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Tectono-sedimentary evolution of the peripheral basins of the Alboran Sea in the arc of Gibraltar during the latest Messinian-Pliocene

Antonio Guerra-Merchán[a,*], Francisco Serrano[a], Rachid Hlila[b], Khalil El Kadiri[b], Carlos Sanz de Galdeano[c], Miguel Garcés[d]

[a] *Departamento de Ecología y Geología, Universidad de Málaga, 29071 Málaga, Spain*
[b] *Département de Géologie, Faculté des Sciences, Université Abdel Malek Essaâdi, 93003 Tétouan, Morocco*
[c] *Instituto Andaluz de Ciencias de la Tierra, CSIC-Universidad de Granada, 18071 Granada, Spain*
[d] *Departamento Estratigrafía, Paleontología y Geociencias Marinas, Universidad de Barcelona, 08028 Barcelona, Spain*

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ABSTRACT

In the peripheral basins of the Alboran Sea, five stratigraphic units (latest Messinian-Pliocene) separated by discontinuities and representing transgressive–regressive cycles have been recognized. The first unit (LM) is latest Messinian in age and precisely characterizes the Lago-Mare event at the end of the Messinian Salinity Crisis, i.e. just before the opening of the Strait of Gibraltar at the beginning of the Pliocene. The three following units (Pl-1, Pl-2 and Pl-3) are Zanclean in age, whereas the last one (Pl-4) is Piacenzian. These four Pliocene units consist of alluvial, deltaic, and littoral deposits in the marginal areas, changing to open marine deposits with planktonic components in the basinal areas, although their extension varies in each basin. Regionally, these units do not necessarily stack in a single stratigraphic succession because of tectonics that controlled their hosting basins. Thus, the LM and Pl-1 units occur only in the Malaga and Estepona-Marbella basins, revealing that the onset of the sedimentation after the Messinian evaporitic stage and the Pliocene transgression was not a single and synchronous event in the western Alboran Sea. Moreover, the Pl-3 and Pl-4 units do not appear in all basins, so that the subsequent continentalization process of these Alboran peripheral areas during the Pliocene was also diachronous.

The sedimentary evolution of the peripheral basins was controlled mainly by tectonics. During the latest Messinian-early Pliocene, the sedimentation took place in a context marked by a NNW–SSE compression and ENE–WSW perpendicular tension. The onset of the sedimentation (LM and Pl-1 units) could be linked to preexisting E–W faults that mark part of the borders of the Malaga basin and the Estepona-Marbella sector. During the deposition of the Pl-2 unit, the movements of E–W, NW–SE, and NE–SW normal faults determined a continuous subsidence in several basins, resulting in the accumulation of thick clastic marine sequences (i.e. Malaga, Vélez-Málaga, and Nerja basins in Spain and Tirinesse basin in Morocco). Tectonic activity during the early Zanclean leads to a new paleogeographic configuration of the Alboran peripheral areas. The main features are: (i) continentalization of the Nerja sector in the Betics, Tetouan, and Oued Laou-Tirinesse sectors in the Rif; (ii) on the contrary, a period of intense subsidence started in the coastal sectors between Torremolinos and Manilva, allowing the development of the Pl-3 unit directly on the substratum; and (iii) the Malaga, Vélez-Málaga, and Malalyine basins maintained the marine regime, so their sedimentary infilling recorded the Pl-2–Pl-3 unconformity. Nevertheless, these last basins emerged shortly afterwards, before the end of the early Zanclean (FO of *Globorotalia puncticulata*), probably in relation to the beginning of the sea-level fall which characterizes the upper part of the TB 3.4 cycle by Haq et al. (1987).

During the late Zanclean, sedimentation occurred only in the Betic basins, where NNE–SSW faults – conjugated with NW–SE faults – induced a major subsidence, permitting better development of the Pl-3 unit. On the contrary, NW–SE faults in the sector between Malaga and Nerja, and NE–SW faults in the Tirinesse basin, became practically inactive. Before the end of the Zanclean, the subsidence ceased also in the westernmost Betic basins, thus causing emersion, firstly in the sector between Torremolinos and Manilva and, slightly later, in the San Roque-Algeciras sector. Thus, the whole geodynamic activity conditioned the time–space evolution of the northern edge of the Alboran Sea, which was emerging throughout the Zanclean, successively from the E to the W. A similar E to W continentalization trend can be suggested for the Rifian Pliocene sectors when taking into account the Oued Laou-Tirinesse basins that emerged before the Malalyine one.

* Corresponding author. Tel.: +34 952131860.
E-mail address: antguerra@uma.es (A. Guerra-Merchán).

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Moreover, the unit boundaries do not coincide with those of the familiar *Exxon* coastal aggradational curve, but rather with the local or regional tectonic activity. Consequently, the correlation of the unit boundaries with those of the Pliocene deposits of the eastern Betic basins remains difficult. According to the biostratigraphical data, the Pl-1, Pl-2, and Pl-3 units correspond to the Pliocene-I by Montenat (1990), while the Pl-4 unit may be equivalent to the Pliocene-II.

1. Introduction

The continentalization of the postorogenic Betic basins occurred diachronously throughout the Late Neogene (Serrano, 1979; Montenat, 1990; Sanz de Galdeano and Vera, 1992; Rodríguez-Fernández and Sanz de Galdeano, 1992). Most of the intramontane basins (i.e. Antequera, Lorca, Fortuna, Las Alpujarras Corridor, Guadix-Baza, and Granada basins) first emerged during the late Tortonian. Other basins (i.e. Ronda, Huércal-Overa, and Almanzora Corridor) emerged during the Messinian due to tectonics and/or eustatic fall before the Messinian Salinity Crisis (MSC). MSC sedimentation is well recorded in the eastern Betic basins (i.e. Sorbas, Nijar, Cartagena, San Miguel de Salinas, and elsewhere). Two phases can be clearly differentiated during the MSC in the Mediterranean realm: (i) the evaporitic phase (Hsü et al., 1973a,b; Cita et al., 1978) featured by an arid climate and negative water balance (as at present), leading to a strong drying and accumulation of evaporites in deep and peripheral Mediterranean basins, and (ii) the Lago-Mare phase (Ruggieri, 1962, 1967; Roveri and Manzi, 2006) characterized by a predominant positive balance between rain + runoff and evaporation. The Lago-Mare conditions could have given rise to a marked stratification of the Mediterranean waters, with an oligo- to mesohaline surface layer and a more saline layer below (Guerra-Merchán et al., 2010). No significant evaporite accumulations during the MSC have been detected in the Alboran basin (Comas et al., 1999); on the contrary, deposits related to the Lago-Mare event are found in the Spanish Malaga and Marbella areas (Guerra-Merchán et al., 2010) and African Melilla area (Rouchy et al., 2003).

Some authors point to the possibility of episodic exchanges between Atlantic and Mediterranean seawaters during the latest Messinian MSC (see comments in Orszag-Sperber, 2006; Rouchy and Caruso, 2006; Guerra-Merchán et al., 2010 with references therein). However, it is generally considered that the opening of the Strait of Gibraltar at the beginning of the Pliocene (5.33 Ma, Hilgen and Langereis, 1993) was the essential cause for the re-establishment of normal marine conditions in the Mediterranean. The quick change from brackish conditions during the Lago-Mare event, in the latest Messinian, to the Pliocene open marine conditions seems to have occurred synchronously (Iaccarino et al., 1999; Rouchy et al., 2001; Pierre et al., 2006 among others), and represents a key event characterizing the beginning of the Pliocene in the Mediterranean domain (Cita, 1975).

The Pliocene marine transgression is noticeable mainly in the basins located near the current coastline (i.e. Alicante-Cartagena, Vera, Sorbas-Tabernas, Almería-Níjar-Carboneras, Campo de Dalías, Vélez-Málaga, Malaga, Fuengirola, Marbella-Estepona, Manilva, San Roque, and Algeciras basins). However, most of these basins remained under marine regime for a short time and therefore emerged before the end of the Zanclean.

Ever since Montenat (1977), it has been generally accepted that in the Eastern Betic basins, the Pliocene deposits consist of two units separated by an intra-Pliocene discontinuity (e.g. Montenat, 1977, 1990; Megías et al., 1983; Aguirre, 1995; Estrada et al., 1997). The Pliocene I unit would correspond to the early Pliocene, based on the presence of *G. margaritae* and *G. puncticulata* (formal names in Table 1), whereas the Pliocene II unit has been considered late Pliocene in age based mainly on its stratigraphic position

Table 1
Taxonomic appendix: apocopated forms and their respective formal names for planktonic foraminifera used throughout the text.

Apocopated form	Formal name
G. bulloides	*Globigerina bulloides* d'Orbigny, 1826
G. apertura	*Globoturboralita apertura* (Cushman, 1918)
G. decoraperta	*Globoturboralita decoraperta* Takayanagi & Saito, 1962
G. obesa	*Globigerinella obesa* (Bolli, 1957)
G. elongatus	*Globigerinoides elongatus* (d'Orbigny, 1826)
G. extremus	*Globigerinoides extremus* Bolli & Bermúdez, 1965
G. obliquus	*Globigerinoides obliquus* Bolli, 1957
G. ruber	*Globigerinoides ruber* (d'Orbigny, 1839)
G. sacculifer	*Globigerinoides sacculifer* (Brady, 1877)
G. trilobus	*Globigerinoides trilobus* (Reuss, 1850)
G. aemeliana	*Globorotalia aemiliana* Colalongo & Sartoni, 1967
G. bononiensis	*Globorotalia bononiensis* Dondi, 1962
G. crassaformis	*Globorotalia crassaformis* (Galloway & Wissler, 1927)
G. hirsuta	*Globorotalia hirsuta* (d'Orbigny, 1839)
G. inflata	*Globorotalia inflata* (d'Orbigny, 1839)
G. margaritae	*Globorotalia margaritae* Bolli & Bermúdez, 1965
G. puncticulata	*Globorotalia puncticulata* (Deshayes, 1832)
Neogloboquadrina spp., including:	
	Neogloboquadrina acostaensis (Blow, 1959)
	Neogloboquadrina humerosa (Takayanagi & Saito, 1962)
O. universa	*Orbulina universa* d'Orbigny, 1839
Sphaeroidinellopsis spp., including:	
	Sphaeroidinellopsis seminulina (Schwager, 1866)
	Sphaeroidinellopsis subdehiscens Blow, 1959

(Montenat, 1977, 1990). This stratigraphic framework has been extended to other Betic basins as two Pliocene sequences separated by an unconformity were recognized. The scarcity or lack of biostratigraphic and chronostratigraphic data has led to notable discrepancies concerning the assignment of sedimentation in these basins to the Pliocene I or II. However, in peripheral basins of the Alboran Sea from the province of Malaga (Guerra-Merchán et al., 2000, 2010), Zanclean deposits show one or several unconformities, leading to a more complex stratigraphic scheme with several units within the Pliocene I.

In all the basins, the Pleistocene sedimentation is characterized mainly by continental deposits, and only Pleistocene coastal deposits are spread close to the current shoreline from Gibraltar to Alicante (Goy and Zazo, 1986; Goy et al., 1986; Lario et al., 1993; Rodríguez-Vidal et al., 2004 among others).

In the present work, we study latest Messinian-Pliocene deposits outcropping in the peripheral areas of the western Alboran (Fig. 1). In the literature available (Sanz de Galdeano and López Garrido, 1991; Guerra-Merchán and Serrano, 1993; Aguirre, 1995; Guerra-Merchán et al., 2000, 2002, 2004, 2010 with references therein), there are notable discrepancies regarding the differentiation of stratigraphic units and their age. Based on unconformities, facies, and sedimentary analysis, biostratigraphic control by means of planktonic foraminifera, and paleomagnetic data, we establish a chronostratigraphic and tectonic framework for the latest Messinian-Pliocene deposits currently emerged in the western Alboran. This integrated approach allows us to correlate these deposits with Pliocene marine units from other sectors of the Betic Cordillera, the Moroccan Rif, as well as with sediments from cores inside the Alboran Sea. The results highlight the main lines of the