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MIOCENE ATLANTIC TRANSGRESSIVE- REGRESSIVE EVENTS IN NORTHEASTERN AND OFFSHORE PATAGONIA: A PALYNOLOGICAL PERSPECTIVE

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ABSTRACT

Key information for regional biostratigraphic, climatic and environmental reconstructions for the Miocene of the southwestern Atlantic margin can be obtained by qualitative and quantitative palynological analysis at the onshore YPF-CH-PV.es-1 borehole (PV borehole) in the Valdés Basin, combined with previously documented organic-walled dinoflagellate cyst data from the Colorado Basin and well-dated outcropping sections on the east coast of Patagonia. A sequence of eleven significant dinocyst bioevents (highest occurrence, HO; highest common occurrence, HCOs) is recognized across the Valdés and Colorado basins. The bioevents occur in the same stratigraphic order and seem to be synchronous across both basins. From the oldest to the youngest, these are: HO of *Emmetrocysta urnaformis*, HO of *Cannosphaeropsis quattrocchiae*, HCO and HO of *Hystrichokolpoma rigaudiae*, HO of *Cousteaudinium auybriae*, HCO and HO of *Dapsilidinium pseudocolligerum*, HO of *Cleistosphaeridium ancyreum*, HO of *Labyrinthodinium truncatum*, HO of *Operculodinium piaseckii* and HO of *Reticulatosphaera actinocoronata*. The presumed climatically-driven extinctions of *Dapsilidinum pseudocolligerum* and *Hystrichokolpoma rigaudiae* around the Burdigalian to earliest Langhian, may be linked to global cooling and the re-establishments of the Antarctic ice-sheets since ~14 Ma. Two maximum flooding episodes, characterized by warm, outer (distal) neritic environmental conditions were identified at the PV borehole, presumably related to glacio-eustatic sea level rise. The older occurred in the Burdigalian – earliest Langhian and the younger, in the Tortonian. The latter maximum flooding is followed by environmental and/ or climatically-driven change, implying abrupt shifting from neritic to nearshore conditions, the extinction of the warm-water taxa, and dinocysts being largely replaced by acritarchs.

KEYWORDS. Palynology, Miocene, Biostratigraphy, Paleoenvironmets, Patagonia

1. Introduction

The Miocene was a period of substantial climate changes with major impact in the evolution of marine and terrestrial biota. Global climate evolved from a prolonged phase of warming that peaked in a Miocene climatic optimum interval between ~ 17 and 15 Ma (Zachos et al., 2001; Holbourn et al., 2013; Westerhold et al., 2020). This warming event was followed by a long-term cooling trend, with reestablishment of ice-sheet growth on Antarctica since ~14 Ma (e.g. Shevenell et al., 2004, Holbourn et al., 2013), culminating with extensive glaciation over the Northern and Southern Hemispheres in the Pleistocene (e.g. Zachos et al., 2001). The Miocene reconstructions from Patagonian floras and faunas largely agree with the global climatic trends. Marine molluscan fauna and continental palynomorphs show extinction events during the middle Miocene and at the end of the late Miocene (Cuitiño et al., 2017, and references therein), culminating with the onset of the Patagonian desertification that occurred during the last 6 Ma (Palazzesi et al., 2014).

Two major marine geological events occurred in the Southwestern Atlantic margin during the Miocene (e.g. Uliana and Biddle, 1988; Malumián, 1999; Malumián and Náñez, 2011). These episodes that flooded wide areas in Patagonia occurred during the Burdigalian–earliest Langhian (e.g. Cuitiño et al., 2015; Parras et al., 2012) and the latest Serravalian – Messinian (e.g. del Rio et al., 2018). Nevertheless, the sedimentary successions, informally known as ´Patagoniense´ and ´Paranense´, accumulated during both marine events include complete marine sedimentary cycles including transgressive and regressive phases (e.g. Cuitiño et al., 2017). These deposits are well-represented in the Colorado and Valdés basins, mostly in the subsurface (Fryklund et al., 1996; Malumián and Náñez, 1996; Martinelli and Franzin, 1996; Continanzia et al., 2011). In northeastern Patagonia, deposits of the ´Patagoniense´ succession are represented by outcrops of the Gaiman Formation (Haller and Mendía, 1980) in the northeast of Chubut (Valdés Basin). Instead, deposits related to the ´Paranense´ succession, belong to the Puerto Madryn Formation (Haller 1979), widely exposed along the coastal cliffs of

Valdés Peninsula (Valdés Basin), and to the Barranca Final Formation (Kaasschieter, 1965) cropping out along the northern flank of the San Matías Gulf (Colorado Basin). The configuration of the paleocoast and the westward extension of both marine incursions were controlled by the Jurassic to Early Cretaceous volcanic Marifil complex (e.g. Malumián, 1999), the main positive feature in the area (Figs. 1 and 2). The sedimentology and the excellently preserved fossil content of these outcropping units in northeastern Patagonia has been extensively analyzed in numerous works (e g. Malumián, 1999; Scasso and del Río, 1987; del Río, 1988; 1990; Scasso et al., 1999; 2001; Dozo et al., 2002; Fazio et al 2007; Cuitiño et al., 2015; 2019; del Río et al., 2001; 2018).

Organic-walled dinoflagellate cysts (dinocysts) are sensitive to changing marine conditions and hence they are a useful proxy for reconstructing past marine environments. Dinocysts have their highest diversity in shallow marine (i.e. shelfal) settings (e.g. Wall et al., 1977; Dale, 1996) and the diversity highly depends on the stress in ecosystems, usually low diversity is related to relative shoreline proximity (e.g. Patten, 1962; Bradford and Wall, 1984; Pross and Schmiedl, 2002). Furthermore, high abundance of certain taxa reflects (sub) optimal environmental conditions and/or wider tolerance towards certain environmental conditions (e.g. Sluijs and Brinkhuis, 2009). The deciphering of the ecological affinities of Neogene dinocyst taxa has been a great challenge in the last decades (e.g. Head et al., 1989b; Head, 1996; 1997; Versteegh and Zonneveld, 1994; Marret and Zonneveld, 2003; Schreck and Matthiessen, 2013; Egger et al., 2018), resulting in useful databases for climate reconstructions. More recently, the establishment of the quantitative relationship between Neogene dinocyst assemblages and organic geochemical-based sea surface temperatures (De Schepper et al., 2011; Schreck et al., 2017), provides a better understanding of temperature ranges of dinocyst taxa in the past. Moreover, the composition of dinocyst assemblages vary across marine environments (from coastal to open conditions) (e.g. Wall et al., 1977; Harland, 1983; Bradford and Wall, 1984), and hence they are widely employed to reconstruct Cenozoic nearshore-offshore trends and sea level fluctuations (e.g. Brinkhuis, 1994; Crouch and Brinkhuis, 2005; Pross and Brinkhuis, 2005; Sluijs et al., 2005, 2008).

Furthermore, dinocysts offer a powerful tool to elucidate the biostratigraphy in neritic marine settings worldwide. Neogene dinocyst biostratigraphy refined by high resolution magneto- and chemostratigraphically well-calibrated global age-diagnostic dinocyst bioevents and zonal schemes elsewhere (e.g. De Verteuil et al., 1996; Fensome et al., 2008; Louwye, 2005; Louwye et al. 2008; Schreck et al., 2012; Dybkjær and Piasecki 2010; Egger et al., 2018), constitute invaluable available information for the Miocene dinocysts interpretation in our basins.

Miocene marine sedimentary successions from northeastern Patagonia and the adjacent continental shelf – Colorado and Valdés basins — contain a rich and well-preserved dinocyst record providing a useful tool for biostratigraphical and paleoenvironmental resolution. Miocene dinocyst assemblages have been documented largely from subsurface deposits in the Colorado Basin (e.g. Gamerro and Archangelsky, 1981; Archangelsky, 1996; Guerstein and Guler, 2000; Guerstein and Junciel, 2001; Guler et al., 2001; Guler and Guerstein, 2002; 2003) and Valdés Basin (Guler et al., 2018; Fuentes, 2020). Also, dinocyst assemblages were recorded from well-dated shallow marine deposits of the Puerto Madryn Formation (~10 Ma; del Río et al., 2018) in Valdés Peninsula, Valdés Basin (Fuentes et al., 2016, 2019), and from the Barranca Final Formation type section (~6–9 Ma; Palazzesi et al., 2014) at the north coast of the San Matías Gulf, Colorado Basin (Guler et al., 2002; Palazzesi et al., 2014; Fuentes et al., 2016) (Fig. 1).

In this contribution we aim to evaluate the potential of the Miocene marine palynomorphs as important proxies for biostratigraphical, paleoclimatic and paleoenvironmental inferences in the southwestern Atlantic margin. In this context, our approach is two-fold: **(1)** to review and re-assess the age-diagnostic and ecologically-driven events in northeastern Patagonia and the neighboring continental shelf, to provide a useful chronostratigraphic context (bioevents) for the Miocene successions in the Colorado and Valdés basins; and **(2)** to evaluate our bioevents in the light of a new quantitative dinocyst analysis in the Valdés Basin (onshore PV borehole). Overall, our analyses provide a new and refined context, useful for future studies during the Miocene in the southwestern Atlantic margin.

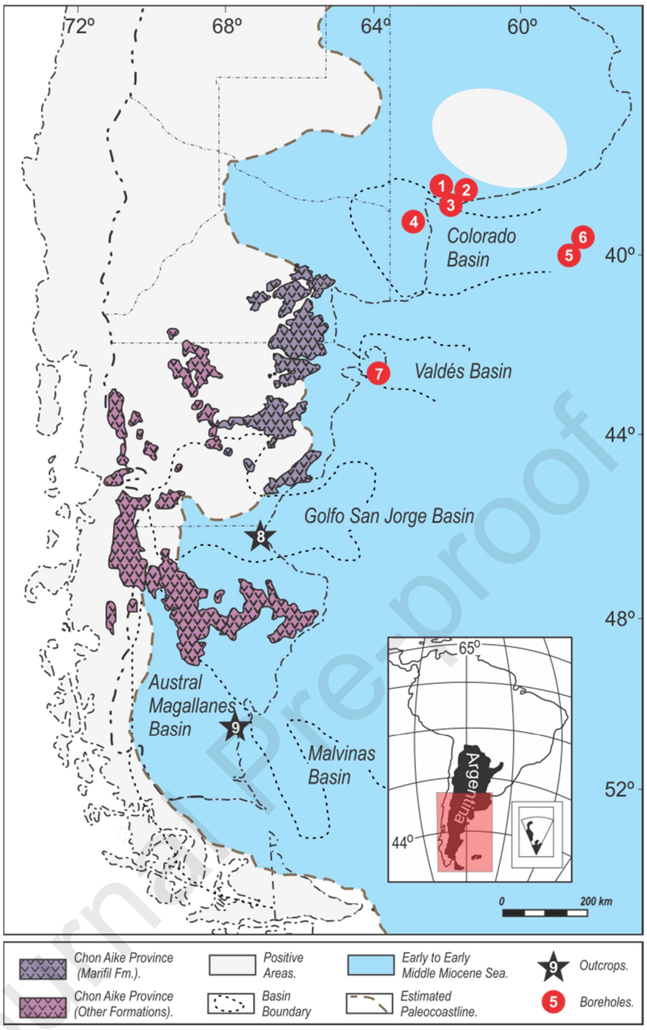

Fig. 1. Paleogeographic map (modified from Malumián and Náñez, 2011) showing the main sites with lower to lower middle Miocene dinocyst records in the east coast of Patagonia and the neighboring southwestern Atlantic shelf. **1–6.** Colorado Basin: **1.** Fx-1 borehole (Guler and Guerstein, 2002), **2.** Dx-1 borehole (Guler and Guerstein, 2002), **3.** Cx-1 borehole (Guerstein and Junciel, 2001; Guler and Guerstein, 2002), **4.** Ombucta x-1 borehole (Guerstein and Guler, 2000), **5.** Puelche x-1 borehole (Gamerro and Archangelsky, 1981), **6.** Ranquel x-1 borehole (Gamerro and Archangelsky, 1981). **7.** Valdés Basin: PV borehole (Guler et al., 2018; Fuentes et al., 2020). **8.** Golfo San Jorge Basin: Chenque Formation

(Palamarczuk and Barreda, 1998; Barreda and Palamarczuk, 2000a). **9.** Austral Basin: Monte León Formation (Barreda and Palamarczuk 2000b; Parras et al., 2012, 2020; Pérez Panera et al., 2014).

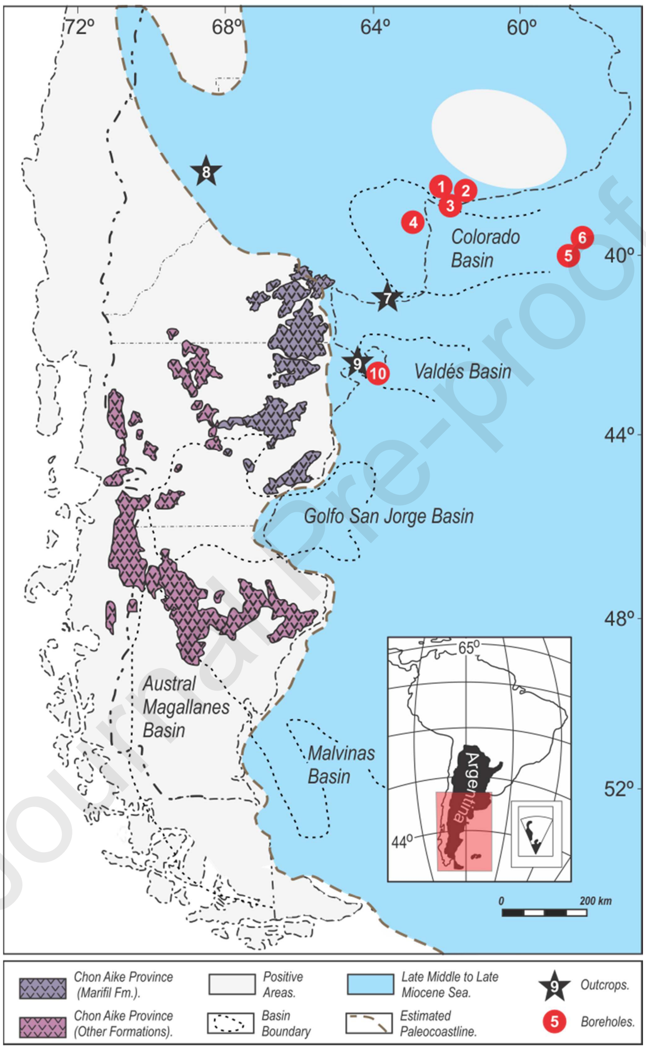

Fig. 2. Paleogeographic map (modified from Malumián and Náñez, 2011 and Náñez and Malumián, 2019) showing the main sites with middle to late Miocene dinocyst records in Patagonia and the neighboring southwestern Atlantic platform. **1–7.** Colorado Basin: 1. Fx-1 borehole (Guler and Guerstein, 2002), **2.** Dx-1 borehole (Guler and Guerstein, 2002), **3.** Cx-1 borehole (Guerstein and Junciel, 2001; Guler and Guerstein, 2002), **4.** Ombucta x-1 borehole (Guerstein and Guler,

2000), **5.** Puelche x-1 borehole (Gamerro and Archangelsky, 1981), **6.** Ranquel x-1 borehole (Gamerro and Archangelsky, 1981), **7.** Barranca Final Formation type section (Guler et al., 2002; Palazzesi et al., 2004; Fuentes et al., 2016), **8.** Neuquén Basin: Bajada de Añelo region (Náñez and Malumián, 2019), **9-10.** Valdés Basin: **9.** Puerto Madryn Formation, Valdés Península (Fuentes et al., 2019), **10.** PV borehole (Guler et al., 2018; Fuentes et al., 2020).

2. Methods

We examined published Miocene dinocyst events data from neritic sections from Colorado and Valdés basins. Bioevents were reviewed in five previously published Miocene subsurface sections in the Colorado Basin (Dx-1 borehole, Guler and Guerstein, 2002; Fx-1 borehole, Guler and Guerstein, 2002; Cx-1 borehole, Guerstein and Junciel, 2001; Ombucta x-1 borehole, Guerstein and Guler, 2000), one subsurface section in the Valdés Basin (CH-PV.es-1 borehole, Guler et al., 2018; Fuentes, 2020) (Figs. 1, 2, 4). Dinocyst events represent highest occurrence (HO) and/ or highest common occurrence (HCO) of taxa. Lowest Occurrences (LOs) could not be reliably determined as these assemblages come mostly from cutting samples that may be subjected to downhole contamination. The raw quantitative palynological data from the CH-PV.es-1 borehole used in the statistical analysis were presented in Data in brief, related article. The dinocyst nomenclature follows Williams et al. (2017). Selected specimens of dinocysts were illustrated in Fig. 3. The Shannon diversity index (H) was calculated using PAST (Paleontological Statistics) software.

For the multivariate statistical analysis we used counting data of 60 samples from the onshore PV borehole, Valdés Basin. We select four ecologically important individuals, or groups of taxa, these are: (1) *Spiniferites* complex, dominated by species of *Spiniferites* including the morphologically-related genera *Achomosphera*. *Spiniferites* complex is abundant in outer neritic environments (e.g. Brinkhuis, 1994; Marret and Zonneveld, 2003; Pross and Brinkhuis, 2005; Sluijs et al., 2005). (2) *Nematosphaeropsis* (*N. rigida* + *N. lativittata*), *Cannosphaeropsis* (*C. quattrocchiae*), *Tectatodinium* (*T. pellitum*), *Hystrichokolpoma* (*H. rigaudiae*) (e.g. Brinkhuis 1994; Pross and Brinkhuis, 2005) and *Batiacasphaera micropapillata* (B. *micropapillata* and *B. minuta*) complex (Schreck and Matthiessen, 2013), suggests affinity to outer-neritic to oceanic conditions. (3) Taxa adapted to warmer waters *Lingulodinium machaerophorum* (e.g. Head, 1997; De Schepper et al., 2015; Egger et al., 2018), *Tectatodinum pellitum* (e.g. Head, 1994; 1997), *Tuberculodinium vancampoae* (e.g. Head et al., 1989a; Head 1996), *Melitasphaeridium choanophorum* (e.g. Head, 1997; De Schepper et al., 2015), *Labyrinthodinium truncatum* (e.g. Schreck et al., 2017; Egger et al., 2018), *Dapsilidinium pseudocolligerum* (Head and Westphal, 1999, and references therein; De Schepper et al., 2015), *Hystrichokolpoma rigaudiae* (e.g. Head and Westphal, 1999 and references therein; De Schepper 2006; Egger et al., 2018), *Reticulatosphaera actinocoronata* (Schreck et al., 2017) and *B. micropapillata* complex (Schreck et al., 2017). (4) Acanthomorph (micrhystridid) acritarchs, they are characteristic of shallow-water marine conditions (Tyson 1995 and reference therein).

Additionally, the relative abundance of terrestrially-derived palynomorphs (pollen and spores) and marine palynomorphs (dinoflagellate cysts, acritarchs and foraminiferal linings) ratio (t/m ratio) is widely used to reconstruct variations of the coastline. It assesses the relative terrestrial and marine influence, as a measure for the distance between the depositional area and the coastline and/ or source of the terrestrial input (e.g. Versteegh, 1994; Tyson, 1995; Louwye et al., 2007). In this study, we assume that low t/m ratio represents the greater distance between the depositional site and the coast, whereas high t/m ratio indicates the most proximity to the coastline.

The dissimilarity between the samples in the PV borehole was compared using Principal Component Analysis (PCA) and it was performed using XLSTAT Software. In order to avoid that most of the information of any of the variables was expressed mostly by one of the components, we used a correlation matrix (Jolliffe, 2002). The variables used include: (1) warm-water dinocyst taxa (*M. choanophorum* + *L. machaerophorum* + *R. actinocoronata* + *D. pseudocolligerum* + *H. rigaudiae* + *B. micropapillata* + *L. truncatum*) over total dinocysts (warm-water/d_{x100}), (2) outer neritic to oceanic dinocyst taxa (*C. quattrocchiae* + *H. rigaudiae* + *B. micropapillata* complex + *N. rigida* + *N. lativittata*) over total dinocysts (outer neritic to oceanic/ d_{x100}), (3) acritarch over total dinocysts (a/ d_{x100}), and (4) terrestrially-derived/ marine palynomorphs ratio (t/m ratio). For descriptive statistics (quantitative data) and PCA see Table 1 and 2 in Navarro et al. (Data in Brief, related article).

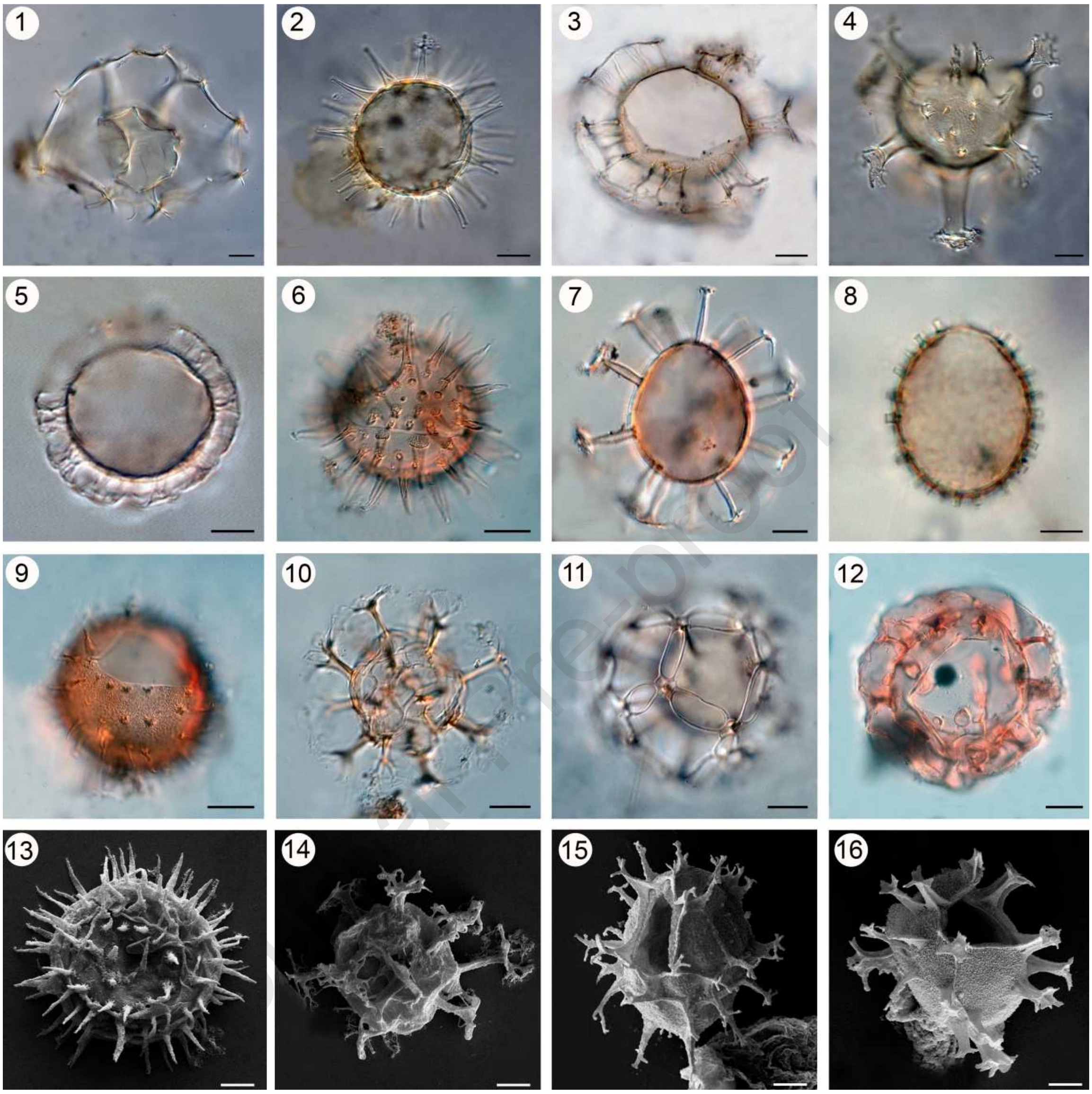

Fig. 3. Selected dinocyst specimens from Miocene sites of Patagonia. **1–12.** Light microscopy digital images were taken using Differential Interference Contrast (DIC). **1.** *Cannosphaeropsis quattrocchiae*, PV borehole, cross section. **2.** *Dapsilidinium pseudocolligerum*, PV borehole, general view. **3.** *Emmetrocysta urnaformis*, PV borehole, oblique apical view. **4.** *Hystrichokolpoma rigaudiae*, PV borehole, ventral view. **5.** *Labyrinthodinium truncatum*, PV borehole, cross section. **6.** *Lingulodinium machaerophorum*, Puerto Madryn Formation, dorsal view. **7.**

Melitasphaeridium choanophorum, Puerto Madryn Formation, cross section. **8.** *Operculodinium piaseckii*, PV borehole, cross section. **9.** *Operculodinium centrocarpum*, Puerto Madryn Formation, dorsal view. **10.** *Reticulatosphaera actinocoronata*, Puerto Madryn Formation, general view. **11.** *Nematosphaeropsis rigida*, Puerto Madryn Formation, general view. **12.** *Tuberculodinium vancampoae*, Puerto Madryn Formation, antapical view. **13-16.** Scanning electron microscope images. **13.** *Lingulodinium machaerophorum*, Puerto Madryn Formation, general view. **14.** *Reticulatosphaera actinocoronata*, Puerto Madryn Formation, general view. **15.** *Spiniferites* sp., Puerto Madryn Formation, dorsal view. **16.** *Achomosphaera/Spiniferites* sp., Puerto Madryn Formation, dorsal view. Scale bar: 10 µm.

3. Results

Here, we firstly present eleven bioevents from a review of previous palynological studies in the Colorado and Valdés basins. Secondly, we present new quantitative data from the PV borehole in the Valdés Basin.

3.a. Significant Miocene dinocyst events in northeastern and offshore Patagonia

In the southwestern Atlantic Ocean margin, dinocysts have contributed to the stratigraphic resolution of the Cenozoic marine sedimentary basins (e.g. Gamerro and Archangelsky, 1981; Palamarczuk and Barreda, 1998; Guerstein and Guler, 2000; Guerstein and Junciel, 2001; Guler and Guerstein 2002; Guler et al., 2002;

González Estebenet et al., 2017; Guler et al., 2019; Fuentes, 2020; González Estebenet et al., 2020; Parras et al., 2020). Gamerro and Archangelsky (1981) stated an informal palynological zonal scheme spanning the Upper Cretaceous to Cenozoic in two offshore wells (Ranquel x-1 and Puelche x-1) in the Colorado Basin. The five palynozones were named A to E, the youngest (Palynozone A) extends to the late Miocene and the oldest (Palynozone E) was assigned to a Turonian-Campanian age, being recognized in subsequent studies of the Colorado Basin (e.g. Guerstein and Guler, 2000; Guler et al., 2001; Guerstein and Junciel, 2002). However, new advances in taxonomy indicate that the zonation should be revised. A comparison between neritic sections from the Colorado and Valdés basins (Figs. 1 and 2), suggests that several Miocene dinocyst events, mostly highest occurrences (HOs) and highest common occurrences (HCOs) data, are common to several sites, present the same stratigraphic order and appears to be synchronous. Here, we present a sequence of eleven bioevents potentially useful to correlate the Miocene marine deposits in both basins (Fig. 4). These bioevents were examined in four subsurface sections in the Colorado Basin (Ombucta, Cx-1, Fx-1 and Dx-1 boreholes) and one subsurface section in the Valdés Basin (PV borehole) (Figs. 1 and 2). The dinocyst biostratigraphy from the Colorado Basin boreholes were originally presented and discussed in Guerstein and Guler (2000, Ombucta x-1 borehole), Guler and Junciel (2001, Cx-1 borehole) and Guler and Guerstein (2000, Fx-1 and Dx-1 boreholes). These boreholes have no age control based on other fossil groups. The dinocyst biostratigraphy of the PV borehole was described in detail in Guler et al. (2018) and Fuentes (2020). Furthermore, two well-defined intervals were interpreted at the PV borehole based on the foraminifera fauna (Masiuk et al., 1976; Caramés et al., 2004). An upper middle to upper Miocene interval, between 55 and 350 mbgs contains the benthic foraminifiera *Protelphidium tuberculatum* fauna. The lower interval, between 350 and 630 mbgs, contains the *Cribrorotalia hornibrooki* foraminifera assemblage, between 350 - 570 mbsg (Masiuk et al., 1976), comparable with the early Miocene *Globigerina woodi woodi* assemblage of temperate regions, and *Spirosigmoilinella-Martinottiella* assemblage, between 570 – 630 mbgs, including *Transversigerina tenua*, *Antarcticella antarctica* and *Spirosigmoilinella compressa* (Caramés et al., 2004). Our palynological results from the PV borehole largely agree with the foraminifera-based differentiation of the two stratigraphical intervals (Fig. 4). Nevertheless, the age of the bioevents in the boreholes are mostly calibrated with ^{87}Sr/ ^{86}Sr ages from outcropping sections in Patagonia (Fig.4), as well as some of them refers to well-calibrated dinocyst biostratigraphic schemes from the Northern Hemisphere. From the oldest to the youngest, these bioevents are: the HO of *Emmetrocysta urnaformis*, the HO of *Cannosphaeropsis quattrocchiae*, the HCO and HO of *Hystrichokolpoma rigaudiae*, the HO of *Cousteaudinium auybriae*, the HCO and HO of *Dapsilidinium pseudocolligerum*, the HO of *Cleistosphaeridium ancyreum*, the HO of *Labyrinthodinium truncatum*, the HO of *Operculodinium piaseckii* and the HO of *Reticulatosphaera actinocoronata*.

The HO of ***Emmetrocysta urnaformis*** is recorded at 587 meters below ground surface (mbgs) in the Ombucta borehole, at 725 meters below sea floor (mbsf) in the Fx-1 (Guler and Guerstein, 2002), at 1050 mbsf in the Cx-1 (Guerstein and Junciel, 2001), at 795 mbsf in the Dx-1 (Guler and Guerstein, 2002) and at 425 mbgs in the PV borehole (Guler et al., 2018; Fuentes, 2020) (Fig. 4). *E.*

urnaformis is a cosmopolitan species recorded from the Eocene to the middle Miocene elsewhere (e.g. Martin, 1993; Brinkhuis et al., 2003; Mahboub and Slimani, 2020; Paredes et al., 2015; Chekar et al., 2018). However, the records of HO of the species in the boreholes are invariably placed below the HO of *Cannosphaeropsis quattrocchiae* (HO: Burdigalian to lowermost Langhian; see below) (Fig. 4) and above the HO of *Chiropteridium galea* (HO: Aquitanian; Fensome et al., 2008) (Guler et al., 2018; Fuentes, 2020), implying that *E. urnaformis* may have its HO in the Aquitanian or Burdigalian (lower Miocene) in both the Colorado and Valdés Basins. Moreover, dinocyst assemblages dominated by *Emmetrocysta* sp. cf. *E. urnaformis* from the Monte León Formation (Austral Basin) related to ^{86}Sr/^{87}Sr ages of 17.9 and 18.1 Ma (Parras et al., 2020) support the HO of the species in the Burdigalian.

The HO of ***Cannosphaeropsis quattrocchiae*** is identified at 512 mbgs in the Ombucta borehole (Guerstein and Guler, 2000), at 645 mbsf in the Fx-1, at 945 mbsf in the Cx-1 (Guerstein and Junciel 2001), at 755 mbsf in the Dx-1 (Guler and Guerstein, 2002), and at 410 mbgs in the PV borehole (Fuentes, 2020) (Fig. 4). *C. quattrocchiae* is an endemic species to the Southwestern Atlantic Basins (e.g. Gamerro and Archangelsky, 1981 (as *Cannosphaeropsis* aff. *utinensis*); Palamarczuk and Barreda, 1998 (as *C. utinensis*); Guerstein and Junciel, 2001; Guler and Guerstein, 2002; Premaor et al., 2013; Fuentes, 2020). Among other taxa, *C. quattrocchiae* marks the top of the Palynozone C of Gamerro and Archangelsky (1981) in the Colorado Basin. The records of *C. quattrocchiae* in well-dated outcropping sections in eastern Patagonia, indicate that this species has a short biochron related to the Burdigalian – earliest Langhian in the Golfo San

Jorge Basin, between 19.69 and 15.37 Ma (Cuitiño et al., 2015) and to the Burdigalian in the Austral Basin, between 17.5 and 18.5 Ma (Burdigalian, Parras et al., 2012; Pérez Panera et al., 2014; Parras, et al., 2020). Hence, the HO of *C. quattrocchiae* may be considered not younger than Burdigalian to earliest Langhian.

The HCO of ***Hystrichokolpoma rigaudiae*** is recorded at 755 mbbp in the Dx-1 (Guler, pers. obs.), and at 410 mbgs in the PV borehole (Fuentes, 2020).

Hystrichokolpoma rigaudiae has the HO at 645 mbsf in the Fx-1 borehole, at 735 mbsf in the Dx-1 borehole (VG *personal observation*; at 695 mbsl in Guler and Guerstein, 2002), at 945 mbsf in the Cx-1 (Guerstein and Junciel 2001), and at 405 mbgs at the PV borehole (Fuentes, 2020).

The HO of ***Cousteaudinium aubryae*** was recorded at 885 mbsf in the Cx-1 borehole (as *C*. cf. *aubryae*; Guerstein and Junciel, 2001), at 625 mbsf in the Fx-1 borehole (Guler and Guerstein, 2002) and at 380 mbgs in the PV borehole (Fuentes, 2020), exhibiting a wide intraspecific morphological variability in an acme episode of the species (Guler, pers. obs.). In the Northern Hemisphere, *C. aubryae* has the HO around the Burdigalian/ Langhian boundary and lowermost Langhian (de Verteuil and Norris, 1996; Köthe, 2003; Musterman and Brinkhuis, 2004; Donders et al., 2009) and in the Langhian (Dybkjær and Piasecki, 2010).

The HCO of ***Dapsilidinium pseudocolligerum*** was recorded at 695 mbsf coinciding with its HO in the Dx-1 (probably by low density of samples; Guler, pers. obs.), and at 390 mbgs in the PV borehole (Fuentes, 2020).

Dapsilidinium pseudocolligerum has its HO at 545 mbsf in the Fx-1 borehole, at 885 mbsf in the Cx-1, at 695 mbsf in the Dx-1 (Guler and Guerstein, 2002) and at 380 mbgs in the PV borehole (Fuentes, 2020).

The HOs and HCOs events of *Hystrichokolpoma rigaudiae* and *Dapsilidinium pseudocolligerum* are close to/ or coincide with the two latter HOs of *C. quattrocchiae* and *C. aubryae* in most of the sites of the Valdés and Colorado basins, around the Burdigalian to lowermost Langhian and lower Langhian, respectively (Fig. 4). In the Northern Hemisphere, *H. rigaudiae* persisted through the Pleistocene (e.g. Fensome et al., 2008), as well as the HO of *D. pseudocolligerum* is recorded in the Tortonian (e.g. Head et al., 1989b; De Verteuil and Norris, 1996; Köthe, 2003; Köthe and Piesker, 2007; Schreck et al., 2012), Pliocene (Louwye et al., 2004; De Schepper et al., 2015) and Pleistocene (Head and Westphal, 1999; Eberli et al., 1997). It is worth mentioning that *H. rigaudiae* show strong environmental preferences, with peak abundances related to warm sea surface waters conditions (Louwye et al., 2008; Egger et al., 2018). Likewise, the warm-water taxa *D. pseudocolligerum* (Head and Westphal, 1999) exhibits asynchronous HO across the North Atlantic high and mid to low – latitudes attributed to the late Miocene cooling (Schreck et al., 2012). In this regard, the early disappearance of *H. rigaudiae* and *D. pseudocolligerum* (HOs and HCOs) herein documented, imply shortened stratigraphical ranges in the southwestern Atlantic compared with those of the Northern Hemisphere.

The HO of ***Cleistosphaeridium ancyreum*** is recorded at 825 mbsf in the Cx-1 borehole, at 525 mbsf in the Fx-1, at 655 mbsf in the Dx-1 in the Colorado Basin, and at 325 mbgs at the PV borehole in the Valdés Basin. *C. ancyreum* was considered as a junior synonym of *Cleistosphaeridium placacanthum* (Bujak and Matsuoka, l986) as well as a variety of the species (Strauss and Lund, 1992). Further taxonomic treatments considered *Cleistosphaeridium ancyreum*, *Cleistosphaeridium diversispinosum* and *Cleistosphaeridium placacanthum* a gradational morphological complex, based on the degree of development of the penitabular ridges of their processes complexes (Eaton et al., 2001). We observe in our basins the presence of intergrades between the three taxa, being *Cleistosphaeridium ancyreum* and *C. placacanthum* the most common species. The HO of *C. placacanthum* shows an erratic record through most of the subsurface sections in the northeastern and offshore Patagonia, not discarding any accuracy in the taxonomic identifications between the intergrade morphotypes. Instead, *C. ancyreum* shows a consistent as well as the highest occurrence of the two taxa. In the PV borehole, the HO of *C. ancyreum* coincide with the base of the middle to upper Miocene interval (55 - 350 mbgs) containing the typical "Paranense" benthic foraminifera *Protelphidium tuberculatum* association. In the Northern Hemisphere, stepwise HOs of *C. diversispinosum*, *C. ancyreum* and *C. placacanthum* were proposed at the upper Oligocene, middle Miocene and upper Miocene, respectively (see Eaton et al., 2001 and references therein). Also, the HO of *C. ancyreun* and the co-generic *C. diversispinosum* coincide with top of the *Cleistosphaeridium placacanthum* Interval Biozone (GOS4) (upper Burdigalian, Langhian, and lower Serravallian; Soliman et al., 2012). Hence, based on the HO of *C. ancyreum* related to the base of the middle to upper Miocene interval in the PV borehole (Fig. 4), as well as the age of this bioevent in the Northern

Hemisphere, we may considered its HO in Patagonia not younger than lower Serravallian.

Labyrinthodium truncatum has its HO at 425 mbsf in the Fx-1 borehole (Guler and Guerstein, 2002), at 705 mbsf in the Cx-1 borehole (Guerstein and Junciel, 2001), at 575 mbsf in the Dx-1 borehole (Guler and Guerstein, 2002) and at 170 mbgs in the PV borehole (Fuentes, 2020). *L. truncatum* was also identified at the Barranca Final Formation (type section) in the north coast of the San Matías Gulf, Colorado Basin (Guler et al., 2002; Fuentes et al., 2016), and at the Puerto Madryn Formation (Olazábal section), Valdés Basin (Fuentes et al., 2019). The HO of *L. trucatum* is related to the Tortonian, between 9.61 and 8.3 Ma at the Barranca Final section (Palazzesi et al., 2014), and ~10 Ma in the Puerto Madryn Formation (Scasso et al., 2001; del Río et al., 2018). The ^{87}Sr/ ^{86}Sr age control of these records allows us to infer that only the end of the stratigraphic range of *L. truncatum* would be represented in those outcropping sections (Fig. 4). The age of the HO of *L. truncatum* in Patagonia agrees with the age of this bioevent in the Northern Hemisphere, where the well-calibrated HO of the species is placed in the upper Tortonian (between ~7,5 and ~8,5 Ma; de Verteuil and Norris, 1996; Williams et al., 2004; Donders et al., 2009; Schreck et al., 2012). The HO of *L. truncatum* appears to be synchronous in Patagonia and the northern latitudes and therefore, this bioevent may be an excellent marker for stratigraphic correlation between the south and the north Atlantic. Although we are considering only the HOs of diagnostic species, it worth mentioning that the LO of *L. truncatum* in the PV borehole occurs next to the HOs of *Cannosphaeropsis quattrocchiae* and *Cousteaudinium aubryae*, associated to a Burdigalian to early Langhian age, in coincidence with its global LO (de Verteuil and Norris, 1996; Munsterman and Brinkhuis, 2004; Williams et al., 2004; Louwye et al., 2007; Donders et al., 2009), This suggests that *L. truncatum* exhibits, at least in the subsurface, its complete stratigraphical range (Figs. 4 and 5).

The HO of ***Operculodinium piaseckii*** was recorded at 425 mbsf and 535 mbsf in the Fx-1 and Dx-1 borehole, respectively (as *Operculodinum* sp.3, Guler et al., 2002), and at 170 mbgs in the PV borehole (Fuentes, 2020). The HO of *O. piaseckii* in these boreholes is coincident/ or close to the HO of *Labyrinthodinium truncatum*, the latter associated with Tortonian ages in Patagonia (see above). In this way, the HO of *O. piaseckii* in the Colorado and Valdés Basins may be synchronous with the HO of the species in the Northern Hemisphere, which have a well-constrained HO in the late Tortonian between 8.5 and 7.6 Ma (e.g. Dybkjær and Piasecki, 2010; Schreck et al., 2012).

Reticulatosphaera actinocoronata was recorded at 306 mbgs in the Ombucta borehole (Guerstein and Guler, 2000), at 365 mbsf in the Fx-1 borehole (Guler, pers. obs.; at 485 mbsf in Guler and Guerstein, 2002), at 220 mbsf in the Cx-1 borehole (Guerstein and Junciel, 2001), at 535 mbsf in the Dx-1 borehole (Guler and Guerstein, 2002), and at 80 (mbgs) in the PV borehole (Fuentes, 2020). The HO of *R. actinocoronata* was recorded in the Barranca Final Formation from strata of 6.48 Ma (Messinian) ^{87}Sr/ ^{86}Sr age (Palazzesi et al., 2014). Comparing with the global HO of *R. actinocoronata* in the Zanclean (4.80 Ma – 4.2 Ma; e.g. Fensome et al., 2008; Schreck et al., 2012) and considering that the HO in all boreholes is associated with the beginning of nearshore marine conditions, it suggest an early environmentally - controlled extinction of the species, related to an abrupt shallowing in the southwestern Atlantic Colorado and Valdés basins towards the end of the Miocene (Fryklund et al., 1996; Continanzia et al., 2011).

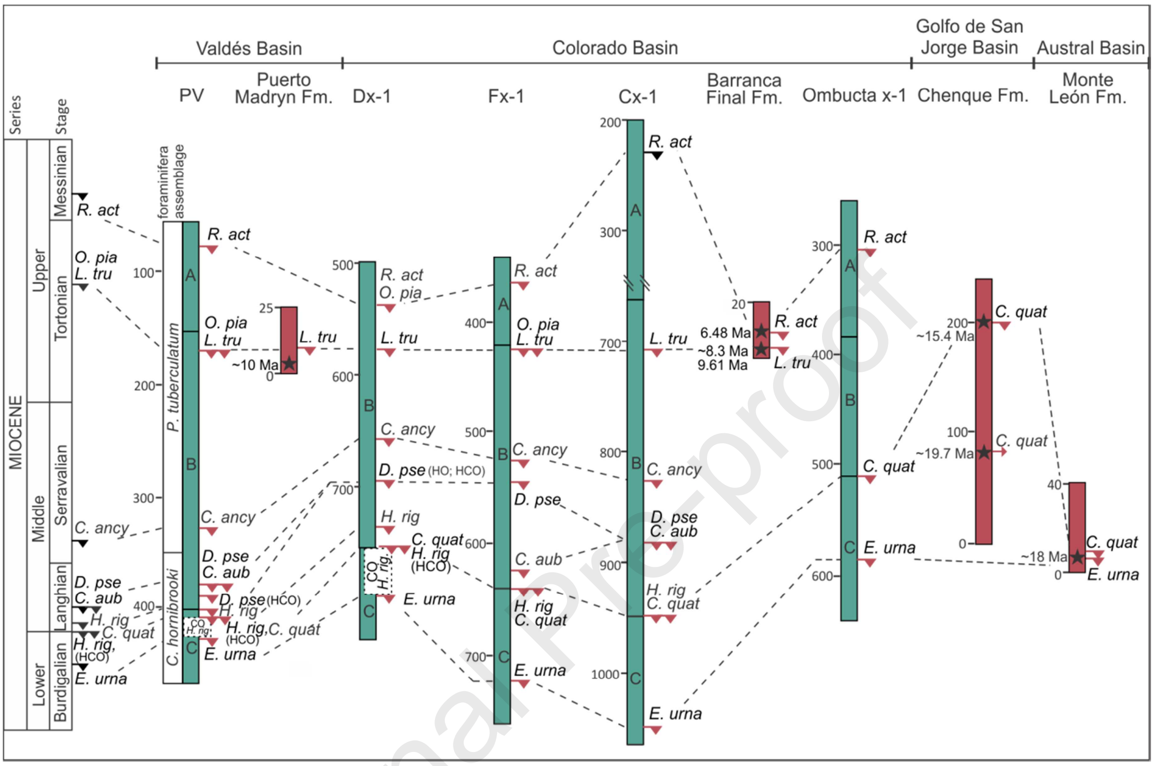

Fig. 4. Regional correlation of Miocene age-diagnostic and environmentally/ climatically-driven events of highest occurrences (HOs) and highest common occurrences (HCOs) of selected dinocyst taxa across the Valdés and Colorado basins. Datum: HO of *Labyrinthodinium truncatum*. Dinocyst biostratigraphic data come from PV borehole (Guler et al., 2018; Fuentes, 2020); Puerto Madryn Formation outcrop (Fuentes et al., 2019); Dx-1 borehole, (Guler and Guerstein, 2002); Fx-1 borehole (Guler and Guerstein, 2002); Cx-1 borehole (Guerstein and Junciel, 2001); Ombucta x-1 borehole (Guerstein and Guler, 2000); Barranca Final Formation outcrop (Palazzesi et al., 2014). Letters A to C refers to the informal palynological zones of Gamerro and Archangelsky (1981). Star symbol refers to ^{86}Sr/^{87}Sr ages from del Río et al., 2018 (Puerto Madryn Formation), Palazzesi et

al., 2014 (Barranca Final Formation), Cuitiño et al., 2015 (Chenque Formation) and Parras et al, 2012; Pérez Panera, et al., 2014; Parras et al., 2020 (Monte León Formation). Foraminifera *Cribrorotalia hornibrooki* and *Protelphidium tuberculatum* assemblages from the PV borehole follows Caramés et al. (2004). R. act = *Reticulatosphaera actinocoronata*, O. pia = *Operculodinium piaseckii*, L. tru = *Labyrinthodinium truncatum*, C. ancy = *Cleistosphaeridium ancyreum*, D. pse = *Dapsilidinium pseudocolligerum*, C. aub = *Cousteaudinium aubryae*, H. rig = *Hystrichokolpoma rigaudiae*, C. quat = *Cannosphaeropsis quattrocchiae*, E. urna = *Emmetrocysta urnaformis.*

3.b. Quantitative palynological analysis in the PV borehole, Valdés Basin.

Quantitative palynological data from the PV borehole (onshore Valdés Basin) yielded a regional picture of how paleoclimatic and paleoenvironmental changes occur in the mid-latitudes of southwestern South Atlantic Ocean through the Miocene. The PV borehole is well situated to integrate data with other stratigraphical and paleontological information from outcrops of deposits originated during the Miocene flooding episodes in northern Patagonia (Figs. 1 and 2). In comparison to outcrop counterparts, the PV borehole has a far more continuous quantitative dinocyst record (Guler et al., 2018; Fuentes, 2020), allowing us to evaluate in detail the paleoenvironmental and paleoclimatic changes that occurred during the Miocene marine events.

3.b.1. Paleoenvironmental and paleoclimatic inferences

The paleoecology of some selected species led us to assume that important paleoenvironmental and paleoclimatic shifts occurred across the Miocene. Our PCA analysis (Fig. 6) shows four main groups (Group 1 to 4) of samples in accordance to different environmental and ecological conditions. The two PC axes account for 77.2% of the cumulative explained variation. In particular, for the first PC the positive contribution corresponds to a/ d ratio (¨acritarchs¨ in fig. 6) and t/m variables (32.4% and 17.7%, respectively), while warm-water and outer neritic to oceanic variables present negative contribution (26.1% and 23.9%, respectively). On the other hand, for the second PC, the variables t/m and warm-water present a positive contribution (41.1% and 28.5%, respectively) while outer neritic to oceanic and a/ d ratio exhibits a negative contribution (17.7% and 12.7%, respectively). Group 1 (Fig. 6; lower-left quadrant of the plot) presents the highest proportions of outer neritic to oceanic taxa together with warm-water taxa, with scarce representation of terrestrial-derived palynomorphs. Group 2 (lower intermediate position of the plot) encompasses the largest number of samples. The assemblages are dominated by outer neritic taxa, highly represented by *Spiniferites* spp. and the t/m ratio is relatively low. Group 3 (upper-right quadrant of the plot) includes dinocyst assemblages with high proportions of neritic taxa and the decrease of the terrestrial components. Group 4 (upper position of the plot) exhibits the highest proportions of terrestrially-derived palynomorphs, less abundance of dinocysts proportions, that is, the highest t/m ratio, and acritarchs contribute notably to the marine palynomorph assemblages.

The representation of 1CP and 2CP individual values of each sample (Fig. 6) shows the environmental aspects reflected by the four groups of samples throughout the PV borehole stratigraphy (Fig. 7). The outer neritic to oceanic, most distal depositional environments, associated with warming conditions (Group 1) mark the two maximum flooding pulses of the two major transgressive - regressive cycles recorded throughout the analyzed Miocene section (Figs. 6 and 7). The older maximum flooding episode occurred in the Burdigalian to earliest Langhian and the younger in the Tortonian (Fig.5; see discussion below in item 4). Fully oceanic settings may have not prevailed during the Miocene at the PV borehole site, since the genus *Impagidinium*, usually indicative of oceanic environments (e.g. Dale, 1996; Brinkhuis et al., 2003) is almost absent. Warm sea surface conditions related to the Burdigalian to earliest Langhian maximum flooding episode are marked by a peak abundance of thermophilic taxa including *M. choanophorum*, *R. actinocoronata*, *L. machaerophorum*, *D. pseudocolligerum* and mostly *H. rigaudiae.* Whereas the taxa adapted to warmer waters like *Batiacasphaera micropapillata*, *Tuberculodinium vancampoae*, *Reticulatosphaera actinocoronata, Lingulodinium machaeorophorum*, *Labyrinthodinium truncatum* and *Melitasphaeridium choanophorum* (Fig. 5) contribute to warm-water conditions during the Tortonian maximum flooding interval. The alternation of Group 2 and Group 3 (Fig. 7a) may indicate shifting of the coastline, related — in part – to successive high-frequency fluctuations of the relative sea level and in turn, interpreted as successive lower hierarchy transgressive - regressive cycles (Fig. 7).

Finally, Group 4, only represented in the uppermost interval (~60/ 65 – 100/ 105 mbgs) in the PV borehole, represents a nearshore, shallow marine depositional setting. Dinocysts drastically decrease the proportions and number of species associated with increasing sporomorphs and small size acanthomorph acritarchs of the genus *Micrhystridium* (Figs. 5, 6 and 7a). Relative abundance of small acanthomorph (micrhystridid) acritarchs are most characteristic of shallow-marine waters, mainly brackish marginal environments (e.g. Tyson, 1995 and references therein). The variation of these parameters, clearly exhibit a shallowing trend toward the uppermost part of the sedimentary succession, and reflect the progressive transition from open marine (neritic) to nearshore depositional environmental conditions.

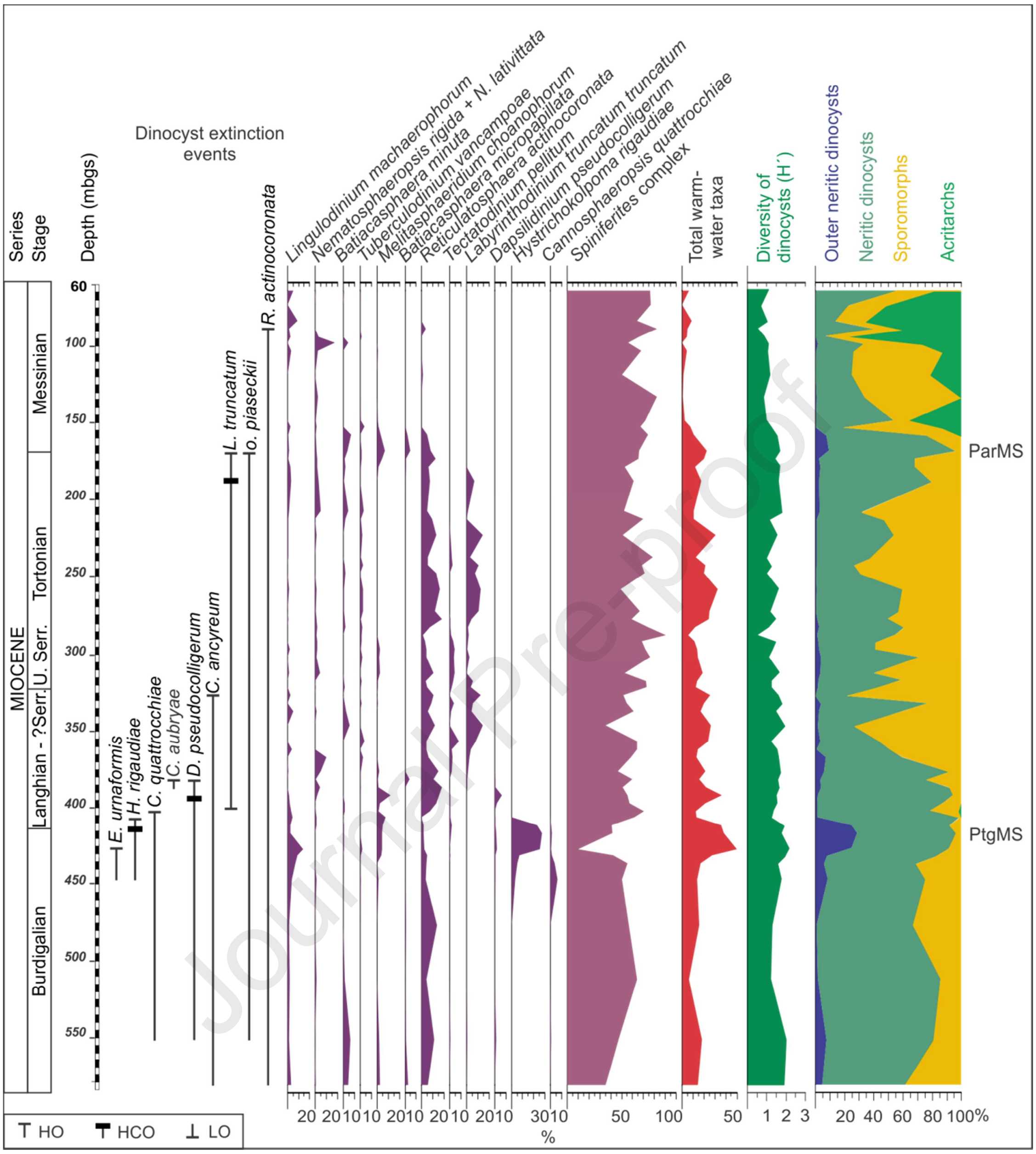

Fig. 5. Highest occurrences and relative abundances of selected paleoecologically dinocyst taxa recorded at the PV borehole, Valdés Basin. Total warm taxa: *M. choanophorum* + *L. machaerophorum* + *R. actinocoronata* + *D. pseudocolligerum* + *H. rigaudiae* + *B. micropapillata* + *L. truncatum*. Total outer neritic to oceanic taxa: *C. quattrocchiae* + *H. rigaud*iae + *B. micropapillata* + *B. minuta* + *N. rigida* + *N. lativitattus*. Neritic taxa: *Spiniferites* complex. PtgMF:

´Patagoniense´ maximum flooding. ParMF: ´Paranense´ maximum flooding. HO: highest occurrence; HCO: highest common occurrence; LO: lowest occurrence.

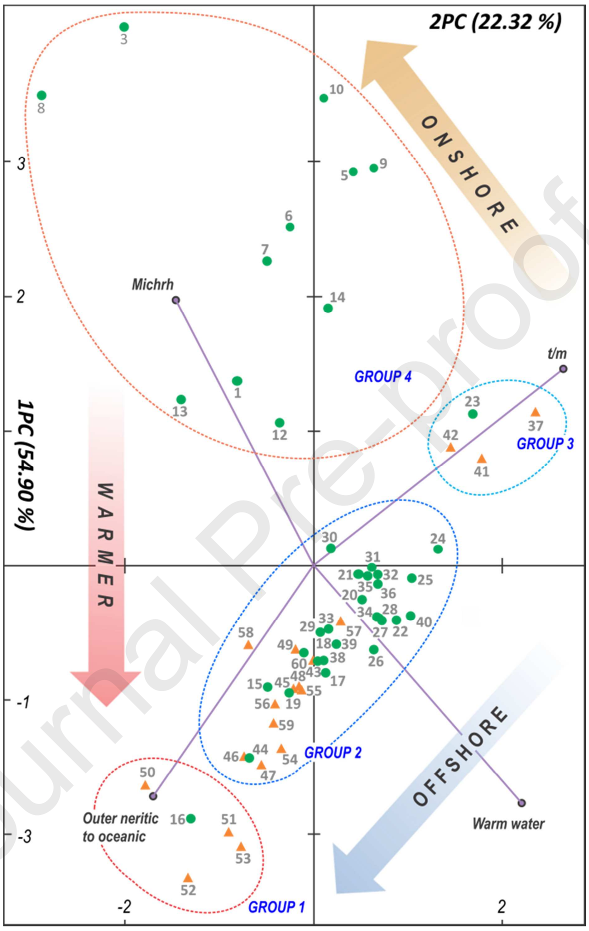

Fig.6. Principal component analysis (PCA) results with environmental variables of samples from the PV borehole. Samples from the early to early middle Miocene ´Patagoniense´ succession interval are represented by orange triangles, and the late middle to late Miocene ´Paranense´ succession interval by green circles. The plot shows the first and second axis scores and vectors of the environmental and climatic variables. The used variables include: outer neritic to oceanic taxa over total dinocysts (outer neritic-oceanic), taxa adapted to warmer waters over total

dinocysts (warm-water), terrestrial/ marine palynomorphs ratio (t/ m) and acritarchs over total dinocysts (acritarchs).

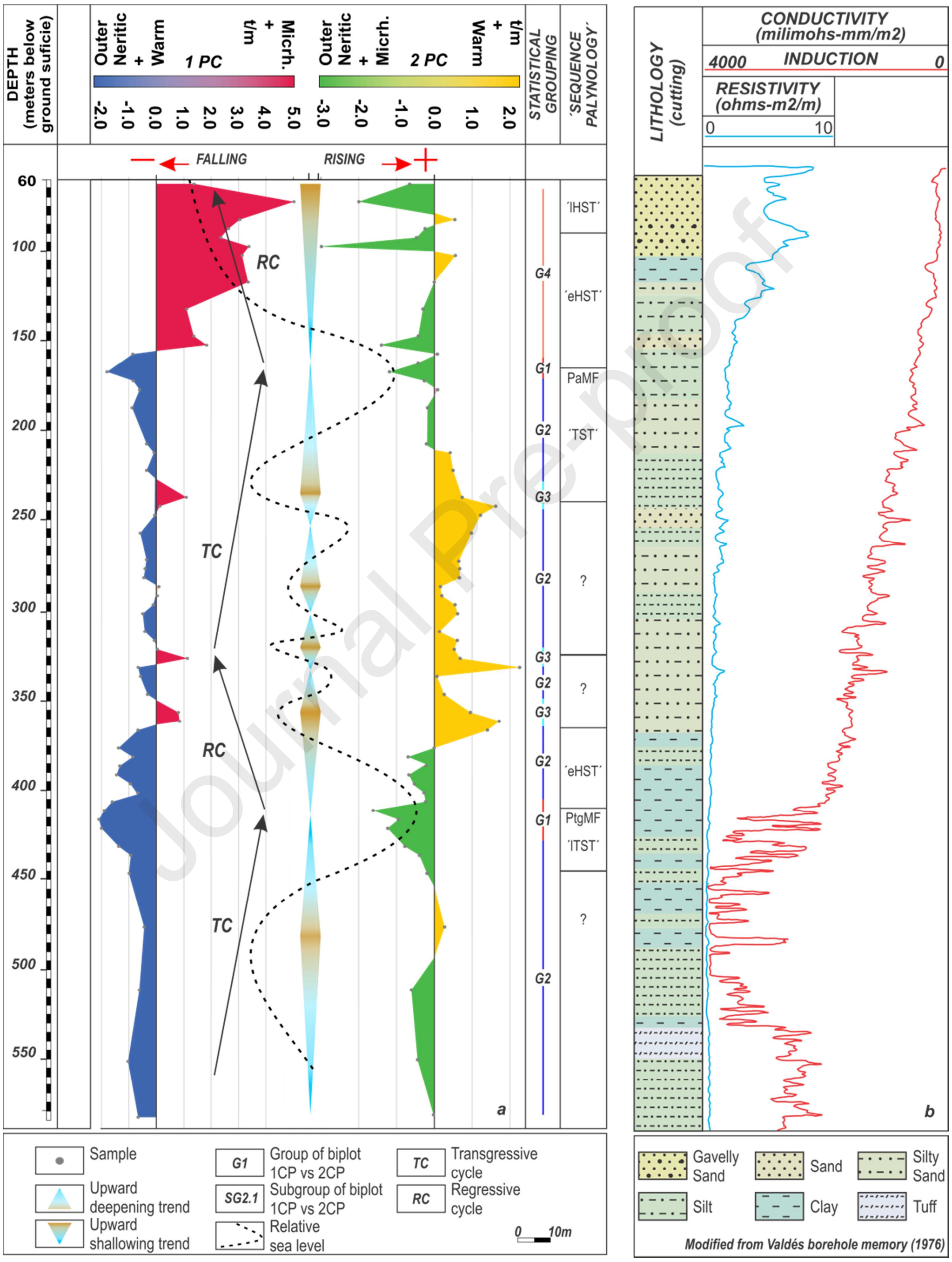

Fig. 7a. Stratigraphic representation of the individual values of 1PC and 2PC of each sample and the distribution of Group 1 to 4 throughout the PV borehole.

Black arrows indicate the successive transgressive-regressive cycles. PtgMF: ´Patagoniense´ maximum flooding. ParMF: ´Paranense´ maximum flooding. TST: Transgressive systems tract. eHST: early highstand system tract. lHST: late highstand system tract. **Fig. 7b**. Liithological and geophysical logs of the YPF-CH-PV.es-1 borehole (PV borehole) in the Valdés Basin.

3.b.2. Miocene ´Maximum flooding surfaces´ and transgressive – regressive cycles

General dinocyst patterns applied to sequence stratigraphy state that the diversity and abundance of dinocysts increases in the Transgressive Systems Tract (TST), reaching the maximum at or immediately above the maximum flooding surface, followed by a gradual and then, a marked decrease during the early and late Highstand Systems Tract (HST), respectively (e.g. Habib et al., 1992; Stover and Handerbol, 1994). Moreover, the LOs often occur at the TST whereas most of the HOs are situated within HSTs (Stover and Hardenbol, 1994). Otherwise, t/m index values trends related to the distance to the coastaline and/ or relative sea level changes have been interpreted according to the concept of ´sequence palynology´ (Prauss, 1993). In this regard, the boundary between the TST and the following HST typifying the maximum flooding surface is indicated by the change from a decreasing to an increasing t/m index values trends (Prauss, 1993, 2000, 2001).

Our evidence from the 1PC and 2PC, where t/m ratio show the highest contribution for the PCs (58,8%) points to two ´maximum flooding surfaces´, related to the two main transgressive - regressive cycles (Figs. 5 and 7). In this context, the older maximum flooding surface at 410/ 415 mbsg is placed in the Burdigalian to lowermost Langhian linked to the ´Patagoniense´ succession (PtgMF; Figs 5, 7), whereas the younger was identified at 165/ 170 mbsg in the Tortonian associated with the ´Paranense´ deposits (ParMF).

The older ´maximum flooding surface´ (PtgMF) in the PV borehole was quantitatively detected by a marked change from a strongly decreasing 1PC component values trend to an increasing 1PC component values mode at 410/415 mbgs (sample 50) (Figs. 5 and 7). Dinocyst assemblages from the PtgMF contain the highest relative abundance of dinocyst (lowest t/m ratio values) with abundance of outer neritic to oceanic species (e.g. *Cannosphaeropsis quattrocchiae*) and increased diversity of dinocyst (Figs. 5 and 7). Below the PtgMF, from 445/ 450 to 410/ 415 mbgs (samples 56 to 51) the strongly upward decreasing t/m ratio trend is probably related to a late TST. Above the PtgMF, between 400/ 405 and 365/ 370 mbsg (samples 49 to 44), the progressive upward reduction in both relative abundance (slightly increase in the t/m values) and diversity of dinocysts, with a drastic diminishing of the outer neritic taxa proportions, associated to the extinctions of a significant number of species (HOs), may be diagnostic of an ´early HST´ (Fig. 7).

The younger maximum flooding surface (ParMF) was detected by a marked change from a strongly decreasing 1PC component values trend, to an increasing 1PC component values mode at 165/ 170 mbsg (sample 16). The assemblage associated to the ParMF presents the lowest t/m ratio value, high diversity of dinocyst, and peak abundance of outer neritic taxa (e.g. *Batiacasphaera micropapillata* complex) (Figs. 5 and 7). Below the ParMF, between ~240/ 245 to

165/170 mbgs (samples 24 to 16), the decreasing t/m index values is probably related to a TST. Immediately above the ParMF, the abrupt shift of the 1PC from negative to positive values, associated to the extinctions of a significant number of dinocyst taxa (HOs), suggests a ´HST´ interval. This shallowing upward trend is accentuated toward the top of the section, between 60/ 65 and 90/ 95 mbgs (samples 8 to 1), in which assemblages show a significant reduction in the relative abundance and number of dinocyst species (less than 10 species). In this interval, dinocyst were progressively largely replaced by acritarchs. Thus, acanthomorph (micrhystridid) acritarchs dominate the marine phytoplankton by the top of the section, implying nearshore environmental conditions.

4. Discussion

The two most important maximum flooding episodes related to the two main Miocene transgressive-regressive cycles were clearly identified in the PV borehole (Figs. 4 and 6). Our comprehensive review, plus quantitative data analysis gives us the chance to detect stratigraphically significant dinocyst events useful for chronostratigraphic correlation in northeastern and offshore Patagonia.

The older maximum flooding in the PV borehole (Burdigalian-earliest Langhian) occurred under warm, outer neritic to oceanic (distal) environmental conditions. The age of this episode mainly rely on the occurrence of the endemic taxa *Cannosphaeropsis quattrocchiae*, which have a short biochron linked to ^{86}Sr/ ^{87}Sr ages between 17.5 and 18.5 Ma (Cuitiño et al., 2015; Parras et al., 2012; Pérez Panera et al., 2014). The extinction *of C. quattrocchiae* next to the PtgMF at the PV borehole (at 400/ 405 mbgs, Fig. 5), seems to be a consistent and isochronous event in several subsurface sections in the Colorado Basin (e.g. Guerstein and Guler, 2000; Guerstein and Junciel, 2001; Guler and Guerstein 2002; see Fig. 4). This fact enhances *C. quattrocchiae* as key taxa for regional correlation of the Burdigalian to earliest Langhian maximum flooding interval in the subsurface across the Valdés and Colorado basins (Fig. 4). Besides, dinocyst assemblages from the maximum flooding interval at the PV borehole suggest correlation with the lower Miocene marine strata along the east coast of Patagonia, i.e. the ´Patagoniense´ successions of the Chenque Formation in the Golfo San Jorge Basin (Palamarczuk and Barreda, 1998; Barreda and Palamarczuk 2000a) and the Monte León Formation in the Austral Basin (Parras et al., 2012; 2020; Barreda and Palamarczuk 2000b) and probably the Gaiman Formation west of the PV borehole (Cuitiño et al., 2017; 2019).

The Valdés Basin is located far from the direct action of the Andean orogenesis. As for Colorado Basin, the Cenozoic record of the Valdés Basin is believed to be the consequence of relatively constant and low subsidence rates which are estimated as being produced by non-orogenic processes as a part of the passive margin stage (Continanzia et al., 2011). In parallel, several high-frequency global sea-level fluctuations are recorded for the time interval analyzed here (Miller et al., 2020). Recently, Parras and Cuitiño (this volume) suggested that the regional early Miocene marine sedimentation period in Patagonia was controlled by subsidence, whereas the higher frequency marine flooding events were controlled by global sea level rising events. Based on our observations, warm sea-surface conditions would have accompanied the early Miocene maximum flooding event, as reflected by increased relative abundances of warm-water dinocyst taxa, suggesting a superimposed subsidence plus glacio-eustatic control on the sea-level rise (Figs. 5 – 7). Peaks abundance of *Hystrichokolpoma rigaudiae* (e.g. Egger et al., 2018) and *Dapsilidinium pseudocolligerum* (Head and Westphal, 1999) up to 36 % and 25%, respectively, together with increased proportions of other warm-water taxa like *Tuberculodinium vancampoae*, *Melitasphaeridium choanophorum*, *Tectatodinium pellitum*, *Operculodinium centrocarpum* and *Lingulodinium machaerophorum* (e.g. Head, 1993, 1997; Edwards and Andrle, 1992; Versteegh, 1994; Head, 1996; De Schepper, 2006; De Schepper et al., 2011; Schreck et al., 2017), support relatively high sea surface temperatures (SSTs) during the Burdigalian to earliest Langhian in Patagonia. The highest relative abundances of *Reticulatosphaera actinocoronata* were associated to SSTs higher than 18℃ as well as *Lingulodinium machaerophorum* and *Operculodinium centrocarpum* suggest SSTs above 15℃ and 20℃, respectively (De Schepper et al., 2011; Schreck et al., 2017). Furthermore, the HOs and HCOs of warm-water taxa *H. rigaudiae* and *D. pseudocolligerum* in the Valdés and Colorado basins, coinciding or next to the HOs of *Cannosphaeropsis quattrocchiae* and/ or *Cousteaudinium auybriae*, suggest that both taxa do not extend beyond the lowermost Langhian (Figs. 4 and 5), whereas both warm-water taxa persisted longer in the North Atlantic ranging into the Pliocene (e.g. Schreck et al., 2012). Therefore, the early extinctions of the *H. rigaudiae* and *D. pseudocolligerum* in the southwestern Atlantic basins seem to be climatically-driven, presumably related to a gradual cooling and ice-sheets expansion on Antarctica, following the end of the global Miocene warming (~17–14 Ma, e.g. Holbourn et al., 2013; Zachos et al., 2001; Westerhold et al., 2020). During the middle Miocene climate transition (14.2 to 13.8 Ma) in the high-latitude southwest Pacific the SSTs cooled 6° to 7℃ (Shevenell et al., 2004). Further palynological data provide evidence of a significant drop in number of terrestrial palynomorphs from the early to late Miocene in eastern Patagonia, associated with the extinction in the middle Miocene of several tropical taxa, such as several ferns (for example Cyatheaceae) and gymnosperm (*Dacrycarpus*, *Dacrydium*, *Lagarostrobus*, *Mychrocacrys*) (e.g. Barreda and Palazzesi 2007; Palazzesi et al., 2014).

The younger maximum flooding (ParMF) in the PV borehole (Tortonian) took place under outer neritic to oceanic environmental conditions. The HOs of *Labyrinthodinium truncatum* and *Operculodinium piaseckii* next to the top of this interval indicate an age not younger than Tortonian for this episode. Upwards, assemblages show a marked shallowing trend together with increased terrestrial influence, presumably related to increasing coastal proximity. Dinocysts are reduced to a few number of taxa, indicating environmentally unfavorable conditions for most marine dinoflagellates, being largely replaced by small acanthomorph acritarchs (*Micrhystridium*).

This transition from maximum flooding followed by progradation, characteristic of a highstand systems tract in the PV borehole (´HST´; Fig. 7), suggests correlation with the Maximum Flooding/ Highstand Phase (del Río et al., 2001; Cuitiño et al., 2017) recognized in exposures of the Puerto Madryn Formation in Valdés Peninsula (at ~10 Ma; del Río et al., 2018). A thin layer associated with the Maximum Flooding/ lowermost Highstand Phase contains peak abundances of dinocysts and calcareous nannofossils, followed by increasing terrestrial influence, dinocysts being replaced by phrasinophycean (tasmanitids) and chlorococcalean algae (*Botryococcus* and *Pediastrum*) (Fuentes et al., 2019). The shallowing upward trend could be equivalent to that registered for outcrops of the upper part of the Puerto Madryn Formation to the west of the PV borehole, defined as the Regressive Phase of the unit (del Río et al., 2001; Cuitiño et al., 2017).

The late Miocene environmental and/ or climatically-driven change, implying abrupt shift from neritic to nearshore marine conditions, with palynological signals accordant with ´maximum flooding/ highstand´ phases identified in the Valdés Basin were also consistently documented in the subsurface Colorado Basin (e.g. Guerstein and Guler, 2000; Guerstein and Junciel, 2001; Guler et al., 2001; Guler et al., 2002) as well as in the outcropping Barranca Final Formation (Guler et al., 2002; Fuentes et al., 2016).

Furthermore, the last peak abundance of dinocysts when the sea-level was at its maximum is followed by the disappearance of a significant number of species, among them, the index taxa *Labyrinthodinium truncatum* (Fig. 4 and 5). The HO of *Labyrinthodinium truncatum* invariably placed at or next to the ´maximum flooding suface´ in the Puerto Madryn Formation (at ~10 Ma; Fuentes et al., 2019), at the Barranca Final type section (~ 8.5 - 9 Ma; Palazzesi et al., 2014) as well as in the subsurface Valdés and Colorado basins (Fig. 4), become a useful marker for long distance correlation of the Tortonian maximum flooding episode, across a wide area in northeast Patagonia and the adjacent continental shelf (Fig. 4).

The progressive extinctions of dinocyst taxa examined through the Miocene in the Colorado and Valdés basins, expressed in a sequence of diagnostic HOs and

HCOs events (Fig. 4), may be a response to the worldwide stepwise declining temperatures context since ~14 Ma (e.g. Zachos et al., 2001; Shevenell et al., 2004; Holbourn et al., 2013; Westerhold et al, 2020) and the overall progressive shallowing trend in both basins (e.g. Malumián, 1999; Continanzia et al., 2011; Malumián and Náñez, 2011). Nevertheless, the continuous and consistent occurrence of *Labyrinthodinium truncatum* since the 410/ 415 mbgs (around the Burdigalian to Langhian, Fig. 4 and 5) until its extinction at 165/ 170 mbgs (Tortonian) in the PV borehole, suggest relatively warm conditions in much of the Miocene record in the mid-latitude southwestern Atlantic basins. The presumed warm-water species is restricted to a narrow temperature interval in the North Atlantic (between 16℃ and 22℃), as it was not rec orded at SSTs below 15 ℃ (Schreck et al., 2017). Furthermore, high relative abundances of warm-water taxa like *Melitasphaeridium choanophorum*, *Labyrinthodinium truncatum*, *Reticulatosphaera actinocoronata* and *Operculodinum centrocarpum*, between 165/170 and 185/190 mbsg at the PV borehole, suggest increasing SSTs during the Tortonian in northeastern Patagonia (Fig. 5). Other dinocyst signal of warmth in the northeast of Patagonia were observed in Valdés Peninsula (~10 Ma) and Barranca Final (~8,5-9 Ma; Fuentes et al., 2016; Fuentes et al., 2019), where assemblages comprise common warm-waters taxa, including *Invertocysta lacrymosa*, *Melitasphaeridium choanophorum*, *Spiniferites mirabilis*, *Selenopemphix nephroides*, *Tuberculodinium vancampoae*, *Operculodinium centrocarpum* and *Reticulatosphaera actinocoronata* (Head et al., 1989a, 1993, Head, 1996, 1997; Edwards and Andrle, 1992; Versteegh, 1994; Versteegh and Zonneveld, 1994; Dale, 1996; Head, 1997; De Schepper, 2006; De Schepper et al., 2011; Hennissen et al., 2016). In agreement, the molluscan association from the lower to middle part of the Puerto Madryn Formation (e.g. del Río, 1990), represents the immigration of Caribbean components in Patagonia and the warmest-water faunas that developed in Patagonia during Cenozoic times (Martínez and del Río, 2002). Also, terrestrial palynomorphs show that in eastern Patagonia, the flora would have been significantly more diverse than today, comparable with those prevailing at lower (subtropical) latitudes. The presence of some key neotropical lineages (*e.g.*, Asteraceae, Acantaceae, Malpighiaceae, Loranthaceae) indicate that coldest temperatures were between 11.4℃ and 16.9℃ (Palazzesi et al., 2014). In addition, some freshwater fish records (e.g. Loricarids) records in the Puerto Madryn Formation, suggested a much more southwards distribution of the Brazilian fish fauna during the Cenozoic, and warm continental temperatures (Cione et al., 2005; Cione et al., 2011).

5. Conclusions

The palynological analysis in the onshore PV borehole in the Valdés Basin, combined with previously documented palynological data from the subsurface of the Colorado Basin and the outcropping sections along the northeast coast of Patagonia, provided valuable information for regional biostratigraphic, climatic and environmental reconstructions for the Miocene record of both basins.

A sequence of eleven biostratigraphic and/ or ecologically significant dinocyst events is recognized in the Valdés and Colorado basins. From the oldest to the youngest these bioevents are: HO of *Emmetrocysta urnaformis*, HO of

Cannosphaeropsis quattrocchiae, HCO and HO of *Hystrichokolpoma rigaudiae*, HO of *Cousteaudinium auybriae*, HCO and HO of *Dapsilidinium pseudocolligerum*, HO of *Cleistosphaeridium ancyreum*, HO of *Labyrinthodinium truncatum*, HO of *Operculodinium piaseckii* and HO of *Reticulatosphaera actinocoronata*.

Quantitative changes in the palynological assemblages from the PV borehole, evidence the two major maximum flooding episodes related to regional transgressive - regressive cycles occurred during the Miocene in the southwestern Atlantic margin. The two maximum flooding intervals are characterized by warm, outer neritic to oceanic (distal) environmental conditions. The older is estimated to occur in the Burdigalian–lowermost Langhian and the younger in the Tortonian. These maximum flooding events, associated with warm sea surface temperatures, conditions, may be related to glacio-eustatic sea level rises, related to the Antarctic ice-sheet dynamics during the Miocene. Abrupt environmental and/or climatically-driven changes, implying shifting from neritic to nearshore environmental conditions were identified in the upper part of the section, associated with the extinction of the warm-water dinocyst taxa, increasing terrestrial influence, being dinocysts largely replaced by acritarchs.

The occurrence of the endemic *Cannosphaerosis quattrocchiae* appears to be a key species for the correlation of the Burdigalian to lowermost Langhian maximum flooding interval in the southwestern Atlantic Colorado and Valdés basins. Likewise, the HO of *Labyrinthodinium truncatum* becomes a useful event to correlate the late Miocene (Tortonian) maximum flooding episode between neritic successions across both basins.

The extinctions of the warm-water taxa *Hystrichokolpoma rigaudiae* and *Dapsilidinum pseudocolligerum* in the Burdigalian to earliest Langhian in the southwestern Valdés and Colorado basins, denoting the shortening of their stratigraphic ranges, might be in response to declining sea surface temperatures related to global cooling and the reestablishment of the Antarctic ice-sheets since ~14 Ma. These warm-water taxa that persisted longer (late Miocene and Pliocene, respectively) in the Northern Hemisphere suggest an apparent climatically-driven diachronism across both hemispheres, regarding the intensification of glaciation in the Northern Hemisphere occurred in the Pliocene. Nevertheless, peak relative abundances of warm-water taxa like *D. pseudocolligerum*, *H. rigaudiae*, *R. actinocoronata*, together with the continuous record of *Labyrinthodinium truncatum* since the Burdigalian to earliest Langhian until its disappearance in the Tortonian, suggest relatively warm water conditions prevailing during most of the Miocene.

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Warm, outer neritic environmental conditions characterize Miocene maximum floodings

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Bahia Blanca, October 30th, 2020

Dr. Andrés Folguera

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No conflict of interests

Sincerely,

Dr. M. Verónica Guler