Research paper

Upper Miocene deposits at the southern margin of the Guadalquivir Foreland Basin (central Betic Cordillera, S. Spain). Implications for the closure timing of the Atlantic-Mediterranean connections

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A B S T R A C T

Mixed siliciclastic-carbonate deposits accumulated in several satellite sub-basins at the southern margin of the Guadalquivir Basin, the foreland basin of the Betic Cordillera (S. Spain). The prevailing coarse-grained sediments and deposition in shallow-water settings make it difficult to establish the precise age of the complete successions. For this reason, in previous studies, these deposits were attributed to the late Tortonian, although a Messinian age was not totally ruled out. The age of the upper Miocene deposits in the central part of the Guadalquivir Basin is here re-evaluated based on the analysis of several sections distributed in different areas: Antequera, Iznájar-Cuevas de San Marcos, Teba, and Bobadilla Estación. According to planktonic foraminifer and nannoplankton assemblages, the marine sedimentary infill of this sector of the southern margin of the Guadalquivir Basin is late Tortonian-early Messinian (late Miocene) in age. The occurrence of marine deposits characterized by the dominance of *Globorotalia miotumida* group, dextrally-coiled *G. scitula*, and the presence of *G. margaritae, Globigerina multiloba, Discoaster quinqueramus, Amaurolithus primus, A. amplificus*, and *Reticulofenestra rotaria* at the northern end of the Guadalhorce Corridor, the last active gateway in the Betic Cordillera connecting the Atlantic and the Mediterranean, indicates that it remained open until the early Messinian.

1. Introduction

The location and closure timing of the Atlantic-Mediterranean connections leading to the Messinian salinity crisis (MSC) have been the subject of intense research in the last decades (Benson et al., 1991; Martín et al., 2001, 2009, 2014; Betzler et al., 2006; Pérez-Asensio et al., 2012; 2013; Flecker et al., 2015; Achalhi et al., 2016; Tulbure et al., 2017; Krijgsman et al., 2018; Haq et al., 2020; Puga-Bernabéu et al., 2022). Dating the last stages of closing of straits is elusive due to the coarse-grained nature of deposits filling them and, therefore, the cessation of active connection at a given seaway is constrained by the age of laterally-equivalent marine sediments at its ends. One of the last active Atlantic-Mediterranean connections prior to the MSC was the Guadalhorce Corridor in the Betic Cordillera (Martín et al., 2001; 2014) (Fig. 1). Nonetheless, the early Messinian closure of this seaway (Martín et al., 2001) has been questioned due to the apparent absence of Messinian marine sediments at its northern end in the Atlantic-linked Guadalquivir Basin (van der Schee et al., 2018).

The paleogeographic configuration, the geological evolution and the exact closing time of the late Miocene gateways connecting the Atlantic

and the Mediterranean are crucial issues. Their closure affected global oceanographic circulation patterns, heat exchange, salinity variations, as well as climate changes, and impact on marine and terrestrial biota dispersals (Martín et al., 2010; Pérez-Asensio et al., 2012; 2013; 2014; Flecker et al., 2015; García-Alix et al., 2016; Krijgsman et al., 2018; Haq et al., 2020; de Weger et al., 2020). In addition, a steady or episodic marine water flow into the Mediterranean was needed during the MSC to precipitate evaporite giants (see recent reviews in Krijgsman et al., 2018; Haq et al., 2020). Therefore, an earlier (late Tortonian) closure of the Guadalhorce Corridor, as stated by van der Schee et al. (2018), had wide implications in the timing and position of the last connection of the Mediterranean with the open oceans. Here, we show that marine sedimentation took place during the early Messinian at the northern end, as well as to the east of the northern end of the Guadalhorce Corridor in the Guadalquivir Basin, and, therefore, there is no reason to assume a pre-Messinian closure of this seaway.

The Guadalquivir Basin (S. Spain) is the foreland basin of the Betic Cordillera. It has an east-west elongated triangular outline with a passive northern margin on the Iberian plate and an active southern one delimited by the Betic front. Numerous studies have focused on the tec-
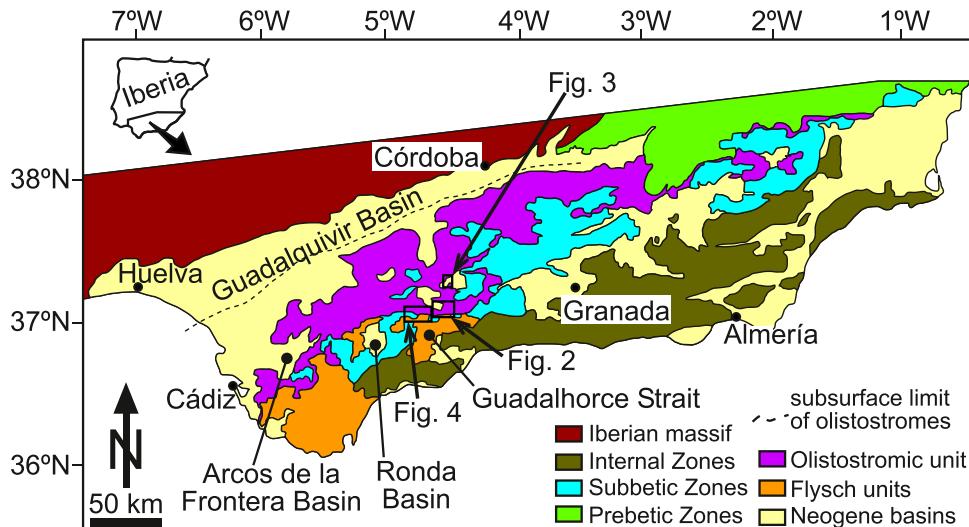
Fig. 1. Geologic map of the Betic Cordillera showing the main domains and Neogene basins. Rectangles indicate the geologic maps of the study areas represented in Figs. 2–4. In addition, arrows with dots indicate different areas mentioned in the text, such as the Guadalhorce Corridor, the Arcos de la Frontera Basin, and the Ronda Basin.

tonic evolution of the frontal Betic wedge along the southern margin of the Guadalquivir Basin in the central Betic Cordillera (e.g., Peyre, 1960–62; Pérez-López and Sanz de Galdeano, 1994; Berasátegui et al., 1998; Fernàndez et al., 1998; Roldán 2008; Rodríguez-Fernández et al., 2012, 2013; Martínez del Olmo 2019). However, the late Miocene sedimentary record in this part of the basin has been largely overlooked, except for a few regional studies (Vera and González-Donoso 1969; Serrano, 1979; Rodríguez-Fernández, 1982; Roldán, 1995).

It has been generally assumed that the deposits in the satellite sub-basins at the southern margin of the Guadalquivir Basin range from early Tortonian to the late Tortonian in age, e.g., Montefrío, Antequera, Iznájar and Cuevas de San Marcos (Vera and González-Donoso, 1969; Peyre, 1974; Serrano, 1979; González-Donoso et al., 1980; Rodríguez-Fernández, 1982; Martín-Serrano, 1986a; van der Schee et al., 2018). Nonetheless, some biostratigraphic studies recognize that the upper part of the successions was not accurately dated since planktonic foraminifers are absent, scarce, or lack any biostratigraphic significance (Peyre, 1974; Serrano, 1979; van der Schee et al., 2018). As a consequence, a Messinian age was not totally discarded by Peyre (1974) for the uppermost part of the deposits, which were considered late Tortonian-early Messinian age by Martín-Serrano (1986a, 1986b) and Cruz-Sanjulián (1990).

In this paper, a detailed lithostratigraphic analysis of the upper Miocene deposits in the central southern margin of the Guadalquivir Basin is presented. Samples were collected in the marls, as well as in silt and fine-grained sand beds to analyze the planktonic foraminifer and calcareous nannoplankton assemblages in order to precise the age of the different stratigraphic units. This work does not intend to propose a biostratigraphic zonation; its purpose is to date the study deposits by fitting the obtained data in the available biostratigraphic schemes. The study focuses on those areas already studied by previous authors, such as the aforementioned Antequera and Iznájar-Cuevas de San Marcos areas, as well as on new areas not yet investigated, namely Bobadilla Estación and Teba, all of them located on the Atlantic side of the Guadalhorce Corridor. The aims are to update and refine the lithological successions and to revisit their biochronology. In this regard, critical issues to face are: 1) limited occurrence of biostratigraphically significant species, 2) poor preservation (dissolution, recrystallization, deformation) hindering reliable species identification, and 3) dominance of coarse-grained lithofacies devoid of microfossils. These aspects tackle the usage of some standard biostratigraphic markers proposed for the late Tortonian-early Messinian interval. Our data, however, show that the study deposits range from the late Tortonian to the early Messinian and, therefore, support that the Atlantic-Mediterranean marine connection through the

Guadalhorce Corridor remained active well into the early Messinian times as proposed by Martín et al. (2001), and corroborated by Pérez-Asensio et al. (2012, 2013).

2. Geological setting

The Betic Cordillera in southern Spain constitutes the northern branch of the Betic-Rifian belt, which arches in the Gibraltar Arc, and is formed by three major domains: the Internal Zones, the External Zones, and the Campo de Gibraltar or Flysch Units (e.g., Sanz de Galdeano and Vera, 1992) (Fig. 1). Sediments deposited originally on the southern Iberian margin were folded and thrusted forming the External Zones, which is divided into the Prebetic Zone, located closest to the Iberian Massif, and the Subbetic Zone, in a more distal position (García-Hernández et al., 1980) (Fig. 1).

The Guadalquivir Basin formed by the flexure of the Iberian paleomargin as a consequence of the piling of tectonic units on the frontal wedge of the Betic Cordillera (Perconig, 1960–62, 1968; García-Castellanos et al., 2002; Larrasoaña et al., 2019). The instability in the orogen front due to the stacking of Subbetic thrusts resulted in the north-northwestwardly displacement of large amounts of materials. The diapirs and chaotic depositional-tectonic mélange of mostly unconsolidated Triassic clays, sands and gypsum are known as the Olistostromic Unit (Peyre, 1960–62; Berasátegui et al., 1998; Roldán, 2008; Rodríguez-Fernández et al., 2012; 2013; González-Castillo et al., 2015) (Fig. 1).

The marine sedimentary infilling of the Guadalquivir Basin consists of several unconformity-bounded depositional sequences ranging from the early Tortonian to the late Pliocene in age (Viguier, 1974; Aguirre, 1991; 1995; Riaza and Martínez del Olmo, 1996; Sierro et al., 1996; Fernàndez et al., 1998; Aguirre et al., 2015; Martínez del Olmo and Martín, 2016, 2019; Martínez del Olmo 2019; Larrasoaña et al., 2019). Subsurface seismic-stratigraphic and borehole results, together with data from exposed sections, indicate that major sediment accumulation took place in ENE-WSW prograding depositional systems along the axis of the basin (Riaza and Martínez del Olmo 1996; Sierro et al., 1996; Martínez del Olmo and Martín, 2016, 2019). Nonetheless, there are still substantial discrepancies among authors regarding the stratigraphic architecture, as well as the age of the depositional sequences (Fernàndez et al., 1998; Martínez del Olmo and Martín, 2019; Martínez del Olmo, 2019).

As the thrusting orogen front advanced, the southern margin of the Guadalquivir Basin acquired an irregular configuration and different satellite sub-basins developed, associated with emergent relieves
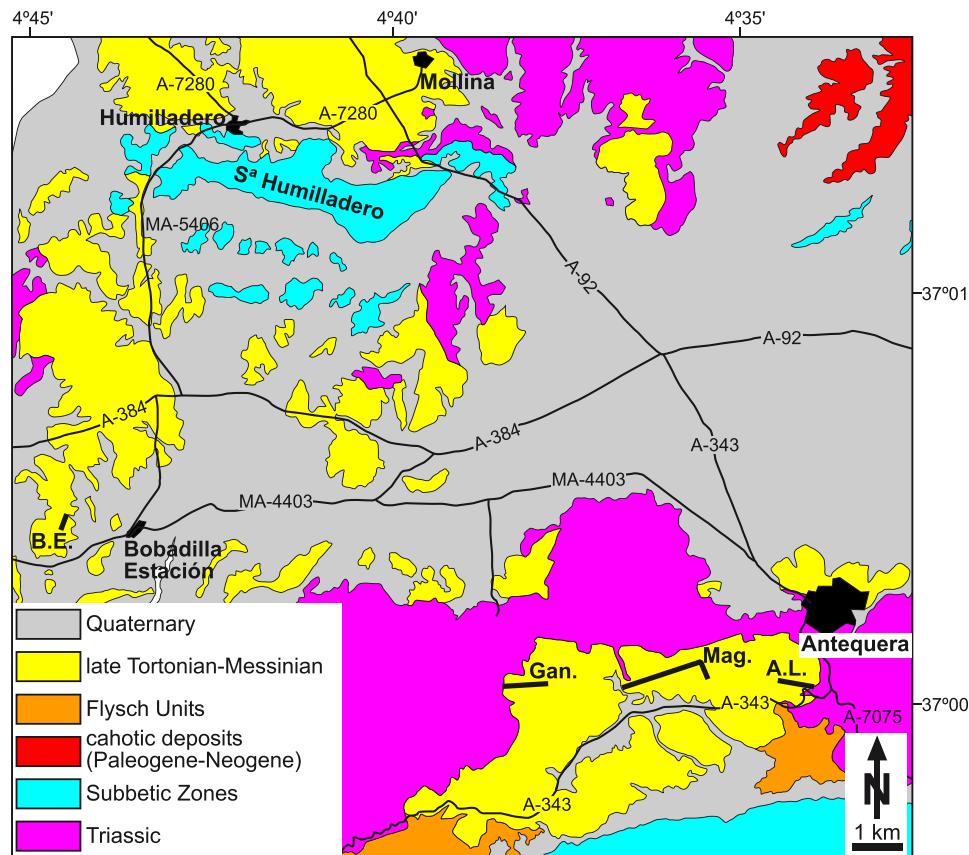
Fig. 2. Geologic map showing the location of Antequera and Bobadilla Estación areas and indicating the location of the study stratigraphic sections. Black lines and labels indicate roads. Pinar del Hacho is located at the western end of the Arroyo Lagarto section (A.L.) and La Magdalena Hotel is at the western end of the La Magdalena section (Mag.). Gan. = Gandigüela section. B.E. = Bobadilla Estación section. (Modified from Martín-Serrano, 1986a).

during the late Miocene. These sub-basins, largely infilled by coarse-grained mixed siliciclastic-carbonate and carbonate deposits, evolved as top-thrust or piggyback basins (Roldán and Rodríguez-Fernández, 1991; Sanz de Galdeano and Vera, 1992; Jabaloy et al., 1992; Martín-Martín and Martín-Algarra, 2002; Rodríguez-Fernández et al., 2012).

As a consequence of the uplift of the Betic orogen, the connections between the Atlantic (through the Guadalquivir foreland basin) and the Mediterranean were restricted to several straits (Martín et al., 2014; Puga-Bernabéu et al., 2022). These marine passages, in turn, closed at different times, from the earliest Tortonian to the early Messinian (Martín et al., 2001, 2009; 2014; Betzler et al., 2006; Puga-Bernabéu et al., 2022). On the Atlantic side of the emergent relieves marine sedimentation continued in the Guadalquivir Basin connected to the open ocean during the late Miocene.

3. Methods

All outcrops assigned to the late Miocene in the IGME (Spanish Geological Survey) geological maps (1:50,000) in the central sector of the southern margin of the Guadalquivir Basin were examined. Four areas with upper Miocene marine deposits were selected: 1) Antequera, 2) Iznájar-Cuevas de San Marcos, 3) Bobadilla Estación, and 4) Teba (Figs 2-4). In each area, stratigraphic sections were logged in the best-exposed outcrops.

Conglomerates and coarse-grained carbonate and mixed siliciclastic-carbonate deposits dominate in the study sections, hampering a systematically spaced sampling of microfossils. Therefore, in order to examine the planktonic foraminifer and calcareous nannoplankton assemblages to date the deposits, samples were collected in every fine-grained interval, from fine-grained sands to marls. When possible, the samples were taken at the base, middle and upper part of the sections. In some sections, where silty and marly deposits crop out extensively, we collected several successive samples.

To extract planktonic foraminifera, samples were washed using meshes of 0.5, 0.125, and 0.065 mm and then dried in an oven at 40 °C. The residue in the 0.125 mm fraction was the one examined. In some cases, samples were barren, thus precluding any biostratigraphic results. In other cases, microfossils were poorly preserved, as casts or intensively affected by recrystallization and deformation, preventing the identification of species. In those samples where preservation was adequate, more than 250 specimens of planktonic foraminifer were identified and counted to obtain the relative abundance of relevant species and coiling directions of *Neogloboquadrina acostaensis* and the *Globorotalia scitula* group (see van der Schee et al., 2018).

Previous authors have conventionally used the Mediterranean standard biostratigraphic zonation schemes of planktonic foraminifer to date the study deposits, despite they accumulated in Atlantic-linked satellite basins (e.g., van der Schee et al., 2018). The same biostratigraphic markers have been used to date upper Miocene sediments in the east-northeast Atlantic (Sierro, 1985; 1986; Sierro et al., 1993; Hilgen et al., 2000; Lourens et al., 2004; Krijgsman et al., 2004; Tulbure et al., 2017). Due to problems derived from preservation and lithofacies, as highlighted above, we discuss the difficulties to use the Mediterranean Neogene standard biozonation and foraminifer markers. The Guadalquivir Basin was open to the Atlantic but also was influenced by Mediterranean waters through the Betic seaways (Martín et al., 2014; Puga-Bernabéu et al., 2022). Thus, it is reasonable to combine Mediterranean (Lirer et al., 2019) and non-Mediterranean biostratigraphic data (e.g., Kennett and Srinivasan 1983; Berggren et al., 1995; Wade et al., 2011; BouDagher-Fadel, 2015) in order to provide a more robust and consistent age framework for the study deposits (Fig. 5). Age ranges of particular planktonic foraminifer species have also been contrasted with the information provided by the Mikrotax webpage (http://www.mikrotax.org/pforams/index) (Young et al., 2017).

For calcareous nannofossil assemblages, smeared slides of sediment were prepared. Scarcity and poor preservation of nannoplankton content preclude quantitative analyses. Therefore, preparations

were examined looking for the biostratigraphically significant species. We use the nannoplankton biostratigraphic zonation schemes of Martini (1971) and Okada and Bukry (1980), with some additional nannoplankton events as indicated by Young et al. (1994), Raffi and Flores (1995), Marino and Flores (2002), Backman et al. (2012) and Agnini et al. (2017). Taxonomic identification and age distribution of nannofossil species has been checked with the information in Nannotax3 webpage (https://www.mikrotax.org/Nannotax3/index.html) (Young et al., 2022).

All the samples and the identified material are housed at the Dpt. Estratigrafía y Paleontología (University of Granada).

4. Results

4.1. Antequera area

The study deposits are exposed immediately southwest of the Antequera city, between Pinar del Hacho and Gandigüela. They unconformably overlie vertical strata of the Flysch Units and chaotic deposits of the Olistostromic Unit (Fig. 2). Three sections were logged, from east to west: Arroyo Lagartos, La Magdalena, and Gandigüela (Figs 2, 6). The study deposits consist of two units separated by an erosive unconformity. The lower unit, formed by dark blue marls, crops only locally out west of La Magdalena Hotel, in the El Alcázar ravine.

The upper unit can be divided into two parts. The lower part is made up of calcarenites and calcirudites, with intercalations of channelled conglomerates and breccias made up of limestone, sandstone, and chert pebbles to boulders embedded in a sandy carbonate matrix. Calcarenites and calcirudites show pervasive trough cross-bedding and, less frequently, tabular cross-stratifications. The upper part of the successions is characterized by a gradual decrease in carbonate content and a concomitant increase in fine-grained sands and, finally, silty marls. Tabular and channelled bodies of conglomerates and sandy calcarenites-calcirudites intercalate in the silty marls (Fig. 6).

4.1.1. Microfossil assemblages and age

The blue marls west of La Magdalena Hotel (sample MAGDA-W; Fig. 6) contain a rich planktonic foraminifer assemblage that is characterized by the presence of *Neogloboquadrina humerosa, N. acostaensis* (sinistral = 70.8%; dextral = 29.2%), *Globorotalia scitula* (sinistral = 90%; dextral = 10%), dominance of the *G. menardii* group (85% of sinistral *G. menardii* 4), and a few specimens of the *G. miotumida* group (15%). This assemblage indicates an early late Tortonian age, between the first occurrence of *N. humerosa*, 8.50 Ma *sensu* Wade et al. (2011) or the base of subzone MMi12a (8.37 *sensu* Lirer et al., 2019), and the last occurrence of *G. menardii* 4 at 7.51 Ma (Lirer et al., 2019). Corbí and Soria (2016) place the second influx of the *G. miotumida* group at the top of the MMi11 biozone of the Mediterranean biozonation scheme, immediately below the appearance of *G. extremus* marking the base of subzone MMi12a (Lirer et al., 2019) (Fig. 5b).

In the upper unit, sample ANTEQ-1, in the lower part of the Arroyo Lagartos section (Fig. 6), is dominated by shallow-water benthic foraminifers, mostly *Ammonia* spp., *Elphidium crispum, Nonionella* spp., and *Hanzawaia boueana*. Planktonic forms are scarce and preserved as deformed and recrystallized casts. In addition, they are small in size, a characteristic already highlighted by Serrano (1979), hindering species identification. Among the feasibly identifiable species, there are *Globigerinoides extremus, Neogloboquadrina humerosa, N. acostaensis, Globorotalia scitula, G. suterae*, and *G. menardii* group. This assemblage indicates a late Tortonian age, above the first occurrence of *G. suterae* (~7.8 Ma), which marks the base of the MMi12b biozone of Lirer et al. (2019).

Samples MAGDA-1 and ANTEQ-3 (Fig. 6), at the base of the silts and fine-grained sand of the upper part of the La Magdalena sec-

tion, cannot be dated. They are dominated by benthic foraminifers, mostly *Ammonia beccarii* followed by *Elphidium* spp., *Biastigerina planorbis, Lobatula lobatula*, and *Cibicides* spp., indicating deposition in shallow-water inner-mid platform settings. Microfossils are nearly absent, and the few specimens of planktonic foraminifera (*Globigerina* spp.) and calcareous nannoplankton have no biostratigraphic meaning.

The uppermost sample collected in the La Magdalena section, ANTEQ-2 (Fig. 6), is dominated by planktonic foraminifers (73%). Nonetheless, they are poorly preserved and quantitative analysis could not be properly performed. The assemblage consists of *Globigerinoides conglobatus, G. extremus, Neogloboquadrina humerosa*, sinistral *N. acostaensis*, sinistral *Globorotalia scitula*, and a few specimens of *Globorotalia miotumida* group (forms attributable to *G. dalii*). The first occurrence of *G. conglobatus* took place at 6.20 Ma, in the Messinian (Kennett and Srinivasan, 1983; Chaisson and Pearson, 1997; Lourens et al., 2004; Wade et al., 2011) (Fig. 5a), thus indicating that the uppermost part of the section can be assigned to the early Messinian.

Samples collected in the Gandigüela (Fig. 6) confirm a late Tortonian-early Messinian age for the study deposits. Planktonic foraminifer assemblages of samples GAND-0 and GAND-2 are dominated by *Globigerina* spp., *Turborotalita quinqueloba*, and neogloboquadrinids (*N. acostaensis, N. humerosa, N. incompta, N. atlantica, N. pachyderma*). Among the biostratigraphically significant species, there are sinistral forms of *N. acostaensis* (Fig. 7a) as well as specimens from *G. scitula*, the *G. miotumida* group, and the *G. menardii* group. The keeled globorotaliids show similar proportions (ca. 50%). Therefore, these samples can be close to the Tortonian-Messinian boundary in age.

Samples GAND-3 and GAND-4 show similar planktonic foraminifer assemblages but the *G. miotumida* group (66.7% in GAND-3 and 83.9% in GAND-4) is more abundant than the *G. menardii* group. Among the *G. miotumida* group, there are some individuals identifiable as *G. mediterranea-conomiozea* morphotypes (Figs 7b-7d). Dominance of the former species group indicates a Messinian age. This age attribution is also supported by the presence of *Globigerina multiloba* (Figs 7e-7f), *Globigerinoides conglobatus* (Fig. 7g), and *Globigerinoides bulloideus*, three species that first appeared in the Messinian (Romeo, 1965; Kennett and Srinivasan, 1983; Iaccarino, 1985; Lirer et al., 2019) (Fig. 5). In addition, the occurrence of specimens closely resembling *Globorotalia margaritae* confirms a Messinian age (see discussion below) (Fig. 5a).

G. miotumida group (Figs 7h-7i), with some forms attributable to *G. mediterranea-G. conomiozea* morphotypes (Fig. 7i), *G. scitula* dextral (Fig. 7j), and *Globigerinoides bulloideus* are also present in sample GAND-9, several tens of meters above GAND-8. This corroborates that this part of the sequence is early Messinian in age. According to Sierro (1985) and Lirer et al. (2019), the occurrence of strong ventrally-convex morphotypes *G. mediterranea-G. conomiozea* characterizes the Messinian in the Mediterranean.

Calcareous nannoplankton content in all the analyzed samples in Antequera area is scarce and microfossils are poorly preserved, except in the sample GAND-5 from the Gandigüela section. Here, the calcareous nannoplankton assemblage is dominated by discoasters, such as *Discoaster brouweri, D. neorectus, D. challengeri, D. icarus, D. surculus*, together with *Triquetrorhabdulus rugosus* and *Helicosphaera carteri* (Figs 8a-8c). The first occurrence of *D. surculus* took place during the latest late Tortonian (Young et al., 1994; Backman et al., 2012), in the upper part of the biozone NN11A of Martini (1971) or of the biozone CN9a of Okada and Bukry (1980). Additionally, the last appearance of *T. rugosus* occurred at the top of the Messinian (Young et al., 1994; Agnini et al., 2017). The specimens of *D. challengeri* of the nannofossil assemblage show a well-defined hexagonal central knob and slender, parallel ray walls (Fig. 8b). These morphotypes are close to the subspecies *D. challengeri neillensis* described by Singh and Vimal (1976), which is recorded in early Messinian-early Zanclean deposits in the eastern Betic Cordillera (Lancis, 1998; E. Lancis and Flores, 2004d).
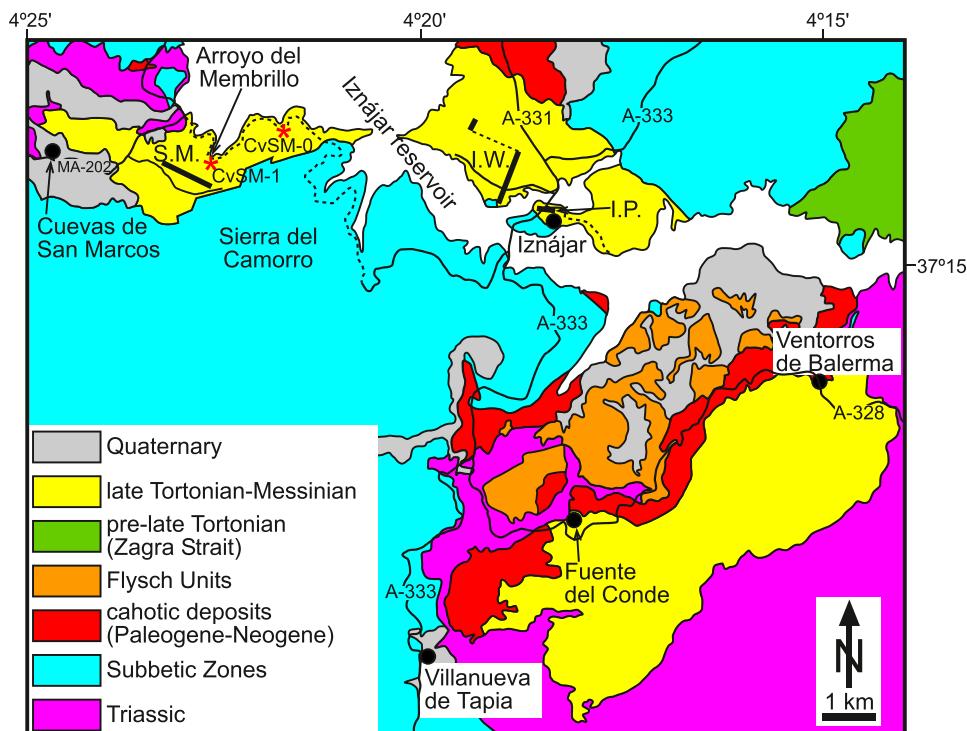
In short, both nannofossils and planktonic foraminifer suggest that the upper unit in the Antequera area ranges from the late Tortonian to the early Messinian in age.

4.2. Iznájar-Cuevas de San Marcos area

Upper Miocene deposits crop out extensively in the Iznájar-Cuevas de San Marcos area. Three sections have been logged: Iznájar-Pueblo, Iznájar-W, and Cuevas de San Marcos sections (Figs 3, 9, 10). The upper Miocene sediments unconformably overlie Jurassic marls and marly limestones, as well as chaotic materials of the Olistostromic Unit.

The study materials consist of two units separated by an angular unconformity. Both units include carbonate and mixed siliciclastic-carbonate deposits at the base, which change to silts and marls towards the top. The lower unit, which is intensely tectonized in the Cuevas de San Marcos area (Fig. 10), shows pervasive trough cross-bedding and numerous channelled conglomerates and breccias (Fig. 9). Towards the top of the lower unit, grain size decreases and sediment changes to silty marls. In the Iznájar sections, the upper unit is dominated by calcarenites-calcirudites displaying pervasive trough cross-bedding that change upward to silts and marls (Fig. 9). In Cuevas de San Marcos, this unit starts with clast-supported breccias including angular boulders up to 50 cm embedded in a matrix of microconglomerate to calcirudite (Fig. 10). The terrigenous content decreases quickly upwards and calcarenites-calcirudites with pervasive trough-cross bedding overlie the breccias. They change upwards to fine-grained calcarenites and, finally, to silty sands covered by soils (Fig. 10). Silts and marls of the upper part of this upper unit crop out along the track between Iznájar and Cuevas de San Marcos bordering the water reservoir, where several samples were collected (Fig. 3).

4.2.1. Microfossil assemblages and age

Calcareous nannoplankton assemblages of the samples collected in the Iznájar sections do not provide reliable biostratigraphic data since the specimens are very scarce and taphonomically altered.

Regarding planktonic foraminifer, the lowermost sample IZN-P-0 is almost barren, with no microfossils. They are also scarce in samples IZN-P-1 and IZN-P-2 (Fig. 9). *Dentoglobigerina* spp., *Globigerina* spp. and *Globigerinoides* spp. are the dominant components. Among the biostratigraphically significant species, there are a few specimens of *Neogloboquadrina acostaensis* (sinistral = 50%; dextral = 50%), and *Globorotalia scitula* (sinistral = 67%; dextral = 33%). Among keeled globorotaliids, the *G. menardii* group dominates (Figs 7k-7l) and only a few individuals possibly attributable to the *G. miotumida* group are present.

The scarcity of foraminifers and nannoplankton precludes a precise dating of these samples, although the microfossil assemblages can be confidently assigned to the late Tortonian.

Samples in Iznájar W section, CERRO CUCHILLO-0, CERRO CUCHILLO-1, IZN–CAM-W-0, and IZN–CAM-W-1 (Fig. 9), are characterized by sinistral-dominated *N. acostaensis, G. suterae*, and *G. scitula*, as well as predominating *G. menardii* group with a few individuals attributable to *G. miotumida* group (mostly *Globorotalia dalii*). This planktonic foraminifer assemblage indicates a late Tortonian age.

Finally, the uppermost sample CERRO CUCHILLO-2 (Fig. 9), from the upper unit, contains a few individuals of putative *Globorotalia margaritae* (Figs 7m-7n), which indicates an early Messinian age.

In Cuevas de San Marcos, sample CvSM-2 collected in silts of the lower unit (Fig. 10) is dominated by sinistral forms of *N. acostaensis* (dextral = 18.2%; sinistral = 81.8%) and *G. scitula* (dextral = 20%; sinistral = 80%), as well as by *G. menardii* group. This assemblage indicates a late Tortonian age.

Planktonic foraminifer assemblages of samples CvSM-0 and CvSM-1, corresponding to the marls of the upper unit (Fig. 3), contain specimens of *Globorotalia margaritae* (Figs 11a-11c) together with *G. miotumida* and *Globigerinoides conglobatus*. These species association indicates a Messinian age (Fig. 5a). In addition, sample CvSM-0 contains a rich calcareous nannoplankton assemblage dominated by scyphosphaerids, with the presence of *Scyphosphaera recurvata, S. ampla, S. gladstonensis, S. cantharellus, S. lagena*, and *S. apsteiniii* (Figs 8d-8g). Lancis and Flores (2004a; 2004b, 2004c, 2004d) and Lancis et al. (2004) show a significant increase in abundance and diversity of the genus *Scyhosphaera* during the Messinian in the Cartagena-Alicante Basin (east Betic Cordillera). In the study samples, specimens of *S. apsteinii* are short and display a characteristic barrel shape (Fig. 8f) very close to the morphotypes *S. ap-*

steinii morpho B of Lancis and Flores (2004a), which first occur at the base of the Messinian.

In conclusion, these samples from the upper unit in Cuevas de San Marcos are Messinian in age.

4.3. Bobadilla estación area

Upper Miocene deposits crop out at several sites in the vicinity of the Bobadilla railway station (Fig. 2). At the western side of the station, a section was logged in an abandoned quarry: Bobadilla Estación section (Fig. 2). The basal contact of the study materials with the basement is not exposed in the quarry. Further to the north, west of the Sierra del Humilladero (Fig. 2), the base of the upper Miocene sediments consists of sandy calcarenites with trough cross-bedding lying over breccias, which line an irregular surface carved in Upper Jurassic marls and marlstones.

The Bobadilla Estación section consists of three unconformable units (Fig. 12). The lower unit can be divided into two intervals. The lower one consists of calcarenites and calcirudites displaying pervasive trough cross-bedding, occasionally deformed, and the upper one is made up of silts and marls (Fig. 12). The transition from the carbonates to the fine-grained sediments is gradual. Grain size increases gradually towards the top of the upper part, as sediments change from marls to silts and lastly, fine-grained sands at the top of the section.

The intermediate unit is only locally exposed in pockets carved at the top of the lower unit. It consists of greenish marls with whitish carbonate nodules (Fig. 12).

The uppermost unit overlies an erosive surface on the previous ones. It consists of highly cemented reddish conglomerates exhibiting tabular cross-bedding.

4.3.1. Microfossil assemblages and age

The lowest sample, Sta. ANA (Fig. 12), is barren of foraminifers and nannofossils. The sample EST.BOB-0 (Fig. 12) is characterized by the presence of *Globorotalia miotumida* group (75%), *G. menardii* group (25%), *Globigerinoides bulloideus* (Fig. 11d), *Neogloboquadrina humerosa*, predominantly sinistral *N. acostaensis* (sinistral = 82.7%; dextral = 17.3%) and sinistral *Globorotalia scitula* (sinistral = 81.8%; dextral = 18.2%). *G. bulloideus* ranges from the base of the Messinian to the top of the Zanclean (early Pliocene) (Kennett and Srinivasan, 1983; BouDagher-Fadel, 2015). Therefore, the beginning of the silts and marls of the lower unit in the Bobadilla Estación section can be assigned to the earliest Messinian, between the first occurrence of *G. bulloideus* at the base of the stage and the sinitral-to-dextral coiling change in *G. scitula* group dated at 7.09 Ma (Lirer and Iaccarino, 2011; Lirer et al., 2019).

The sample EST-BOB-4 (Fig. 12) contains *Globigerinoides conglobatus*, *N. humerosa*, sinistral *N. acostaensis* (sinistral = 74.3%; dextral = 25.7%), dextral *G. scitula* (sinistral = 36.4%; dextral = 63.6%), and *G. miotumida* group (85%) (Figs 11e-11f) dominating over *G. menardii* group (15%). The non-keeled globorotalid *Globorotalia scitula* experienced a coiling change, from predominantly sinistrally coiled during the Tortonian to dextrally coiled during the Messinian (Sierro et al., 1993, 2001; Lirer et al., 2019). Therefore, dominance of *G. miotumida* and dextral *G. scitula*, in agreement with the age of the previous sample, indicates a Messinian age, younger than the last occurrence of the dominantly sinistral *G. scitula* at 7.09 Ma (Lirer and Iaccarino, 2011). This age is also consistent with the presence of *G. conglobatus* that first appeared in the Messinian (Chaisson and Pearson, 1997; Lourens et al., 2004; Wade et al., 2011).

Planktonic foraminifers in sample EST-BOB-8 (Fig. 12) are highly recrystallized and taphonomically altered, precluding a feasible identification of the species.

The sample in the intermediate unit, EST-BOB-10 (Fig. 12), has scarce planktonic foraminifers. The scarcity of planktonic foraminifer suggests that the marls of this unit most likely formed in a restricted embayment of the Guadalquivir Basin. The existence of a few individuals of putative *G. margaritae* (Fig. 11g) points to a Messinian age.

Nannofossils are generally very rare and, when present, they are unrecognizable or taphonomically highly distorted, except in samples EST-BOB-4 and EST-BOB-5. Here, *Discoaster broweri, D. quinqueramus, D. berggrenii*, and *D. loeblichii* (Figs 8h-8k) are found. The presence of *D. quinqueramus* (Fig. 8i) allows assigning these samples to the biozones NN11 of Martini (1971) or CN9 of Okada and Bukry (1980). This biozone ranges the late Tortonian-early Messinian interval.

4.4. Teba area

Middle-Upper Jurassic limestone and chaotic deposits of the Olistostromic Unit constitute the basement of the upper Miocene deposits, which are well exposed N–NE of Teba (Fig. 4). They start with calcirrudites displaying cross bedding on top of the Jurassic basement. The grain size of the carbonates decreases upsection, changing to sandy calcarenites, then silts and, finally, marls (Fig. 13). The study stratigraphic section ends with channelled calcirrudites (Fig. 13). Several samples were collected at the base and at the top of the marls (Fig. 13), because most of the marl outcrop is covered by olive tree fields.

4.4.1. Microfossil assemblages and age

The sample TEBA-0 is characterized by the presence of *G. suterae*, the dominance of sinistral-coiled *N. acostaensis* (93%), and a similar proportion of *G. miotumida* group (56%) and *G. menardii* group (44%). The non-keeled *G. scitula* is virtually absent and, therefore, no quantitative analysis can be performed of the abundance of dextral and sinistral forms.

In samples TEBA-1 and TEBA-1A, *Globorotalia miotumida* group (*G. mediterranea-conomiozea* morphotype) (Figs 11h-11i), dextrally-coiled *G. scitula* (82.5%), and sinistrally-coiled *N. acostaensis* (90%) dominate the planktonic foraminifera assemblages. It is also remarkable the presence of *Globillerinoides bulloideus, G. conglobatus* (Fig. 11j), *Globoturborotalita nepenthes*, and *N. humerosa*. The sinistral to dextral coiling change of *G. scitula* is dated at 7.09 Ma; that is, earliest Messinian (Lirer and Iaccarino, 2011). This age attribution agrees with the abundance of *G. miotumida* group (specifically, presence of morphotypes of *G. mediterranea-conomiozea*). This age is consistent with the presence of *G. bulloideus*, whose first occurrence marks the base of the Messinian (Kennett and Srinivasan, 1983; BouDagher-Fadel, 2015), and *G. conglobatus*, which first appeared in the Messinian (Chaisson and Pearson, 1997; Lourens et al., 2004; Wade et al., 2011).

Nannofossil content is generally scarce, although *Reticulofenestra rotaria, R. pseudoumbilicus, Discoaster brouweri, Scyphosphaera ventriosa, Calcidiscus leptoporus, Helicosphaera carteri, Geminilithella jafari, G. rotula, Pontosphaera multipora, Amaurolithus amplificus* and *A. primus* have been identified in samples TEBA-1, TEBA-1A, Teba-1c, Teba-1d, and Teba-1f (Figs 14a-14c). The first occurrence of the genus *Amaurolithus*, with the species *A. primus* (Fig. 14b), marks the NN11A-NN11B boundary of the Martini (1971) biozonation scheme or the CN9a-CN9b boundary of Okada and Bukry (1980) biozones. This first appearance is dated at 7.4 Ma (e.g., Raffi et al., 2003), close to the Tortonian-Messinian boundary. In addition, the total range of *A. amplificus* (Fig. 14c), which has been recorded in TEBA-1, is Messinian (Martini, 1971; Okada and Bukry, 1980; Young et al., 1994; Raffi and Flores, 1995; Berggren et al., 1995; Marino and Flores, 2002; Backman et al., 2012; Agnini et al., 2017), either between 6.6 Ma and 5.9 Ma (Berggren et al., 1995), 6.5–5.88 Ma (Raffi and Flores, 1995), or 6.82–5.98 (Backman et al., 2012; Agnini et al., 2017). Raffi and Flores (1995; see also Marino and Flores, 2002) defined the subzone CN9bB within the Messinian based on the total range of *A. amplificus*. Similarly, Backman et al. (2012) and Agnini et al. (2017) defined the biozone CNM18 based on the total range of the nominal species. Therefore, the microfossil assemblage unequivocally assigns the deposits of the lower part of the Teba section to the early Messinian.

Furthermore, the species *Reticulofenestra rotaria*, found in Teba-1c and Teba-1f (Figs 14d-14e), shows a total range distribution in the
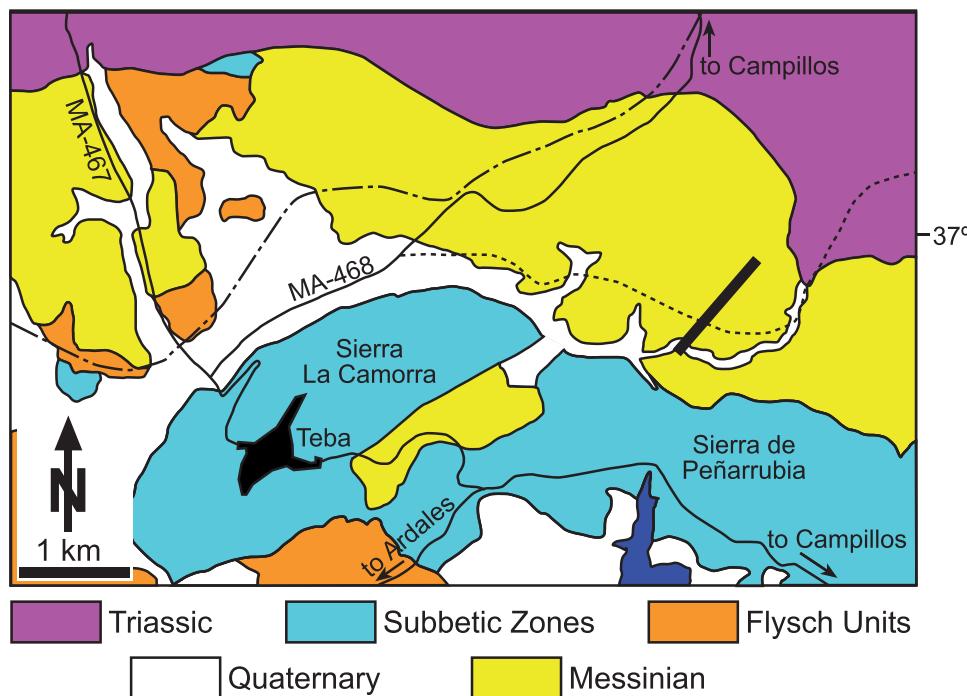
Fig. 4. Geologic map showing the location of Teba area and indicating the location of the study stratigraphic section. Black lines and labels indicate roads; dashed line is a track; dash-dot line is the railway between Campillo and Almargen. (Modified from Cruz-Sanjulián, 1991).

Messinian within the same time interval than *A. amplificus*, from ~7 to ~6 Ma (Theodoridis, 1984; Young et al., 1994; Young, 1998; Siesser and de Kaenel, 1999; Marino and Flores, 2002; Raffi et al., 2003; Wei, 2003). This species, however, is rare in the Mediterranean, and its validity as biomarker has been discussed (e.g., Raffi et al., 2003). Nonetheless, there is common agreement that the first occurrence of *R. rotaria* is unquestionably Messinian (Young, 1998; Young et al., 1994; Siesser and de Kaenel, 1999; Raffi et al., 2003).

In the upper part of the section, samples TEBA-2A to TEBA-4A are mostly silts with abundant quartz grains. Foraminifera are rare, mostly benthic foraminifera; therefore, no quantitative analysis could be performed. Among planktonic foraminifera, these samples contain *N. acostaensis*, *Globorotalia miotumida* group, *G. menardii* group, *G. scitula*, *Globigerinoides extremus*, and *G. conglobatus*. As commented above, the presence of *G. conglobatus* is consistent with a Messinian age.

Finally, in sample TEBA-5A, the planktonic foraminifer assemblage is dominated by *Globigerina* spp. and *G. miotumida* group (86%), accompanied by *Globigerinoides conglobatus*, *G. bulloideus*, *G. extremus*, and *Sphaeroidinellopsis* spp. Non-keeled globorotaliids are virtually absent. The overabundance of *G. miotumida* group, together with the presence of *G. bulloideus* and *G. conglonbatus*, corroborates the Messinian age obtained in samples TEBA-1 and TEBA-1A. The nannofossil content in sample Teba-1h is very scarce. In addition, they are recrystallized, fragmented and, in general, very badly preserved.

5. Discussion

5.1. Caveats due to the nature of the study deposits

As mentioned above, the age of the study deposits has been contentious. Most authors indicate an early-late Tortonian age for them, although a Messinian age was not completely discarded for the top of the successions (Peyre, 1974; Martín-Serrano, 1986a; 1986b; Cruz-Sanjulián, 1990). The main difficulties regarding the biochronology of the upper Miocene rocks at the southern margin of the Guadalquivir Basin are due to the scarcity or absence of relevant planktonic foraminifera and calcareous nannoplankton, as well as to taphonomic alterations of the preserved microfossils, caused by the prevalence of coarse-grained, shallow-water deposits. All these determinants preclude

using some of the standard biostratigraphic events of the late Tortonian-early Messinian time interval.

The Tortonian-Messinian (T/M) boundary is defined in the northeast Atlantic and Mediterranean by the replacement in the dominance of the keeled globorotaliids *Globorotalia menardii* group (dextrally coiled *G. menardii* 5) by the *Globorotalia miotumida* group (Sierro, 1985; Sierro et al., 1993; Lirer et al., 2019). This event is dated at 7.25 Ma (Hilgen et al., 2000, 2012; Lirer and Iaccarino, 2011) or recalibrated at 7.24 (Lourens et al., 2004; Lirer et al., 2019) (Fig. 5b).

In relation to this biostratigraphic event defining the T/M boundary, it is worth mentioning that there are, at least, two events of abundance maxima of the *G. miotumida* group predating this boundary (Fig. 5b); a first one in the early Tortonian (Corbí and Soria, 2016) and a second one in the late Tortonian (Sierro et al., 1993; Krijgsman et al., 1995, 2000; Hüsing et al., 2009; Corbí et al., 2012; Corbí and Soria, 2016). Therefore, the T/M boundary would correspond to the third influx of the *G. miotumida* species group according to Corbí and Soria (2016) (Fig. 5b). Consequently, when sampling is limited due to the lithologies (predominance of calcareous and siliciclastic coarse-grained sediments in the case study) and it is impossible to carry out a regularly spaced detailed sampling, the use of the replacement of *G. menardii* group by *G. miotumida* group as an indicator of the T/M boundary is challenging and highly arguable. In addition, both keeled globorotaliid species are preferentially more abundant in deep-water deposits, thus using their relative abundance as a biochronologic datum event is complicated when sediments formed in relatively shallow waters, as it is in the case study.

The same reasoning applies for the use of the last occurrence of *G. miotumida* group. In the Mediterranean, Lirer et al. (2019) date the last occurrence of *G. miotumida* group at 6.52 Ma, within their MMi13c biozone (Fig. 5b). However, a fourth influx event of the nominal species group is well recognized in the lowermost early Pliocene of the Segura Basin (SE Spain), between the acme of *Sphaeroidinellopsis* and the first common occurrence of *Globorotalia margaritae* in the Mediterranean (Corbí and Soria, 2016) (Fig. 5b). In the Atlantic, the *Globoconella* group, including different species of the *Globorotalia miotumida* group as defined by Sierro (1985) and Sierro et al. (1993), shows a continuous stratigraphic distribution since the Tortonian onwards. For instance, *G. conomiozea* disappeared at 5.72 Ma, and *G. margaritae* first occurred at 5.95 Ma (Fig. 5a). Therefore, both species can coexist in the Atlantic during the Messinian, in the M14 biozone of Wade et al. (2011).
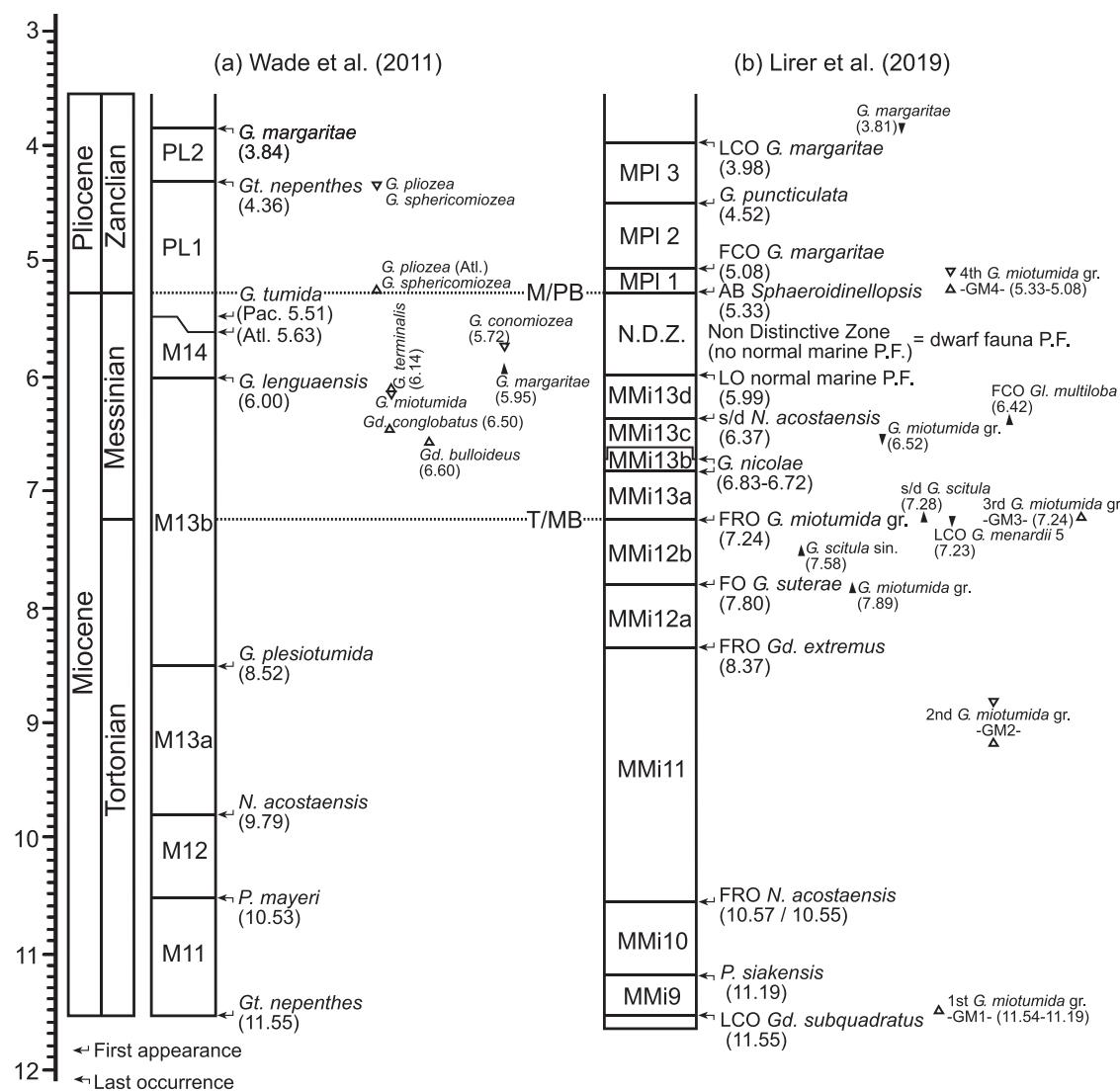
Fig. 5. a) Biozonation proposed by Wade et al. (2011) with first appearances and last occurrences (arrows) of planktonic foraminifer species. Black triangle marks an additional bioevent considered by Wade et al. (2011). White triangles are additional datum events based on Kennett and Srinivasan (1983) and Young et al. (2017; Mikrotax webpage). b) Biozonation scheme of Lirer et al. (2019) with indication of first and last occurrences (FO and LO respectively) (arrows), as well as first regular occurrences (FRO) and first and last common occurrences (FCO and LCO respectively). Black triangles show additional bioevents considered by Lirer et al. (2019). White triangles are additional datum events based on Corbí and Soria (2016). T/MB = Tortonian/Messinian boundary; M/PB = Miocene/Pliocene boundary; AB = Acme Bottom; Atl. = Atlantic; Pac. = Pacific; s/d = Sinistral to dextral coiling change; P.F. = Planktonic foraminifera. Abbreviations of genera: G. = *Globorotalia*; Gd. = *Globigerinoides*; Gl. = *Globigerina*; Gt. = *Globoturborotalita*; N. = *Neogloboquadrina*; P. = *Paragloborotalia*.

Additionally, coiling change events in several species have been used as biostratigraphic markers during the late Tortonian and early Messinian, both in the NE Atlantic and in the Mediterranean (Sierro, 1985; Sierro et al., 1993; Hilgen et al., 2000; Lourens et al., 2004; Krijgsman et al., 2004; Tulbure et al., 2017; van der Schee et al., 2018; Lirer et al., 2019). In this regard, the last common occurrence of *Globorotalia menardii* 4 (sinistrally coiled) took place at 7.51 Ma and the last common occurrence of *G. menardii* 5 (dextrally coiled) is dated at 7.23 Ma (Fig. 5b) in the GSSP at Oued Akrech section (NE Morocco) immediately above the T/M boundary (Hilgen et al., 2000; Lirer and Iaccarino 2011; Lirer et al., 2019). The temporal succession of *G. menardii* forms 3, 4 (both sinistral forms) and *G. menardii* form 5 (dextral) during the late Tortonian, although recognized in some stratigraphic sections from Crete, was very discontinuous (Zachariasse, 1975, p. 29). Therefore, this author discarded the use of their ranges as feasible markers. Sprovieri et al. (1996) also noted several coiling changes in the *G. menardii* group during the late Tortonian and detected a peak in sinistral forms occurring immediately below the T/M

boundary in several sections of the central Mediterranean. Furthermore, Sierro et al. (1993) located the disappearance of *G. menardii* 5 slightly below the T/M boundary in several DSDP Sites from the NE Atlantic, as well as in onshore sections in the Guadalquivir Basin and in NW Morocco. In the Abad composite section (SE Spain), which is considered a reference section where several late Tortonian-early Messinian datum events have been defined (Sierro et al., 2001; Lirer et al., 2019), the last occurrence of the dextral forms of *G. menardii* took place at 7.26 (Sierro et al., 2001); that is, also predating the T/M boundary (see also Sierro et al., 1993).

Assuming the potential value of the coiling change in *G. menardii* group as biostratigraphic marker of the T/M boundary in the Mediterranean, which is not disputed here, Knappertsbusch (2016, 2022) shows that coiling changes in menardiform globorotaliids since the late Miocene onwards is controlled by environmental conditions in the water column: "the abundance and coiling change of members of the *G. menardii*- and *G. tumida* groups, and the concurrent divergence trends in the *G. menardii-limbata-multicamerata* lineage may thus provide hints
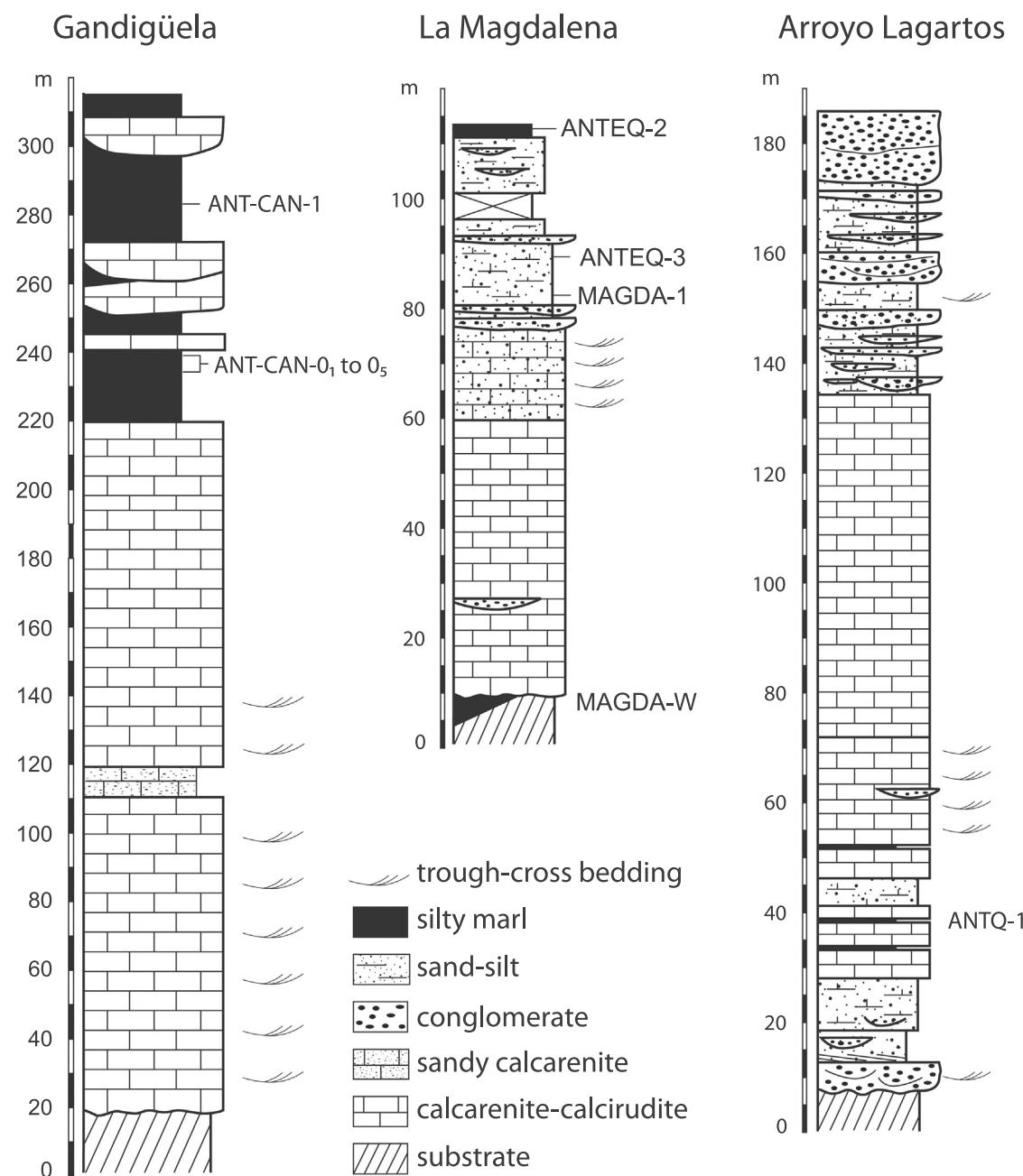
Fig. 6. Stratigraphic logs in Antequera area with indication of the position of the study samples.

to changes of the upper water column structure and stratification over longer time" (Knappertsbusch, 2022, p. 20).

Among the non-keeled globorotaliids, the coiling change from dominantly sinistral to dextral forms of the *Globorotalia scitula* group has also been considered an important datum event. This coiling shift is dated at 7.28 Ma (Fig. 5b) and has been used as an isochronous reference biostratigraphic marker for the entire Mediterranean realm as well as for the NE Atlantic (Sierro et al., 1993; Hilgen et al., 2000; Lourens et al., 2004; van der Schee et al., 2018; Lirer et al., 2019). However, Sierro et al. (2001) dated this event at 7.095 Ma in the Abad composite section, well after the T/M boundary, and Lirer and Iaccarino (2011) confirmed this age in their revision of the Mediterranean Neogene stratotype sections.

Shifts in coiling direction in recent planktonic foraminifer species can be genetically controlled (Brummer and Kroon, 1988; Darling et al.,

2006; Kucera 2007; Aze et al., 2011; Mazunder et al., 2014; BouDagher-Fadel 2015). It is also well documented that the relative abundance of either of the two morphotypes (sinistral or dextral forms) varies both through time and space mostly in relation to sea surface temperatures (Ericson et al., 1954; Ericson, 1959; Saito, 1976; Carrasco et al., 1979; Kucera, 2007; Mazunder et al., 2014; Knappertsbusch, 2022) and/or chemical composition of waters (Mazunder et al., 2014; Knappertsbusch, 2022). Therefore, quantitative analyses of coiling preferences have been largely used as proxies to infer paleotemperatures/paleolatitudes (Ericson et al., 1954; Ericson, 1959; Saito, 1976; Chaisson and Pearson, 1997; Pfuhl and Shackleton, 2004; Kucera 2007; Knappertsbusch, 2016) or local changes in sea surface temperatures (Carrasco et al., 1979). In this regard, Poore (1981) indicated that the replacement of *G. menardii* 5 (dextral) by the *G. miotumida* group (sinistral) was related to paleoclimatic oscillations in the central northern Atlantic.
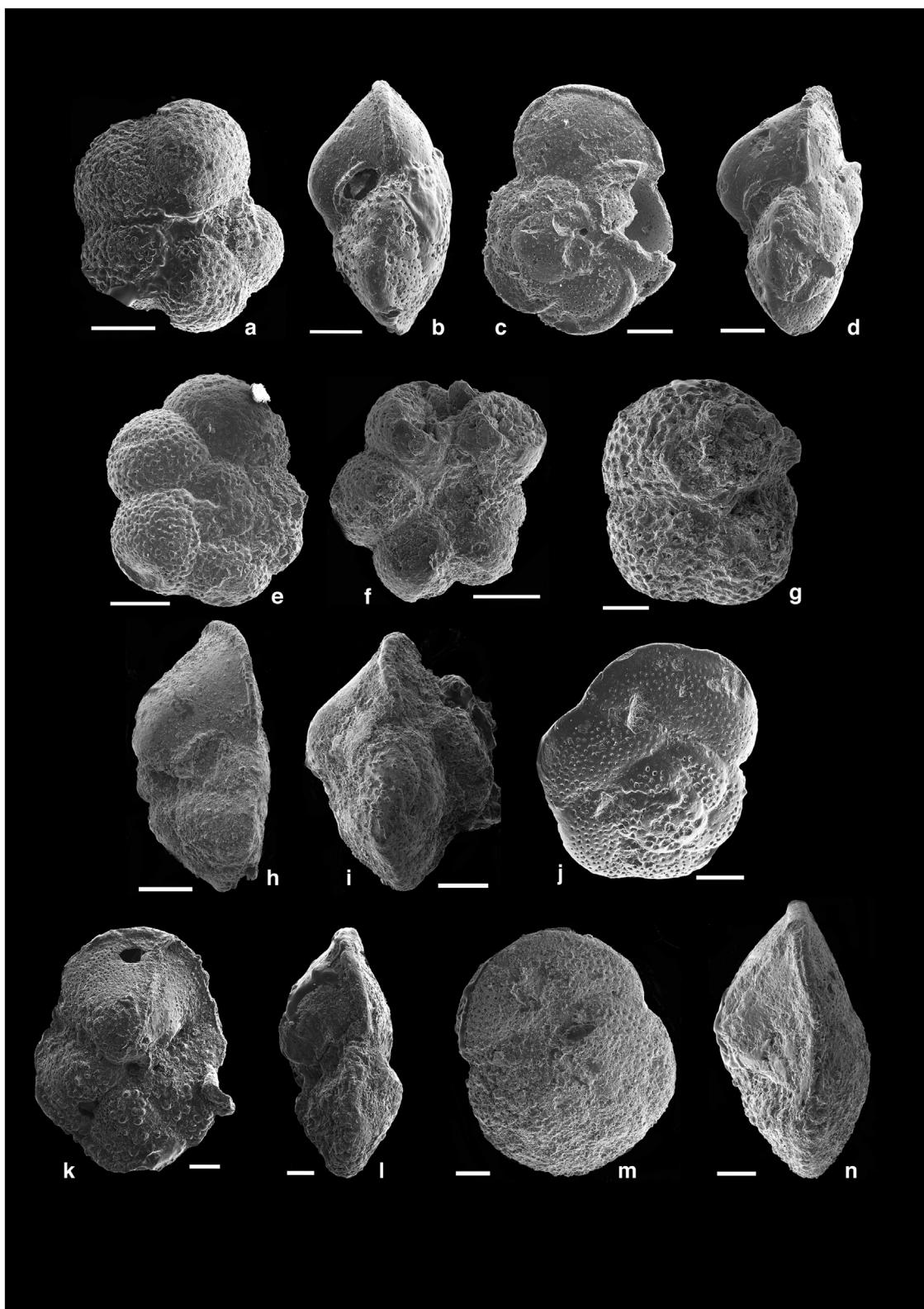
Fig. 7. Biostratigraphically relevant planktonic foraminifer species. a) Sinistral *Neogloboquadrina acostanensis*, umbilical view (GAND-2). b-d) *Globorotalia miotumida* group (*G. mediterranea-conomiozea* morphotypes) in lateral (b and d) and dorsal (c) views (GAND-3). e-f) *Globigerina multiloba*, dorsal (e) and umbilical (f) views (GAND-4 and GAND-3 respectively). g) *Globigerinoides conglobatus*, umbilical view (GAND-4). h-i) *Globorotalia miotumida* group, lateral views (GAND-9). j) Dextral *Globorotalia scitula*, dorsal view (GAND-9). k-l) *Globorotalia menardii* group, umbilical (k) and lateral (l) views (IZN-P-2). m-n) *Globorotalia margaritae*, dorsal (m) and lateral (n) views (CERRO–CUCHILLO-2). Scale bars = 50 μm.
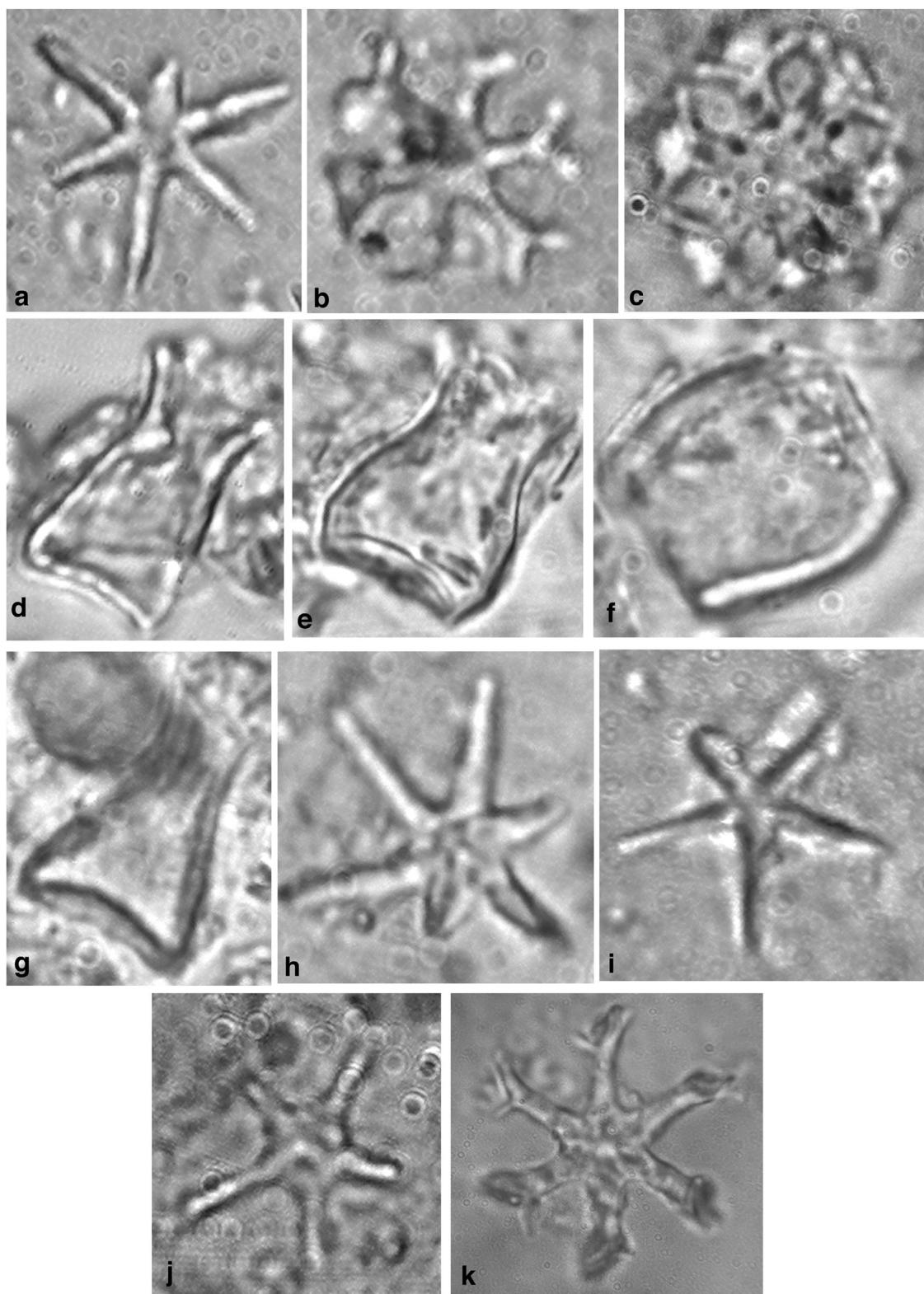
Fig. 8. Biostratigraphically relevant calcareous nannoplankton species. a) *Discoaster brouweri* (GAND-5). b) *D. challengeri* (GAND-5). c) *D. icarus* (GAND-5). d) *S. cantharellus* (CvSM-0). e) *Scyphosphaera glastonensis* (CvSM-0). f) *S. apsteinii* (CvSM-0). g) *S. lagena* (CvSM-0). h) *D. brouweri* (EST-BOB-5). i) *Discoaster quinqueramus* (EST-BOB-5). j) *D. bergrenii* (EST-BOB-5). k) *D. loeblichii* (EST-BOB-5).
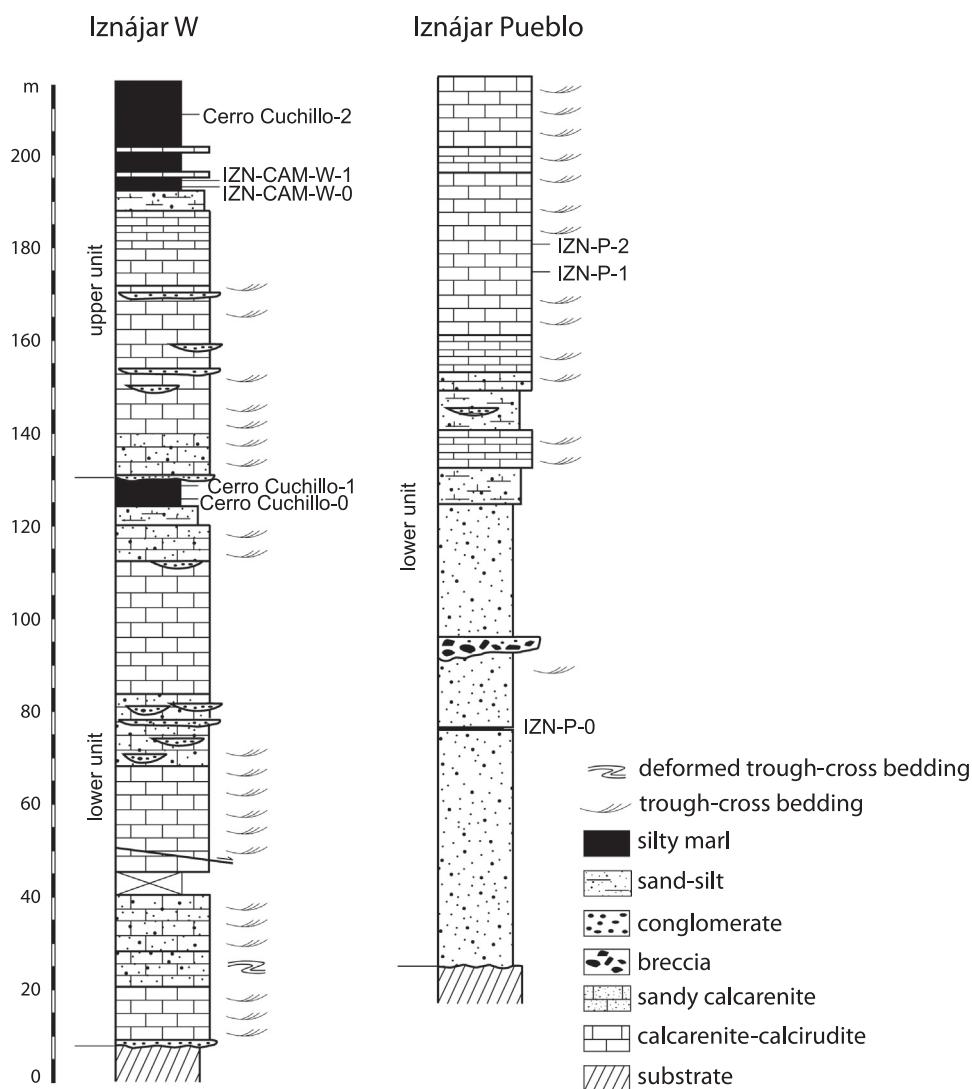
Fig. 9. Stratigraphic logs in Iznájar area with indication of the position of the study samples.
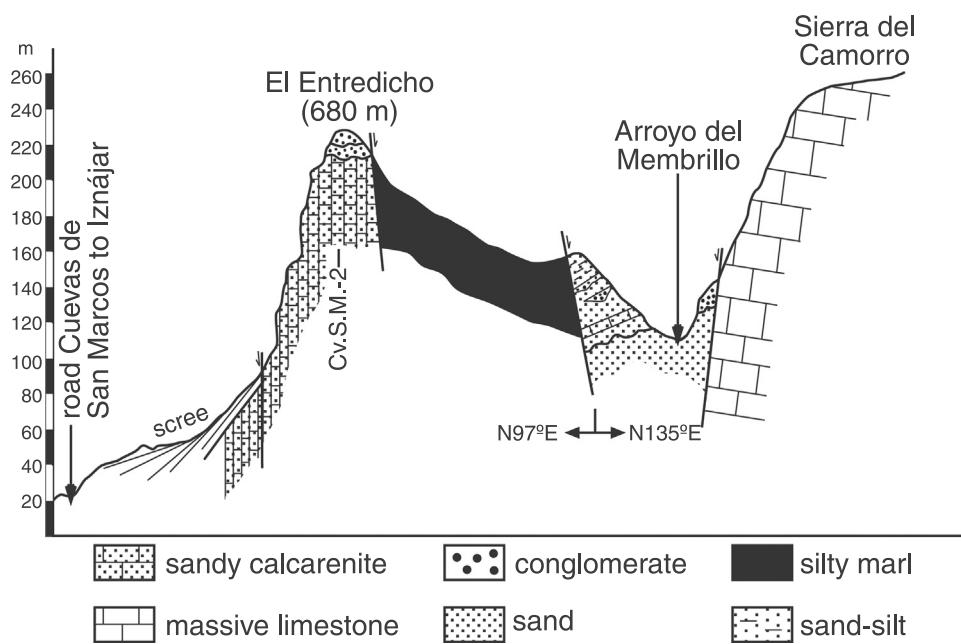
Fig. 10. Stratigraphic section in Cuevas de San Marcos with indication of the position of the study sample.
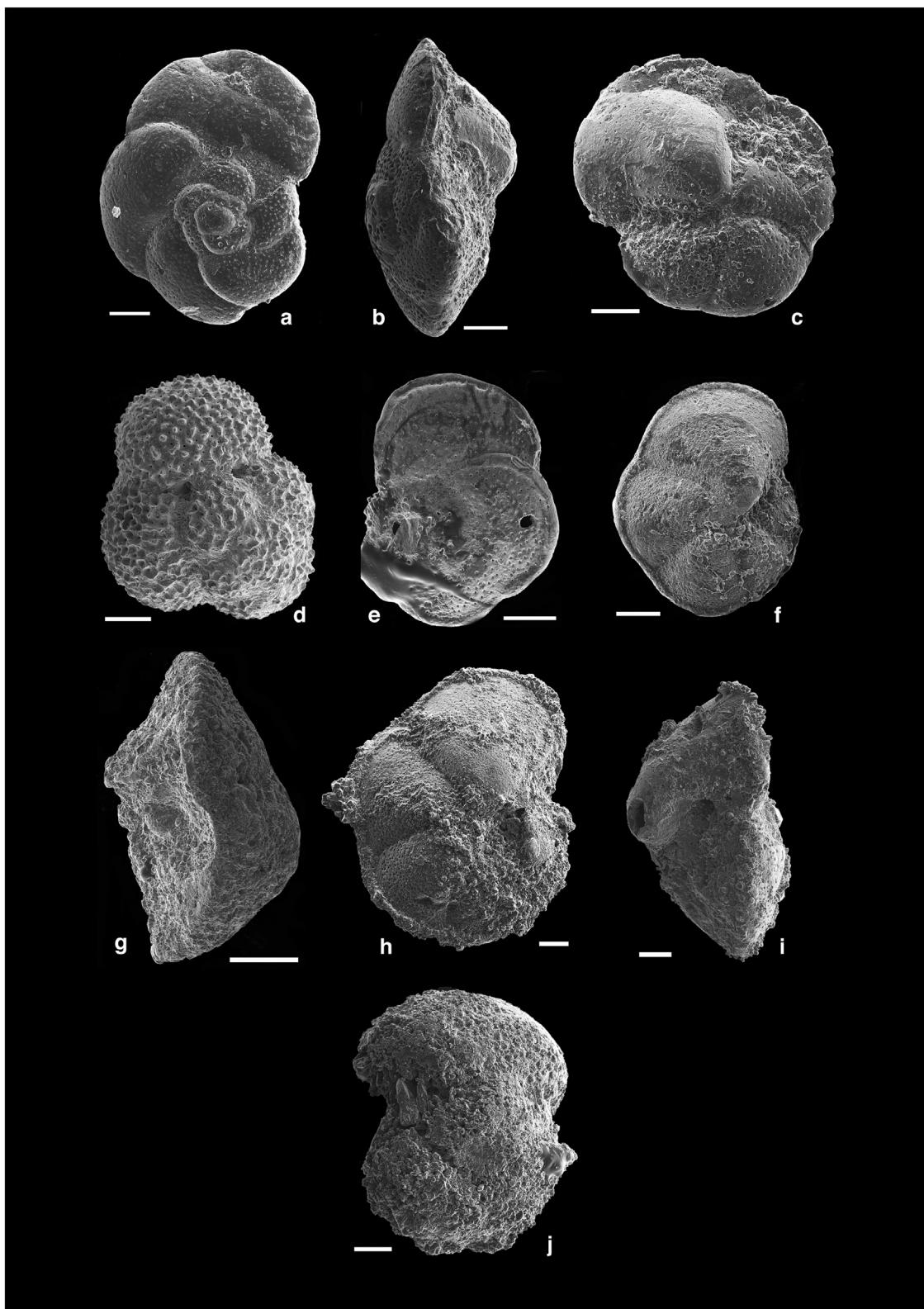
Fig. 11. Biostratigraphically relevant planktonic foraminifer species. a-c) *Globorotalia margaritae*, dorsal (a), lateral (b), and umbilical (c) views (CvSM-1). Note that the penultimate and part of the last chamber are broken in the umbilical view. d) *Globigerinoides bulloideus*, dorsal view (EST-BOB-0). e-f) *Globorotalia miotumida* group, dorsal (e) and umbilical (f) views (EST-BOB-4). g) *Globorotalia margaritae*, lateral view (EST-BOB-10). h-i) *Globorotalia miotumida* group, umbilical (h) and lateral (i) views (TEBA-1A). j) *Globigerinoides conglobatus*, lateral view (TEBA-1A). Note the recrystallization of the test, with calcite crystals partially closing the aperture in the umbilical side. Scale bars = 50 μm.
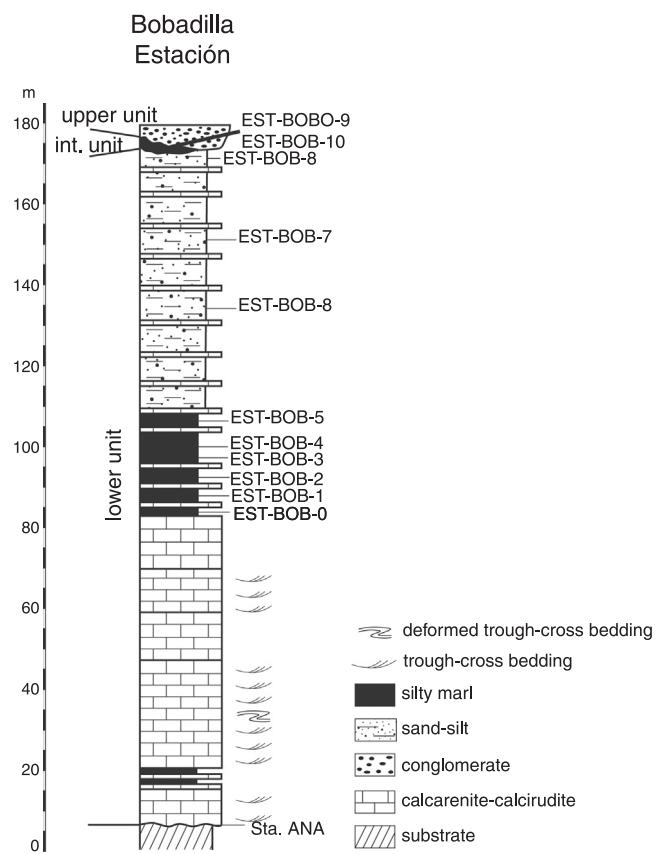
Fig. 12. Bobadilla Estación section with indication of the position of the study samples.

5.2. Age of the study deposits

Despite the problems and limitations commented above, combined planktonic foraminifer and calcareous nannoplankton data show robust results that allow precisely dating the upper Miocene deposits in the central sector of the southern margin of the Guadalquivir Basin.

In those areas where accurate biostratigraphic data were obtained, late Miocene sedimentation started during the late Tortonian. The oldest deposits are the blue marls that crop out at the base of the La Magdalena section, in the Antequera area. They can be assigned to the early late Tortonian, upper MMi11 biozone of Lirer et al. (2019).

Unconformably above the marls, deposition in the Antequera area started during the late Tortonian, MMi12 biozone of Lirer et al. (2019). For the upper part of the successions in La Magdalena and Gandigüela sections, biostratigraphic evidence points out that marine sedimentation continued into and ended during the early Messinian: dominance of the *Globorotalia miotumida* group (including *Globorotalia mediterranea-G. conomiozea* morphotypes) over the *G. menardii* group, and the presence of *Globigerinoides conglobatus, G. bulloideus, Globigerina multiloba*, and putative specimens of *Globorotalia margaritae*.

Globigerina multiloba (=*Turborotalia multiloba*) is considered an endemic species of the Mediterranean (Iaccarino, 1985; Lirer et al., 2019). Its first common occurrence in the Mediterranean is dated at 6.42 Ma (Lourens et al., 2004; Lirer et al., 2019). Lirer et al. (2019) recorded the last influx of the species at 6.07 Ma. The taxonomic status of this species has been questioned, as it has been considered an ecophenotypic variant of *Turborotalita quinqueloba* (Lirer et al., 2019). In addition, *G. multiloba* has never been found in the Atlantic and its first appearance in the Mediterranean was probably due to ecological factors (Iaccarino, 1985). Therefore, its validity as biostratigraphic marker is arguable. Nonetheless, considering that the study area is in the confluence of the Atlantic and the Mediterranean and taking into consideration the limitations to
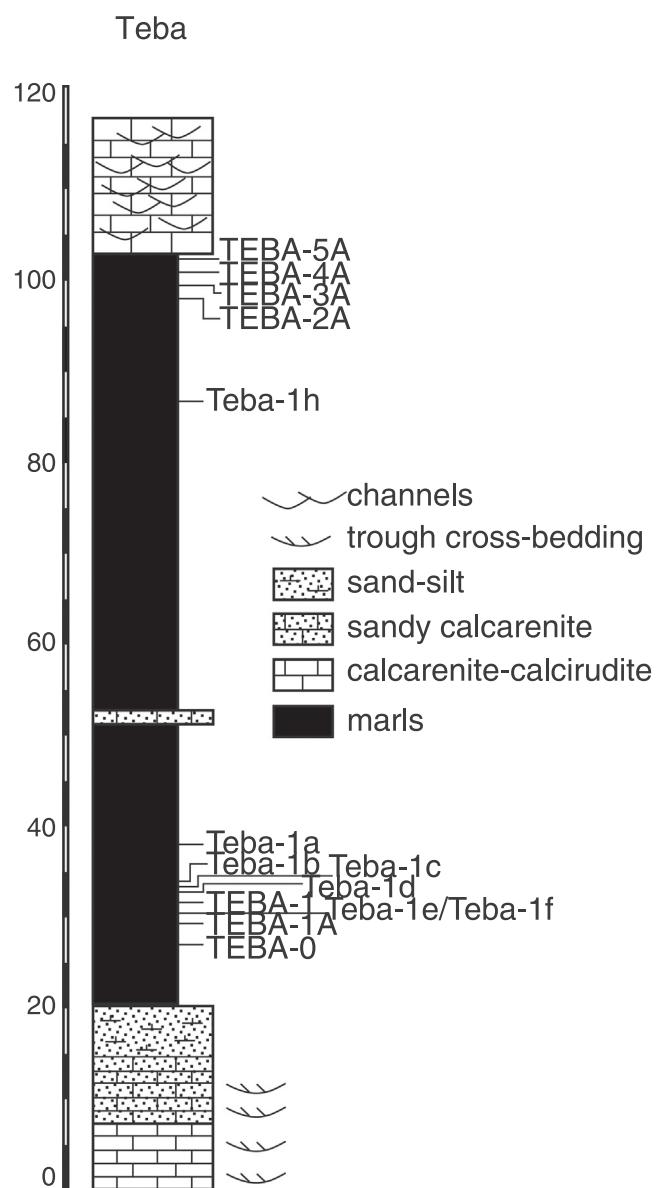
Fig. 13. Teba section with indication of the position of the study samples.

date the stratigraphic units, it is interesting to highlight the presence of that species as additional evidence to constraint the age of the deposits.

G. bulloideus ranges from the base of the Messinian to the top of the Zanclean (early Pliocene) (Kennett and Srinivasan, 1983) (Fig. 5a). The first occurrence of *G. conglobatus* also took place in the Messinian (Serrano, 1979; Kennett and Srinivasan, 1983; Chaisson and Pearson, 1997; Lourens et al., 2004; Wade et al., 2011), at 6.20 Ma (Lourens et al., 2004; Wade et al., 2011) (Fig. 5a).

Finally, the first occurrence of *G. margaritae* is recorded at about 6 Ma (Wade et al., 2011) or at 6.4 (Chaisson and Pearson, 1997), while in the Mediterranean its first common occurrence is at 5.08 Ma, in the early (not basal) Zanclean (early Pliocene) (Lourens et al., 2004; Lirer et al., 2019) (Fig. 5). Different morphotypes close to *G. margaritae* have been described in Messinian deposits, both in the Mediterranean and in the Atlantic (e.g. González-Donoso et al., 1977-78; Benson and Rakic-El Bied, 1991; Violanti 2012): *Globorotalia martinezi* (Perconig, 1968), *G. praemargaritae* (Catalano and Sprovieri, 1969, 1972), *G. margaritae primitiva* (Cita, 1973), ancestral *G. margaritae* (Perconig, 1973; Martínez-Fresneda, 1977), *G. margaritae* 'mediterranea' form (Carrasco et al., 1979), or *G. andalusiana* (Perconig et al., 1980). Regardless of their
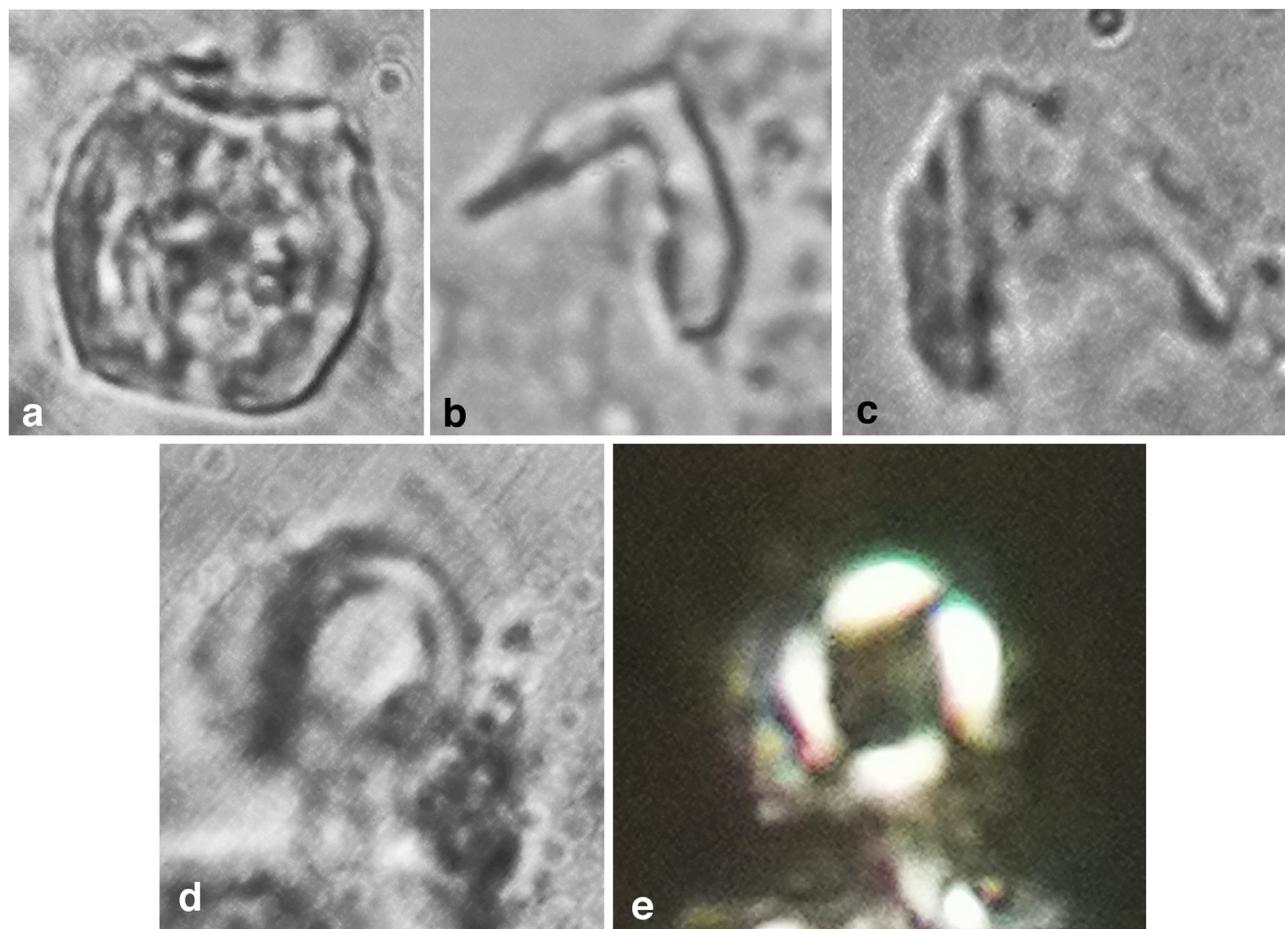
Fig. 14. Biostratigraphically relevant calcareous nannoplankton species from the Teba section. a) *Scyphosphaera ventriosa* (Teba-1c). b) *Amaurolithus primus* (Teba-1f). c) *Amaurolithus amplificus* (TEBA-1). d-e) *Reticulofenestra rotaria* with transmitted (d) and polarized (e) light (Teba-1f).

taxonomic validity, an issue well beyond the scope of this paper, all these taxa have been considered as forms within the *G. margaritae* plexus (Aze et al., 2011; Violanti 2012). All species of the taxon plexus have been recorded in Messinian deposits in different areas along the southern margin of the Guadalquivir Basin (Verdenius, 1970; Perconig, 1973; Perconig and Granados 1973; Berggren and Haq, 1976; Martínez-Fresneda, 1977; González-Donoso and Serrano, 1977; Serrano, 1979; Perconig et al., 1980; Aguirre et al., 2015).

A similar age interval is obtained for the lower unit in Estación Bobadilla area. Here, marine sedimentation started during the late Tortonian and continued in the Messinian as corroborated by dominance of the *G. miotumida* group together with the presence of *G. bulloideus, G. conglobatus*, and dextrally-coiled *G. scitula*.

Putative individuals of *G. margaritae* are also present in the upper unit of the Iznájar-Cuevas de San Marcos area, as well as in the intermediate unit at Bobadilla Estación area. The dominance of scyphosphaerids, with the presence of *S. apsteinii* morpho B of Lancis and Flores (2004a), in the upper unit in Cuevas de San Marcos agrees with a Messinian age.

Finally, the marls of Teba area are unquestionably early Messinian in age as confirmed by the dominance of the *G. miotumida* group, dominantly dextral-coiled *G. scitula*, and the presence of *Reticulofenestra rotaria, Amaurolithus primus*, and *A. amplificus*. The presence of *Globigerinoides conglobatus* and *G. bulloideus* confirms this age.

5.2. Implications for the closure of the Guadalhorce Corridor

The confirmation that sedimentation in the study areas of the southern Guadalquivir Basin in the central Betic Cordillera ranges from the late Tortonian to the early Messinian in age implies that no data indicate that the Guadalhorce Corridor was already closed in the early Messinian. Martín et al. (2001), based on planktonic foraminifer data, showed that this Betic gateway connecting the Atlantic and the Mediterranean was still open in the earliest Messinian and was closed afterwards. Magnetobiostratigraphic data, together with oxygen stable isotope stratigraphy, in the western Guadalquivir Basin corroborated that the Guadalhorce Corridor closed in the early Messinian, at about 6.18 Ma (Pérez-Asensio et al., 2012; 2013).

Recently, however, van der Schee et al. (2018) have questioned this chronology and argued that the corridor was closed during the late Tortonian. These authors, however, recognize that they did not find reliable biostratigraphic results to conclusively date the Guadalhorce deposits and, consequently, the end of the sedimentation in the Guadalhorce gateway (van der Schee et al., 2018; p. 328). They obtained imprecise results ("age undetermined" according to van der Schee et al., 2018; Guadalhorce section in their Fig. 3) yielded from samples collected in rip-up clasts eroded away from the basement and incorporated in the large-scale trough cross-bedded strait facies and additional samples taken in marlstones cropping out further to the north. Due to the lack of data, van der Schee et al. (2018) established the age of the Guadalhorce deposits and the closure of the corridor based on indirect and questionable lithological correlations with deposits found in close areas, such as Antequera, and additional distant and separate areas, such as Ronda and Arcos de la Frontera (Figs 1, 15): "For the deposits in the Guadalhorce Valley, we agree with López-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. Therefore, these sediments were probably also de-
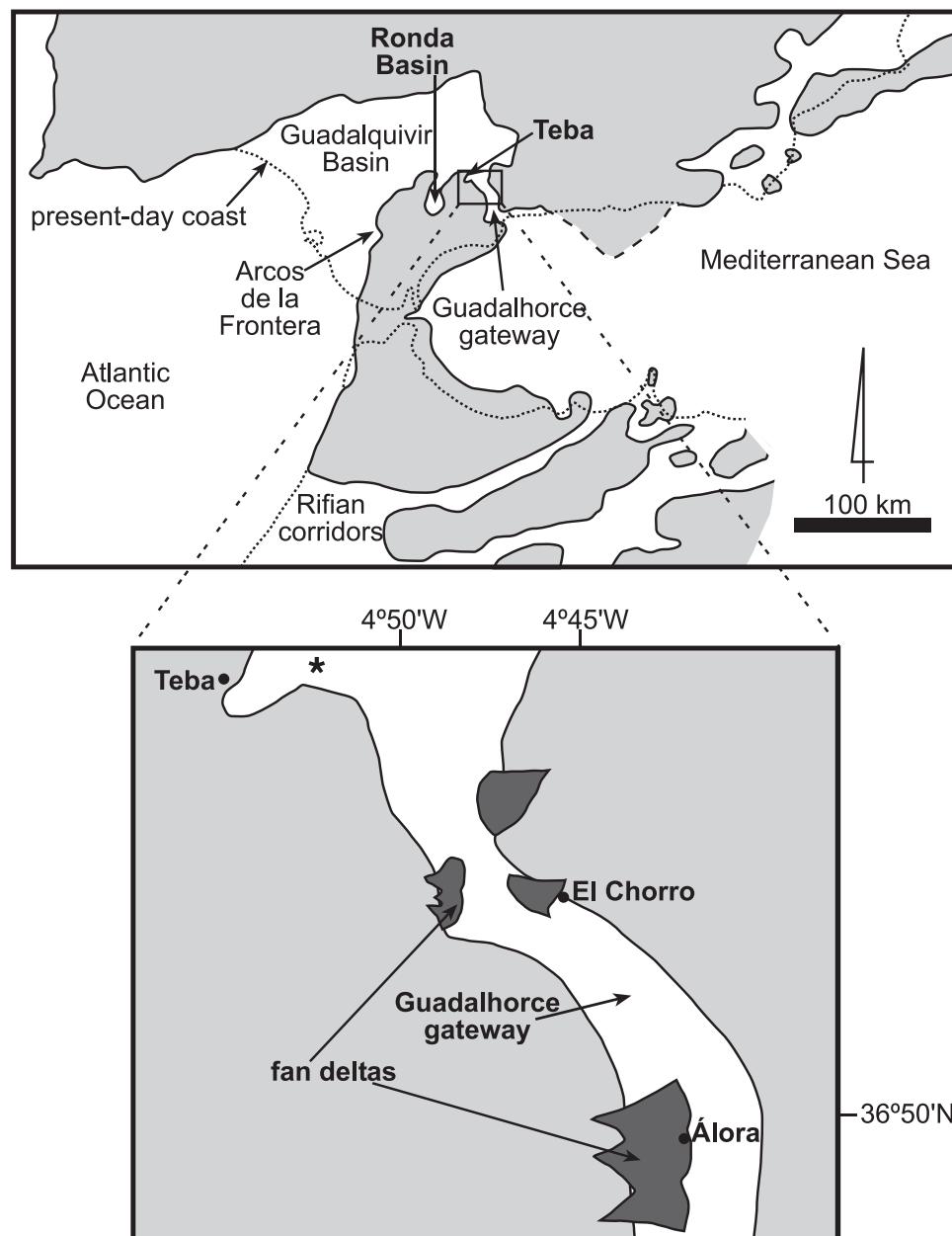
Fig. 15. Paleogeographic reconstruction of the Guadalhorce gateway during the earliest Messinian. The upper panel shows a general paleogeographic map indicating the position of the Guadalhorce gateway, and the location of the Atlantic-linked Ronda Basin as well as of the Arcos de la Frontera Basin, both areas located away from the Guadalhorce northern end. The lower panel shows the enlarged area of the square in the upper panel. Modified from Martín et al. (2001).

posited in the late Tortonian" (van der Schee et al., 2018; pp 328–329).

The Ronda and Arcos de la Frontera basins (Figs 1, 15) were opened to the Atlantic during the late Miocene and lower Messinian sediments ended deposition both in Ronda (Martínez-Fresneda, 1977; González-Donoso and Serrano, 1977; Serrano, 1979; Rodríguez-Fernández, 1982; Gläser and Betzler, 2002) and in Arcos de la Frontera basins (Viguier, 1974; Perconig and Granados, 1973; Martínez-Fresneda, 1977; Jerez-Mir, 1990; Gutiérrez-Mas et al., 1991; Clauss, 1991; 1995). The data presented herein also show that marine sedimentation continued until the early Messinian in the Antequera and Bobadilla Estación areas, to the east of the northern end of the Guadalhorce seaway. In addition, especially significant are the results obtained in Teba, located just at NW end of the Guadalhorce Strait (Fig. 15), where *Globorotalia miotumida* dominates the keeled globorotaliid assemblages, with the presence of *G. mediterranea-conomiozea* morphotypes, dextrally-coiled *Globorotalia scitula* dominates the non-keeled globorotaliid assemblages, and *Reticulofenestra rotaria*, *Amaurolithus primus*, and *A. amplificus* are present in the calcareous nannoplankton assemblages (Figs 14b-14e).

This scenario entails that the Guadalhorce corridor was still active, at least during the early Messinian, as demonstrated by the presence of Messinian deposits in areas adjacent to the northern end of this gateway and farther east in the Guadalquivir Basin. Probably the uplifting of the Betic basement triggering the gateway closing was also responsible of the end of marine sedimentation in the nearby Antequera area during the early Messinian.

6. Conclusions

Several depocenters or satellite sub-basins formed at the southern margin of the Guadalquivir foreland basin in the central Betic Cordillera (S. Spain) during the late Miocene. Mixed siliciclastic-carbonate and carbonate sedimentation prevailed in the basin infillings. Re-assessment of the biochronology and the stratigraphy of the upper Miocene deposits in these sub-basins indicates that sedimentation took place from the late Tortonian to the early Messinian.

In the Antequera area, the study deposits locally overlie blue marls dated between the first occurrence of *Neogloboquadrina humerosa* and

the last occurrence of *Globorotalia menardii* 4 at 7.51 Ma. The overlying carbonate and mixed siliciclastic-carbonate deposits range from the late Tortonian at the base to the early Messinian at the top. This is based on the dominance of the *Globorotalia miotumida* group and the presence of dextrally-coiled *Globorotalia scitula* group, *Globigerina multiloba, Globigerinoides bulloideus, Globigerinoides conglobatus*, and putative representatives of *Globorotalia margaritae*. The upper part of the unit is dominated by discoasters, such as *Discoaster brouweri, D. neorectus, D. challengeri, D. icarus, D. surculus*, together with *Triquetrorhabdulus rugosus* and *Helicosphaera carteri*. This assemblage indicates a latest late Tortonian-early Messinian age; that is, upper part of the biozone NN11A of Martini (1971) or of the biozone CN9a of Okada and Bukry (1980).

In the Iznájar-Cuevas de San Marcos area, there are two unconformable units. The lower one belongs to the late Tortonian, above the first occurrence of *Globorotalia suterae* (~7.8 Ma). The upper unit is early Messinian in age, based on the presence of individuals of putative *Globorotalia margaritae*, and the abundant and diversified calcareous nannoplankton assemblages dominated by scyphosphaerids (*Scyphosphaera recurvata, S. ampla, S. gladstonensis, S. cantharellus, S. lagena*, and *S. apsteinii*).

Three units are recognized in the Bobadilla Estación area. The lower one ranges from the late Tortonian to the early Messinian based on the dominance of the *Globorotalia miotumida* group and sinistrally-dominated forms of *N. acostaensis* as well as the *Globorotalia scitula* group. The presence of *G. bulloideus* and *G. conglobatus* in the middle part of the lower unit is consistent with an early Messinian age. Here, *Discoaster quinqueramus*, which ranges from the late Tortonian to the Messinian, is also present. The intermediate unit is spatially limited and represented by green marls belonging to the early Messinian based on the presence of putative *Globorotalia margaritae* together with the *G. miotumida* group. The uppermost unit cannot be dated.

In Teba, planktonic foraminifer assemblages dominated by *Globorotalia miotumida* group and dextral *G. scitula*, together with the presence of *Reticulofenestra rotaria, Amaurolithus primus*, and *A. amplificus* among calcareous nannoplankton assemblages unequivocally indicate a Messinian age.

The presence of Messinian sediments in areas at the northern end of the Guadalhorce Corridor (Teba), as well as farther east (Bobadilla Estación and Antequera), supports that this gateway was active during the early Messinian.

Résumé

Des dépôts mixtes siliciclastiques-carbonatés se sont déposés dans plusieurs sous-bassins satellites à la marge méridionale du bassin du Guadalquivir, le bassin d'avant-pays de la Cordillère Bétique (Sud de l'Espagne). Les sédiments à gros grains dominants et le dépôt dans des eaux peu profondes rendent difficile l'établissement de l'âge précis des successions stratigraphiques complètes. Pour cette raison, dans les études précédentes, ces dépôts ont été attribués à la fin du Tortonien, bien qu'un âge Messinien n'ait pas été totalement exclu. L'âge des dépôts du Miocène supérieur dans la partie centrale du bassin du Guadalquivir est ici réévalué sur la base de l'analyse de plusieurs sections distribuées dans différentes zones: Antequera, Iznájar-Cuevas de San Marcos, Teba, et Bobadilla Estación. D'après les assemblages de foraminifères planctoniques et de nannoplancton, le remplissage sédimentaire marin de ce secteur de la marge sud du bassin du Guadalquivir est d'âge Tortonien supérieur-Messinien inferieur (Miocène supérieur). La présence de dépôts marins caractérisés par la dominance du groupe *Globorotalia miotumida*, de *G. scitula* à enroulement dextrogyre, et la présence de *G. margaritae, Globigerina multiloba, Discoaster quinqueramus* et *Amaurolithus primus, A. amplificus*, et *Reticulofenestra rotaria* au bout nord du Corridor du Guadalhorce, la dernière connexion marine active de la Cordillère Bétique reliant l'Atlantique et la Méditerranée, indique qu'il est resté ouvert jusqu'au Messinien inferieur.

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