**Late Miocene and Early Pliocene coastal deposits from the Canary Islands: New records and paleoclimatic significance**

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**Abstract**

New records of Miocene and Pliocene coastal deposits of paleoclimatic significance are registered in the eastern Canary Islands, a hundred km off the NW Africa’s coasts.

Late Miocene marine deposits are assigned to the Tortonian through a new 40Ar/39Ar age (9.60 ± 0.05 Ma) of an overlying lava flow at the Janubio site in Lanzarote Island. These deposits contain littoral and intertropical genera of fossils as the gastropod *Nerita* and the coral *Siderastrea*, they are almost horizontal and were elevated up to 36 m in height by regional or local tectonics.

Furthermore, Early Pliocene coastal deposits studied, are mainly marine conglomerates and sandstones and derived aeolianites, that are spread over the south of Lanzarote and the west of the Jandía peninsula in Fuerteventura Island. No associated lava flow permits their dating, and the absence of aragonite in their fossils also eliminates the possibility of strontium isotope dating. Nevertheless, a series of characteristics allow attributing them to the Zanclean: (a) They are all inclined toward the coast in the form of a large layer elevated up to 70 m a.s.l.; (b) they contain marine fossils of littoral and intertropical genera, as the gastropods *Nerita* and *Persististrombus* and the coral *Siderastrea*, in a surrounding geological environment with gypsum and aeolianites all formed during a eustatic marine regression; (c) the nearby existence of paleosols with particular structures indicates the start of climatic seasonality in the region; and (d) the only possible time interval in a global context (record of deep-sea oxygen isotopes and sea-level history) fits in the most notable Pliocene global climatic change (~4 Ma) that is registered in the Canary Islands by mean of these coastal and aeolian deposits.

**Key words:** Northwestern Africa, Tortonian, Zanclean, 40Ar/39Ar geochronology, Paleoclimatology

**1. Introduction**

Emergent shallow-water marine deposits, many of them highly fossiliferous, are common along the coastlines of the Canary Islands of Spain. The importance of these fossil-bearing deposits has been considered for more than a century, since the pioneering work of Hernandez-Pacheco (1909) was published. Later studies noted that marine deposits are located at a range of elevations, particularly on the islands of Lanzarote and Fuerteventura (**Fig. 1**). Indeed, the occurrence of marine sediments at different elevations formed the basis of early estimates of these ages of these deposits. Choubert (1962) and Lecointre (1965), having studied deposits on the Atlantic coast of Morocco, summarized a sequence of marine transgressions and regressions, all of which were considered to have occurred in the Quaternary. Thus, many investigators studying coastal exposures on the Canary Islands considered all the marine deposits to be of Quaternary age and correlated these units with the Moroccan sequence (Driscoll et al., 1965; Tinkler, 1966; Crofts, 1967; Lecointre et al., 1967; Fuster et al., 1968). None of these studies provided numerical age control and correlation to events in the Quaternary along the Moroccan coast was based dominantly on elevation.

Later, Meco and Stearns (1981) challenged the concept that all of the marine deposits on the Canary Islands were of Quaternary age. These investigators pointed out that some of the deposits, notably those on the southeastern coast of Lanzarote and the western coast of Fuerteventura, contain a characteristic assemblage of fossils of extinct taxa. Meco and Stearns (1981) suggested that these deposits were of pre-Quaternary age. Based on stratigraphic relations with new and previously reported K/Ar ages of lavas, they proposed that the deposits with the extinct fauna were likely of Pliocene age. There was a return to the concept of marine deposit elevation as a means of correlation with a later study by Zazo et al. (2002). Finally, in the most recent study, Meco et al. (2015) reported new stratigraphic and 40Ar/39Ar data from Gran Canaria, as well as previously published K/Ar ages from this island and Fuerteventura. Data from both islands show that marine deposits are overlain by lavas, dated ~5.8-4.8 Ma (Fuerteventura) and ~4.8 Ma and 4.2 Ma (Gran Canaria). Thus, Meco et al. (2015) concluded that the marine deposits on these islands must be of Pliocene age. To date, however, the age, origin and climatic significance of these marine deposits have not been discussed in detail, and that is the aims of the present study.

**2. Study area**

As the Canary Islands are mainly of volcanic origin, the study of raised coastal (or emergent littoral) deposits, volcanic constructive phases and probable subsidence or tectonic effects have also to take into consideration.

*2.1 Absence of subsidence in Fuerteventura and Lanzarote Islands*

Van den Bogaard (2013) considers the Canary Island Seamount Province to be the oldest hotspot in the Atlantic Ocean and the most long-lived mantle anomaly on Earth. These islands have the following peculiarities: (a) low plate motion velocity (~2 cm per year) around a Euler Pole of rotation, that is only about 3,800 km from the Canaries on the Atlantic Plate (Zaczek et al., 2015); (b) the crust on which the Canary Islands rest has a thickness up to 18 km and close to the African coast; (c) significantly the crust is also not very rigid; (d) the proximity of the buoyant African continental crust. As a result of all these factors it dominates an absence of significant subsidence on the Canary Islands (Carracedo and Troll, 2016). Among the volcanic islands on Earth, this is certainly unusual and could be a unique case.

*2.2. Age of the volcanic bedrock*

The Canary Archipelago formed during the Neogene and Quaternary

(Carracedo et al., 2002) with Fuerteventura and Lanzarote being the oldest islands (Coello et al., 1992; Ancochea et al., 1996; Ancochea and Huertas, 2003).

They are separate islands at present, but during a considerable amount of geological time these islands were connected and formed a long, single, ridge-like landmass more than 220 km long (Troll & Carracedo, 2016).

In the areas studied for the present paper, the west and south of Lanzarote (**Figs. 1, 2**) and the west and south of the Jandía peninsula in Fuerteventura (**Figs. 1, 3**), marine deposits rest on the volcanic rocks. The youngest ages of these underlying volcanic rocks (Coello et al., 1992) correspond to the Serravallian (13.82 Ma to 11.62 Ma; Gradstein et al., 2004), which is therefore considered the lower chronostratigraphic boundary of these marine deposits. The ages of the basalts that lie under thesedeposits are 12.3 Ma and 12.0 Ma in the south of Lanzarote and the Jandía peninsula, respectively (Coello et al., 1992; Ancochea et al., 1996). In the Jandía peninsula of Fuerteventura, no lava flow younger than the marine deposits has been found. On Lanzarote, however, a basalt flow, the subject of a part of the present paper, overlies the marine deposits.

*2.3. Coastal deposits, relationship with lavas and volcanism*

There is only one place, the Janubio site in the SW coast of Lanzarote, where a basaltic lava flow overlies a Late Miocene littoral deposit. There have been two previous attempts to date this lava by K/Ar methods, with uncertain results (Coello et al., 1992; Meco et al., 2007). This present study attempts to clarify this issue by means of a new 40Ar/39Ar age.

It is important to consider whether there could have been any tilting of the marine deposits studied here. Gran Canaria, to the west is the closest island to the Fuerteventura and Lanzarote volcanic edifice. It formed in two stages: the first (Paleocanaria stage) was during the Miocene (between ca 14 Ma and ca 8 Ma) and, after a large hiatus in volcanic activity (ca 8.2 to 4.8 Ma), the second stage (Neocanaria stage) occurred in the Plio-Quaternary, after 4.8 Ma (Carracedo and Troll, 2016). The Miocene volcanism of Gran Canaria did not have any tilting effect on the littoral deposits of Fuerteventura and Lanzarote, because the deposits are younger than the Paleocanaria stage. The only possible cause of tilting on Lanzarote could occur by the loading effect of the Famara volcanic edifice in northern Lanzarote itself, built up between ca 10 Ma and ca 4 Ma (Coello et al., 1992).

**3. Materials and methods**

The coastal deposits containing marine fossils are characterized by an underlying bench sloping seaward. We measured the altitude of this bench at several points, and at the seaward and landward end. Moreover, from the fossils collected we selected the most valuable of them in a chrono-stratigraphic sense for additional study. The selected fossil species are: *Siderastraea crenulate;* *Siderastraea miocenica; Isognomon soldanii;* *Gigantopecten latissimus;* *Saccostrea virleti; Patella ambroggii;* *Nerita Emiliana;* *Perististrombus coronatus; Amalda glandiformis and* (endemic) *Rothpletzia rudista.* We obtained a new 40Ar/30Ar age from an overlying basaltic lava and we also made an unsuccessful attempt of fossil shell dating.

3.1. *Elevation measurements*

A field analysis of the marine deposits was conducted in a shore-parallel sense and in a shore-normal sense where exposures allowed it. After establishing the highest and lowest points which define each section (UTM coordinates), the elevations of the points were taken at fifty-two (52) localities using Global Positioning System (GPS) techniques and they were geographically referenced based on a Universal Transversal Mercator (UTM) projection and the WGS 84 reference ellipsoid. Measurements of the sites (**Figs. 1, 2, 3; Tables 1, 2**) were performed through calculation of baselines between two receivers, with similar atmospheric conditions and observing the same group of satellites simultaneously. Baselines were always referred to geodetic vertices, and the distances between the GPS-measured points never exceeded 5 km. Observation durations of 5-10 min were needed during daylight, as well as good satellite geometry (geometric dilution of precision (GDOP) between 0 and 5). Signals from 5 or more satellites were checked. Calculation of geographic and UTM coordinates was carried out using SKI software.

We used a Leica 530 GPS system, with a double frequency satellite receiver and two channels for continuous searching. A static precision for the baseline of 5 mm ± 1 ppm was achieved for the differential phase and of 30 cm for the differential codex. The geodetic vertices of Playa Quemada, Papagayo and Piedra Alta were used in Lanzarote, and of Jurado, Aguda, Baja del Trabajo and Granillo in Fuerteventura. The orthometric heights refer to the mean sea level recorded by the mareograph in Lanzarote at Puerto de Arrecife (REGCAN 95).

*3.2. Selection of fossils for chronostratigraphic purposes*

Index fossils are the key to biostratigraphic studies, and in our initial examination of the fossil assemblages, the diversity of the fauna indicated to us that index fossils might be usefully established for this deposit. We therefore selected the ten most representative taxa which provide the most appropriate chronostratigraphic and biogeographic information for the aims of the present study (**Appendix A**).

*3.3. 40Ar/39Ar geochronology of basalt and aragonite content of fossils*

For this study, we collected a sample of basaltic rock and we obtained a new age by the 40Ar/39Ardating method (**Table 3**). The sample was irradiated for 6 hours in the TRIGA nuclear reactor at Oregon State University under specific controls (Kuiper et al., 2008) (**Supplementary materials 1, 2**).On the other hand, we had hoped to obtain age estimates of the fossils themselves using 87Sr/86Sr analyses. Unfortunately, fossils collected from different localities were examined in the laboratories of the US Geological Survey (Federal Center, Denver, CO, USA) andno aragonite was present in the fossils. As a result, reliable 87Sr/86Sr analyses that would have allowed the correlation of deposits from different localities and age estimates using the seawater strontium isotope curve (Howarth and McArthur, 1997) were not feasible.

**4. Results**

The results we obtained allowed us to distinguish and focus on two different deposits: the Tortonian (Miocene) marine deposits and the Zanclean (Pliocene) coastal (marine and eolian) deposits.

*4.1. The Tortonian (Miocene) marine deposits*

The key point is that only in the locality of Janubio (**Figs. 4 and 5**), on the southwest coast of Lanzarote, was a lava flow found overlying the marine deposits. According to Coello et al. (1992), this lava flow is from the Messinian (**Table 3**), but according to Meco et al. (2007) it is older and belongs to the Tortonian (**Table 3**). Because of these conflicting age estimates, we provide a new 40Ar/39Ar age of the same lava flow overlying the marine deposits. The new 40Ar/39Ar age that has been obtained (this study, **Table 3; Supplementary material 2**) of the only lava flow that covers the studied deposits (**Fig. 4 and 5**) allows the establishment of a minimum age of ca. 9.6 Ma for these marine deposits of Lanzarote. As the two previous estimates differed from each other by some margin (**Table 1**), this new dating enables a more precise determination of their age.

These lava-covered marine deposits were first attributed to the Miocene by Hernández Pacheco (1969) and their subaerial occurrence at some localities beyond the lava cover suggested to Zazo et al. (2002) that they could be of Quaternary age. They are located on a wave-cut platform ca 36 m (**Fig. 4B**) above sea level sloping gently towards the coast. This platform was eroded in Miocene volcanic rocks that are dated to 15.5 Ma to 12.3 Ma (Coello et al.1992; Carracedo et al., 2002), the oldest on the island (**Fig. 1, Fig. 4**). The marine deposits beneath the lava flow consist of a fossil-bearing conglomerate which contains calcareous algae, rounded clasts with reddish-brown external coatings and masses of corals (*Siderastrea*) in isolated areas (**Fig. 5, Appendix A**). The littoral nature of this deposit is demonstrated by the abundant presence of *Nerita emiliana* (**Fig. 5C**). Furthermore, this taxon has long time been of considerable palaeoclimatic significance. Modern species of this genus are largely present in intertropical waters (Nicklès, 1950; Abbott, 1974; Vermeij et al., 2009) and thus *Nerita emiliana* is a paleoclimatic indicator of relatively warm marine environments. A littoral and intertropical origin of the deposit is supported by the presence of corals of the genus *Siderastrea* (Chevalier, 1966). The closest modern occurrence of extant species of *Siderastrea* is the Cape Verde islands, ~1500 Km Southwest of the Canary Islands. A high degree of compaction is evident due to the pressure and temperatures caused by the immediately overlying lava flow, though this same marine level, in its occurrence beyond the margins of the lava flow, is considerably less compacted (**Fig. 4B, Fig. 5A**).

*4.2. The Zanclean (early Pliocene) coastal deposits*

In Lanzarote*,* the Zanclean deposits are comprised of conglomerates and sandstones with thicknesses ranging from 1 to 2 m. The fossils (**Appendix A**) indicate a littoral environment and mark an ancient coastline. The clasts are basalt and reddened in many localities, indicating weathering in the presence of freshwater. Finally, at the base of the marine deposits and overlying the volcanic substrate there are thin beds of gypsum (**Figs. 6, 7**), which, in this context, indicate that the deposits could be the remains of a regressing sea. This marine regression favored the generation of bioclastic sands and the formation of eolian sand. In Corral Blanco (Lanzarote) (**Fig. 6**), these dunes contain Acrididae egg pods (Meco et al., 2010). The appearance of these pods is a clear indicator of the appearance of climatic change, from intertropical and a year-round warm climate to a temperate and seasonally warm climate, in the region (Meco et al., 2011, their Fig. 3). The present African Acrididae ootheca do not have a resistant chamber to get protection against environmental changes and therefore preservation of trace fossils is rare. In contrast, the Eurasian Acrididae (Zimin, 1938; Morales Agacino, 1951) need firm protection against winter cooling and preservation of trace fossil is more common.

There are two roughly shore-parallel reaches of these deposits in the S-SE of Lanzarote, one of which extends from El Papagayo to Punta del Garajao, and the other from Playa Quemada to Las Coronas (**Fig. 2**). El Janubio is located on the west coast of the same island, separated from these two reaches by dunes, alluvial fan deposits and, above all, by the Femés Pleistocene lavas, which occupy a large area in the southwestern part of the island. Between La Punta del Garajao and Las Coronas, marine deposits are not found, likely the result of coastal cliff erosion and fluvial erosion in the mouths of the area’s very deep ravines. The cliff along this stretch of coast extends as high as 70 m, exceeding the highest elevations of the marine deposits (**Fig. 2, Table 1**).

The same platform on which the marine deposits are found extends southward, forming Punta Papagayo. There, the marine deposits, sloping towards the sea, stretch from the foot of the Ajaches Range, where they disappear under the bioclastic aeolian sands, to the coast. The deposits display a reddish-brown external coating in some of the clasts and contain coral of the genus *Siderastrea* in isolated masses (**Fig. 2, Table 1**). Between the marine deposits and the volcanic substrate there are beds of gypsum and overlying all of them there is an aeolian deposit with an interbedded sandy paleosol containing locust egg pods (**Fig. 6**). These deposits are only slightly consolidated, easily subject to erosion by runoff water and dispersed by gravity onto lower elevations, e.g. at Las Coronas locality.

On the western half of the Jandía peninsula, Fuerteventura, there are extensive, seaward sloping stretches of marine deposits (**Figs. 3, 6**), similar to those in the south of Lanzarote. They have been undercut by the retreat of the coastal cliff and large portions of fossil-bearing deposits are falling into the present-day littoral zone. At Punta del Corralito locality (**Table 2**) these deposits can be traced along the edge of the littoral zone, reaching altitudes from 7 to 19 m. Inland, the deposits are found seaward of the mountain front on the Jandía peninsula and are hidden under Pleistocene aeolian sand at elevations ranging from 27 m to 40 m. At Punta Junquillo and Roque del Moro, the retreat of the cliffs has exposed the marine deposits at about 50 m elevation and overlying Pliocene aeolian sands reach elevations of over 200 m, forming thick sand ramps, some of which even cover the lee sides of inland hills. At Los Atolladeros, on the southern coast of the Jandía Peninsula, the marine deposits are continuously visible and descend in height from around 40 m to 28 m. At El Cantil, Jorós and Morro Jable localities the *Nerita* bearing marine deposits and the dune deposits have faults, with about 10 m of vertical displacement (**Fig. 7**). All the ravines heading in the inland hills dissect the marine deposits (**Fig.3, Table 2).**

The more significant fossil species of these marine deposits are: (a) corals *Siderastrea crenulata* (**Appendix A**, their Fig. 1a) and *Siderastrea miocenica* (**Appendix A**, their Fig. 1b); (b) bivalves *Isognomon soldanii*(**Appendix A**, their Fig. 2A), *Gigantopecten latissimus* and *Saccostrea virleti* (**Appendix A**, their Fig. 2B);

(c) gastropods *Patella ambroggii* (**Appendix A**, their Fig. 3**),** *Nerita emiliana* (**Appendix A**, their Fig. 2C), *Persististrombus coronatus* (**Appendix A**, their Fig. 4) and *Amalda glandiformis* (**Appendix A**, their Fig. 2 E); and (d) *Rothpletzia rudista,* a gastropod endemic to the Canary Islands(**Appendix A**, their Fig. 5). The only reported existence worldwide of *Rothpletzia rudista* pertain to the Lower Pliocene of the Canary Islands. All in all, the deposits have a fauna corresponding to an early Zanclean age.

**5. Discussion**

Considering the new data reported here, we discuss the model of the Quaternary stepped terraces proposed by other authors, the tectonic issue in the study area, the regressive nature of the Zanclean deposits and the paleoclimatic significance of the coastal deposits.

*5.1 The terraces issue*

Zazo et al. (2002) reported U-series ages and amino acid data from fossils that they used to develop a sequence of what was considered to be 12 separate marine transgressions (+65-70 m, +50-55 m, +40-45 m, +35-40 m, +25-30 m, +20-25 m, +17-18 m, +12-14 m, +8-10 m, +1-2 m, +1 m, +0.5 m) found at similar elevations on both southern Lanzarote and southern Fuerteventura. Their U-series and amino acid data were all from fossil mollusks of Lanzarote, largely sampled from the southwestern and southern coasts of the island, and from the topographically lower five terraces. On Fuerteventura, Zazo et al. (2002) presented amino acid and U-series data for mollusks from the lower two terraces. It has been recognized for several decades that U-series ages on mollusks are not reliable (Kaufman et al., 1971). Thus, the apparent ages for the lower terraces on both Lanzarote and Fuerteventura presented by Zazo et al. (2002) are questionable. Furthermore, four of the terraces that Zazo et al. (2002) studied on Fuerteventura (their terraces I, II, VII, and VIII) contain the extinct gastropod *Nerita emiliana*. Nevertheless, these investigators proposed (see Zazo et al., 2002, p. 2043) that the entire sequence of terraces (I through XII) on these islands could be of Quaternary age.

The results from the present study, however, indicate that the fossil species contained in these deposits have no relation with their heights. In contrast, the fossil content indicates the presence of a unique marine episode. Furthermore, many of the heights of fossil-bearing deposits do not have any correspondence with the terraces proposed by Zazo et al. (2002).

*5.1.1. Height-fauna pairing*

On Lanzarote and Fuerteventura, the heights above mean sea level (m a.s.l.) at which these fossil-bearing deposits are found are considered very important. This is because, on these islands, the criterion of height has been practically the only one used by other authors for assigning ages to the deposits (Driscoll et al., 1965; Tinkler, 1966; Lecointre et al., 1967; Klug, 1968; Hernández-Pacheco, 1969; Zazo et al., 2002). However, we have found that using solely the criterion of height is not feasible and can lead to misinterpretations. Another criterion, namely that of the faunal composition, is necessary for an adequate interpretation of the deposits.

In Lanzarote (**Table 1, Appendix A**), *Rothpletzia rudista* appears in deposits found at around 24 m, but also in those found at around 51 m; *Amalda glandiformis* appears at around 21 m, but also at around 60 m; and *Siderastrea miocenica* appears at around 36 m, but also at around 70 m. However, at El Paso del Andrés these three species appear together, along with *Saccostrea, Nerita* and *Persististrombus*, at around 50 m. Although all these species are extinct, as is the genus *Rothpletzia*; the genera *Persististrombus*, *Nerita* and *Siderastrea* all have present-day species which, as well as being littoral, live only in intertropical warm waters (Nicklès, 1950; Chevalier, 1966; Meco, 1972; Abbott, 1974). This leads us to conclude that the marine deposits were laid down before major global cooling in the second half of the Pliocene. If this inference is correct, then it also follows that these deposits must certainly be older than the Quaternary, in contrast to the conclusions of Lecointre et al. (1967) and Zazo et al., (2002)

Moreover, in the Jandía peninsula (**Table 2,** **Appendix A**), the fossil fauna reveals abundant remains pertaining to the genera *Persististrombus*, *Nerit*a, and *Saccostrea*, which appear sporadically, accompanied by *Amalda glandiformis*, *Rothpletzia rudista* and *Siderastrea miocenica,* which are species exclusive to the Mio-Pliocene (Rothpletz and Simonell, 1890; Meco et al., 2015). The presence of these fossils also shows no correlation with the height of the deposits above the present-day sea level. For example, *Amalda glandiformis* has been found at the lowest elevations, at around 8 m. *Rothpletzia rudista* is found at localities at around 15 m, but also at localities as high as 50 m. Therefore, the criterion of using the heights of the fossil-bearing deposits does not, by itself, allow the drawing of any conclusions regarding age.

*5.1.2. Elevations of the marine deposits*

At Hacha Chica, Lanzarote, large portions of fossil-bearing deposits are visible and descend continuously from 69 m to 39 m a.s.l. towards the coast (**Table 1**). They presumably correspond to the “steps” of marine terraces I, II, III and IV from Zazo et al. (2002, their Fig. 5). On the other hand, in Salinas de Janubio and at 36 m (**Fig. 7**, **Table 1**) the Tortonian marine deposits (or Miocene beach) underlie a lava flow dated 9.6 Ma (this work) and continue laterally to the coast to an elevation of 34 m (**Figs. 4, 5**). These deposits were called raised marine terraces IV (40 m) and V (30 m) by Zazo et al. (2002, their Fig. 11), and were also referred with this nomenclature by Carracedo and Troll (2016, their Fig. 7.18). The multi-terrace model with 12 transgressive episodes by Zazo et al. (2002, their Fig. 7) was based on a section of the Tablero de Jorós, considered representative of Jandía area, Fuerteventura. This section was modified and referred by Carracedo and Troll (2016, their Fig. 8.38).

We have studied the area of Tablero de Jorós and can recognize only a single, continuous layer of marine deposits, descending to the south coast (Fig. 4), with two exceptions: a topographic discontinuity due to a fault, with about 9 m of vertical displacement (51.52 m to 42.68 m) (**Table 1**), and the cutting slopes of a local road. This means that the “episodes” IV, V, VI, VII, VIII and IX of Zazo et al. (2002) is only a single, continuous layer of deposits. Moreover, five dunes of probable Pleistocene age were also reported by Zazo et al. (2002, their Fig. 7) and related to transgressive episodes. However, all these dunes and others found eastward appear to be of a similar age (Fig. 6), overlie the single age of marine deposits and are cut by the fault as well.

Consequently, we suggest that in the area there is only one layer of marine deposits, produced by a regressive episode and, very likely, the dune deposits are also of only one age, but were affected by faulting. In addition, at Punta del Corralito about 4 km westward Jorós, the Zanclean marine deposits are also present, containing identical fossil species, being continuously visible from at 18 m to 8 m high. Our field work reveals then that the episodes VII, VIII and IX by Zazo et al. (2002) indeed represent only a single marine episode.

Taking into consideration all the above data from Lanzarote and Fuerteventura, the multi-terrace model of Zazo et al. (2002), including their I to IX marine terraces, does not appear to be valid. Our conclusions do not apply to the younger (X to XII) marine terraces of Zazo et al. (2002), of Late Quaternary age deposits that have been studied more recently (Meco et al., 2018; Montesinos et al., 2014; Muhs et al., 2014).

*5.2. The tectonic issue*

The Eastern Canary Islands, Lanzarote and Fuerteventura, are situated on an oceanic crust that is not very rigid, they are the nearest to the African continental crust of all the islands and their volcanic substrate, dated 20.2 Ma, is the oldest in the archipelago. These are the main reasons for the lack of subsidence in the area since the Miocene. However, tectonic tilting has been documented on some of the Canary Islands (e.g., Gran Canaria). This tilting has been attributed to the successive growth and loading of younger islands on older islands (Collier and Watts, 2001; Carracedo et al., 2002; Menéndez et al., 2008).

Our studies show that the Tortonian deposits of ~9.6 Ma in southern Lanzarote occur at a present elevation of ~40 m above sea level.  The reconstruction of sea level history presented by Haq et al. (1987) indicates that eustatic sea level at this time may have been about -20 m relative to present (**Fig. 8**).  If that reconstruction is correct, it follows that Lanzarote may have experienced ~60 m of uplift in ~9.6 Ma, yielding a relatively low rate of uplift of ~6.25 m/Ma.

Haq et al.'s (1987) sea level curve also proposes that eustatic sea level may have been relatively high at ~5 Ma, perhaps up to +70 m above present, but fell gradually over the next million years and then fell dramatically after ~3.8 Ma.  The Zanclean deposits, found as high as ~70 m above modern sea level on Lanzarote, may have initially been laid down during this ~5 Ma high stand of sea.  These deposits, however, on both Lanzarote and Fuerteventura, are found over a wide elevation range in a shore-normal sense (**Figs. 1C, 4C**).  For example, at Los Ajaches, Zanclean deposits occur as high as ~65 m above sea level and ramp downward to the southeast –on the same marine platform– to an elevation of ~45 m (**Fig. 1C**).  With a very low, long-term rate of uplift, based on the age and elevation of the Tortonian deposits, Zanclean deposits initially laid down at a eustatic sea level of +70 m may have experienced, at most, only a couple meters of uplift.  If sea level fell over the next ~1.0 Ma, as Haq et al.'s (1987) reconstruction seems to indicate, uplift on Lanzarote and Fuerteventura may not have been able to keep pace with a falling sea level.  If this is the case, the result may have been marine deposition at successively lower elevations in a seaward direction over the next million years.  Thus, fossils at higher, landward positions should be older than those at lower, seaward positions, even though both are situated on the same marine terrace.  When sea level fell dramatically after ~3.8 Ma (**Fig. 8C**), the Zanclean platforms would have been abandoned.  Such a mechanism explains the broad (in a shore-normal sense) marine platforms created on both islands during Zanclean time.  If this scenario is correct, marine platforms on Lanzarote and Fuerteventura formed initially as transgressive features in early Zanclean time but developed subsequently as regressive features with a lowering sea level.  After the major sea level fall at ~3.8 Ma, carbonate skeletal sands newly exposed on the insular shelves would have been blown into aeolian sheet sands and/or dunes overlying the marine deposits.

*5.3. Regressive nature of the Zanclean deposits and the eustatic issue*

As dunes of Lanzarote and Fuerteventura are formed by bioclastic sands and they are situated inland and above the Zanclean marine deposits, they were likely formed during a lowering of sea level after deposition of the marine deposits. In the upper part of the dune there is an interbedded paleosol that contains Acrididae egg pods (Meco et al., 2010; 2011). The first appearance of these egg pods in the Canary Islands was in the Orzola eolian calcarenite, in the north of Lanzarote. They have been dated in the range 4.3 ±0.7 and 3.78 ±0.71 Ma (Lomoschitz et al., 2016) and their presence coincides roughly in time with the first arrival of African dust to these islands (Muhs et al., 2019). These marine deposits of Lanzarote and Fuerteventura, therefore, must be older than ca. 4 Ma. Moreover, the Zanclean deposits were laid down during a regressive episode. We infer this in part from the layers of gypsum in the lower parts of the marine deposits (**Figs. 5, 6**). These gypsum layers likely formed by evaporation in a shallow aqueous terrestrial environment. Furthermore, in the south of Lanzarote, the height difference between the highest part and the lowest part of the same deposit is around 48 m (**Table 1**), with the highest point at 70 m above sea level, and in the Jandía peninsula of Fuerteventura, the difference in height is around 50 m. From a eustatic view, if it were to melt, the current volume of ice in the Antarctic ice sheet would equate to a sea level rise of around 58 m (Fretwell et al., 2013).

These considerable differences in height (~ 50 m) would seem to indicate a continuous lowering of the sea level over an extensive period of time, i.e., a long-term sea-level regression that is consistent with continuous deposits sloping gently seaward. Searching possible causes, this sea level lowering can be attributed to ice accumulation in east Antarctica, which would be directly reflected in the Canary Archipelago, because there has been no subsidence of the islands from the Miocene to present time (Troll and Carracedo 2016). A similar sea level lowering ca. 4 Ma was registered by Haq et al. (1987) **(Fig. 8C**) and as the sea level descended, the bioclastic marine sands were transported by wind and then cemented into aeolianites. All the above considerations indicate a regressive character of the Zanclean marine deposits. We suggest that formation of these deposits during the Zanclean global sea-level lowering (Haq et al., 1987) can be inferred from the record of global deep-sea oxygen isotopes from marine cores (Zachos et al., 2001) for the time period considered in our study (**Fig. 8B**). A correlation has been established between the δ18O 0/00 composition of the oceans and the establishment of the Antarctic ice-sheet and global sea level fall (Zachos et al., 2001) (**Fig. 8**).

*5.4. Paleoclimatic significance of the coastal deposits*

About 14 Ma ago, after the Mid-Miocene climatic optimum, a general period of global cooling took place and, therefore, a principal increase of ice volume occurred in eastern Antarctica. That cooling period has been related to ocean circulation changes (Nisancioglu et al., 2003) and is recorded as an increase of δ18O in the Atlantic Ocean (Zachos et al., 2001). At the same time, the Los Ajaches volcanic edifice formed in Southern Lanzarote, dated 12.3 Ma to 15.5 Ma (Coello et al., 1992) and the Jandía edifice formed in southern Fuerteventura, dated ca 12 Ma to 16 Ma (Ancochea et al., 1996).

With respect to the Pliocene, a previous paleoclimatic reconstruction of the north African Atlantic was done by Meco et al. (2015). The authors pointed out the warm nature of the fossil fauna of the marine deposits and the temperate climate of the associated aeolianite. Moreover, the arrival of the first desert-origin dust from Africa occurred in the Pliocene and after the Canary Pliocene marine deposits (Muhs et al., 2019).

Our study also contributes to our understanding of the warm nature of seawater during the Tortonian stage, the oldest occurrence of Acrididae egg-pods (in concordance with lava flows dated by Lomoschitz et al., 2016) and, finally, the start of the dramatic Pliocene climate change ca 4 Ma (Fig. 9).

**6. Conclusions**

This study contributes to a better understanding of Miocene and Pliocene epochs in the North African Atlantic. Our records consist of many littoral deposits whose ages are constrained between ca. 12 Ma lava flows and ca. 4 Ma aeolianites. They have in common the presence of fossils of the *Nerita* genera, an intertropical gastropod, and the tropical coral *Siderastrea*. Previously, the deposits had been mostly interpreted to be of Quaternary age, but they date to two different epochs, late Miocene and early Pliocene and, more specifically, to two sub-epochs: the Tortonian and the Zanclean.

A new 40Ar/39Ar age of 9.60 ± 0.05 Ma is obtained from the lava flow which partially covers the almost horizontal Tortonian deposits at the Janubio site in the southwest of Lanzarote. With this age, the deposits, which occurs as high as from 36 m a.s.l., could have experienced local tectonic movements. This is the first main uplift of our record. The Zanclean deposits, dated to ca. 5 Ma to 4.2 Ma, have elevations as high as 70 m a.s.l. Such a significant elevation could be initially explained by a high-stand, sea as some global RSL curves show. However, the presence of faults crossing the Miocene bedrock (consisting of lava flows, pyroclastic deposits and dikes) and displacing the Zanclean marine and aeolianite deposits providence evidence of later tectonic movements. Consequently, we suggest a combined effect of tectonic movements and global sea level rises to be the main causes of these emergent deposits.

The Canary records we obtained also have paleoclimatic significance. The records help to understand the climatic evolution in the North African Atlantic Ocean from the earliest history of the East Antarctic ice-sheet, ca. 12 Ma, and the beginning of an extended presence of the North Hemisphere ice-sheets, at about 4 to 3 Ma. After the Mid-Miocene climatic optimum, about 15 Ma ago, the most representative warm genera of fossils were corals of *Siderastrea* genera and gastropods of *Strombus* and *Nerita* genera. All these genera are currently living only in intertropical areas.

The fossil fauna was present in the area since ca. 9.6 Ma (marine Tortonian deposits of Janubio, Lanzarote) and remained in the region until ca. 4.1-4.2 Ma, when the principal climate change of the Pliocene took place. After the Zanclean, the global sea level decreased, from a high of at least 40 m, the cool Canary Current was established, and the Trade Winds appeared. Moreover, aeolianites from marine bioclastic sand formed and several paleosols developed, containing Saharan or Sahelian dust.

These climate changes caused the disappearance of warm marine species in the area and the establishment of the present climate. It includes the Antarctic ice-sheet, the cold Canary Current, the Trade Winds regime and the desertification of North Africa. The turning point of this major climate change in the Pliocene was ca. 4 Ma in age and is well recorded in the geologic record of the Canaries by the Zanclean marine and aeolianite deposits.

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**Appendix A**

Marine Paleontology of selected species, nine of them are of Atlantic-Mediterranean origin and one is endemic to the Canary Islands.

**Atlantic – Mediterranean species**

**A*.-******Corals*** (Coelenterata, Anthozoa, Scleractinia).

Among the most abundant hermatypic corals there are two species of S*iderastrea* (*S. crenulata* and *S*. *miocenica*) that clearly indicate a Miocene age, independently of their somehow inaccurate taxonomy (see Chaix & Saint Martin, 2008; Chevalier, 1961).

Both fossiliferous deposits, in Southern Lanzarote (**Fig. 2**) and in the Jandía Peninsula, Fuerteventura (**Fig. 3**), overlie lava flows of the final Serravallian, with 12.3 Ma (Coello et al., 1992), and then they are all Late Miocene.

**(1) - *Siderastrea crenulata*** (Goldfuss, 1826) (**Appendix A, Fig. 1A**)

Our specimens fit very well to the original description of the species (*Astrea crenulata* Goldfuss,1826; p. 71 Pl. 24, Fig. 6) and also to the following descriptions (Seguenza, 1864; Reuss, 1871; Simonelli, 1896; Kopek, 1954; Chevalier, 1961, 1962; Marcopoulo-Diacantoni, 1979; Oosterbaan, 1990).

*S. crenulata* is present in Fuerteventura and Lanzarote (this work: **Tables 2 and 3**), in the Tortonian of mainland Italy, Sicily, Greece, Hungary, North-Atlantic Morocco and Tunis; in the Lower Pliocene of Sicily (Chevalier, 1961); in the Middle Tortonian of Morocco (Chevalier 1962) and in the Tortonian of Crete (Marcopoulo-Diacantoni, 1979).

**(2) *- Siderastrea miocenica*** Osasco 1897 (**Appendix A, Fig. 1B**).

Our materials fit very well to the original species description (Osasco, 1897, p. 440, Fig. 6) and following descriptions (Chevalier, 1961, 1962) and also to the specimen assigned to *S. bertrandiana* by Hernández-Pacheco (1969, p. 905, Figs. 32, 33). It was founded by him at the Barranco de Juan Perdomo, near La Fuentecita, and it came from “the Quaternary beach at a high of 60 m”. Sismonda (1871) considered *S. bertrandiana* and *S. italica* as synonyms, fossil species pertaining to the Middle Miocene.

According to Chevalier (1961; 1962) there are many of *S. miocenica* varieties. The *Italic* variety (Chaix, & Saint Martin, 2008); the *regularis* variety; and other similar species as *S. bertrandiana* those occasionally are difficult to be differentiated from the others.

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**Appendix A Fig. 1.** Selected coral specimens, Punta Gorda, Lanzarote**.**

(A) *Siderastrea crenulata*; (B) *Siderastrea miocenica*.

*S. miocenica* is present in Fuerteventura and Lanzarote (**Tables 2 y 3**), in the Lower Tortonian of Morocco (Chevalier 1962), in the Aquitanian, Burdigalian and Vindobonian of France, and in the Vindobonian of Italy, Spain and Central Europe. *S. italica* has been considered as a variety of *S. miocenica* (Chevalier, 1961; Chaix & Saint Martin, 2008). *S. miocenica italica* is present in the Helvetian of France, and in the Tortonian of Hungary and Italy. *S. miocenica regularis* is from the Helvetian of France.

**B***.-* ***Bivalves*** (Mollusca, Bivalvia, Anisomyaria)

**(3) - *Isognomon soldanii*** (Deshayes, 1836) (**Appendix A, Fig. 2A**).

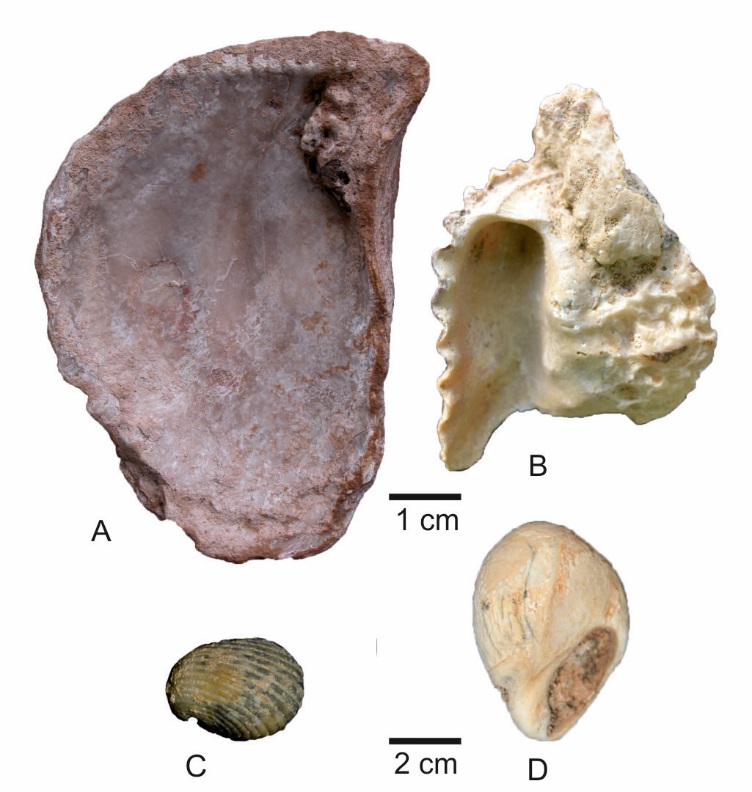
First described by Lamarck (1836, p.79), it has been found in Corral Blanco, Lanzarote. (**Table 1**), and recently found in the Early Pliocene deposit of Guiniguada, Gran Canaria (this study). It appeared in the Aquitanian of Portugal and, after a major abundancy in the Lower Pliocene, it became extinct before the Pleistocene (Palla 1966; Ben Moussa, 1994). It is present in the Tortonian of Porto Santo, Madeira; in the Helvetian of Turin and in the Tortonian of Modena (Mayer, 1864, p. 41) and of the Vienna basin (Sacco, F. 1898 p. 26 Pl. 7, fig. 2-6).

**(4) - *Gigantopecten latissimus*** (Brocchi, 1814).

It was described by Brocchi (1814, p. 581) and it has been found in El Papagayo, Southern Lanzarote (**Table 1**), showing the most typical species morphology from the Canaries (Meco, 1982, Pl. 4, Fig. 1; Pl. 7, Fig. 1; 1983, pp. 581 and 583). This species is present in the Helvetian and in the Tortonian and it has their major development in the Mediterranean Pliocene (Raffi, 1970).

**(5) - *Saccostrea virleti*** (Deshayes, 1832) = *S. chili* (Rothpletz & Simonelli 1890) (**Appendix A, Fig. 2B).**

*S. virleti* (Deshayes, 1832, p. 123, Pl.21 Figs. 1 and 2; Meco, 1982, p.32 Pl.3 Figs. 6 and 7; Pl.8 Figs. 1-8, Pl.12 Fig. 7) is present in all Mio-Pliocene sites of Lanzarote and Fuerteventura (**Table 1 and 2**). In the Canaries was named as *Ostrea Chili* (Rothpletz & Simonelli, 1890 p. 699, Pl.35, Fig. 5). It is very abundant in the Miocene and Pliocene of Europe, and also of Morocco (Lecointre, 1952, II, p.32, Pl.3 Figs. 6 and 7; Pl.8 Figs. 1-8; Pl.12 Fig. 7).

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**Appendix A Fig. 2** (A) *Isognomon soldani*, Corral Blanco, Lanzarote; (B) *Saccostrea virleti,* El Papagayo, Lanzarote; (C) *Nerita emiliana*, El Papagayo, Lanzarote; (D) *Amalda glandiformis*, La Colorada, Lanzarote.

**C.- Mollusca Gastropoda Archaeogastropoda**

**(6) - *Patella ambroggii*** Lecointre 1952 (**Appendix A, Fig. 3)**

It was described in the Pliocene of Morocco (Lecointre, 1952, p. 92, Pl. 24, Fig. 6-8) and of Oran, Algeria (Segre, 1954, p.145, Fig. 2; Lecointre, 1963, p. 58). It is very abundant in the Lower Pliocene of Gran Canaria and Fuerteventura (Meco et al., 2015), in Southern Lanzarote and in Jandía peninsula, Fuerteventura.

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**Appendix A Fig. 3** *Patella ambrogii* from Southern Lanzarote sites. (A) El Garajao; (C) El Papagayo; (B) the species type (Lecointre, 1952, Pl. 24, Fig. 6. S.G.M. coll. Lecointre), Morocco, between Tildi and Imsouane, in the Agadir region. Specimens of *Patella ambrogii* are abundant in the Canary Islands sites (Meco et al., 2015).

**(7) - *Nerita emiliana*** Mayer, 1872 (**Appendix A, Fig. 2C**)

*N. emiliana* (Mayer, 1872, p.231, Pl.14, Fig., 4; Sacco, 1896, 20, p.49, Pl. 5, Fig. 47) is present at several sites of Gran Canaria, Fuerteventura (Meco et al., 2015) and Lanzarote (**Table 2 and 3**). It is characteristic of the Miocene and Pliocene of Europe and Northern Africa.

**D.- Mollusca Gastropoda Neogastropoda**

**(8) *- Perististrombus coronatus*** (Defrance 1827) (**Appendix A, Fig. 4**)

*P. coronatus* (Defrance, 1827, 51, p. 124, Eichwald,1830; Hörnes, 1853, Pl. 17, Fig. 1; Harzhauser & Kronenberg, 2008; 2013) is present in Southern Lanzarote (Meco, 1977, Pl.14, Fig. 2; Pl. 15, Fig. 1, Pl. 19, Fig 1; Pl. 20, Fig.1, Pl. 21, Fig. 1) and in the Jandía Peninsula, Fuerteventura (Meco, 1977, Pl.16, Fig. 1, Pl.17, Fig 1, Pl. 18 Figs. 1 and 2). The *P. coronatus* morphology in the Canaries was not affected by the Messinian Mediterranean salinity crisis (Rögl, 1998). They appeared in the Mediterranean Sea during the Tortonian (Sacco, 1893, p.7, Figs 19-27), later it becomes a very common species during the Zanclean and the Early Piacenzian (Stchépinsky 1939, 1946; Harzhauser and Kronenberg 2008).

**(9) - *Amalda glandiformis*** (Lamarck 1810)(**Appendix A, Fig. 2 E**)

*A. glandiformis* (Lamarck, 1810, 16, p.305; 1822, p. 414) shows the typical Tortonian morphology (Pilot et alii 1975, Pl. 1 Fig. 8) in their “*dertocallosa”* form (Sacco 1904, 30, p.80, Pl.17, figs 71 - 73), as it was photographed by Meco (1981, Pl. 1, Figs. 1, 4, 9 and 11) and it is characterized by a long anterior transverse furrow. It is present in Southern Lanzarote and Jandía Peninsula, Fuerteventura (**Tables 1 and 2**), in the Miocene of Europe (Landau et al. 2013) and in the Pliocene of Morocco (Lecointre, 1952).

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**Appendix A Fig. 4** *Persististrombus coronatus* from. (A) Morro Jable, Jandía Peninsula, Fuerteventura, collected by Simón Benítez Padilla; (B) Punta del Garajao, Lanzarote (Meco, 1977); (C) Corral Blanco, Lanzarote (El Museo Canario collection).

**Canary Islands endemic species**

**E.- Mollusca Gastropoda Mesogastropoda**

**(10) *- Rothpletzia rudista*** Simonelli in Rothpletz y Simonelli 1890 (**Appendix A, Fig. 5)**

*R. rudista* (Rothpletz and Simonelli, 1890, p. 711, Pl. 36, Fig. 6) was firstly described as a Miocene species (Early Pliocene) from Las Palmas (Gran Canaria) and later on it was found in Fuerteventura (Meco, 1975) and in Lanzarote (Meco, 1977). It also has been recently found (this study) in the marine deposits of La Isleta, Gran Canaria, previously dated ca. 4.2 Ma (Meco et al., 2015). This species had never been found in other territories, neither Pliocene nor Pleistocene, but in the Canaries. Their crucial chronostratigraphic significance is based on the presence of radiometrically dated lava flows. They constrain their presence to the Canary Lower Pliocene, between 4.8 Ma (Meco et al., 2015).

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**Appendix A Fig. 5** *Rothpletzia rudista*. El Papagayo, Lanzarote.

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