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Late Quaternary subsidence records from the Datça graben and Cnidus ancient city (SW Turkey): Sea-level changes versus tectonics

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ABSTRACT

The Datça Graben in southwestern Anatolia is a WNW-trending seismically active depression, with tectonic activity since Pliocene time. This tectonic activity is controlled by normal faults, which have effected ancient settlements. The Cnidus city (old and modern) –an ancient mercantile centre during the Hellenistic, Roman and Byzantine periods– is one of the places that has recorded this activity. The ancient harbour walls of Cnidus, lying 2.2-4.0m below sea level, contain important traces about sea-level changes and tectonics over the past 2.6kyr. Palaeostress analysis along boundary faults in the Datça graben yields an almost N–S oriented pure tensional regime, compatible with earthquake focal mechanism solutions located around the Datça peninsula. Additionally, an almost E–W trending surface rupture related to a historical earthquake in modern Cnidus, which shows normal fault characteristics, gives further support to the ongoing extension along the Kızlan, Karaköy and Cnidus fault zones. Previous studies on late Quaternary sea-level changes around the Datça peninsula suggest that 2.6kyr ago sea level was 1.0-1.25m lower than today. From the present-day depth of the old Cnidus harbour remains and regional sea-level records, it can be inferred that tectonics has played a significant role. Our calculations show that the Datça graben is subsiding at rates of 0.36-0.46mm/yr in the central part and 1.05-1.15mm/yr in the southern part. These values match those found in other areas around the Datça peninsula.

KEYWORDS **Cnidus; Datça graben; Eastern Mediterranean; Quaternary tectonics; SW Turkey.**

INTRODUCTION

Sea-level fluctuations are mainly related to climate changes (Flemming *et al.,* 1998; Vacchi *et al.,* 2014) and tectonics (Donovan and Jones, 1979; Fairbridge, 1961). Thus, shoreline variations are the result of complex interactions between sediment deposition, sea-level changes, regional tectonics and climate (Haq, 1991).

Fluctuations incompatible with global sea-level oscillations are defined as relative sea-level changes (Vail *et al.,* 1977). Global and relative sea-level fluctuations must be properly separated in order to extract the effect of regional tectonics.

The Mediterranean region is recording both global and relative sea-level oscillations (*e.g.* Haq, 1991; Hsü *et al.,* 1973; Krijgsman *et al.,* 1999). Several historical ruins located in the eastern Mediterranean coasts preserve records of sea-level changes, as well as sedimentological and structural records (*e.g.* Altunel *et al.,* 2003; Anzidei *et al.,* 2011).

Western Anatolia, located in the eastern part of the Mediterranean region, is known to be one of the most seismically active areas in the world. This seismicity is caused by the interaction between African and Anatolian plates, which has given rise to continental extension, and basin formation (*e.g.* McKenzie, 1978; Şengör and Yılmaz, 1981).

The Datça Peninsula, located in the southern part of Western Anatolia, is an area subjected to active tectonics and sea-level changes. It seems that several E–W trending active faults controlled the formation of the Datça graben.

The Cnidus ancient cities (old and modern) were settled in the Datça Peninsula between the 7th and 3rd centuries B.C. (Bean and Cook, 1952; Grant, 1986). The Modern Cnidus city is located in the westernmost part of the Datça Peninsula at a distance of around 30km from the old city. Both cities were important coastal mercantile centres in areas of active tectonics. The most remarkable indicators are the harbours of these ancient cities, which are now situated below sea level.

This study aims to investigate why the old and modern Cnidus harbours are nowadays located below sea level and to determine the geological features and rates of the driving forces causing it.

METHODS

The ancient ruins located in the Datça Peninsula might be affected by: i) active tectonics leading to relative sea-level changes and ii) global/local sea-level fluctuations due to climatic changes. Slip-data of outcropping faults were collected for kinematic and stress inversion analysis. The relative time of fault activity has been inferred from cut-off relationship between the stratigraphic sequence and faults. Angelier's Direct Inversion method (ver. 5.42) has been used to analyse the fault-slip data (Angelier, 1991). For the characterization of the palaeostress field, the vertical/subvertical stress axis and the R= $[(\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)]$ ratio was taken into account (Delvaux and Sperner, 2003). Stress fields may vary according to R-ratio (Delvaux *et al.,* 1997). Then, palaeostress fields were compared with focal mechanism solutions of the recent earthquakes occurred around the Datça Peninsula in order to check the relationship between the active faults mapped and the present-day stress field.

The record of sea-level changes around the Mediterranean and Aegean regions (Vacchi *et al.,* 2014) has been used to extract tectonic subsidence. The two ancient harbour remains have been geo-refereed using Google Earth images and bathymetry maps.

GEOLOGICAL SETTING

Regional geology and tectonics

The Anatolia region is affected by the northward motion of the African and Arabian plates against the relatively stable margin of the Eurasian plate (Şengör and Yılmaz, 1981; Şengör *et al.,* 1985). This convergence is accommodated by the North and East Anatolian Fault Systems that displaced westwards the Anatolian plate (Barka and Reilinger, 1997; Şengör, 1979; Şengör and Yılmaz, 1981). The southwestern movement of the Anatolian plate towards the Aegean arc causes N–S oriented continental extension (McKenzie, 1978; Meulenkamp *et al.,* 1988; Şengör and Yılmaz, 1981) (Fig. 1A). Different models have been proposed for the origin of this extension such as tectonic escape, back-arc spreading, orogenic collapse, and episodic two-stage graben (Bozkurt, 2000; Meulenkamp *et al.,* 1988; McKenzie 1978; Şengör and Yılmaz, 1981; Şengör *et al.,* 1985; Seyitoğlu and Scott, 1991). GPS measurements indicate counter-clockwise rotation of the western Anatolia region (McClusky *et al.,* 2000; Morris and Robertson, 1993).

A system of E–W trending grabens and horsts characterizes western Anatolia (*e.g.* Alçiçek, 2010; Dirik, 2007; Ocakoğlu *et al.,* 2014; Özsayın, 2016; Sümer *et al.,* 2013) (Fig. 1B), where extension occurs at rates of 30-40mm/yr (McClusky *et al.,* 2000). These E–W trending grabens cross-cut N–S trending grabens and were formed during Early Miocene. The rotation mentioned above reactivates the N–S-trending grabens together with the E–W ones (Yılmaz *et al.,* 2000).

Records of sea-level changes in the Mediterranean region

Sea-level change is the sum of eustatic and tectonic factors. A study, performed in Italy, indicated +4m eustatic sea-level change during the Holocene for the Mediterranean region (Lambeck *et al.,* 2004a). The Holocene relative sea-level fluctuation shows regional differences that result from

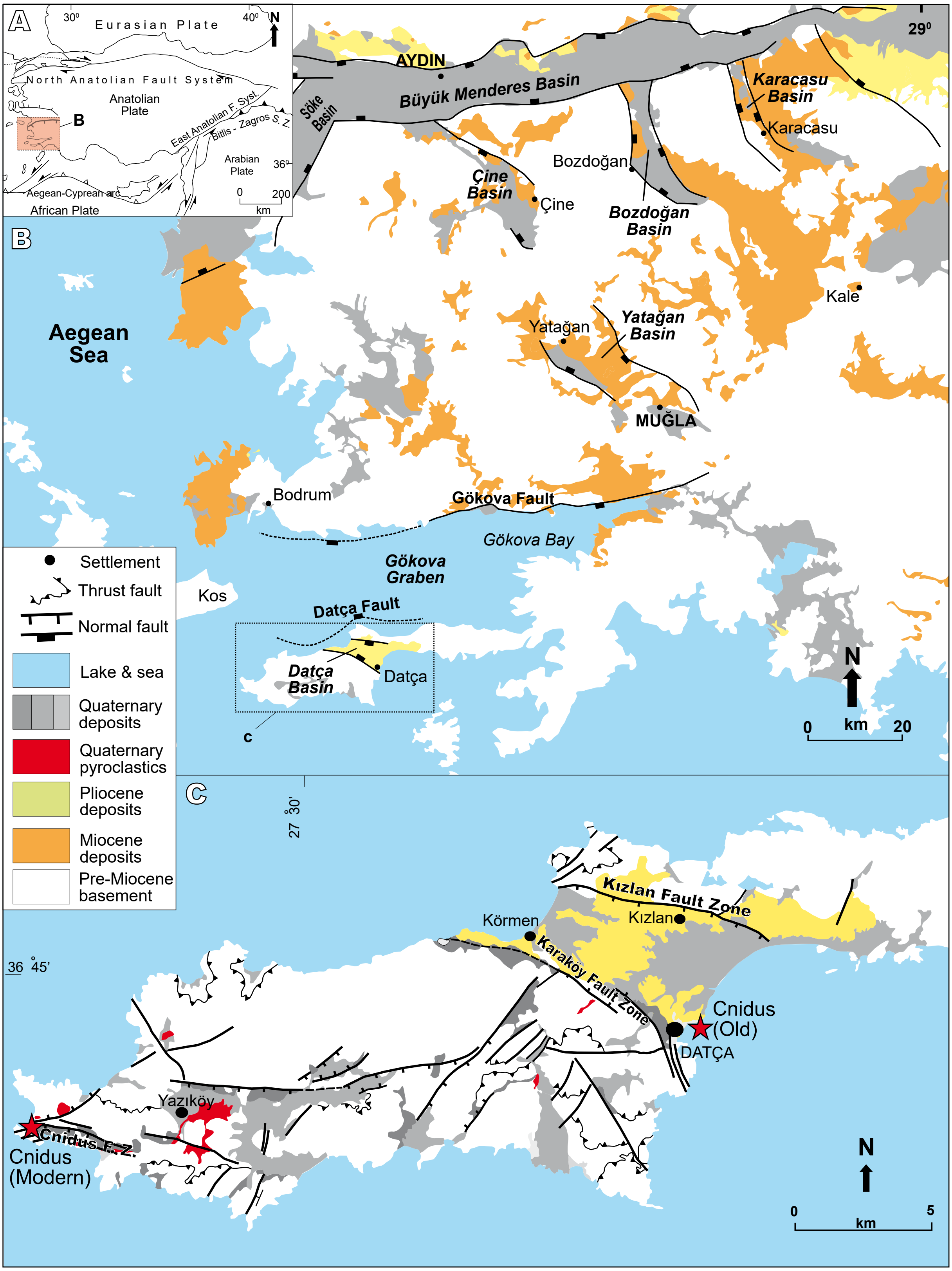

FIGURE 1. A) Simplified map showing the major plates and bounding structures around the Anatolian plate. B) Major neotectonic structures in the western Anatolian province (Şenel, 2002; Tur *et al.*, 2015; simplified from Özsayın, 2016). C) Geological map of the Datça Peninsula showing location of the old and modern Cnidus (Dirik, 2007; Ersoy 1991).

the effect of regional tectonics. Relative sea-level changes are calculated as -80cm in the last 5000 years in Almeria, Spain (Goy *et al.,* 2003), +1.6m in the last 5000 years in the Provençal Coast, France (Pirazzoli, 2005), +14m in the last 9000 years in Apulia, Italy (Roy and Peltier, 2018), +35m in the last 10000 years in Brijuni, Croatia (Antonioli *et al.,* 2007), +7m in the Büyük Menderes delta, Turkey in the last 6000 years, and +7m in the last 7000 years at the Dalyan delta, Turkey (Brückner *et al.,* 2010).

According to the location and position of the ruins, several sea-level measurements have been carried out from neighbouring regions such as Greece, Cyprus, Israel or Lebanon as well as Turkey for the same period (*e.g.* Lambeck *et al.,* 2004b; Lambeck and Purcell, 2005; Lykousis, 1991; Morhange *et al*., 2006; Pavlopoulos *et al*., 2013).

Geology of the Datça Peninsula

The units exposed in the Datça Peninsula are divided into two main groups: basement rocks of Pre-Pliocene age, and Plio-Quaternary deposits that constitute the basin-infill (Fig. 1C).

The basement rocks contain Lower Triassic–Cretaceous ophiolitic mélanges, crystalline carbonates, radiolarite and cherty limestones of the Lycian Nappe Units and Beydağları platform carbonates (Ersoy, 1990). Also, Upper Cretaceous clayey limestone-marl alternation and Upper Cretaceous–Lower Eocene flysch deposits are considered as basement rocks (Dirik *et al.*, 2003; Dirik, 2007; Ersoy, 1991). The basin-infill sequence initiates with lower Pliocene continental clastic rocks that unconformably cover the basement rocks. They are composed of greenish brown and beige conglomerates, containing serpentinite, radiolarite, marble, and peridotite pebbles (Dirik *et al.,* 2003; Dirik, 2007; Ersoy, 1991). These clastic rocks are unconformably overlain by late Pliocene light brown, marine conglomerate-sandstone-marl alternations. Pleistocene continental conglomerates with intercalations of sandstone and mudstone are located at the southwestern margin of the Datça graben, unconformably overlying the marine sequence. White-coloured pyroclastic rocks (Dirik *et al.,* 2003; Dirik, 2007), dated to 161ka by the Ar-Ar method (Smith *et al.,* 1996), unconformably overlie the conglomeratic formation. The youngest units are terrace deposits, colluvium, talus, alluvial fans, beach rocks, beach sands and alluvium.

RESULTS

Structure of the Datça Peninsula

The WNW-trending Datça graben is a depression ca. 10km-long and 5km-wide (Fig. 2), bounded by the Kızlan

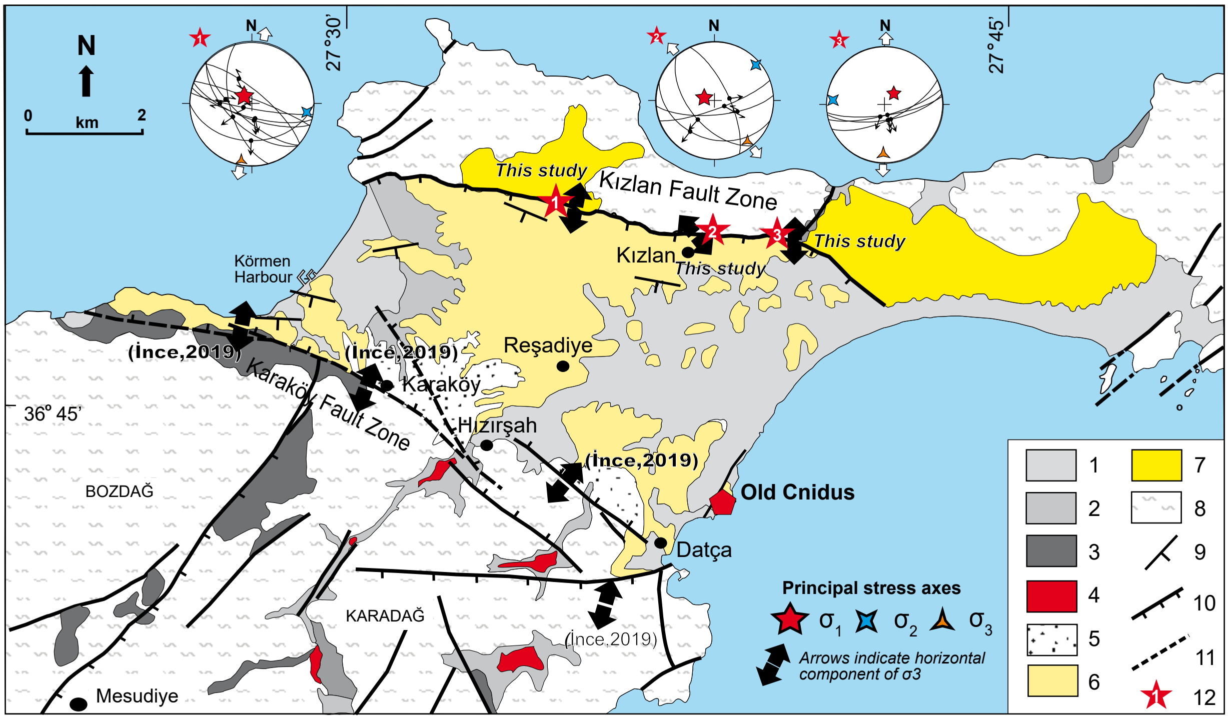

FIGURE 2. Geological map of the Datça Graben and surrounding area [1. Alluvium, 2. Alluvial fan, 3. Talus, 4. Pyroclastics, 5. Quaternary terrestrial clastics, 6. Pliocene marine sequence, 7. Pliocene terrestrial clastics, 8. Basement rocks, 9. Dip and strike of bedding, 10. Normal fault, 11. Inferred fault, 12. Stations of slip-data measurements] (modified from Dirik, 2007; Ersoy, 1991).

fault zone in the north and the Karaköy fault zone in the south (Kahraman *et al.*, 2013). Furthermore, two major faults are located close to Modern Cnidus, the Cnidus fault in the south and the Damlaca fault in the north (Fig. 3).

The N100º-trending Kızlan fault zone is about 10km-long and formed by S-dipping normal faults (Fig. 4A). This trend can be followed for approximately 2km from the northeast of the Körmen harbour to Kızlan. At Kızlan, the fault changes its trend to the E–W and continues for about 2km eastwards, and finally it changes the strike to N122º. Fault scarps, triangular facets, alluvial fans and the lineation of the vegetation along with the fault trend evidence the recent activity of these faults (Fig. 5A). The Kızlan fault zone juxtaposes basement units and Pliocene clastics with the Pliocene marine sequence and younger units of the basin infill. Colluvium and fault breccia can be observed in the fault planes (Fig. 4B). Slickenlines are well-preserved along the basement (footwall), which have been used for paleostress analysis yielding N–S-oriented extension (Fig. 2; Table 1).

The NW-trending Karaköy fault zone is approximately 9km-long and composed of two segments (Fig. 2). The western segment extends 3km from the Körmen harbour to Hızırşah with a trend of N097º. The eastern segment trends N117º and has a trace ca. 2km-long. At Hızırşah, the fault steps over 1 km northwards and continues 3km to the Datça harbour with a trend of N120º. The Karaköy fault zone marks a slope break and a vegetation lineament (Fig. 5B). This fault zone juxtaposes basement units with Pliocene clastic and marine rocks. A previous study indicates a NNE–SSW to NE–SW oriented extensional regime for this fault (İnce, 2019) (Fig. 2).

Modern Cnidus is cross-cut by NE- and NW-trending normal faults (Fig. 3). The trace of the N050º-trending Damlaca fault has approximately 3km-long and is NW-dip-slipping, with a similar trend with that the Datça fault, which is bounding the Gökova bay (Fig. 1B). At surface, fault scarps and topographic slope breaks are highlighting the fault trace. This fault juxtaposes basement units with Quaternary rocks. There are three normal faults cutting the marbles of the basement with N075º, N080º and N081º trends. These fault traces are 300 to 500m-long and also dip to the NW.

The Cnidus fault is composed of several segments with lengths ranging between 200m and 2km. These segments have N105º trend and dip steeply to the SW, juxtaposing basement units with Quaternary deposits. Fault scarps and topographic slope breaks are the expression of the fault trace (Fig. 5C). The stress inversion for this fault indicates a stress regime with maxima horizontal extension oriented NNE–SSW (Altunel *et al.*, 2003).

Seismicity of the region

The western Anatolia province is one of the most seismically active regions in the world. Due to the subduction along the Aegean arc and related magmatism and back-arc extension processes, several destructive

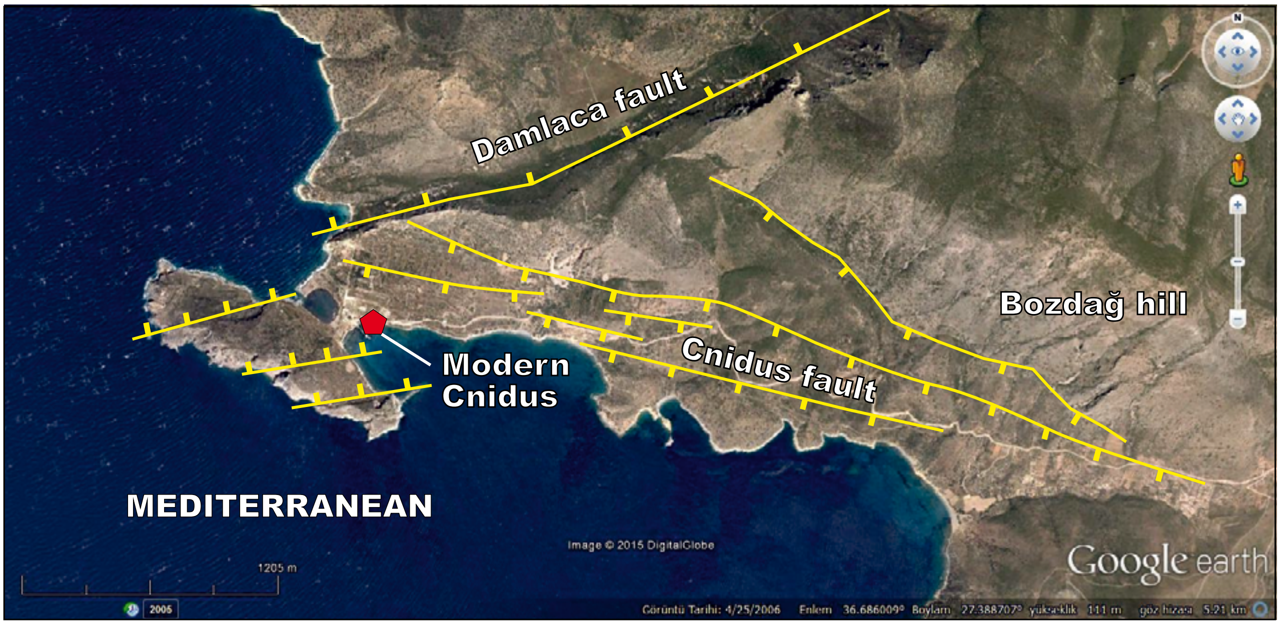

FIGURE 3. Google Earth satellite image, showing NE- and NW-trending normal faults located at the Modern Cnidus city (modified from Dirik *et al.*, 2003; Dirik, 2007).

FIGURE 4. A) General view of the Kızlan fault zone bounding the basement rocks with the basin deposits. B) Close-up view of the fault plane.

earthquakes occurred which were recorded in both historical and instrumental times. Archaeological studies indicate that two major earthquakes hit Modern Cnidus in the 2nd century B.C. and in 459 A.D. (Altunel *et al.,* 2003; Dirik *et al.,* 2003; Guidoboni *et al.,* 1994). A total of 149 earthquakes around the Datça Peninsula were recorded between 1917 and 2020 with magnitudes ≥4 (Fig. 6). The focal mechanism solutions of these earthquakes fall into two main groups. In the first group the earthquakes were generated by NE- and NW-trending strike-slip faults with a subordinate normal component, whereas in the second group the earthquakes were compatible with E–W trending normal faults. The second group is mostly located in the Gökova graben bounded by the Gökova fault to the north and the Datça fault to the south (see Fig. 1B for locations). These are mostly shallow earthquakes. The most recent activity around the Gökova graben was the 21st July 2017 Bodrum-Kos earthquake with a magnitude of Mw: 6.6.

Observations in the ruins of old and modern Cnidus

The Modern Cnidus, located at the western end of the Datça Peninsula, was one of the most important mercantile centres during the Hellenistic, Roman, and Byzantium periods in the eastern Mediterranean region (Altunel *et al.,* 2003; Anzidei *et al.,* 2011). The original

FIGURE 5. Google Earth satellite images, showing the morphological features along A) the Kızlan fault zone, B) the Karaköy fault zone and C) the Cnidus fault zone.

Cnidus city (old Cnidus) was established in the early 7th century B.C. in the centre of the Datça Peninsula, near the actual town of Datça (Bean and Cook, 1952; Grant, 1986) (Figs. 1; 2). The city was moved to the westernmost Datça Peninsula in the 3rd century B.C. (Bean and Cook, 1952) (Figs. 1; 4).

Two harbours in old Cnidus were used during the Hellenistic period before the 3rd century B.C. (Altunel *et al.*, 2003). They have important structures that directly mark the sea level at the time of construction. Harbour ruins at the first inhabited area provide an exact measure of sea-level change since 2.6kyr and 2.2kyr. The southern ruin is

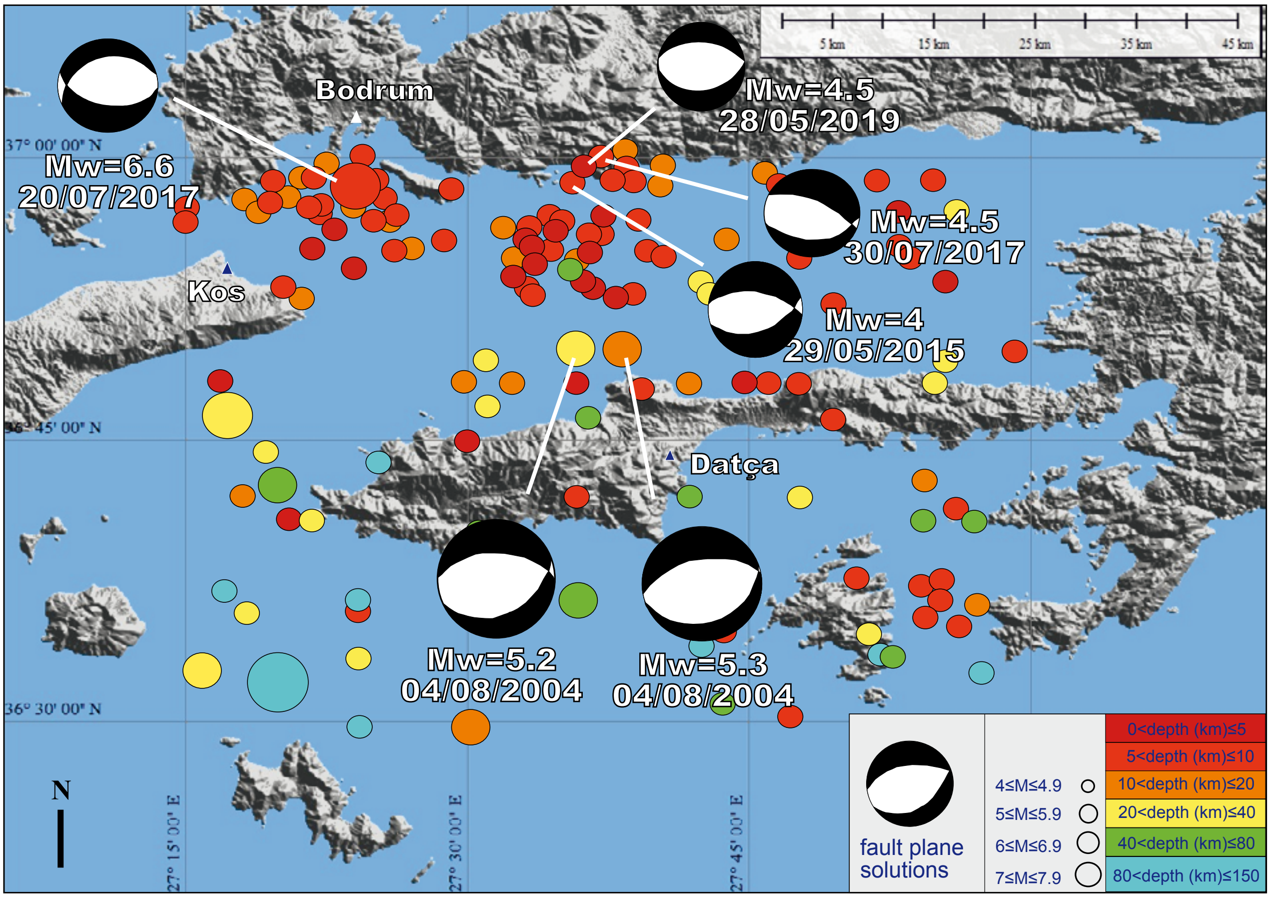

FIGURE 6. Epicentres of earthquakes (with magnitudes ≥4) occurred between 1900–2020 around the Datça Peninsula. The epicentres are taken from KOERI (2020). The focal mechanism solutions are taken from KOERI (2020), Tan *et al.* (2008), Tiryakioğlu *et al.* (2018), Yolsal-Çevikbilen *et al.* (2014).

400m-long, and the northern one is 250m-long (Fig. 7). Both harbour walls which were constructed in the coastline and prolonged into the sea at that time to serve as barriers for ships, are under sea level today (Kayan, 1988a) (Fig. 8). The base levels of the walls, originally constructed to the coastline, are standing below 2.2m for the deepest part for the northern harbour and 4.0m for the southern harbour of current sea level.

Modern Cnidus was built between the 3rd-2nd centuries B.C. (Bean and Cook, 1952). Two harbours were constructed, namely the northern (military) and southern (commercial). The southern harbour walls were constructed onto sandy sea floor, and nowadays are located 26-27m below sea level (Büyüközer, 2012). Although the southern wall remains in its original position, 140m long the northern wall is located at depths between 1.0-5.0m below current sea level (Büyüközer, 2012) (Figs. 9; 10).

DISCUSSION

Ancient coastal structures can provide significant information about the sea level at the time of construction. The Mediterranean and Aegean coasts of Turkey preserve several archaeological sites, such as urban structures and

TABLE 1. Kinematic analysis results of slip-data measurements of Kızlan fault zone. See Figure 2 for stations of slip-data measurements

Station	Number of Fault-Slip Data	Principle stress axes (dip°/plunge°) σ_1	σ_2	σ_3	Φ
1	9	333/72	92/9	185/15	0.184
2	5	285/75	49/8	141/12	0.367
3	4	40/70	275/12	181/16	0.450

Φ= ratio of the stress magnitude differences= $[(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)]$

FIGURE 7. Google Earth satellite images, showing the ruins of A) the northern harbour and B) the southern harbour of Old Cnidus, remaining under the sea-level. Yellow arrows indicate the wall lineation).

harbours that can be useful to study sea-level fluctuations (Anzidei *et al.,* 2011; Flemming *et al.,* 1973). In this case, regional sea-level changes come into prominence to distinguish the effect of active tectonics.

Several studies have been carried out to evaluate sea-level changes in the Mediterranean and Aegean seas during the Quaternary (*e.g.* Kayan, 1988b; Lambeck and Purcell, 2005; Pavlopoulos, 2010; Pavlopoulos *et al.,* 2010, 2013; Uluğ *et al.,* 2005; Vacchi *et al.,* 2014). Since this study deals with ruins dated to the 7th century B.C. (Bean and Cook, 1952), we have taken into account the last 2.6kyr sea-level record from neighbouring areas. This record states that the sea level was 1-1.25m below present-day sea level 2.6kyr ago (Lambeck *et al.* 2004a; Lambeck and Purcell, 2005; Mourtzas *et al.,* 2016; Pavlopoulos, 2010; Pavlopoulos *et al.,* 2010, 2013).

Taking into account the sea-level record and our observations in the old Cnidus harbours (2.2m depth–1m/1.25m below current sea level for the northern one, 4.0m depth–1m/1.25m for southern one), 0.95-1.20m of tectonic subsidence can be calculated for the northern harbour and 2.75-3.00m for the southern harbour. With these data, the calculated subsidence rates for the northern harbour are 0.36-0.46mm/yr and for the southern harbour

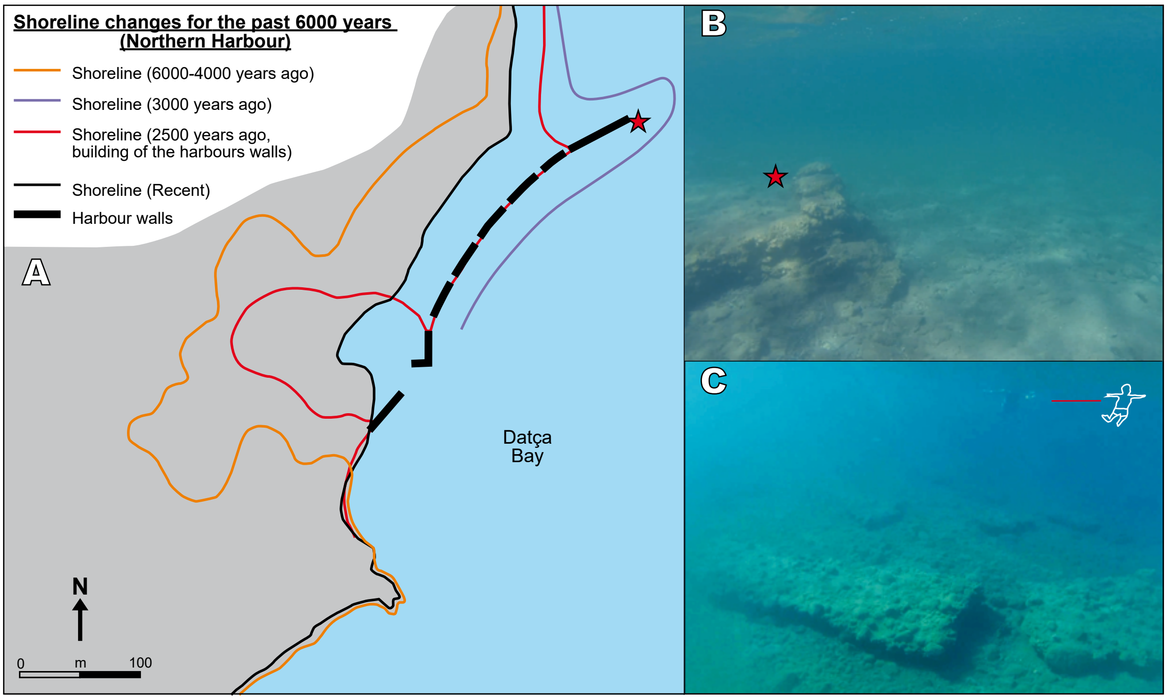

FIGURE 8. A) Map showing shoreline changes in the northern harbour of Old Cnidus over the past 6kyr, based on sedimentological data and archaeological findings (from Kayan, 1988a). B) Underwater photo showing the corner of the northern harbour wall at 2.2m below sea-level. C) Underwater photo showing the wall of the southern harbour at 4.0m below sea-level (white drawing is scale for swimming man).

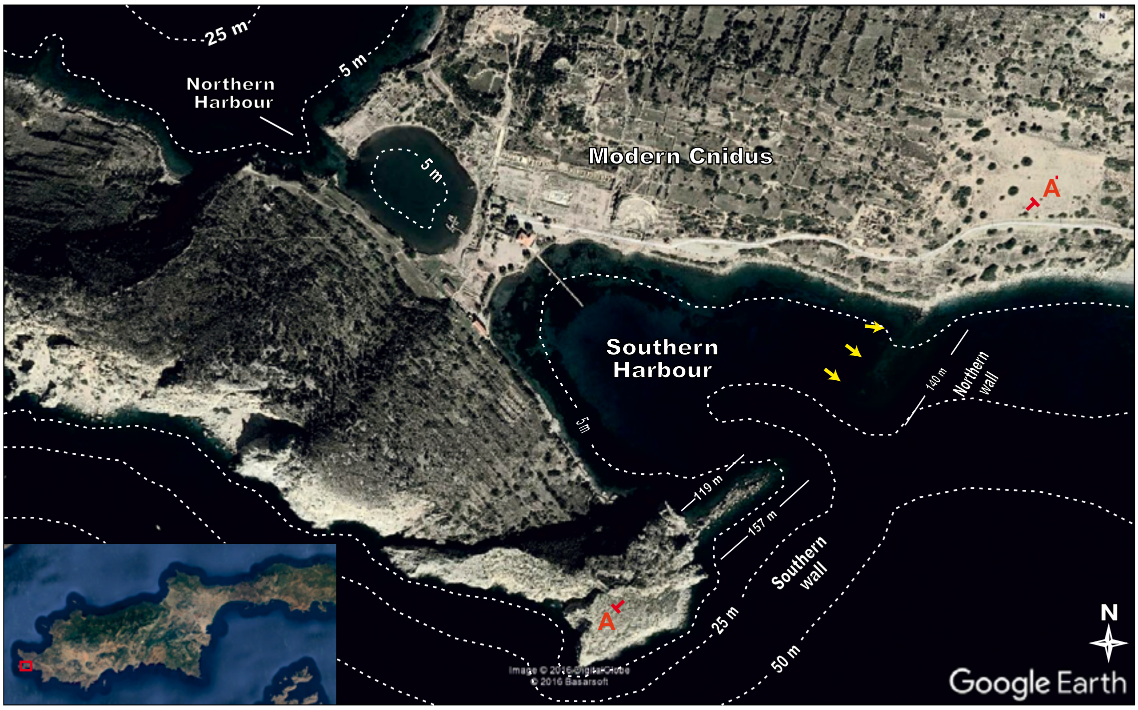

FIGURE 9. Google Earth satellite image, showing the ruins of the Modern Cnidus city (yellow arrows indicate the harbour wall lineation). See Figure 10 for A-A' cross-section.

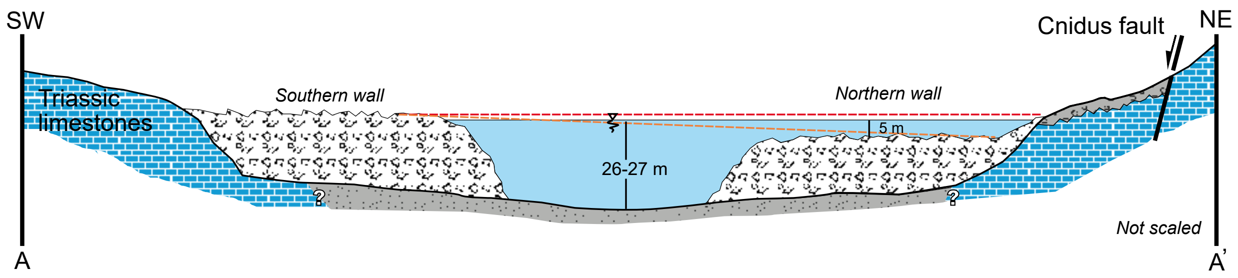

FIGURE 10. Schematic cross-section showing the northward tilting of the harbour walls, located on the hanging wall of Cnidus fault zone, with respect to the sea-level (Red dash lines show the equivalent level of the walls and brown dash lines show tilting).

1.05-1.15mm/yr. The rates obtained for the northern harbour perfectly match those calculated for the Gökova graben (0.3-0.4mm/yr) (Uluğ *et al.,* 2005). Yıldırım *et al.* (2016) suggested a rate of 1.93±0.3mm/yr, which is higher than our estimate for the southern harbour.

Unfortunately, it was not possible to calculate the subsidence rates for the modern Cnidus harbours as the walls were constructed with rock fill technique and the depth of the sea floor at that time is not known. Nevertheless, it could be discussed the situation of the northern wall, which is below present-day sea level (unlike the southern wall), and its possible relation to the activity of the Cnidus fault (Figs. 9; 10). Both, northern and southern harbour walls are located on the hanging wall of this fault. Previous studies indicate 11.4m of vertical displacement on the Cnidus fault for the last 5.9±0.5kyr, with at least 7 earthquakes, having a recurrence period of 350yrs (Yıldırım *et al.,* 2016, 2019). The fact that the northern harbour wall is below present-day sea level whereas 120m of the southern wall remain over the sea might be explain by northward tilting of the footwall along the Cnidus fault plane.

The location and seismic activity of the Kızlan, Karaköy, and Cnidus fault zones and the subsidence rates obtained from the current location of the ancient city and harbour ruins are compatible with the tectonic setting of the region.

CONCLUSIONS

The structural data of the faults that border the Datça graben compared with regional sea-level fluctuations allow the quantification of regional tectonics.

The Datça graben is an active depression bounded by the Kızlan and Karaköy fault zones.

The palaeostress analysis of the Kızlan fault zone indicates an almost N–S oriented extension, which matches with the focal mechanism solutions of the earthquakes recorded in the Gökova bay.

From the depth of the ancient harbour remnants in the old and modern Cnidus cities it can be inferred that, in addition to global sea-level hanges in the late Holocene, regional tectonics have played a major role in the local sea-level changes.

Subsidence rates of 0.36-0.46mm/yr and 1.05-1.15mm/yr are estimated for the old Cnidus harbours. Although the rates obtained from the northern harbour match those calculated in the Gökova bay, the rates determined from the southern harbour are higher. The increase in the rates from north to south might be related to the seismic/aseismic activity along the Karaköy fault zone controlling the southern margin of the graben.

Overall, our investigation highlights that ancient coastal settlements can preserve clues about sea-level changes and tectonic activity. Nevertheless, these clues should be carefully investigated in order to obtain meaningful results.

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