2015

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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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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; Martenson 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 “Tyrrenian.” 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 Tyrrenian, 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...
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 (Bardaji 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 \(234U/238U\) 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 \(234U/238U\) values indistinguishable from seawater. Thus, coral ages can be evaluated not only for bulk U loss or gain but \(234U/238U\) values serve as a secondary geochronometer when compared to \(230Th/234U\) 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; and 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. 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, 1973, 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
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 Raddke, 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
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,
resolutions 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) de-
scribe the bedrock geology of Mallorca in detail, so their work is summa-
rized 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 (Sierra de Tramuntana or Sierra
Norte and Serres de Llevant or Sierra de Levante) are horst blocks com-
posed 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 allu-
vial, colluvial, aeolian, and marine origin (Butzer and Cuerda, 1962;
Butzer, 1975; Cuerda, 1975, 1989; Rose, 1985; Cuerda and Sacarés,
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 238U and its long-lived daughter products, 234U and 230Th,
after death and emergence. On Mallorca, the corals collected from
Campo de Tiro have been identified by Cuerda (1989) as Cladocora
caspiotis Linné. C. caspiotis 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. caspiotis from eastern mainland Spain and Mallorca
have U contents of 2.5–3.3 ppm and 234U/238U values of 1.142 to 1.154
(Goy et al., 2006), in good agreement with the range of seawater values
for 234U/238U reported from the Mediterranean Sea and other ocean
basins (Delanghe et al., 2002).

Nine specimens of the coral C. caspiotis 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 dis-
solved in HNO3, spiked with 229Th, 233U, and 236U and purified with ion
exchange methods. Purified U and Th were loaded with colloidal graphi-
te on separate Re filaments and isotopic abundances were determined
by thermal ionization mass spectrometry (TIMS). The U–Th spike is cal-
bilated 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 234U/238U and 230Th/238U (Ludwig
and Paces, 2002). In addition, an in-house, carefully homogenized, ara-
gonitic 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
230Th and a half-life of 245,620 years for 234U (Cheng et al., 2013).

The best criterion for determining closed-system conditions during
the post-emergence history of a fossil is concordance between
230Th,234U and 231Pa/235U ages (Edwards et al., 1997, 2003). We did not
determine 231Pa/235U ages for our samples. However, a second
criterion for closed-system history is whether the back-calculated initial
234U/238U value, based on its present measured value and the 230Th/234U
age, is within the range of modern seawater. Edwards et al. (1997) show
that corals with initial 234U/238U activity values as high as 1.16 showed
concordance between 230Th and 231Pa/235U ages. This study, we
consider as “reliable” any corals with initial 234U/238U 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 Sacarés (1992). Most of the marine invertebrate taxa of the Pleisto-
cene faunas of Mallorca are composed of extant species. In making
paleozoogeographic interpretations of these taxa, we used modern spec-
ies ranges from the latest available sources, including Nicklès (1950),
Kensley and Penrhyn (1973), Radwin and D’Attillio (1976), Cuerda
Rolán and Rayal (1999), Ardovini and Cossignani (2004), Riusmore-
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 Bahía
de Palma, between Cala Gamba and Cala Estancia (Fig. 4). In this area,
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), fissiliferous beds of reddish-brown marine sand and rare gravel, ~50–70 cm thick, capped by a thin calcrite, 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” by 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 fissiliferous, and an upper layer, 50 cm thick, of sandy gravels that are highly fissiliferous. 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](image-url)
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 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 through 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.

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.

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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 through 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.
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) marine deposits 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 extra-limital 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, implied to be Eutyrrhenian deposits on Mallorca is the presence of extra-limital northern species (implying cooler-than-present waters during this earlier sea stand) whereas younger (~80 ka) deposits have a number of extra-limital northern species (implying cooler-than-present waters during 1975; Cuerda, 1975, 1987, 1989). This fossil assemblage consists of a number of taxa whose present ranges are well to the south of Mallorca, implied to be Eutyrrhenian deposits on Mallorca is the presence of extra-limital northern species (implying cooler-than-present waters during this earlier sea stand) whereas younger (~80 ka) deposits have a number of extra-limital northern species (implying cooler-than-present waters during...
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., 2008; 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 Sacarelles (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 = 6), 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 Eutyrrhenian 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 234U/238U 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 234U/238U 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 234U/238U 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 234U/238U 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.
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 Eutyrrhenian (at Son Grauet and Campo de Tiro) and Neotyrhenian (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 Neotyrhenian deposits at Campo de Tiro. The uppermost, fossil-rich Neotyrhenian 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 on the California coast 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 paleo zoogeographic 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 paleo zoogeographic 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 paleo zoogeographic 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 foraminernal 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 foraminernal 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 extralimatal 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 foraminernal 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 extralimatal fauna from the Neotyrrhenian deposits of Mallorca, however, currently live (Fig. 9) no farther north than those latitudes where modern SSTs are ~22–20 °C (C. viveratoides 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; Voudoukas 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 Voudoukas 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...
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.

Acknowledgements

Work by U.S. Geological Survey authors was supported by the Climate and Land Use Change Research and Development Program of the U.S. Geological Survey and is a contribution to the “Geologic Records of High Sea Levels” Project. Special thanks go to Gary Skipp (USGS), who X-rayed all the corals in this study. We thank Robert Halley (USGS, retired) for very helpful discussions. Our sincere appreciation is extended to Dr. Belen Martrat for advice on which ODP core records to examine and to Dr. Francisco Sierra for providing the planktonic foraminiferal-derived SST data from ODP core 977. Dr. William G. Thompson (Woods Hole) kindly provided his U-series open-system correction system software and guided us in its use, for which we express our thanks. Drs. Margaret Berry and Keith Lucey (both U.S. Geological Survey), Jim Rose (Royal Holloway, University of London), two anonymous reviewers, and editor Thierry Corrège provided helpful comments on an earlier version of the paper.

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