SEA SURFACE RADIOCARBON RESERVOIR AGE CHANGES IN THE AEGEAN SEA FROM ABOUT 11,200 BP TO PRESENT

Yorgos Facorellis
Department of Antiquities and Works of Art Conservation, Faculty of Fine Arts, Technological Educational Institute of Athens, Aghiou Spyridonos St., 12210 Egaleo, Athens, Greece. Corresponding author. Email: yfacorel@teiath.gr.

Evi Vardala-Theodorou
Hydrobiological Department, Goulandris Natural History Museum, 100 Othonos St., 14562 Kifissia, Athens, Greece. Email: evard@gnhm.gr.

ABSTRACT. Archaeological excavations in two coastal sites of Greece, Ftelia on Mykonos and Cyclops Cave on Youra, have provided suitable material (charcoal/marine mollusk shell paired samples deposited simultaneously in undisturbed anthropogenic layers) to estimate regional changes of the sea surface radiocarbon reservoir effect (ΔR) in the Aegean Sea. Moreover, pre-bomb 14C ages of marine mollusk shells of known collection date, from Piraeus and Naftilion in Greece and Smyrna in Turkey, also contributed to the marine reservoir calculation during recent years. In this article, these already published results, 10 in total, are considered and calibrated again using the latest issues of the calibration curves IntCal13 and Marine13. The same calibration data were applied to 11 more paired samples from the archaeological sites of Palamari on Skyros and Franchthi Cave in the Argolic Gulf, published here for the first time, in order to investigate the fluctuation of the reservoir ages R(t) and ΔR values in the Aegean Sea from ~11,200 BP (~13,000 cal BP) to present. Our data show that R(t) and ΔR values are not constant through time and may vary from 1220 ± 148 to –3 ± 53 yr and –451 ± 68 to 858 ± 154 14C yr, respectively. An attempt was also made to correlate these fluctuations with eastern Mediterranean paleo-environmental proxies and other relevant paleoceanographic data found in the literature.

INTRODUCTION

It is well known that samples from species living contemporaneously in the atmosphere and sea surface waters (<100 m depth) show different conventional 14C ages. This difference between the 14C ages of such paired samples is called the marine reservoir age R(t), or apparent age. R(t) is not constant (t = cal age) due to the difference in sea surface reservoir and atmosphere 14C-specific activity changes caused by (1) oceanic circulation processes that tend to advect intermediate and deep 14C-depleted water masses to the surface, (2) atmospheric 14C production changes, and (3) air-sea CO2 exchange processes (Stuiver et al. 1986, 1998; Stuiver and Braziunas 1993; Siani et al. 2000, 2001).

A global box-diffusion carbon model (Oeschger et al. 1975), which reproduces depth-dependent marine 14C variations in response to atmospheric 14C production changes (Stuiver et al. 1986; Stuiver and Braziunas 1993), is used in order to estimate the reservoir ages of the global mixed sea surface layer. These were found to be ~400 yr older in the well-ventilated gyres of the central North and South Pacific and the Atlantic Ocean (Bard 1988). Moreover, the magnitude of this effect may also differ from region to region due to e.g. long residence time of deep waters in upwelling areas, which is in turn affected by the coastline shape, climate, and sea bottom topography (Robinson and Thompson 1981; Domack 1992; Dye 1994; Heier-Nielsen et al. 1995; Berkman and Forman 1996) and the hardwater effect in marine organisms that have grown near estuaries (Ingram and Southon 1997; Goodfriend and Flessa 1997).

The local sea surface reservoir deviations (ΔR) from R(t) may be determined either by 14C dating of (1) live-collected pre-bomb marine mollusk shells (Siani et al. 2000; Reimer and McCormac 2002); (2) foraminifera or mollusk shells extracted from marine sediments and plant material from terrestrial settings, such as peat profiles paired samples, assuming a coeval date of organism death for both sample types, based on volcanic ash onshore/offshore isochrones (Ascough et al. 2005); and (3) marine mollusk shell/charcoal paired samples, assumed to be deposited simultaneously, collected from undisturbed archaeological layers (Facorellis et al. 1998).

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Consequently, calculation of ΔR allows (1) reliable calibration of the conventional 14C ages of marine samples (e.g. marine mollusk shells), in the absence of other suitable material from an excavated site (as they are usually short-lived samples, rarely transported over long distances), (2) reliable calibration of 14C ages of human bones in case of mixed (marine and terrestrial) diet (Sveinbjörnsdóttir et al. 2010), and (3) obtaining of paleoceanographic information (Siani et al. 2001).

The first ΔR value in the Mediterranean Sea corresponds to a pre-bomb marine mollusk shell sample collected in AD 1954 at the Kouali Point of Tipasa in Algeria (36°40′N, 2°30′E) (Olson and Broecker 1959; Broecker and Olson 1961), which produced a ΔR value of −133 ± 83 14C yr (Stuiver et al. 1986). Facorellis et al. (1998) then published a mean R(t) of 515 ± 22 yr and a ΔR value of 149 ± 30 14C yr in the Aegean Sea for the time interval 8800–7400 BP (9900–8000 cal BP) based on three paired charcoal/marine mollusk shell samples collected from the Mesolithic anthropogenic layers of Cyclops Cave on Youra Island. Siani et al. (2000) followed with the publication of 26 modern, pre-bomb marine mollusk shells live-collected between AD 1837 and 1950 throughout the Mediterranean Sea, which enabled estimation of the R(t)mean = 390 ± 85 yr and the ΔRmean = 35 ± 70 14C yr. They also calculated a pre-bomb R(t) value of 520 ± 40 yr in the Dardanelles Strait (collection year AD 1900), which is in a very good agreement with the several millennia older one from Youra Island. Siani et al. (2001) then published another seven tephra charcoal/planktonic foraminifera paired samples from the South Adriatic Sea spanning from 16,130 to 3820 BP (19,790–4090 cal BP), which showed significant deviations from the Mediterranean R(t)mean. Additionally, Reimer and McCormac (2002) found that pre-bomb R(t) in at least two Aegean sites [Piraeus, collection year AD 1943, R(t) = 427 yr; and Nafplion, collection year AD 1940, R(t) = 324 yr] is statistically the same at a 95% level with the aforementioned values. A third pre-bomb marine mollusk shell from Smyrna, Turkey (collection year AD 1893/4) produced a much higher R(t) of 652 yr, which may be attributed to the estuarine environment that this marine mollusk species often inhabits (Reimer and McCormac 2002). Subsequently, Facorellis and Maniatis (2002), based on three paired charcoal/marine mollusk shell samples collected from the Middle Neolithic layers of the Ftelia site on Mykonos, calculated a regional mean R(t) of −32 ± 31 yr and a mean ΔR value of −393 ± 40 14C yr for the time interval 6080–5720 BP (7150–6400 cal BP), showing that during that time period there was no significant local sea surface reservoir effect. All the aforementioned data, together with the Mediterranean Sea R(t) changes since the Last Glacial Maximum reported by Siani et al. (2001), indicate that R(t) is not constant through time. In order to estimate these changes in the Aegean Sea, we reconsidered all the available data found in the literature (Facorellis et al. 1998; Siani et al. 2000, 2001; Facorellis and Maniatis 2002; Reimer and McCormac 2002), as well as 11 new paired samples we dated from two other archaeological sites in that region, which are presented here for the first time. More specifically, two pairs from Palamari on Skyros and nine more from Franchthi Cave in the Argolic Gulf have been dated. This study aims to present all the up-to-date published regional R(t) values and recalculate the corresponding ΔR values using the latest IntCal13 and Marine13 calibration curves (Reimer et al. 2013), together with the 11 new R(t) and ΔR values from Palamari and Franchthi Cave. Finally, an attempt was made to correlate these values with published southeastern Mediterranean paleoproxies and regional paleoceanographic data in order to understand the underlying reasons for the variability observed.

**MATERIALS AND METHODS**

The new charcoal and marine mollusk shell samples were 14C dated in the laboratory of Archaeometry of NCSR “Demokritos” in Athens using the conventional gas counting technique, as described elsewhere (de Vries and Barendsen 1953; Münnich 1957; Kromer and Münnich 1992; Facorellis 1996; Facorellis et al. 1997; Maniatis and Papadopoulos 2011).
The two charcoal samples from Palamari (DEM-1036 and DEM-1038) were thoroughly examined and manually cleaned under a stereoscope. The samples were then chemically treated using the standard acid-base-acid treatment to remove all carbon contaminants (Olsson 1979, 1986; Mook and Streurman 1983).

The 11 marine mollusk shells, two from Palamari (DEM-1074 and DEM-1076) and nine from Franchthi Cave (DEM-1048 to DEM-1056), were washed with deionized water in an ultrasonic bath and the depositions on the surface were removed with a dentist’s drill. Next, more than 35% of their remaining weight was removed with a solution of 2% HCl to eliminate any recrystallized carbonates during the time of burial (Goslar and Pazdur 1985; Facorellis et al. 1998). 14C ages of the nine marine mollusk shells samples from Franchthi Cave were paired with the corresponding published 14C ages of charcoal samples originating from the same undisturbed archaeological layers (W R Farrand, personal communication, 2000), which were dated in the University of Pennsylvania 14C laboratory (Lawn 1971, 1974, 1975; Fishman et al. 1977).

The shells of short-lived marine mollusks living in relatively shallow waters are ideal material to be used for the calculation of the sea surface regional reservoir effect R(t) and ΔR values, as they reflect the 14C content of their environment and they are directly related to their archaeological use. Such marine mollusk shells are appropriate only if they are food residues, originating from the same undisturbed anthropogenic layers with the paired charcoal samples. Table 1 summarizes all the available aforementioned information for the marine mollusk species used in this study, proving that they fulfill all the above requirements. From the table, one can see that most of the marine mollusks belong to short-lived (<20 yr), edible species living from just offshore in shallow waters and deeper, on the sea floor at depths less than 100 m (Shackleton and van Andel 1980; Forster 1981; Sabelli et al. 1990; Delamotte and Vardala-Theodorou 2001; Papanathanassiou and Zenetos 2005; Papaconstantinou et al. 2007; Peharda et al. 2012).

Figure 1 shows the locations of the sites in the Aegean Sea region involved in this study. More specifically, the samples originate from undisturbed anthropogenic layers of the following:

1. The Bronze Age site Palamari on Skyros (38°58′N, 24°30′E) [2 pairs] (Parlama 2007, 2009; Parlama et al. 2010; Pavlopoulos et al. 2010);
3. The Neolithic site Ftelia on Mykonos (37°27′N, 25°22′E) [3 pairs] (Sampson 2002; Facorellis and Maniatis 2002);
4. The Neolithic and Mesolithic layers of Cyclops Cave on Youra (37°27′N, 24°10′E) [4 pairs] (Facorellis et al. 1998; Facorellis 2003, 2013; Sampson 2008, 2011); and
5. Three pre-bomb 14C ages of marine mollusk shells from Piraeus (37°56′N, 23°38′E), Nafplion (37°32′N, 22°47′E), and Smyrna, Turkey (38°26′N, 27°9′E) (Reimer and McCormac 2002).

It is worth noting that the successive cultural phases in the Helladic area are roughly correlated to the Paleolithic, which ends at ~10,000 BC, the Mesolithic (10,000 to ~6500 BC), the Neolithic (~6500 to 3200/3000 BC), and the Bronze Age (3200/3000 to 1050/1025 BC).
Table 1  Summary of the marine mollusk shell species information used in this study for the estimation of the sea surface reservoir in the Aegean Sea.

<table>
<thead>
<tr>
<th>Shell species</th>
<th>Lifespan</th>
<th>Consumption interest</th>
<th>Living zone</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Arca noae</em> Linnaeus, 1758</td>
<td>Up to 16 yr, with max length 7 cm</td>
<td>Edible; in some locations the species is commercially important as seafood resource; major interest</td>
<td>Intertidal zone, just offshore to depths of 100 m</td>
</tr>
<tr>
<td><em>Acanthocardia tuberculata</em> Linnaeus, 1758</td>
<td>Ages range from 5 months to 11 yr (Peharda et al. 2012)</td>
<td>Edible; Croatian cuisine</td>
<td>Intertidal zone to depths of 100 m, distributed in ~1–40 m</td>
</tr>
<tr>
<td><em>Barbatia barbata</em> Linnaeus, 1758</td>
<td></td>
<td>Edible; widely collected for human consumption; major interest</td>
<td></td>
</tr>
<tr>
<td><em>Callista chione</em> Linnaeus, 1758</td>
<td>&gt;40 yr (Forster 1981), slow growing, 6 cm in 15–17 yr (Forster 1981; Papaconstantinou et al. 2007)</td>
<td>Edible; excellent seafood; major interest</td>
<td>From just offshore to 130 m depth</td>
</tr>
<tr>
<td><em>Cerastoderma glaucum</em> Poiret, 1789</td>
<td></td>
<td>Edible; collected locally in Nestos and Vistonis lagoons for human consumption</td>
<td>Upper sublittoral zone transitional ecosystem lagoons, estuaries 1–40 m</td>
</tr>
<tr>
<td><em>Cerastoderma edule</em> Linnaeus, 1758</td>
<td>10–16 yr (Peharda et al. 2012)</td>
<td>Edible; French: <em>coques</em>; English: edible cockle or common European cockle</td>
<td>Upper sublittoral zone 1–20 m</td>
</tr>
<tr>
<td><em>Mytilus edulis</em> Linnaeus, 1758</td>
<td></td>
<td>Edible; excellent seafood; major interest</td>
<td>Intertidal 0.5 m to 40 m depth</td>
</tr>
<tr>
<td><em>Ostrea edulis</em> Linnaeus, 1758</td>
<td>grow very old &gt;20 yr</td>
<td>Edible; excellent seafood; major interest</td>
<td>1–150 m sublittoral to circalittoral zone</td>
</tr>
<tr>
<td><em>Pinna nobilis</em> Linnaeus, 1758</td>
<td>20+ yr (Papaconstantinou et al. 2007)</td>
<td>Edible; minor commercial interest</td>
<td>Midlittoral to sublittoral and more from 0.5–60 m</td>
</tr>
<tr>
<td><strong>Gastropoda</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Cerithium vulgatum</em> Bruguière, 1792</td>
<td></td>
<td>Inedible, used as fishing bait</td>
<td>Midlittoral to sublittoral 1–40 m</td>
</tr>
<tr>
<td><em>Columbella rustica</em> Linnaeus, 1758</td>
<td></td>
<td>Inedible</td>
<td>Midlittoral to sublittoral 1–40 m</td>
</tr>
<tr>
<td><em>Conus mediterraneus</em> HAWSS IN BRUGUIRE, 1792</td>
<td>Inedible</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Diodora italica</em> Defrance, 1820</td>
<td></td>
<td>Edible</td>
<td>Midlittoral to sublittoral 1–40 m</td>
</tr>
</tbody>
</table>
Table 1 Summary of the marine mollusk shell species information used in this study for the estimation of the sea surface reservoir in the Aegean Sea.

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<tbody>
<tr>
<td><em>Hexaplex trunculus</em> Linnaeus, 1758</td>
<td></td>
<td>Edible; excellent seafood; major interest, fishing bait</td>
<td>Subtidal to sublittoral 5–30 m</td>
</tr>
<tr>
<td><em>Patella caerulea</em> Linnaeus, 1758</td>
<td></td>
<td>Edible; limpets are widely collected for human consumption and as fishing bait; minor commercial interest</td>
<td>Lower Midlittoral</td>
</tr>
<tr>
<td><em>Patella ulyssiponensis</em> Gmelin in L., 1791</td>
<td></td>
<td>Edible; limpets are widely collected for human consumption and as fishing bait; minor commercial interest</td>
<td>Midlittoral</td>
</tr>
</tbody>
</table>

Figure 1 Map of the Aegean Sea indicating the geographic location of the study sites (modified from Google Earth®)
RESULTS AND DISCUSSION

The Appendix (online supplemental file) presents all the dating results sorted by age. A total of 21 pairs of samples are shown, including the three single pre-bomb marine mollusk samples of known collection date. The conventional $^{14}$C ages of the samples were calculated using $\delta^{13}$C values of $-25\%$ for charcoal and $1\%$ for marine mollusk shells (Stuiver and Polach 1977), which are the typical values used for that type of material in the Aegean region (Facorellis et al. 1998). However, these $\delta^{13}$C values may have a possible $\pm2\%$ error due to $^{13}$C variation (Stuiver and Polach 1977), which corresponds to an additional $\pm32$ yr error in the calculated $^{14}$C ages. This was incorporated into the final $^{14}$C age error of the new samples by using the following formula for summing errors:

$$\sigma_{\text{final}} = \sqrt{\sigma_{14C}^2 + \sigma_{13C}^2}$$  \hspace{1cm} (1)

The $^{14}$C ages of the charcoal samples were then calibrated with the IntCal13 calibration curve (Reimer et al. 2013). The $^{14}$C ages of the marine mollusk shell samples were calibrated using the calculated $\Delta R$ value corresponding for each pair (Appendix) in conjunction with the Marine13 international calibration curve. All calibrations were performed with the OxCal v 4.2.4 software (Bronk Ramsey 2009). All calibrated dates are rounded to the nearest decade.

The regional sea surface reservoir $R(t)$ value of each pair is calculated by subtracting the $^{14}$C conventional age of the charcoal sample from that of the marine mollusk sample. The $R(t)$ error is calculated using a similar formula for summing errors as mentioned above.

The local deviation $\Delta R$ values are calculated by combining the calibrated ages of the terrestrial and marine samples, using the latest issues of the atmospheric and marine international curves (Reimer et al. 2013), respectively, as follows (Southon et al. 1995; Facorellis et al. 1998). The measured $^{14}$C age of the terrestrial sample gives a calendar date using the atmospheric calibration curve. Based on this calendar date, the marine calibration curve gives an equivalent $^{14}$C age. $\Delta R$ is the difference between this equivalent and the measured $^{14}$C age for the marine sample. In this study, this is performed with the OxCal v 4.2.4 software using the following routine, as adapted for the Palamari-1 paired samples (Appendix, Figure 2). For each pair of samples, the uncertainty $U(x_1,x_2)$ was set accordingly, so that the $\Delta R$ probability distribution is at the center of the plot.

```r
Plot()
{
  Curve("=IntCal13");
  Curve("Marine13","Marine13.14c");
  Delta_R("PALAMARI-1",U(0,600));
  Combine()
  {
    Curve("=IntCal13");
    R_Date("DEM-1036", 3545, 41);
    Curve("=PALAMARI-1");
    R_Date("DEM-1076", 4161, 51);
  }
}
```


**14C Reservoir Age in the Aegean Sea, 11,200 BP to Present**

Figure 3 shows the plot of \( R(t) \) values in the Aegean Sea versus \(^{14}\)C age from ~11,200 yr BP until present (black dash-dotted line), with respect to the pre-bomb mean \( R(t) \) value in the Mediterranean Sea \( [R(t)_{\text{mean}} = 390 \pm 85 \text{ yr}, \text{area between the red dotted lines}] \), as estimated by Siani et al. (2000). This figure also includes, for comparison purposes, data (spanning from ~10,400 to 16,000 BP) from the South Adriatic Sea (Siani et al. 2001, supplementary online material). One can see that the \( R(t) \) values fluctuate significantly from \( 1220 \pm 148 \) yr (Franchthi-9) to \(-3 \pm 53 \) yr (Ftelia-2), resulting in regional \( \Delta R \) values ranging from \(-451 \pm 68 \) yr (Ftelia-3) to \( 858 \pm 154 \) \(^{14}\)C yr (Franchthi-9). Of the 21 pairs (Appendix), 13 pairs (Piraeus, Nafplion, Palamari-1 and -2, Franchthi-1, -2, -3, -6 and -7, Youra-1, -2, -3 and -4) produced \( R(t) \) values falling within two standard deviations (2σ, probability 95.4%) in the range of the Mediterranean pre-bomb mean value.

The prevailing question concerning our data is whether these sea surface reservoir ages \( R(t) \) are valid for all over the Aegean Sea within the same time period. Until further research adds new evidence, the black dash-dotted line connecting the points in Figure 3 is only tentative. By carefully looking at our results, one can see that there is an intrasite repeatability, overlapping within one standard deviation (1σ, probability 68.3%), in the following cases:

1. Ftelia site on Mykonos, three pairs (Ftelia-1, -2 and -3): mean \( R(t) = 26 \pm 96 \) yr and mean \( \Delta R = -400 \pm 113 \) \(^{14}\)C yr for the time interval 7150–6400 cal BP.

2. Franchthi Cave, two pairs (Franchthi-2 and -3): mean \( R(t) = 357 \pm 120 \) yr and mean \( \Delta R = -34 \pm 123 \) \(^{14}\)C yr and for two more pairs (Franchthi-4 and Franchthi-5): mean \( R(t) = 765 \pm 161 \) yr and mean \( \Delta R = 461 \pm 140 \) \(^{14}\)C yr for the time intervals 7690–7440 and 9140–8520 cal BP, respectively.

3. Cyclops Cave on Youra, three pairs (Youra-1, -2, -3 and -4): mean \( R(t) = 529 \pm 90 \) yr and mean \( \Delta R = 167 \pm 116 \) \(^{14}\)C yr for the time interval 9530–8050 cal BP.
Intraregional repeatability is observed between the Franchthi-6 (10,000–9540 cal BP) and Youra-4 (9910–9700 cal BP) pairs, which happen to be the only pairs of our study that chronologically overlap: mean $R(t) = 267 \pm 88$ yr and mean $\Delta R = -37 \pm 99^{14}$C yr. Although this specific sea surface reservoir effect is now confirmed by the measurement of two independent pairs from two different sites, one mainland (Franchthi Cave) and one island (Cyclops Cave on Youra), the Youra-4 pair was initially rejected by Facorellis et al. (1998), as it was considered an outlier at the time due to lack of confirming evidence.

There are two sites that produced outlying $R(t)$ values, Franchthi Cave in the Argolic Gulf (Franchthi-4, -5, -8, and -9 pairs) and Ftelia on Mykonos Island (Ftelia-1, -2, and -3 pairs). The $R(t)$ values of the Franchthi-8 and -9 pairs and those of Franchthi-4 and -5 are higher than the Mediterranean $R(t)_{\text{mean}}$ value by a factor of 3 and 2, respectively (Appendix, Figure 3). On the other hand, the Ftelia pairs $R(t)$ values are lower by a factor of 1.

There is only one data set of paired samples from the eastern Mediterranean Sea found in the literature (Siani et al. 2001, supplemental online data) that coincides chronologically with our data. More specifically, this is the charcoal/planktonic foraminifera pair (OCF97129PP & R-704/GIFA96208), whose charcoal (from the Agnano Pomici Principali eruption) age (10,450 ± 40 BP) overlaps within 2$\sigma$ with the charcoal age (10,260 ± 110 BP) of the Franchthi-8 pair (Figure 3, dashed rectangle).
Their corresponding R(t) values are 380 ± 100 and 988 ± 120 yr, respectively. This important R(t) difference shows that there is a different prevailing mechanism providing \(^{14}\)C-depleted water in the Argolic Gulf, than that of the Mediterranean Sea.

The subsurface hydraulic communication between the Argolic plain (Argon field) and the Argolic Gulf was known since ancient times. Pausanias (Arcadia, §7–8) mentions that the word argon means “slow cultivation”; thus, “Argon field” means a field of slow cultivation. This is due to the occasional flooding during wintertime, caused by water coming from the surrounding mountains and the karstic springs flowing from the margins, consisting mainly of multifolded cretaceous limestones (Pindos geotectonic unit). The Argon field would have probably turned into a lake if the water had not been drained through a ground rift. In this case, the rift is apparently the cave-sinkhole of Nestani, which is located at the lowest topographic point of the whole field. After a few days (based on modern tracing experiments), the water reappears from this sinkhole in a submarine system of karstic springs in the Argolic Gulf, that in ancient times were known as Dini, located near Kiveri village (Mariolakos and Mariolakos 2004). In addition, there are also three rivers, named Tanos, Kephalari (Erasinos), and Inachos, emanating from the mountains Lirkio and Trachi that flow into the Argolic Gulf. Consequently, the aforementioned sources of freshwater near Franchthi Cave indicate that the significantly higher R(t) values of the regional sea surface reservoir, compared to Mediterranean mean, may be a phenomenon caused by a combination of a predominant local hard-water effect and coastal retreat events during deglaciation (Shackleton and van Andel 1980; van Andel and Lianos 1983; Lambeck 1996). The higher R(t) value of the Franchthi-9 pair, of 1220 ± 148 yr, is observed during the Younger Dryas stadial (11,240 ± 140 BP or 13,380–12,790 cal BP).

Mykonos is an island of the Cyclades located almost at the center of the Aegean Sea. The three pairs from the Ftelia site gave R(t) values that are overlapped within 1 standard deviation, thus leaving no room for doubt about their validity. However, the calculated mean R(t) value (26 ± 96 yr) is considerably lower than the Mediterranean mean. The low regional R(t) value could only be explained by reduced mixing rates of the surface waters with \(^{14}\)C-depleted waters from greater depths, during the time period studied (about 6100–5700 BP or 7150–6400 cal BP).

In an attempt to propose a mechanism involved, we discuss the following environmental events and paleoproxies: (1) the sea surface temperature fluctuation and (2) the sapropel S1 formation in the Aegean Sea.

**1. Sea Surface Temperature Fluctuation**

The Aegean Intermediate Water is derived from the Levantine Intermediate Water, which travels north along the Turkish coast. Prevailing offshore winds allow upwelling of the intermediate water to the surface, thus forming a single uniform water mass from the surface to the seafloor (Lascaratos 1989; Yüce 1995). As the upwelled Aegean Intermediate Water moves northward, its salinity continues to increase due to evaporation and this together with winter cooling increases its density. This buoyancy loss drives the formation of Aegean Deep Water. The modern Aegean Sea is an important source of deep water for the eastern Mediterranean (Casford et al. 2002). Several Holocene cooling events reconstructed for the southern Adriatic Sea, lasting some hundred years, are apparently synchronous with those in the Aegean Sea, in which sea surface temperatures declined by approximately 2°C around 6000 and 3000 yr BP (Sangiorgi et al. 2003). Figure 3 shows the R(t) changes in the Aegean Sea with respect to the sea surface temperature fluctuation in the South Adriatic Sea (modified from Siani et al. 2001). Our data show that the 6000 yr BP cooling event coincides with an important decrease of R(t) values of the three paired samples from the Neolithic site Ftelia on Mykonos. However, cooling of the surface waters is expected to increase their density and make
them move deeper into the sea, causing high mixing rates with $^{14}$C-depleted bottom waters, thus resulting in higher rather than lower $R(t)$ values, as in the case of the Ftelia pairs.

(2) Sapropel S1 Formation in the Aegean Sea

Sapropels develop during episodes of reduced oxygen availability and increase the nutrient supply in bottom waters as a result of reduced deep seawater circulation. The most recent sapropel S1 in the eastern Mediterranean Sea formed from 9500 until 6000 yr BP (Mercone et al. 2000; Casford et al. 2002). The low $R(t)$ values of the Ftelia pairs (Appendix, Figure 3) were likely caused by the low mixing rates of the sea surface waters due to the reduced deep-sea circulation of $^{14}$C-depleted waters during the sapropel S1 formation.

CONCLUSIONS

Three live-taken pre-bomb marine mollusk shells from Piraeus and Nafplion in Greece and Smyrna in Turkey, as well as 18 charcoal/marine mollusk shells pairs from the archaeological sites of Franchthi Cave in the Argolic Gulf, Cyclops Cave on Youra, Ftelia on Mykonos, and Palamari on Skyros allowed calculation of the sea surface reservoir age changes $R(t)$ and regional deviations $\Delta R$ in the Aegean Sea from ~11,200 BP (~13,000 cal BP) to present. Our data show that the $R(t)$ and $\Delta R$ values in the Aegean Sea are not constant through time and may vary from $1220 \pm 148$ to $–3 \pm 53$ yr and $–451 \pm 68$ to $858 \pm 154$ $^{14}$C yr, respectively.

Thirteen pairs produced $R(t)$ values falling within $2\sigma$ of the Mediterranean pre-bomb mean value $R(t)_{mean} = 390 \pm 85$ yr. Two sites produced outlying $R(t)$ values, Franchthi Cave and Ftelia. The mean $R(t)$ and $\Delta R$ values for the Ftelia site is $R(t) = 26 \pm 96$ yr and $\Delta R = –400 \pm 113$ $^{14}$C yr for the time interval 7150–6400 cal BP. This very low $R(t)$ value is probably due to the reduced deep-sea circulation of $^{14}$C-depleted waters during the sapropel S1 formation. The Franchthi Cave mean $R(t)$ and $\Delta R$ values exhibit significant fluctuation probably due to the hardwater effect in the Argolic Gulf. During the time intervals 9140–8520 and 7690–7440 cal BP, the following mean values were calculated, respectively: $R(t) = 765 \pm 161$ yr and $\Delta R = 461 \pm 140$ $^{14}$C yr and $R(t) = 357 \pm 120$ yr and $\Delta R = –34 \pm 123$ $^{14}$C yr. The Cyclops Cave paired samples resulted in mean $R(t) = 529 \pm 90$ yr and $\Delta R = 167 \pm 116$ $^{14}$C yr for the time interval 9530–8050 cal BP. Combined data from Franchthi and Cyclops Cave produced mean $R(t) = 267 \pm 88$ yr and $\Delta R = –37 \pm 99$ $^{14}$C yr for the time interval 10,000–9540 cal BP.

The final goal of this ongoing project is to establish a regional detailed curve for short-lived marine mollusk shells from various coastal sites in the Aegean covering all the time range of the $^{14}$C dating method. This will allow accurate calibration of marine samples from that region in conjunction with the marine international calibration curve, and to obtain more paleoceanographic information for the region and time periods studied.

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