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NOTA PALEONTOLÓGICA

Stratigraphic implications of latest middle Miocene to earliest late Miocene diatoms in the Navidad Formation at Lo Abarca, central Chile (33° 30'S)

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Introduction

Neogene marine strata crop out at various localities along the Chilean coastline (see Encinas *et al.*, 2008 and references therein). The best studied of these successions occurs in the Navidad area, between San Antonio and Punta Topocalma (33°30'-34°30'S) (figure 1). Named and described by Darwin (1846) as the Navidad Formation, the geology and paleontology of this unit was subsequently studied by many other authors (*e.g.*, Philippi, 1887; Brüggen, 1950; García, 1968; Tavera, 1979) and has been considered the stratigraphic reference for the marine Neogene of Chile (*e.g.*, Cecioni, 1980; De Vries and Frassinetti, 2003). However, its age, stratigraphy and depositional environment were a matter of debate for several decades (*e.g.*, Brüggen, 1950; García, 1968; Tavera, 1979; Encinas *et al.*, 2006). Recent foraminiferal and sedimentologic studies indicate a late Miocene to early Pliocene age and a deep-marine setting for this unit (Finger *et al.*, 2007; Encinas *et al.*, 2008). Yet, the older latest Oligocene to middle Miocene age proposed for the molluscan fauna of this unit (De Vries and Frassinetti, 2003) still constitutes an unresolved problem (see below).

North of the Navidad area, between Valparaíso and San Antonio (33°00'?33°30'S), Neogene successions have been traditionally referred to as the "capas de Lo Abarca" (Covacevich and Frassinetti, 1990) (figure 1). These strata have been considered equivalent to the Navidad Formation by some authors (Brüggen, 1950; Fuenzalida and Varela 1964; Encinas *et al.*, 2006) and as a different unit by others (Martínez-Pardo and Parada, 1968; Covacevich and Frassinetti 1990). The main argument for distinguishing the successions is based on their different molluscan faunas (Covacevich and Frassinetti, 1990). Nevertheless, Encinas *et al.* (2006) considered both successions as corrrelative and included the Lo Abarca strata in the Navidad Formation because their diatoms and foraminifera indicate similar ages and both units show similar facies. Essential to the age constraint of the Lo Abarca succession and its correlation with the Navidad Formation is the diatom assemblage found at Lo Abarca section that we document in this note.

Geologic setting

The study area is located along the coast and western Coastal Cordillera of central Chile, between Valparaíso and Punta Topocalma (~33°00'-34ºS) (figure 1), approximately 100 km west of Santiago de Chile. The stratigraphic succession comprises Paleozoic, Triassic and Jurassic plutonic and metamorphic rocks overlain by Late Cretaceous, Eocene, and Neogene marine strata (Gana *et al.*, 1996; Wall *et al.*, 1996). Neogene marine strata are widely exposed around Navidad village and also found as small outcrops scattered between San Antonio and Valparaíso (figure 1). Encinas *et al.* (2006) divided the succession into the Navidad, Licancheu, Rapel and La Cueva formations and included the Lo Abarca beds in the Navidad Formation (see above).

In its type area (around Navidad village), the Navidad Formation is at least 100 to 200 m thick and consists of sandstone, siltstone, conglomerate and coquina. Sedimentary facies, trace fossils and benthic foraminifera indicate that this formation was deposited in a deep-marine environment (Finger *et al.*, 2007; Encinas *et al.*, 2008). Planktonic foraminifera in-

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dicate a Tortonian (late Miocene, N16) to Zanclean (early Pliocene, N19) age for this unit (Finger *et al.*, 2007). Shallow marine Pliocene strata of the Licancheu, Rapel and La Cueva formations overlie this formation in its type area (Encinas *et al.*, 2006).

North of the Navidad area, between Valparaíso and San Antonio (figure 1) the Navidad Formation consists of a basal conglomerate or coquina overlain by sandstone and siltstone. Benthic foraminifers, sampled from two localities near Laguna El Peral (figure 1) indicate lower bathyal depositional depths (Encinas *et al.*, 2008). Planktonic foraminifera ob-

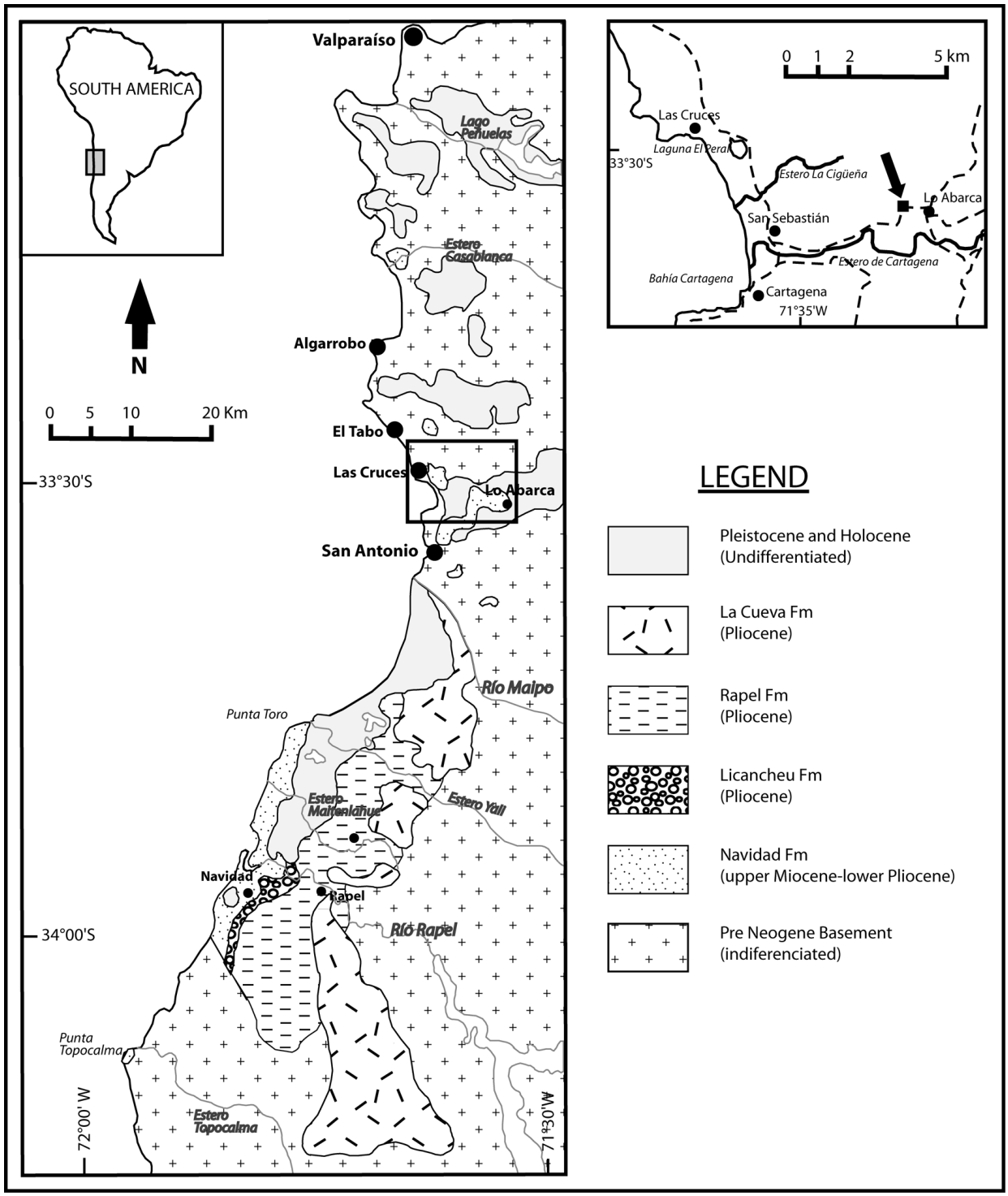

Figure 1. Geologic map showing the extension of Neogene marine deposits in the study area. Location of the section in figure 2 is indicated with an arrow in the upper right inset / *mapa geológico mostrando los afloramientos de los depósitos Neógenos marinos en el área de estudio. La ubicación de la sección de la figura 2 se indica con una flecha en la parte superior derecha.*

tained from one of the cited sections include *Globigerina venezuelana* Hedberg (Eocene?N19), *Globigerina bulloides* d'Orbigny (N9-Recent), and *Orbulina* universa d'Orbigny (upper N15-Recent) (Encinas *et al.*, 2008). The concurrent range (upper N15?N19) of these species comprises the Tortonian (earliest late Miocene) to Zanclean (early Pliocene) interval. Martínez-Pardo and Parada (1968) suggested a Pliocene age for the Laguna el Peral assemblage because it includes *Bolivina argentea* Cushman, a benthic foraminifer that first appears in the lower Pliocene of California (Ingle, 1980; Finger, 1990). Diatoms sampled at Lo Abarca section (see below) indicate a latest middle Miocene to earliest late Miocene for this section. Thus, age intervals obtained for the Lo Abarca and Navidad successions are nearly identical (Encinas *et al.*, 2006).

Diatoms

Fossil diatoms were recovered in a section located approximately 750 m west of Lo Abarca village (figure 1). The exposed stratigraphic section overlies the metamorphic Paleozoic basement and is 21 m thick. It begins with a two meter-thick clast-supported conglomerate that grades upward into very coarse-grained sandstone and overlies the metamorphic Paleozoic basement (figure 2). The conglomerate contains granite and schist clasts, and mollusks, and is overlain by a succession of rhythmically interbedded sandstone and siltstone that form centimeters to meters thick beds. Sandstones are generally massive or less commonly parallel-laminated. They often contain siltstone rip-up clasts up to 50 cm in diameter and occasionally show erosive contacts and water escape structures. Siltstones and very fine sandstones contain *Chondrites* isp., *Zoophycos* isp., and rare *Thalassinoides* isp. The Lo Abarca marine succession is disconformably overlain by the quartz-rich sandstones of the continental Pleistocene(?) "Los Paraguas" Formation (Fuenzalida and Varela, 1964).

The diatom-bearing samples were obtained from siltstone beds lying at 5 m (sample ABAR.1), 8 m (sample ABAR.2) and 16 m (sample ABAR.3) stratigraphically above the base of the section (figure 2). The assemblage comprises a mixture of marine and freshwater species. Marine species include planktonic diatoms, such as *Chaetoceros* spp., *Coscinodiscus* spp., and *Thalassionema nitzschioides* (Grunow) Mereschkowsky, and marine neritic diatoms such as *Paralia sulcata* (Ehrenberg) Cleve, *Actinoptychus* spp., and *Diploneis* spp. One of the most common freshwater species is an *Aulacoseira*-like form; it is very similar to the taxon described as *Melosira solida* var. *multiformis* by Frenguelli (1933) from Miocene lacustrine deposits in northern Patagonia. Other freshwater diatoms include *Synedra* sp., *Fragilaria* sp., *Opephora* sp., *Aulacoseira distans* (Ehr.) Simonsen, *Aulacoseira granulata* (Ehr.) Simonsen and *Aulacoseira* sp. The presence of freshwater diatoms in marine sediments is not unusual (Fourtanier 1986; Gasse *et al.*, 1989), as they are often windblown or transported by rivers.

Stratigraphic markers were only found in samples ABAR.2 and ABAR.3 (figure 2). The most important of these markers are *Craspedodiscus coscinodiscus* Ehrenberg (16.9 to 11.3 Myr), *Coscinodiscus gigas* var. *diorama* (A. Schmidt) Grunow (13.0 to 11.1 Myr), *Denticulopsis simonsenii* Yanagisawa and Akiba (14.5 to 8.6 Myr), *Thalassiosira grunowii* Akiba and Yanagisawa (13.6 to 7.8 Myr), and *Thalassiosira brunii* Akiba and Yanagisawa (12.2 to 8.9 Myr) (figure 3). The age ranges listed in parentheses are based on those calculated by Barron (2003) for the cited species in the equatorial Pacific. The concurrent occurrence of these markers indicates an age interval of ca 12.2 to 11.3 Myr (latest middle Miocene to earliest late Miocene according to the scale of Gradstein *et al.*, 2004) for the Lo Abarca section.

Discussion

The diatom assemblage of the Lo Abarca section constitutes one of the few Miocene records of these taxa in marine deposits of the Chilean forearc. Contrary to Perú, where Miocene diatomites are abundant, most Neogene diatom-bearing marine strata in Chile are Pliocene or younger (Tsuchi *et al.*, 1992).

Latest middle to earliest late Miocene diatoms, however, have been documented elsewhere in Chile. Le Roux *et al.* (2006) discussed the stratigraphy and age of the Coquimbo Formation which is exposed near the Bay of Tongoy in central Chile. They noted the report by Tsuchi *et al.* (1990) on diatoms of this unit that were obtained from the basal strata of the Pachingo (also called El Rincón) section. The assemblage includes *Azpeitia nodulifera* (Schmidt) Fryxell and Sims, *Coscinodiscus plicatus* Grunow (=*Thalassiosira grunowii* Akiba and Yanagisawa), *Denticulopsis hustedtii* (Simonsen and Kanaya) Simonsen (= *D. simonsenii* Yanagisawa and Akiba), and *Synedra jouseana* Sheshukova, which indicate a late middle to early late Miocene age (14.2 to 10.4 Myr.). Le Roux *et al.* (2006) suggest that the basal part of the Pachingo section, has a mean age close to 11.2 Ma, which is very close to the 11.3 to 12.2 Myr interval indicated by the Lo Abarca diatom assemblage.

The latest middle Miocene to earliest late Miocene age indicated by the diatom assemblage of the Lo Abarca section constitutes an important record not

only to correlate this succession with the Navidad Formation, but also to clarify some uncertainties with the biostratigraphy of the molluscan fauna of this unit. Ages indicated by molluscan and foraminiferal faunas of the Navidad Formation at its type area (around the homonymous locality) are contradictory. De Vries and Frassinetti (2003) proposed a latest Oligocene to middle Miocene age for the molluscan fauna of the Navidad Formation (at its type area). This age is based on the occurrence of some typical species of the Navidad fauna that occur in well dated late Oligocene-early Miocene units from Perú but not in younger successions (De Vries and Frassinetti, 2003). In contrast, planktonic foraminifera indicate a younger late Miocene-early Pliocene age for the Navidad Formation (Finger *et al.*, 2007). Another unresolved problem is that this unit contains different molluscan faunas in the sections of the Navidad and Lo Abarca areas with a rather small percentage (~8%) of species in common (Covacevich and Frassinetti, 1990). According to Covacevich and Frassinetti (1990), the Lo Abarca molluscan fauna includes a relatively high number of endemic species, some species in common with the Navidad Formation, and some species in common with the younger Licancheu, Rapel, and La Cueva formations (*i.e.*, it seems to be a mixture of Navidad and younger faunas). This led them to propose that the Lo Abarca succession has an age intermediate between those of the Navidad and La Cueva formations. However, the diatom assemblage recovered from beds overlying the basal mollusc-bearing conglomerate at Lo Abarca section indicates a latest middle Miocene to earliest late Miocene age. Hence, the Lo Abarca molluscan-bearing strata are not younger than those of the Navidad type area. A possible solution is that the Navidad molluscan fauna is reworked, as suggested by Finger *et al.* (2007) and Nielsen and Glodny (2009), whereas the Lo Abarca molluscan fauna is coeval with the age of deposition. Another possibility is that the differences between both faunas are simply due to different paleoecological conditions. In this sense, it is important to note that the mollusks of the Lo Abarca succession were recovered almost exclusively from the basal shallow-marine conglomerate or coquina (Covacevich and Frassinetti, 1990), whereas those of the Navidad Formation mostly come from the deep-marine succession of sandstone and silt-

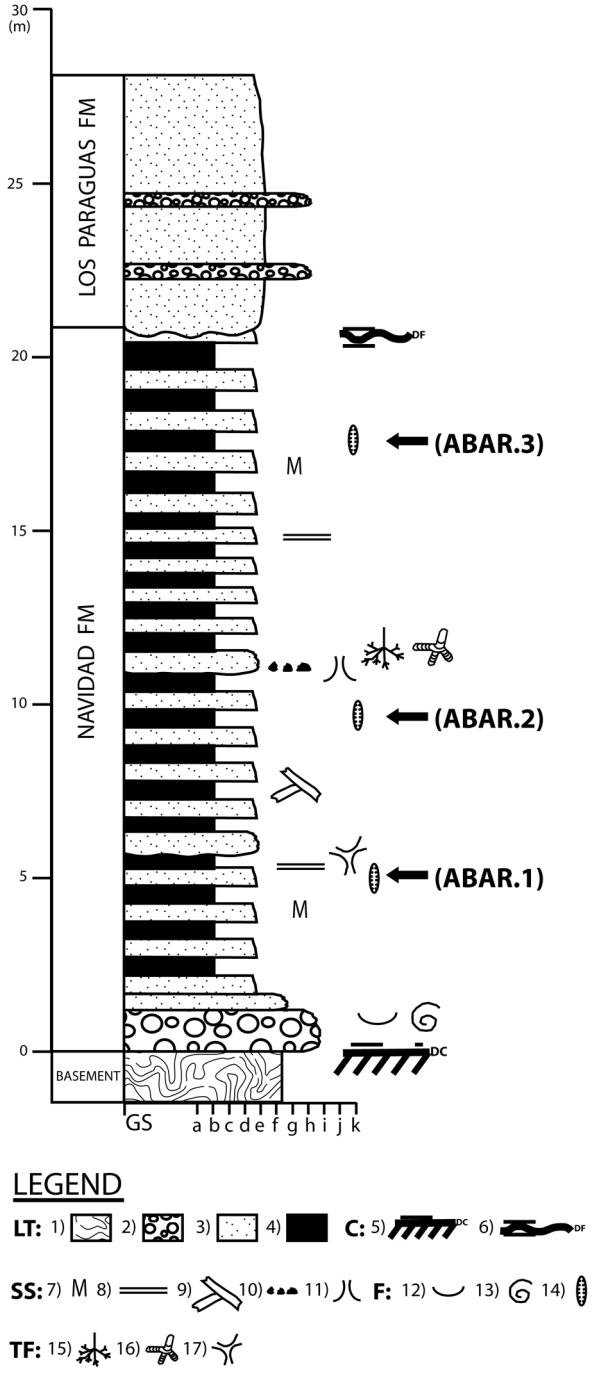

Figure 2. Section of the Navidad Formation at Lo Abarca. The position of diatom samples (ABAR.1, 2 and 3) is indicated. LEGEND, **GS:** Grain size, (**a**) clay, (**b**) silt, (**c**) very fine sandstone, (**d**) fine sandstone, (**e**) medium sandstone, (**f**) coarse sandstone, (**g**) very coarse sandstone, (**h**) gravel (granules), (**i**) gravel (pebbles), (**j**) gravel (cobbles), (**k**) gravel (boulders); **LT:** Lithology, (**1**) metamorphic basement, (**2**) conglomerate, (**3**) sandstone, (**4**) siltstone; **C:** Contact type, (**5**) unconformity, (**6**) disconformity; **SS:** Sedimentary structures, (**7**) massive, (**8**) parallel lamination, (**9**) slides, (**10**) rip-up clasts, (**11**) water-escape structures; **F:** Fossils, (**12**) bivalves, (**13**) gastropods, (**14**) diatoms; **TF:** Trace fossils, (**15**) *Chondrites*, (**16**) *Zoophycos*, (**17**) *Thalassinoides / sección de la Formación Navidad en Lo Abarca. Se indica la ubicación de las muestras de diatomeas (ABAR. 1, 2 y 3). LEYENDA, **GS:** Tamaño de grano,* (**a**) *arcilla,* (**b**) *limo,* (**c**) *arenisca muy fina,* (**d**) *arenisca fina,* (**e**) *arenisca media,* (**f**) *arenisca gruesa,* (**g**) *arenisca muy gruesa,* (**h**) *gravilla,* (**i**) *grava,* (**j**) *ripio,* (**k**) *bolones;* **LT:** *Litología,* (**1**) *basamento metamórfico,* (**2**) *conglomerado,* (**3**) *arenisca,* (**4**) *limolita;* **C:** *Tipo de contacto,* (**5**) *discordancia,* (**6**) *disconformidad;* **SS:** *Estructuras sedimentarias,* (**7**) *masiva,* (**8**) *laminación paralela,* (**9**) *capas deslizadas,* (**10**) *intraclastos,* (**11**) *huellas de escape de fluidos;* **F:** *Fósiles,* (**12**) *bivalvos,* (**13**) *gastrópodos,* (**14**) *diatomeas;* **TF:** *Trazas fósiles,* (**15**) Chondrites, (**16**) Zoophycos, (**17**) Thalassinoides.

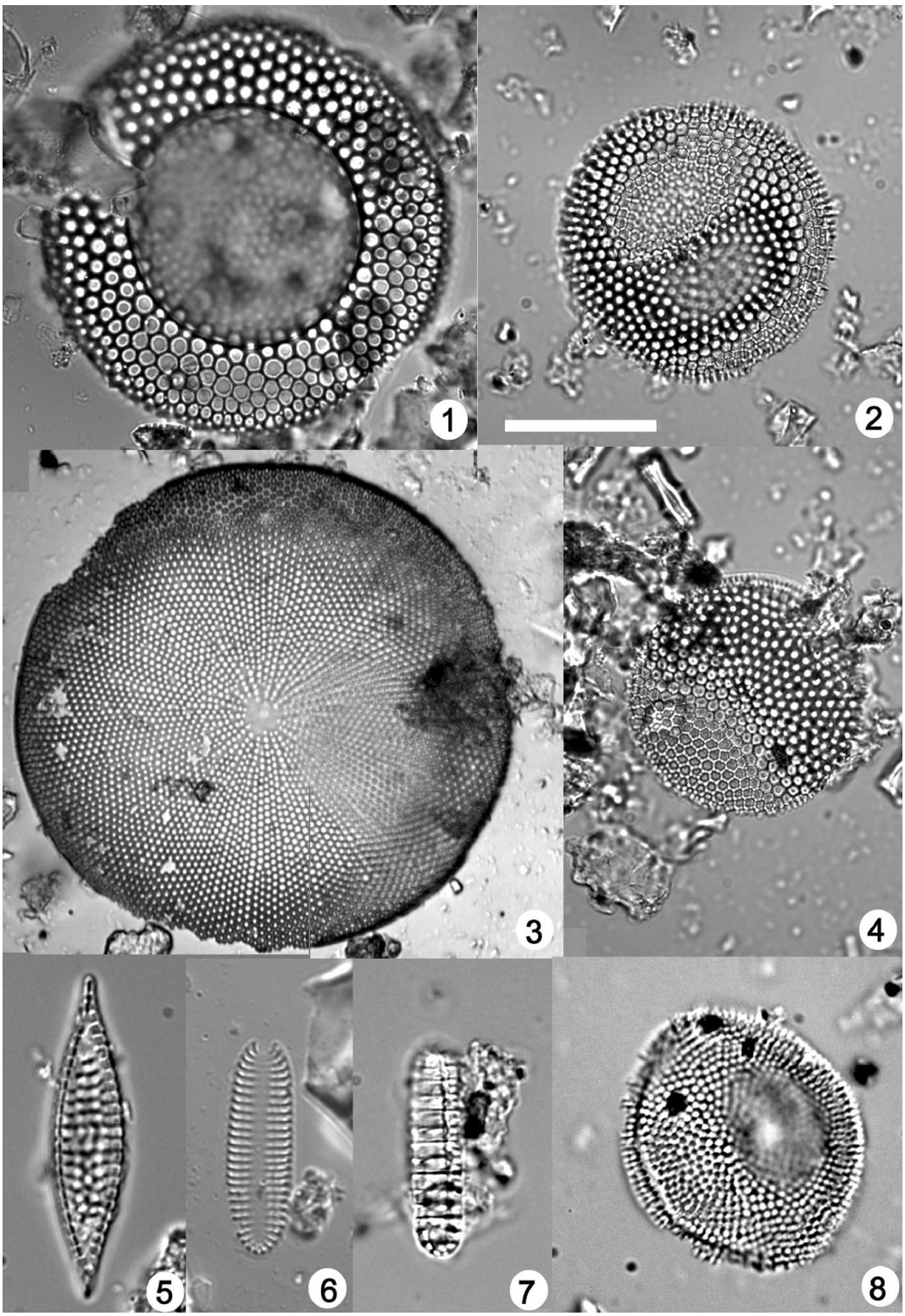

Figure 3. Most important diatom stratigraphic markers found at Lo Abarca section (see figures 1 and 2). The concurrent occurrence of these fossils indicates an age range of 12.2-11.3 Ma (latest middle Miocene-earliest late Miocene) / *marcadores estratigráficos más importantes dentro de las especies de diatomeas que se encontraron en la sección de Lo Abarca (ver figuras 1 y 2). El rango concurrente de estos fósiles indica una edad de 12.2 a 11.3 Ma (Miocene medio terminal-Mioceno tardío basal).* **3.1, *Craspedodiscus coscinodiscus*** Ehrenberg; **3.2, *Thalassiosira grunowii*** Akiba and Yanagisawa; **3.3, *Coscinodiscus gigas*** var. ***diorama*** (A. Schmidt) Grunow; **3.4, *Azpeitia*** sp.cf. ***A. salisburyana*** (Lohman) Sims; **3.5, *Koizumia adaroi*** (Azpeitia) Yanagisawa; **3.6, *Delphineis lineata*** Andrews; **3.7, *Denticulopsis simonsenii*** Yanagisawa and Akiba; **3.8, *Thalassiosira brunii*** Akiba and Yanagisawa. Scale bar = 20 µm for figures 3.1, 3.2 and 3.4; = 50 µm for figure 3.3; = 13 µm for figures 3.5-3.8 / *barra de escala = 20 µm para las figuras 3.1, 3.2 y 3.4; = 50 µm para la figura 3.3; = 13 µm para las figuras 3.5-3.8.*

stone that overlies the basal conglomerate (*e.g.*, Tavera, 1979; Covacevich and Frassinetti, 1986; Nielsen and Frassinetti, 2003). However, in comparing both faunal associations, it must be considered that although several studies have been carried out on the Navidad molluscan fauna (*e.g.*, Philippi, 1887; Tavera, 1979; Covacevich and Frassinetti, 1986; Nielsen and Frassinetti, 2003; Nielsen, 2005), considerably fewer and less detailed studies have been undertaken on those of the Lo Abarca succession (Fuenzalida and Varela, 1964; Herm, 1969; Covacevich and Frassinetti, 1990). Further work is therefore needed to explain the differences between these faunas. In this sense, it is significant that the diatom assemblage documented in the present contribution indicates a latest middle Miocene to earliest late Miocene age (12.2-11.3 Myr) for the Lo Abarca section, because it refutes former studies suggesting that this succession is younger than that of the Navidad area.

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