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Vertical displacement trends in the Aegean coastal zone (NE Mediterranean) during the Holocene assessed by geo-archaeological data

Kosmas Pavlopoulos,[1] Vasilios Kapsimalis,[2] Katerina Theodorakopoulou[1] and Ioannis P Panagiotopoulos[2]

Abstract

Trends in the vertical displacement (i.e. uplift or subsidence) of the Aegean Sea coastal zone have been assessed by comparing observational data with those derived from the predictive glacio-hydro-isostatic model of Lambeck and Purcell (2005) for a period spanning from the Mesolithic to the late Roman times. The data base comprises published studies that use both geomorphological (with associated biological material) and archaeological sea level indicators/markers. Localities demonstrating uplift of high amplitude were detected in front of the Hellenic Arc (Antikythira, Crete, Rhodes, Nisyros) and in the northeast Aegean region (Thrace), whilst areas experiencing tectonic subsidence were mainly observed in the central Aegean region which is characterized by an extensional tectonic domain. However, regional-scale tectonic particularities have caused uplift in parts of the west and east coast of central Aegean. Tectonically 'stable' sites can be found in the Cyclades Plateau, however, this is due to a balance between uplifting and subsiding movements. Sediment compaction and sediment loading may have affected districts with high sedimentation rates such as the Thessaloniki Plain-Thermaikos Gulf (NW Aegean). Finally, tectonic fragmentation of the coastal area in Minor Asia is responsible for localised uplifting and subsiding events.

Keywords

Aegean Sea, geoarchaeological indicators, Lambeck's model, relative sea level changes, vertical movements

Introduction

The determination of relative sea level (RSL) change is a multifactor approach that requires the understanding of several variables associated with interactive geodynamic processes. RSL change is the resultant of eustatic changes, glacio-hydro-isostatic variations, and regional vertical displacement trends (Vtr) which are a function of tectonism (V_T) (i.e. structural deformation of the crust, co-seismic earthquake movements, aseismic vertical creep, fault displacements, large-scale tectonic crustal movements associated with plate boundaries and plate movements), sediment budget (S_b; deposition-erosion), sediment load isostasy (S_i), and sediment compaction (S_d; also due to anthropogenic activities) (Antonioli et al., 2009; Lambeck et al., 2004; Tsimplis et al., 2011). This may be expressed mathematically by the following equation:

$$\mathrm{Vtr} = V_T + S_b + S_i + S_d \quad (1)$$

with the parameter Vtr corresponding to the 'tectonic' factor of Lambeck's equation (Lambeck, 1995, 1996).

Eustatic fluctuations, occurring since the end of the last major glaciation, have been determined in tectonically stable sites such as the reef sequences of Papua New Guinea or in sites where correction for tectonic movements is possible such as Barbados Island. Similar data have been derived for the Mediterranean Sea after the application of a glacio-hydro-isostatic model developed by Lambeck and his colleagues (Lambeck, 1995; Lambeck and Chappell, 2001; Lambeck and Purcell, 2005). This model predicts the rheological response function of Earth's lithosphere for each locality and epoch, taking into account a series of variables such as timing and amount of meltwater addition, geometry of the ocean basin where the meltwater has been added, thickness of lithosphere, viscosity of the upper and lower mantle, and location of the ocean basins in relation to the high-latitude ice sheet (Lambeck and Chappell, 2001; Lambeck et al., 2003). The model has been calibrated by field data at tectonically 'stable' Mediterranean coasts such as Cote d'Azur in France (Dubar et al., 1992), Versilia Plain and Sardinia in Italy (Antonioli et al., 1999), Cyclades Plateau in Greece (Hejl et al., 2002).

The data extracted from the foreseeing model of Lambeck can be compared with observational data concerning the Holocene RSL stands in unstable localities to estimate rates of change of vertical displacement and, therefore, to detect uplifting, 'stable' and subsiding regions. Many studies based on this approach have been undertaken for the Mediterranean coasts, e.g. Lambeck and Bard (2000) in the French Mediterranean coast, Lambeck (1995, 1996) and Lambeck and Purcell (2007) in the Aegean Sea, Lambeck et al. (2004) and Antonioli et al. (2007, 2009) in Italy, and Sivan et al. (2001, 2004) in Israel.

The observational determination of RSL change is initially based on the dating of natural markers, including both geomorphological features (with associated biological material)

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and archaeological findings, and is finalized by plotting marker's elevation above or below mean sea level versus calibrated radiocarbon age (Stanley, 1995). However, reliable information about the relative motions between crust and sea level is provided only by those markers that are accurate, preservable and datable (Bruckner et al., 2010). The geomorphological features may comprise (a) erosion indicators such as notches, benches, trottoirs, platforms, abrasional marine terraces, strandflats, pools, potholes, sea caves; and (b) deposition indicators such as tidal flats, marine-built shore platforms and terraces, beaches, beachrocks, reef flats (Pirazzoli, 1996). Erosion indicators must be considered with caution when past sea levels have to be dated, while deposition indicators may include biological markers such as guide fossils (e.g. Vermetids, Lamellibranchia *Cerastoderma glaucum*, Speleothems; Lambeck et al., 2004), or organic material. Further, archaeological remains provide RSL change estimates of variable accuracy depending on the age, dimensions, type, usage, and manner of the construction. The most important of them found in the Mediterranean Sea are harbour structures (dry dock foundations, quays, piers, breakwaters, navy yards), fishponds, nymphaea caves, private and public buildings (foundations, floorings, roads and pavements), thermal baths, plumbing installations (wells, cisterns, drains, gullies), tombs, quarries, beached wrecks, and anchorages (Auriemma and Solinas, 2009).

The present study attempts to establish a data base with information about the relative vertical displacements between land and sea in the Aegean region. Furthermore, it contributes to the investigation of the process of the vertical crustal movement in the coastal zone of Eastern Mediterranean, complementing other relative researches that have used a similar with the current study approach, e.g. Anzidei et al. (2011a) in southern Turkey and Israel, Anzidei et al. (2011b) in Tunisia and western Libya, Faivre et al. (2011) in the northwestern coast of Croatia, and Lambeck et al. (2011) in the Italian coast. In particular, the present investigation (a) demonstrates the spatial distribution of uplift and subsidence in the coastal areas of the Aegean Sea by comparing observational data with those predicted from the hydro-glacio-isostatic model of Lambeck and Purcell (2005); and (b) determines the relationship of this distribution with tectonic and sedimentary processes operating within the Aegean region.

Finally, the current study has considered from the available literature a greater number of sites and RSL indicators/markers compared with other published studies concerning RSL changes in the Aegean Sea (e.g. Kambouroglou et al., 1988; Lambeck, 1995, 1996; Lambeck and Purcell, 2005; Poulos et al., 2009; Vouvalidis et al., 2005).

The study area

Geodynamic and physiographic setting

The geodynamic configuration of the Aegean Sea region is strongly associated with the collision between the African and Eurasian mega-plates in the eastern Mediterranean. The compressional tectonic regime, established during the early Quaternary, was followed by an extensional tectonic regime lasting from the Middle Pleistocene up to the present time (Mercier et al., 1976). A great variety of topographic features and geological structures, and complex tectonic patterns (see Figure 1) characterize the Aegean Sea floor which, in general, drifts towards the southwest at a rate of 40–50 mm/yr (Jackson and McKenzie, 1988; McKenzie, 1978). The Late Pleistocene sedimentary evolution and palaeogeography of the Aegean margins have been dominated by the eustatic sea level fluctuations which, together with tectonics, have affected the present-day shape of the area (Aksu and Piper, 1983; Aksu et al., 1987a, b; Kapsimalis et al., 2009; Lykousis, 1991; Lykousis et al., 2005; Pavlides and Caputo, 2004; Perissoratis and Conispoliatis, 2003; Perissoratis and Mitropoulos, 1989; Perissoratis and Van Andel, 1988; Piper and Perissoratis, 1991; Van Andel et al., 1990, 1993). Lykousis (2009) points out that during the postglacial peaks of Middle–Late Pleistocene almost 50–60% of the present Aegean Sea bottom was exposed to subaerial conditions and characterized by large lakes, well-developed drainage systems and extensive deltaic plains. In particular, during the last sea-level highstand, the rapid and broad deltaic progradation was the reason for the burial of many archaeological sites, artefacts and prehistoric human imprints (Stanley, 2005; Westley and Dix, 2006). High sedimentation took place mainly in the central and north Aegean region where wide continental shelves and large rivers exist, whilst low sedimentation occurred in the southern Aegean because of a lack of large suppliers of terrigenous (riverine) material throughout the Holocene (Poulos, 2009).

Archaeological periods in the Aegean Sea region

Archaeological findings from Melos suggest that human presence in the Aegean Sea is dated since the Upper Paleolithic (35 000–11 950 cal. yr BP), although the region was not systematically inhabited up to the Neolithic Epoch (8950–5150 cal. yr BP) (Demoule and Perle, 1993). Traces of more permanent settlements of Mesolithic Age (11 950–8950 cal. yr BP) have been discovered in the Cyclops Cave on Youra of the Northern Sporades (Sampson, 1996a) and in Maroulas on Kythnos (Sampson, 1996b). During the Neolithic Epoch, the development of navigation and the search for durable raw materials, such as obsidian and metals (Renfrew et al., 1987), gave impetus for island habitation. Many important Neolithic settlements were established in the Aegean Sea islands and along the coastline of the Greek mainland such as Ftelia in Mykonos (Sampson, 2002), Za cave in Naxos (Zachos, 1990), Saliagos in Antiparos (Morisson, 1968), Kefala in Keos (Coleman, 1977), and Marathon in Attica (Pantelidou-Gofa, 1997).

During the Bronze Age (5150–3000 cal. yr BP), the Aegean Sea was the 'bridge' that connected the Greek mainland with Minor Asia and Crete, and the areas south of the Aegean region with the northern Hellenic region, Balkans and Black Sea, thus constituting the field for intense economic, social and cultural activities (Papathanassopoulos, 1996). During that era, the Aegean Sea accommodated the most important civilizations (i.e. Cycladic, Minoan and Mycenaean) of Greek prehistory. The importance of the Aegean region to the transfer of culture and new ideas was also maintained during the historic periods of Greece (i.e. Archaic, 700–480 BC; Classical, 480–323 BC; Hellenistic, 323–146 BC; and Roman, 146 BC–AD330). Important coastal sites – harbours (e.g. Piraeus, Corinth, Chalkis, Eretria, Delos) (Boardman, 1984) – flourished, whilst trading with the Near East started to be developed.

Methodology

Geomorphological and archaeological data for RSL changes during the Holocene in 74 coastal sites of the Aegean Sea were considered from the literature. Geomorphological indicators (including also biological markers) were used for 49 of the study sites and included notches, marine platforms, beachrocks, coastal lagoons, marine shells and fossils, corals, algae, marshy organic material, and peats. For the rest of the study sites evidence of RSL change was provided by archaeological findings such as ruins, harbours, hydraulic installations, quarries, naval bases, shipways, breakwaters, fish tanks, and tombs.

The elevation measurement uncertainties associated with the various geomorphological (including biological) indicators, with respect to mean sea level (m.s.l.) in the past, are: ±0.3–0.7 m for notches and platforms, ±0.2 m for beachrocks, ±0.3 m for coastal

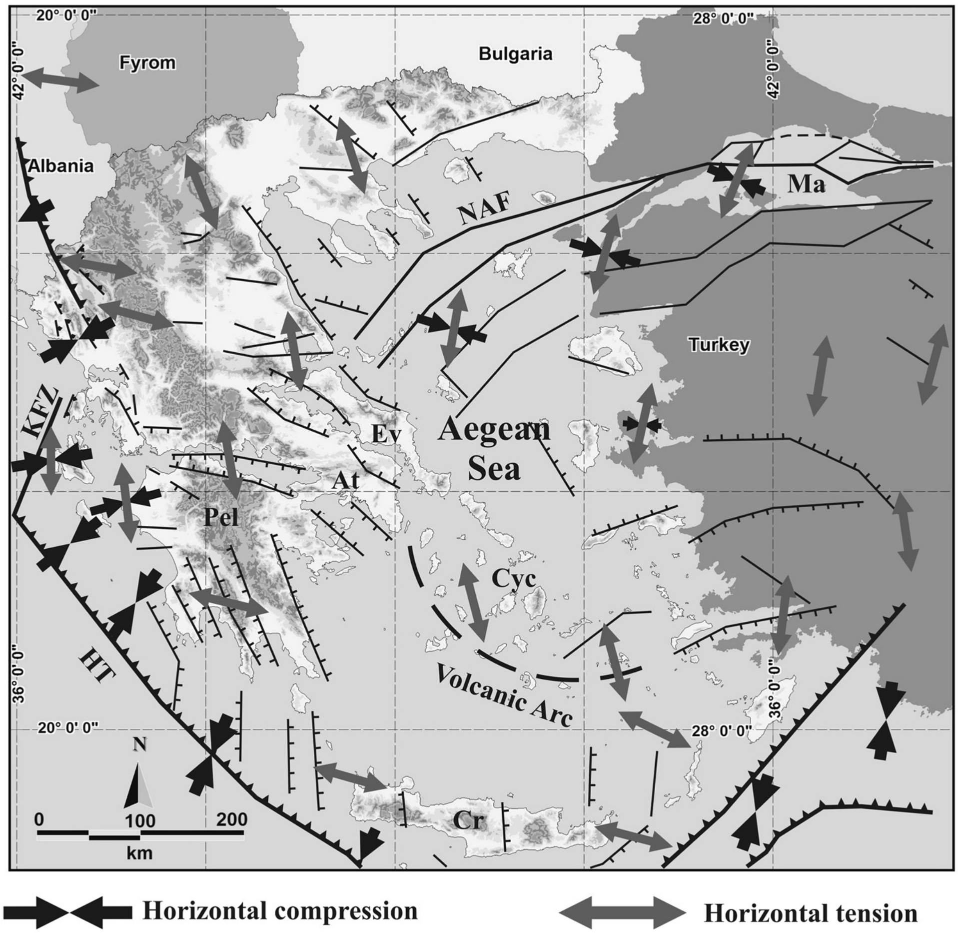

Figure 1. Tectonic setting and stress field of the Aegean Sea and surrounding area. Horizontal compression dominates along the frontal side of the Hellenic Arc, while N–S extension prevails in the back-arc basin. A combined compression and tension regime occurs along the N Aegean-Marmara area, where strike-slip faulting is the principal process (modified from Hollenstein et al., 2008; Papazachos et al., 1999). HT, Hellenic Trench; KFZ, Kefalonia Fault Zone; NAF, North Anatolian Fault; Ma, Marmara; At, Attica; Cr, Crete; Cyc, Cyclades; Ev, Evia; Pel, Peloponnese

lagoons and marshy organic material, ±0.3–0.7 for corals and marine mollusks such as *Cerastoderma glaucum*, Oysters and Lithophaga, ±0.1–0.5 m for marine gastropod mollusks (e.g. Vermetids, Dendropora, Murex), ±0.3–0.5 m for base peats, and ±0.5 m for algae such as Neogoniolithon (Bruckner et al., 2010). Finally, for all elevation determinations, the local mean tidal amplitude was considered.

The elevation measurement uncertainties associated with the archaeological indicators depend on the functional height (m) of the construction above mean sea level (a.m.s.l.) or above high tide in the past. According to Antonioli et al. (2007), the functional height for harbours and naval bases is estimated at 0.6–1.0 m a.m.s.l., and for fishponds and breakwaters at 0.6 m a.m.s.l. In addition, the functional height for buildings and coastal quarries is estimated at about 0.6 and 0.3 m a.m.s.l., respectively (Lambeck et al., 2004), while for hydraulic installations is considered to be above high tide (Auriemma et al., 2004). Also, for tombs, it is assumed a minimum elevation at 0.3 m above high tide. Finally, for all elevation determinations, the local mean tidal amplitude was taken into account.

Radiocarbon ages of geomorphological indicators were calibrated using the CalPal calibration software (Cologne Radiocarbon Calibration and Palaeoclimate Research Package). This software contains an update of the ^{14}C-age calibration curve, called CalPal-2007-Hulu, and is based on the corresponding Hulu-referenced Cariaco data from Hughen et al. (2006). Concerning the archaeological indicators, the range of temporal error for harbour installations, fishponds and buildings is ≤100 yr, whilst for breakwaters, coastal quarries and hydraulic installations is ≥100 yr (Antonioli et al., 2007; Auriemma and Solinas, 2009; Auriemma et al., 2004; Lambeck et al., 2004).

Predictions of RSL for each of the study sites were obtained from the glacio-hydro-isostatic model of Lambeck and Purcell (2005), which is based on the following nominal parameters: (a) 65 km of lithospheric thickness; (b) 3×10^{20} Pa s of Upper Mantle viscosity; (c) 10^{22} Pa s of Lower Mantle viscosity; (d) the NE-2 and NA-2 ice models for north Europe and north America, respectively; and (e) an equivalent sea level (esl) function which uses data from a number of far-field localities around the world. Nevertheless, the uncertainty ranges of this model, derived by the variance of its principal components (i.e. earth model, ice sheet model and esl function), are estimated to be about 5.5, 4, and 1.5 m at 20 000, 12 000, and 6000 cal. yr BP, respectively, in the regions of Peloponnese and northeastern Ionian Sea (40°N latitude, 20°E longitude) (Lambeck and Purcell, 2005).

Estimated ages of the used indicators (ranging from 1306 to 10 788 cal. yr BP) were classified in a descending order and correlated with prehistoric and historic phases (Mesolithic to late Roman) of the Aegean culture (see Table 1). This correlation was regarded as being informative since the human presence and cultural evolution in the Aegean Sea were strongly related to marine environment and sea level fluctuations. Further, Table 1 displays the following information: (a) the different types of used indicators/markers for the definition of past RSLs together with their age estimations and relative uncertainties; (b) the measured RSL elevations (in relation to the present m.s.l.) with their uncertainties; (c) the calculated time-averaged rate (mm/yr) of RSL change based on the observational data; (d) the predicted RSL position, with its uncertainty range, (extracted from the glacio-hydro-isostatic model of Lambeck and Purcell, 2005) for each of the study sites and the consequent time-averaged rate (mm/yr) of RSL change;

Table 1. Vertical displacement trends (Vtr) estimated by the predicted (Pred.) and observational (Obs.) data. The numbers in the column of sites indicate the localities displayed in Figure 2. Relative references for all study sites appear below the table. The local mean tidal amplitude has been obtained from the Hellenic Navy Hydrographic Service

Site	Indicator/marker	Age (cal. yr BP)	RSL stand					Time-averaged rate of RSL change		Vtr
			Elevation (m)	Uncertainty (m)	Obs. (m)	Mean tidal amplitude (m)	Pred. (m)	Obs. (mm/yr)	Pred. (mm/yr)	Obs.–Pred. (mm/yr)
Mesolithic (11 950–8950)										
60. Thessaloniki	Marine mollusks from the coastal zone	10788±485	−29.0	±0.5	−29.0±0.5	0.24	−45.9 (3.9[a])	2.7	4.3	−1.6
71. Samothrace	Marshy organic material	9890±173	−9.9	±0.3	−9.9±0.3	0.18	−32.2 (3.6[a])	1.0	3.3	−2.3
69. Samothrace	Marshy organic material	9370±53	−8.2	±0.3	−8.2±0.3	0.18	−29.9 (3.5[a])	0.9	3.2	−2.3
59a. Epanomi	corals	9315±151	−29.3	±0.5	−29.3±0.5	0.24	−27.1 (3.3[a])	3.1	2.9	0.2
Neolithic (8950–5150)										
59b. Epanomi	corals	8466±83	−28.9	±0.5	−28.9±0.5	0.24	−16.7 (2.8[a])	3.4	2.0	1.4
61. Thessaloniki	Marine mollusks from the coastal zone	8322±81	−15.5	±0.5	−15.5±0.5	0.24	−15.2 (2.8[a])	1.9	1.8	0.1
72. Samothrace	Cerastoderma. glaucum	8005±49	−5.9	±0.5	−5.9±0.5	0.18	−13.2 (2.7[a])	0.7	1.6	−0.9
62. Thessaloniki	Marine mollusks	7707±104	−18.0	±0.5	−18.0±0.5	0.24	−10.2 (2.6[a])	2.3	1.3	1.0
73. Samothrace.	Cerastoderma. glaucum	6970±45	−3.5	±0.5	−3.5±0.5	0.18	−6.9 (2.4[a])	0.5	1.0	−0.5
70a. Lafrouda	Coastal lagoon	6904±77	−2.5	±0.3	−2.5±0.3	0.26	−6.3 (2.4[a])	0.4	0.9	−0.5
74. Samothrace	Cerastoderma. glaucum	6795±46	−5.5	±0.5	−5.5±0.5	0.18	−6.4 (2.4[a])	0.8	0.9	−0.1
8. Istron	Coastal lagoon	6620±93	−5.1	±0.3	−5.1±0.3	0.10	−10.4 (2.6[a])	0.8	1.6	−0.8
63. Thessaloniki	Marine mollusks	6512±49	−13.0	±0.5	−13.0±0.5	0.24	−4.9 (2.3[a])	2.0	0.8	1.2
17. Rhodes	Notches (tidal type)	6351±123	2.4	±0.3	2.4±0.3	0.14	−6.1 (2.4[a])	−0.4	1.0	−1.4
56. Skyros	Base peats	6300±80	−7.1	±0.4	−7.1±0.4	0.28	−6.6 (2.4[a])	1.1	1.0	0.1
18. Rhodes	Notches (tidal type)	6261±119	2.1	±0.3	2.1±0.3	0.14	−5.8 (2.4[a])	−0.3	0.9	−1.2
59c. Epanomi	corals	6152±164	−28.5	±0.5	−28.5±0.5	0.24	−5.8 (2.4[a])	4.6	0.7	3.9
35. Naxos	Coastal lagoon (sand with laminations of organic material)	6144±84	−4.7	±0.3	−4.7±0.3	0.16	−6.9 (2.4[a])	0.8	1.1	−0.3
34. Saliagos	Submerged structures	6000 (≤100)	−6.0	0.6[b]	−6.6	0.16	−6.6 (2.4[a])	1.1	1.1	0.0
19. Rhodes	Notches	5641±122	3.3	±0.3	3.3±0.3	0.14	−4.3 (2.2[a])	−0.6	0.8	−1.4
37a. Mykonos-Delos-Rhenia	Beachrocks	5615±23	−3.5	±0.2	−3.5±0.2	0.16	−5.5 (2.3[a])	0.6	1.0	−0.4
33. Miletus	Architectural ruins lying on bedrock	5500 (≤100)	−1.0	0.6[b]	−1.6	0.06	−3.5 (2.0[a])	0.3	0.6	−0.3
50a. Marathon	Base peats	5250±60	−2.6	±0.3	−2.6±0.3	0.10	−4.9 (2.2[a])	0.5	0.9	−0.4
50b. Marathon	Base peats	5244±176	−2.4	±0.3	−2.4±0.3	0.10	−4.9 (2.3[a])	0.5	1.0	−0.5
Bronze Age (5150–3000)										
68. Samothrace	Cerastoderma. glaucum	4980±40	−4.5	±0.5	−4.5±0.5	0.18	−3.2 (2.0[a])	0.9	0.6	0.3
51. Vravron	Marine gastropods	4710±105	−4.8	±0.1	−4.8±0.1	0.10	−4.2 (2.1[a])	1.0	0.9	0.1
50c. Marathon	Base peats	4698±98	−2.2	±0.3	−2.2±0.3	0.10	−4.2 (2.2[a])	0.5	0.9	−0.4
64. Thessaloniki	Marshy sediment (fresh water marshes with debris)	4548±132	−4.5	±0.3	−4.5±0.3	0.24	−2.4 (1.6[a])	1.0	0.5	0.5
32. Miletus	Architectural ruins	4500 (≤100)	−0.3	0.6[b]	−0.9	0.06	−2.7 (1.8[a])	0.2	0.6	−0.4
67. Samothrace	Cerastoderma. glaucum	4320±40	−3.2	±0.5	−3.2±0.5	0.18	−2.6 (1.7[a])	0.7	0.6	0.1
37b. Mykonos-Delos-Rhenia	Beachrocks	4214±47	−3.6	±0.2	−3.6±0.2	0.16	−3.6 (2.0[a])	0.9	0.9	0.0
37c. Mykonos-Delos-Rhenia	Beachrocks	4089±60	−2.8	±0.2	−2.8±0.2	0.16	−3.4 (2.0[a])	0.7	0.8	−0.1
37d. Mykonos-Delos-Rhenia	Beachrocks	4000±35	−3.8	±0.2	−3.8±0.2	0.16	−3.3 (2.0[a])	1.0	0.8	0.2

Table 1. (Continued)

Site	Indicator/marker	Age (cal. yr BP)	RSL stand					Time-averaged rate of RSL change		Vtr
			Elevation (m)	Uncertainty (m)	Obs. (m)	Mean tidal amplitude (m)	Pred. (m)	Obs. (mm/yr)	Pred. (mm/yr)	Obs.–Pred. (mm/yr)
7. Amnissos	Architectural ruins	4000 (≤100)	−1.5	0.6[b]	−2.1	0.10	−4.0 (2.1[a])	0.5	1.0	−0.5
50d. Marathon	Base peats	3829±94	−1.7	±0.3	−1.7±0.3	0.10	−3.2 (1.9[a])	0.4	0.8	−0.4
13. Zakros	Hydraulic installations	3800 (≥100)	−0.7	above high tide (0.05 a.m.s.l.)	−0.75	0.10	−3.7 (2.1[a])	0.2	1.0	−0.8
20. Rhodes	Notches	3739±99	2.6	±0.3	2.6±0.3	0.14	−2.6 (1.7[a])	−0.7	0.7	−1.4
30. NW Samos	Notches, Marine fossils (Murex) from microreefs	3671±50	2.0	±0.3	2.0±0.3	0.18	−2.2 (1.4[a])	−0.5	0.6	−1.1
22. Rhodes	Notches	3503±108	1.0	±0.3	1.0±0.3	0.14	−2.4 (1.6[a])	−0.3	0.7	−1.0
37e. Mykonos-Delos-Rhenia	Beachrocks	3416±36	−3.8	±0.2	−3.8±0.2	0.16	−2.7 (1.8[a])	1.1	0.8	0.3
21. Rhodes	Notches	3159±121	0.5	±0.3	0.5±0.3	0.14	−2.3 (1.5[a])	−0.2	0.7	−0.9
27. Orontes Delta	Notches, Calcareous algae, Vermetids, Oysters	3074±118	2.0	±0.3	2.0±0.3	0.14	−1.65 (1.1[a])	−0.7	0.5	−1.2
52. NE Evia	Notches, Lithophaga	3025±110	1.2	±0.7	1.2±0.7	0.10	−2.1 (1.4[a])	−0.4	0.7	−1.1
28. Nisyros	Dendropoma and Vermetous triqueter bioconstructions	3000±50	3.8	±0.3	3.8±0.3	0.10	−2.0 (1.3[a])	−1.3	0.7	−2.0
Classical Antiquity (3000–1981)										
37f. Mykonos-Delos-Rhenia	Beachrocks	2875±45	−3.2	±0.2	−3.2±0.2	0.16	−2.1 (1.4[a])	1.1	0.7	0.4
53. NE Evia	Notches, Lithophaga	2875±110	1.0	±0.7	1.0±0.7	0.10	−2.0 (1.3[a])	−0.3	0.7	−1.0
70b. Lafrouda	Coastal lagoon	2868±47	−0.6	±0.3	−0.6±0.3	0.26	−1.3 (0.8[a])	0.2	0.5	−0.3
31. NW Samos	Notches, Dendropoma	2787±45	1.1	±0.3	1.1±0.3	0.18	−1.5 (1.0[a])	−0.4	0.5	−0.9
49. Ephesus	Coastal lagoon	2775±100	−3.6	±0.3	−3.6±0.3	0.18	−1.3 (0.8[a])	1.3	0.5	0.8
37g. Mykonos-Delos-Rhenia	Beachrocks	2742±13	−3.4	±0.2	−3.4±0.2	0.16	−2.0 (1.3[a])	1.2	0.7	0.5
37h. Mykonos-Delos-Rhenia	Beachrocks	2652±81	−1.7	±0.2	−1.7±0.2	0.16	−1.9 (1.5[a])	0.6	0.7	−0.1
50e. Marathon	Base peats	2560±119	−0.1	±0.3	−0.1±0.3	0.10	−1.8 (1.2[a])	0.04	0.7	−0.7
37i. Mykonos-Delos-Rhenia	Beachrocks	2552±118	−1.5	±0.2	−1.5±0.2	0.16	−1.8 (1.6[a])	0.6	0.7	−0.1
54. NE Evia	Notches	2515±110	0.4	±0.7	0.4±0.7	0.10	−1.7 (1.1[a])	−0.2	0.7	−0.9
46. SE Samos	Harbour	2500 (≤100)	−2.8	0.8[b]	−3.6	0.18	−1.4 (0.9[a])	1.4	0.5	0.9
66. Thassos	Naval base	2500 (≤100)	−1.0	0.8[b]	−1.8	0.26	−1.1 (0.7[a])	0.7	0.4	0.3
48. Ephesus	Coastal lagoon	2415±110	−7.6	±0.3	−7.6±0.3	0.18	−1.0 (0.6[a])	3.1	0.4	2.7
39. Salamis	Harbour	2400 (≤100)	−1.5	0.8[b]	−2.3	0.06	−1.6 (1.0[a])	1.0	0.7	0.3
40. Piraeus	Shipways	2400 (≤100)	−1.5	0.8[b]	−2.3	0.06	−1.6 (1.0[a])	1.0	0.7	0.3
42. Sounion	Naval base	2400 (≤100)	−2.5	0.8[b]	−3.3	0.06	−1.7 (1.1[a])	1.4	0.7	0.7
41. Aigina	Harbour	2400 (≤100)	−2.3	0.8[b]	−3.1	0.06	−1.6 (1.0[a])	1.3	0.7	0.6
43. Porto Heli	Harbour	2400 (≤100)	−2.0	0.8[b]	−2.8	0.06	−1.7 (1.1[a])	1.2	0.7	0.5
44. Kea	Naval base	2400 (≤100)	−2.5	0.8[b]	−3.3	0.16	−1.7 (1.1[a])	1.4	0.7	0.7
45. Kythnos	Harbour	2400 (≤100)	−2.2	0.8[b]	−3.0	0.16	−1.8 (1.1[a])	1.3	0.7	0.6
65. Lemnos	Harbour	2400 (≤100)	−0.7	0.8[b]	−1.5	0.18	−1.3 (0.8[a])	0.6	0.5	0.1
47. Ephesus	Coastal lagoon	2340±100	−3.6	±0.3	−3.6±0.3	0.18	−1.0 (0.6[a])	1.5	0.4	1.1
55. NE Evia	Notches	2325±110	0.7	±0.7	0.7±0.7	0.10	−1.5 (1.0[a])	−0.3	0.7	−1.0
57. Antissa	Harbour	2300 (≤100)	−1.5	0.8[b]	−2.3	0.18	−1.1 (0.7[a])	1.0	0.6	0.4
58. Eressos	Harbour	2300 (≤100)	−1.5	0.8[b]	−2.3	0.18	−1.1 (0.7[a])	1.0	0.8	0.2
25. Castelorizo	Harbour	2300 (≤100)	−2.5	0.8[b]	−3.3	0.14	−1.4 (0.9[a])	1.4	0.5	0.9
2. Phalassarna	Harbour	2300 (≤100)	6.6	0.8[b]	7.4	0.06	−1.9 (1.2[a])	−3.2	0.5	−3.7
9. Istron	Coastal lagoon	2270±68	−1.0	±0.3	−1.0±0.3	0.10	−1.8 (1.5[a])	0.4	0.8	−0.4
37j. Mykonos-Delos-Rhenia	Beachrocks	2267±65	−2.2	±0.2	−2.2±0.2	0.16	−1.5 (1.5[a])	1.0	0.7	0.3
37k. Mykonos-Delos-Rhenia	Beachrocks	2219±70	−1.5	±0.2	−1.5±0.2	0.16	−1.5 (1.5[a])	0.7	0.7	0.0

(Continued)

Table 1. (Continued)

Site	Indicator/marker	Age (cal. yr BP)	RSL stand					Time-averaged rate of RSL change		Vtr
			Elevation (m)	Uncertainty (m)	Obs. (m)	Mean tidal amplitude (m)	Pred. (m)	Obs. (mm/yr)	Pred. (mm/yr)	Obs.–Pred. (mm/yr)
23. Rhodes	Quarries	2200 (≥100)	–0.4	0.3[b]	–0.7	0.14	–1.3 (0.8[a])	0.3	0.6	–0.3
14. Strongilo islet	Notches-Marine platforms	2192±118	0.9	±0.3	0.9±0.3	0.10	–1.7 (1.1[a])	–0.4	0.8	–1.2
26. Orontes Delta	Notches, Vermetids, Oysters	2028±86	0.8	±0.5	0.8±0.5	0.14	–0.9 (0.6[a])	–0.4	0.5	–0.9
11. Palaikastro	Architectural ruins (wall footings)	2000 (≤100)	–1.6	0.6[b]	–2.2	0.10	–1.5 (1.0[a])	1.1	0.6	0.5
29. Nisyros	Dendropoma and Vermetous triqueter bioconstructions	2000±45	3.5	±0.3	3.5±0.3	0.14	–1.1 (0.7[a])	–1.8	0.6	–2.4
38. Mykonos	Beachrocks	2000±35	–2.4	±0.2	–2.4±0.2	0.16	–1.3 (0.8[a])	1.2	0.8	0.4
Roman Period (1981–1310)										
16. Antikythira	Notches, Neogoniolithon, Dendropoma	1818±79	2.0	±0.5	2.0±0.5	0.06	–1.3 (0.9[a])	–1.1	0.7	–1.8
6. Chersonissos	Breakwaters	1800 (≥100)	–1.0	0.6[b]	–1.6	0.10	–1.3 (0.8[a])	0.9	0.6	0.3
10. Mochlos	Fish tank	1800 (≤100)	–0.7	0.6[b]	–1.3	0.10	–1.3 (0.8[a])	0.7	0.7	0.0
5. Matala	Tombs	1800 (≤100)	–2.0	0.3 above high tide (0.05 a.m.s.l.)	–2.35	0.10	–1.3 (0.8[a])	1.3	0.7	0.6
36. NW Amorgos	Architectural ruins	1800 (≤100)	–1.3	0.6[b]	–1.9	0.16	–1.2 (0.7[a])	1.1	0.7	0.4
1. Phalasarna	Notches, Neogoniolithon	1798±77	4.2	±0.5	4.2±0.5	0.06	–1.3 (0.9[a])	–2.3	0.7	–3.0
24. Rhodes	Notches (tidal type)	1787±78	0.3	±0.3	0.3±0.3	0.14	–0.9 (0.6[a])	–0.2	0.5	–0.7
12. Zakros	Marine platform	1726±89	–1.0	±0.5	–1.0±0.5	0.10	–1.3 (0.8[a])	0.6	0.7	–0.1
4. Agia Roumeli	Notches, Neogoniolithon	1706±107	6.6	±0.5	6.6±0.5	0.06	–1.3 (0.8[a])	–3.9	0.7	–4.6
37l. Mykonos-Delos-Rhenia	Beachrocks	1703±66	–1.3	±0.2	–1.3±0.2	0.16	–1.0 (0.7[a])	0.8	0.6	0.2
37m. Mykonos-Delos-Rhenia	Beachrocks	1663±36	–3.0	±0.2	–3.0±0.2	0.16	–1.0 (0.7[a])	1.8	0.6	1.2
37n. Mykonos-Delos-Rhenia	Beachrocks	1624±53	–1.8	±0.2	–1.8±0.2	0.16	–1.0 (0.6[a])	1.1	0.6	0.5
37o. Mykonos-Delos-Rhenia	Beachrocks	1511±52	–2.0	±0.2	–2.0±0.2	0.16	–0.9 (0.6[a])	1.3	0.6	0.7
37p. Mykonos-Delos-Rhenia	Beachrocks	1487±48	–1.0	±0.2	–1.0±0.2	0.16	–0.9 (0.6[a])	0.7	0.6	0.1
3. Chrisoskalitissa	Notches, Neogoniolithon, Dendropoma	1452±77	7.9	±0.5	7.9±0.5	0.06	–1.0 (0.6[a])	–5.4	0.7	–6.1
15. Antikythira	Notches, Neogoniolithon, Dendropoma	1436±72	2.7	±0.5	2.7±0.5	0.06	–1.0 (0.6[a])	–1.9	0.7	–2.6
37q. Mykonos-Delos-Rhenia	Beachrocks	1306±14	–2.1	±0.2	–2.1±0.2	0.16	–0.7 (0.5[a])	1.6	0.6	1.0

[a]This represents the uncertainty range of the value extracted from Lambeck's sea-level curve.
[b]This represents the potential functional height of the construction above mean sea level in the past.
(1, 3, 4, 5, 6, 10, 11, 12) Leatham and Hood (1959), Pirazzoli et al. (1982), Blackman (2005); (2) Pirazzoli et al. (1992); (7, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24) Pirazzoli (1988); (8, 9) Theodorakopoulou et al. (2009); (13) Blackman (2005); (14) Pirazzoli et al. (1996); (25) Pirazzoli (1987); (26, 27) Pirazzoli et al. (1991); (28, 29) Pirazzoli (2005); (30, 31, 46) Stiros et al. (2000); (32, 33) Bruckner et al. (2010); (34) Morisson (1968); (35) Evelpidou et al. (2010); (36) Leatham and Hood (1959), Blackman (2005); (37) Fouache et al. (2005); (38) Fouache et al. (2005), Desruelles et al. (2009); (39) Lolos (1995); (40) Loven (2003); (41, 42) Knoblauch (1972); (43) Jameson (1973); (44) Spondylis (1998); (45) Charalabidou et al. (2010); (47, 48, 49) Bruckner (2005); (50) Pavlopoulos et al. (2006); (51) Triantaphyllou et al. (2008); (52, 53) Stiros et al. (1992); (54, 55) Stiros (1993) ; Stiros et al. (1994); (56) Pavlopoulos et al. (2007); (57, 58) Theodoulou (2008); (59) Chronis (1986); (60, 61, 62, 63, 64) Vouvalidis et al. (2005); (65) Simossi (1985); (66) Archontidou-Argyri et al. (1989); (67, 68, 69, 71, 72, 73, 74) Syrides et al. (2009); (70) Ammerman et al. (2008); Pavlopoulos (2010).

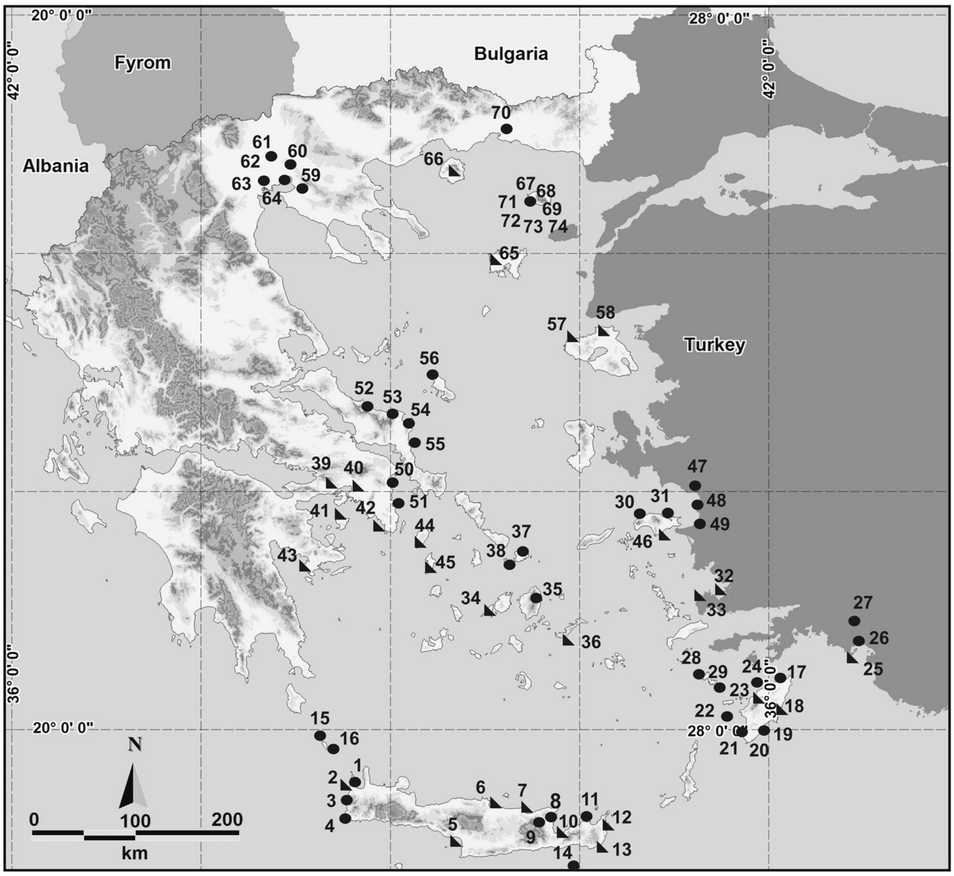

Figure 2. Location map of the study sites. The type of indicator/marker used for each site is also shown (dots, geomorphological; triangles, archaeological)

and (e) the difference between the observational and predicted rates, which derives the vertical displacement trend (Vtr). Positive Vtr values are associated with RSL changes higher than those predicted by Lambeck's model, while negative Vtr values are related to RSL changes lower than those foreseen by the model.

Results and discussion

The evaluated vertical displacement trends (Vtr) for the 74 study sites (see Figure 2 for locations) of Mesolithic, Neolithic, Bronze, Classical, and Roman Era are displayed in Table 1. It should be emphasized that demonstrated time-averaged Vtr values do not necessarily imply that vertical movement was at a steady rate over hundreds to thousands of years, and that it is continuing now at the same steady rate. Movements which are tectonic in the strict sense of seismic forces may be co-seismic and discontinuous. They can also reverse for short periods, because of the stick-slip behaviour of faults, where strain builds up and is then released. Even sedimentary compaction processes can include slump faulting which is discontinuous. Hence, vertical displacement rates averaged over hundreds or thousands of years are not necessarily the same for shorter time intervals (Tsimplis et al., 2011).

For the most accurate determination of vertical trends, the temporal and vertical uncertainties of observational data have also been superimposed on Lambeck's predictive sea level curves. If observational data and their uncertainty bars interfere with Lambeck's curves, then this implies agreement with the prediction and, subsequently, site 'stability'. If not, this indicates the positive or negative relative vertical trend (Figures 3 and4).

Negative Vtr values have been evaluated for Antikythira (−1.8 to −2.6 mm/yr), many sites in Crete such as Amnissos, Chrisoskalitissa, Agia Roumeli, Phalassarna, Zakros, and Istron (−0.4 to −6.1 mm/yr), Rhodes (−0.3 to −1.4mm/yr), and Nisyros (−2.0 to −2.4 mm/yr) (Table 1, Figure 3a). This suggests 'slower' rates of sea level rise due to a tectonic uplift of the above areas (see Figure 5). These areas are located in the outer margin of the Hellenic Arc and are related to the compressional front and accretionary wedge developed because of the collision of the Eurasian with African plate. A characteristic example of the intense and complicated tectonic pattern of that region is derived from the Phalassarna site, where a sequence of (up to 11) small-amplitude (20–30 cm) subsidence events (Pirazzoli et al., 1982), over a period of 2500 years (1500–4000 cal. yr BP), was followed by a major (up to 9 m) uplift and tilting of the western Crete in the fourth or fifth century AD, as a consequence of a major (M ≥ 8.5) earthquake (Stiros, 2010). Furthermore, archaeological and geological data from the southeastern coast of Rhodes display a sequence of uplifts and subsidence events associated with earthquakes (M ≥ 7.5) occurred over the last 5000 years. Kontogianni et al. (2002) suggest that generation or reactivation of different faults in the same faulting zone as well as reactivation of the same faults but with different amounts of seismic slip have caused small- and large-amplitude uplifts, and in some places during specific time intervals subsidence events too (see Chersonissos and Matala in Crete; Table 1, Figure 5).

Furthermore, uplifting trends (rates from −0.3 to −2.3 mm/yr) are displayed for the majority of the sites in the northeast Aegean region (see Samothrace and Lafrouda; Table 1, Figures 3b, 5). These have probably been induced by the trans-tensional tectonic setting of the North Anatolian Fault (NAF) (Figure 1). Coastal uplift is the dominant mechanism on either side of the NAF over the Plio-Quaternary, as it is indicated in Gokceada (Imbros) Island (Koral et al., 2009) and the Turkish part of the Enez (Evros) River delta (Alpar, 2001).

Likewise, both sides of the central Aegean region (i.e. Marathon in Attica and NE Evia coasts to the west, and NW Samos

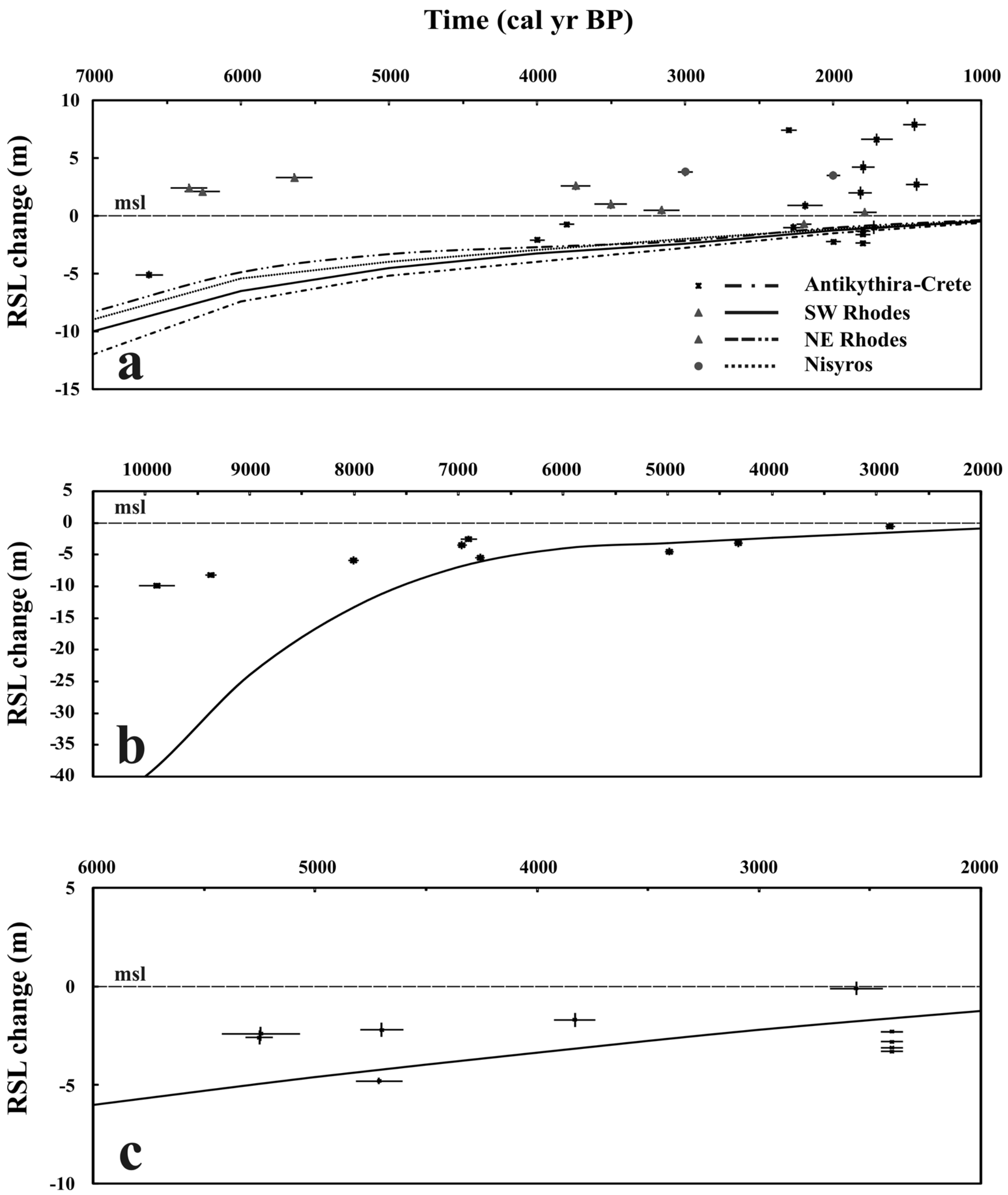

Figure 3. Comparison of observational data from various coastal sites of the Aegean Sea with Lambeck's predictive sea-level curves (illustrated lines): (a) Antikythira-Crete-Rhodes-Nisyros; (b) Samothrace-Lafrouda; (c) Attica-Porto Heli (data lying above the predictive curve are from Marathon). Temporal and vertical uncertainties of data are displayed

coasts to the east) display negative Vtr values (−0.4 to −1.1) (see Table 1, Figure 5), though the broader area is characterized by an extensional tectonic regime (Stiros et al., 1992, 2000). This exception may be attributed to regional-scale tectonic particularities according to which the general subsidence of the Aegean margins is associated with local uplifts. For example, the observed uplift at the northwestern coasts of Samos is probably related to a zone of intense seismicity and faulting following the Great Meander (Buyuk Menderes) River graben in Western Anatolia (Stiros et al., 2000).

Many areas in the central Aegean region exhibits positive Vtr values as a result of a dominant extensional tectonic regime. This indicates a 'faster' rate of sea level rise, which may be attributed to crustal subsidence caused by tectonic activity and/or sediment load isostacy. Subsidence characterizes all sites in Attica (Aigina, Sounion, Salamis, Piraeus, Vravron), except Marathon, and Porto Heli (0.3–0.7 mm/yr) (Table 1, Figures 3c, 5); sites in Cyclades such as the Mykonos-Rhenia-Delos district (although several data from this area reveal 'stability'), Kea, Kythnos, and NW Amorgos (0.2–1.2 mm/yr) (Table 1, Figures 4a, 5); sites in Lesvos such as Antissa and Eressos (0.2–0.4 mm/yr); and Skyros (0.1 mm/yr) (Table 1, Figure 5). These coastal sites have followed the long-term subsidence trend of the Aegean Sea continental shelf and slope determined for the Middle to Upper Pleistocene through high-resolution seismic profiling (Lykousis, 2009). Spatial and temporal differences in the subsidence rates may be assigned to the variable stress and deformation pattern of the Aegean region (Kokkalas and Doutsos, 2001; Papazachos, 1990).

Positive Vtr values (0.2–3.9 mm/yr) characterize the majority of the sites from Thessaloniki and Epanomi (Table 1, Figure 4b). The fact that one site (No. 60) of Mesolithic age demonstrates a high negative Vtr value may be attributed to false radiocarbon dating of the biological indicator used because of contamination. The identified subsidence for this area (Figure 5) is mainly the result of intense sediment compaction, though the tectonic impact cannot be neglected. Rapid sediment accumulation in the Thessaloniki Plain-Thermaikos Gulf, caused by the Axios, Aliakmon, Loudias, and Galikos rivers, has created a thick (of a few tens of meters)

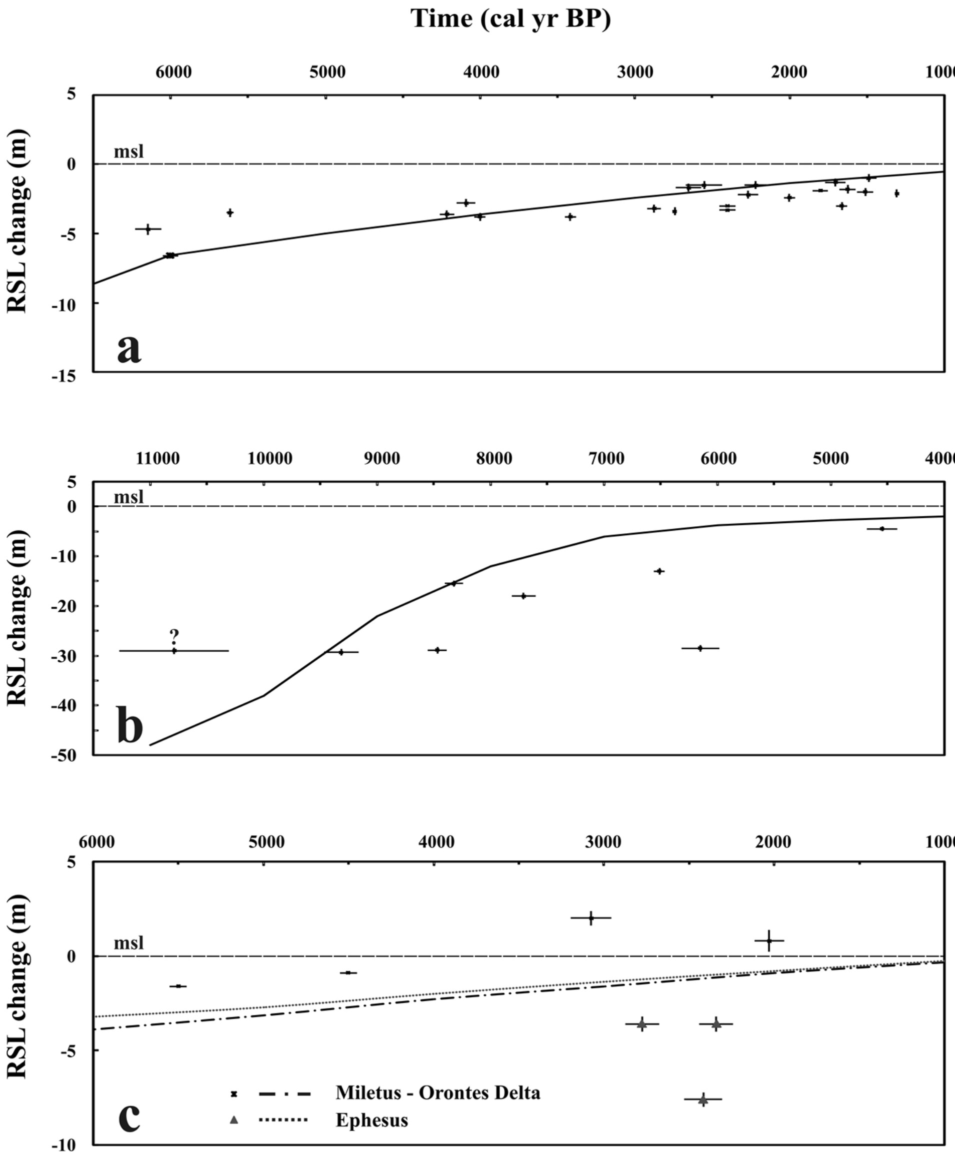

Figure 4. Comparison of observational data from various coastal sites of the Aegean Sea with Lambeck's predictive sea-level curves (illustrated lines): (a) Cyclades; (b) Thessaloniki-Epanomi; (c) Minor Asia. Temporal and vertical uncertainties of data are displayed

Holocene sedimentary cover (Lykousis et al., 2005) which has been progressively compacted (a maximum subsidence of 4 m has been observed by Stiros, 2001) because of the oxidation of peat soils in the vadose zone, groundwater overpumping, and synsedimentary deformation and loading-induced consolidation of deeper sediments (Psimoulis et al., 2007). Furthermore, the Thessaloniki Plain may suffer a subsidence resulting from the loading of the entire Holocene sedimentary cover since its thickness is significant and in many places exceeds 30 m (Fouache et al., 2008). The additional weight of the Holocene sediments probably pushes the area downwards causing a regional descending movement. Although there are a lack of data for this type of subsidence in the Aegean region, it should play a major role in areas of massive sediment accumulation, e.g. the delta of Evros River (Alpar, 2001; Perissoratis and Mitropoulos, 1989).

Contradictory vertical trends are exhibited for the sites in Minor Asia (i.e. Ephesus, Orontes Delta, Miletus) (Table 1, Figures 4c, 5). This complexity is perhaps the result of active tectonics that fragment western Minor Asia in a W–E direction, perpendicular to the coastline, creating numerous small blocks with differential (vertical and horizontal) motion (Kayan, 1988).

Finally, Saliagos (Antiparos) and part of the Mykonos-Rhenia-Delos district in the Cyclades insular complex do not reveal any vertical trends (Figure 4a). This 'stability' could be the result of an extremely low tectonic activity according to Poulos et al. (2009) who believe that the Cyclades Plateau is an aseismic area. However, the rest of the data regarding Cyclades do not support that concept since uplifting (e.g. Naxos) and subsiding trends (see above) are quite evident (see Figures 4a, 5). Hence, identified 'stability' is probably the result of a dynamic equilibrium between uplift and subsidence in a tectonically active area.

Conclusions

Relative sea level changes in the Aegean Sea reflect global eustatic changes, regional glacio-hydro-isostatic adjustments of the lithosphere, and vertical displacements caused by tectonic activity, sediment-isostasy, sediment compaction, and sedimentary material budget (erosion–deposition). The comparison of observational data from 74 coastal sites in the Aegean Sea with the eustatic and glacio-hydro-isostatic data extracted from the predictive curves of Lambeck and Purcell (2005) has demonstrated local vertical displacements trends. The analysis of these trends shows that tectonic uplift occurs along the frontal margin of the Hellenic Arc (Antikythira, Crete, Rhodes, Nisyros), in the northeast Aegean region (Thrace), and in parts of the periphery of

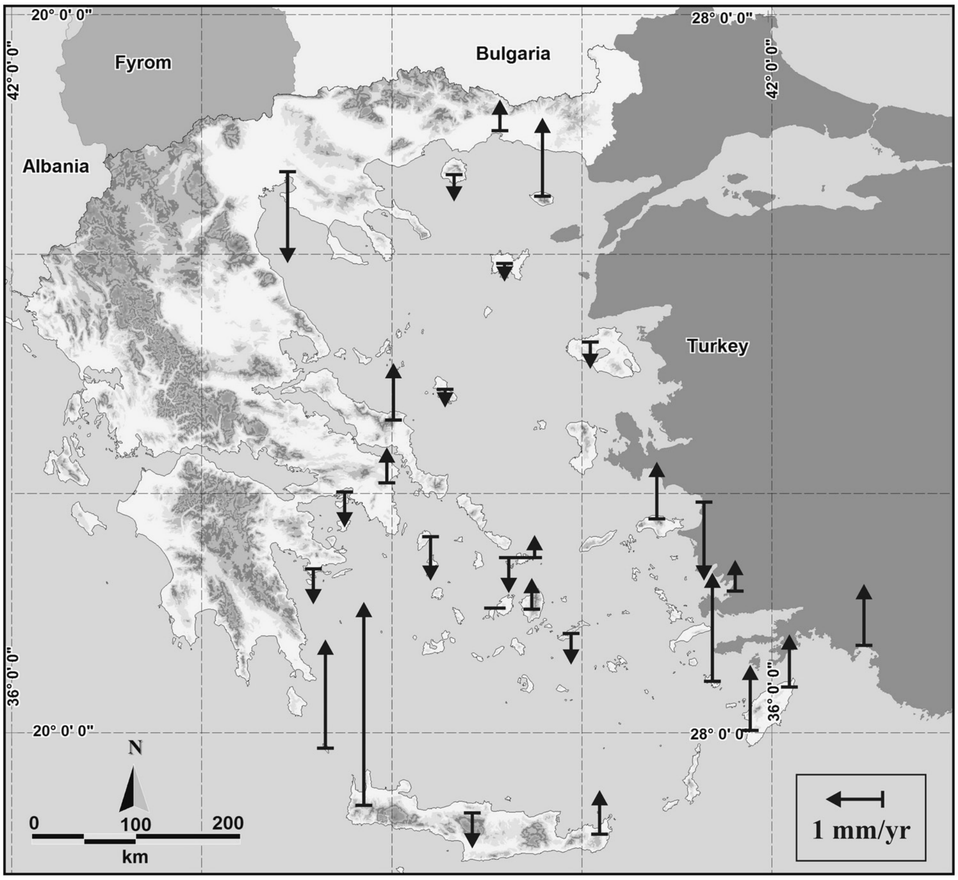

Figure 5. Spatial distribution of uplifting (upward arrows) and subsiding movements (downward arrows) in the Aegean region. Arrow lengths are scaled and represent mm/yr

the central Aegean region (E Attica, NE Evia, NW Samos) because of local intense tectonic compressions. However, the major part of the central Aegean region mostly includes tectonically subsiding areas (Porto Heli, Cyclades, Attica, Skyros, Lesvos) because of the domination of an extensional structural pattern. Tectonically 'stable' sites are detected in the Cyclades Plateau (Antiparos, part of the Mykonos-Delos-Rhenia district), probably because of an equilibrium between crustal uplift and subsidence. Sediment compaction and sediment loading play a basic role in the subsidence of areas in the northwest Aegean region (e.g. Thessaloniki Plain-Thermaikos Gulf). Finally, the coastal sites in Minor Asia demonstrate localised opposite trends in the vertical displacement because of tectonic fragmentation.

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