thiatyra (Manisa) were also struck by an earthquake.

46-47 Miletus - Bodrum
Ambraseys (2009) attributes this event to Miletus, while mentioning that some records claim damage in Halicarnassus due to an earthquake. Guidoboni *et al*. (1994) expand the affected area including Ephesus, Loadicea, Kos and Samos. The source is not clearly identifiable, but probably lies inland somewhere in the Menderes graben.

A.D. 141/142 Gökova, Kos, Rhodos:
After Guidoboni *et al*. (1994) the date (142-144) and the earthquake epicentre area are not well constrained for this event. Nevertheless, extensive damage for the entire Caria region is reported within all contemporary accounts. Ambraseys (2009) provides a better constrain and documents that these records correspond to two separate events.

AD 141 Gökova: The first shock probably occurred in the Gulf of Gökova, because Stratonicea was severely damaged and received a large sum of financial support from the Emperor Antoninus for rebuilding the city (Ambraseys, 2009). Kos, Simi and Rhodes have also suffered from this shock. According to Altunel *et al*. (2003), Knidos has also been affected from an earthquake within the same time period.

AD 142 Kos, Rhodos, Dodecanese: A second large shock has affected a very wide area in southwest Turkey including the island Cos, Rhodes and Dodecanese. The distribution of damage covers nearly the entire Caria and Lycia regions. Stratonicae suffered probably from both events and was therefore heavily damaged. Ambraseys (2009) provides details on the timing of the shock and extension of the damage. Therefore, the description of the second indicate a large magnitude earthquake M > 7.5 that most probably occurred offshore in the Mediterranean along the Hellenic arc.

AD 465 July 6 Knidos,
An earthquake caused damage to Knidos and Kos, the event affected also Ionia and Cycladic islands (Ambraseys, 2009). At Knidos, part of the city walls collapsed. Kos was totally destroyed (Guidoboni *et al*., 1994). Altunel *et al*. (2003) documented archaeological evidence of the destruction in Knidos.

AD 515 Rhodos,
An earthquake caused large destruction in the Rhodos island, killing many people (Ambraseys, 2009). In fact, more earthquake are mentioned for Rhodos at the same interval (Guidoboni *et al*., 1994).

AD 554-558 Kos
An earthquake and followed tsunami almost destroyed completely the Kos island. Stone houses were ruined, while mud or unbacked brick houses survived the shaking. The height of the sea-waves are described as enormous swallowing many buildings and sweeping away habitants (Guidoboni *et al*., 1994; Ambraseys, 2009).

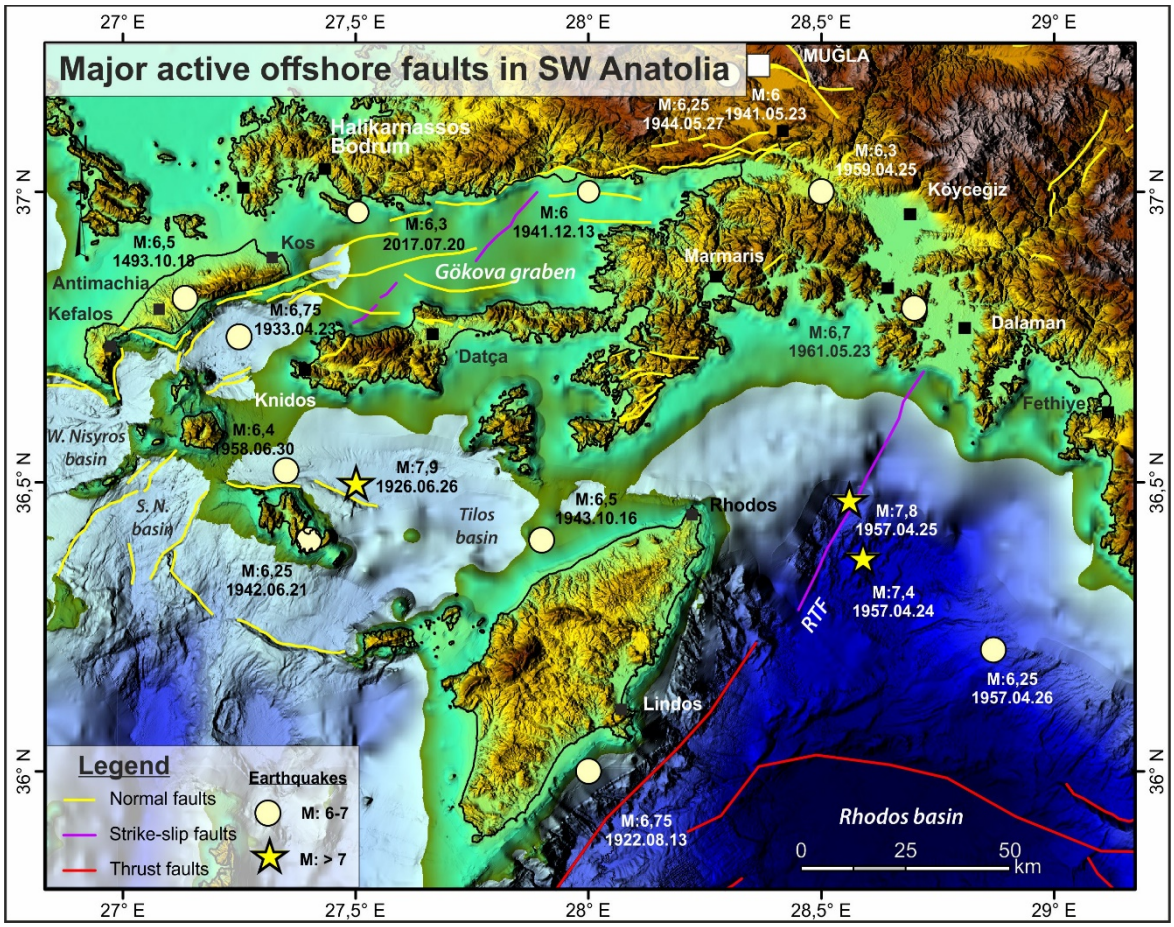

Figure 2. There are several seismic sources offshore of SW Anatolia that caused large and destructive earthquakes within the islands and coastal settlements. The seismicity of the instrumental period by Tan *et al*., (2008) for 1900 to present allows a better constrain for their source faults compared. In the figure, the digital elevation and bathymetry model is from EMODnet, faults are compiled from Yolsal-Çevikbilen and Taymaz (2012), Ganas *et al*., (2017), Tiryakioğlu *et al*., (2018), İşcan *et al*., (2013), Kurt *et al*., (1999) Ocakoğlu et al., (2018) and Nomikou and Papanikolaou (2011). RTF: Rhodos Transform fault.

The association of a tsunami indicates that the earthquake occurred on an offshore fault, if not causing a sub-marine landslide. Between the 554 and 1437 there are no earthquakes reported in catalogues for this area (Ambraseys, 2009, Guidoboni *et al*., 1994; Guidoboni and Comastri, 2005).

AD 1437 Kos

There is limited information on the event, reporting an earthquake destroyed buildings and castles (Ambraseys, 2009). The event is not mentioned in Guidoboni and Comastri (2005).

AD 1481 May 3 – December 18, Rhodos

Guidoboni and Comastri (2005) reports a sequence of large shocks that occurred on 3 May, 3 October, 17, 18 (2 or 3 events), 19 December 1481 all affecting Rhodos. Among these events only the 3 May event caused a tsunami and the second shock of 18 December caused serious damage in Rhodos. Same events are mentioned by Ambraseys (2009), however he writes that on the 18th there were three earthquakes and the damage was from the third event. Both authors mention about fissures and ground openings during the 18 December event.

Interestingly only on the 3 May event tsunami waves hit Rhodos city. Three-meter high waves hit a ship against cliffs and sunk it.

Table 1: Historical earthquakes that caused damage in the coastal areas of SW Anatolia. 1- Ambraseys, 2009, 2- Guidoboni *et al*., 1994; 3- Guidoboni and Comastri, 2005, 4- Soloviev *et al*., 2000. Mag=Ms, Io: Intensity from AFAD Historical Earthquake Catalogue and Soysal *et al*., (1981); Possible source faults abbreviations: a- Rhodos Transform Fault, b- Pliny-Strabo Trench faults, c- Rhodos basin margin faults, d-faults near Nisyros, e- Northern Gökova graben faults, f- southern Gökova graben faults; g- Kos faults see figure 1 and 2 for location.

Date	Affected locations*	Mag.	I_o	Possible Source	Ref
BC 412-411	Kos		VIII	e,f,g	1,2
BC 227 +	Rhodos, Caria, Lycia		X	a,b,c	1,2,4
BC 199-198 +	Dodecanese, Rhodos, Caria		VIII	a,b,c	1,2,4
BC 24	Kos			e,f,g	1,2
46-47	Miletus (Bodrum)		VIII	e	1,2
141 +	Gökova, ,Stratonicea, Knidos		VIII	e	1,2
142	Kos, Rhodos, Dodecanese, entire Caria and Lycia	7.5	VIII	a,b,c	1,2,4
06.07.465	Knidos		VII	d,f	1,2
515	Rhodos		VII	a,b,c	1,2
554-558	Kos		X	e,f, g	1,2,4
883 year gap of any seismicity record					
1437	Kos			e,f, g	1,3
3.05.1481	Rhodos		VIII	a,b,c	1,3
03.10.1481	Rhodos			a,b,c	1,3
18.12.1481	Rhodos			a,b,c	1,3
18.12.1481	Rhodos		IX	a,b,c	1,3
19.12.1481	Rhodos			a,b,c	1,3
18.10.1493	Kos (Bodrum)		IX	e,f,g	1,3

AD 1493 October 18 Kos

The earthquake hit mainly Kos and caused heavy damage to dwellings and the fortifications also in the other villages of Kos (Asfendiou, Kefalos, Antimachia, Kokkino and Pilli). The earthquakes seems to have affected Bodrum too and probably the famous mausoleum of Halicarnassus collapsed for the last time during this event (Ambraseys, 2009; Guidoboni and Comastri, 2005)

3.2. Instrumental Seismicity

During the instrumental time period, (~80 years) observatories recorded 9 shocks with M_w 6-7 and 3 events with M_w: >7. The epicenters of these shocks are given in figure 2. The Rhodos Transform Fault (RTF) and its southern continuation is the source of two M_w >7 earthquakes. The epicenter of the other M_w 7.9 shock however is in the Tilos basin, closely located to two other M_w 6.4 and 6.3 earthquakes. There are five M_w >6 shocks in the Gökova graben and Kos area.

4. DISCUSSIONS

The historical earthquake catalogues enable evaluating the level and distribution of the damage and assign and intensity value for the events. The intensity consequently allows an approximation of the order of earthquake magnitude. However, epicenter and source fault estimations with historical data involves ambiguity. Nevertheless, knowing the approximate magnitude of an historical earthquake may allow determining a suitable dimension for the responsible fault using scaling laws (Wells and Coppersmith, 1994). If multiple faults exist in the region, the ambiguity remains if not the earthquake may be attributed to that fault.

The history of SW Anatolia dates back almost for 5000 years. The available historical earthquake data for the regions is however limited to the last 2500 years with a large period of 880 years with no record. The period coincides within the division of the Roman Empire and the rule of the East Roman Empire in the region. The absence of information may be related to this event. The timing of the events varies among catalogues, particularly many earthquakes in Soysal *et al*., (1981) were on different dates compared to the modern work of Ambraseys (2009). In addition, historical accounts report damage largely for Kos and Rhodos while information for other important coastal settlements such as Bodrum, Fethiye, Dalaman, Gökova, Marmaris, Datça, Tilos, Lindos and Nisyros are limited or do not exist.

Although, the unbalanced distribution of information hinders the assessment of the source faults, some consideration and classification of source areas is possible (Figure 1, 2, Table 1). The length of the fault in the Kos and Gökova area are suitable for M_w >6 earthquakes (Wells and Coppersmith, 1994). The Gökova Graben consists of several normal faults, along its Northern and Southern margins. Besides, some authors suggest left lateral strike-slip faulting, limiting the Gökova basin (İşcan *et al*., 2013). The faults NE of Kos are another important source for large earthquakes. The most recent event in this area is the 20 July 2017 Bodrum-Kos earthquake (M_w 6.3; Ganas *et al*., 2017). Information on offshore faults in the Tilos basin are very limited. The North and South of Nisyros island is bounded by normal faults (Nomikou and Papanikolaou, 2011). Two major seismic sources exist in the North. The total length of these faults is about 40 km and may likely the source of the 1958 M 6.4 event but is unlikely to produce the 1926 M.7.9 shock (Figure 1). A source for major earthquake, exceeding M_w 7, are the faults along the Pliny-Strabo trenches and the Rhodos basin. Therefore such large earthquakes in the study area are most

likely produced by these plate boundary faults. The most recent M_w 7.8 and 7.4 earthquakes that hit Fethiye and Rhodos area occurred most likely on the Rhodos Transform fault.

The historical catalogues and present day events also document that earthquakes in these offshore areas are associated with secondary effects. Tsunamis have been documented for the B.C. 227 and AD 554 earthquakes. Besides, the 2017 Bodrum-Kos earthquake (M 6.3) triggered a small tsunami that did not cause any casualties but economic loss by inundating coastal facilities.

5. CONCLUSIONS

A comprehensive analysis in historical catalogues for the time period of B.C. 2000 until 19th century for SW Anatolia and Greece region showed that numerous earthquakes hit the area severely; resulting in both loss of life and economy.

The catalogues provide information on 17 events. The available intensities for the earthquakes have been summarized in Table 1. Significant difference of dates and intensities are observed among the catalogues; which require further analysis. No record of seismicity was found for the period of AD 558 to AD 1434, a period of 883 years. Further studies are required in order to understand if this gap is due to the absence of seismicity or the historical record.

The present day seismicity shows that the majority of earthquakes may are at the order of M_w 6-7, however can reach up to M_w 7.8 in the region. The seismic sources can be classified into tectonic sub-region. The faults at the Pliny-Strabo trenches and the Rhodos basins form the plate boundary of the subduction between Africa and Anatolian plate. Therefore very large earthquakes (M_w>7) occur most likely on these faults. The Gökova graben and the adjacent Kos offshore area consist of several E-W oriented S and N dipping normal faults. These faults are sources for earthquakes of M_w 6-7. Similarly the North and the South of Nisyros island consist of several normal faults that can produce earthquakes of similar magnitude (M_w 6-7).

The coastal area and islands of SW Anatolia and Greece are major tourist attraction points. In both countries, tourism contributes largely to the economic income. Environmental and economic factors attract also more people to region and increases the permanent population.

Therefore, the assessment and mitigation of earthquake and related geohazards are critical challenges for the economic, social and environmental sustainability of this region.

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DISCLOSURE STATEMENT

The author declare there is no conflict of interest.

ORCID ID

Murat Ersen AKSOY:
https://orcid.org/0000-0002-7778-2018

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