Tectonophysics 611 (2014) 114–120

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Seismic coastal uplift and subsidence in Rhodes Island, Aegean Arc: Evidence from an uplifted ancient harbour

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ARTICLE INFO

Article history:
Received 27 July 2013
Received in revised form 30 October 2013
Accepted 16 November 2013
Available online 26 November 2013

Keywords:
Thin-skin tectonics
Historical seismology
Archaeoseismology
Crete
Radiocarbon dating

ABSTRACT

Archaeological evidence from a 2400 years old harbour, currently about 3 m above sea-level, sheds light on an enigmatic sequence of coastal uplift and subsidence along the coasts of Rhodes Island, close to a >4 km deep trough marking the east edge of the Aegean Arc. The tectonics of this area are not clear, because of the absence of major earthquakes in the last 80 years, but are likely to be controlled by a combination of shear and compression producing strong earthquakes, some associated with tsunamis and some with thrust-uplifted notches. The latter, up to 6000 years old, also show evidence of phases of subsidence.

Our study focuses on remains of shipsheds, in particular a ramp used to pull warships out of the water and keep them protected under cover during winter. This ramp was constructed between approximately 250–225 BC and some decades later it was repaved, after a major earthquake destroyed the town of Rhodes and most probably the harbour and sheltered ships, as historical evidence reveals. 300 years later the harbour was to a great part abandoned because of a coastal uplift. The only reasonable explanation for the ramp reconstruction was to counteract a 1 m seismic subsidence at around 220 BC or earlier. Several possible explanations can be proposed for the earthquake which produced seismic subsidence alternating with uplift in Rhodes, in a pattern of vertical motions different from that observed in Crete, or other convergent boundaries.

1. Introduction

The island of Rhodes, at the SE edge of the Aegean Arc is adjacent to a >4 km deep marine trough bounded by a zone of thrusts (Hall et al., 2009; Kontogianni et al., 2002; Woodside et al., 2000; Fig. 1) and has been affected in the last few thousand years by numerous very strong earthquakes. Ancient reports and inscriptions testify to some of their effects, including tsunamis and the collapse of the "Colossus", a colossal ancient statue, erected at the entrance of the Rhodes harbour in circa 200 BC; this statue was classified among the seven wonders of the Ancient World (Guidoboni et al., 1994). The most recent major earthquake to hit the island was the 1926 earthquake of minimum magnitude Ms = 7.4, which is the first major instrumentally recorded event in the region (Ambraseys and Adams, 1998; Papazachos and Papazachou, 1997). This last earthquake produced limited damage and no coastal changes, in contrast to previous, presumably larger earthquakes, some of which produced coastal uplifts and a flight of Holocene notches (Fig. 2; Flemming, 1978; Pirazzoli et al., 1989). Probably inspired by one of such earthquakes producing coastal uplift and by the widespread marine sediments, Pindar, a famous 5th c. BC poet, described the island to have emerged from the sea. Hence Pindar was the first to recognize the relationship between earthquakes and landscape build-up (Kontogianni et al., 2002).

Landscape build-up in convergent margins by recurring earthquakes is expected to leave signs of fossil sea-levels, with their height increasing with age (Shimazaki and Nakata, 1980). However, biological, sedimentological, petrographic and radiometric data indicate that the situation with Holocene notches in Rhodes is more complicated, because some notches are found at levels higher than older ones, testifying to alternation of uplift with subsidence, poorly, however, constrained (Pirazzoli et al., 1989). This situation raises questions as to whether transient subsidence events reflect gradual strain accumulation, or perhaps seismic movements with a direction opposite to that of the main trend.

In order to shed some light on this alternation of uplift and of subsidence, very important for other convergent margins as well, we focus on the remains of an ancient harbour in Rhodes Town, currently 3 m above the water. The advantage of studies of ancient harbours in the Mediterranean is that they allow us to reconstruct the details of their uplift-subsidence history, *firstly* because, the tide in the region is small (astronomic tide in the modern harbour of Rhodes of the order of 10 cm: Pytharouli and Stiros, 2012); *secondly*, previous studies have provided tools for understanding the details of environmental changes in uplifted and submerged ancient harbours and identifying the sea-level during

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0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.11.020

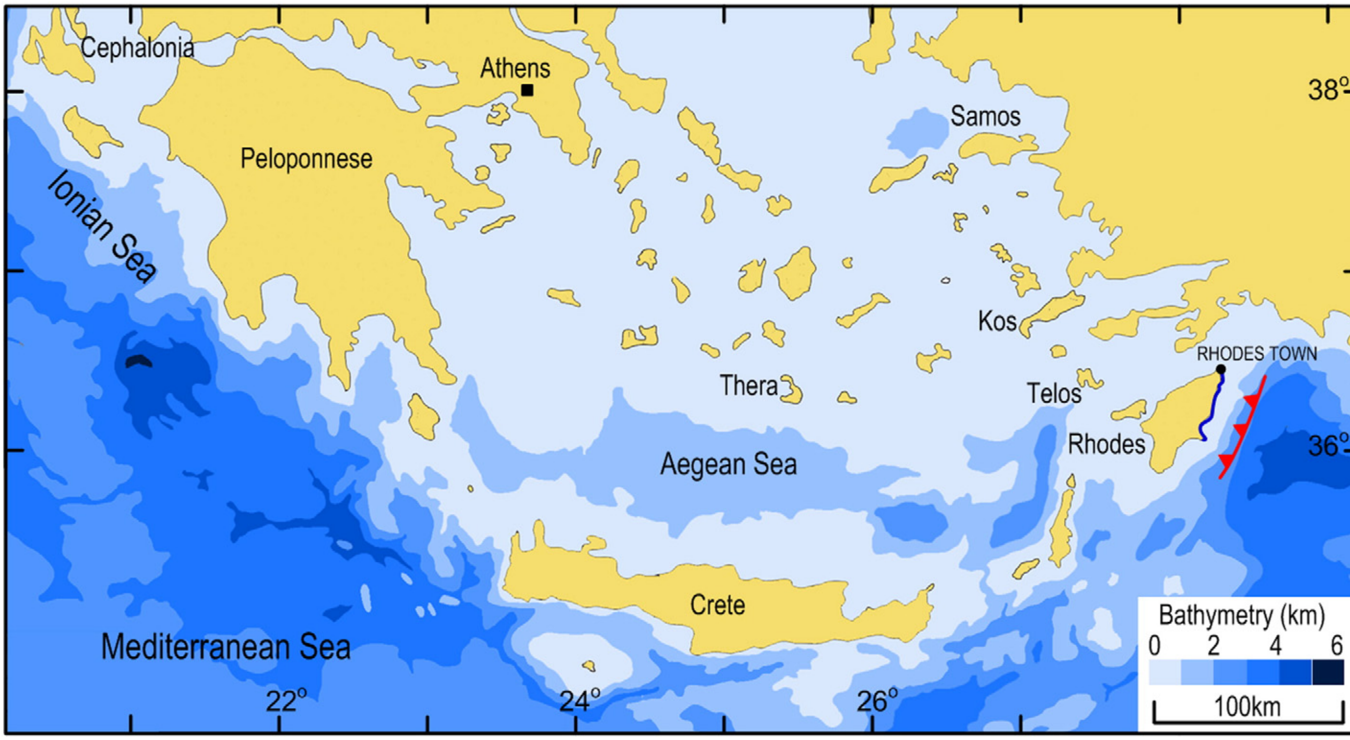

Fig. 1. Location and bathymetric map of the southern Aegean Arc. A thrust zone bounding to the NW a 4 km deep trough at the SE edge of the Arc is shown for simplicity as a single thrust (red line with ticks). This thrust zone controls the geomorphological and structural evolution (emergence) of Rhodes and the Holocene uplifted notches (coast marked by solid blue line).

their period of use (Flemming, 1978; Marriner and Morhange, 2007); and *thirdly*, there are historical reports of highly destructive earthquakes affecting the ancient town during the critical period. It is hence possible to identify seismic movements with amplitude much smaller than in most other tectonically active parts of the world, and shed light on old earthquakes.

The available interdisciplinary evidence (archaeological, historical, radiocarbon, coastal morphological and tectonic data) enables us to refine and revise previous ideas for the coastal evolution of NE Rhodes (including those presented by Kontogianni et al., 2002), provide firm constraints to the history of coastal changes associated with major earthquakes, and even propose some possible explanations for the observed unusual alternation of uplift and subsidence of Rhodes, at the enigmatic eastern edge of the Hellenic Arc.

Fig. 2. View of the flight of notches on the SE Rhodes coast (about 12 km SW of Rhodes Town).
Photo A. Drakos.

2. Geodynamic background

The tectonics of Rhodes Island which mark the east edge of the Aegean Arc have been discussed by various authors using various pieces of evidence (Benetatos et al., 2004; Flemming, 1978; Hollenstein et al., 2008; Kontogianni et al., 2002; Mercier et al., 1979; Shaw and Jackson, 2010; Woodside et al., 2000; Yolsal-Çevikbilen and Taymaz, 2012), but with the lack of major earthquakes in the last decades, they remain a matter of debate.

On one hand seismological data covering half a century and relatively small earthquakes tend to show strike slip and some compressional earthquakes, while GPS data covering a period up to 10–15 years tend to show that Rhodes is slipping southwestwards along the arc as a rather rigid block (Floyd et al., 2010; Hollenstein et al., 2008). Based on such data the east edge of the Aegean Arc has been interpreted as a strike slip margin, with some earthquakes revealing secondary compression (Benetatos et al., 2004; Shaw and Jackson, 2010). On the other hand, elastic dislocation modelling of coastal uplifts and marine geophysical surveys indicate that the >4 km deep trough SE of Rhodes reflects a wide zone of thrusting since the Pliocene (Hall et al., 2009; Kontogianni et al., 2002); a result consistent with GPS data showing an important component of slip normal to the arc (Hollenstein et al., 2008). A somewhat similar situation is observed on the western edge of the Aegean Arc, with recent, relatively small earthquakes indicating a zone of shear along the strike-slip margin (Benetatos et al., 2004; Shaw and Jackson, 2010), while older, major earthquakes and tectonics indicate thrusting (Feng et al., 2010; Stiros et al., 1994). In view of the above, the most likely explanation is that the tectonics of Rhodes are dominated by transpression.

3. Geology and tectonics of Rhodes

Rhodes is mainly built of faulted and folded Mesozoic and Tertiary rocks partly covered by younger marine sediments, while flights of marine Pliocene to Quaternary terraces, up to 250 m high, characterize