MARINE RADIOCARBON RESERVOIR CORRECTIONS FOR THE MEDITERRANEAN AND AEGEAN SEAS

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ABSTRACT. Radiocarbon measurements of nine known age shells from the Mediterranean and the Aegean Seas combined with previous measurements provide an updated value for \( \Delta R \), the local variation in the reservoir correction for marine samples. Comparison of pre-1950s samples from the Algerian coast, with one collected in 1954, indicates early incorporation of nuclear weapons testing \(^{14}\text{C}\) into the shallow surface waters of the Mediterranean. Comparisons between different basins indicate the surface waters of the Mediterranean are relatively homogenous. The recommended \( \Delta R \) for calibration of the Mediterranean marine samples with the 1998 marine calibration dataset is 58 ± 85 \(^{14}\text{C}\) yr, but variations in the reservoir age beyond 6000 cal BP should be considered.

INTRODUCTION

Calibration is essential for interpretation of radiocarbon ages, especially when comparing to historical records or to other data with a different chronological basis. \(^{14}\text{C}\) ages of marine samples also require a correction for the reservoir age of the ocean where they were formed. Because the ocean is a large carbon reservoir, the residence time of \(^{14}\text{C}\) is long compared to the atmosphere. Together with upwelling of older carbon from the deep ocean, this results in an apparent age of marine samples several hundred years older than contemporaneous atmospheric samples (Mangerud 1972). While the pre-industrial global mean reservoir correction (R) is about 400 years, local variations (\( \Delta R \)) can be several hundred years or more (Stuiver et al. 1986).

Until recently, there was only one \( \Delta R \) value from a known age shell for the entire Mediterranean despite the archaeological significance of the region (Broecker and Olson 1959, 1961). This shell collected in 1954 near Algiers yielded a \( \Delta R \) value of –135 ± 85 \(^{14}\text{C}\) yr (Stuiver et al. 1986). The negative \( \Delta R \) value would imply either a smaller reservoir age for the Mediterranean than the global mean or that the mollusc incorporated some \(^{14}\text{C}\) from nuclear weapons testing. Although most marine records do not show incorporation of nuclear weapons carbon this early, the mixing time varies considerably among localities.

Recent work by Siani et al. (2000) has provided a more robust estimate of \( \Delta R \) for the Mediterranean. Their analysis, based on measurements of 26 modern, pre-nuclear testing mollusc shells and a few previously reported apparent ages, was mainly concentrated in the western Mediterranean, the Tyrrhenian Sea, the Black Sea, and the Adriatic Sea. Here we report \( \Delta R \) measurements on seven known age, pre-nuclear weapons testing mollusc shells from the eastern Mediterranean and the Aegean Sea and two from the Algerian coast in the western Mediterranean. We then incorporate our dataset with previously published data for the region and with three measurements from the Tyrrhenian and the Adriatic Seas supplied by M Taviani and A Correggiari (personal communication) in order to investigate possible regional differences in the \( \Delta R \) for the Mediterranean and adjacent seas.

METHODS

Nine known age shells from the Mediterranean and the Aegean Sea were selected for dating from the collections of the Museum National D’histoire Naturelle, the Museum fur Naturkunde der Humboldt-Universitat zu Berlin; the Hebrew University, and Zoologische Statssammlung Muenchen

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Although records were not always adequate to determine that the molluscs had been collected live, all shells were unweathered and all of the bivalves were either articulated or had both shells collected together, which would indicate collection at or shortly after death. Only the outer edges of the shells were used for dating so that shell deposited nearest to the time of death was sampled. \(^{14}\text{C}\) analyses were performed at the Center for AMS dating at Lawrence Livermore National Labs. \(^{14}\text{C}\) ages presented here (Table 1) are corrected for isotope fractionation using the measured \(\delta^{13}\text{C}\) values and normalized to \(-25\ %\ PDB\) (Stuiver and Polach 1977).

Data were compiled from our measurements and \(^{14}\text{C}\) ages from the literature (Table 2). Several reported measurements were omitted from the compilation because the authors suspected an older source of carbon from freshwater carbonates (Siani et al. 2000). The reservoir age \(R\) was calculated from the difference between the conventional \(^{14}\text{C}\) age and the atmospheric age interpolated to the nearest year from the 1998 calibration dataset (Stuiver et al. 1998a). \(\Delta R\) values were calculated from the difference in the conventional \(^{14}\text{C}\) age and the 1998 decadal marine calibration dataset (Stuiver et al. 1998b), which was interpolated to the year of shell growth.

**RESULTS AND DISCUSSION**

The \(^{14}\text{C}\) ages and \(\Delta R\) values measured for this study are given in Table 1 and in the on-line marine reservoir correction database at http://www.calib.org (Reimer and Reimer 2001). The two shells from Algeria had a relatively large spread in \(^{14}\text{C}\) ages but were statistically the same at the 95% confidence level using a chi-squared test (Ward and Wilson 1978). Together with three measurements reported by Siani et al. (2000), a mean \(\Delta R\) value of 83 ± 33 yr was calculated for the Algerian coast. This value is statistically different at the 95% level from the earlier \(\Delta R\) value of \(-135 \pm 85\ \text{^{14}C}\) yr \((-116 \pm 80\ \text{^{14}C}\) yr as recalculated with the 1998 marine dataset) from a shell (species unknown) collected in AD 1954 (Broecker and Olson 1959). If the mollusc were an intertidal species it could have incorporated atmospheric \(^{14}\text{C}\) due to wave action (Hogg et al. 1998). However, an unreasonably large amount of atmospheric carbon would be needed to offset \(\Delta R\) to this degree unless the shell incorporated \(^{14}\text{C}\) produced in nuclear weapons testing. Mixing of atmospheric \(^{14}\text{C}\) into shallow water may have occurred more rapidly than was observed in surface water samples from the central basin of the western Mediterranean (Broecker and Gerard 1969). A similar rise in \(^{14}\text{C}\) is seen in Red Sea corals from near H urghada, which exhibit a \(\Delta^{14}\text{C}\) increase of 12% (\(-90\ \text{^{14}C}\) yr) between 1953 and 1955 (Cember 1989). This may be compared to the \(\Delta^{14}\text{C}\) of *Arctica islandica* shells from the North Sea collected at 37 m, which did not increase until after 1955 (Weidman 1995). Because of the uncertainty surrounding the uptake of bomb \(^{14}\text{C}\) into the shallow waters of the Mediterranean, the Broecker et al. measurement was not included in the regional mean \(\Delta R\).
Table 1 $^{14}$C ages, $\delta^{13}$C, and $\Delta R$ values of known age shells from the Mediterranean and Aegean Seas from this study

<table>
<thead>
<tr>
<th>Location</th>
<th>Mollusc species</th>
<th>Collector, Museum nr</th>
<th>Lab ID</th>
<th>Collection year</th>
<th>$^{14}$C BP (‰)</th>
<th>$\delta^{13}$C (%)</th>
<th>$\Delta R$ (yr)</th>
<th>Reservoir age (BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eastern Mediterranean</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zante, Greece</td>
<td>Chlamys varia</td>
<td>Friedrich #19971367a</td>
<td>CAMS-69547</td>
<td>1942</td>
<td>620 ± 40</td>
<td>0.3</td>
<td>153 ± 41</td>
<td>439</td>
</tr>
<tr>
<td>Beirut, Lebanon</td>
<td>Pinctada radiata</td>
<td>?b</td>
<td>CAMS-69545</td>
<td>1929</td>
<td>490 ± 40</td>
<td>2.4</td>
<td>32 ± 40</td>
<td>344</td>
</tr>
<tr>
<td>Beirut, Lebanon</td>
<td>Chlamys varia</td>
<td>?2</td>
<td>CAMS-69546</td>
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<td>400 ± 50</td>
<td>1.9</td>
<td>153 ± 41</td>
<td>254</td>
</tr>
<tr>
<td>Netamiya, Israel</td>
<td>Osilinus turbinatus</td>
<td>G Haasc</td>
<td>CAMS-69540</td>
<td>1937</td>
<td>510 ± 40</td>
<td>1.4</td>
<td>47 ± 41</td>
<td>324</td>
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<td><strong>Western Mediterranean</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Castiglione, Algeria</td>
<td>Tellina planata</td>
<td>Dieuzede2</td>
<td>CAMS-69543</td>
<td>1931</td>
<td>620 ± 40</td>
<td>1.8</td>
<td>161 ± 40</td>
<td>468</td>
</tr>
<tr>
<td>Castiglione, Algeria</td>
<td>Ruditapes decussatus</td>
<td>Dieuzede2</td>
<td>CAMS-69544</td>
<td>1931</td>
<td>510 ± 40</td>
<td>1.6</td>
<td>51 ± 40</td>
<td>358</td>
</tr>
<tr>
<td><strong>Aegean Sea</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smyrna (Izmir), Turkey</td>
<td>Mytilus edulis</td>
<td>T Loebbecke4</td>
<td>CAMS-69539</td>
<td>1893/94</td>
<td>750 ± 40</td>
<td>−1.3</td>
<td>288 ± 40</td>
<td>652</td>
</tr>
<tr>
<td>Nauplia, Greece</td>
<td>Diodora italic</td>
<td>Friedrich #20002828i</td>
<td>CAMS-69541</td>
<td>1940</td>
<td>500 ± 40</td>
<td>1.3</td>
<td>35 ± 41</td>
<td>324</td>
</tr>
<tr>
<td>Piraeus, Greece</td>
<td>Patella caerula</td>
<td>Friedrich #20001478i</td>
<td>CAMS-69542</td>
<td>1943</td>
<td>610 ± 40</td>
<td>−0.8</td>
<td>143 ± 41</td>
<td>427</td>
</tr>
</tbody>
</table>

*aZoologische Statssammlung Muench (E Schwabe, Curator)*
*bMuseum National D’histoire Naturelle (P Bouchet, Curator)*
*cHebrew University, Jerusalem (J Heller, Professor)*
*dMuseum fur Naturkunde der Humboldt-Universitat zu Berlin (M Glaubrecht, Curator)
Regional mean values of $\Delta R$ were also calculated for the Eastern Mediterranean, Western Mediterranean, Adriatic, and the Tyrrhenian Seas from the new and compiled measurements (Table 3) and are available on-line at www.calib.org. There is little difference in the mean $\Delta R$ values for any of the regions with the possible exception of the Aegean Sea. The Aegean $\Delta R$ is statistically different from that of the rest of the Mediterranean at the 95% confidence level. However, all but one of the Aegean samples fit closely to the other Mediterranean data from the same approximate collection dates (Figure 2). The one higher $\Delta R$ value at AD 1893 is from a mussel shell ($Mytilus edulis$), a species that often inhabits estuarine environments. The slightly high $\Delta R$ for this shell could be due to carbonates derived from limestone depleted in $^{14}C$. If this sample is excluded then the Aegean Sea, $\Delta R$ is similar to the mean Mediterranean value as well as the mean of 75 ± 65 reported for the Black Sea (Siani et al. 2000). This result confirms the need for consideration of species in $^{14}C$ dating marine shells as has been previously noted (Hogg et al. 1998). The empirical standard deviation, that is the square root of

<table>
<thead>
<tr>
<th>Location</th>
<th>Lab ID</th>
<th>Collection year</th>
<th>$^{14}C$ age (BP)</th>
<th>$\Delta R$ (yr)</th>
<th>Reference</th>
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<tr>
<td>Western Mediterranean</td>
<td></td>
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</tr>
<tr>
<td>Alger, Algeria</td>
<td>GifA 96710</td>
<td>1881</td>
<td>620 ± 35</td>
<td>148 ± 35</td>
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<tr>
<td>Cherchel, Algeria</td>
<td>Gif 4067</td>
<td>1905</td>
<td>460 ± 35</td>
<td>7 ± 35</td>
<td>2</td>
</tr>
<tr>
<td>Mahdia, Algeria</td>
<td>Ly 6948</td>
<td>1948</td>
<td>500 ± 50</td>
<td>29 ± 51</td>
<td>3</td>
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<tr>
<td>Castiglione, Algeria</td>
<td>CAMS-69543</td>
<td>1931</td>
<td>620 ± 40</td>
<td>161 ± 40</td>
<td>4</td>
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<tr>
<td>Castiglione, Algeria</td>
<td>CAMS-69544</td>
<td>1931</td>
<td>510 ± 40</td>
<td>51 ± 40</td>
<td>4</td>
</tr>
<tr>
<td>Antibes, France</td>
<td>GifA 96726</td>
<td>1873</td>
<td>450 ± 40</td>
<td>–27 ± 40</td>
<td>1</td>
</tr>
<tr>
<td>St Raphael, France</td>
<td>GifA 96724</td>
<td>1892</td>
<td>455 ± 35</td>
<td>–8 ± 35</td>
<td>1</td>
</tr>
<tr>
<td>La Seyne, France</td>
<td>GifA 96699</td>
<td>1892</td>
<td>470 ± 40</td>
<td>7 ± 40</td>
<td>1</td>
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<tr>
<td>Marseille, France</td>
<td>GifA 96711</td>
<td>1873</td>
<td>510 ± 35</td>
<td>33 ± 35</td>
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<tr>
<td>Marseille, France</td>
<td>GifA 96709</td>
<td>1874</td>
<td>550 ± 40</td>
<td>74 ± 40</td>
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<tr>
<td>Banyuls, Spain</td>
<td>GifA 96716</td>
<td>1906</td>
<td>570 ± 35</td>
<td>118 ± 35</td>
<td>1</td>
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<tr>
<td>Toulon, France</td>
<td>Gif 4068</td>
<td>1837</td>
<td>405 ± 35</td>
<td>–68 ± 35</td>
<td>2</td>
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<tr>
<td>Banyuls, Spain</td>
<td>Ly 6900</td>
<td>1900</td>
<td>565 ± 55</td>
<td>110 ± 55</td>
<td>3</td>
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<tr>
<td>Malaga, Spain</td>
<td>GifA 96715</td>
<td>1929</td>
<td>430 ± 35</td>
<td>–28 ± 35</td>
<td>1</td>
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<tr>
<td>Tyrrenian Sea</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central Tyrrenian Sea</td>
<td>CAMS-16300</td>
<td>1920</td>
<td>430 ± 60</td>
<td>–23 ± 60</td>
<td>5</td>
</tr>
<tr>
<td>Bastia, Corsica</td>
<td>GifA 96704</td>
<td>1921</td>
<td>495 ± 40</td>
<td>42 ± 40</td>
<td>1</td>
</tr>
<tr>
<td>Naples, Italy</td>
<td>GifA 96717</td>
<td>1873</td>
<td>535 ± 40</td>
<td>58 ± 40</td>
<td>1</td>
</tr>
<tr>
<td>Naples, Italy</td>
<td>GifA 96725</td>
<td>1892</td>
<td>610 ± 110</td>
<td>147 ± 110</td>
<td>1</td>
</tr>
<tr>
<td>Sicily</td>
<td>Ly 6863</td>
<td>1900</td>
<td>525 ± 50</td>
<td>70 ± 50</td>
<td>3</td>
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<tr>
<td>Adriatic Sea</td>
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<tr>
<td>Barletta, Italy</td>
<td>CAMS-16299</td>
<td>1906</td>
<td>570 ± 60</td>
<td>118 ± 60</td>
<td>5</td>
</tr>
<tr>
<td>Rimini, Italy</td>
<td>CAMS-12144</td>
<td>1911</td>
<td>587 ± 28</td>
<td>137 ± 28</td>
<td>5,6</td>
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<tr>
<td></td>
<td>CAMS-12901</td>
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<td></td>
<td>CAMS-13120</td>
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<tr>
<td>Dalmatia</td>
<td>GifA 96707</td>
<td>1873</td>
<td>380 ± 35</td>
<td>–97 ± 35</td>
<td>1</td>
</tr>
<tr>
<td>Rovigne, Croatia</td>
<td>GifA 96718</td>
<td>1926</td>
<td>390 ± 50</td>
<td>–66 ± 50</td>
<td>1</td>
</tr>
<tr>
<td>Adriatic Sea</td>
<td>GifA 96722</td>
<td>1867</td>
<td>540 ± 30</td>
<td>60 ± 30</td>
<td>1</td>
</tr>
</tbody>
</table>
the variance or “scatter” in the data, is fairly large except for the Tyrrenian Sea. This is probably the result of the differing habitats and feeding patterns of the various species as well as local variations in the $^{14}$C content of the seawater. For purposes of $^{14}$C calibration, the empirical standard deviation, which is a measurement of the dispersion of the data from the mean, provides a better estimate of the true uncertainty in $\Delta R$ than the uncertainty in the mean. The mean $\Delta R$ for the Mediterranean of $58 \pm 85$ $^{14}$C yr (empirical s.d.) is comparable to the $35 \pm 70$ $^{14}$C yr previously reported by Siani et al. (2000) for predominately western Mediterranean measurements.

A time-dependency in the reservoir age of the Mediterranean Sea and the North Atlantic was previously demonstrated for the early twentieth century (Siani et al. 2000). Our eastern Mediterranean and Aegean data add support to a decline in $\Delta R$ from AD 1900 to 1930 (Figure 2). Larger variations in the Mediterranean $\Delta R$ have occurred in the past due to changes in reservoir age of the North Atlantic water entering the Mediterranean or fluctuations in continental runoff, which contributes $^{14}$C depleted carbonates and may alter the ventilation of deep and intermediate waters (Mercone et al. 2000; Siani et al. 2001).

<table>
<thead>
<tr>
<th>Location</th>
<th>Lab ID</th>
<th>Collection year (AD)</th>
<th>$^{14}$C age (BP)</th>
<th>$\Delta R$ (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Mediterranean</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Zante, Greece</td>
<td>CAMS-69547</td>
<td>1942</td>
<td>620 ± 40</td>
<td>153 ± 41</td>
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<td>Beirut, Lebanon</td>
<td>CAMS-69545</td>
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<td>490 ± 40</td>
<td>32 ± 40</td>
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<td>400 ± 50</td>
<td>-58 ± 50</td>
</tr>
<tr>
<td>Netamiya, Israel</td>
<td>CAMS-69540</td>
<td>1937</td>
<td>510 ± 40</td>
<td>47 ± 41</td>
</tr>
<tr>
<td>Aegean Sea</td>
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</tr>
<tr>
<td>Izmir, Turkey</td>
<td>CAMS-69539</td>
<td>1893</td>
<td>750 ± 40</td>
<td>288 ± 40</td>
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<td>Nauplia, Greece</td>
<td>CAMS-69541</td>
<td>1940</td>
<td>500 ± 40</td>
<td>35 ± 50</td>
</tr>
<tr>
<td>Piraeus, Greece</td>
<td>CAMS-69542</td>
<td>1943</td>
<td>610 ± 40</td>
<td>143 ± 41</td>
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<tr>
<td>Exact location unknown</td>
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<tr>
<td>Mediterranean Sea</td>
<td>GiFA 96700</td>
<td>1887</td>
<td>585 ± 35</td>
<td>118 ± 35</td>
</tr>
</tbody>
</table>

Figure 2 $\Delta R$ values for the western Mediterranean including the Adriatic and the Tyrrenian Seas (diamonds), the eastern Mediterranean (triangles), the Aegean Sea (open circles), and an unknown location in the Mediterranean (square) plotted versus collection year of the shell sample. The error bars represent one standard deviation based on counting statistics and the uncertainty in marine calibration dataset.
Currently, no marine reservoir age data for the Mediterranean is available between the nineteenth century and ~4500 cal BP. However, at present the Atlantic Ocean surface waters flow into the Mediterranean through the Strait of Gibraltar and overturn in the eastern Mediterranean with a residence time of ~100 years (Broecker and Gerard 1969; Stuiver and Ostlund 1983). This circulation pattern appears to have been unchanged for the past 18,000 years except during the S1 sapropel formation between about 6000–9000 14C yr BP (~6800–10,200 cal BP) (Kallel et al. 1997). ∆R in the subpolar North Atlantic has been shown to be constant within ± 95 14C yr over the past 6000 years based on measurements of contemporaneous marine and terrestrial samples (Reimer et al. 2002).

Reservoir ages based on 14C dates of planktonic foraminifera associated with dated tephra layers and on charcoal/shell pairs from archaeological cave excavations support a relatively constant reservoir age for the eastern Mediterranean from about 4000–6000 14C yr BP (~4400–6800 cal BP) (Siani et al. 2001). Between about 7400–8500 14C yr BP (~8200–9500 cal BP), reservoir ages appear to have increased slightly. Facorellis et al. (1998) derived a reservoir age of 515 ± 22 (ΔR = 149 ± 30) from paired mollusc shells (Patella ulyssiponensis) and charcoal samples from Cyclope cave on the island of Youra in the Aegean Sea. This increased reservoir age corresponds to the time of the S1 sapropel formation which may be related to changes in ventilation (Mercone et al. 2000; Siani et al. 2001). After this event reservoir ages return to near modern pre-bomb values.

Siani et al. (2001) measured a reservoir age of 380 ± 100 near the beginning of the Younger Dryas (about 10,500 14C yr BP) which is comparable to the reservoir age of 320–345 yr about 10,700 14C yr BP calculated from paired marine and terrestrial samples from Cyprus (Simmons and Wigand 1994). Reservoir ages rose through the Bølling/Allerød reaching a maximum of 820 ± 120 yr in the Older Dryas interval before declining to around the modern pre-bomb value during the Last Glacial Maximum (Siani et al. 2001). We discuss reservoir ages rather than ΔR values beyond the tree-ring record (about 11,900 cal BP), because there the atmospheric 14C calibration dataset is based on the marine record with an estimated reservoir correction (Stuiver et al. 1998a).

### Table 3

Regional means of ΔR values and reservoir ages. The uncertainty in the mean is the larger of the standard deviation based on counting statistics and the “scatter sigma,” which is the square root of the variance divided by the number of samples. The empirical standard deviation (s.d.) is the square root of the variance. The regional mean for the western Mediterranean includes samples from the Algerian coast, and the Tyrrenian and the Adriatic Seas. The eastern Mediterranean regional mean does not include the Aegean Sea.

<table>
<thead>
<tr>
<th>Region</th>
<th>Mean ΔR (14C yr)</th>
<th>Nr of samples</th>
<th>Empirical s.d. (yr)</th>
<th>Reservoir age (14C yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Mediterranean</td>
<td>40 ± 15</td>
<td>25</td>
<td>75</td>
<td>400 ± 22</td>
</tr>
<tr>
<td>Eastern Mediterranean</td>
<td>53 ± 43</td>
<td>4</td>
<td>86</td>
<td>353 ± 47</td>
</tr>
<tr>
<td>Algerian coast</td>
<td>83 ± 33</td>
<td>5</td>
<td>75</td>
<td>413 ± 51</td>
</tr>
<tr>
<td>Tyrrenian Sea</td>
<td>45 ± 21</td>
<td>6</td>
<td>30</td>
<td>390 ± 21</td>
</tr>
<tr>
<td>Adriatic Sea</td>
<td>43 ± 48</td>
<td>5</td>
<td>108</td>
<td>396 ± 61</td>
</tr>
<tr>
<td>Aegean Sea</td>
<td>154 ± 52</td>
<td>4</td>
<td>105</td>
<td>480 ± 72</td>
</tr>
<tr>
<td>Aegean Sea w/o sample of Mytilus edulis</td>
<td>109 ± 37</td>
<td>3</td>
<td>65</td>
<td>420 ± 55</td>
</tr>
<tr>
<td>All Mediterranean except the Aegean Sea</td>
<td>45 ± 14</td>
<td>30</td>
<td>75</td>
<td>390 ± 15</td>
</tr>
<tr>
<td>All Mediterranean</td>
<td>58 ± 15</td>
<td>34</td>
<td>85</td>
<td>400 ± 16</td>
</tr>
</tbody>
</table>
CONCLUSIONS

ΔR values are indistinguishable for different Mediterranean basins including the Aegean Sea. The recommended ΔR for 14C calibration of marine samples with the 1998 marine calibration dataset is 58 ± 85 14C yr for the entire Mediterranean. The Mediterranean ΔR appears to be relatively constant within this uncertainty for the past 6000 or 7000 yr, but beyond that time frame variations in ΔR should be considered when calibrating 14C ages for marine samples from this region.

ACKNOWLEDGMENTS

We thank the following individuals and institutions for supplying shells from their collections for this project: P. Bouchet, Museum National D’histoire Naturelle, M. Glaubrecht, Museum fur Naturkundede der Humboldt-Universitat zu Berlin; J. Heller, Hebrew University and E. Schwabe, Zoologische Stattssammlung Muenchen. We also thank M. Taviani and A. Correggiari of the Istituto di Geologia Marina for providing previously unpublished 14C ages for samples from the Tyrrhenian and the Adriatic Seas. We also appreciate the constructive review of this manuscript by G. Siani. The project was funded by the Institute for Aegean Prehistory.

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