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Uranium-series ages of fossil corals from Mallorca, Spain: The “Neotyrrhenian” high stand of the Mediterranean Sea revisited

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ABSTRACT

The emergent marine deposits of the Mediterranean basin have been recognized as an important record of Quaternary sea level history for more than a century. Previous workers identified what have been interpreted to be two separate high stands of sea in the late Quaternary, namely the “Eutyrrhenian” (thought to be ~120 ka) and the “Neotyrrhenian” (thought to be either ~100 ka or ~80 ka). On Mallorca, Spain, both of these named deposits lie close to present sea level, implying paleo-sea levels slightly above present during both marine isotope stages (MIS) 5.5/5e and either 5.3/5c or 5.1/5a. If these interpretations are correct, they conflict, at least in part, with sea level records from far-field localities.

We analyzed corals from the Neotyrrhenian beds on Mallorca, which gave U-series ages from ~126 ka to ~118 ka. These ages are consistent with previously published amino acid data that show that the Neotyrrhenian and Eutyrrhenian deposits are not significantly different in age. A fossil molluscan fauna from the Neotyrrhenian deposits on Mallorca has a warm-water paleozoogeographic aspect, with nine southward-ranging species and four extralimital southern species. When compared with sea surface temperatures obtained from planktonic foraminifera and alkenones from ODP core 977 in the nearby Alboran Sea, the only time period that shows comparable warmth is MIS 5.5/5e, consistent with the U-series ages of corals from the Neotyrrhenian deposits. We propose that the Neotyrrhenian deposits are a beachrock facies of the same age as the Eutyrrhenian deposits. This interpretation is consistent with the differences in physical sedimentology of the two deposits, explains the U-series and amino acid data indicating the same age, is consistent with the very slight elevation difference of the Neotyrrhenian and Eutyrrhenian beds, and explains the similar, though not identical paleozoogeographic aspects of their fossil faunas.

1. Introduction

Past warm periods with high sea levels in the geologic record are of considerable interest today because of the prospects of a future warmer Earth with rising seas. One such period that has received much attention is the last interglacial period (LIG), also known as marine isotope stage (MIS) 5.5 or 5e in the oxygen isotope record of foraminifera from deep-sea cores (Imbrie et al., 1984; Martinson et al., 1987). At this time, ~130–115 ka, global ice volume was significantly lower than today, based on numerous sea level records from tectonically stable regions, first reported in the pioneering work of Veeh (1966) and confirmed by later studies (Israelson and Wohlfarth, 1999; Muhs et al., 2002a,2002b, 2011; Dutton et al., 2015).

In the Mediterranean region (Fig. 1), marine deposits thought to date to the last interglacial period have long been identified, though poorly defined, with the term “Tyrrhenian.” Sironi et al. (2005) provide a useful history of this term as it has been applied to the emergent marine deposits of the Mediterranean basin. The Tyrrhenian, as a unit designation, was first used by Issel (1914) to apply to “raised *Strombus* beaches” that had previously been studied by Gignoux (1913) in his classic work on the subject along the Italian coast. These marine deposits, a few meters above present sea level on tectonically stable coasts, contain the tropical, west African gastropod *Strombus bubonius* (= *S. latus*; also known as *Persististrombus latus*: see Montesinos et al., 2014), as well as other extralimital southern species of mollusks. While these taxa are extant in tropical waters off western Africa, they do not live in the Mediterranean today.

Bonifay and Mars (1959) recognized greater complexity in the coastal stratigraphic record of the Mediterranean, identifying what they interpreted as three distinct ages of deposits, and proposed the terms “Paleotyrrhenian,” “Eutyrrhenian,” and “Neotyrrhenian,” from oldest to youngest. “Eutyrrhenian” was the term these investigators applied to relatively low-elevation marine deposits that contain *S. bubonius*. Slightly lower-elevation marine deposits that lack this

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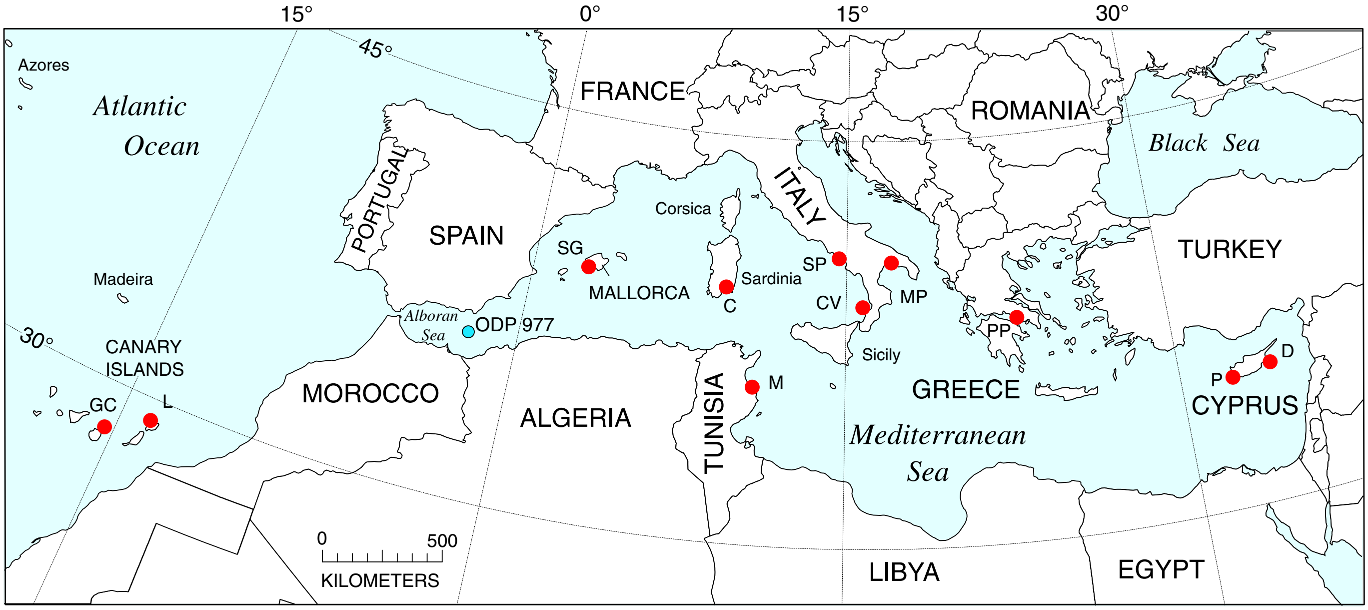


Fig. 1. Map of the Mediterranean Basin, showing location of Mallorca. Also shown are localities (red dots) where marine deposits have been dated (by U-series methods on coral only) to the last interglacial (LIG) or "Eutyrrhenian" high-sea stand and the location of Ocean Drilling Program (ODP) core 977 (Martrat et al., 2004; Pérez-Folgado et al., 2004) in the Alboran Sea (blue dot). LIG localities are from various sources, as follows. From Muhs et al. (2014): GC, Gran Canaria, Spain; L, Lanzarote, Spain. From Hearty et al. (1986): SG, Son Grauet, Mallorca, Spain; C, Calamosca, Sardinia, Italy; M, Monastir, Tunisia; MP, Mare Piccolo, Italy. From Dumas et al. (1991): CV, Capo Vaticano, Italy. From Brancaccio et al. (1978): SP, Sorrentine Peninsula, Italy. From Vita-Finzi (1993), Leeder et al. (2003), and Roberts et al. (2009): PP, Perachora Peninsula, Greece. From Poole et al. (1990): P, Paphos, Cyprus; D, Dhekelia, Cyprus.

taxon were considered to be "Neotyrrhenian," and deposits at elevations higher than those of the Eutyrrhenian were considered to be "Paleotyrrhenian." Bonifay and Mars (1959) recognized coastal sequences with this tripartite division of deposits along mainland Spain, Mallorca, France, and Lebanon; they report Eutyrrhenian and Neotyrrhenian marine deposits on Corsica, Sardinia, and Sicily. Later workers used the terms "Tyrrhenian I," "Tyrrhenian II," and "Tyrrhenian III" for Paleotyrrhenian, Eutyrrhenian, and Neotyrrhenian, respectively (e.g., Solé Sabarís, 1962; Rose, 1985).

One problem that has plagued studies of Quaternary marine deposits throughout the Mediterranean, as well as on European and African coastlines of the eastern Atlantic Ocean, is a lack of reliable ages. Going back half a century and continuing to this day, there has been a reliance on uranium-series ages of mollusks (Stearns and Thurber, 1965, 1967; Bernat et al., 1978; Hearty, 1987; Causse et al., 1993; Hillaire-Marcel et al., 1986, 1996; Zazo et al., 2002, 2003, 2007, 2010; Jedoui et al., 2003; Dubar et al., 2008). Despite an early conclusion that apparent ages derived from such analyses are not reliable (Kaufman et al., 1971), a more recent confirmation of this problem (Edwards et al., 2003), and periodic cautions about the hazards of apparent U-series ages of mollusks, specifically in the Mediterranean basin (Stearns, 1985; McLaren and Rowe, 1996; Meco et al., 2002; Mauz and Antonioli, 2009), there have been continued applications of U-series dating of mollusks or interpretations based on such data (Bardají et al., 2009; Zazo et al., 2010, 2013; Tuccimei et al., 2012; Vicens et al., 2012).

Mollusks and most other marine invertebrates, unlike corals, do not take up significant amounts of U from seawater during growth. What U is present in fossil mollusks is derived dominantly from soil waters or groundwater after emergence. Thus, even if this secondary U and its long-lived daughter products were to experience a closed-system history after a single episode of U uptake in a fossil mollusk shell, apparent ages would be minima, at best. Unfortunately, a secondary origin for mollusk-hosted U is not the only problem. There is no way to determine if a fossil mollusk has remained a closed system with respect to U and its daughters because neither the initial U content nor the initial $^{234}U/^{238}U$ value can be known. Thus, if mollusks can gain U initially after emergence, there is no reason to believe they cannot gain or lose U or its daughter products subsequently.

Corals, on the other hand, take up U from seawater in known concentrations during growth and have initial $^{234}U/^{238}U$ values indistinguishable from seawater. Thus, coral ages can be evaluated not only for bulk U loss or gain but $^{234}U/^{238}U$ values serve as a secondary geochronometer when compared to $^{230}Th/^{234}U$ ages. Although corals are not as common as mollusks in the Quaternary marine invertebrate fossil record of the eastern Atlantic and Mediterranean, they do exist and there have been a number of studies that have utilized these fossils for U-series dating (Fig. 1; Brancaccio et al., 1978; Hearty et al., 1986; Poole et al., 1990; Dumas et al., 1991; Vita-Finzi, 1993; Leeder et al., 2003; Zazo et al., 2007; Roberts et al., 2009; Muhs et al., 2014). In addition, there has been success in dating some emergent Mediterranean marine sediments using luminescence methods (e.g., Rose et al., 1999; Mauz et al., 2009), as well as aminostratigraphy of marine mollusks, allowing correlation to U-series-dated corals at key sites (e.g., Hearty et al., 1986; Demarchi et al., 2015).

The island of Mallorca (Balearic Islands), Spain has figured prominently in the quest for Quaternary sea-level records of the Mediterranean (see reviews by Vicens et al., 2012 and Zazo et al., 2013). Both Eutyrrhenian and Neotyrrhenian deposits, at +3 m and +2 m, respectively, have been identified around the island and in particular at key localities near the city of Palma, Mallorca (Figs. 1, 2, and 3). At present, there is only a single U-series age (~129 ka) on coral from one Eutyrrhenian locality (Fig. 1, Son Grauet), correlating this deposit with MIS 5.5/5e (Hearty et al., 1986). For the Neotyrrhenian beds, there are currently no U-series ages on coral. However, Hearty (1987) found no difference in amino acid ratios in mollusks (*Glycymeris* and *Arca*) from the Eutyrrhenian and Neotyrrhenian beds, which along with the U-series age of ~129 ka for the Eutyrrhenian, could be interpreted to mean that both deposits correlate to MIS 5.5/5e. Hillaire-Marcel et al. (1996) infer an age of ~100 ka (MIS 5.3/5c) for the Neotyrrhenian beds, but this is based on U-series ages of mollusks, now known to be unreliable. Several workers (Cuerda, 1975, 1989; Butzer, 1975; Pomar and Cuerda, 1979; Zazo et al., 2003, 2013; Tuccimei et al., 2006; Fornós et al., 2012; Vicens et al., 2012) conclude or at least imply that

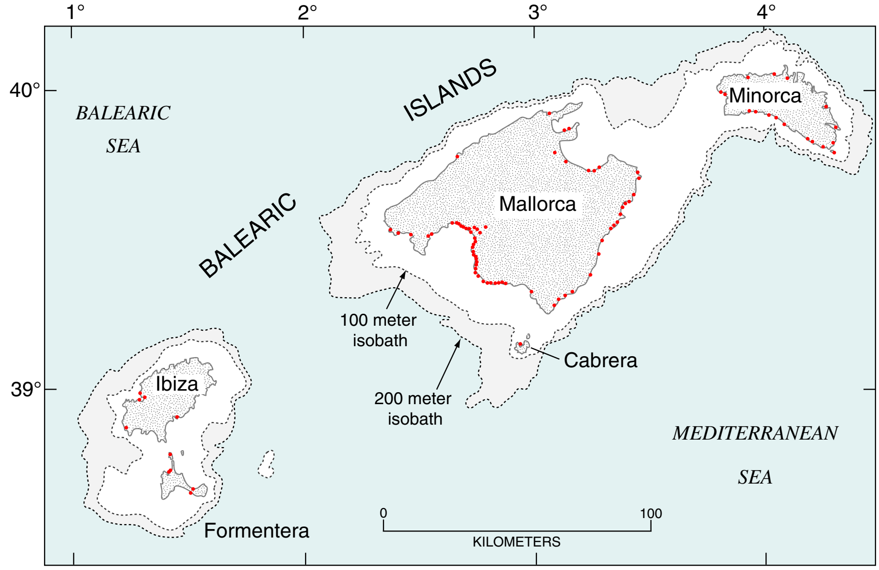


Fig. 2. Map of Mallorca and the other Balearic Islands of Spain, showing bathymetry and location of emergent marine deposits (red dots) thought to date to some part of the last interglacial period ("Eutyrrhenian" or "Neotyrrhenian"). Localities from Cuerda (1975, 1989). Note that sea level during the last glacial maximum may have been ~120 m below present (Fairbanks, 1989) and Mallorca and Minorca would have been connected.

the Neotyrrhenian deposits correspond to the ~80 ka high-sea stand, or MIS 5.1/5a. Indeed, Vicens et al. (2012) stated that a "consensus" had been reached that the deposit was of MIS 5.1/5a age.

Recent inferences of an ~80 ka age for the Neotyrrhenian beds, slightly above present sea level on Mallorca, may have been reinforced by studies of speleothems on the island. Vesica et al. (2000), Tuccimei et al. (2006), Dorale et al. (2010), and Ginés et al. (2012a) report phreatic overgrowths on speleothems (POS) that imply a paleo-sea level slightly above present (+1.4 m to +1.6 m) at ~80 ka. Ages of POS from Mallorca that date from ~138 ka to ~110 ka, correlated to MIS 5.5/5e, are found at elevations of +1.5 m to +2.6 m. These results differ significantly from the sea level record derived from low-latitude tropical reef terraces, where paleo-sea level during MIS 5.1/5a is interpreted to be appreciably (as much as 20–25 m) below that of MIS 5.5/5e (Chappell and Shackleton, 1986; Bard et al., 1990; Cutler et al., 2003; Schellmann and Radtke, 2004).

Here, we present new U-series ages of corals from emergent marine deposits on Mallorca (Figs. 1 and 2). The corals come from one of the key stratigraphic sections on the island, a locality called Campo de Tiro (also known as the Carnatge locality) near the city of Palma (Fig. 3). The locality is an important one because what have been called Eutyrrhenian and Neotyrrhenian marine deposits are both found there. While most investigators consider the deposits at Campo de Tiro to date from one or more parts of the last interglacial complex (MIS 5), there is disagreement as to

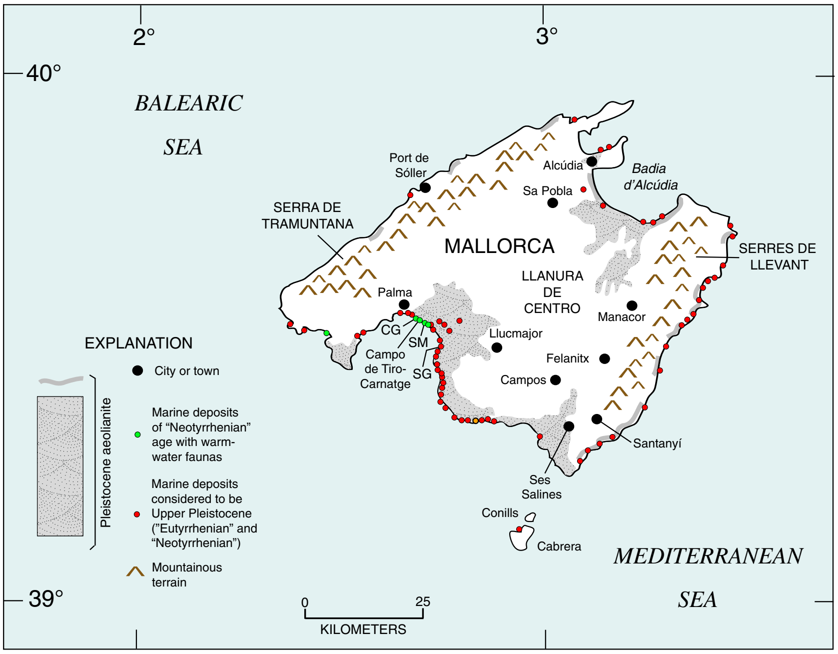


Fig. 3. Quaternary geology of Mallorca and location of study sites. Eolianite distribution simplified from Butzer and Cuerda (1962), González-Hernández et al. (2001), and Fornós et al. (2002); red dots indicate localities where marine deposits thought to date from the last interglacial period ("Eutyrrhenian") have been found, taken from Cuerda (1975, 1989). Green dots show where localities identified as "Neotyrrhenian," but with a warm-water fauna, have been reported (Cuerda, 1975, 1989). Abbreviations for localities: CG, Cala Gamba; SM, Son Mosson; SG, Son Grauet.

how many sea-level high stands are represented at this locality as well as disagreement over the specific age assignments that have been made. Furthermore, because the existing interpretations about paleo-sea level on Mallorca during MIS 5, derived from both from the marine deposits and the speleothem record, are at variance with the tropical reef record, resolution of the ages of marine deposits on Mallorca is crucial.

2. Study area

Mallorca is the largest of the Balearic Islands, situated to the east of mainland Spain in the Mediterranean Sea (Figs. 1 and 2). Jenkyns et al. (1990), Gelabert et al. (1992, 2003), and Pomar and Ward (1995) describe the bedrock geology of Mallorca in detail, so their work is summarized only briefly here. The island has a basin-and-range structure and topography, resulting from Miocene to early Pleistocene extension and faulting. The mountain ranges (Serra de Tramuntana or Sierra Norte and Serres de Llevant or Sierra de Levante) are horst blocks composed of Mesozoic-to-Tertiary sedimentary rocks (Fig. 3). Another area of upland topography, though of lower elevation, is the Llanura del Centro. The basins between the southwest-to-northeast-trending mountains and the Llanura del Centro are floored by Miocene carbonate rocks (primarily reef platforms) or Pliocene–Pleistocene conglomerates. Overall, much of the island is composed of carbonate rock of Mesozoic or Tertiary age (Instituto Geológico y Minero de España, 1986, 1987).

The Quaternary geology of Mallorca is dominated by deposits of alluvial, colluvial, aeolian, and marine origin (Butzer and Cuerda, 1962; Butzer, 1975; Cuerda, 1975, 1989; Rose, 1985; Cuerda and Sacarès, 1992; Clemmensen et al., 1997, 2001; Rose et al., 1999; Nielsen et al., 2004). Ginés et al. (2012b) provide a superb, up-to-date summary of the current understanding of the origins of these sediments and their paleoclimatic significance. Much of the coastal area of the island is rimmed by carbonate aeolianite, probably deposited during periods when sea level was lower. This inference is based on the observation that aeolianites with landward, high-angle dips (foresets) are found along the coast where no sand source is present now (see examples in Nielsen et al., 2004; Muhs et al., 2010), but where broad insular shelf areas would have been exposed during glacial and interstadial periods (Fig. 2). The aeolianites contain intercalated paleosols that developed when aeolian sand was stabilized. These paleosols formed partly from weathering of the aeolianite, but also are derived in part from additions of African dust (Muhs et al., 2010). During interglacial high stands of sea, thin deposits of highly fossiliferous sand and gravel were laid down from what is now near sea level to a few meters above present sea level. Cuerda (1975, 1987, 1989) shows that these deposits are found along much of the coast of Mallorca, but especially along the southwestern and southeastern coasts, as well as on the other Balearic Islands (Figs. 2 and 3). On Mallorca, Quaternary marine deposits are particularly well exposed in the area just southeast of Palma, where we conducted our studies. Because the island is composed largely of carbonate materials, either of Quaternary or pre-Quaternary age, karst is common on many parts of the island. Coastal caves that contain phreatic overgrowths on speleothems give important records of Quaternary sea-level history (Vesica et al., 2000; Tuccimei et al., 2006, 2012; Dorale et al., 2010; Ginés et al., 2012a; Onac et al., 2012).

3. Methods

3.1. Uranium-series dating

All corals, whether colonial or solitary, hermatypic or ahermatypic, take up U in isotopic equilibrium with sea water, contain little or no Th, and under favorable circumstances behave as closed systems with respect to ^{238}U and its long-lived daughter products, ^{234}U and ^{230}Th, after death and emergence. On Mallorca, the corals collected from Campo de Tiro have been identified by Cuerda (1989) as *Cladocora caespitosa* Linné. *C. caespitosa* is a shallow-water form that lives at present throughout the Mediterranean and possibly parts of the Atlantic Ocean, although only dead colonies have been found in the latter (Aguirre and Jiménez, 1998; Kruzic and Pozar-Domac, 2003). Modern specimens of *C. caespitosa* from eastern mainland Spain and Mallorca have U contents of 2.5–3.3 ppm and ^{234}U/^{238}U values of 1.142 to 1.154 (Goy et al., 2006), in good agreement with the range of seawater values for ^{234}U/^{238}U reported from the Mediterranean Sea and other ocean basins (Delanghe et al., 2002).

Nine specimens of the coral *C. caespitosa* were collected in this study and analyzed in laboratories of the U.S. Geological Survey, Denver, Colorado, USA. Coral samples were prepared by hand removal of detrital mineral grains and careful scraping of secondary carbonates under magnification, followed by multiple ultrasonic baths in distilled water. Only seven of the nine coral samples were of sufficient size to allow determinations of aragonite content by X-ray diffractometry (XRD). Six of these are 99–100% aragonite and the seventh was 97% (Table 1).

After cleaning, sample preparation followed methods outlined by Ludwig et al. (1992), summarized briefly here. Cleaned corals were dissolved in HNO_3, spiked with ^{229}Th, ^{233}U, and ^{236}U and purified with ion exchange methods. Purified U and Th were loaded with colloidal graphite on separate Re filaments and isotopic abundances were determined by thermal ionization mass spectrometry (TIMS). The U–Th spike is calibrated against a solution of uranium ore from the Schwartzwalder Mine that has yielded concordant U/Pb ages (Ludwig et al., 1985) and sample-to-sample agreement of ^{234}U/^{238}U and ^{230}Th/^{238}U (Ludwig and Paces, 2002). In addition, an in-house, carefully homogenized, aragonitic fossil coral of last interglacial age (~120 ka) is used for run-to-run checks. Ages were calculated using a half-life of 75,584 years for ^{230}Th and a half-life of 245,620 years for ^{234}U (Cheng et al., 2013).

The best criterion for determining closed-system conditions during the post-emergence history of a fossil is concordance between ^{230}Th/^{234}U and ^{231}Pa/^{235}U ages (Edwards et al., 1997, 2003). We did not determine ^{231}Pa/^{235}U ages for our samples. However, a second criterion for closed-system history is whether the back-calculated initial ^{234}U/^{238}U value, based on its present measured value and the ^{230}Th/^{234}U age, is within the range of modern seawater. Edwards et al. (1997) show that corals with initial ^{234}U/^{238}U activity values as high as 1.166 showed concordance between ^{230}Th/^{234}U and ^{231}Pa/^{235}U ages. In this study, we consider as "reliable" any corals with initial ^{234}U/^{238}U activity values from 1.147 to 1.159 (following Stirling et al., 1998). This range of values is only slightly higher than the reported range of values in modern seawater, 1.141–1.155 (Delanghe et al., 2002).

3.2. Paleozoogeography

For paleozoogeographic assessment of fossil assemblages from Mallorca, no new collections were made, but we reassessed the published fossil lists given by Cuerda (1975, 1987, 1989) and Cuerda and Sacarès (1992). Most of the marine invertebrate taxa of the Pleistocene faunas of Mallorca are composed of extant species. In making paleozoogeographic interpretations of these taxa, we used modern species ranges from the latest available sources, including Nicklès (1950), Kensley and Penrith (1973), Radwin and D'Attilio (1976), Cuerda (1987), Poppe and Goto (1991, 1993), Oliver and Von Cosel (1992), Rolán and Ryall (1999), Ardovini and Cossignani (2004), Rusmore-Villaume (2008), Rolán (2005), Huber (2010), Hernández et al. (2011), and Morton (2012).

4. Results

4.1. Stratigraphy

Cuerda (1975, 1989) shows that there are numerous exposures of late Quaternary marine deposits southeast of the city of Palma (Fig. 3). Some of the most intensively studied localities are those along Bahia de Palma, between Cala Gamba and Cala Estancia (Fig. 4). In this area,

Table 1
U and Th concentrations, isotopic activity ratios (AR), and U-series ages of corals (*Cladocora caespitosa*) from "Neotyrrhenian" deposits*, Mallorca, Spain.

Sample	Locality*	Aragonite content (%)	U ppm	+/−	^{232}Th ppm	^{234}U/^{238}U AR	+/−	^{230}Th/^{238}U AR	+/−	^{230}Th/^{232}Th AR	^{230}Th/^{238}U age (ka)**	+/−	^{234}U/^{238}U initial AR	+/−	Open-system age (ka)***	+/−
MA-1	Campo de Tiro	99	2.90	0.12	0.0023	1.1056	0.0020	0.7472	0.0024	2,907	**119.6**	**0.8**	1.1481	0.0026	119.2	1.7
MA-4	Campo de Tiro	100	2.70	0.10	0.0024	1.1117	0.0016	0.7622	0.0024	2,592	**122.6**	**0.8**	1.1579	0.0021	118.1	1.3
MA-5	Campo de Tiro	99	3.08	0.13	0.0047	1.1160	0.0026	0.7619	0.0021	1,502	**121.5**	**0.8**	1.1634	0.0034	114.8	2.0
MA-6	Campo de Tiro	99	3.01	0.11	0.0006	1.1138	0.0020	0.7745	0.0019	12,248	**125.7**	**0.7**	1.1623	0.0027	119.4	1.6
MA-7	Campo de Tiro	100	2.98	0.11	0.0064	1.1163	0.0015	0.7491	0.0038	1,053	**117.8**	**1.1**	1.1621	0.0019	111.7	1.4
MA-10	Campo de Tiro	100	3.71	0.11	0.0022	1.1074	0.0021	0.7515	0.0018	3,787	**120.4**	**0.7**	1.1508	0.0028	118.8	1.6
MA-11	Campo de Tiro	97	3.80	0.11	0.0044	1.1112	0.0018	0.7568	0.0024	1,998	**121.1**	**0.8**	1.1565	0.0023	117.2	1.5

* Elevations of all corals collected are 1.5 to 2.0 m above modern sea level.
** Calculated with half-lives of ^{230}Th = 75,584 years and ^{234}U = 245,620 years (Cheng et al., 2013); errors on all concentrations, AR, and ages are two-sigma.
*** Open-system ages calculated using method of Thompson et al. (2003), but using half-lives of Cheng et al. (2013).

at the Campo de Tiro/Carnatge locality (shown as coastal exposure locality 2 in Figs. 4, 5, and 6), Cuerda (1975, 1989), Rose (1985), and Hearty (1987) report that three marine units are exposed. Later workers (Hillaire-Marcel et al., 1996; Zazo et al., 2003; Bardají et al., 2009; Vicens et al., 2012) report four marine units. The oldest two marine units recognized by all workers are the "Eutyrrhenian" (also known as "Tyrrhenian II") beds shown in Fig. 6. These sediments consist of horizontal (0° dip), fossiliferous beds of reddish-brown marine sand and rare gravel, ~50–70 cm thick, capped by a thin calcrete, and in places capped by a reddish-brown, eroded soil B horizon. The "Eutyrrhenian" beds can be traced horizontally to the north (shown as locality 1, "Campo de Tiro" in Fig. 6; see also Muhs et al., 2010, their Fig. 7a), and to the south (shown as locality 3, "Casas del Carnatge" in Fig. 6). The older of these two units is referred to as unit "c" in Cuerda (1975, 1989) and Rose (1985) and "CTC I" by Hearty (1987); later workers (as cited above) refer to this as marine unit 1, or "U1." The upper, younger unit of the "Eutyrrhenian" beds is referred to as unit "d" by Cuerda (1975, 1989) and Rose (1985), and "CTC II" by Hearty (1987). Later workers (as cited above) refer to this as marine unit 2 or "U2." The highest elevation of these beds that we measured is 3 m (±0.2 m), consistent with what previous workers have reported (see Vicens et al., 2012 and Fornós et al., 2012). At our locality 1 (Fig. 6), the Eutyrrhenian beds are underlain by a thick, red, clay-rich paleosol that has developed on aeolianite considered to be of penultimate glacial (MIS 6) age by Rose (1985).

Seaward of the Eutyrrhenian beds at our locality 2 (Fig. 6) are what has been referred to as "Neotyrrhenian" (also known as "Tyrrhenian III") beds. These deposits are called units "g" and "f" by Cuerda (1975, 1989) and Rose (1985), "CTC III" by Hearty (1987), and marine unit 4 or "U4" by Hillaire-Marcel et al. (1996), Zazo et al. (2003), Bardají et al. (2009), and Vicens et al. (2012). The Neotyrrhenian beds consist of a lower layer, 40 cm thick, of gravelly sands that are sparsely fossiliferous, and an upper layer, 50 cm thick, of sandy gravels that are highly fossiliferous. We measured a maximum elevation of 2 m (±0.2 m; see Figs. 5 and 6) for the top of these beds, consistent with what previous workers have reported (see Fornós et al., 2012; Vicens et al., 2012). Both Neotyrrhenian beds dip seaward at ~6°. The lower bed rests on a reddish-brown paleosol that is clay-rich and has strong brown (7.5YR 5/6) to reddish yellow (7.5YR 7/6) colors. The distinctive

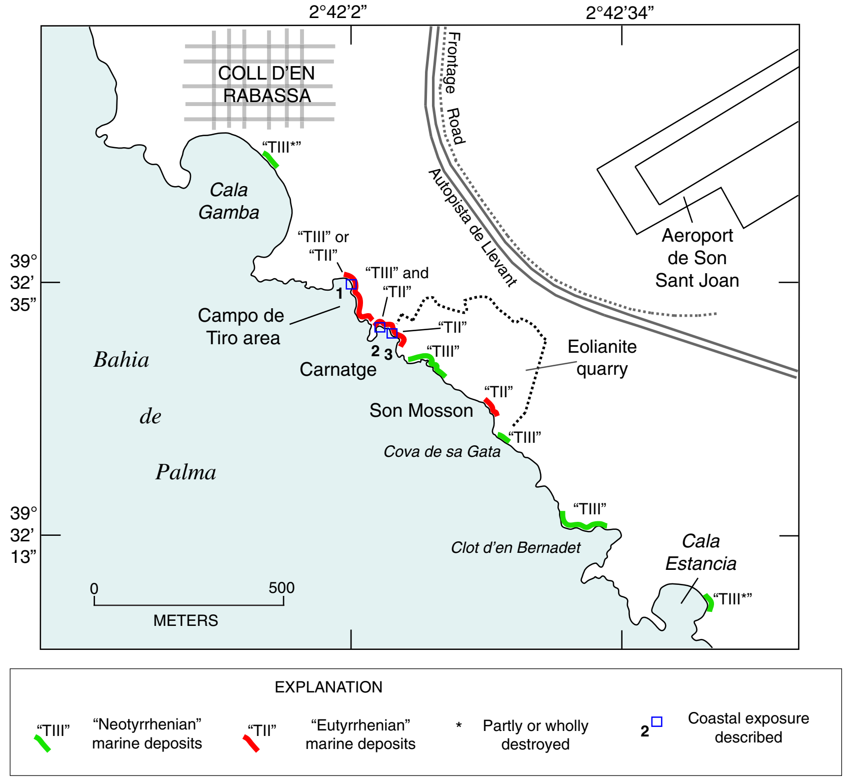


Fig. 4. Study area in the Palma area of Mallorca (see Fig. 3), showing distribution of Eutyrrhenian (also called "TII" by Rose, 1985, in red) and Neotyrrhenian (also called "TIII" by Rose, 1985, in green) marine deposits. Coastal exposures described in the present study (open squares) are numbered 1, 2, and 3. Marine deposit distribution from Rose (1985).

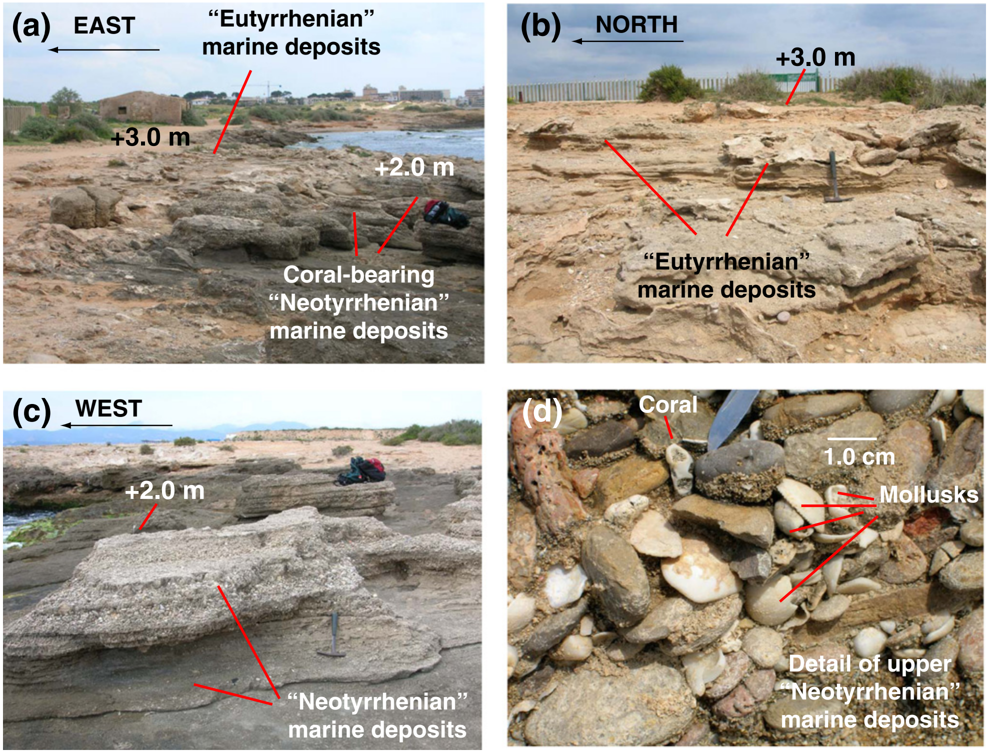


Fig. 5. Photographs of the Campo de Tiro-Carnatge area near Palma (locality "2" in Figs. 4 and 6), showing (a) both Eutyrrhenian and Neotyrrhenian deposits, (b) detail of Eutyrrhenian deposits, (c) detail of Neotyrrhenian deposits, and (d) close-up view of Neotyrrhenian deposits with mollusks and corals (next to knife blade). Note flat-lying Eutyrrhenian deposits and seaward dip of Neotyrrhenian deposits (a, b, c) and poorly sorted nature of clasts, mollusks, and corals in Neotyrrhenian deposits (d). Photos by D.R. Muhs.

paleosol can be traced to the north at least as far as locality 1 shown in Figs. 4 and 6 (see also Muhs et al., 2010, their Fig. 7a), where it is entirely exposed, is developed on aeolianite, and is overlain by marine deposits, as alluded to above. The paleosol also can be traced at least 100 m to the south of locality 2 (as shown in Figs. 4 and 6) where again it is exposed in its entirety, is developed on aeolianite, and is overlain by marine deposits. The aeolianite is pink (7.5YR 8/4) and is a well-sorted, bedded and weakly cemented sand with high-angle (~29°) dips exposed at the southernmost exposures. Thus, it is inferred that aeolianite also underlies the reddish paleosol at locality 2, as shown in Fig. 6. Cuerda (1975, 1989) and Rose (1985) correlate this aeolianite to the penultimate glacial period, equivalent to MIS 6.

Later workers (Hillaire-Marcel et al., 1996; Zazo et al., 2003; Bardají et al., 2009; Vicens et al., 2012) recognized another marine unit at this site that they refer to as marine unit 3, or "U3," that consists of blocks eroded from the adjacent "Eutyrrhenian" units 1 and 2 (Fig. 6). They show these blocks as a separate marine unit that underlies the "Neotyrrhenian" beds. Cuerda (1975, 1989) and Rose (1985) do not show these blocks as underlying the "Neotyrrhenian" beds and we also saw no such evidence in our field examination of these units. We agree, however, that these blocks of sediment do appear to be eroded from the "Eutyrrhenian" beds, but we could not trace them under the "Neotyrrhenian" beds. Where we observed them, the "Neotyrrhenian" beds appear to lie directly on the reddish-brown paleosol that is developed on the aeolianite described above (Figs. 5 and 6).

4.2. Uranium-series dating of fossil corals from Campo de Tiro, Mallorca, Spain

Although there have been attempts at dating all of the marine units at Campo de Tiro, all efforts have been either U-series or amino acid geochronology on fossil mollusks. There are, unfortunately, no U-series ages on corals for any of these deposits, specifically at Campo de Tiro, although Cuerda (1975, 1989) reports corals (*C. caespitosa*) from both the "Eutyrrhenian" and "Neotyrrhenian" beds from a number of localities around Mallorca. Despite several days of searches, we were able to find corals only in the "Neotyrrhenian" beds at the Campo de Tiro-Carnatge locality (#2 in Fig. 6), all from the uppermost, gravel-and-fossil-rich unit (Figs. 5c, d and 6). Here we found nine coral fragments that were sampled for U-series dating. We note that, as with most other fossils in Quaternary marine deposits on Mallorca, the corals sampled were not in growth position. As is the case in marine terrace deposits on the coast of California (e.g., Muhs et al., 2002b, 2006), Mallorcan marine fossils are generally a poorly sorted assemblage of specimens (Fig. 5d) that may be derived by wave action from original growth positions that span several meters of water depth. Thus, no inferences about paleo-water depth at a given fossil site can be made by the presence of mixtures of both shallow-water and deeper-water taxa.

The seven corals that are 97–100% aragonite yielded U contents of 2.7–3.8 ppm (Table 1), broadly within the range of modern specimens of *C. caespitosa* (Goy et al., 2006) and similar to the range of U contents in fossil specimens of this genus reported elsewhere (Hearty et al., 1986; Leeder et al., 2003; Roberts et al., 2009). The $^{230}Th/^{232}Th$ values of the corals range from ~1000 to ~12,000, indicating no significant amount of inherited ^{230}Th. Back-calculated initial $^{234}U/^{238}U$ values for four of the samples range from 1.148 to 1.158, indicating closed or mostly closed-system histories with respect to ^{230}Th, ^{234}U, and ^{238}U. These four corals yield ages ranging from 122.6 ± 0.8 ka to 119.6 ± 0.8 ka.

The other three corals have calculated initial $^{234}U/^{238}U$ values that range from 1.162 to 1.163. These samples plot slightly above an ideal, closed-system isotopic evolutionary pathway, as shown on a $^{230}Th/^{238}U$ vs. $^{234}U/^{238}U$ plot (Fig. 7). Gallup et al. (1994), studying reef corals on Barbados, also observed elevated initial $^{234}U/^{238}U$ values in a number of their samples. They noted a roughly linear trend of older apparent ages with increasing elevated $^{234}U/^{238}U$ values, suggesting that the latter value is an indication of bias to older apparent ages. Recoil emplacement of ^{230}Th and ^{234}U by U-bearing waters percolating

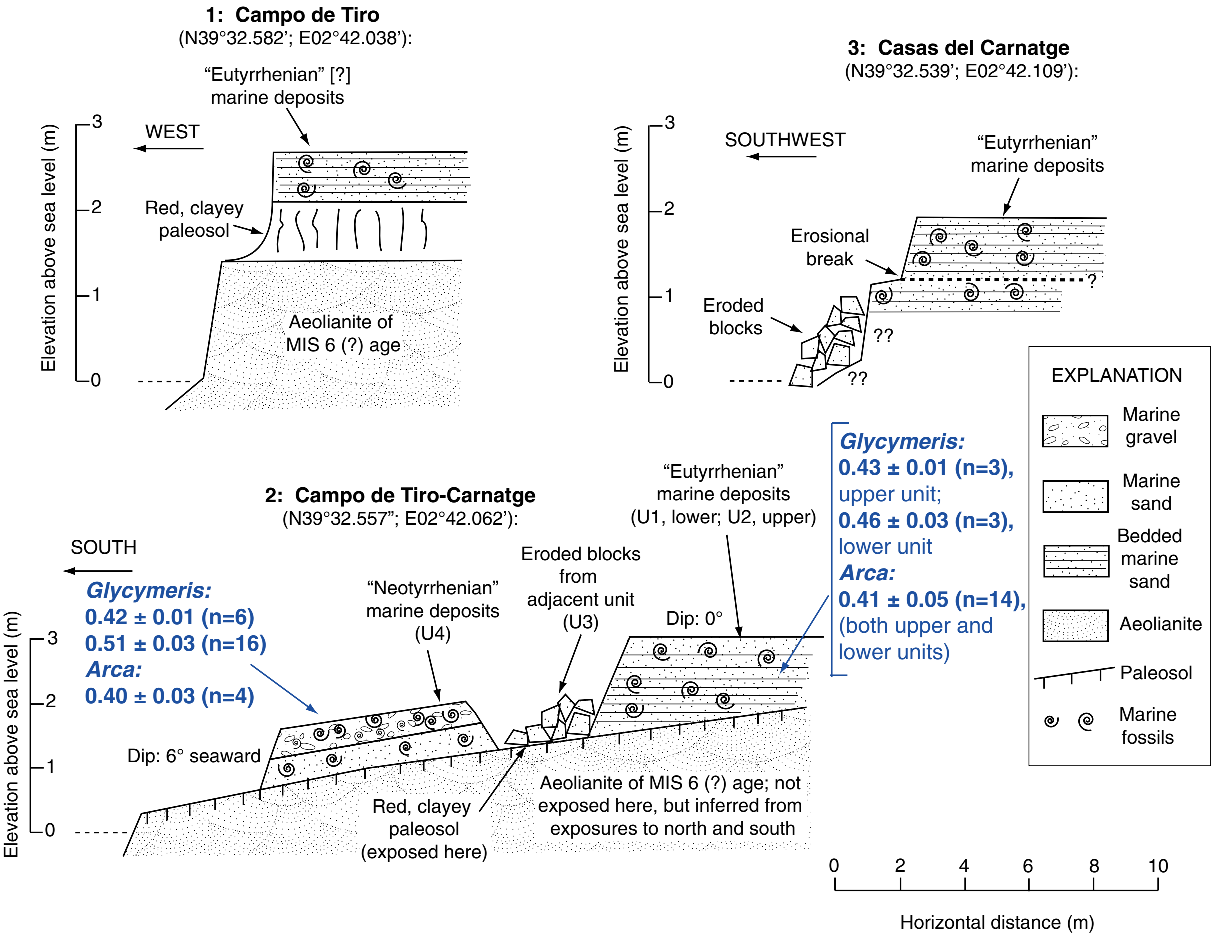


Fig. 6. Stratigraphy of coastal exposures in the Palma bay area (localities keyed to Fig. 4) and amino acid ratios (D-alloisoleucine to L-isoleucine, shown in bold blue type) for fossil mollusks *Glycymeris* and *Arca*. Stratigraphy from the present study; amino acid data from Hearty (1987). At locality 2, unit designations shown (U1, U2, U3, and U4) are the equivalents of marine units 1, 2, 3, and 4, respectively in Bardají et al. (2009; their Fig. 6).

through host reef, sediment, or soil has been observed for many years and is the basis for the experimental, open-system, U-trend dating method described by Szabo and Rosholt (1982) and Muhs et al. (1989).

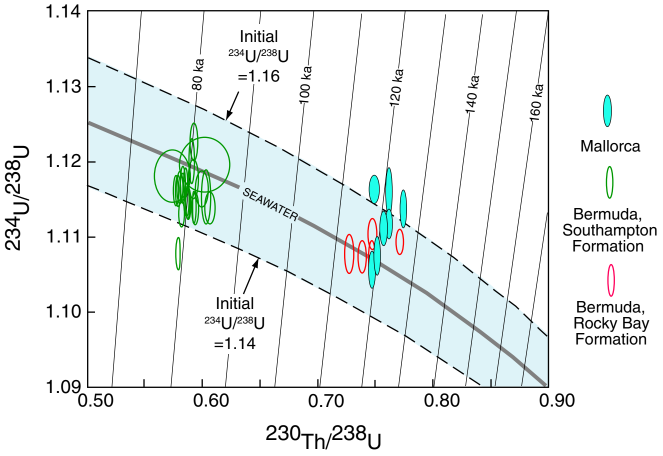
Thompson et al. (2003) developed a method for correcting U-series ages with elevated initial $^{234}U/^{238}U$ values. The U-series geochronology community is still divided on the validity of this approach (Stirling and Andersen, 2009), but application of the method to corals with elevated initial $^{234}U/^{238}U$ values in the Bahamas seems to yield geologically reasonable results (Thompson et al., 2011). In order to assess the amount of potential age bias, we applied the Thompson et al. (2003) correction scheme to our data (software provided courtesy of W.G. Thompson of Woods Hole), adjusting the software to use the new decay constants of Cheng et al. (2013). Results show that the four least-biased corals have open-system ("corrected") ages ranging from ~119 ka to ~117 ka (Table 1). The three most-biased corals have open-system ages ranging from ~119 ka to ~112 ka. The age range of all seven corals from Mallorca is similar to corals from last interglacial-age (~120 ka) formations on the Florida Keys and Bermuda and clearly much older than the younger (~80 ka) marine formations from both these islands (Fig. 7). All but one of the Mallorca corals (MA-7, with a conventional, or uncorrected age of ~117 ka and an open-system, or corrected age of ~112 ka) fall squarely within the range of MIS 5.5/5e, as given in the deep-sea oxygen isotope record (Imbrie et al., 1984; Martinson et al., 1987). The two corals that were too small for XRD analysis gave apparent ages of ~131 ka and ~102 ka, which bracket the ages of the aragonitic corals given in Table 1. Because we do not know the aragonite concentrations of these two samples, we do not include them in our interpretations.

4.3. Paleontology and paleozoogeography of marine deposits on Mallorca

One of the distinguishing characteristics of what have been considered to be Eutyrrhenian deposits on Mallorca is the presence of extralimital southern species of mollusks (Butzer and Cuerda, 1962; Butzer, 1975; Cuerda, 1975, 1987, 1989). This fossil assemblage consists of a number of taxa whose present ranges are well to the south of Mallorca, mostly within warm tropical Atlantic waters off western Africa (Fig. 8). Thus, the Eutyrrhenian assemblage as a whole has been described as a "Senegalese" fauna. In this regard, the Eutyrrhenian deposits have fossil assemblages similar to the faunal aspects of deposits dated to the peak of the last interglacial period (~120 ka) from other Atlantic and Pacific islands (e.g., Muhs et al., 2002a, 2002b, 2014).

Neotyrrhenian deposits of Mallorca, lacking many of these Senegalese forms, have been distinguished from Eutyrrhenian deposits on the basis of faunal thermal aspects for more than half a century (Butzer and Cuerda, 1962). On the California coast, there is also a contrast in faunal thermal aspects in deposits dated to ~120 ka compared to those dated to ~80 ka (see examples in Muhs et al., 2002b, 2006, 2012). Older (~120 ka) deposits in California, like the Eutyrrhenian deposits of Mallorca, have a number of extralimital southern species of mollusks (implying warmer-than-present waters during this earlier sea stand) whereas younger (~80 ka) deposits have a number of extralimital northern species (implying cooler-than-present waters during

(a) Mallorca and Bermuda:



(b) Mallorca and Florida:

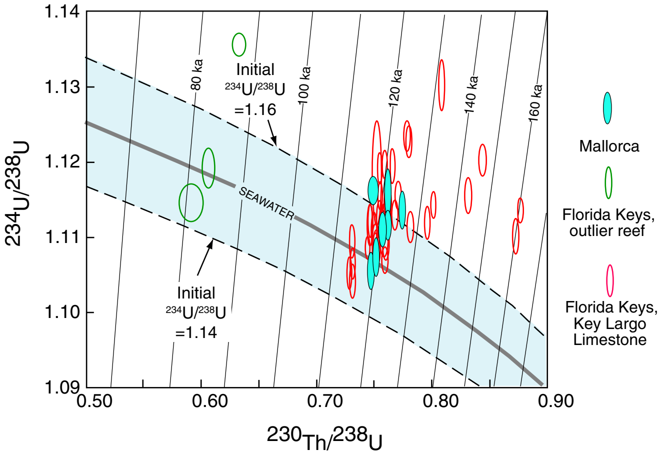


Fig. 7. Isotopic evolution diagram (using Isoplot, from Ludwig, 2001) with curved lines showing hypothetical sympathetic changes in ^{230}Th/^{238}U and ^{234}U/^{238}U in corals with different initial ^{234}U/^{238}U values (1.14–1.16) that include the range of measured values in modern seawater. Thick gray line shows pathway from average value of ^{234}U/^{238}U of 1.15 in seawater (Delanghe et al., 2002). Filled ellipses in blue in both (a) and (b) show measured (uncorrected) values of these ratios with 2-sigma uncertainties in corals from Mallorca (this study; Table 1). Green ellipses in (a) are from corals of the Southampton Formation of Bermuda and red ellipses in (a) are from the Devonshire marine member of the Rocky Bay Formation of Bermuda (data from Ludwig et al., 1996; Muhs et al., 2002a). Green ellipses in (b) are from corals of a submerged "outlier reef" of the Florida Keys and red ellipses in (b) are corals from the Key Largo Limestone of the Florida Keys (data from Ludwig et al., 1996; Muhs et al., 2011).

the later sea stand). It is pertinent, therefore, to assess whether a similar contrast in faunal thermal aspects exists for Eutyrrhenian vs. Neotyrrhenian deposits on Mallorca, using the latest information about the present zoogeography of the species present as fossils.

Reexamination of the Neotyrrhenian fossils in the present study comes from the list for the Neotyrrhenian beds given by Cuerda (1975, 1989, pp. 125–126, pp. 205–206 for *Brachidontes senegalensis*). These fossils are from the same locality where our dated corals were collected. All species are extant, and here we present an updated modern zoogeography of all molluscan species reported by Cuerda (1975, 1987, 1989). In the Neotyrrhenian beds at Campo de Tiro, there are no extralimital northern species and there is only a single northward-ranging species, *Dentalium vulgare*. On the other hand, there are nine southward-ranging species, i.e., taxa that live in the Mediterranean today, but whose modern range is mostly to the south of it. These warmer-water taxa include the gastropods *Fisurella nubecula* (south to Senegal), *Patella caerulea* (south to Senegal), *Smaragdia viridis* (south to Angola), *Trivia mediterranea* (south to the Canary Islands), *Lurida lurida* (south to Angola), *Cabestana cutacea* (south to the Canary Islands) and *Stramonita haemastoma* (south to Angola and Namibia), as well as the bivalves *Glycymeris violacescens* (south to the Canary Islands), and *Lithophaga lithophaga* (south to Angola).

Importantly, Neotyrrhenian beds at Campo de Tiro host four extralimital southern species of mollusks, including *Cantharus viverratus* (= *Cantharus viverratoides*), *Conus testudinarius* (= *Conus ermineus*), *Acar plicata* (= *Barbatia plicata*), and *B. senegalensis* (= *Brachidontes puniceous*) (Figs. 8 and 9). Three of these taxa (*C. viverratoides*, *C. ermineus*, and *B. puniceous*) are members of the classical "Senegalese" faunal group that has figured so prominently in Mediterranean Quaternary sea level history and paleozoogeography (Cuerda, 1975, 1989). *C. viverratoides* presently lives from Angola to only as far north as the Canary Islands (Rolán and Ryall, 1999; Rolán, 2005; Hernández et al., 2011); thus, its presence on Mallorca indicates a northward range extension of more than ~1800 km (Fig. 9). *C. ermineus* also presently lives as far south as Angola, but ranges only as far north as the Cape Verde Islands (Rolán and Ryall, 1999; Rolán, 2005), indicating a past northward range extension of ~3500 km. Similar to *C. ermineus*, *B. puniceous* ranges from Angola to only as far north as the Cape Verde Islands (Nicklès, 1950; Kensley and Penrith, 1973; Morton, 2012) or possibly Mauritania (Ardovini and Cossignani, 2004), indicating a past northward range extension of at least ~3000 km. Zazo et al. (1993), in referring to the Mallorcan paleontological record, stated that *B. plicata* "lacks climatic significance." Here we offer an alternative view, that this species has considerable climatic significance. At present, *B. plicata* is found along the coast of western Africa from Angola to only as far north as the Cape Verde Islands (Oliver and Von Cosel, 1992). It is also apparently present in the warm waters of the Red Sea (Rusmore-Villaume, 2008). Relative to the closest modern occurrences off tropical Africa, the presence of fossil *B. plicata* on Mallorca indicates a past northward range extension of more than 3500 km. Overall, the presence of several extralimital southern species of mollusks and no extralimital northern species implies warmer-than-present waters when the Neotyrrhenian beds were deposited on Mallorca.

5. Discussion

5.1. Geochronology

As alluded to earlier, many studies have inferred that the Neotyrrhenian deposits on Mallorca date to ~80 ka, or MIS 5.1/5a. A careful sifting of the evidence through the years of study of these deposits on Mallorca indicates that the interpretation of an 80 ka age ultimately goes back to two early U-series analyses of mollusks. One of these is mollusk sample L-884G from the "Tyrrhenian III" deposit ("Neotyrrhenian") at Campo de Tiro that gave an apparent age of 75 ± 5 ka, reported by Stearns and Thurber (1965, 1967). The other mollusk analysis (sample L-934A) is from Magaluf, west of Palma, and gave an apparent age of 88 ± 5 ka. This latter age estimate was apparently never published with stratigraphic information or analytical details, but was listed by Butzer (1975, his Table 1) and Cuerda (1975, 1989, p. 154). The apparent ages of these "Tyrrhenian III" samples (75 ± 5 ka and 88 ± 5 ka), when set against the early apparent ages of mollusks from "Tyrrhenian II" deposits (>300 ka, 200 ± 20 ka, 135 ± 10 ka, 115 ± 5 ka), also reported by Stearns and Thurber (1965, 1967) from elsewhere on Mallorca, probably reinforced the concept of the "Tyrrhenian III" or "Neotyrrhenian" deposits being much younger. Recent reinforcement of an ~80 ka age for the Neotyrrhenian beds comes from the recognition that they are only slightly above modern sea level (+2 m) and U-series ages of speleothems on Mallorca imply a sea level slightly above present at this time (Vesica et al., 2000; Tuccimei et al., 2006; Dorale et al., 2010; Ginés et al., 2012a). Zazo et al. (2013) favored an ~80 ka age for the Neotyrrhenian deposits

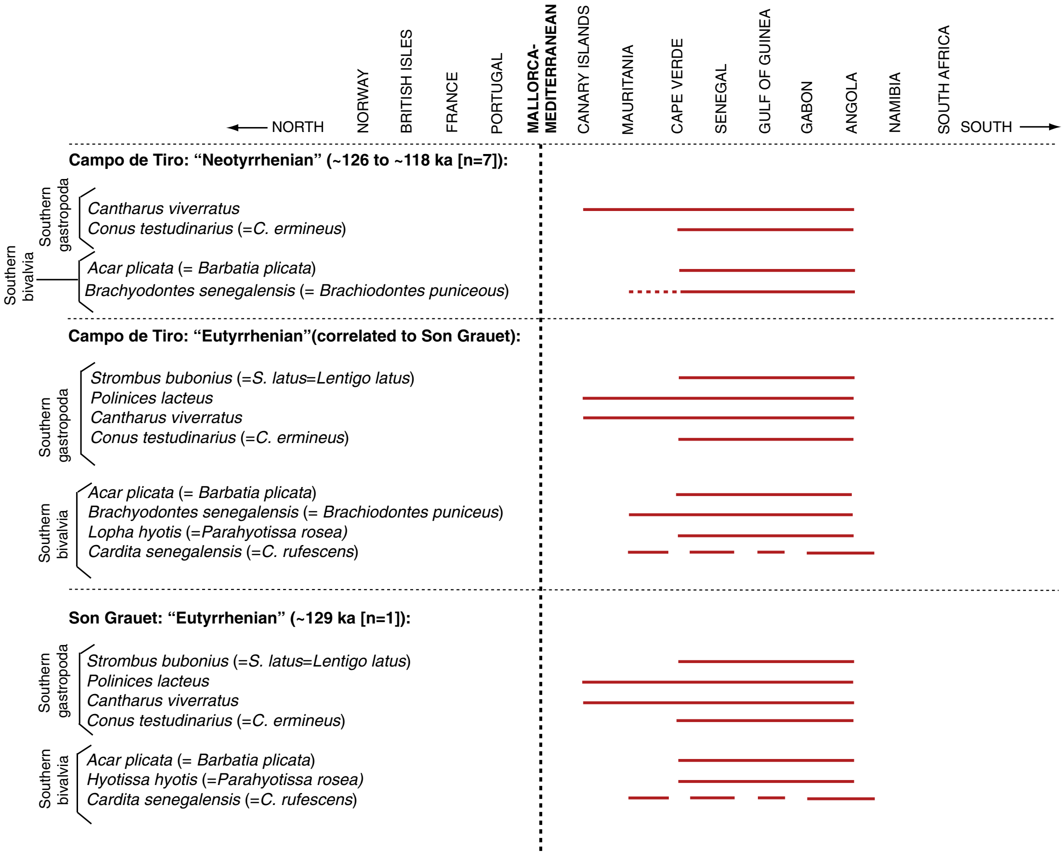


Fig. 8. Modern geographic distribution of extralimital southern molluscan species found as fossils in marine deposits of Mallorca from three localities. See text for sources of modern zoogeography. Fossil data for the Campo de Tiro localities are from Cuerda (1975, 1987, 1989) and fossil data from Son Grauet are from Cuerda and Sacarès (1992). U-series ages given are from this study for Campo de Tiro and Hearty et al. (1986) for Son Grauet.

on Mallorca in part based on the POS data indicating a slightly higher-than-present sea level at ~80 ka.

Another interpretation that has been presented is that the Neotyrrhenian deposits at Campo de Tiro date to the ~100 ka high-sea stand, or MIS 5.3/5c. Hillaire-Marcel et al. (1996) offered this possibility when they reported apparent U-series ages on mollusks from this unit of ~90 ka, ~102 ka, ~109 ka, and ~125 ka. They interpreted the ~125 ka specimen as reworked and considered that the other three ages indicated that the deposit could date to MIS 5.3/5c. Bardají et al. (2009) also apparently accepted an age estimate of ~100 ka (see their Fig. 6), but provided no new age information to support this.

Amino acid data reported by Hearty (1987) present yet another possibility. He analyzed both *Glycymeris* and *Arca* shells from what have been called the Eutyrrhenian and Neotyrrhenian deposits at Campo de Tiro. From the Eutyrrhenian units, *Arca* shells have mean D-alloisoleucine/L-isoleucine (A/I) values of 0.41 ± 0.05 (n = 14), for both of what Hearty (1987) refers to as CTC I and II. A/I values in *Glycymeris* shells from the Eutyrrhenian units are 0.46 ± 0.03 (n = 3) for CTC I (lower part), and 0.43 ± 0.01 (n = 3) for CTC II (upper part). In the Neotyrrhenian deposits, A/I values in *Arca* shells average 0.40 ± 0.03 (n = 4) and are thus indistinguishable from those in the Eutyrrhenian deposit (Fig. 6). A/I values in *Glycymeris* shells from the Neotyrrhenian deposits fall into two groups, one with a mean value of 0.42 ± 0.01 (n = 6), indistinguishable from both of the Eutyrrhenian shells (CTC I and CTC II), and the other with a mean value of 0.51 ± 0.03 (n = 16). Including the *Glycymeris* shells with the higher A/I values averaging 0.51, one could make the case that the Neotyrrhenian deposits are actually *older* than the Eutryrrhenian deposits. Hearty's (1987) *Glycymeris* shells from the Eutyrrhenian deposit at Son Grauet, not far from Campo de Tiro (Fig. 3), have a mean A/I value of 0.40 ± 0.03 (n = 13), whereas *Arca* shells from this deposit have a mean A/I value of 0.27 ± 0.02 (n = 9). The Son Grauet locality also hosts *Cladocora* corals, and Hearty et al. (1986) report a single alpha-spectrometry U-series age of 129 ± 14 ka (two-sigma errors). At Campo de Tiro, Hearty (1987) interpreted the *Glycymeris* shells with the higher A/I values in the Neotyrrhenian deposits to be reworked from (hypothesized) submerged pre-last interglacial deposits, but allowed for the possibility that the deposits themselves could represent a younger-than-MIS 5.5/5e event.

The U-series data presented here provide no persuasive evidence that the Neotyrrhenian deposits at Campo de Tiro date to the ~80 ka high-sea stand (MIS 5.1/5a) or the ~100 ka high-sea stand (MIS 5.3/5c) (Fig. 7). Those corals that show the least amount of potential age bias based on initial $^{234}U/^{238}U$ values (MA-1, MA-4, MA-10, MA-11) yield ages ranging from 122.6 ± 0.8 ka to 119.6 ± 0.8 ka. The other corals have slightly elevated initial $^{234}U/^{238}U$ values, but consideration of possible age bias (Thompson et al., 2003) would lower these ages only to ~119 ka to ~112 ka, still well within the age range of MIS 5.5/5e corals and clearly much older than MIS 5.1/5a corals reported elsewhere (Fig. 7). The overall likely age range of all seven corals from Mallorca, whether "uncorrected" or "corrected" is similar to the age range for corals from last-interglacial-age marine formations we have studied on the tectonically stable Florida Keys and Bermuda. Corals from the last-interglacial Key Largo Limestone of Florida with calculated initial $^{234}U/^{238}U$ values ranging from 1.148 to 1.158 have ages ranging from ~123 ka to ~113 ka (Muhs et al., 2011). On Bermuda, corals from the Devonshire marine member of the Rocky Bay Formation with this same range of calculated initial $^{234}U/^{238}U$ values have ages ranging from ~125 ka to ~113 ka (Muhs et al., 2002a). As mentioned earlier, one coral we analyzed gave an apparent age of ~102 ka, but because this sample was too small to X-ray, we cannot assess the validity of this age.

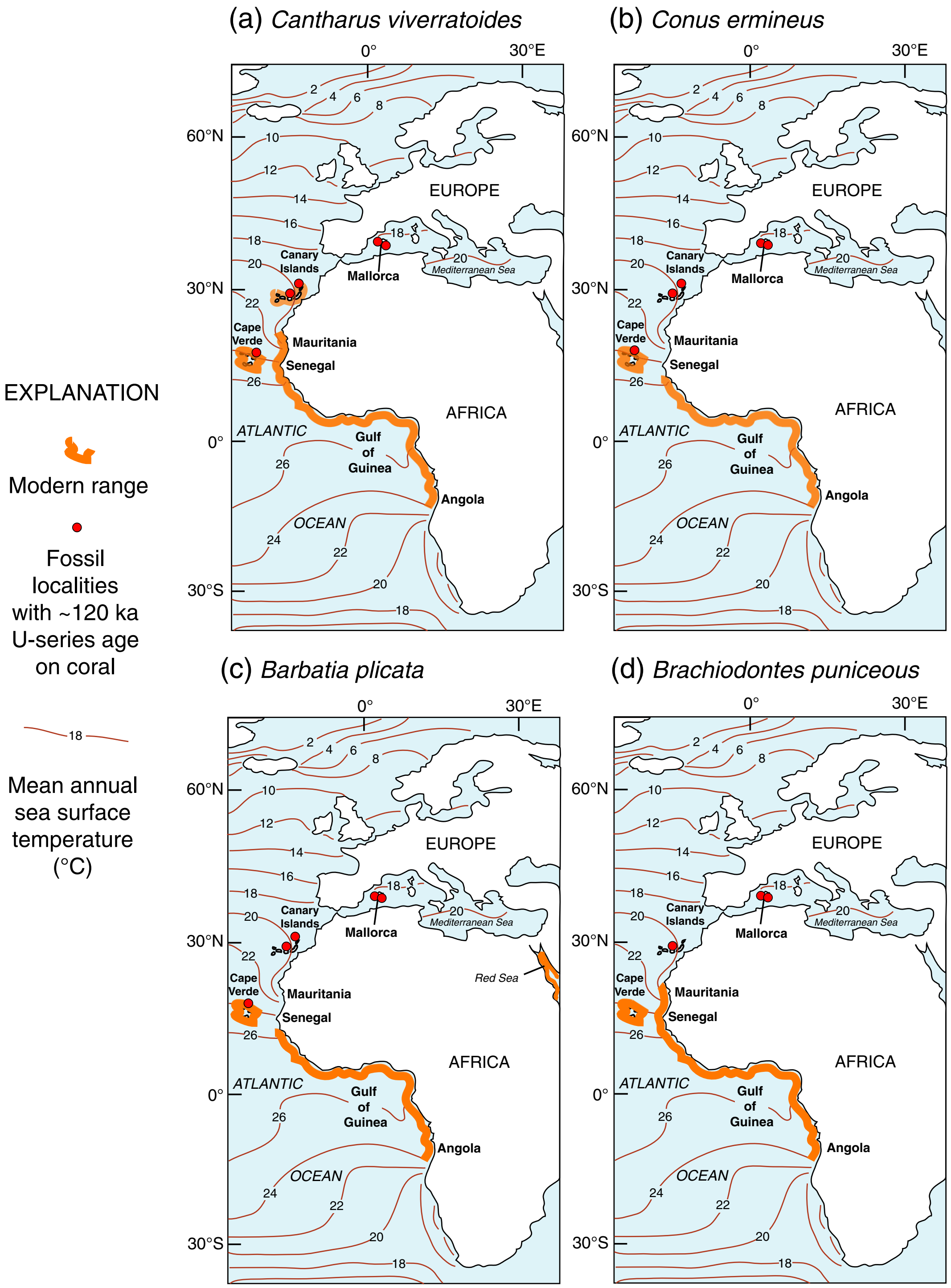


Fig. 9. Mean annual sea surface temperatures over the eastern Atlantic Ocean (redrawn from Conkright and Boyer, 2002), and the modern distribution of extralimital southern taxa found in dated, ~120 ka marine deposits at Campo de Tiro, Mallorca: (a) *Cantharus viverratoides,* (b) *Conus ermineus* (c) *Barbatia plicata*, and (d) *Brachidontes puniceous*. Modern zoogeography taken from Rolán (2005) for *Cantharus viverratoides* and *Conus ermineus*; from Oliver and Von Cosel (1992) and Rusmore-Villaume (2008) for *Barbatia plicata*; and Nicklès (1950) and Huber (2010) for *Brachidontes puniceous*. Also shown are dated (U-series on coral) localities (filled red circles) where other last-interglacial (~130–115 ka) occurrences of these taxa have been documented. Sources of fossil data: *Mallorca* (paleontology, Cuerda, 1975, 1989; Cuerda and Sacarès, 1992; chronology, Hearty et al., 1986, and this study); *Canary Islands* (paleontology, Meco et al., 2002, 2006; chronology, Muhs et al., 2014); *Cape Verde* (paleontology and chronology, Zazo et al., 2007).

The U-series data reported here are consistent with Hearty's (1987) amino acid data (particularly *Glycymeris*) that there is no significant difference in age between the Eutyrrehenian (at Son Grauet and Campo de Tiro) and Neotyrrhenian (at Campo de Tiro) deposits. Such an interpretation requires, however, an explanation for the higher (mean of 0.51 ± 0.03) amino acid ratios in *Glycymeris* in the Neotyrrhenian deposits at Campo de Tiro. The uppermost, fossil-rich Neotyrrhenian deposits at Campo de Tiro (Fig. 5c) are only ~50 cm thick. Thus, because all fossils taken from this unit would have been buried at only shallow depths, surface-heating effects could have increased the epimerization rate in some shells. Wehmiller (1977) documented higher-than-expected amino acid ratios in marine mollusks due to surface heating from shallow burial. At Campo de Tiro, this process could explain the higher *Glycymeris* values without having to resort to the idea of reworking of as-yet unidentified older deposits (Hearty, 1987).

5.2. Consideration of paleo-sea levels and glacial isostatic adjustment (GIA) effects

As discussed above, other workers have considered that the Neotyrrhenian deposits at Campo de Tiro are either ~80 ka (MIS 5.1/5a) or ~100 ka (MIS 5.3/5c). With the exception of one ~100 ka coral that cannot be properly evaluated because of a lack of XRD data, all U-series and amino acid data support a ~120 ka age. Nevertheless, it is useful to consider some scenarios where a younger age for the Neotyrrhenian deposits might be inferred. One possibility is that the Neotyrrhenian deposit itself at Campo de Tiro is actually ~100 ka and that all but possibly one of the corals are reworked from Eutyrrhenian deposits. Considering Hearty's (1987) amino acid data, however, this would also require that all *Glycymeris* and *Arca* shells in the Neotyrrhenian deposits were reworked from Eutyrrhenian deposits as well. While this scenario seems unlikely, there are precedents for similar, though not identical, sequences of events. Muhs et al. (2002b, 2012) document the co-existence, within the same deposit, of both ~120 ka and ~100 ka corals in marine terrace deposits at three widely separated localities in California. GIA effects on the coast of California are significant, the consequence of North America hosting the Cordilleran and Laurentide ice sheets during past glacial periods. One result of these GIA effects on North America is that local sea levels during MIS 5.3/5c and 5.1/5a were higher, relative to present, than paleo-sea level estimates from coral reef terraces of similar age in far-field localities, such as New Guinea, or even intermediate-field localities, such as Barbados. For both Barbados and New Guinea, paleo-sea level estimates for the ~100 ka and ~80 ka sea stands are estimated to be about 19–20 m below present (Chappell and Shackleton, 1986; Bard et al., 1990; Schellmann and Radtke, 2004). Because these localities are distant from Northern Hemisphere ice sheets, terraces there are considered to record primarily a eustatic sea level history. In contrast, Muhs et al. (2012) estimate, on the basis of both GIA modeling and field studies, that paleo-sea level on the California coast was around −11 m to −12 m, relative to present, at ~80 ka and +2 m to +6 m at ~100 ka. There is additional support for the importance of GIA effects on or near North America, from both the tectonically stable Atlantic Coastal Plain of the USA and the island of Bermuda. On both of these Atlantic coasts, paleo-sea level above present is documented for at least the ~80 ka high sea-stand, with well-dated coral-bearing deposits (Muhs et al., 2002a; Wehmiller et al., 2004). Potter and Lambeck (2003) attribute these 80 ka deposits above sea level to GIA effects.

In view of the North America sea level record, the question arises as to whether GIA processes from the Eurasian ice sheets might have affected the apparent sea level record on Mediterranean coasts. Creveling et al. (2015) modeled possible deviations of the peak, last-interglacial high-sea stand (MIS 5.5/5e) from purely eustatic values at both the beginning and end of MIS 5.5/5e for a variety of localities worldwide. They report that in the central Mediterranean (Rome) and eastern Atlantic (Canary Islands), MIS 5.5/5e sea level at the end of the last interglacial period (~120 ka) would differ little from eustatic values, whether +6 m or a +8 m eustatic values were considered. If these results are correct, they imply that GIA effects in the Mediterranean basin around Mallorca, situated between the central Mediterranean and eastern Atlantic, could be minimal. On the other hand, on the basis of speleothem data, both Tuccimei et al. (2006), Dorale et al. (2010), and Ginés et al. (2012a) propose that sea levels in the Mediterranean during MIS 5.5/5e, 5.3/5c, and 5.1/5a were about +2.6 m, −11 m, and +1 m, respectively. We note that these authors do not attribute the differences in sea level history from their speleothem records and the reef terraces of Barbados and New Guinea specifically to GIA effects. Nevertheless, their data argue for a sea-level history that could be consistent with higher-than-eustatic (relative) paleo-sea levels during MIS 5.3/5c and 5.1/5a on Mallorca.

We test the hypothesis of higher-than-expected MIS 5 sea levels in the Mediterranean/Mallorca by examination of a well-studied sequence of marine terraces in the tectonically rising area of the Perachora Peninsula, Greece (Fig. 1). Roberts et al. (2009) mapped a number of elevated marine terraces in this region, the lower three of which are correlated to MIS 5. The 3rd emergent terrace is dated (U-series on coral) to ~120 ka (MIS 5.5/5e) and the 1st emergent terrace is dated to ~80 ka (MIS 5.1/5a), also by U-series on coral. Roberts et al. (2009) infer that the intermediate-elevation 2nd terrace likely dates to ~100 ka (MIS 5.3/5c), an interpretation we accept here. Using shoreline angle elevations of the ~120 ka terrace, which range from ~60 m to ~75 m, and assuming a paleo-sea level of +6 m, we calculate uplift rates ranging from 0.45 m/ka to 0.575 m/ka for this part of the Perachora Peninsula. Elevations of the ~80 ka terrace range from ~8 m to ~15 m and the hypothesized ~100 ka terrace has elevations of ~21 m to ~31 m. Using the calculated uplift rates derived from the ~120 ka terrace, paleo-sea level at ~80 ka is estimated to be about −27 m to −37 m, relative to present, and paleo-sea level at ~100 ka is estimated to be about −21 m to −27 m, relative to present. These values are much closer to the far-field and intermediate-field paleo-sea level estimates from New Guinea and Barbados (considered to be dominated by a eustatic component) than they are to paleo-sea level estimates from the intermediate-to-near-field coasts in North America (where the eustatic component is overprinted by GIA effects). These data, along with modeling by Creveling et al. (2015), suggest that GIA effects may have been minimal along Mediterranean Sea coastlines, although it is recognized that there may be minor variability with the basin (e.g., Tuccimei et al., 2012).

5.3. Evaluation of the Neotyrrhenian deposit ages using paleozoogeographic data

As discussed earlier, a number of Mallorcan workers (Butzer, 1975; Cuerda, 1975, 1987, 1989; Rose, 1985; Vicens et al., 2012) have emphasized the difference in faunal composition of Neotyrrhenian vs. Eutyrrhenian marine deposits on Mallorca. The latter are characterized by a greater number of extralimital southern species from the Guinean or Senegalese faunal province. Indeed, the Neotyrrhenian faunas have often been described as "impoverished" Senegalese assemblages, lacking *S. bubonius* (= *S. latus*), but containing some warm-water indicators. As we alluded to earlier, this kind of interpretation has parallels with paleozoogeographic studies conducted elsewhere. On the California coast, the interpretation (from marine terrace faunas) of warmer waters at ~120 ka and cooler waters at ~80 ka (Muhs et al., 2002b, 2006, 2012) is consistent with paleozoogeographic interpretations of planktonic foraminifera acquired from nearby cores (Kennett, 1995; Kennett and Venz, 1995).

It is possible to make similar comparisons of sea surface temperature (SST) on Mallorca from the emergent marine molluscan record and SST records derived from deep-sea cores in the Mediterranean. The most detailed and long SST records in the western Mediterranean Sea come from Ocean Drilling Program (ODP) Hole 977, in the Alboran Sea (Fig. 1). Paleotemperature estimates from this core have been made from both planktonic foraminiferal species abundances (Pérez-Folgado et al., 2004) and alkenones (Martrat et al., 2004, 2014; see also supplementary data in Martrat et al., 2007). Alkenones give annual SST estimates, but planktonic foraminiferal data can yield seasonal estimates of SST, using transfer functions. Planktonic foraminiferal data from ODP 977 indicate that the only time period when SSTs were significantly warmer than modern SSTs was during MIS 5.5/5e, when water temperatures were above Holocene values during all seasons (Fig. 10). MIS 5.3/5c shows one season (winter) when there is a short-lived warm spike of SST at ~100 ka that is about the same as the Holocene, but all other seasons show cooler-than-Holocene paleotemperatures during MIS 5.3/5c. Paleotemperatures during MIS 5.1/5a were lower than the Holocene average for all four seasons.

The alkenone SST record from ODP 977 is similar to the planktonic foraminferal record, but exhibits some differences. The general shape of the alkenone paleotemperature curve is similar to what the annual average SST would be for that derived from the planktonic foraminiferal data. Similar to the latter, MIS 5.5/5e emerges from the alkenone record as the warmest period of the past ~150 ka (Fig. 10). Two periods during MIS 5.3/5c (~110–107 ka and ~100–94 ka) and two periods during MIS 5.1/5a (~86 ka and ~77 ka) show brief periods of SST above the Holocene average. However, none of these excursions reach the warmth of MIS 5.5/5e and those during MIS 5.1/5a appear to be of very short duration.

The combination of both planktonic and alkenone records from ODP 977 in the Alboran Sea can be usefully compared to the faunal data from the Eutyrrhenian and Neotyrrhenian molluscan record at Campo de Tiro on Mallorca. The extreme warmth of MIS 5.5/5e in the ODP 977 core shown by both records matches the large number of extralimital southern species found in the Eutyrrhenian deposits on Mallorca (Fig. 8). However, the Neotyrrhenian fauna, with four extralimital southern species (Figs. 8 and 9) and nine southward-ranging species, also indicates significantly warmer-than-present waters. Based on the planktonic foraminiferal paleozoogeographic record of ODP 977, only MIS 5.5/5e is consistent with such a molluscan record. The alkenone record of ODP 977 does show brief warmer-than present SSTs in the Alboran Sea during MIS 5.1/5a and 5.3/5c, which in principle could support an MIS 5.1/5a or MIS 5.3/5c age for the Neotyrrhenian fauna on Mallorca. However, the SST estimates during MIS 5.1/5a and 5.3/5c from ODP 977 are all below ~20 °C, except for one brief spike during MIS 5.1/5a (Fig. 10). The extralimital fauna from the Neotyrrhenian of Mallorca, however, currently live (Fig. 9) no farther north than those latitudes where modern SSTs are ~22–20 °C (*C. viverratoides* and *B. puniceous*) or 26–24 °C (*C. ermineus* and *B. plicata*). The only time period when such SSTs were approached in the alkenone record is during MIS 5.5/5e. We conclude from these observations and comparisons that the Neotyrrhenian fauna at Campo de Tiro is much more consistent with the SST estimates for MIS 5.5/5e in the ODP 977 records for both planktonic foraminifera and alkenones.

5.4. Origin of the Neotyrrhenian deposits on Mallorca as a beachrock facies of the Eutyrrhenian marine deposits

Based on U-series ages presented here, combined with previously published amino acid data and faunal data, we interpret the so-called “Neotyrrhenian” deposits on Mallorca, and perhaps elsewhere in the Mediterranean, to be of MIS 5.5/5e age, and date to the same high stand of sea as the so-called “Eutyrrhenian” deposits. However, this interpretation must be reconciled with observations of the distinct sedimentology of the two deposits. At Campo de Tiro, the Eutyrrhenian deposits occur landward of the Neotyrrhenian deposits, have a slightly higher elevation (+3 m), are not as well cemented as the Neotyrrhenian deposits, and are composed of beds that are flat-lying. The Neotyrrhenian deposits, in contrast, are of lower elevation (+2 m), are cemented into tabular slabs, and dip seaward at ~6° (Figs. 5 and 6).

We propose that the Neotyrrhenian beds at Campo de Tiro on Mallorca are a beachrock facies of the last-interglacial (MIS 5.5/5e) sedimentary complex. Beachrock is common among many tropical and subtropical coastlines (Fig. 11) where offshore carbonate production is high and/or the local bedrock is carbonate-rich (Scoffin and Stoddart, 1983; Vousdoukas et al., 2007; Mauz et al., 2015), both of which apply to Mallorca (Fornós and Ahr, 1997). The Neotyrrhenian beds at Campo de Tiro have seven of the most important characteristics of beachrock summarized by Vousdoukas et al. (2007): (1) the sediments are cemented; (2) the width and thickness are similar to those of beachrock deposits reported elsewhere; (3) the beds occur in the surf zone (or what would have been the former surf zone in the past); (4) the

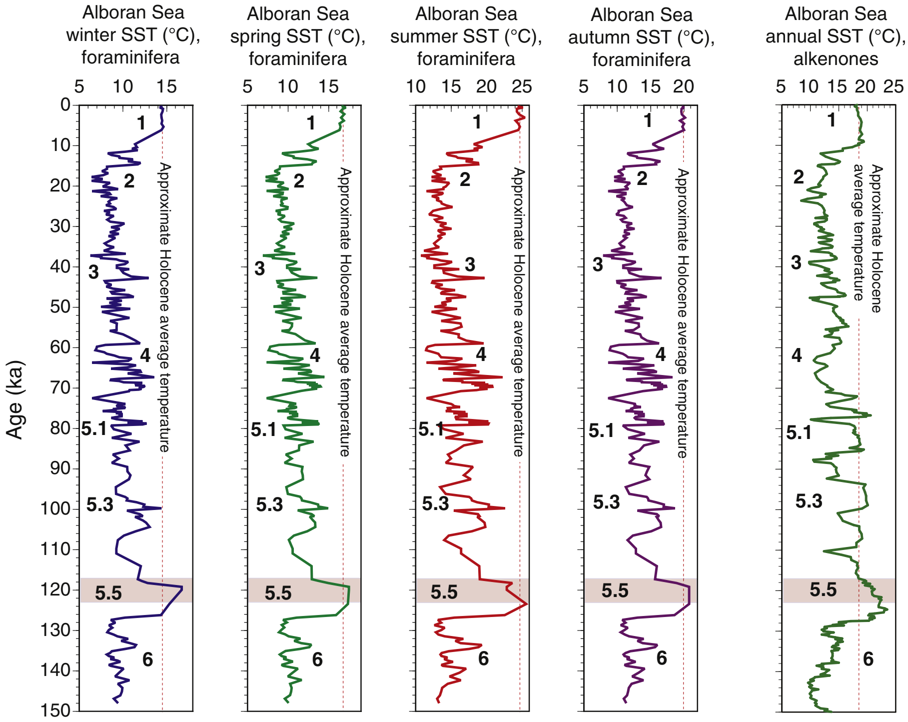
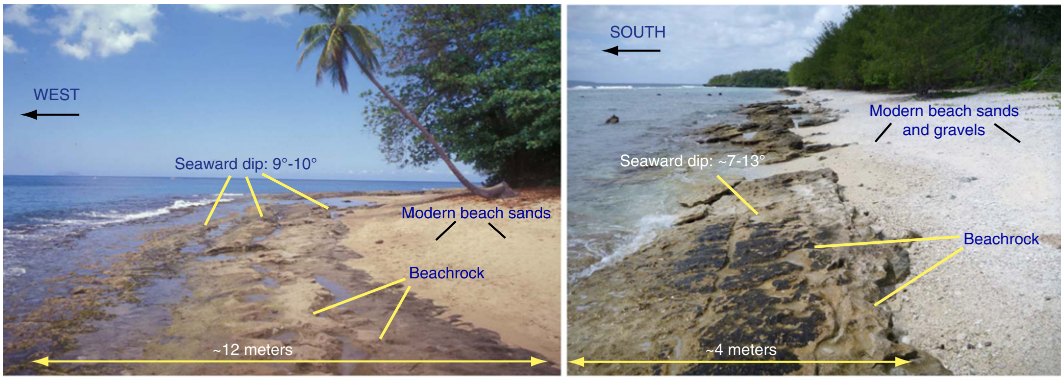
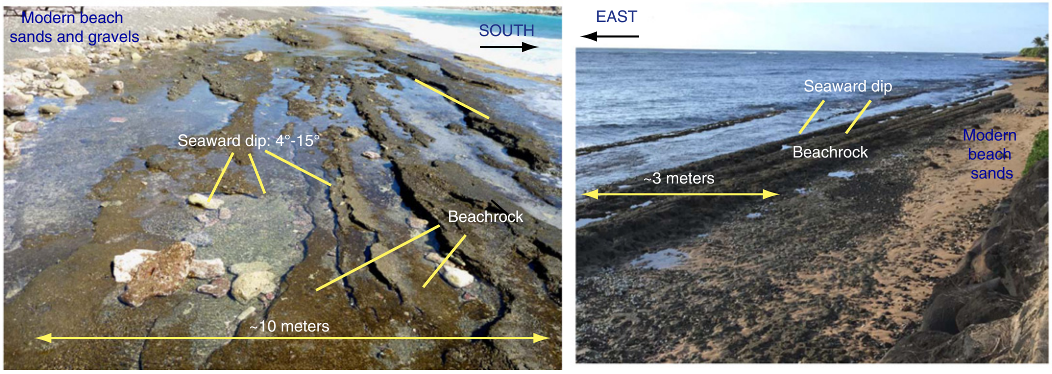


Fig. 10. Left four panels: sea surface temperatures (SST) for each season derived from planktonic foraminiferal census counts shown as a function of age in a core raised from ODP Hole 977, Alboran Sea (data from Pérez-Folgado et al., 2004). Right panel: annual sea surface temperatures in core from ODP Hole 977 derived from alkenone data (from Martrat et al., 2004). Bold numbers in all five panels are marine isotope stages (MIS); shaded area in MIS 5.5/5e shows range of U-series ages of corals from Neotyrrhenian deposits at Campo de Tiro, Mallorca (this study; Table 1).


(a) Punta Ensenada, Puerto Rico

(b) Opyan Beach, Saipan, Northern Mariana Islands


(c) Windmill Beach, near Guantanamo Bay, Cuba

(d) East coast of Kauai, Hawaiian Islands

Fig. 11. Photographs of beachrock and modern beach sediments at: (a) Punta Ensenada near Rincón, Puerto Rico; (b) Opyan Beach, Saipan, Commonwealth of the Northern Mariana Islands; (c) Windmill Beach, just east of Guantanamo Bay, Cuba; and (d) on the eastern side of the island of Kauai, Hawaii; compare to Figs. 5(a) and 5(c). All photographs by D.R. Muhs.

sediments show sequences of bands and/or laminations; (5) the beds dip seaward at a gentle but measurable angle (compare to Fig. 1 of Vousdoukas et al., 2007); (6) the sedimentary particles are diverse, reflecting the nature of the ambient material; and (7) thin sections of the cemented Neotyrrhenian sediment show calcitic, isopachous rim cement surrounding detrital, sand-sized grains (Fig. 12; compare to Fig. 5 of Vousdoukas et al., 2007). Interpretation of the Neotyrrhenian beds at Campo de Tiro as beachrock explains the "impoverished" warm fauna that has figured so largely in the Mallorcan literature. Beachrock in many environments contains a number of the same taxa that might be found in the adjacent, unconsolidated beach sediments, but need not contain *exactly* the same species. The faunal composition in beachrock will be a function of what taxa were available locally at the time of particle cementation.

We have personally observed modern or fossil occurrences of beachrock in California, Hawaii, Saipan, Israel, Egypt, Puerto Rico, Cuba, Barbados, and the Canary Islands. The Neotyrrhenian beds at Campo de Tiro, in association with the Eutyrrhenian beds, are very similar to the beachrock and modern beach facies that we have observed at all these localities. Good examples can be illustrated by beachrock we have observed at Punta Ensenada near Rincón, Puerto Rico, on the southern end of the island of Saipan, just east of Guantanamo Bay, Cuba, and on the eastern side of the island of Kauai, Hawaii (Fig. 11). At all these localities, beachrock beds are found at or near the surf zone, seaward of the modern beach sands. In contrast to the landward, unconsolidated, beach sands, the beachrock deposits are tabular, layered beds, cemented, and have seaward dips. The geomorphology and sedimentology of the modern beach and beachrock at all four of these localities is very similar in appearance to those of the Eutyrrhenian and Neotyrrhenian beds on Mallorca (compare Figs. 5 and 11). Thus, the Eutyrrhenian and Neotyrrhenian beds on Mallorca can be considered as different facies of the same age of deposit and do not represent separate high stands of sea. This explanation reconciles: (1) the similar, but slightly different elevations; (2) the similar, but slightly different faunas; (3) the similar amino acid ratios in mollusks; and (4) the similar U-series ages on coral.

6. Conclusions

Based on our studies on Mallorca, we conclude the following:

(1) Stratigraphic observations indicate that both "Eutyrrhenian" (3 m above sea level) and "Neotyrrhenian" (2 m above sea level) beds at Campo de Tiro are underlain by the same paleosol, in turn developed on aeolianite of probable penultimate glacial (MIS 6) age. Eutyrrhenian beds are weakly cemented and flat, whereas Neotyrrhenian beds are well cemented and dip seaward.

(2) Seven corals from the Neotyrrhenian beds yield U-series ages ranging from ~126 ka to ~118 ka; some show little or no age bias as determined by calculated initial $^{234}U/^{238}U$ values and have ages of ~123 ka to ~120 ka. Other corals are only slightly biased, and even with corrections for open-system behavior, their ages range from ~119 ka to ~112 ka, similar to MIS 5.5/5e corals from other localities. These ages are consistent with published amino acid data that show that the Neotyrrhenian and Eutyrrhenian deposits are not significantly different in age

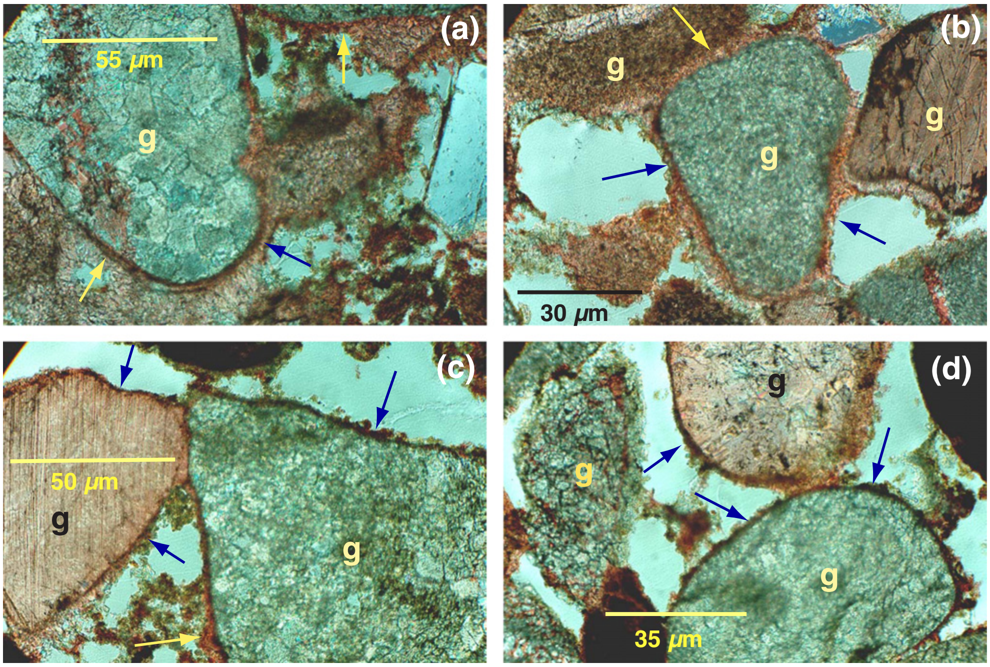


Fig. 12. Photomicrographs (plain light) of beachrock from Neotyrrhenian deposits near Campo de Tiro, Mallorca (same location as in Fig. 5c). Arrows point to calcitic, isopachous rim cement surrounding sand-sized detrital grains (g). Samples have been stained so that calcite shows as pink or red.

and the latter were previously dated to an MIS 5.5/5e age by U-series on coral. On the basis of geochronological data, therefore, both the Neotyrrhenian and Eutyrrhenian deposits likely date to the peak of the last interglacial period, MIS 5.5/5e.

(3) Examination of published fossil molluscan data from the Neotyrrhenian deposits on Mallorca show that they contain no extralimital northern species and only one northward-ranging species, but they do contain nine southward-ranging species and four extralimital southern species. Although there are fewer warm-water taxa in the Neotyrrhenian beds than are found in Eutyrrhenian deposits on Mallorca, the paleontology still indicates warmer-than-present waters when the Neotyrrhenian beds were deposited. When compared with sea surface temperatures obtained from planktonic foraminifera and alkenones from ODP core 977 in the nearby Alboran Sea, the only time period that shows comparable warmth is MIS 5.5/5e, consistent with U-series ages of corals from the Neotyrrhenian deposits.

(4) Glacial isostatic adjustment processes cannot explain the similar elevations of the Neotyrrhenian and Eutyrrhenian deposits on Mallorca if these sediments were laid down during separate high stands of sea. The elevations of the Neotyrrhenian deposits (+2 m) and Eutyrrhenian deposits (+3 m) are too close to be explained by separate high stands of sea, such as an ~80 ka (MIS 5.1/5a) or ~100 ka (MIS 5.3/5c) age for the Neotyrrhenian beds and an ~120 ka age for the Eutyrrhenian beds, proposed by earlier workers. Paleo-sea levels at these times estimated from elevations of dated marine terraces from tectonically rising coasts found elsewhere in the Mediterranean (Perachora Peninsula, Greece) do not agree with the altitudinal spacing of Neotyrrhenian and Eutyrrhenian deposits on Mallorca if the former were ~80 or ~100 ka and the latter were ~120 ka.

(5) We propose that the Neotyrrhenian deposits on Mallorca, and perhaps elsewhere in the Mediterranean, are a beachrock facies of the same age as deposits that have been called Eutyrrhenian sediments. The physical characteristics of the Neotyrrhenian beds at Campo de Tiro on Mallorca are very similar to those for beachrock that has been described elsewhere, such as examples we provide from Puerto Rico, Saipan, Cuba, and Hawaii. A beachrock interpretation of the sediments is consistent with the U-series and amino acid data, explains the similar (but not identical) elevations of the Neotyrrhenian and Eutyrrhenian beds, and is consistent with the similar (but not identical) paleozoogeographic aspects of their fossil faunas.

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