

# New age constraints on the western Betic intramontane basins: A late Tortonian closure of the Guadalhorce Corridor?

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## Abstract

Several gateways connected the Mediterranean with the Atlantic during the late Miocene but the timing of closure and therefore their role prior to and during the Messinian Salinity Crisis (5.97–5.33 Ma) is still under debate. The timing of closure of the Guadalhorce Corridor is especially disputed as the common lack of marine microfossils hampers precise age determination. Here we present new biostratigraphic age constraints on the sediments of the Ronda, Antequera and Arcos regions, which formed the northern part of the Guadalhorce Corridor. The general presence of *Globorotalia menardii* 4 in the youngest deep-marine sediments of all three regions indicates a late Tortonian age, older than 7.51 Ma. We conclude that the Guadalhorce Corridor closed during the late Tortonian, well before the onset of the Messinian Salinity Crisis and that the late Tortonian tectonic uplift of the eastern Betics extended into the western Betics.

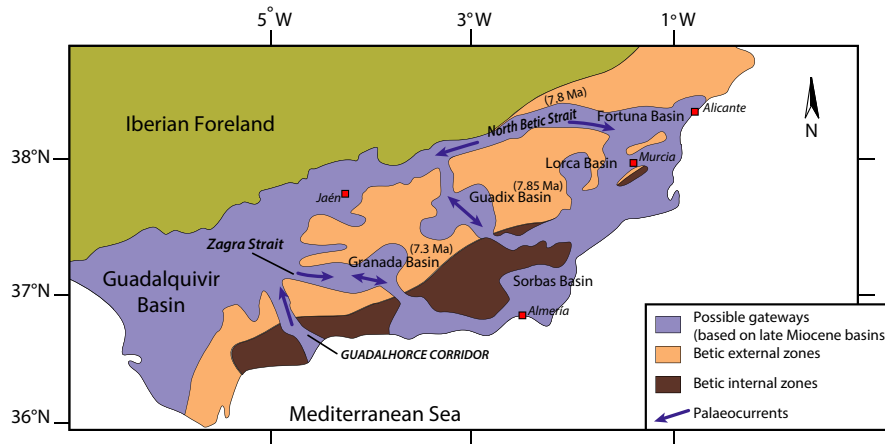
## 1 | INTRODUCTION

The Betic Corridor (Figure 1) was one of the late Miocene Mediterranean–Atlantic gateways (Flecker et al., 2015). Restriction of these gateways led to the Mediterranean Messinian Salinity Crisis (MSC; 5.97–5.33 Ma; Roveri et al., 2014). The Guadalhorce Corridor is regarded as the last remaining Betic gateway during the early Messinian (Martín, Braga, & Betzler, 2001; Pérez-Asensio, Aguirre, Schmiedl, & Civis, 2012), because the other strands of the Betic Corridor are generally assumed to have closed in the Tortonian (Betzler, Braga, Martín, Sánchez-Almazo, & Lindhorst, 2006; Hüsing et al., 2010; Krijgsman et al., 2000; Martín, Puga-Bernabéu, Aguirre, & Braga, 2014) and its dimensions could have sustained an enhanced Mediterranean salinity (e.g. Simon & Meijer, 2015). Due to uncertainties on the dating and evolution of the Guadalhorce Corridor, its role and progression throughout the late Miocene remain unclear and with it the role of the entire Betic Corridor.

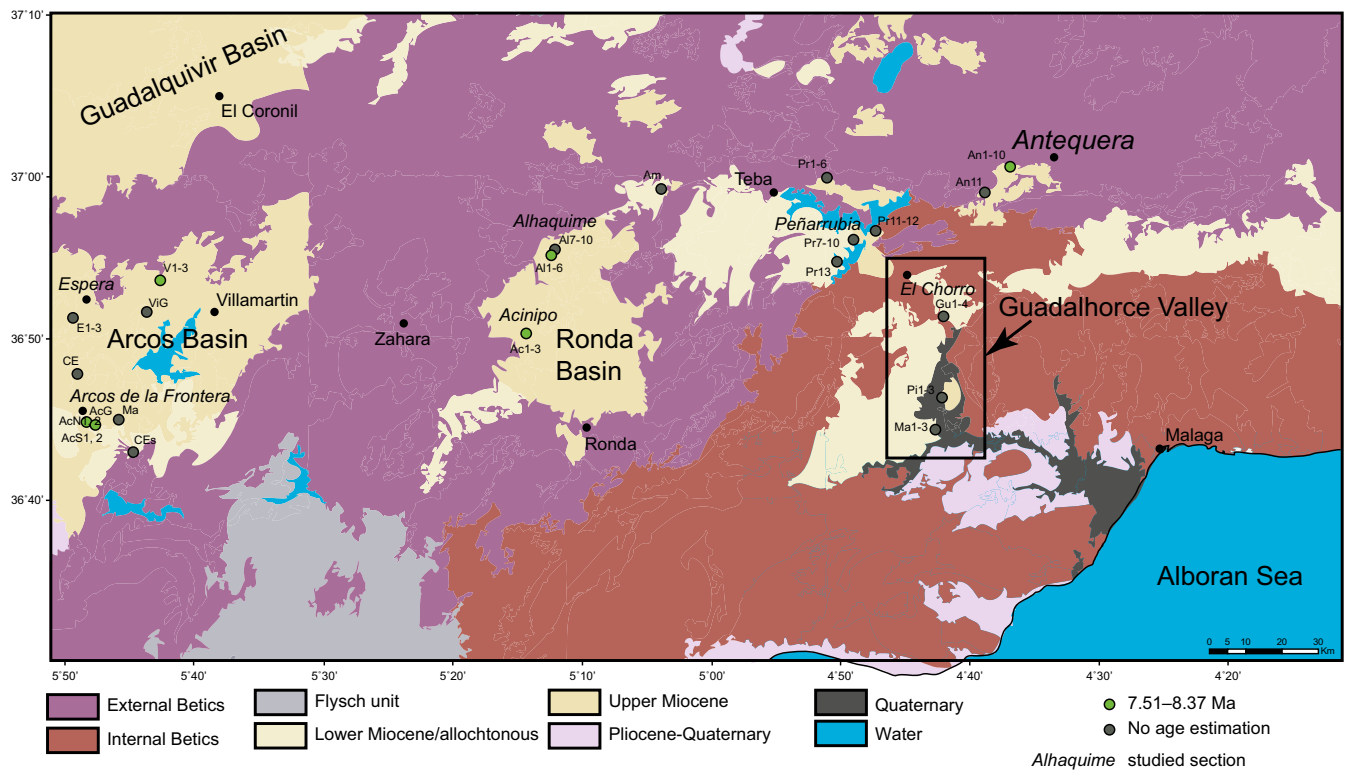
Palaeogeographic reconstructions of the Guadalhorce Corridor are based on the study of the sedimentary infill of the Guadalhorce

Valley (Figure 2). However, difficulties in assessing the timing and evolution of the Guadalhorce Corridor are caused by the absence of adequate sedimentary successions, impeding precise dating through integrated bio-, magneto- and cyclostratigraphy. Dating of these sediments relies exclusively on possible but uncertain lithostratigraphic correlations to adjacent marly deposits of the Antequera and Peñarubia exposures (López-Garrido & Sanz de Galdeano, 1999; Martín et al., 2001; Serrano Lozano, 1979). The Ronda and Arcos de la Frontera depocentres (Figure 2) are intramontane basins that were likely relicts of the same connection through the western Betics and could assist in resolving this issue.

To complicate matters, these intramontane basins lack studies correlating them to the high-resolution astrobiochronologic frameworks for the late Miocene Mediterranean Basin and nearby Atlantic margins (Hilgen, Lourens, & Van Dam, 2012; Hilgen et al., 1995; Krijgsman et al., 2004; Sierro, 1985; Sierro, Flores, Civis, González Delgado, & Francés, 1993; Sierro, González Delgado, Dabio, Flores, & Civis, 1996; Sierro, Ledesma, Flores, Torrescusa, & Olmo, 2000; Zachariasse, 1975). The aims of this paper were to reassess and



**FIGURE 1** Overview map of the Betic Corridor showing the main geological units and the different branches including their closure dates (Modified after Santisteban & Taberner, 1983) [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 2** Detailed geological map of the southwestern Betics, focused on the late Miocene basins, studied sections, sample locations and codes. Locations in *italics* are sampling locations [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

improve the chronostratigraphy of sediments in the Guadalhorce Valley and connecting intramontane basins (Figure 2) based on modern biostratigraphic schemes and to use the results to reassess the evolution of the Guadalhorce Corridor.

## 2 | METHODS

We revisited the Guadalhorce Valley, the adjacent Ronda and Arcos basins and the Antequera region to sample and study the outcrops and sections in areas marked as ‘Tortonian’, ‘Messinian’ or ‘Andalusian’ on the geological map (Cano Medina, 1982; Jerez Mir, 1983; Martín-Serrano García, 1982). Samples were taken from different

localities and combined into composite sections for each basin (Figure 2).

The youngest sediments in the basins were targeted for qualitative biostratigraphic analyses. A total of 54 samples from sandy to silty marls were analysed. If possible, these were taken at finer grained intervals to increase the probability of finding microfossils. Samples of about 100 g were disintegrated in water and washed over a >150 µm sieve. The presence of the following biomarkers from the astronomically tuned Neogene time-scale (Hilgen et al., 2012) was qualitatively analysed: *Globorotalia margaritae*, *Globorotalia miotumida*, *Neogloboquadrina acostaensis*, *Globorotalia menardii* 4 and 5, *Globorotalia scitula* with corresponding coiling directions and *Globigerinoides extremus* (Table 1 and references within).

### 3 | RESULTS

#### 3.1 | Guadalhorce

The upper Miocene succession in the Guadalhorce Valley starts near the village of El Chorro (Figure 2) with coarse to very coarse grey sands and conglomerates with large-scale erosional features (Figure 3). Lobes of grain-supported, boulder-bearing and more angular conglomerates are found within polymict, matrix-supported conglomerates alternating with sands (Martín et al., 2001). These attest to debris flows from the basin margins. Within the lower part of the succession some cm- to dm-scale rip-up clasts are found (Figure 4a). Towards the top of the section, coarse sandstones show large-scale cross-bedding with predominant northwestward direction (Martín et al., 2001). We sampled up to 50 cm thick rip-up clasts in the Guadalhorce Valley (Figure 4a) and the marlstones of the contiguous Peñarubia exposures (Figure 2). Despite taking 23 samples, no planktic foraminiferal markers were found; this is probably due to the coarse-grained and shallow-environmental character of the deposits within this region.

#### 3.2 | Ronda

In the Ronda Basin, the uppermost sequences of the late Miocene infilling were studied (Figure 4b). The Alhaquime section starts with

**TABLE 1** Late Miocene biostratigraphic foraminiferal events in the Mediterranean Basin and nearby Atlantic margins with corresponding ages and applicable references (Modified from Tulbure et al., 2017)

Planktic foraminiferal events	Age (Ma)	References
Sinistral to dextral coiling change of the <i>N. acostaensis</i> group	6.35	Sierro et al. 1993, 2001; Hilgen & Krijgsman, 1999; Lourens et al., 2004
Replacement <i>G. menardii</i> group by <i>G. miotumida</i> group	7.25	Sierro, 1985; Sierro et al., 1993
First common occurrence of <i>G. menardii</i> 5	7.35	Sierro, 1985; Sierro et al., 1993; Hilgen et al., 2000; Lourens et al., 2004
Last common occurrence of <i>G. menardii</i> 4	7.51	Sierro, 1985; Sierro et al., 1993; Hilgen et al., 2000; Lourens et al., 2004
Onset dominant sinistral <i>N. acostaensis</i>	7.92–8	Krijgsman et al., 1995; Hilgen et al., 1995
First occurrence <i>G. extremus</i>	8.37	Sprovieri et al., 1999
Highest regular occurrence of dextral <i>N. acostaensis</i>	9.51	Krijgsman et al., 1995; Hilgen et al., 1995; Lourens et al., 2004
First regular occurrence of <i>N. acostaensis</i>	10.57	Hilgen et al., 2000; Lourens et al., 2004

the La Mina Fm: 10–20 m thick grey marls with small (1–2 m) calcarenite intervals (Figure 3; Rodríguez Fernández, 1982; Serrano Lozano, 1979), which become dominant up section, where the marls form lenses within 10 m thick calcarenitic units (Figure 4c). Above we find increasingly thicker (up to 20 m) deposits of sandy bryozoan calcarenites and brown-to-yellow siliciclastic sandstones intercalated with marls, all belonging to the Setenil Fm (Rodríguez Fernández, 1982; Serrano Lozano, 1979). In these sandy intervals, both tabular cross-bedding and trough cross-bedding were observed (Figure 4d). Biostratigraphic samples were taken from the marls between the calcarenitic alternations.

The Acinipo section contains marls of the La Mina Fm that are overlain locally by a ~20–30 m thick rhodalgal carbonate unit known as the Las Mesas Fm (Figure 3; Rodríguez Fernández, 1982; Serrano Lozano, 1979). Biostratigraphic samples were taken from the marls just below the carbonate unit.

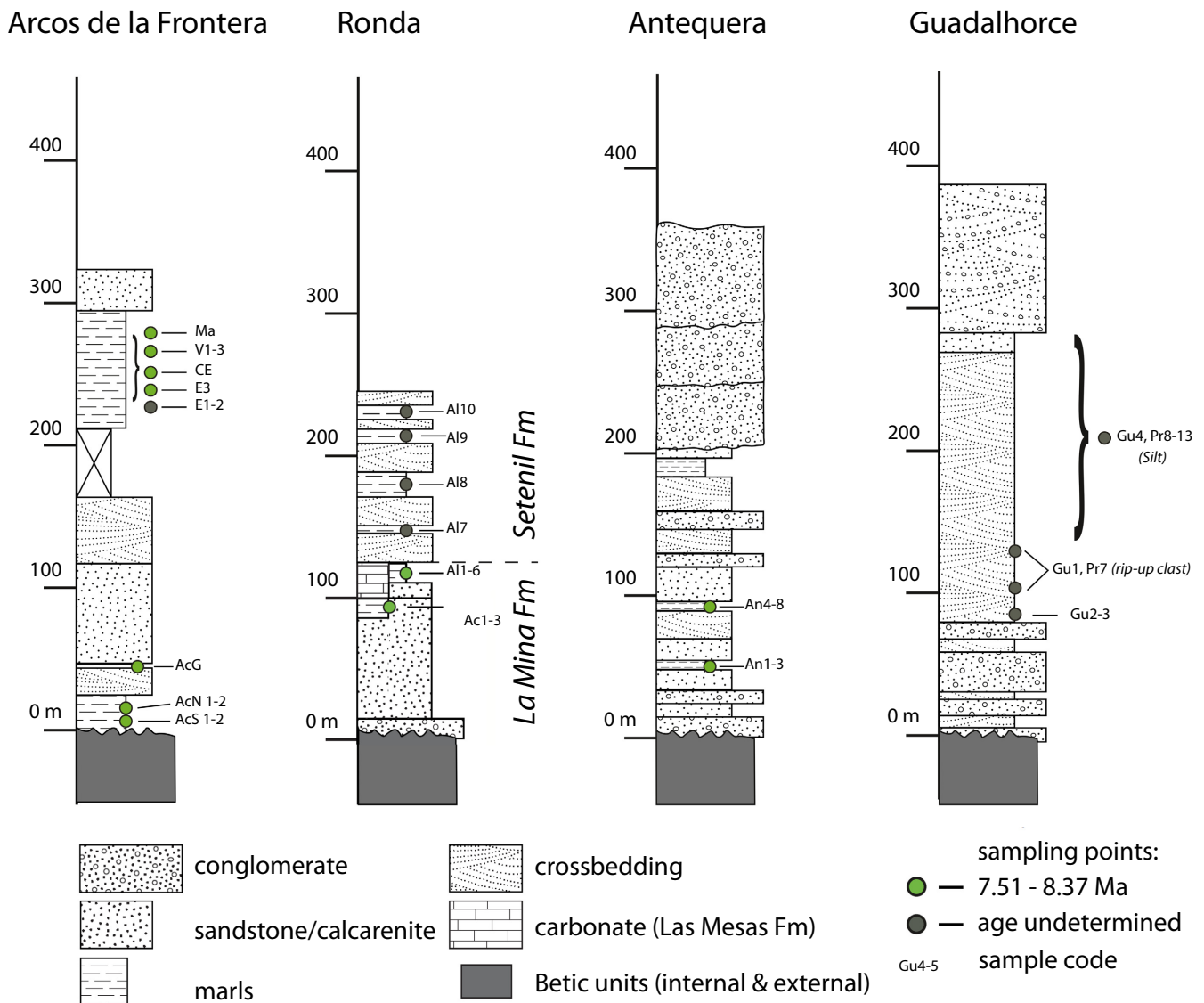
Only the marls in the La Mina Fm and bottom of the Setenil Fm contain planktic foraminiferal biomarkers: *G. menardii* 4 sinistral, *G. scitula*, *G. extremus* and *N. acostaensis* mainly sinistral (Figure 5). The sandy calcarenitic samples contain mainly benthic foraminifera. Although specimens with a morphology intermediate between *G. menardii* 4 and *G. miotumida* can be found in the Ronda Basin, the former morphotype is always dominant.

#### 3.3 | Antequera

The lowest part of the Antequera sequence consists of grey, silty to very sandy marls, which are subsequently replaced by sandy calcarenites and conglomerates (Figure 3). The marls contain microfossils, while the calcarenites show large bryozoans, ostracods, benthic foraminifera and shell fragments. The samples taken in the marls contain *G. menardii* 4 sinistral, *G. scitula*, very rare *G. extremus* and *N. acostaensis* mainly sinistral.

#### 3.4 | Arcos de la Frontera

In the Arcos area, we sampled the uppermost marine lithostratigraphic units, which were assigned to the Tortonian, Messinian and Pliocene on the geological map (Jerez Mir, 1983). We sampled the grey marls (outcropping under the village of Arcos de la Frontera), which merge upwards into a 100–150 m thick sandy calcarenite unit (Figures 2 and 4e). The calcarenites are rich in bioclastic content, bryozoans and shell fragments. Furthermore, the calcarenite unit shows inverse faults, which are capped by horizontal surfaces (Figure 3e). Additional samples were taken in units placed stratigraphically above the calcarenites: grey–green sandy marls which outcrop in other parts of the basin (i.e. close to Espera; Figure 2) and correspond to the Messinian unit of Jerez Mir (1983). All these marls contain *G. menardii* 4 sinistral, *G. scitula* and *N. acostaensis* mainly sinistral. Rare specimens of *G. extremus* are observed. The clayey marls assigned to the Pliocene (Jerez Mir, 1983) were also sampled but are barren of foraminifera.



**FIGURE 3** Composite logs of the studied sections with, if known, the sample stratigraphic positions. Exact positions of the Peñarrubia samples are unclear. Formation names in the Ronda sections are shown (Rodríguez Fernández, 1982; Serrano Lozano, 1979). Note the predominantly coarse sediments hamper reliable dating of large parts of the sections [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

#### 4 | BIOSTRATIGRAPHIC DATING AND AGE CONSTRAINTS

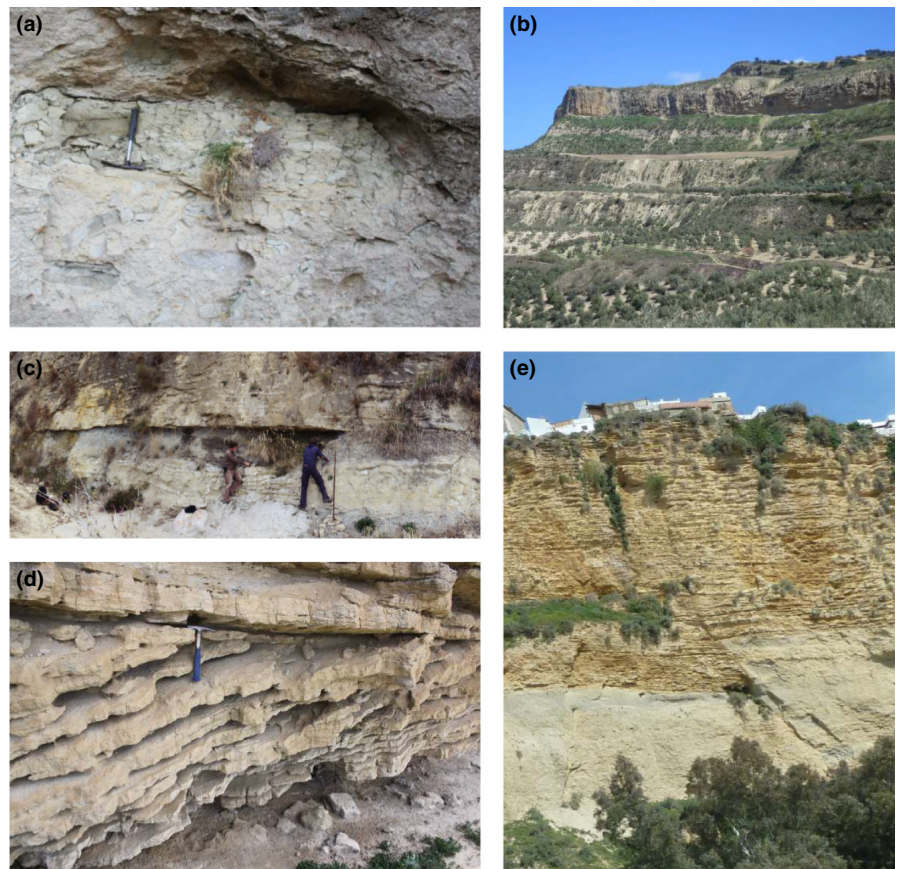
When present, the foraminifers are generally well-preserved, suggesting minor influence of reworked sediments and inner shelf depths. In many samples, however, microfauna is scarce, absent or without any marker species (grey sampling points in Figures 2 and 3). The matrix of these samples generally consists of (rounded) quartz grains, silts, (secondary) gypsum, bioclastic fragments, (reworked) glauconite, detrital wood and/or shell fragments. These types of coarse-grained sediment severely limit the possibilities for reliable dating, since silty to sandy sediments are more often deposited in shallow and high-energy environments where the targeted species do not dwell.

All samples that contain marker species consist of (sandy/silty) marls. In these samples, the same planktic biomarkers, i.e. *G. menardii*

4 sinistral, *G. scitula*, *G. extremus* and *N. acostaensis* mainly sinistral, were found. This indicates an age older than the last common occurrence of *G. menardii* 4, dated at 7.51 Ma, and younger than the first common occurrence of *G. extremus*, dated at 8.37 Ma (Table 1; Lourens et al., 2004). Additionally, the occurrence of *N. acostaensis* mainly sinistral suggests an age younger than 7.92–8 Ma (Table 1 and references within). Consequently, all sediments that allowed age determination are assigned a late Tortonian age (7.51–8.37 Ma).

The dated marine marls are subsequently replaced by calcarenites or carbonates in the Arcos and Ronda basins and Antequera region. Since there is no available method to reliably date these calcarenites or carbonates, we cannot assess the exact time at which the observed marine sedimentation terminates. However, coarse-grained deposits typically have high sedimentation rates, suggesting that the calcarenites were also deposited during the late Tortonian. For the deposits in the Guadalhorce Valley, we agree with López-





**FIGURE 4** (a) Example of a rip-up clast in the El Chorro section (Guadalhorce Valley). (b) Overview of the Alhaquime section (Ronda Basin). (c) Marl lenses in thick calcarenite deposits at the Alhaquime section (Ronda Basin). (d) Tabular cross-bedding in Sequence 3 of the Alhaquime section (Ronda Basin). (e) Overview of calcarenite deposits showing synsedimentary inverse faults at the Arcos section [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Garrido and Sanz de Galdeano (1999) that, based on the similarities in lithology, these should be associated with the coarse-grained calcarenitic deposits in nearby regions like Ronda and Antequera (Figure 4). Therefore, these sediments were probably also deposited in the late Tortonian.

This late Tortonian age assigned to all studied marine sediments is in contrast with previous studies (Gläser & Betzler, 2002; Martín et al., 2001; Serrano Lozano, 1979), which claim that at least the upper part of the deep-marine infilling is Messinian in age. Gläser and Betzler (2002), however, rely on the work of Serrano Lozano (1979) who assigned a Tortonian–Messinian age to the deposits of the Ronda Basin with a biostratigraphic framework that is not connected to current high-resolution astrobiochronologic frameworks for the late Miocene Mediterranean Basin and nearby Atlantic margins (Hilgen et al., 2012). Martín et al. (2001) based their Messinian age determination for the Guadalhorce Corridor on the occurrence of *Globorotalia* gr. *miotumida*, *G. conomiozea* and sinistral *N. acostans* in the Peñarrubia exposure. Many biostratigraphic studies performed in late Miocene basins from the Mediterranean and eastern Atlantic used *G. conomiozea* and *G. miotumida* as marker species of the Messinian, but these species also occurred in the Tortonian (Krijgsman et al., 2000; Sierro et al., 1993) where they coexisted with *G. menardii* 4 and 5, although they only became continuously dominant in the Messinian when they replaced *G. menardii* 5 (Sierro, 1985; Sierro et al., 1993). Despite extensive research and sampling in this area, we were not able to find assemblages with planktic

foraminiferal marker species indicating a latest Tortonian (<7.51 Ma) to early Messinian age.

## 5 | DISCUSSION AND CONCLUSION

### 5.1 | Basin evolution—Late Tortonian uplift of the (western) Betics

The general presence of *G. menardii* 4 in the youngest dated marine sediments of all studied regions suggests that the Guadalhorce Corridor closed during the late Tortonian, well before the onset of the MSC. The precise time of closure remains uncertain since it is impossible to assess how much marine sediment was deposited and subsequently eroded on top of the studied late Tortonian sequences. However, since no remains of latest Tortonian (<7.51 Ma) or Messinian sedimentation were found in the entire studied region, we consider it most likely that marine sedimentation ceased before the end of the Tortonian. This is roughly coherent with indirect evidence from Guadalquivir Basin subsurface sediments that suggested a significant restriction or even closure of the Betic Corridor occurring at 7.16 Ma (Van den Berg et al., 2018). However, it does not support a much later age of closure at 6.18 Ma of the same connection (Pérez-Asensio et al., 2012).

A general change is observed from off-shore marine marls containing ample amounts of benthic and planktic foraminifers, towards coarse-grained, shallow-marine calcarenites with mollusc fragments



**FIGURE 5** Photographs of specimens of used planktic biomarkers from the Alhaquime section. 1–7: *Globorotalia menardii* 4 on the ventral view (1, 4 and 6), dorsal view (2 and 3) and lateral view (5 and 7). 8–10: *Globorotalia scitula* on the dorsal view (8), ventral view (9) and lateral view (10). 11–12: *Neogloboquadrina acostaensis* sinistral on the umbilical view (11) and spiral view (12). 12–16: *Globigerinoides extremus* on the umbilical view (13 and 15) and spiral view (14 and 16). Scale bar: 100  $\mu\text{m}$  [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

and algae, barren of foraminifers or with benthic foraminifers only. This change suggests a shallowing-upward trend, superposed to possible smaller scale sea-level fluctuations (e.g. Gläser & Betzler, 2002). Tectonic studies in the Ronda Basin showed that the presence of syndepositional shortening structures point towards transpressive tectonics resulting in basin uplift and isolation (Jiménez-Bonilla, Expósito, Balanyá, & Barcos, 2015). Our age refinement of the Ronda Basin suggests that this tectonic phase and uplift had already started in the late Tortonian. Similar late Tortonian indications of shortening and basin uplift are found near Arcos de la Frontera (Figure 4e), where syndepositional inverse faults affect the calcarenite units. These findings are supported by seismic reconstructions of the western Alboran region pointing towards a major regional transpressive phase starting in the Tortonian (Do Couto et al., 2016) and concurrent uplift of the intramontane basins within the Gibraltar Arc (Capella, Matenco, et al., 2017; Iribarren, Vergés, & Fernández, 2009).

Other Betic gateways (e.g. Zagra, Dehesa de Guadix, North Betic straits; Figure 1) are also inferred to have shallowed and closed during the late Tortonian due to tectonic uplift (Betzler et al., 2006; Corbí et al., 2012; Hüsing et al., 2010; Krijgsman et al., 2000; Martín, Braga, Aguirre, & Puga-Bernabéu, 2009; Martín et al., 2014;

Meijninger & Vissers, 2007). This resulted in the deposition of Tortonian evaporites in the Granada, Lorca and Fortuna basins (Figure 1; Cambeses & Scarrow, 2013; García-Veigas et al., 2013; Krijgsman et al., 2006). Therefore, we conclude that coeval tectonic uplift and shallowing-upward trends occurred across the entire Betic region, effectively restricting and closing all the branches of the Betic Corridor in the late Tortonian. Consequently, this requires the persistence of another existing Mediterranean–Atlantic gateway in the Gibraltar area during the Messinian to justify the sedimentary record of the MSC (e.g. Flecker et al., 2015; Manzi et al., 2013).

## 5.2 | Connectivity trends: Late Tortonian Mediterranean Outflow

The Guadalhorce and Rifian Corridors were the last known open gateways before the MSC (Martín et al., 2001). Our results imply that the Mediterranean Outflow (MO) through the Guadalhorce Corridor (Martín et al., 2001) occurred in the late Tortonian. Coeval MO is recorded in the Rifian Corridor (Capella, Hernández-Molina, et al., 2017). Models show that the relative gateway depths of the two straits determine whether they both have two-way exchange, or in- and outflow only (De la Vara, Topper, Meijer, & Kouwenhoven,

2015). Since both gateways show indications of similar depth (100–300 m; Capella et al., 2018; Martín et al., 2001), a two-layer exchange regime in both gateways is the most likely possibility. This suggests a vigorous saline input into the North Atlantic at that time, which might therefore have influenced North Atlantic circulation and overturning (Li, 2006; Rogerson, Rohling, Bigg, & Ramirez, 2012).

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