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The palynology of the President Beaches Formation (Early Cretaceous), Byers Peninsula (Livingston Island, Antarctica)

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ABSTRACT. This study reevaluates the chronostratigraphic extent and depositional conditions of the President Beaches Formation at the Byers Peninsula, Livingston Island, South Shetland Islands (Antarctica). Our aim is to constrain its age and improve its regional correlation using new palynological evidence. Dinoflagellate cyst assemblages in four productive samples enabled the recognition of the mid-late Valanginian *Senoniasphaera tabulata* Interval Zone, identified by the presence of its index-species and the coeval occurrence of characteristic dinoflagellate cyst taxa such as *Canningia reticulata*, *Cerbia tabulata*, *Kaiwaradinium scrutillinum*, *Spiniferites* sp., *Oligosphaeridium complex*, *Circulodinium vermiculatum*, and *Heslertonia heslertonensis*. These data extend the scope of the President Beaches Formation, shifting its upper boundary compared to earlier findings. Low-energy neritic conditions are indicated for the investigated succession, characterized by normal marine nutrient availability and relatively oligotrophic water masses. An elevated continental/marine particle ratio (predominance of saccate pollen grains among sporomorphs) further suggests an offshore setting with significant terrestrial input. Palynofacies data support a mid-to-distal shelf depositional environment, consistent with previous lithofacies evidence. The diversity of sporomorphs indicates the hinterland flora primarily comprised pteridophyte-spore generating plants and coniferous woodlands, with nearly equal amounts of *Araucariacites* and *Podocarpidites*. A warm temperate climate with high humidity is also proposed for the mid to late Valanginian in this area.

Keywords: Dinoflagellate cysts, Valanginian, Byers Peninsula, Antarctica.

RESUMEN. Palinología de la Formación President Beaches (Cretático Temprano), Península Byers (Isla Livingston, Antártica). Este estudio reevalúa la extensión cronoestratigráfica y las condiciones de depositación de la Formación President Beaches en la península Byers, isla Livingston, islas Shetland del Sur (Antártica), con el objetivo de restringir su edad y mejorar su correlación regional mediante nueva evidencia palinológica. Los ensamblajes de quistes de dinoflagelados en cuatro muestras productivas permitieron reconocer la zona de intervalo de *Senoniasphaera tabulata* del Valanginiano medio-tardío, identificada por la presencia de su especie índice y la ocurrencia de taxones característicos de quistes de dinoflagelados coetáneos como *Canningia reticulata*, *Cerbia tabulata*, *Kaiwaradinium scrutillinum*, *Spiniferites* sp., *Oligosphaeridium complex*, *Circulodinium vermiculatum* y *Heslertonia heslertonensis*. Estos datos amplían el alcance de la Formación President Beaches, desplazando su límite superior en comparación con hallazgos previos. Se sugieren para la sucesión investigada condiciones neríticas de baja energía, caracterizadas por una disponibilidad normal de nutrientes marinos y masas de agua relativamente oligotróficas, así como una elevada relación continental/marina (predominio entre los esporomorfos de granos de polen sacados), donde esto último indica además, un ambiente marino abierto con una significativa contribución terrestre. Los datos de palinofacies apoyan un ambiente de depositación de plataforma media a distal, consistente con información litofacial previa. La diversidad de esporomorfos indica que la flora del interior comprendió principalmente plantas generadoras de esporas de pteridofitas y bosques de coníferas, con proporciones prácticamente idénticas de *Araucariacites* y *Podocarpidites*. Se sugiere un clima templado cálido y húmedo para el Valanginiano medio-tardío en esta región.

Palabras clave: Quistes de dinoflagelados, Valanginiano, Península Byers, Antártica.

1. Introduction

The Byers Peninsula is the westernmost point of Livingston Island and is the largest ice-free area in the South Shetland archipelago (Fig. 1A). Detailed stratigraphic studies have, however, been difficult due to the large presence of periglacial debris and the small and scattered outcrops of sedimentary rocks. Byers Peninsula geology was first studied by Hobbs (1968), who described volcanic rocks interbedded with sandstones and conglomerates, which he termed the "Younger Volcanic Group" and assigned them to the Miocene. Research over the past five decades has revealed that this area consists of a thick Upper Jurassic-Lower Cretaceous volcano-sedimentary succession, containing abundant coherent igneous

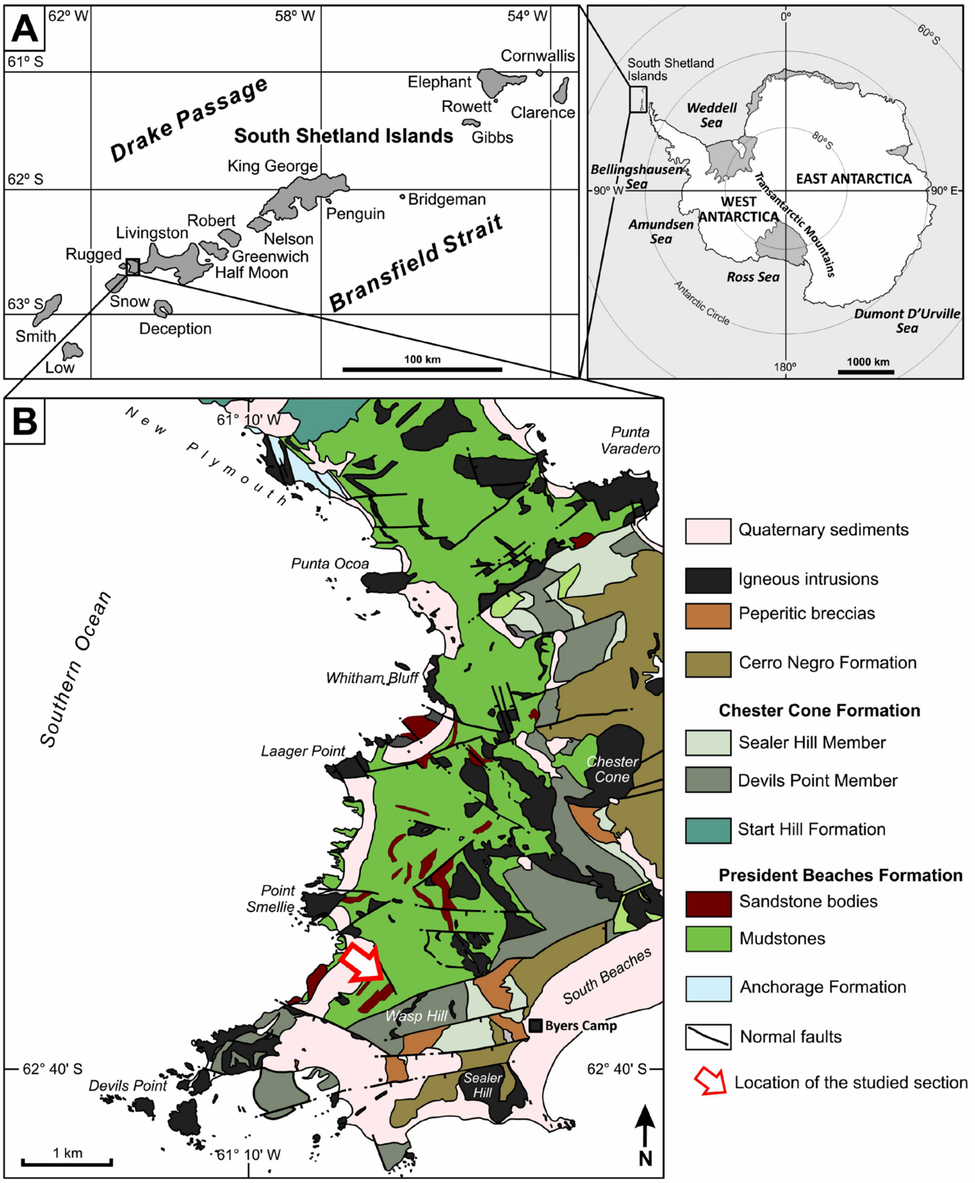

FIG. 1. **A**. Location maps for the South Shetland Archipelago and Livingston Island with the geographic position of Byers Peninsula. **B**. Generalized geological map of Byers Peninsula, showing the location of studied section (modified after Crame *et al*., 1993, and Hathway and Lomas, 1998).

rocks, now known as the Byers Group (Hernández and Azcárate, 1971; Valenzuela and Hervé, 1972; Crame *et al*., 1993; Duane, 1994; Hathway, 1997; Hathway and Lomas, 1998). The Byers Group comprises mudstone-dominated clastic rocks formed in marginal fore-arc basin settings (Smellie *et al*., 1980; Pimpirev and Vangelov, 1998; Bastias *et al*., 2020; Georgiev *et al*., 2023). It includes five superposed lithostratigraphic units, of which four were deposited in marine environments (*i.e*., the Anchorage, President Beaches, Start Hill, and Chester Cone formations, spanning ?Kimmeridgian-Tithonian to Valanginian), while one (the Cerro Negro Formation, which is early Aptian in age) was deposited in a continental environment (Fig. 1B). Among these, the President Beaches Formation (PBF) and the overlying Chester Cone Formation occupy the largest area in the western part of the Byers Peninsula (Fig. 1B). A number of palaeontological studies have been conducted on the PBF. Notably, Chilean researchers made the first discoveries of Lower Cretaceous ammonites (González-Ferrán *et al*., 1970; Tavera, 1970). Fragmented Lower Cretaceous Neocomitidae and Spiticeratidae ammonites were found at mid-levels of the formation (Smellie *et al*., 1980). Covacevich (1976) and Crame *et al*. (1993) reported discoveries of Valanginian cephalopods, bivalves, gastropods, scaphopods, and terebratulid brachiopods from clayey intervals. Crame (1995) described a new bivalve species of *Manticula* from mudrocks. Dochev *et al*. (2017) reported some reworked upper Berriasian ammonites obtained from coarse-grained beds in the PBF.

Askin (1981) conducted the earliest palynological study on Byers Peninsula, reporting the first Tithonian-Barremian palynomorphs from the PBF. These included abundant but poorly preserved spores, pollen, and dinoflagellates. Crame *et al*. (1993) also reported varied spores, pollen, and dinoflagellate cysts, interpreting them as evidence of shallow marine depositional conditions. Duane (1994, 1997) later determined the chronostratigraphic extent of the PBF and the Chester Cone Formation based on dinoflagellate cyst assemblages. According to this author, the PBF dated mid-to-late Berriasian, while the Chester Cone Formation was dated as latest Berriasian to early Valanginian. More recently, Dochev and Pavlishina (2020) identified the dinoflagellate cyst *Batioladinium reticulatum* Zone within the PBF, refining its age to the latest Berriasian, closely approaching the Berriasian/Valanginian boundary.

During the 2023/2024 field season of the XXXII Bulgarian Antarctic Expedition, a new stratigraphic section in the upper levels of the PBF was made. This section is located west of the Byers Field Camp, between Point Smellie, Wasp Hill, and Devils Point (Fig. 1B). Although earlier Bulgarian expeditions had investigated this area, they did so without measured sections and with only scattered, fossil-barren samples. Crucially, our recent PBF mudstone and siltstone samples yielded well-preserved and diverse organic-walled dinoflagellate cyst assemblages, alongside gymnosperms and pteridophyte spores with considerable morphological diversity. Therefore, the aim of this work is to present new palynological results, refine existing palynological data and age assessments, and provide an amended palaeoenvironmental interpretation of the PBF based on the analysis of dinoflagellate cyst assemblages and palynofacies.

2. Stratigraphic and depositional framework of the PBF

The PBF is probably the thickest sedimentary unit of the Byers Group, comprising several hundred metres of silty-argillaceous strata and containing at least four major sandstone packages (cf. Hathway and Lomas, 1998; Pimpirev and Vangelov, 1998; Lomas, 1999; see also Fig. 1B). According to recent views, it overlies with a sharp boundary the radiolarian mudstones of the Anchorage Formation and is sharply overlain by the volcanic breccias of the Start Hill Formation and the coarse siliciclastic rocks of the Chester Cone Formation (cf. Georgiev *et al*., 2023). Our studied section is located within the uppermost parts and south-westernmost outcrops of the PBF, which are tectonically delimited from the rest of the overall profile. Within a thickness of ~69 metres, we divided the strata into five informal units (Fig. 2): a) (21 m): black, fine-laminated and fissile shale, containing irregular, grey-brown sandstone/siltstone interbeds, grading upwards into grey, poorly laminated silty shale with sandstone interbeds; b) (2 m): medium-grained sandstone with sloped cross-bedding and scattered small pyrite nodules; c) (15 m): black, fine-laminated fissile shale interbedded in the upper parts by siltstone; d) (13 m): grey, thin-bedded, medium-grained sandstone (subunits d1: 6 m, and d3: 3 m), incised by unsorted, polymict, matrix-supported pebble conglomerate (subunits d2: 3 m, and d4: 1 m),

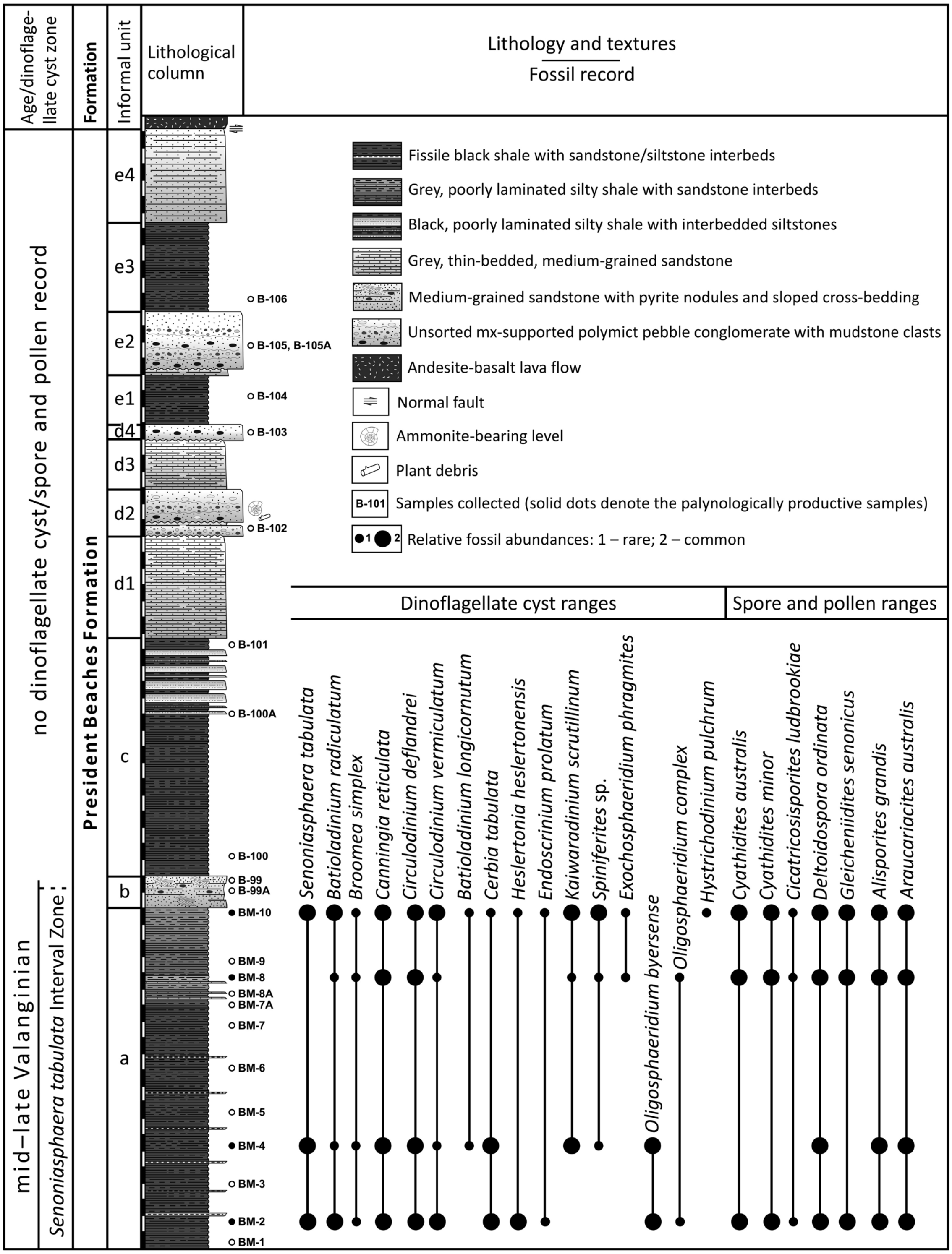

FIG. 2. President Beaches stratigraphic section shown against the dinoflagellate cyst, spore and pollen ranges.

containing intraformational mudstone clasts, wood debris and reworked ammonites; e) (18 m): black, fine-laminated fissile shale (subunits e1: 3 m, and e3: 5.5 m), incised by unsorted, polymict, matrix-supported pebble conglomerate with mudstone clasts (subunit e2: 4 m) and covered by grey, thin-bedded, medium-grained sandstone (subunit e4: 5.5 m).

The bedrock of the succession remains unknown, and its upper limit is unclear as the contact with an overlying andesite-basalt lava flow is normally faulted. We believe that our succession corresponds to alternating lithofacies of F3 to F6 (*sensu* Pimpirev and Vangelov, 1998). This suggests delta slope sediments (mud-dominated facies representing background deposition), intercalated by river floods (sandstone facies), and current-derived sediments (channelized conglomerate facies) formed either through the reworking of fan-derived strata or as debris flow deposits fed by river mouths.

3. Material and methods

The sedimentary succession of the PBF section was sampled from the upper part with 5 samples and the lower part with 17 samples (Fig. 2). Four of them contained dinoflagellate cyst assemblages, particularly BM-2, BM-4, BM-8 and BM-10 (Fig. 2). Palynological samples were processed at the Sample Preparation Laboratory (GeoPrep) of the Institute of Geological Sciences at the Polish Academy of Sciences (Kraków, Poland) following standard palynological techniques. About 50 g of sediment from each sample was processed by HCl (10%) and HF (40-50%) treatment and heavy liquid separation (*e.g.*, zinc chloride). The residues were finally sieved through 10 μm nylon meshes. Strew mounts were made in glycerine jelly. From each sample, two palynological strew mounts were prepared and analysed for their palynological content under a Leica DM5500 microscope. Selected palynomorphs were photographed with Leica DFC310 FX digital camera. The palynological slides and residues are stored in the collections of the Department of Geology, Paleontology and Fossil Fuels at Sofia University "St. Kliment Ohridski".

Quantitative analysis of dinoflagellate cyst associations was based on counts of 50 specimens per slide, where possible. These were described in terms of rare (1-10 specimens) and common (11-20 specimens). Palynofacies analysis involved counting the relative abundance of sedimentary organic constituents based on 400 particles per slide. Three main groups of kerogen constituents proposed by Tyson (1995) and Radmacher *et al.* (2020) were recognized in the slides, namely: 1) phytoclasts (opaque and translucent organic particles); 2) palynomorphs (dinoflagellate cysts, spores and pollen); and 3) amorphous organic matter (AOM). The data were plotted in the ternary AOM-Phytoclast-Palynomorph diagram of Tyson (1993) and in the Microplankton-Spore-Pollen ternary plot (after Fedorova, 1977, and Duringer and Doubinger, 1985). Palynofacies parameters, such as the ratio of continental to marine particles (C/M ratio), the ratio of opaque to translucent phytoclasts (OP/TR ratio) (Tyson 1993, 1995), as well as the ratio of peridinioid to gonyaulacoid (P/G) dinoflagellate cysts (Brinkhuis, 1994; Wilpshaar and Leereveld, 1994; Niechwedowicz *et al*., 2021) were estimated to characterize the palaeoenvironmental settings. The interested reader is referred to Fensome *et al.* (2019) for dinoflagellate cyst taxonomy.

4. Results

Marine and terrestrial palynomorphs are present in the sampled PBF succession, with a high to moderate species diversity. They include abundant dinoflagellate cysts, subordinate plant spores and pollen grains, and rare micro-foraminiferal test linings. The assemblages are dominated by the dinoflagellate cysts (Fig. 2). Dinocyst assemblages are moderately diverse throughout the section, with more than 22 taxa being consistently present, whereas sporomorphs, including spores and pollen, are represented by 7 species (see the Appendix for the full list of taxa recognised in this study). The dinoflagellate cysts encountered in all productive samples are considered to constitute one single association, as no significant differences in their composition were observed. The following key taxa are identified: *Broomea simplex* (Fig. 3A); *Canningia reticulata* (Fig. 3B, C); *Canningia pistica*; *Cerbia tabulata* (Fig. 3D); *Endoscrinium prolatum* (Fig. 3E); *Heslertonia heslertonensis* (Fig. 3F); *Batioladinium longicornutum* (Fig. 3G); *Batioladinium pomum*; *Circulodinium vermiculatum* (Figs. 3H and 4C); *Papuadinium apiculatum* (Fig. 3I); *Senoniasphaera tabulata* (Figs. 3J, 4H, and 4I); *Oligosphaeridium complex* (Fig. 3K); *Batioladinium radiculatum* (Fig. 3L); *Circulodinium deflandrei* (Fig. 4A, B); *Circulodinium distinctum*; *Hystrichodinium*

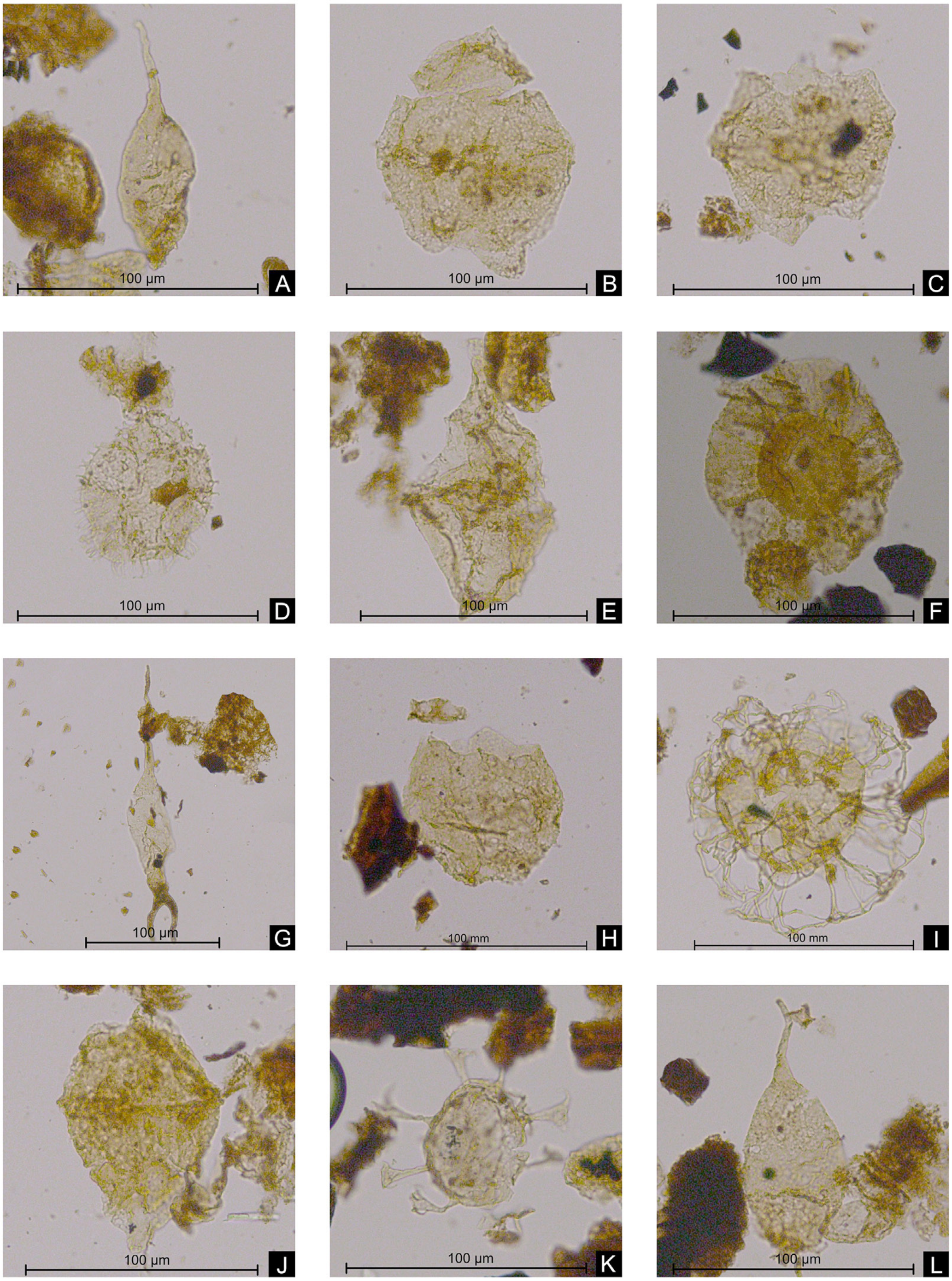

FIG. 3. Biostratigraphically significant dinoflagellate cyst species from the President Beaches Formation, Byers Peninsula, Livingston Island, Antarctica. **A**. *Broomea simplex* (sample BM-2, SU-BM2). **B-C**. *Canningia reticulata* (sample BM-2, SU-BM2). **D**. *Cerbia tabulata* (sample BM-2, SU-BM2). **E**. *Endoscrinium prolatum* (sample BM-2, SU-BM2). **F**. *Heslertonia heslertonensis* (sample BM-2, SU-BM2). **G**. *Batioladinium longicornutum* (sample BM-4, SU-BM4). **H**. *Circulodinium vermiculatum* (sample BM-4, SU-BM4). **I**. *Papuadinium apiculatum* (sample BM-4, SU-BM4). **J**. *Senoniasphaera tabulata* (sample BM-4, SU-BM4). **K**. *Oligosphaeridium complex* (sample BM-8, SU-BM8). **L**. *Batioladinium radiculatum* (sample BM-10, SU-BM 10).

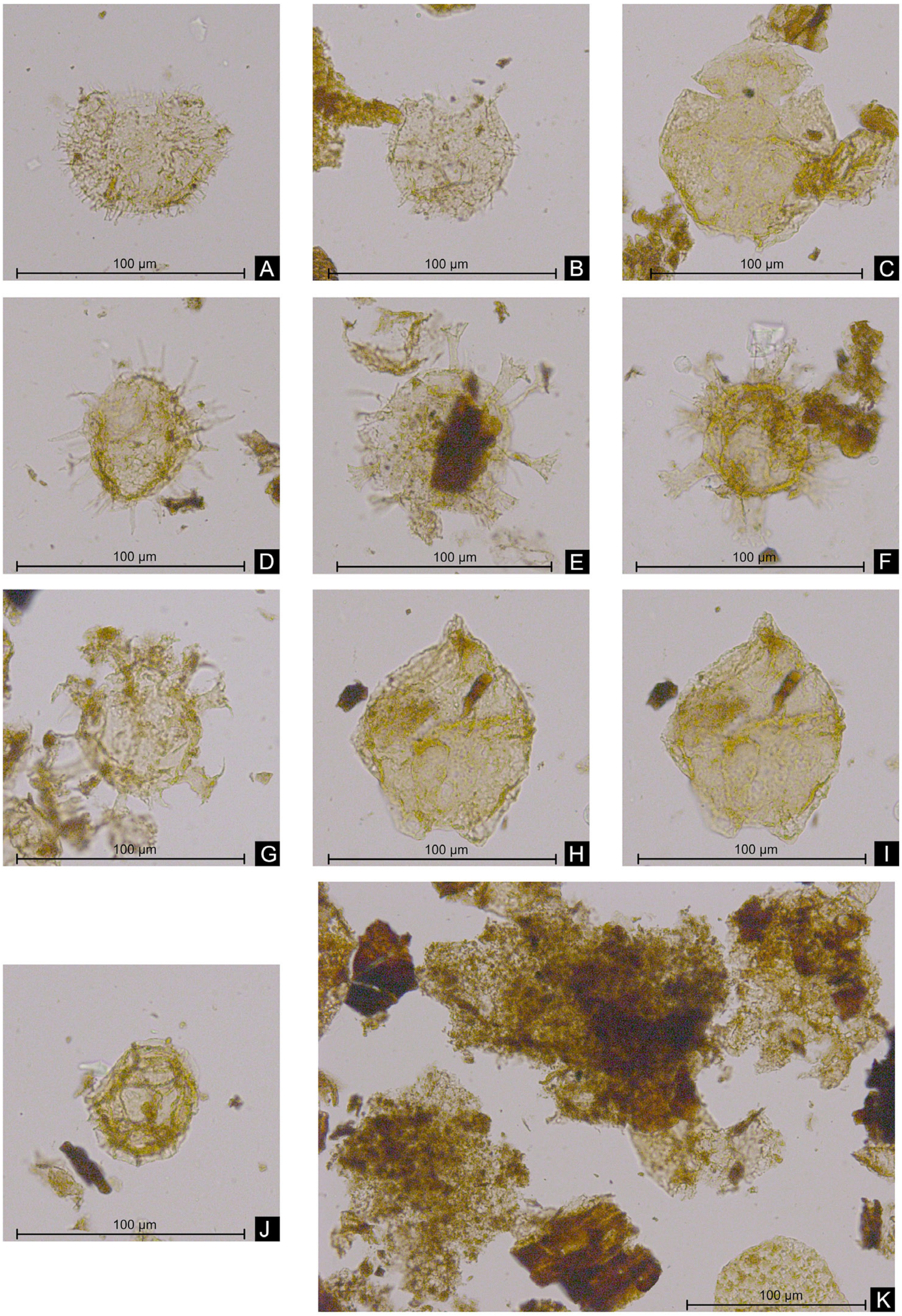

FIG. 4. Biostratigraphically significant dinoflagellate cyst species from the President Beaches Formation, Byers Peninsula, Livingston Island, Antarctica. **A-B**. *Circulodinium deflandrei* (sample BM-10, SU-BM10). **C**. *Circulodinium vermiculatum* (sample BM-10, SU-BM10). **D**. *Hystrichodinium pulchrum* (sample BM-10, SU-BM10). **E-F**. *Kaiwaradinium scrutillinum* (sample BM-10, SU-BM10). **G**. *Oligosphaeridium byersense* (sample BM-4, SU-BM4). **H-I**. *Senoniasphaera tabulata* (sample BM-10, SU-BM10). **J**. *Spiniferites* sp. (sample BM-10, SU-BM10). **K**. Palynofacies with amorphous organic matter (AOM), sample BM-8, SU-BM8.

pulchrum (Fig. 4D); *Kaiwaradinium scrutillinum* (Fig. 4E, F); *Oligosphaeridium byersense* (Fig. 4G); *Oligosphaeridium diluculum*; *Spiniferites* sp. (Fig. 4J); *Exochosphaeridium phragmites*; *Ctenidodinium elegantulum*; *Canninginopsis colliveri*; and *Cassiculosphaeridia delicata*.

Gonyaulacoids dominate dinoflagellate cyst assemblages, most of which show stratigraphical significance. Peridinioid dinoflagellate cysts are common and are mainly represented by species of *Batioladinium* and *Broomea*. Most of the taxa encountered in the assemblages are cosmopolitan, with the exception of *Oligosphaeridium byersense*, which has so far only been recorded from the Byers Peninsula. Spores and pollen grains are encountered in all samples. The spores include examples of *Deltoidospora ordinata*; *Cyathidites australis*; *Cyathidites minor*; *Gleicheniidites senonicus*; and *Cicatricosisporites ludbrookiae*. Gymnosperm pollen is abundant in the assemblages and represented by *Araucariacites australis* and *Alisporites grandis*. *Araucariacites australis* dominates the sporomorph assemblages in all studied samples.

All samples from the PBF section are rich in organic matter (OM). One type of palynofacies covers most intervals of the studied succession and represents approximately the total number of samples (Fig. 4K). The distribution of palynofacies components is illustrated in the ternary AOM-Phytoclast-Palynomorph plot of Tyson (1993) (Fig. 5). The productive samples from the PBF (field numbers BM-2, BM-4, BM-8 and BM-10) contain moderate abundance of phytoclasts (30-50%) with the highest proportion of opaque phytoclasts, but also equidimensional large translucent phytoclasts and a high percentage of AOM (30-40%). Palynomorphs, including dinoflagellate cysts, spores and pollen, comprise up to 30% of the organic components. The ternary plot (Fig. 5) indicates that all samples fall into two distinct but complementary palynofacies fields: VII (distal dysoxic-anoxic shelf) and IV (shelf to basin transition), suggesting therefore a deposition at mid- to distal levels of the low energy dysoxic-anoxic shelf environments (Tyson, 1993, 1995).

5. Discussion

5.1. Dinoflagellate cyst biostratigraphy and age assessment

Dinoflagellate cyst assemblages have been used widely to correlate Cretaceous marine successions across Australia, South America and Antarctica (Backhouse, 1987; Helby *et al*., 1987; Stevens, 1987; Mohr, 1990; Oosting *et al*., 2006; Volkheimer, 2010). While zonal schemes based on diagnostic dinoflagellate cyst events have been developed for the Austral region, notably summarized by Helby *et al*. (2004), a persistent challenge has been the frequent lack of independent age control for these palynological successions. In contrast, several well-calibrated dinoflagellate cyst zonal schemes in the Northern Hemisphere have offered valuable

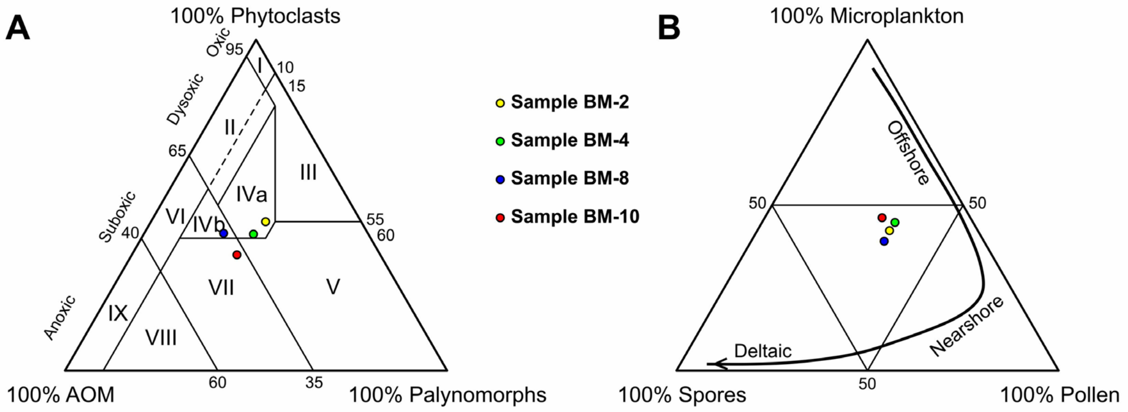

FIG. 5. Palynofacies ternary and palynomorph plots with positions of palynological samples. **A**. AOM-Phytoclast-Palynomorph plot with palynofacies fields of Tyson (1993). Field IV indicates shelf to basin transition. Field VII indicates distal dysoxic-anoxic shelf. **B**. Microplankton-Spore-Pollen ternary plot (after Fedorova, 1977, and Duringer and Doubinger, 1985).

biostratigraphical information for the Lower Cretaceous marine strata (*e.g.*, Hoedemaeker and Leereveld, 1995; Leereveld, 1997; Torricelli, 2000). Specifically, the same sequence of diagnostic dinoflagellate cyst events (first occurrence, FO, or last occurrence, LO) can be found across the Tethyan and Boreal regions, with sound age control provided by ammonite and calpionellid events (Hoedemaeker and Leereveld, 1995; Leereveld, 1997; Torricelli, 2000). Despite some differences among the Lower Cretaceous dinoflagellate cyst zones established for the Austral, Tethyan and Boreal realms, these schemes appear to contain enough cosmopolitan taxa with similar distribution patterns to serve as important interregional correlation markers.

The PBF dinoflagellate cyst association contains several Valanginian interregional marker species, including *Senoniasphaera tabulata*, *Canningia reticulata*, *Cerbia tabulata*, *Kaiwaradinium scrutillinum*, *Spiniferites* sp., and *Oligosphaeridium complex.* Correlation with the Australian Mesozoic palynological zonation proposed by Helby *et al.* (1987) indicates the presence of the *Senoniasphaera tabulata* Interval Zone in our section. This zonal assignment is based on the first occurrences (FOs) of *Senoniasphaera tabulata* and *Canningia reticulata* at the base of the succession, along with their concurrent range with *Cerbia tabulata*, *Kaiwaradinium scrutillinum*, and *Spiniferites* sp. within the sequence. The *S. tabulata* Interval Zone was introduced by Helby *et al.* (1987) for the middle to late Valanginian in Western Australia and Papua New Guinea. Its latest update by Partridge (2006) to the Geologic Time Scale 2004 assigns a late Valanginian age to the zone. The PBF dinoflagellate cyst association also correlates well with the upper Valanginian *Kaiwaradinium scrutillinum* Oppel Zone defined by Backhouse (1987) in the Perth Basin (Western Australia), which commonly features *Kaiwaradinium scrutillinum*, *Senoniasphaera tabulata*, and *Canningia reticulata*.

The FO of representatives of *Spiniferites* sp. and *Oligosphaeridium complex* have been reported from Valanginian strata in both the Northern and Southern hemispheres (Leereveld, 1997). The consistent presence of these taxa in the PBF assemblages is comparable to the dinoflagellate cyst association of the *Spiniferites* spp. Interval Zone, introduced by Leereveld (1997) for the Tethyan realm in the Northern Hemisphere. This assignment is based on the FOs of *Spiniferites* spp. and *Oligosphaeridium complex* at the base of the PBF succession, and their concurrent range with *Cerbia tabulata*, *Canningia reticulata*, *Circulodinium vermiculatum*, and *Heslertonia heslertonensis*, through the section. The *Spiniferites* spp. Interval Zone has a stratigraphical range from lower to lower-upper Valanginian, calibrated to the ammonite and calpionellid zones in the Tethyan and Boreal Early Cretaceous. According to Leereveld (1997), this zone corresponds to the *Cassiculosphaeridia delicata* Zone in Western Australia (Stevens, 1987), and its upper boundary likely falls within the Austral *Senoniasphaera tabulata* Zone of Helby *et al.* (2004). Following these broad correlations, we can confidently assume a middle to late Valanginian age for the sampled interval of the President Beaches Formation.

5.2. Palaeoenvironmental analysis

The composition of the dinoflagellate cyst assemblages from the PBF suggests neritic conditions for the studied succession. This interpretation is primarily supported by the dominance of gonyaulacoid dinoflagellate cysts, particularly the abundance of *Exochosphaeridium* and *Oligosphaeridium* groups, whose representatives are known to thrive in inner- to outer-neritic settings (*e.g.*, Wilpshaar and Leereveld, 1994; Leereveld, 1995, Niechwedowicz *et al.*, 2021). Furthermore, a relatively high C/M ratio, with a predominance of saccate pollen grains among sporomorphs, also points to an offshore location with high terrestrial input into the basin. The high diversity of dinoflagellate cysts, coupled with a subordinate abundance of peridinioids and a comparatively low P/G ratio, suggest normal nutrient availability and the development of a relatively oligotrophic water mass. This is further supported by the rarity of foraminiferal linings, which tend to be more abundant in high-productivity areas including nearshore and upwelling settings (cf. Niechwedowicz *et al.*, 2021). The overall dominance and diverse composition of the dinoflagellate cyst assemblages strongly indicate normal marine salinity conditions.

Palynofacies data support this palaeoenvironmental analysis. The organic matter in every sample is predominantly characterized by opaque phytoclasts, AOM, and abundant dinoflagellate cysts, along with lesser amounts of large translucent phytoclasts, spores and pollen. The opaque phytoclasts are typically equidimensional and medium-sized, rarely lath-shaped.

According to Tyson (1995) and Radmacher *et al.* (2020), a large proportion of equidimensional and rounded opaque phytoclasts indicates a mid-to-distal shelf depositional environment. Moreover, based on the principles of palynofacies analysis, a significant amount of AOM points to a combination of elevated preservation rates and low-energy settings (Tyson, 1993, 1995). The preservation of AOM is directly related to anoxic conditions. Consequently, this palynofacies suggests deposition in a mid-to-distal shelf anoxic environment, characterized by substantial terrestrial input into the basin.

The distribution of palynofacies components is further illustrated using ternary plots: the AOM-Phytoclast-Palynomorph plot of Tyson (1993) and the Microplankton-Spore-Pollen ternary plot (after Fedorova, 1977, and Duringer and Doubinger, 1985) (Fig. 5). Based on the percentages of phytoclast, palynomorph and the AOM, the samples from the PBF plot within two complementary palynofacies fields: IV and VII (Fig. 5A). This distribution suggests deposition occurred in a mid-to-distal dysoxic-anoxic shelf to shelf-to-basin transition (Tyson, 1993, 1995). Palaeoenvironmental interpretations are further developed by plotting the data on the Microplankton-Spore-Pollen diagram. The dominance of the microplankton group, primarily consisting of dinoflagellate cysts, indicates that all samples fall within the offshore field, although a significant terrestrial input is evidenced by the detected pollen and spores (Fig. 5B). Taken together, the inferred settings indicate deposition occurring in a mid-to-distal shelf environment, with concurrently elevated terrestrial input into the basin during the PBF deposition.

The moderate diversity of sporomorphs across all PBF samples indicates fairly varied hinterland vegetation. This land vegetation likely comprised primarily spore-producing pteridophytes and coniferous woodlands, with almost equal proportions of *Araucariacites* and *Podocarpidites*. Given that spore-producing pteridophytes and *Araucariacites* are generally considered to thrive in wet biotopes under warm conditions (cf. Kujau *et al.*, 2013), a warm temperate palaeoclimate characterized by high humidity is proposed for the mid to late Valanginian in the studied area.

5.3. Regional correlations

The dinoflagellate cyst assemblages of the PBF succession exhibit notable similarities with Lower Cretaceous assemblages and zones established in both the Southern Hemisphere (*i.e.*, Australia, New Zealand and South America) and the low palaeolatitudes of the Tethyan realm in the Northern Hemisphere. Crame *et al.* (1993) observed that the terrestrial component of the PBF (spores and pollen) resembled that of the Lower Cretaceous Baqueró Formation in Santa Cruz Province, Argentina, and the Berriasian-Valanginian Springhill Formation within the Magallanes Basin. Their comparison to the Australian Mesozoic palynological zonal scheme by Helby *et al.* (1987) suggested a relationship to the *Fromea cylindrica* Superzone, which spans from Tithonian to early Valanginian. Similarly, Duane (1994, 1996) identified the *F. cylindrica* Superzone in the PBF, but also recognized the *Kalyptea wisemaniae* Interval Zone and the following *Cassiculosphaeridia delicata* Interval Zone within this superzone. Based on similarities with these Australian interval zones and the limited distributions of *Kalyptea wisemaniae*, *Flamingoia cometa*, *Batiacasphaera angularis*, *Apteodinium palliatum*, *Cassiculosphaeridia delicata*, *Endoscrinium prolatum*, and the *Senoniasphaera ptomatis-Canningia reticulata* complex within or at the end of the latest Berriasian in this framework, Duane (1994, 1997) proposed a mid-to-late Berriasian age for the PBF, and a latest Berriasian to early Valanginian age for the Chester Cone Formation. Duane (1996) also noted the common distribution of *Canningia reticulata* and *Canninginopsis* sp. cf. *C. tabulata sensu* Helby *el al.* (1987), in both the PBF and Chester Cone Formation. Crucially, the absence of *Senoniasphaera tabulata* in these assemblages implies an upper age limit of mid-Valanginian for the uppermost marine successions of the Byers Group.

Volkheimer (2010) characterized upper Valanginian-lower Hauterivian dinoflagellate cyst assemblages from the southern Neuquén Basin in Argentina. He compared these with Lower Cretaceous assemblages from central western Argentina, Patagonia, the Antarctic Peninsula and Australia, highlighting a notable taxonomic similarity with those from the PBF. This author further suggested that the dinoflagellate cyst assemblages from the lowermost part of the Agrio Formation (Neuquén Basin) align with elements of the Australian *Muderongia* Superzone. Significant species identified within this late Valanginian to early Hauterivian age interval include *Kaiwaradinium scrutillinum*, *Systematophora areolata*, and *Senoniasphaera tabulata*. The marine dinoflagellate cyst assemblages found in the Agrio Formation at the Estancia Santa Elena site exhibit a cosmopolitan nature, with a majority of species also found in European and Tethyan regions. This cosmopolitan character indicated an open marine connection between the Neuquén Basin, the Tethyan Realm and western/northwestern Europe in the late Valanginian and early Hauterivian. It also suggested a minimal palaeotemperature gradient from the palaeoequator to the poles (Volkheimer, 2010). These interregional connections were further validated by studies examining the correlation of Barremian-Aptian dinoflagellate cyst assemblages across the Tethyan and Austral realms (Oosting *et al*., 2006; Paolillo *et al*., 2018). The dinoflagellate cyst association of the PBF succession documented in this study also largely comprises cosmopolitan species. As previously noted, it correlates well not only with zonal schemes in Australia and South America (specifically, the *Senoniasphaera tabulata* Zone from the Australian Mesozoic and the *Kaiwaradinium scrutillinum* Zone in the Perth Basin, Western Australia), but also with the well-calibrated Tethyan *Spiniferites* spp. Interval Zone.

This broad correlation and the more precise age assessment are enabled by the common distribution of *Spiniferites* spp. and *Oligosphaeridium complex* at the base of this zone, as well as their concurrent range with *Cerbia tabulata*, *Canningia reticulata*, *Circulodinium vermiculatum*, and *Heslertonia heslertonensis*. It is in this context that *Canningia reticulata* and *C. tabulata* are not limited to the latest Berriasian; rather they persist as part of the Valanginian dinoflagellate cyst assemblages alongside characteristic Valanginian species such as *Senoniasphaera tabulata*, *Kaiwaradinium scrutillinum*, *Oligosphaeridium complex*, *Spiniferites* sp., *Circulodinium vermiculatum*, and *Heslertonia heslertonensis*.

5.4. Palaeobiogeographical notes and suggestions on basin evolution

Provincialism is known to depend on the characteristics of water masses and latitudinal gradients, as well as the patterns and relationships of surface water circulation. Dinoflagellate cyst assemblages found in the PBF indicate a noteworthy austral provincialism. The main similarities are observed with the assemblages recorded from the Early Cretaceous in both onshore and offshore Australia, particularly those noted by Helby *et al.* (1987). Furthermore, the relevance of the Lower Cretaceous dinoflagellate cyst zonal frameworks established for Southern Hemisphere successions (Backhouse, 1987; Helby *et al*., 1987; Stevens, 1987; Oosting *et al*., 2006; Volkheimer, 2010) demonstrate possible palaeobiogeographical connections between the Byers assemblages and those from the Austral Realm. Valanginian dinoflagellate cyst assemblages from the PBF appear to contain sufficient proportion of cosmopolitan taxa with similar distribution patterns to serve as markers of interregional correlation. Their affinities are with those from Western Australia and Papua New Guinea (Helby *et al*., 1987), as well as the Perth Basin (Backhouse, 1987), with a common occurrence of the *Canningia-Senoniasphaera* group, a consistent presence of *Senoniasphaera tabulata*, and *Kaiwaradinium scrutillinum*. Additionally, the relative abundance of *Oligosphaeridium* spp., including the very close species *Oligosphaeridium byersense* and *O. quattrocchioae,* along with *Kaiwaradinium scrutillinum*, *Systematophora areolata* and *Senoniasphaera tabulata*, indicates that the Byers palynoflora is also associated with those from southern South America, including north-east Tierra del Fuego and the Neuquén Basin (Quattrocchio *et al*., 2006; Volkheimer, 2010). The South American examples show low to moderate diversity and are dominated by broadly distributed species (*e.g*., *Circulodinium distinctum*, *Cribroperidinium* spp., *Exochosphaeridium* spp., and *Oligosphaeridium complex*) rather than strict southern elements. Valanginian East Gondwanan dinoflagellate cysts suggest probable export of assemblages to the Antarctic/East Gondwanan basins, although more precise calibration is needed to confirm this assumption. Dinoflagellate cysts reveal open marine connections across southern Gondwana during the Valanginian, demonstrating their potential for biostratigraphy and reconstruction of palaeoenvironments.

Represented palynological results are not the only basis for studying marine sediments of the Byers Group. Assemblages of calcareous dinoflagellate cysts were also identified in stratigraphic sections of the Chester Cone Formation located near the succession of interest in this study. They indicated the presence of three Tethyan zones: 1) *Carpistomiosphaera valanginiana* Zone (with a range at the lower part of the upper Valanginian); 2) *Stomiosphaera echinata* Zone (indicating the upper parts of the upper Valanginian and lower Hauterivian); and

3) *Cadosinopsis nowaki* Zone (with a range from the uppermost parts of the upper Valanginian to the lower Hauterivian). Their recognition follows the definitions given by Lakova *et al.* (1999) and Reháková (2000). Our data are most closely related to the *C. valanginiana* and *S. echinata* zones identified in the Neuquén Basin (Kietzmann and Scasso, 2020). Using calcareous dinoflagellate cyst data correlated with the coeval ammonite and calpionellid zones, Kietzmann and Sturlesi (2023) concluded that the *C. valanginiana* Zone corresponds to the lower-upper Valanginian (excluding the lowermost Valanginian), whereas the *S. echinata* Zone conforms to the Hauterivian. However, *Cadosinopsis nowaki* has not been discovered by these authors. The data from Byers can be linked to those from Argentina based on these insights. Therefore, we can assume that in Byers calcareous dinoflagellate cyst associations the *C. valanginiana* Zone covers the Valanginian, and the *S. echinata* and *C. nowaki* zones cover the Hauterivian. Essentially, the Byers Group, in addition to the PBF, corresponds to a broader stratigraphic range than previously considered. This dataset will be featured in an upcoming paper, yet it is noted here to support the palynological evidence without going to deeper details. Taking these data into consideration, we also note that there are no recent observations of the Start Hill Formation because its type area currently has restricted access to field studies. It is however relevant to the determination of the maximum age of marine sediments comprising the Byers Group below and the continental strata covering them above. Hathway and Lomas (1998) provided age estimates from the Start Hill Formation in the range of 143±5 to 128±3 and even 123±4 Ma, which are highly discordant, yet they roughly align with the timeframe obtained from our calcareous dinoflagellate cyst data. In addition, the isotopic age reported by Haase *et al.* (2012) is nearly equivalent. Based on these findings and our working data, we presuppose that the Start Hill Formation is coeval with both the upper levels of the PBF and the Chester Cone Formation, so it may be laterally intercalated within these strata. It is therefore assumed here that the Valanginian-Aptian erosional hiatus between the Chester Cone and Cerro Negro formations was of shorter duration, *i.e.*, early Hauterivian-Aptian. Consequently, it is likely that the uplift of the marine marginal basins, part of the continental island volcanic arc on the western flank of the northern Antarctic Peninsula, suggested by Hathway and Lomas (1998) and widely accepted thereafter, occurred later and more rapidly than previously estimated. A study by Gao *et al.* (2021) revealed the origin and southward translation of the South Shetland Islands from the western margin of the Southern Patagonian-Fuegian Andes between mid-Berriasian and early Albian. Observations of similarities between Australian palynofloras and South American palynofloras support this conclusion. Thus, the succession of the Byers Group can be considered evidence for continental fragmentation and fore-arc basin uplift, which resulted in the expansion of the basin and its association with parts of the Antarctic Peninsula, including the Adelaide and Alexander Islands regions, as suggested by Bastias *et al.* (2020).

6. Conclusions

The President Beaches Formation section on Byers Peninsula (Antarctica), records a continuous siliciclastic succession rich in diverse and well-preserved organic-walled dinoflagellate cyst assemblages, along with gymnosperms and pteridophyte spores. Dinoflagellate cyst analysis enabled the recognition of the *Senoniasphaera tabulata* Interval Zone, dating the sampled succession to the mid-late Valanginian. The analysis of dinoflagellate cyst assemblages further revealed low-energy neritic conditions, characterized by normal marine productivity and nutrient availability, and the development of relatively oligotrophic water mass. Supporting this, a relatively high C/M particle ratio indicates an offshore location with significant terrestrial input into the basin. Palynofacies data consistently support a mid-to-distal shelf depositional environment. Sporomorph diversity reveals a hinterland vegetation primarily composed of pteridophyte-spore producing plants and coniferous forests, with nearly equal proportions of *Araucariacites* and *Podocarpidites*. Based on these findings, we propose a warm temperate climate with high humidity in the studied area.

It is noteworthy that the dinoflagellate cyst assemblages of the President Beaches Formation reflect a notable austral provincialism. Their distribution patterns are similar enough to serve as markers of interregional correlation, since they contain a sufficient proportion of cosmopolitan taxa. They show affinities with Australia and Papua New Guinea, but the relative abundance of *Oligosphaeridium*, *Kaiwaradinium*, *Systematophora*, and *Senoniasphaera* also indicate an association with South America.

Based on the palynological data, along with the calcareous dinocyst data of the covering strata, whose processing is in progress, it appears that the Byers Group corresponds to a broader stratigraphic range than previously thought. Hence, the uplift of the marine marginal basins on the western flank of the northern Antarctic Peninsula, including those in which the marine sediments of the Byers Group were deposited, is likely to have occurred later and more rapidly than previously recognized.

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Appendix

Taxonomic list

Alphabetic list of all dinoflagellate cyst, spore and pollen taxa mentioned in the text and figures.
Araucariacites australis Cookson, 1947
Alisporites grandis (Cookson, 1953) Dettmann, 1963
Batioladinium longicornutum (Alberti, 1961) Brideaux, 1975
Batioladinium radiculatum Davey, 1982
Broomea simplex Cookson and Eisenack, 1958
Canningia pistica Helby, 1987
Canningia reticulata Cookson and Eisenack, 1960
Canninginopsis colliveri (Cookson and Eisenack, 1960) Backhouse, 1987
Cassiculosphaeridia delicata Stover and Helby, 1987
Cerbia tabulata (Davey and Verdier, 1974) Below, 1981
Cicatricosisporites ludbrookiae Dettmann, 1963
Circulodinium deflandrei Alberti, 1961
Circulodinium distinctum (Deflandre and Cookson, 1955) Jansonius, 1986
Circulodinium vermiculatum Stover and Helby, 1987
Cyathidites australis Couper, 1953
Cyathidites minor Couper, 1953
Deltoidospora ordinata Brelie, 1964
Endoscrinium prolatum (Stevens, 1987) Lentin and Williams, 1989
Exochosphaeridium phragmites Davey *et al*., 1966
Gleicheniidites senonicus Ross, 1949
Heslertonia heslertonensis (Neale and Sarjeant, 1962) Sarjeant, 1966
Hystrichodinium pulchrum Deflandre, 1935
Kaiwaradinium scrutillinum Backhouse, 1987
Oligosphaeridium byersense Duane, 1997
Oligosphaeridium complex (White, 1842) Davey and Williams, 1966
Oligosphaeridium diluculum Davey, 1982
Papuadinium apiculatum (Cookson and Eisenack, 1960) Davey, 1988
Senoniasphaera tabulata Backhouse and Helby, 1987
Spiniferites sp.