First report of a surf zone diatom accumulation in the Eastern South Pacific: *Aulacodiscus kittonii* Arnott ex Ralfs (Bacillariophyta) as the dominant and exclusive species

Primera cita de una acumulación de diatomeas de la zona de rompiente de las olas en el Pacífico Sur Oriental: *Aulacodiscus kittonii* Arnott ex Ralfs (Bacillariophyta) como la especie dominante y exclusiva

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ABSTRACT

The so-called "surf diatoms" constitute a small group of species that are present with great abundance in the surf zones of some sandy beaches where often the accumulations are dominated only for one of these species. They adhere to air bubbles generated by wave action forming green or brown patches that float in the surf zone, remaining as long streaks on the beach. In May 2015 a green accumulation was detected in Coquimbo Bay in northern Chile. The study of samples with light and electron microscopy techniques showed the presence of *Aulacodiscus kittonii*, a well-known surf diatom. This is the first report of this kind for Chile and for the whole coast of the Eastern South Pacific Ocean with *A. kittonii* as the dominant species. It is also the first report for Chile as a living taxon. A description of the Chilean specimens is given with comments and photographs on the variation of some of its morphological features.

Keywords: Surf diatoms, sandy beaches, diatom bloom, morphology, Chile.

RESUMEN

Las diatomeas de la zona de rompiente de las olas constituyen un grupo reducido de especies que producen acumulaciones masivas sobre playas arenosas con fuerte oleaje, a menudo como únicas dominantes de la comunidad. Se unen a las burbujas generadas por el oleaje y forman masas flotantes de color marrón o verde, de forma irregular, las que luego con la marea se depositan sobre la playa formando franjas largas. En mayo de 2015 una de estas acumulaciones, de color verde, fue detectada en la Bahía de Coquimbo. El análisis de las muestras mediante microscopía óptica y electrónica de barrido demostró la presencia de la diatomea *Aulacodiscus kittonii*, un taxón muy conocido por participar en este tipo de eventos. Este es el primer registro para Chile y para el Pacífico Sur Oriental, evento en el cual *A. kittonii* fue la especie dominante, como también el primer registro para Chile de *A. kittonii* como una especie viviente. Se entrega una descripción de los especímenes chilenos y se comenta e ilustra la variabilidad de algunas de sus características morfológicas.

Palabras clave: Diatomea de rompiente, playas arenosas, proliferación de diatomeas, morfología, Chile.

INTRODUCTION

"Surf diatoms" constitute a small group of species that accumulate in great abundance in the surf zones of some sandy beaches with high wave energy (Campbell 1996). They accumulate in the foam by adhering to air bubbles generated by wave action (Odebrecht *et al*. 2014), forming green or brown irregular patches floating in the surf zone, causing deep coloration of the water and remaining as long streaks on the beach (Lewin 1973). After some hours the cells lose buoyancy and the accumulations tend to disappear (Du Preez & Campbell 1996). The populations are dominated only by one or two unrelated species, centric or pennate diatoms, single cells to colonies, but several species can be present as sub-dominant (Campbell 1996). According to Campbell (1996) and Odebrecht *et al*. (2014) there are only seven confirmed surf diatom species: *Anaulus australis* Drebes *et* Schulz, *Attheya armata* (West) Crawford, *Asterionellopsis glacialis s.l.* (see Kaczmarska *et al*. 2014), *Aulacodiscus kittonii* Arnott ex Ralfs, *Aulacodiscus africanus* Cottam, *Aulacodiscus johnsonii* Arnott *in* Pritchard and *Aulacodiscus petersii* Ehrenberg, the last two taxa as subdominants in South Africa (Campbell, 1996). According to Talbot & Bate (1990) surf diatom accumulations have occurred in the Southern Hemisphere between the latitudes 29° to 34°S, but more recently Odebrecht *et al*. (2014) extended the area between 42° N and 42° S, emphasizing that most of the localities are located in the southern Hemisphere. However, at that time, they were completely unknown for the Eastern South Pacific.

This work aims to report for the first time for Chile a surf diatom accumulation that recently occurred in the northern coast of the country, investigate its species composition using light and electron microscopy, contributing information on the variability of some characteristics of the frustule of the dominant species.

MATERIAL AND METHODS

The samples were collected on May 28, 2015 in Coquimbo Bay (Enjoy Beach), centered approximately at 29°53'S-71°17'W, within the Coquimbo Region of Chile (Fig. 1). The bay extends between Tortuga Point in the south and Teatinos Point in the north and it is affected by the prevailing south-west winds producing strong waves (Tabilo *et al*. 1990). However, winds from the north are frequent throughout the year (Olivares 1989). The bay opens to the west and has a sandy beach of 18 km in length. The bathymetry shows a mean depth of 25 m and a maximum depth of 50 m. The bathymetry changes abruptly around the Points but slopes gently elsewhere. It receives the influence of several freshwater streams, domestic wastes from La Serena city, and before the construction of Puclaro Reservoir (2000), the discharges of the Elqui River had an important influence on this bay (Soto *et al*. 2015). Actually, they have not any influence (Soto *et al*. 2015). The Elqui River provided a large proportion of fine sediments to the Bay, especially in the austral spring and summer months caused by snow-melt from the Andes mountain range (Valle-Levison *et al*. 2000). Precipitation in the area occurs mainly during winter months and increase noticeably during El Niño events (Soto *et al*. 2015).

We have no information about the physical, chemical and biological factors present when the material was obtained. The collections were done during a rather warm, sunny and calm day, and during the three previous days the predominant winds were from the E and SE, with intensities between 5.5 and 11.1 km/h (Dirección Meteorológica de Chile 2016). Collections were made at Enjoy Beach directly from the surf zone and from the material accumulated along the beach (Fig. 2. A-C). Samples were preserved with formaldehyde (4%) and were deposited at the Diatom Collection, Department of Botany, University of Concepcion, Chile with the numbers DIAT-CONC M-3471, 3472, and as permanent slides (Hyrax) with de numbers DIAT-CONC 7666, 7667 and 7668. A fraction of the samples was treated for the removal of organic matter according to the method described by Hasle & Fryxell (1970). More than 2000 cells were analyzed by means of light microscopy (LM) using a Zeiss Photomicroscope III and a Olympus CT-31, and by Scanning Electron Microscopy (SEM) using a JEOL JSM-6380 LVY. Critical point drying, as described by Anderson (1951) was used to observe the cingulum and velum structure. Terminology used is that suggested by Anonymous (1975), Ross *et al*. (1979) and Holmes & Mahood (1980).

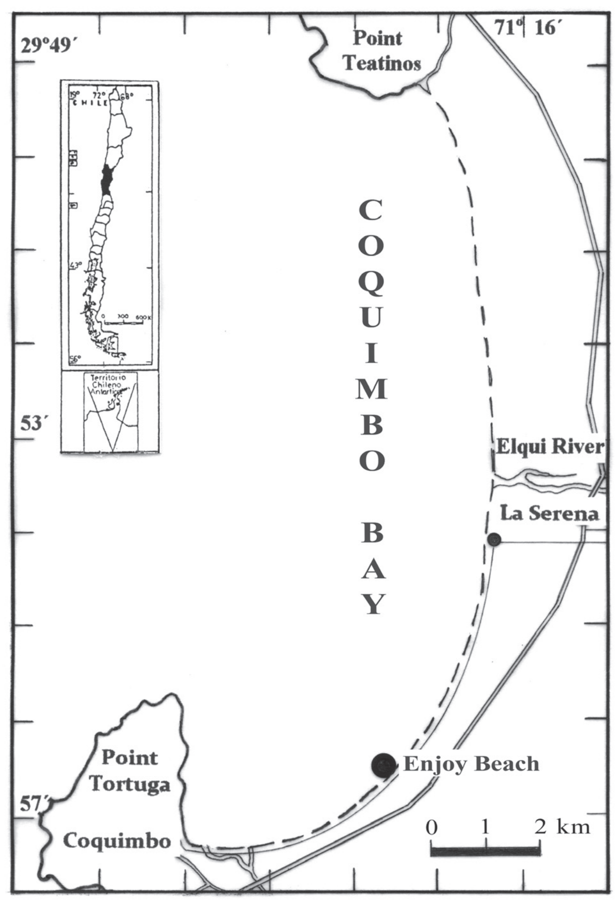

Figure 1. Upper left, map of Chile characterizing the Region of Coquimbo. Right, map of Coquimbo Bay and location of Enjoy Beach.

Figura 1. Arriba izquierda, mapa de Chile caracterizando a la Región de Coquimbo. Derecha, mapa de la Bahía de Coquimbo y ubicación de la Playa Enjoy.

RESULTS

The water of Coquimbo Bay had a deep green color when the samples were collected from irregular patches being stranded by the gentle wave action forming extensive deposits on the beach as tide receded (Fig. 2. A-C).

The analysis with light and scanning electron microscopy of the material collected, showed the exclusive presence of *Aulacodiscus kittonii* Arnott ex Ralfs, a well-known surf diatom species. No other genera or species of diatoms, or representatives from other groups of microalgae were present.

The cells of *A. kittonii* are solitary, circular in outline with diameters ranging from 66 to 170 µm, truncated oblong in girdle view with the submarginal processes protruding (Fig. 3. A). The green-brown chloroplasts are discoid, numerous and large, 5.5-9.0 µm in diameter (Fig. 2. D). The valves present a flat central surface, rising at the submarginal processes and concave between them (Fig. 3. F-J). The labiate processes are normally four (Fig. 3. B, F-G), occasionally five (Fig. 3. I-J; Fig. 4. F), and rarely six (Fig. 3. C, H; see comment in Discussion, third paragraph), expanded into large hyaline hood-like structures (Fig. 3. A). Valves are strongly areolated, arranged in radial rows (Fig. 3. I, K). The loculate areolae are hexagonal, but those on the central area are angular and larger; some areolae located at the hyaline rays are pentagonal (Fig. 3. K). Areolae number five in 10 µm at the center, being barely denser towards the margin, six to seven in 10 µm. A central rosette (5.7-9.0 µm in diameter), without a hyaline area, is present in all observed external valves (Fig. 3. I, K). The outer velum of each areola has pores arranged in more or less parallel lines and lacks a raised central papilla (Fig. 3. L-M). However, two to seven small papillae are present on the external marginal walls of each areola (Fig. 3. M). The foramina are internal, large (Fig. 4. C, D) with an eccentric location in the central areolae, and in those areolae bordering the hyaline rays, lying in the internal side of the valves between the center and the processes (Fig. 3. K). The external surface of each labiate process consists of a domed hood with three slits suggesting a trident (Fig. 4. B). Internally, and attached to the top of each submarginal valve cavity, appears a raised double horse-shoe-shaped structure of the labiate process (Fig. 4. C). Each cingulum is composed of five to six non-perforated open bands with a long ligula (Fig. 4. A). The valvocopula is 5.0-6.4 µm wide, the width decreasing slightly in the abvalvar direction.

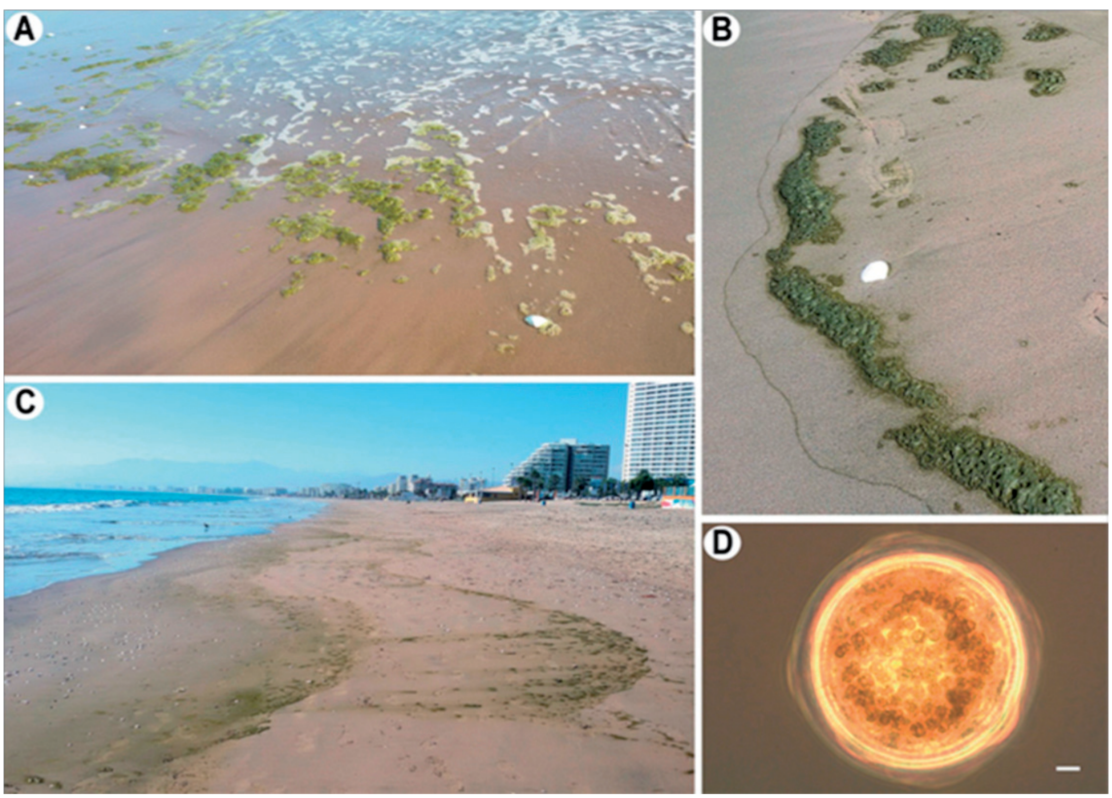

Figure 2. A. Green irregular patches of *A. kittonii* floating in the surface water of Coquimbo Bay. B-C. Deposits of *A. kittonii* masses on the Enjoy Beach. D. Cell of *A. kittonii* with numerous plastids. Scale = 10 µm. (Photos A-C by V.A. Gallardo).

Figura 2. A. Aglomerados verdes de *A. kittonii* de forma irregular flotando en la superficie del agua de la Bahía de Coquimbo. B-C. Depósitos de aglomerados de *A. kittonii* sobre la Playa Enjoy. D. Célula de *A. kittonii* con numerosos plastidios. Escala = 10 µm. (Fotos A-C de V.A. Gallardo).

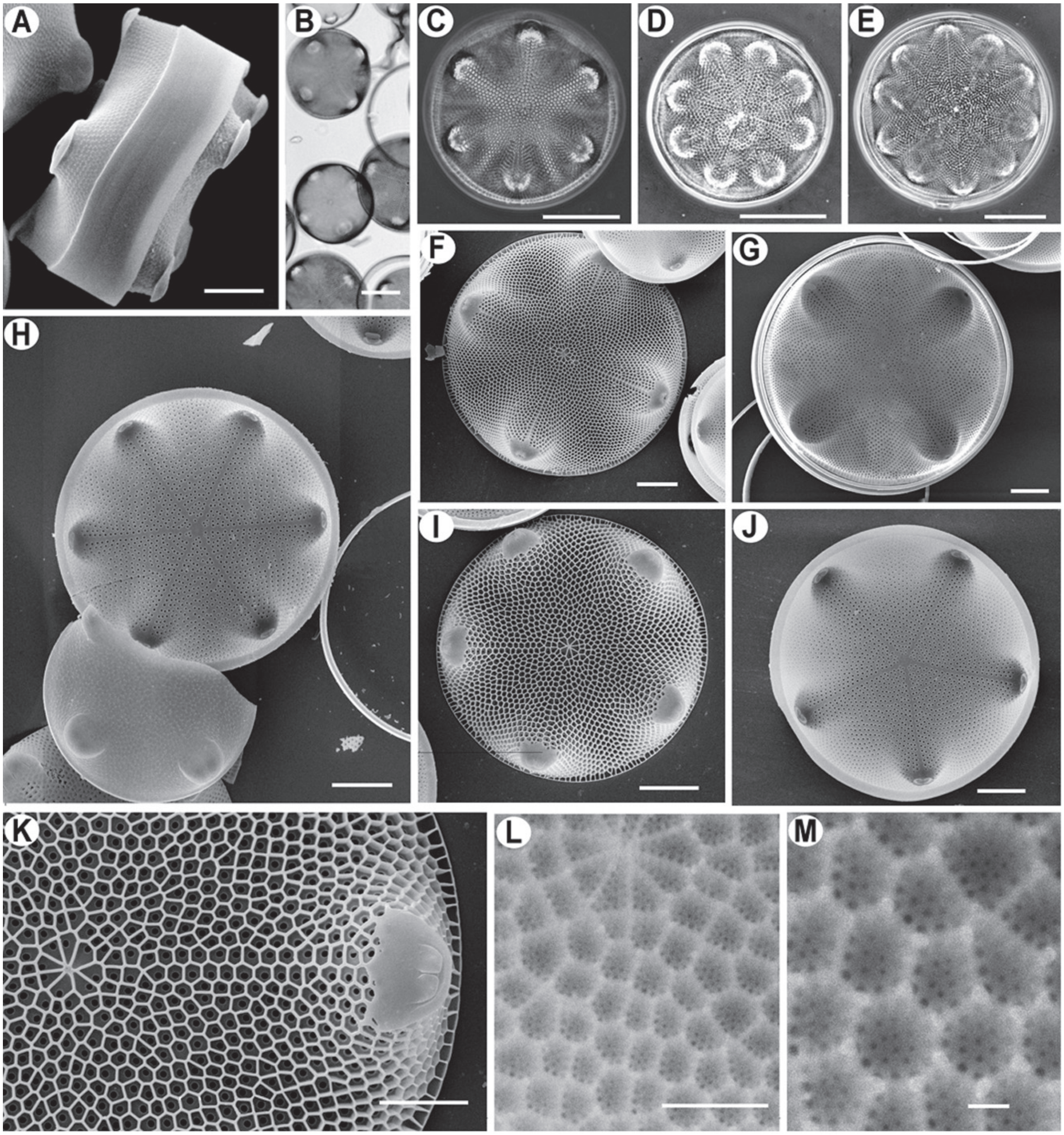

Figure 3. *Aulacodiscus kittonii*. A, F-M, Scanning Electron Microscopy; B-E, Light Microscopy. A. Frustule in conectival view. B-E. Valves with four, six, eight and ten labiate processes respectively. F-G. External and internal views of valves with four labiate processes. H. Internal view of valve with six labiate processes. I-J. External and internal views of valves with five labiate processes. K. External view of areolae in radial rows and lacking velum. Central rosette with angular areolae. Submarginal labiate process. L. External velum of areolae. M. Papillae on the marginal walls of each areola. Scale bars: A, F-J = 20 µm; B-E = 40 µm; K = 10 µm; L = 5 µm; M = 1 µm.

Figura 3. *Aulacodiscus kittonii*. A, F-M, Microscopía Electrónica de Barrido; B-E, Microscopía Fotónica. A. Frústulo en vista conectival. B-E. Valvas con cuatro, seis, ocho y diez procesos labiados respectivamente. F-G. Valvas externa e interna con cuatro procesos labiados. H. Vista interna de valva con seis procesos labiados. I-J. Vista externa e interna de valvas con cinco procesos labiados. K. Vista externa de aréolas dispuestas en líneas radiales y carentes de velum. Roseta central con aréolas angulares. Proceso labiado submarginal. L. Velum externo de las aréolas. M. Papilas sobre las paredes externas de las aréolas. Escalas: A, F-J = 20 µm; B-E = 40 µm; K = 10 µm; L = 5 µm; M = 1 µm.

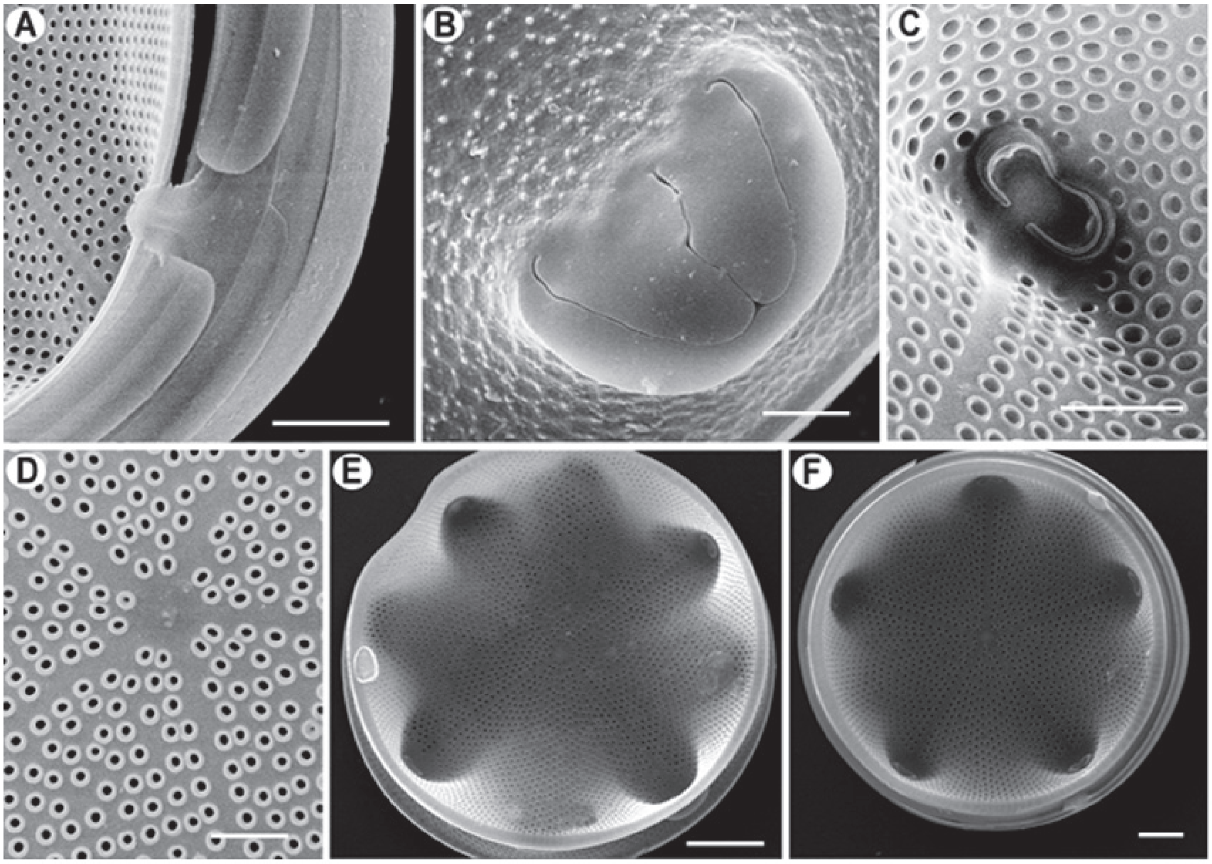

Figure 4. *Aulacodiscus kittonii*. A-F, Scanning Electron Microscopy. A. Cingulum with ligulate non perforated open bands. B. Three slits on the exterior surface of the labiate processes. C. Internal double horse-shoe-shaped labiate process. D. Internal foramina of areolae. E-F. Previously encircled valves observed with light microscopy having eight and ten labiate processes respectively show under scanning microscopy only four and five processes. Scale bars : A, F = 10 µm; B-D = 5 µm; E = 20 µm.

Figura 4. *Aulacodiscus kittonii*. A-F, Microscopía Electrónica de Barrido. A. Cingulum con bandas liguladas no perforadas. B. Tres surcos sobre la cara exterior de cada proceso labiado. C. Parte interna del proceso labiado con forma de una doble herradura. D. Foramina interna de las aréolas. E-F. Valvas previamente marcadas en el microscopio fotónico provistas de ocho y diez procesos labiados respectivamente muestran en el microscopio de barrido solamente cuatro y cinco procesos. Escalas: A, F = 10 µm; B-D = 5 µm; E = 20 µm.

DISCUSSION

Aulacodiscus kittonii belongs to the "kittonii" group of *Aulacodiscus* species, widely distributed in tropical and temperate waters and distinguished from other species of the genus by their external submarginal labiate processes expanded into large hyaline hood-like structures. According to Sims & Holmes (1983) the group includes five taxa: *A. kittonii* Arnott in Pritchard 1861, described from recent marine material collected in New Zealand and Monterey Bay, California, and also fossil from this last locality; *A. kittonii* subsp. *brightwellii* (Janisch) Sims & Holmes 1983, an extinct species described originally as *A. brightwellii* from Peruvian guano; *A. johnsonii* Arnott in Pritchard 1861, found as fossil in Algoa Bay guano, Africa; *A. johnsonii* var. *amherstia* (Venkateswarlu & Round) Sims & Holmes 1983, planktonic from Bay of Bengal India and described as *Aulacodiscus amherstia,* and *A. africanus* Cottam 1876, a recent and fossil species from the West coast of Africa.

A. kittonii differs from *A. johnsonii* and its variety *amherstia* by having three slits on the external part of each process which are not completely raised from the valve and by lacking a centrally raised papilla on the areolae. *A. africanus* is closely related to *A. kittonii* and mainly differs from it by having a single slit on the hood of processes. Differences between *A. kittonii* and *A. kittonii* subsp. *brightwellii* seem to be limited. While Wise (1951) considered *Aulacodiscus brightwellii* Janisch as a valid taxon (based mainly on the number of processes that ranges from five to nine and on the greater depth of the valves), Rattray (1888) and Hustedt (1930) considered it as a synonym of *A. kittonii,* and Sims & Holmes (1983) as a subspecies. Considering that the remainder frustule features are similar in both species (morphology of areolae, processes, central rosette and morphometric values), we also agree to considerer it as a synonym of *A. kittonii.*

Aulacodiscus ehrenbergii described by Janisch 1861 from Peruvian guano is also a synonymous of *A. kittonii.* On the other hand, and in agreement with Holmes & Mahood (1980), the description of "*A. kittonii"* by Ross & Sims (1970) does not correspond to this species.

The morphological characteristics of the studied specimens of *A. kittonii* agree well with those described by Holmes & Mahood (1980), Sims & Holmes (1983) and Tiffany (2008). The number of labiate processes on each cell is a variable feature. With light microscopy, we observed normally valves with four, five, and six processes, and rarely, cells with eight or ten processes were also found (Fig. 3. D-E). As valves with those characteristics had not been found in our previous SEM observations of the same samples, clean material dried on cover glasses at room temperature was observed under a light microscope and valves with eight or ten processes were encircled with an special diamond objective. Their observation with scanning microscopy showed valves only with four (Fig. 4. E), or five processes (Fig. 4. F), proving that the "eight" and "ten" processes valves observed at low magnification with light microscopy were an optical effect produced by two un-separated valves, each one with four or five processes respectively. The same opinion was expressed by Holmes & Mahood (1980).

The small papillae on the external marginal walls of the areolae are also variable in number, but are present in all the individuals, and cells without papillae were not found in the Chilean material. They can be also observed in the valves studied by Sims & Holmes (1983, Fig. 32) and Holmes & Mahood (1980, Fig.19). Some variation was also found in the size of the areolae on the valve face. They are regularly 5 in 10 µm on each striae at the central part, but those areolae, bordering the hyaline rays were wider and pentagonal in shape. This feature, and the fact that these areolae also have the internal foramina in an eccentric location, makes the hyaline rays very notorious when observed by light microscopy (Fig. 3. C-E).

This is the first record of *Aulacodiscus kittonii* as a recent and dominant "surf-diatom" species from the northern coast of Chile in the South Eastern Pacific Ocean. Accumulations of *A. kittonii* as the dominant species have until now only been reported from New Zealand, Brazil and the coast of Washington (Odebrecht *et al*. 2014).

Aulacodiscus kittonii is a littoral marine species with a wide distribution in both hemispheres: AFRICA: West coast of Africa; Algoa Bay guano; Madagascar (Sims & Holmes 1983); Walvis Bay, South Africa (Burke & Woodward 1963-1969). NORTH AMERICA: Washington; Oregon; Monterrey California (Arnott in Pritchard 1861, Holmes & Mahood 1980, Cupp 1943, Levin 1973), Pacific Coast (Boyer 1926-1927). CENTRAL AMERICA: VeraCruz, Mexico; Colon, Panama (Sims & Holmes 1983); Maria Madre, Mexico (Burke & Woodward 1963-1969). SOUTH AMERICA: Mejillones, Chile, fossil (Moeller 1891, Tempére & Peragallo 1907, Frenguelli 1949); Pernambuco, Brasil (Rosevel *et al*. 2005 and Cabanez *et al*. 2010); Peruvian guano (Janisch 1861 as *A. ehrenbergii* and *A. brightwellii*.); Perú, neritic (Fernandez 1999). ASIA: Sendai, Japan (Sims & Holmes 1983). AUSTRALASIA: New Zealand; Thursday Island (Arnott *in* Pritchard 1861, Foged 1979); Eocene of Connack's Rock, Oamaru, New Zealand (Tempére & Peragallo 1889-1895). EUROPE incl. USSR: Golfe Juan, France; Moron, Spain; Baldjick, Bulgaria; Kamischer, USSR (Sims & Holmes 1983); coast of Norway (Hendey 1964); Coast of England (Sims 1996).

According to the literature the beach of Coquimbo Bay presents several suitable conditions for the occurrence of "surf-diatom" accumulations: long sandy beach, near an active seaport, increased urbanization and human activities, strong winds and river discharge, among others (Lewin 1973, Campbell 1996, Odebrecht *et al*. 2014). On account to the above mentioned characteristics of the bay it could well be expected that new surf diatoms accumulations will repeat in the area in the future.

However, on September 16, 2015, a severe 8.4 Richter earthquake occurred in the Region of Coquimbo, Chile (covering the present studied area). The major earthquake triggered a tsunami event that destroyed several coastal localities in the Region and was particularly strong in Coquimbo Bay (La Serena City, Enjoy Beach), especially in the Coquimbo Port. This catastrophe could have drastic consequences on the ecosystems in the affected area, as was previously detected from some marine regions of Chile after the earthquake of 2010 (Fariña *et al*. 2012, Choi 2012). It is worth mentioning that the accumulations here described occurred when a new 2015 El Niño event was developing off Peru and northern Chile. Odebrecht *et al.* (2014) suggested that these events may, in the long term, lead to significant changes in "surf diatom" populations, as was found by Lange *et al*. (2000) in California coastal waters during El Niño 1997-98 conditions.

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