



GEOSCIENCES

Cretaceous spreite-dominated ichnoassemblages in Antarctica

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Abstract: This study investigates ichnoassemblages characterized by spreite trace fossils from the Upper Cretaceous Snow Hill Island Formation on Vega Island, Antarctica. The succession reveals alternating heterolithic beds of sandy siltstones to very fine- to fine-grained sandstones, suggestive of a deltaic depositional setting influenced by fluctuating energy conditions. The dominance of spreite structures, such as *Paradictyodora antarctica* and *Euflabella*, suggests the prevalence of a colonization window for deposit- or detritus-feeding activity. Notably, the prevalence of *Euflabella* towards the upper levels of the succession, in more proximal and impacted depositional setting, suggests an adaptive strategy for coping with varying food resources, corroborating its role as a trophic generalist. Additionally, the absence of distinct shifts between fully marine and stressed ichnofauna challenges a clear assignation to the *Phycosiphon* or *Rosselia* ichnofacies, although in vertical succession the *Euflabella* dominance in upper levels is related to a lower diverse ichnoassemblage than *Paradictyodora* in lower levels, suggesting some freshwater impact in the top. The occurrence of horizontal and vertical sessile deposit feeding structures would align with the *Rosselia* ichnofacies definition, but the presence of spreite burrows and high ichnodisparity better fits into the *Cruziana* ichnofacies. These spreite-dominated ichnoassemblages are here attributed to *Cruziana* ichnofacies.

Key words: Vega Island, Cape Lamb, Snow Hill Island Formation, *Paradictyodora*, *Euflabella*.

INTRODUCTION

Trace fossils are widely used for paleoenvironmental reconstructions, mainly after the seminal works of Seilacher (1953, 1967), when the concept of ichnofacies emerged. Since then, this paradigm has undergone successive modifications by subsequent authors, resulting in new ichnofacies and ongoing debates concerning their characterization (e.g., Buatois & Mángano 2011, Knaust & Bromley 2012, MacEachern & Bann 2020). Currently, trace fossils have been recognized in almost all depositional settings after the origin of metazoans and its distribution

is a guide to interpret paleoecological parameters and paleodepositional scenarios (Mángano & Buatois 2016, Sedorko & Francischini 2020). In soft ground shallow marine depositional setting, four ichnofacies have been described: the *Skolithos*, the *Phycosiphon*, the *Rosselia*, and the *Cruziana* ichnofacies (e.g., MacEachern & Bann 2020).

The *Cruziana* ichnofacies is referred to as “Seilacherian or archetypical” because it was proposed with the concept of ichnofacies. It is widely recognized in shallow marine settings, above a storm wave base level, during the

Phanerozoic, with a dominance of horizontal deposit and detritus feeding trace fossil, associated with variable ethological categories, high ichnodiversity, and high abundance (MacEachern & Pemberton 1992). It can be argued that the *Cruziana* ichnofacies, as well the *Skolithos* ichnofacies, are the most investigated and recurrent ichnofacies in the trace fossil literature (MacEachern et al. 2010, 2012).

The *Cruziana* ichnofacies in fact includes several variations, which has allowed for the identification of a proximal, archetypal, distal, and depauperated ichnoassemblages in this ichnofacies (MacEachern et al. 2005, Sedorko et al. 2018a, 2019, 2021). The boundaries between these variations are not clear, and new ichnofacies were suggested for assemblages that deviate from the archetypal model (e.g., *Phycosiphon* and *Rosselia* ichnofacies, MacEachern & Bann 2020). Ichnoassemblages dominated by spreite structures such as *Zoophycos*, are often attributed to the *Zoophycos* ichnofacies (Buatois & Mángano 2011), even though the ichnogenus *Zoophycos* can be also a component of the *Cruziana* ichnofacies, especially for Paleozoic records (Zhang et al. 2015, Sedorko et al. 2018b).

Recently, two ichnofacies were proposed for deltaic settings, the *Rosselia* and the *Phycosiphon* ichnofacies (MacEachern & Bann 2020). The *Rosselia* ichnofacies was proposed for sandy delta-front environments, characterized by deposit-feeding behaviors and structures that reflect high sedimentation rates and sporadic deposition. These include equilibration with spreite and escape traces, with occasional marine ichnogenes indicating shifts between stable and stressed conditions. In contrast, the *Phycosiphon* ichnofacies was proposed for muddy prodelta settings, marked by diverse marine trace fossils. These are interspersed with low-diversity traces, reflecting short-term alternations between stable marine

conditions and physico-chemically stressed environments.

Under the Brazilian Antarctic Program (PROANTAR, Simões et al. 2023), the Project PALEOANTAR has carried out fieldwork on the Antarctic Peninsula, obtaining results regarding fossil vertebrates (e.g., Kellner et al. 2019, Souza et al. 2023), including paleohistological analyses (e.g., Brum et al. 2023), invertebrates (e.g., Pinheiro et al. 2020), fossil plants (e.g., Lima et al. 2021, Santos Filho et al. 2023), and microfossils (e.g., Santos et al. 2022). Here, the first contribution focused on trace fossils is presented, opening a new research line of this project. In this study, ichnoassemblages dominated by spreite trace fossils from a Late Cretaceous succession in the Antarctic Peninsula are analyzed, discussing implications for ichnofacies attribution. We interpret the significance of the dominance of spreite structures in the Snow Hill Island Formation on Vega Island based on an integrated sedimentological and ichnological analyses.

Geological Setting

The studied area is located in the Antarctic Peninsula (Fig. 1), specifically in the James Ross Basin (JRB) which is part of the larger Larsen Basin (Macdonald et al. 1988). The basin evolved during the Cretaceous and Paleogene due to southeast-directed subduction of the proto-Pacific Plate (Hathway 2000), resulting in the deposition of approximately 7,000 m of Cretaceous–Paleogene clastic strata (Rinaldi et al. 1978, Olivero et al. 1986, Pirrie 1989, Crame et al. 1991, Pirrie et al. 1991, Olivero 2012, Crame 2019). These strata are divided into three major depositional cycles: the Gustav Group, the Marambio Group, and the Seymour Island Group.

The Gustav Group represents deep marine facies, succeeded by the shallowing up settings of the Marambio Group, likely associated with basin filling, uplift, and sea-level changes

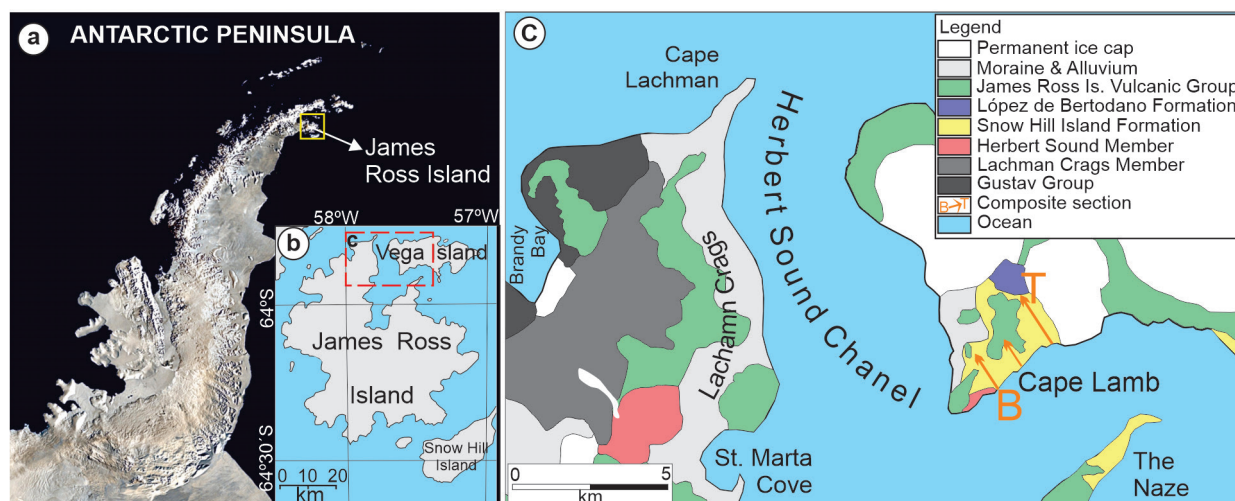


Figure 1. Location of the studied area. a. Position of the studied area in the Antarctic Peninsula. b. Location of Vega Island. c. Cropping out lithological units in part of James Ross Island and Vega Island; the three profiles, part of the composite sections, were located at $63^{\circ}54'15.6''$ S $57^{\circ}35'47.5''$ W; $63^{\circ}53'10.0''$ S $57^{\circ}33'49.22''$ W; and $63^{\circ}53'07.5''$ S $57^{\circ}32'27.8''$ W (orange arrows). Adapted from Pinheiro et al. (2020).

during the Late Cretaceous and early to middle Paleogene (Hathway 2000). The depositional environment extended across a broad shelf, influenced significantly by sea level fluctuations linked to third-order eustatic sea level cycles (Olivero 2012).

The Marambio Group crops out on Vega Island, where the Cape Lamb Member of the Snow Hill Island Formation (SHIF) occurs. This unit is characterized by grayish-green massive, fine-grained muddy sandstones to sandy mudstones with carbonate concretions. Planar lamination is only visible within concretions, which also enhance the visibility of trace fossils (Roberts et al. 2014). The SHIF is overlain by the López de Bertodano Formation. This study focuses on the trace fossil assemblage of SHIF on Vega Island.

MATERIALS AND METHODS

The data acquisition considered an integrated ichno-sedimentological analysis. Trace fossils were photographed and described considering

the level of occurrence and associated sedimentary facies, which also considered texture, physical sedimentary structures, composition, relations of contact, and macrofossil content. Three sedimentologic logs with trace fossil occurrences were prospected, resulting in a composite geological succession for the SHIF in the studied area (Fig. 2).

The trace fossil analysis considered ichnotaxonomic assignment, the tier structure, ichnodiversity, and ichnodisparity for the characterization of the ichnoassemblages (based on the categories of Buatois et al. 2017). Also, the amount of bioturbation (AB) was estimated on a linear scale (Knaust 2012), ranging from 1 (0-20%) to 5 (80-100%).

RESULTS

Three geological successions were examined, resulting in a composite section of the SHIF in the studied area (Figs. 1, 2a). It is dominated by sandy siltstone interbedded with very fine-grained sandstone (Fig. 2b) and is abundant in carbonate

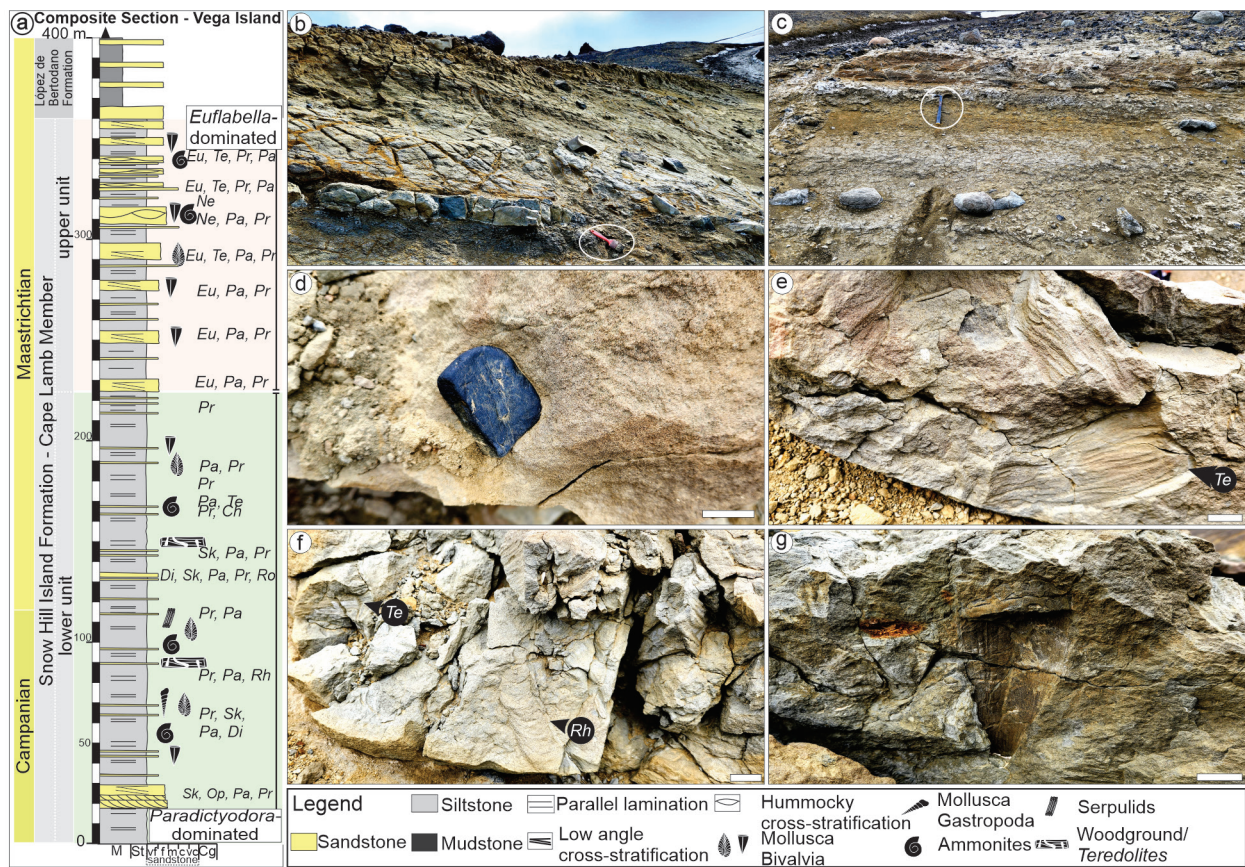


Figure 2. Facies and trace fossil distribution in studied succession. a. Geological composite log section with levels of trace fossil occurrences (Ch=Chondrites, Di=Diplocraterion, Eu=Euflabella, Ne=Nereites, Op=Ophiomorpha, Pa=Palaeophycus, Pr=Paradictyodora, Ro=Rosselia, Sk=Skolithos, Te=Teichichnus); in green the lower unit, mostly representing transitional offshore settings, and in light pink the upper unit mostly representing a prodelta reaching transitional offshore zone. b. Sandy siltstone typical of Snow Hill Island Formation interbedded in the base by a fine-grained sandstone bed. c. Level with concretions within a siltstone bed. d. Pebbles in the silty matrix. e, f. Sandstone beds with spreite-burrows, such as *Teichichnus* (Te) and *Rhizocorallium* (Rh). g. In situ *Pinna* sp. in a sandstone bed. Scale bar = 2cm.

concretions that are frequently fossiliferous (Fig. 2c). The succession shows an upward increase in the occurrence of lenticular beds of sandstone, occasionally with basal erosive contact and containing pebbles (Fig. 2a, d), often displaying hummocky cross-stratification and spreite burrows (Fig. 2e, f). These sandstones are also fossiliferous, including bivalves among other groups (Fig. 2g). In weathered outcrops, the color tends to be rusty-brown, while in fresh expositions it appears gray. The mudstone facies typically exhibit thinly laminated beds with abundant mica flakes, occasionally preserving

thin lenses of rippled or parallel-laminated sandstones. Conversely, the sandstone facies are characterized by massive or low-angle cross-stratified beds, reaching thicknesses of up to 60 cm. Climbing ripples and wave ripples are less common, but present in some sandstone beds, being more frequent to the top. The cyclic package begins with a thin, highly bioturbated siltstone, locally with lenses of wave-rippled sandstone, overlaid by lenticular sandstone locally bearing hummocky cross-stratification.

The poorly consolidated sandy siltstones are often bioturbated, but it is difficult to

specifically identify the trace fossils due to the highly fractured sediment. When trace fossils are visible, they appear as simple vertical or horizontal burrows, which can be tentatively identified as *Skolithos* and *Palaeophycus*, respectively. In these beds, the siltstone occurs as moderately bioturbated, with AB = 3. Concretions are common in these siltstones, and, in addition to several macroinvertebrates, also preserve trace fossils.

Palaeophycus and *Skolithos* occur in the lower part of Cape Lamb Member associated with simple horizontal spreite structures, identified as *Teichichnus rectus* (Fig. 3a). Very small, ramified vertical to oblique structures, identified as *Chondrites* isp. (Fig. 3b) and “U”-shaped vertical structures bearing protusive spreite, identified as *Diplocraterion* can occur associated with whitish, very small meandering burrows with a lining identified as *Macaronichnus* (Fig. 3c, d). U-shaped horizontal burrows are identified as *Rhizocorallium commune* (Fig. 3e). Less common are vertical burrows with a pelleted wall, identified as *Ophiomorpha* (Fig. 3f), and concentrically filled vertical burrows, identified as *Rosselia*. This interval is defined as *Paradictyodora*-dominated (Fig. 2) because of the dominance of burrows bearing a vertical spreite structure with upward enlargement and prismatic-to-conical shape made of subvertical folded laminae, identified as *Paradictyodora antarctica* (Fig. 3g). These traces occur dominantly in moderated bioturbation amount (AB = 3), but can locally reach high intensities (AB = 4-5).

In the basal *Paradictyodora*-dominated interval, ten ichnogenera are present and correspondingly categories of architectural designs (*sensu* Buatois et al. 2017). In these architectural categories, *Chondrites* is defined in the category of “a burrow with shaft or bunch with downwards radiating probes”; *Diplocraterion* as “a vertical single U- or

Y-shaped burrows”; *Ophiomorpha* “as maze and boxwork burrows”; *Macaronichnus* as “a simple actively filled (massive) horizontal to oblique structure”; *Palaeophycus* as “a passively filled horizontal burrow”; *Paradictyodora* as “a burrow with complex vertically oriented spreite”; *Rhizocorallium* as “a burrow with horizontal spreite”; *Rosselia* as “a vertical concentrically filled burrow”; *Skolithos* as “a vertical unbranched burrow”; and *Teichichnus* as “a horizontal burrow with simple vertically oriented spreite”.

In the upper part of the succession, in the informal “upper unit of Cape Lamb Member”, fine-grained sandstones are more frequent. In these sandstones, simple horizontal burrows, identified as *Palaeophycus* isp. and *Palaeophycus striatus* (Fig. 3h) are common. It also occurs an alternating sequence of paired depressions flanked on either side by a diffuse, irregular to lobed surrounding area, identified as *Nereites biserialis* (Fig. 3i). In addition, there are common *Paradictyodora*, but this interval is dominated by horizontal to oblique burrows with single or multiple spreite, including laminae with curved or sigmoidal backfill connected with an oblique to subvertical tube at the base, identified as *Euflabella*. Two morphologies can be recognized for *Euflabella*: one presents a single spreite, typically consisting of folded, subhorizontal to slightly oblique laminae, diverging from a common tube and expanding laterally, referred to as *Euflabella singulari* (Fig. 4a-b), and the other shows a radial arrangement of spreite, with single or folded laminae extending in subhorizontal to oblique directions, identified as *Euflabella radiata* (Fig. 4c-d). Associated to *Euflabella*, it is also present vertical structures with relatively long spreite, identified as *Teichichnus* (Fig. 4e-f). *Paradictyodora antarctica* is subordinated (Fig. 4g) while *Euflabella* and *Teichichnus* dominate in these sandstones from the upper informal member (Fig. 2). Where



Figure 3. Trace fossils from low interval in Vega Island. a. *Teichichnus rectus* (*Te*) in vertical view. b. *Chondrites* isp. (*Ch*) in an oblique view. c. *Diplocraterion* isp. (*Di*) in vertical view. d. *Diplocraterion* isp. (*Di*) and *Macaronichnus* (*Ma*) in vertical view. e. *Rhizocorallium comune* (*Rh*) in horizontal view; f. *Ophiomorpha* (*Op*) and *Skolithos* (*Sk*) in vertical view; g. *Paradiptyodora antarctica* (*Pr*) in vertical view; h. *Palaeophycus striatus* (*Pa*) in horizontal view. i. *Nereites biserialis* (*Nb*) as concave epirelief (bedding plane view). Scale bar = 2 cm.

Euflabella is present, the amount of bioturbation is usually high (AB = 4-5) (Fig. 4h).

In the basal levels of the *Euflabella*-dominated interval, five ichnogenera are present and represent four categories of architectural designs (as defined by Buatois et al. 2017). Both *Euflabella* and *Paradiptyodora* are in the category of “burrows with complex vertically oriented spreite”; *Teichichnus* is “a horizontal burrow with simple vertically oriented spreite”; *Nereites* is “a complex actively filled horizontal structure”; and *Palaeophycus* is “a passively filled horizontal burrow”.

DISCUSSION

The composite section is dominated by sandy siltstone interbedded with very fine- to fine-grained sandstones, locally with hummocky cross-stratification in the upper part of the section. The coarsening upward arrangement and lenticular bodies suggest a lobate form typical of deltaic environments (Macellari 1988, Pirrie 1989, Scasso et al. 1991). The erosion surface at the base of sandstone packages (Fig. 2b, e) along with the presence of wave ripples and their distribution towards the top of the succession, indicates shifting and abandonment of active mouth bar deposition

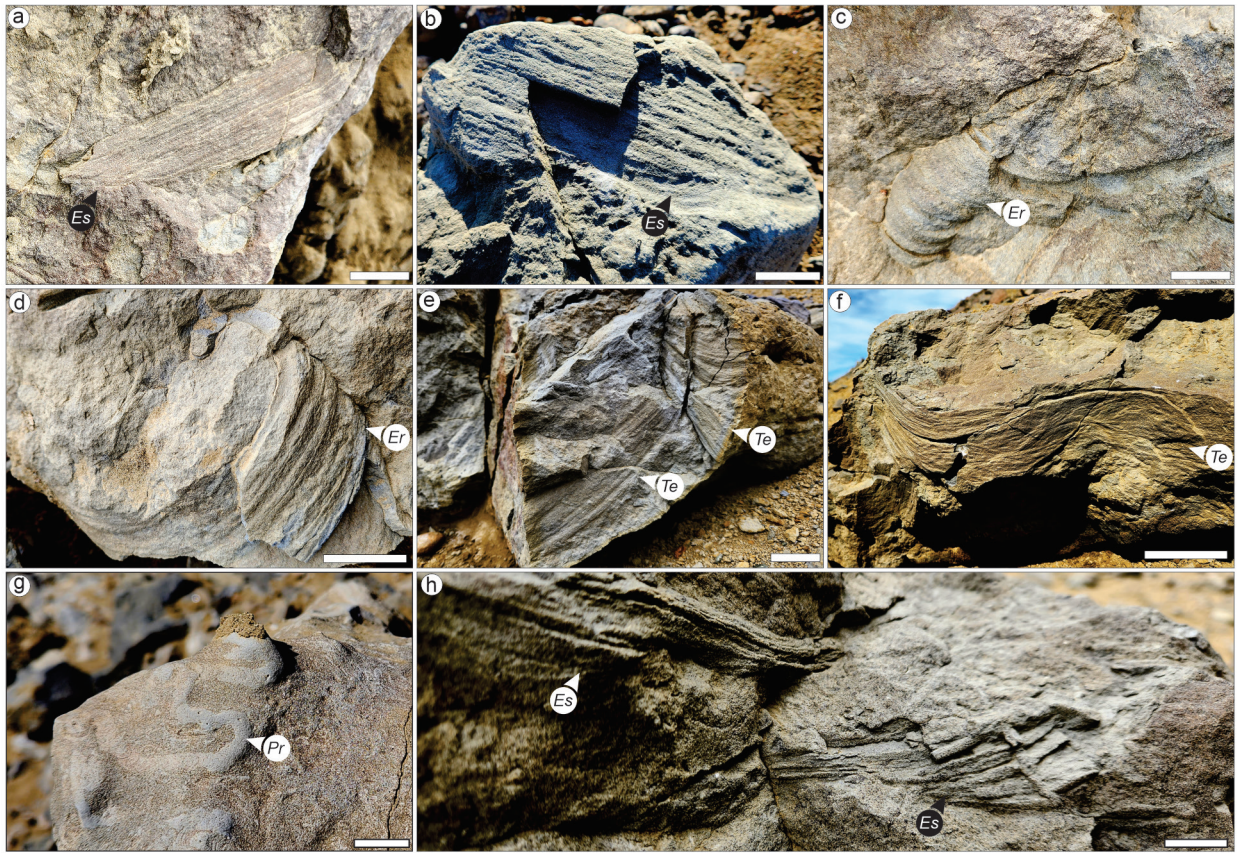


Figure 4. Spreite-dominated beds in upper interval of studied section. a-b. *Euflabella singulari* (Es) in bedding plane view. c-d. *Euflabella radiata* (Er) in bedding plane to slight oblique view. e-f. *Teichichnus rectus* (Te) in vertical view. g. *Paradictyodora antarctica* (Pr) in horizontal views. h. High bioturbated level with *Euflabella singulari* (Es) in bedding plane view. Scale bar = 2 cm.

sites. During abandonment phases, wave action reworked previous sandstone beds, forming erosion surfaces and basal sandstone layers (Bhattacharya 2006). The lack of fluvial delta plain deposits between successive packages suggests a permanent subaqueous deposition (Bhattacharya 2006). Thus, the alternating beds of bioturbated siltstones and sandstones suggests the interplay of depositional processes in a deltaic setting, as inferred from the cyclical stacking pattern observed within the formation (Olivero et al. 2008). Additionally, there is a rich fossil assemblage within concretionary horizons indicating marine conditions, including ammonites, bivalves, gastropods, echinoderms, and decapod crustaceans (Roberts et al. 2014).

Noteworthy among these are the ammonites *Gunnarites antarcticus* and bivalves such as *Lahillia*, *Modiolus*, and *Pinna* (Fig. 2g). *Pinna* is very common in these beds (Pirrie et al. 1991, Olivero 2012).

In the basal informal unit, a transitional offshore setting in a prodelta depositional scenario thus predominates, with a lesser influence of sandy bodies (Fig. 5). In these beds, the ichnoassemblage is dominated by the spreite burrows *Paradictyodora antarctica* and *Teichichnus rectus*, with the subordinated presence of *Chondrites*, *Diplocraterion*, *Macaronichnus*, *Ophiomorpha*, *Palaeophycus*, *Rosselia*, *Rhizocorallium*, and *Skolithos*. The mixture of shallow-, mid-, and deep-tier trace

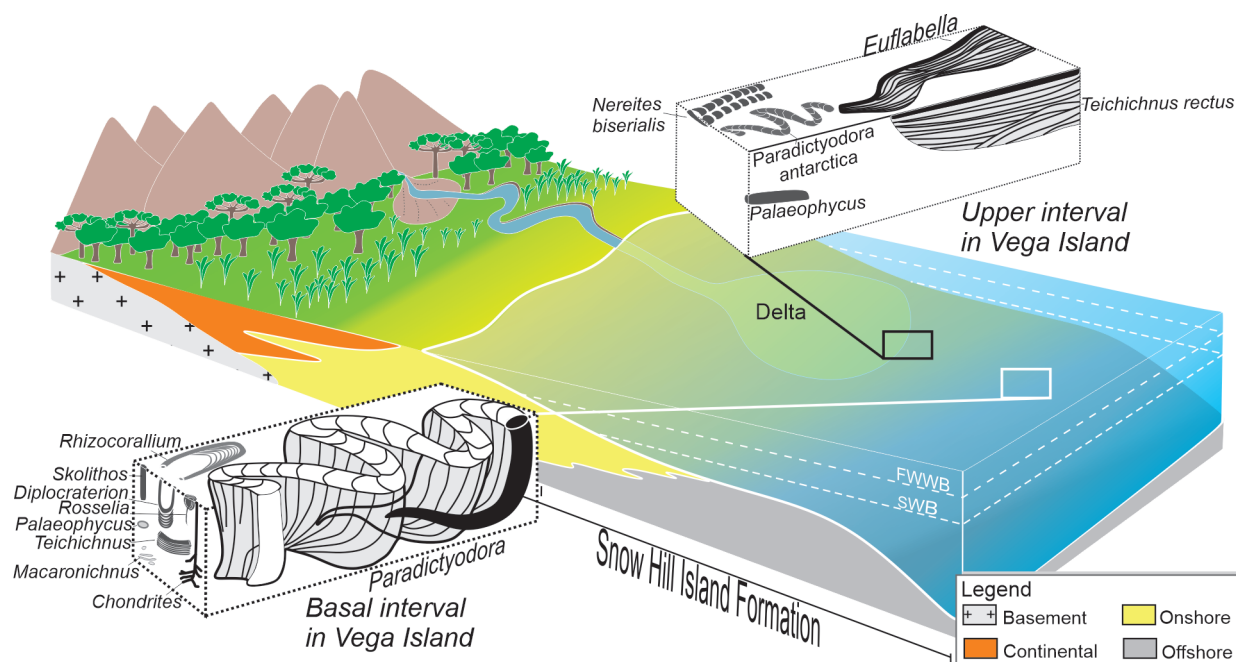


Figure 5. Reconstruction of depositional environment represented in the Snow Hill Island Formation by dominance of *Paradiptyodora* in the base and *Euflabella* to the top of the unit, composing a *Cruziana* ichnofacies. *Paradiptyodora* morphology inspired in Olivero et al. (2004). FWWB = Fair-weather wave base; SWB = Storm wave base.

fossils, associated with different ethological categories supports the assignment for this ichnoassemblage to the *Cruziana* ichnofacies, as has been previously done (e.g., Olivero & Cabrera 2013). The presence of ten categories of architectural designs (*sensu* Buatois et al. 2017), characterizing a high ichnodiversity, corroborates this attribution.

The overlying beds of the informal upper unit of Cape Lamb Member, in contrast, are dominated by sandy bodies representing a prodelta to delta front, where mainly characterized by *Euflabella* and a lower diverse ichnoassemblage (Fig. 5). An unconformity was proposed for this interval, placed in a conglomerate bed that would separate the informal lower and upper units (Olivero 2012). In these layers, *Teichichnus*, *Nereites*, *Palaeophycus*, and *Paradiptyodora* are also present. The behavior associated to biserial arrangement in *Nereites biserialis* is unexplained. It likely aids in feeding in

nutrient-rich sediments, possibly requiring extra space in the tunnel for waste disposal. Sideways movement may also aid in respiration (Olivero & Cabrera 2016). These ichnogenera are here representing four categories of architectural designs (*sensu* Buatois et al. 2017), what might be assumed as depauperated expressions of the *Cruziana* ichnofacies (MacEachern et al. 2010).

Euflabella and *Paradiptyodora* are uncommon trace fossils, being reported for few localities. In Tierra del Fuego, *Euflabella singularis* and *E. radiata* are prevalent in shelfal fine-grained silty sandstones, indicative of relatively low-energy conditions within the depositional environment. Particularly, *E. singularis* dominates in organic-rich, storm-influenced to offshore deposits (Olivero & Cabrera 2013). On the other hand, *E. radiata* is prominent in fine-grained sandstones interpreted as event beds in a shelf setting or at the base of prodelta parasequences, occasionally found in prodelta thin-bedded alternations

or distal subtidal settings (Olivero & Cabrera 2013). Conversely, *Paradictyodora* in Tierra del Fuego mostly occurs in fodinichnia-dominated ichnocoenosis within basinal fan delta systems characterized by sporadic low energy conditions and low sedimentation rates, possibly featuring disaerobic or poorly oxygenated bottoms. In the Santa Marta Formation, however, this ichnogenus occurs in deposits interpreted as delta slope and distal subaqueous delta platform (Olivero et al. 2004).

Recently, two new ichnofacies were proposed for delta settings, the *Phycosiphon* and the *Rosselia* ichnofacies (MacEachern & Bann 2020). The *Phycosiphon* ichnofacies is characterized by diverse marine trace-fossil associations intercalated with low-diversity suites, reflecting recurrent shifts between stable marine conditions and physico-chemically stressed environments triggered by fluctuations in fluvial influence and other shallow marine agents (wave, storms, tides). The *Rosselia* ichnofacies also reflects recurrent alternations between stable marine conditions and physico-chemically stressed environments, but with a prevalence of deposit feeding and equilibrium ethologic categories in sandy substrates (MacEachern & Bann 2020).

In the studied succession, it is not clear if there is an alternation between fully marine and impoverished ichnofauna, as expected for the *Phycosiphon* and *Rosselia* ichnofacies (MacEachern & Bann 2020), probably because the visualization of trace fossils was not favored in the siltstone facies (e.g., Savrda 2007). The overall dominance of spreite burrows in the Cape Lamb Member at Vega Island, however, suggests a colonization window from detritus- or deposit-feeding activity in this deltaic paleoenvironment, mainly for upper beds dominated by *Euflabella*, where suspension-feeding habits are absent. This scenario could fit in the definition of the

Rosselia ichnofacies, however, the absence of fugichnia/equilibrichnia structures precludes this attribution. Additionally, the dominance of spreite burrows is not part of the definition of *Rosselia* ichnofacies (MacEachern & Bann 2020).

Another point is that the vertical replacement observed in the prograding section, transitioning from a *Paradictyodora*-dominated to an *Euflabella*-dominated succession, appears to be driven by the slight differing ecological strategies employed by these tracemakers. *Paradictyodora* likely dominates in a more stable, deeper-water prodeltaic setting where sedimentation rates were relatively constant. *Euflabella* seems to be exhibiting a more opportunistic behavior suited to exploit proximal, impacted deltaic settings. *Euflabella*, with its diverse spreite burrows extending in subhorizontal to oblique directions, appears to have adapted to the dynamic conditions of shallower, proximal deltaic environments, where fluctuating river discharge and sediment supply create a patchy, resource-rich landscape. Furthermore, the increase in *Euflabella* occurrences towards the upper levels of the Cape Lamb Member supports the interpretation that *Euflabella* represents a trophic generalist tracemaker, adapted for deposit- or detritus-feeding activity. This adaptation allows it to prospect the substrate amidst varying food resources (Olivero & Cabrera 2013).

CONCLUSIONS

The proposal of the *Rosselia* and *Phycosiphon* ichnofacies reflects ongoing efforts to refine our understanding of deltaic settings and their trace fossil associations. In the Upper Cretaceous succession of the Antarctic Peninsula's Snow Hill Island Formation, the dominance of spreite burrows suggest the prevalence of a colonization window for detritus- or deposit-feeding activity,

but it is part of the *Cruziana* ichnofacies. The vertical replacement in a prograding section, from a *Paradictyodora* dominated to an *Euflabella* dominated succession seems to be related to the more opportunistic behavior reflected by the latter, which would better exploit proximal, impacted deltaic paleoenvironments.

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Author contributions

D.S. conceived of the presented idea. D.S., C.G., P.J.P., R.C. and J.H.N. presented ichnological descriptions and discussions. D.S., L.C.W., and M.G. provided geological characterization. D.S., J.M.S., and A.K. provided financial support. All authors discussed the results and contributed to the final manuscript.

