NEOGENE CALCAREOUS NANNOFOSSILS FROM SAN JOSÉ ISLAND, BAJA CALIFORNIA SUR, MEXICO

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ABSTRACT – A study of calcareous nannofossils was carried out in two sedimentary columns from the Palma Sola Basin, San José Island, Baja California Sur, Mexico, in order to establish the age of these deposits and to place them in a chronostratigraphic context within the evolution of the Gulf of California. A total of 66 species were identified and based on the presence of small *Gephyrocapsa*, *Reticulofenestra minuta*, *R. minutula*, *R. haqii*, *Pseudoemiliania lacunosa* and *P. ovate*, an age of ≈ 3.6 Ma for Palma Sola I and at least for most part of the Palma Sola II equivalent to the standard NN15 *Reticulofenestra pseudumbilica* Zone is assigned. The top of the Palma Sola II column does not contain reticulofenestrids. If its absence is stratigraphic, a younger age could be inferred; however, considering also the absence of zonal indicators, is tentatively, at least ≈ 3.6 Ma. On the basis of the abundance of *Coccolithus pelagicus* s.l., small to medium *Reticulofenestra* spp., and small *Gephyrocapsa* and *Helicosphaera* spp., a paleoenvironment influenced by coastal upwelling is inferred.

Keywords: Neogene, nannofossils, Foraminifera, Gulf of California, Mexico.

RESUMO – Um estudo de nanofósseis calcários foi realizado em duas colunas sedimentares da Bacia de Palma Sola, na ilha de San Jose, Baja California Sur, México, a fim de estabelecer a idade desses depósitos e colocá-los em um contexto cronoestratigráfico dentro da evolução do Golfo da Califórnia. Foram identificadas 66 espécies e com base na presença de *Gephyrocapsa* de tamanho reduzido, *Reticulofenestra minuta*, *R. minutula*, *R. haqii*, *Pseudoemiliania lacunosa* e *P. ovata*, é atribuído às colunas Palma Sola I e a base e parte média da coluna Palma Sola II, uma idade de pelo menos 3.6 Ma, equivalente a zona padrão NN15 de *Reticulofenestra pseudumbilica*. O topo da coluna Palma Sola II não contém reticulofenestridos. Se a sua ausência é estratigráfica, ela poderia ser mais jovem; no entanto, a falta de indicadores zonais não permite uma atribuição de idade, a qual é tentativamente considerada de pelo menos 3,6 Ma. Com base na abundância de *Coccolithus pelagicus* s.l., pequenos a médios *Reticulofenestra* spp., pequenos *Gephyrocapsa* e *Helicosphaera* spp., é inferido um paleoambiente influenciado pela ressurgência costeira.

Palavras-chave: Neógeno, nanofósseis, Foraminifera, Golfo de Califórnia, México.

INTRODUCTION

The presence of the calcareous nannofossils in Jurassic, Cretaceous, and Cenozoic marine sequences in Mexico has been largely documented in several unpublished reports by PEMEX (Petróleos Mexicanos). Nevertheless, published papers dealing with paleontological aspects are scarce. Specifically for Baja California Coleman (1979), Carreño (1992a,b) and García-Cordero & Carreño (2009) can be mentioned. In several reports, dealing with the Neogene tectonic evolution of the Gulf of California is a common practice to report a checklist of microfossils species (Colleta & Angelier, 1981; Vázquez-Hernández *et al.*, 1996; Martín-Barajas *et al.*, 2001; Dorsey *et al.*, 2002; Umhoefer *et al.*, 2007; McDougall, 2008; Gómez-Sánchez, 2013; Schwennicke *et al.*, 2017). These microfossils are utilized to provide a chronostratigraphic framework that allows establishing the time of basin formation and its paleoceanographic configuration. However, this information is irrelevant when the exact distribution and abundance of the species is not known and when it is not possible to know the repository of the specimens. The more reliable research using the calcareous nannofossils for biostratigraphic purposes in the Neogene of Baja California was done by Piña-Arce (2010), but unfortunately it remains unpublished.

An extensive project dealing with the marine evolution of the Gulf of California is undergoing and the calcareous microfossils have been documented throughout the Neogene key-localities. This paper documents the presence of calcareous nannofossils throughout two sedimentary columns cropping out in San José Island, Baja California Sur, México, in order to establish the age of the deposits based on the species assemblages.

Previous studies

Macrofossils in San José Island were noted during the California Academy of Science Expeditions in 1921 and 1923, which were later studied by Hanna & Hertlein (1927). The finding of the elephantid *Rhyncotherium* in the Pleistocene (Applegate & Carranza-Castañeda, 1993) was interpreted as evidence that during this time San José Island was emerged and attached to the peninsula. In a preliminary mapping of the island reported by Puy-Alquiza (1992), a regional basement constituted by Cretaceous granitic rocks is covered in the southern portion of the island by volcanic rocks of the Oligocene–Miocene Comondú Group and younger sedimentary units. To the north, the Palma Sola and Punta Colorado basins develop on the granitic rocks basement that is unconformably overlaid by Neogene marine deposits. According with Umhoefer *et al.* (2007), there are eight sedimentary facies associations overlying the granitic rocks as part of four sequences, described from bottom to top as: Sequence 1, conglomerate and sandstone overlaid by conglomerate interpreted as fluvial to alluvial fan; Sequence

2, massive sparsely shelly sandstone (bay), shelly sandstone and conglomerate (delta, nearshore), conglomerate and sandstone (fluvial) and conglomerate (alluvial fan); Sequence 3, mudstone (outer shelf to upper slope), cross-bedded shelly sandstone (Gilbert deltas), bedded sandstone and calcarenite (inner shelf) bedded sandstone (inner shelf), massive sparsely shelly sandstone (bay), shelly sandstone (tidal near shore) shelly sandstone and conglomerate (delta, nearshore) conglomerate (alluvial fan); and Sequence 4, calcarenite (shallow marine), shelly conglomerate (gravel beach) and conglomerate and sandstone (fluvial). An important characteristic overlooked in previous reports is the presence of the thin layers of shelly biocalcarene in some parts of the columns, as well as that the massive shelly sandstone is the result of gravity flows processes affecting older units, being underwater all the time.

According with Umhoefer *et al.* (2007), an $^{40}\text{Ar}/^{39}\text{Ar}$ dating in a tuffaceous sandstone in the western embayment of Punta Colorada (lower sequence 2 interpreted as deposited in shallow water) yielded a $3.6 \pm 0.5 - 3.1$ Ma age. A checklist of the microfossils recovered from the upper sequence 3 (middle to lower upper part of the La Gata mudstone) has been published by Umhoefer *et al.* (2007), giving a latest Pliocene/earliest Pleistocene age (2.4–2.5 Ma) for this part of the sequence, interpreted as deposited under an oscillating oxygenated to oxygen-deficient bottom water in an upper slope environment.

MATERIAL AND METHODS

San José Island is located 4.61 km off North La Paz Bay ($24^{\circ}52'$ and $25^{\circ}06'$ N - $110^{\circ}43'$ W and $110^{\circ}35'$ W) Baja California Sur, Mexico (Figure 1). It has an area of approximately 187.16 m² (González-Bourillon, 1988). Two sedimentary columns corresponding to the upper part of the Sequence 3 (La Gata mudstone) of Umhoefer *et al.* (2007) were measured in the Palma Sola Basin using a Brunton compass and a Jacob Staff. Forty-nine samples were collected: column Palma Sola I with a total thickness of 518.7 cm (Loc. IGM-3938, 10 samples; $25^{\circ}03'38.3''$ N - $110^{\circ}40'51.5''$ W), and column Palma Sola II with a total thickness of 3708.5 cm (Loc. IGM-3939; 39 samples; $25^{\circ}03'43''$ N $110^{\circ}40'57.17''$ W; Figure 2).

Smear slides were prepared according to Perch-Nielsen (1985)'s method. They were observed to identify and tabulate the calcareous nannofossil content. Sediment equivalent to the head of a pin was placed over a 76 X 26 mm microscope slides and dispersed with one milliliter of deionized water over it, using a toothpick. It was dried placing the slide on a hot plate. Once cooled, a mounting medium (Canada balsam) was applied to a square cover-glass and then cooked in a hot-plate for half minute. Two smear slides per sample were prepared. Observation was made under a polarized microscope (Olympus model BH-

Figure 1. San José Island, Baja California Sur, Mexico. Location of the two columns sampled throughout the La Gata mudstone I and II. Geologic features from Puy-Alquiza (1992) modified by Umhoefer *et al.* (2007).

Figure 2. Columns (I and II) sampled throughout the La Gata mudstone and columns (X and Y) by Umhoefer *et al.* (2007) in Palma Sola subbasin in San José Island, Baja California Sur, Mexico.

2) at 100X immersion with crossed Nichols 40X and 100X achromatic objectives. In some cases, a $\frac{1}{2} \lambda$ gypsum plate with a 30m wavelength delay was used to facilitate the observation and identification of non birefringent nannoliths and discoasterids. Species identification follows the criteria of several authors (Bramlette & Sullivan, 1961; Bramlette & Wilcoxon, 1967; Bukry, 1971; Perch-Nielsen, 1977, 1985; Sherwood *et al.*, 2002; Young *et al.*, 2014). Micrographs were obtained using a Carl Zeiss AxioCam of 1.4 megapixels and the AxioVision 4.8 software.

The taxonomic identification was corroborated when necessary and possible under the Scanning Electron Microscope (SEM) JEOL: JSM 6360LV using an adapted technique (Perch-Nielsen, 1985; Bollmann *et al.*, 2002), where the water with the cleaned coccoliths is filtered through a cellulose membrane (Millipore 25 mm in diameter and 0.45 μm pore) and rinsed with Milli-Q water. Then, it is allowed to dry at room temperature and coated with gold using a thin palladium ionizer JFC-1100 JEOL. SEM was particularly useful for the study of the genus *Gephyrocapsa* (<3 μm) due to the diverse morphologies that exhibited the specimens. Some specimens might be referred as *G. aperta*, *G. muelleriae*/*margerei* or to other species; nevertheless, we considered not practical to identify them by light microscopy, and they are simply referred to the informal category small *Gephyrocapsa* and the different morphotypes illustrated. In addition, the SEM was important to discriminate the specimens belonging to the genus *Pontosphaera* from those belonging to *Scyphosphaera*. In Recent sediments it is relatively easy to distinguish one from another genus, but both genera produce muroliths and for this reason these are assigned in the fossil record to *Pontosphaera* whereas the lopadoliths are assigned to *Scyphosphaera*.

Due to dilution, the calcareous nannofossils at both localities were sparse and scarce and it was not possible to make a quantitative analysis following the standard methodology (Perch-Nielsen, 1985). Nevertheless, smear slides with concentrate residue were prepared and their abundance was tabulated using the following criteria:

R = rare: 1–16 specimens by observed transect at X1000;
F = few: 17–600 specimens by observed transect at X1000;
C = common: 601–6000 specimens by observed transect at X1000;
A = abundant: >6000 specimens by observed transect at X1000

Digital files of the identified species (IGMD 95 Mi-IGMD 160 Mi) and the smear slides from each sample (IGML 150 Mi-IGML 247 Mi) were housed in the micropaleontological collection of the Museo de Paleontología, Instituto de Geología (UNAM).

RESULTS

Two sedimentary columns were measured and sampled in the Palma Sola Basin in the upper part of Sequence 3 named the La Gata mudstone of Umhoefer *et al.* (2007). The lithic attributes of both columns are shown in Figure 2, as well as the columns of Umhoefer *et al.* (2007).

The Column I was divided into six units. The base is not exposed and its lower unit is composed by massive shale followed by interbedded mudstone and fine sandstone with chert and fine-grained sandstone lenses. Upper section siltstone and medium-grained sandstone grading to fine-grained sandstone are present overlain by siltstone and lenses of fine-grained sandstone with fragments of mollusks; the top consists of laminated shale and upper contact non-conformable. Calcareous nannofossils and foraminifers present.

The Column II is a repetitive sequence of shales interbedded with fine, medium and coarse grain sandstones. Most of the units contain foraminifera and calcareous nannofossils. Total thickness of this amalgamated part of the column is 4,233 cm. At the top of the column a coarse-grained biocalcarene 90.9 cm thick with remains of mollusks and echinoderms rest unconformably. This unit was described as massive sparsely shelly sandstone by Umhoefer *et al.* (2017). The contact with the previous unit is not conformable due to erosion, associated to a possible gravity flow, and it is shown in the field as unconformable both laterally and on the base of the flow.

Sixty-six species were identified. Thirty-seven species were present in both sedimentary columns. All the species here reported has been extensively described and illustrated by other authors and for this reason only a checklist in alphabetical order is included; the most conspicuous taxa are illustrated in Figures 3–7.

The most employed Neogene Standard Zonal Schemes for the low latitude regions using the stratigraphic record of calcareous nannofossils species are Martini (1971), Martini & Worsley (1971), Bukry (1973a, 1975) and Okada & Bukry (1980). In the Gulf of California, ages based on this group have been established using two of them (Martini, 1971; Bukry, 1973a); nevertheless, many zones have not been recognized due to the absence of several index species. Therefore, in this paper we use as far as possible the classical zonal scheme of Bukry (1975), as well as the updated stratigraphic range of some species used by several authors (Okada & Bukry, 1980; Perch-Nielsen, 1985; Young & Bown, 1997; Bown, 1998). The taxonomic checklist includes the consensual stratigraphic ranges for species recorded in both columns (Appendix 1).

In Palma Sola I, samples 3, 5 and 7 do not contain calcareous nannofossils, samples 6, 8 and 9 have common abundances and good preservation, while in the rest of the samples the nannofossils are rare to few and moderately preserved, with evident signs of dissolution and overgrowth (Figure 8). A total of forty-three species were identified, being the most conspicuous and with common abundances *Coccolithus pelagicus*, *Gephyrocapsa* small, *Helicosphaera sellii* and *Reticulofenestra haqii*. Also, some reworked Miocene species were observed: *Coronocyclus nitescens*, *Discoaster formosus*, and *Helicosphaera burkei*.

The calcareous nannofossils have a highly erratic distribution throughout. At the base, none of the recorded

Figure 3. Isochrysa dales. Distal shields except 11–12, Cromosphaera; 18–19; proximal shields. 3–14; sample 8b from Palma Sola I: 15–17; sample 30b Palma Sola II 18; 20–22. **A**, *Gephyrocapsa aperta* Kamptner, 1963 IGMD-109-Mi. **S**, *G. margereli* Bréhéret, 1978 IGMD-110-Mi. **C**, *G. protohuxleyi* McIntyre, 1970 IGMD-111-Mi. **D**, *Gephyrocapsa* small type 1 IGMD-112-Mi. **E**, *Gephyrocapsa* small Type 2 IGMD-113-Mi. **F**, *Gephyrocapsa* small type 3 IGMD-114-Mi. **G**, *Gephyrocapsa* small type 4 IGMD-115-Mi. **H**, *Gephyrocapsa* small type 5 IGMD-116-Mi. **I**, *Gephyrocapsa* small type 6 IGMD-117-Mi. **J**, *Gephyrocapsa* small type 7 IGMD-118-Mi. **K**, *Pseudoemiliania lacunosa* (Kamptner, 1963) Gartner, 1969 IGMD-132-Mi. **L**, *P. ovata* (Bukry, 1973) Young, 1998, IGMD-133-Mi. **M**, *Reticulofenestra haqii* Backman, 1978 IGMD-134a-Mi. **N**, *R. minuta* Roth, 1970 IGMD-135a-Mi. **O**, *R. minutula* (Gartner, 1967) Haq & Berggren, 1978 IGMD-136a-Mi. **P**, *Reticulofenestra* sp. 1 IGMD-138-Mi. **Q**, *Reticulofenestra* sp. 2 IGMD-139-Mi. **R**, *R. haqii* IGMD-134b-Mi. **S**, *R. minuta* IGMD-135b-Mi. **T**, *R. minutula* IGMD-136b-Mi. Scale bars = 1 µm.

species allows to do an age assignment. It is in sample 6, located at 1.82 m from the base that *Reticulofenestra haqii* and small *Gephyrocapsa* co-exist. This co-occurrence is indicative of a minimum age equivalent to the lower Pliocene NN15 *Reticulofenestra pseudumbilica* Zone of Martini (1971), where *R. haqii* has its last occurrence (LO) in the top of the zone. The presence of small *Gephyrocapsa* has been recorded in the Equatorial Pacific in rocks older than 4.5 Ma (Pujos, 1987; Site 572). However, there seems to be consensus among the authors to consider a younger age for the first small *Gephyrocapsa* bloom, which has been calibrated by magnetostratigraphy in ≈ 3.5 – 3.6 Ma at site 503B in the Equatorial Pacific and in the 502 in the Caribbean Sea region (Rio, 1982).

The absence of other characteristic species does not allow the exactly biostratigraphic location of the middle and upper part of Palma Sola I, and therefore it is only possible to assign it to a time span between the first occurrence (FO) of small *Gephyrocapsa* and the LO of *Reticulofenestra haqii* (≈ 3.5 – 3.6 Ma) in the Zanclean (lower Pliocene) (Gradstein *et al.*, 2012) (Figure 8). In Palma Sola II, 37 samples contain calcareous nannofossils. Sample 30 is the richest and diverse, whereas samples 13 and 26 do not contain microfossils. Sixty species were identified (Figure 9). The most conspicuous are *Calcidiscus leptoporus*, *C. macintyre*, *Coccolithus pelagicus*, *Helicosphaera carteri*, *H. kamptneri*, *H. sellii*, small *Gephyrocapsa*, *Pontosphaera discopora*, *P.*

Figure 4. Coccolithales. Distal shields except A, Cocosphere, and D, F, M proximal shields. Sample 30b Palma Sola II: A, D–G, N, sample 6b Palma Sola I: B, H, sample 8b Palma Sola I: I, L, sample 8b Palma Sola I: C, sample 29b Palma Sola II: G, sample 10b Palma Sola II: J, sample 5b Palma Sola II: K. A, *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930 IGMD-101-Mi. B, *C. pliipelagicus* Wise, 1973 IGMD-102a-Mi. C, *C. streckeri* Takayama & Sato, 1987 IGMD-103-Mi. D, *Calcidiscus leptoporus* (Murray & Blackman, 1898) Loeblich & Tappan, 1978 IGMD-96-Mi. E, *C. macintyreii* (Bukry & Bramlette, 1969) Loeblich & Tappan, 1978 IGMD-97-Mi. F, *Umbilicosphaera foliosa* (Kamptner, 1963) Geisen *In*: Sáez *et al.*, 2003 IGMD-159a-Mi. G, *U. sibogae* (Weber-van Bosse, 1901) Gaarder, 1970 IGMD-160-Mi. H, *C. pliipelagicus* Wise, 1973 IGMD-102b-Mi. I, *Coronocyclus nitescens* (Kamptner, 1963) Bramlette and Wilcoxon, 1967 IGMD-104-Mi. J, *Hayaster perplexus* (Bramlette and Riedel, 1954) Bukry, 1973b IGMD-119-Mi. K, *Hayella* sp. IGMD-120-Mi. L, *Oolitothus* sp. IGMD-127-Mi. M, *U. foliosa* (Kamptner, 1963) Geisen *in* Sáez *et al.* 2003 IGMD-159b-Mi. Scale bars = 1 μ m.

japonica, *Pseudoemiliana lacunosa*, *Reticulofenestra haqii*, *R. minuta*, *R. minutula*, *Syracosphaera histricea*, *S. pulchra*, *Umbilicosphaera foliosa*, and *U. sibogae*. The calcareous nannofossils are rare to common, moderate well preserved. In addition, some reworked Miocene species were identified, as *Discoaster formosus*, *Helicosphaera ampliaperata*, and *Helicosphaera burkei*. In Palma Sola II the calcareous nannofossils have a homogeneous distribution throughout the sedimentary column. Nevertheless, there are intervals where the record of several species is abruptly interrupted, making it difficult to know if the absence of one species is due to ecological or stratigraphic reasons.

Following the distribution pattern of the index species through the column, it is not possible to give with certainty an age for the Palma Sola II base; nevertheless, the presence of *Ceratolithus rugosus* that has its FO in the NN13 of the *Ceratolithus rugosus* Zone (Martini, 1971) allows an age assignment not older than the Pliocene. *Pseudoemiliana lacunosa* and *P. ovata* co-occurs intermittently from sample five to ten (3.27 to 7.55 m from the base); both are indicative

of an age not older than the *R. pseudoumbilica* (NN15) Zone (Martini, 1971), where *P. lacunosa* occurs for the first time (≈ 3.92 – 3.70 Ma, Zanclean stage; Young, 1998).

At Unit III (samples 11, 12, 14; 8.54 to 11 m from the base), there are no index species recorded. Because no unconformity was observed in the field, it is assumed a continuous sedimentation and therefore an equal or younger age is assigned to this part of the column. Units IV, V, VI and VII (samples 15–25; 27–37; 12.9 to 32.63 m), in particular from sample 17 (located 14.36 m from the base) to the top, contain a highly diverse association and the species become more diverse and well preserved. At sample 18 (at 15.45 m from the base) small *Gephyrocapsa*, *Reticulofenestra minuta*, *R. haqii* and *R. minutula* co-dominate and co-exist with an almost homogenous distribution, except for some brief absences, until sample 37 (Unit VII, 32.6 m). *R. minutula* has its FO (≈ 3.92 – 3.70 Ma) in the Zanclean stage, in the base of the NN15 *R. pseudoumbilica* Zone (Martini, 1971), whereas *R. haqii* has its LO in the top of this same zone (Bown, 1998). The co-occurrence of these species in

Figure 5. Zygodiscals. Distal shields **A, C, F, H, J–L**, proximal shields **B, D, E, G, I**. Sample 8b Palma Sola I: **A, B, F–K**, sample 30b Palma Sola II: **C–E**, sample 5b Palma Sola II: **L**. **A**, *Helicosphaera* aff. *ampliapertura* Bramlette and Wilcoxon, 1967 IGMD-121-Mi. **B**, *H. burkei* (Black, 1971) Theodoridis, 1984 IGMD-122-Mi. **C**, *H. carteri* (Wallich, 1877) Kamptner, 1954 IGMD-123-Mi. **D**, *H. kamptneri* (Hay & Mohler in Hay *et al.*, 1967) Locker, 1973 IGMD-124-Mi. **E**, *H. sellii* (Bukry & Bramlette, 1969) Jafar & Martini, 1975 IGMD-125-Mi. **F**, *Pontosphaera* aff. *japonica* (Takayama, 1967) Nishida, 1971 IGMD-130-Mi. **G**, *P. discopora* Schiller, 1925 IGMD-129-Mi. **H**, *P. multipora* (Kamptner, 1948) Roth, 1970 IGMD-131-Mi. **I**, *Pontosphaera* sp.1 IGMD-159-Mi. **J**, *Pontosphaera* sp. 2 IGMD-160-Mi. **K**, *Pontosphaera* sp. 3 IGMD-161-Mi. **L**, *P. callosa* (Martini, 1969) Varol, 1982 IGMD-128-Mi. Scale bars = 1µm.

samples 17 to 37 situates this part of the deposit into this zone with an age of ≈ 3.6 Ma. At Unit VIII (samples 38 and 39, 33.72–36 m) the absence of reticulofenestrids suggest a younger time interval, equivalent to the *Discoaster surculus* NN16 Standard Zone (Martini, 1971). Nevertheless, *Discoaster* and *Sphenolithus*, as well as other warm to temperate index species, were not recorded at all, and therefore it is not possible to recognize this biozone. In conclusion, the only age that it is possible to assign with certainty for Unit III is equivalent to the lower Pliocene *R. pseudumbilica* Zone (Martini, 1971), around 3.6 Ma in the Zanclean (Gradstein *et al.*, 2012) (Figure 9).

The calcareous nannofossils recorded through the sedimentary (Figure 3 to 7) columns are dominated by medium sized *Coccolithus pelagicus* s.l., small to medium *Reticulofenestra* (*R. minuta*, *R. minutula*, and *R. haqii*), small *Gephyrocapsa*, *Helicosphaera* spp. and Reticulofenestrids

has been associated to tropical upwellings (Okada & Honjo, 1973), periods of high fertility (Bickart, 1989; Wade and Bown, 2006), and to a shallow, unstable thermocline (Flores *et al.*, 2005). Abundance of small *Gephyrocapsa* has been considered as indicative of a poorer stratification of surface waters (Gartner *et al.*, 1977), whereas *C. pelagicus* has been largely considered as indicative of surface cold waters (Okada & McIntyre, 1979; Bukry, 1980; Winterer *et al.*, 1994), but its relation with increased productivity has been discussed (*e.g.* Cachão & Moita, 1995; Filippelli *et al.*, 2003; Boeckel & Baumann, 2004; Flores *et al.*, 2005). Taxonomic studies (Geisen *et al.*, 2002) separate two subspecies, *C. pelagicus pelagicus* and *C. pelagicus braarudii* that are considered as related with the presence of cool and temperate water masses, respectively (Cachão & Moita, 2000). In the Palma Sola columns *C. pelagicus* is represented mostly by heterococcoliths with bridge and

Figure 6. Zygodiscals. Side view, except A–C in distal view, sample 30b Palma Sola II: E–G, J, P–R, sample 8b Palma Sola I: A–C, I, sample 1b Palma Sola I: L–M, sample 9b Palma Sola I: D, sample 6b Palma Sola II: H, sample 10b Palma Sola II: K, sample 5c Palma Sola II: N, sample 24b Palma Sola II: O, sample 6b Palma Sola I: R. A, *Scyphosphaera apsteinii* Lohmann, 1902 IGMD-140a-Mi. B, *S. apsteinii* IGMD-140b-Mi. C, *Scyphosphaera* sp. IGMD-162-Mi. D, *S. apsteinii* IGMD-140c-Mi. E, *S. biarritzensis* Lezaud, 1968 IGMD-141-Mi. F, *S. brevis* Varol, 1984 IGMD-142-Mi. G, *S. campanula* Deflandre, 1942 IGMD-143-Mi. H, *S. darraghi* Rade, 1975 IGMD-144-Mi. I, *S. gladstonensis* Rade, 1975 IGMD-145-Mi. J, *S. globulata* Bukry & Percival, 1971 IGMD-146-Mi. K, *S. halldali* Deflandre in Deflandre & Fert, 1954 IGMD-147-Mi. L, *S. aff. kamptneri* Müller, 1974 IGMD-148-Mi. M, *S. pacifica* Rade, 1975 IGMD-149-Mi. N, *S. penna* Kamptner, 1955 IGMD-150-Mi. O, *S. pulcherrima* Deflandre, 1942 IGMD-151-Mi. P, *S. recta* (Deflandre, 1942) Kamptner, 1955 IGMD-152-Mi. Q, *S. recurvata* Deflandre, 1942 IGMD-153-Mi. R, *S. aff. rottiensis* Jafar, 1975 IGMD-154-Mi. Scale bars = 1 µm.

medium sized, that correspond to *C. pelagicus braarudii* and to the intermediate (10–13 µm) morphotype illustrated by Parente *et al.* (2004). Therefore, the abundance of these morphotypes, reticulofenestrads, small *Gephyrocapsa*, and helicoids, as well as the virtual absence of asteroliths, typical of deep, warm and unproductive environments (Bukry, 1978), strongly suggest that the area was influenced by coastal upwelling. Nevertheless, it must be noted that there may also be an effect due to taphonomic factors, related to a greater resistance to dissolution of these species.

Based on the abundance of *Coccolithus pelagicus* s.l., small to medium *Reticulofenestra* spp., small *Gephyrocapsa* and *Helicosphaera* spp., it is inferred a temperate (14° to 17°C), eutrophic, nearshore environment with high terrigenous

input and influenced by coastal upwelling. Moreover, absence of warm open sea water, sphenoliths and discoasters (Haq & Lohmann, 1976, 1977; Haq, 1980; Backman *et al.*, 1986; Wei & Wise, 1990), together with the low and monotonous diversity exhibited throughout the whole studied columns, strongly suggests a dynamic nearshore setting. Additionally, abundance of *Scyphosphaera* species seems to confirm the nearshore warm water environment.

DISCUSSION

Taking in consideration the microfossils reported by Umhoefer *et al.* (2007) and those reported and illustrated here, and its ranges updated, several considerations they

Figure 7. Nannolith *Incertae sedis*; Noncocco; Calcareous dinoflagellates. Distal view Discoasterales **A**, **C**–**G**, proximal view; **B**, proximal view; **H**, sample 18b Palma Sola II: **D**–**E**, **G**, sample 8b Palma Sola I: **B**–**C**, sample 30b Palma Sola II: **A**, sample 9b Palma Sola II: **F**, sample 17b Palma Sola II: **H**, sample 7a Palma Sola II: **I**, sample 10b Palma Sola II: **J**, sample 9b Palma Sola II: **K**, sample 5b Palma Sola I: **L**, sample 9b Palma Sola I: **M**, sample 4b Palma Sola I. **A**, *Holodiscolithus macroporus* (Deflandre in Deflandre & Fert, 1954) Roth, 1970 IGMD-126-Mi. **B**, *Discosphaera tubifera* (Murray & Blackman, 1898) Ostenfeld, 1900 IGMD-108-Mi. **C**, *Syracosphaera histrica* Kamptner, 1941 IGMD-155-Mi. **D**, *S. pulchra* Lohmann, 1902 IGMD-156a-Mi. **E**, *S. pulchra* IGMD-156b-Mi. **F**, *Discoaster brouweri* Tan, 1927 emend. Bramlette & Riedel, 1954 IGMD-105-Mi. **G**, *D. formosus* Martini & Worsley, 1971 IGMD-106-Mi. **H**, *D. aff. pentaradiatus* Tan, 1927 IGMD-107-Mi. **I**, *Braarudosphaera bigelowii* (Gran and Braarud, 1935) Deflandre, 1947 IGMD-95-Mi. **J**, *Ceratolithus cristatus* Kamptner, 1950 IGMD-98-Mi. **K**, *C. rugosus* Bukry & Bramlette, 1968 IGMD-99-Mi. **L**, *Ceratolithus* sp. IGMD-100-Mi. **M**, *Cervisiella saxea* (Stradner, 1961) Hildebrand-Habel, Willems & Versteegh, 1999 IGMD-158-Mi. **N**, *Thoracosphaera fossata* Jafar, 1975 IGMD-157-Mi. Scale bars = 1 μ m.

must necessarily be underlined. Concerning the calcareous nannofossils, Umhoefer *et al.* (2007) stated that the presence (in sample 25, section X; Figure 2) of *Emiliania ovata* and the lack of “two early Pliocene species which are normally common even in restricted assemblages” (sic) is enough evidence to consider the deposit as of Late Pliocene age, into the CN12 *Discoaster brouweri* Zone (Bukry, 1973a; 1975; Okada & Bukry, 1980). Nevertheless, *E. ovata* has its FO at 3.92–4.13 Ma and its LO at 0.44–1.93 Ma (Young, 1998); therefore, its presence does not support by itself an age assignment of late Pliocene for the whole unit.

This late Pliocene age (2.5–2.4 Ma) for an interval that include samples 16 to 31 (section X; Figure 2) is reinforced by Umhoefer *et al.* (2007) based on the presence of the planktonic foraminifers *Globorotalia unguolata* Bermúdez, sinistral forms of *Pulleniatina primalis* Banner & Blow, the presence of *Pulleniatina praecursor* Banner & Blow, and the absence of *Pulleniatina obliquiloculata* s.s. Banner & Blow. Nevertheless, *G. angulata* is a shallow dwelling juvenile of *G. tumida* (Brown, 2007), which have its FO at 5 Ma, whereas the FO of *G. unguolata* is unclear and

no attempt was made to situate its first occurrence in the geological record. A mid-Zanclean to Recent stratigraphic range for this species has been reported (BouDagher-Fadel, 2013). Likewise, the age interval of 2.5–2.4 Ma interpreted by Umhoefer *et al.* (2007) based in the presence of sinistral *Pulleniatina primalis* corresponds to a circular reasoning, since there is no way to verify that this event corresponds to the 2.7 Ma dextral-sinistral shift occurring in the Pacific DSDP Site 157 (Keigwin, 1978), especially when it is not possible to document an older or a continuous record of the genera in the studied area to allow the verification of well chronostratigraphic constrained shifts in the *Pulleniatina* coiling. On the other hand, *P. precursor* is considered an Atlantic species characteristic of a short time interval around 3.6 Ma (Bolli & Saunders, 1985). In the Eastern Tropical Pacific, the closest record of this species is located in Maria Madre island off the coast of México, where an age of $\approx$ 3.1 Ma was assigned based on the presence of *P. obliquiloculata* (Parker & Jones), *P. praecursor*, and *Neoglobobadrina dutertrei* (d’Orbigny) while the rocks without *P. praecursor* are considered to have younger age (McCloy *et al.*, 1988).

Figure 8. Calcareous nannofossils recorded throughout column Palma Sola I, San José Island, Baja California Sur, Mexico.

Figure 9. Calcareous nannofossils recorded throughout column Palma Sola II, San José Island, Baja California Sur, Mexico.

Absence of *P. obliquiloculata* is considered by Umhoefer *et al.* (2007) as indicative of a younger age because the genus disappears in the Atlantic realm from 3.5–2.5 Ma, but once again the fact is that in the Pacific it has a continuous record.

In the present study, sinistral forms of *P. obliquiloculata* and *P. primalis* were recovered, and are the most conspicuous planktonic foraminifers together with *Globigerina bulloides* (d'Orbigny) *plexus*, *Neogloboquadrina dutertrei* (d'Orbigny), *Globigerinoides ruber* (d'Orbigny), *Globigerinoides quadrilobatus* (d'Orbigny), *Orbulina. universa* d'Orbigny, *P. primalis*, *P. obliquiloculata* and *Globorotalia tumida*, *Globorotalia menardii*, and variants. Other species are rare, poorly preserved, and sparsely distributed. It is noticed that no *Globorotalia unguolata* Bermúdez, *Globorotalia exilis* Blow, *Globorotalia limbata* Fornasini or *Pulleniatina alticuspis* Carreño, were recorded.

No attempt was made here to study siliceous microfossils, but according to Umhoefer *et al.* (2007) the assemblage recovered by them from one sample of diatomaceous siltstone located 10 m stratigraphically below their sample 15 (sic), corroborates an age of 2.4–2.0 Ma. An updated revision of the data (FO and LO) of the siliceous species used to assign the age of the La Gata Mudstone by Umhoefer *et al.* (2007), following the criteria of the diatom (Burckle, 1972; Barron, 1985) and silicoflagellate biozonations (Bukry, 1972, 1981) indicate that an older age interpretation is possible (Figure 8). Umhoefer *et al.* (2007) reports an age of 2.4–2.0 Ma due to the presence of *Rhizosolenia praebergonii* Mukhina, *Azpeitia nodulifera* var. *cyclopus* (Jousé) Fryxell & Sims, *Asteromphalus elegans* Greville, and the absence of *Fragilariopsis doliolus* (Wallich) Medlin & Sims, *Nitzschia jouseae* Burckle and *Thalassiosira convexa* Mukhina, and the silicoflagellate *Dictyocha staepedia* Haeckel. If as stated by Umhoefer *et al.* (2007) the absence of *N. jouseae*, *A. elegans*, *T. convexa* var. *convexa* and *F. doliolus* in the diatomaceous siltstones of La Gata mudstone is due to stratigraphic reasons, then, according with the stratigraphic ranges of these species (Figure 8) the age of these rocks must be situated after 2.1 Ma, when *T. convexa* have its LO.

However, if the age is based on the stratigraphic ranges of the species as *Rhizosolenia praebergonii*, *Asteromphalus*

elegans, and *Azpeitia nodulifera* var. *cyclopus*, the estimated age for this sample must be not older than ≈ 3.0 (datum of the FO of *R. praebergonii*). The presence of *Dictyocha staepedia*, used by Umhoefer *et al.* (2007) to assign a final age of 2.5–2.4 Ma for the whole marine rocks, occurs for the first time into the *N. jouseae* Zone (Burckle, 1972; Barron, 1985) around 3.0 Ma.

Thus, taking in account only the taxa recorded by Umhoefer *et al.* (2007) instead of the absences, the consensus age for the La Gata mudstone is around 3.7–3.0 Ma, that following Gradstein (2012) situates the sedimentary column here studied in the boundary between the lower Pliocene and the upper Pliocene (Zanclean–Piazzencian). The $\text{Ar}^{40}/\text{Ar}^{39}$ (3.1 ± 0.5 –3.6 Ma) age provided by Umhoefer *et al.* (2007) from the tuffaceous sandstone in the western portion of Punta Colorada sub-basin is consistent with the results here presented but also with the updated data published by Umhoefer *et al.* (2007).

The presence of an intensive upwelling associated to the La Gata mudstone deposit indicated by the calcareous nannofossils assemblages need to be explained within a warm period. According with Dekens *et al.* (2007), around 4.6–3.1 Ma the sea surface temperature of the Eastern Equatorial Pacific at the California margin was warmer than today by 3–9°C, and cold upwelling regions did not exist in the early Pliocene in the same way that they occur today. In contrast, Bakun (1990) considered that under global warming upwelling regions might, become even more pronounced. Consequently, the warmer conditions described by Dekens *et al.* (2007) can be an example of upwelling for the early Pliocene in the newly formed Gulf of California.

In conclusion, the calcareous nannofossils here recorded throughout the upper part of the La Gata mudstone, gives an older age that the previously proposed by Umhoefer *et al.* (2007) for the upper Sequence 3 (within the La Gata mudstone), whereas the updated revision of the biostratigraphic data of diatoms, silicoflagellates, planktonic foraminifera, and calcareous nannofossils used by those authors (Table 1) allow us to estimate an age of 3.7–3.0 Ma for the La Gata mudstone, at least for its lower and middle part, which fits well with the age here proposed of ≈ 3.6 Ma.

Table 1. Diatoms and Silicoflagellates mentioned by Umhoefer *et al.* (2007) from a diatomaceous siltstone located approximately at 30 m from the base of the La Gata mudstone in their Column X at the Palma Sola Basin. Biozones by 1) Burckle (1972) & Barron (1985) for diatoms, 2) Bukry (1972, 1981) for silicoflagellates. Updated Datum by 3) Clemens *et al.* (2016a,b); 3) Sims *et al.* (1989) and Shiono & Koizumi (2002); 4) Barron (1992); 5) Guiry in Guiry & Guiry (2018).

Species	FO	LO
<i>Rhizosolenia praebergonii</i>	base of <i>R. praebergonii</i> Zone ^{1,4} ≈ 3.0 Ma	top of <i>Nitzschia reinholdi</i> Subzone A, at 1.8 Ma ^{1,4}
<i>Fragilariopsis doliolus</i>	top of <i>Nitzschia reinholdi</i> Subzone ¹ at 1.8 Ma ^{1,4}	Recent
<i>Nitzschia jouseae</i>	4.5 Ma ⁴	2.6 Ma ⁴
<i>Thalassiosira convexa</i> var. <i>convexa</i>	3.6 Ma ⁴	2.1 Ma ⁴
<i>Asteromphalus elegans</i>	3.9 Ma ^{2,4}	Recent ⁵
<i>Azpeitia nodulifera</i> var. <i>cyclopus</i>	7.9–7.0 Ma ³	Recent ⁴
<i>Dictyocha staepedia</i>	3.0 Ma into the <i>N. jouseae</i> Zone ²	

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Appendix 1. Check list and consensual stratigraphic ranges of species of calcareous nannofossils recorded in two sedimentary columns measures un the Palma Sola Basin, San José Island, Baja California Sur.

Braarudosphaera bigelowii (Gran & Braarud, 1935) Deflandre, 1947 (100.5–0.0 Ma)

Calcidiscus leptoporus (Murra & Blackman, 1898) Loeblich & Tappan, 1978 (22.8–0.0 Ma)

Calcidiscus macintyreii (Bukry & Bramlette, 1969) Loeblich & Tappan, 1978 (2.4–0.4 Ma)

Ceratolithus cristatus Kamptner, 1950 (5.1–1.7 Ma)

Coccolithus pelagicus (Wallich, 1877) Schiller, 1930 (66.0–0.0 Ma)

Coccolithus pliopelagicus Wise, 1973 (57.2–42.8 Ma)

Coccolithus streckeri Takayama & Sato, 1987 (15.6–0 Ma)

Coronocyclus nitescens (Kamptner, 1963) Bramlette & Wilcoxon (46.29–11.9 Ma)

Discoaster brouweri Tan, 1927 emend. Bramlette & Riedel, 1954 (10.5–1.9 Ma)

Discoaster formosus Martini & Worsley, 1971 (15.6–13.5 Ma)

Discoaster pentaradiatus Tan, 1927 (8.2–5.5 Ma)

Discosphaera sp. Haeckel, 1894 (23.0–0.0 Ma)

Gephyrocapsa small (4.1–0.02 Ma)

Gephyrocapsa aperta (4.1–0.02 Ma)

Gephyrocapsa margereli Bréhéret, 1978 (4.1–0.02 Ma)

Gephyrocapsa proto huxleyi McIntyre, 1970 (4.7–0–0 Ma)

Hayaster perplexus (Bramlette & Riedel, 1954) Bukry, 1973 (57.2–0.0 Ma)

Hayella sp. Gartner, 1969 (49.1–5.1 Ma)

Helicosphaera ampliaperta Bramlette & Wilcoxon, 1967 (22.8–14.9 Ma)

Helicosphaera burkei Black, 1971 (15.6–8.6 Ma)

Helicosphaera carteri (Wallich, 1877) Kamptner, 1954 (23.1–0.0 Ma)

Helicosphaera selli (Bukry & Bramlette, 1969) Jafar & Martini, 1975 (5.5–0.4 Ma)

Holodiscolithus macroporus (Deflandre in Deflandre & Fert, 1954) Roth, 1970 (57.21–0.29 Ma)

Oolithotus sp. Cohen & Reinhardt, 1968 (23.0–0.0 Ma)

Pontosphaera callosa (Martini, 1969) Varol, 1982 (15.6–2.0 Ma)

Pontosphaera discopora Schiller, 1925 (23.0–0.0 Ma)

Pontosphaera var. *japonica* (Takayama, 1967) Nishida, 1971 (23.0–0.0 Ma)

Pontosphaera multipora (Kamptner, 1948) Roth, 1970 (66.0–0.0 Ma)

Pseudoemiliania lacunosa (Kamptner, 1963) Gartner, 1969 (3.9–0.4 Ma)

Pseudoemiliania ovata (Bukry, 1973) Young, 1998 (4.1–0.4 Ma)

Reticulofenestra haqii Backman, 1978 (22.8–3.7 Ma)

Reticulofenestra minuta Roth, 1970 (50.5–2.5 Ma)

Reticulofenestra minutula (Gartner, 1967) Haq & Berggren, 1978 (3.9–1.9 Ma)

Reticulofenestra rotaria Theodoris, 1984 (7.4–6.9 Ma)

Reticulofenestra sp. Hay, Mohler & Wade, 1966 (55.9–0.0 Ma)

Scyphosphaera apsteinii Lohmann, 1902 (53.7–0.0 Ma)

Scyphosphaera biarritzensis Lezard, 1968 (53.7–0.0 Ma)

Scyphosphaera brevis Varol, 1984 (14.8–1.0 Ma)

Scyphosphaera campanula Deflandre, 1942 (14.8–2.0 Ma)

Scyphosphaera darraghi Rade, 1975 (14.8–2.2 Ma)

Scyphosphaera gladstonensis Rade, 1975 (5.6–1.0 Ma)

Scyphosphaera globulata Bukry & Percival, 1971 (8.2–1.9 Ma)

Scyphosphaera halldali Deflandre, 1954 (8.6–5.2 Ma)

Scyphosphaera kamptneri Muller, 1974 (8.6–2.0 Ma)

Scyphosphaera pacifica Rade, 1975 (5.8–1.0 Ma)

Scyphosphaera penna Kamptner, 1955 (10.6–2.8 Ma)

Scyphosphaera pulcherrima Deflandre, 1942 (13.5–0.4 Ma)

Scyphosphaera recta (Deflandre) Kamptner, 1955 (10.6–1.8 Ma)

Scyphosphaera recurvata Deflandre, 1942 (32.3–0.6 Ma)

Scyphosphaera aff. *Rottiensis* Jafar, 1975 (10.6–1.8 Ma)

Syracosphaera histrica Kamptner, 1941 (2.5–0.0 Ma)

Syracosphaera pulchra Lohmann, 1902 (5.3–0.0 Ma)

Thoracosphaera fossata Jafar, 1975 (23.9–5.6 Ma)

Thoracosphaera saxea Stradner, 1961 (62.0–0.0 Ma)

Umbilicosphaera foliosa (Kamptner, 1963, ex Kleijne, 1993) Geisen in Sáez et. al., 2003 (3.7–0.0 Ma)

Umbilicosphaera sibogae (Weber–van Bosse) Gaarder 1970 (3.92–0.0 Ma)