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PALEONTOLOGY

Paleoenvironment of the Cerro Negro Formation (Aptian, Early Cretaceous) of Snow Island, Antarctic Peninsula

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Abstract: A study of macro and microfacies, palynoflora and palynofacies of the non-marine Cerro Negro Formation at President Head Peninsula, Snow Island, northwest of the Antarctic Peninsula, was developed. Two assemblages were recognized: Palynofacies assemblage 1 (P1) at the base of the section with a dominance of fern spores and conifer pollen grains, and facies association consisting of a clastic layer, with the predominance of mudstones; and Palynofacies assemblage 2 (P2) at the top of the section, with remarkable abundance of AOM/Pseudoamorphous particles, associated with facies that includes tuffs. The complete section shows in some levels the presence of freshwater algae and translucent phytoclasts. The integrated data characterizes a fluvial-lacustrine environment, what is reinforced by the occurrence of freshwater algae (*Botryococcus*) in some levels of P1 and P2. We could verify an increase in volcanic activity towards the top of the section that apparently has played an important role in the collapse of the palynoflora. The occurrence of the spore species *Muricingulisporis annulatus*, *Sotasporites elegans*, *S. triangularis*, *Foraminisporis wonthaggiensis,* and *F. asymmetricus* in the Cerro Negro Formation allows the correlation with sections in South America and Australia, suggesting an Aptian age for these deposits.

Key words: Antarctica, Cretaceous, palynology, sedimentology, geochemistry.

INTRODUCTION

Snow Island is part of the South Shetland Archipelago, with a northeast orientation along the Pacific margin of the Antarctic Peninsula, and is largely covered by permanent ice. Outcrops of this island are mainly restricted to the President Head Peninsula. The geology of this area has been described as a volcano-sedimentary sequence that comprises thin sandstone interlayers and thick layers of conglomerates, and calcareous concretions. Two sedimentary units can be recognized, albeit the contact between them does not outcrop: a lower marine unit, overlain by upper volcanic-influenced continental strata (Israel 2015). The lower marine sedimentary unit is restricted to a small-exposed area at the central portion to the western of the Peninsula, near the permanent glacier. This marine deposit consists of ammonite-bearing mudstone, shale, sandstone and breccia strata, which have been litho- and paleontologically correlated with the Sealer Hill Member of Chester Cone Formation at Byers Peninsula, Livingston Island (Crame et al. 1993, Philippe et al. 1995, Duane 1996, Hathway & Lomas 1998). The upper non-marine volcaniclastic unit is more extensive across

President Head Peninsula, and is composed of plant-bearing mudstones, shales, sandstones, conglomerates, and tuffs (Israel 2015). Based on the flora content, these non-marine strata have been correlated with the volcaniclastic Cerro Negro Formation from Byers Peninsula at Livingston Island (Torres et al. 1997a, b, Cantrill 1998). Several hypabyssal, mostly doleritic, intrusive bodies such as sills and stocks outcrop in the Peninsula (Israel 2015), and their age based on whole-rock dating is Eocene (Pankhurst & Smellie 1983, Watts et al. 1984). The Cerro Negro Formation at Byers Peninsula is predominantly composed of plant-bearing pyroclastic and sedimentary rocks that were deposited in a fluvio-lacustrine environment.

The Early Cretaceous paleoflora of Snow Island is dominated by ferns and conifers (Torres et al. 1995, 1997a, Cantrill 2000) and other gymnosperms as Bennetitales (Falcon-Lang & Cantrill 2002). The palynology data from President Head (Snow Island) allows a correlation with sediments from the Byers Peninsula, in Livingston Island, and with palynological assemblages from Western Australia and South America (Duane 1996, Torres et al. 1997a).

Although the macroflora and palynoflora from President Head Peninsula are fairly well known (e.g., Philippe et al. 1995, Duane 1996, Torres et al. 1997a,b, Cantrill 1998, 2000, Césari et al. 1998, 1999, Hathway et al. 1999), there is no study of the palynofacies nor the geochemical features of the volcaniclastic rocks. Also, the petrologic processes in these deposits have not been examined in detail. Aiming a paleoenvironmental reconstitution of the Aptian deposits of President Head Peninsula at Snow Island, in the present study we analyze the palynological and palynofacies information and integrate it with the sedimentology and geochemistry data.

Geology and stratigraphy background

The South Shetland Islands is an ENE–WSW oriented archipelago of ca. 450 km in length (Fig. 1), which constitute part of the geological Western Domain of the Antarctic Peninsula (Vaughan & Storey 2000). It is a crustal block delimited by the South Shetland Trench to the northwest and by an axis of spreading ridge in the Bransfield Strait to the southeast (Galindo-Zaldívar et al. 1996). According to Birkenmajer (1994), the geological history of the Pacific margin of the northern Antarctic Peninsula includes a first stage of marginal basin deposition (?Permian–Triassic), the Gondwanian orogeny (Late Triassic?), a subduction stage (Middle Jurassic–Miocene) during which the inner Antarctic Peninsula and the outer South Shetland Islands magmatic arcs were formed, and the opening of the Bransfield Strait that separates these two magmatic arcs. The Bransfield Strait is a back-arc basin that evolved through rifting and spreading and probably began to open due to significant transtensional effects after the activity of the West Scotia Ridge ceased at ca. 7 Ma. This is thought to be due to Phoenix Plate roll-back under the South Shetland Islands after cessation of the spreading activity of the Phoenix Ridge at ca. 3.3 Ma (Solari et al. 2008).

The South Shetland Islands magmatic arc is founded on a sialic basement of schists and metasedimentary rocks (Smellie et al. 1984). In the western South Shetland Islands the Byers Group is exposed and comprises a thick succession recording Late Jurassic–Early Cretaceous sedimentation and volcanism (Hathway & Lomas 1998). The Byers Group on Byers Peninsula (Livingston Island) is composed of at least 1.3 km of marine clastic rocks, overlain by about 1.4 km of Lower Cretaceous non-marine volcaniclastic strata which record the expansion of the continental-arc facies into a marine intra-arc basin (Hathway 1997). Nevertheless, a

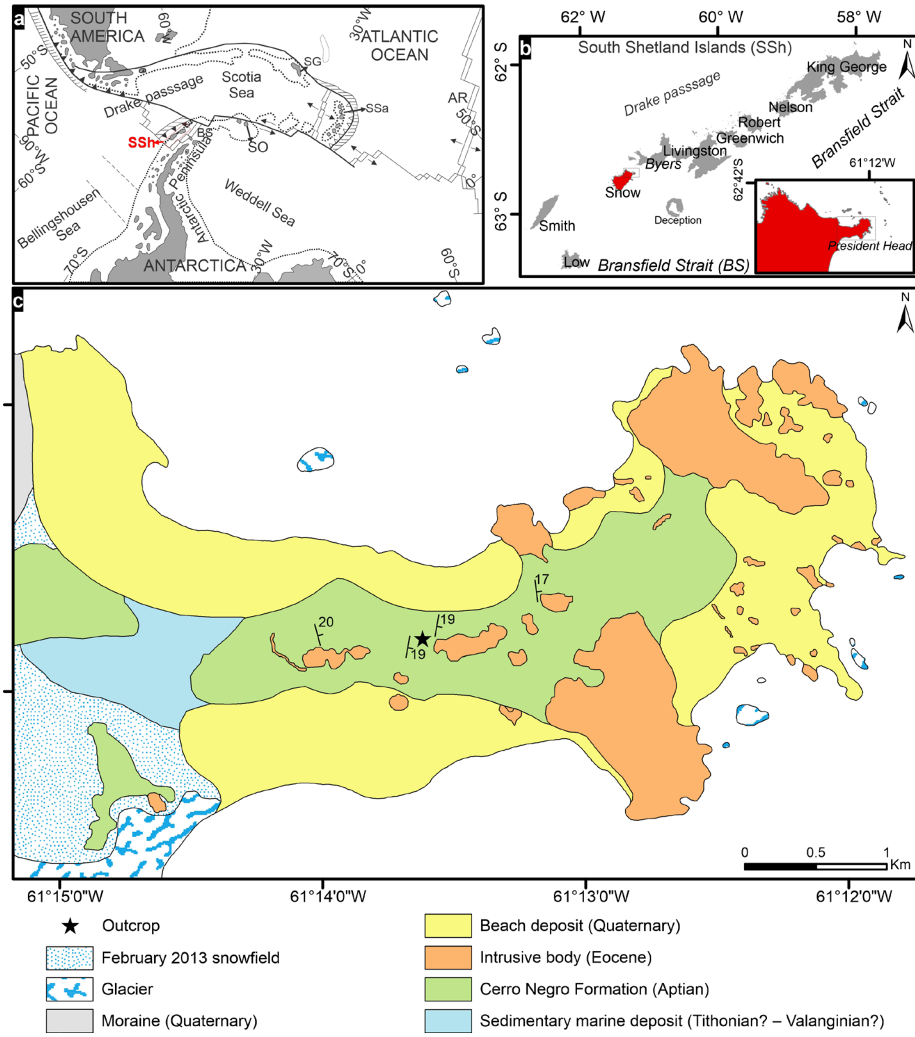

Figure 1. Location of President Head Peninsula, Snow Island. a) Plate tectonic position of the northern Antarctic Peninsula at the present day (adapted from Birkenmajer 1994); AR: Atlantic Ridge, BS: Bransfield Strait, SSa: South Sandwich Islands, SG: South Georgia Islands, SSh: South Shetland Islands, SO: South Orkneys Islands. b) Geographic map positioning the President Head Peninsula, Snow Island at the South Shetland Islands Archipelago, metadata obtained from the Antarctica Digital Database Mapping Services SCAR https://www.add.scar.org/. c) Geological map of President Head Peninsula, indicating the studied section of the Cerro Negro Formation (adapted from Israel 2015).

fore-arc configuration has also been proposed as an alternative of the depositional environment (Crame et al. 1993, Bastias et al. 2020). Rocks of the Byers Group are also exposed on the nearby Rugged Island, at President Head Peninsula in Snow Island (Smellie et al. 1984, Crame et al. 1993, Hathway & Lomas 1998), and to the most southwestern South Shetland Islands at Cape Wallace in Low Island (Bastias et al. 2020). At the base of the Byers Group, deep-marine strata of the Kimmeridgian–Tithonian Anchorage Formation and the Berriasian President Beaches Formation are overlain by Berriasian–Valanginian shallower-marine deposits of the Chester Cone Formation and the volcanic breccias of the Start Hill Formation. These deposits are separated from the Aptian non-marine volcaniclastic rocks of the Cerro Negro Formation at the top by an unconformity (Hathway & Lomas 1998).

The non-marine volcaniclastic Cerro Negro Formation was formally defined by Hathway (1997) and is exposed on the eastern Byers Peninsula (Livingston Island), where it is broadly equivalent to the Volcanic Member of Smellie et al. (1980). This formation dips gently and becomes younger to the ENE. Hathway (1997) divided the non-marine volcaniclastic Cerro Formation strata into two informal units. The lower division consists mainly of welded and non-welded ignimbrites, intercalated with subordinate reworked silicic pyroclastic and epiclastic strata. The upper division consists mainly of poorly sorted, basaltic lapilli-tuffs and tuffaceous breccias. The unit consists largely of primary pyroclastic strata and syn-eruption debris- and flood-flow deposits, but the subordinate conglomerates, sandstones and mudstones record inter-eruption fluvial-lacustrine deposition (Hathway & Lomas 1998).

The main controls on deposition of the Cerro Negro Formation were volcanism and perpendicular extension to the trend of the Antarctic Peninsula arc manifested in the emplacement of a dike swarm, and in syn-sedimentary faulting resulting from differential subsidence, suggesting that the Cerro Negro Formation depocenter was probably fault-bounded (Hathway 1997). Plagioclase and biotite $^{40}Ar/^{39}Ar$ geochronology from lower silicic pyroclast beds and from a welded ignimbrite close to the topmost indicates an Aptian age (between 120.3 ± 2.2 and 119.4 ± 0.6 Ma) for the Cerro Negro Formation, agreeing with the palynomorph taxa relative dating (Hathway et al. 1999).

MATERIALS AND METHODS

The studied material was collected by the PALEOANTAR team from President Head Peninsula, Snow Island in the austral summer of 2017, during the 35th Antarctic Operation (OPERANTAR XXXV), supported by the Brazilian Antarctic Program (PROANTAR). The PALEOANTAR project that has been working in the Antarctic Peninsula for the last years (e.g., Kellner et al. 2019).

Due to the glacier deposits, snow cover and regolith, outcrops at the President Head Peninsula (Fig. 2) are scarce and discontinuous, impeding the establishment of a continuous stratigraphic profile. Three stratigraphic profile intervals were measured, described and joined to build up a stratigraphic composite profile (Fig. 3). Section A (0 to 5.5 m) and section B (7.7 to 9.13 m) were separated by 6 m, and section B and section C (19.11 to 29.64 m) by 29 m. The strata bedding displays NNE-SSW trending strike and a dip of 19° to SE. A total of 27 samples were collected for palynology, microfacies, and whole-rock geochemistry. Additional data is available on-line (https://doi.org/10.5281/zenodo.5140569).

Major oxides and some trace elements of collected samples were determined using X-ray fluorescence (XRF). Each sample was oven dried at 100°C. A portion of the dried sample was taken to a muffle at 1000°C for two hours to determine the loss on fire. Another portion of the dried sample was melted using lithium

Figure 2. Outcrop photographs. a) General view of the studied area that is mostly covered by regolith. b) Stratigraphic profiling process.

tetraborate. Chemical analyses of fused beads were performed using a Rigaku X-Ray Fluorescence Spectrometer model ZSX Primus II equip with a Rh tube and seven analyzer crystals by the calibration curve method based on international references material at the Nucleus for Geochemical Studies and Stable Isotopes Laboratory (NEG-LABISE), Federal University of Pernambuco (UFPE), Recife, Brazil. The petrographic data are based on 12 standard thin sections prepared by GEOLAB Geology Solutions Company, Olinda, Brazil.

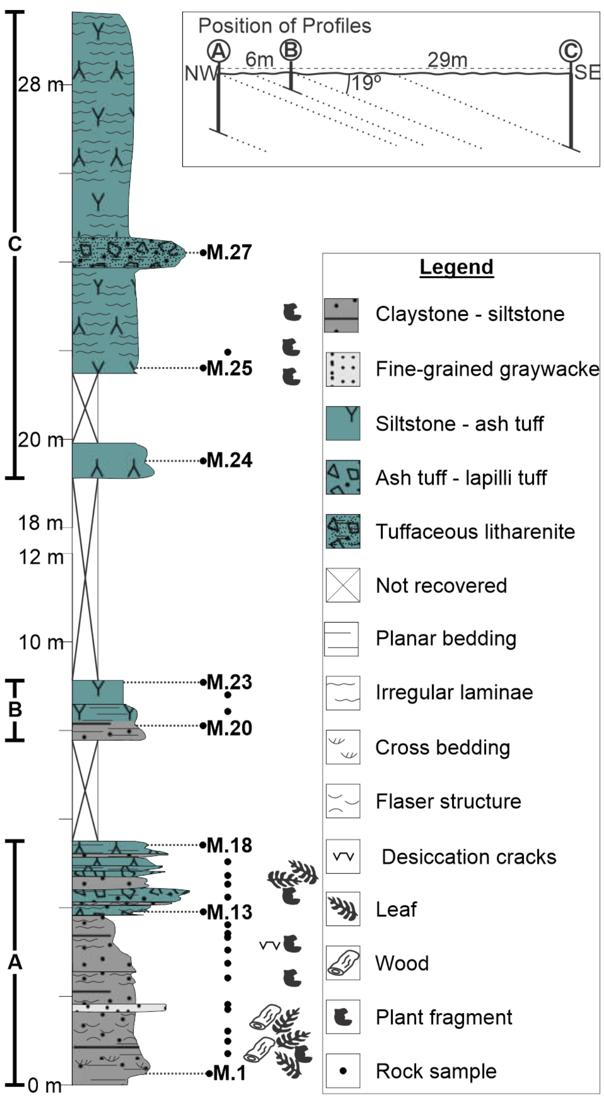

Figure 3. Composite lithostratigraphic profile of the Cerro Negro Formation in the north-central portion of the President Head Peninsula, Snow Island.

A total of 26 samples from an outcrop on Snow Island were processed (~40 g) using standard palynological techniques to dissolve the mineral constituents at the Instituto tecnológico de Paleoceanografia e Mudanças Climáticas (itt Oceaneon), UNISINOS University. This approach was compiled by Wood et al. (1996) and non-oxidative procedures described by Tyson (1995) and Mendonça Filho et al. (2011). The palynological slides are deposited in the LMA (Laboratório de Micropaleontologia Aplicada), at the Federal University of Pernambuco, Brazil, under the collection numbers LMA-P00001–P00026.

The palynological slides were analyzed using transmitted white light and incident blue light/UV fluorescence mode, under a Zeiss-Imager A2 optical microscope, 200X, 630X and 1000X magnification. In each sample, ~300 palynomorphs were counted for palynology and 500 particles for palynofacies (when possible). For a statistical treatment, only samples with more than 400 particles for the palynofacies were used, as well as samples with more than 100 palynomorphs for the palynoflora (SM-1 and SM-2). The raw, percentage and normalized data are presented in the Supplementary Material (SM-1 and SM-2, https://doi.org/10.5281/zenodo.5140569).

The material consists of 5504 palynomorphs (see SM-1). A rarefaction curve was constructed using the PAST software (Hammer et al. 2001) to determine whether most species recovered were enough by combining data from the samples (Gotelli & Colwell 2001).

The palynofacies classification was based on the composition and abundance percentages of the sedimentary organic matter (SOM) (Tyson 1995, Mendonça Filho et al. 2010), The paleoenvironmental inference was based on the application of multivariate statistics and ecological indexes in the studied samples. Cluster analysis was used to identify compositional similarities between SOM (phytoclasts, Amorphous Organic Matter (AOM) and palynomorphs) from different depositional settings. This analysis was employed using agglomerative, hierarchical clustering and stratigraphically constrained cluster analysis (CONISS) to establish groupings of samples (Grimm 1987), displayed in a dendrogram. The kerogen was represented in Ternary graphic (Tyson 1993, 1995), plotted using the PAST software (Hammer et al. 2001). The principal component analysis (PCA) with varimax rotation was performed using the statistical software PAST (Hammer et al. 2001). For this analysis, the raw data were standardized, and each variable was transformed, according to Gotelli & Ellison (2011) (see SM-1 and SM-2). In this study, were the PC loadings >0.2 to palynoflora, and >0.4 to palynofacies. PC scores >5 to palynoflora were assigned to dominant taxa and PC scores between 1 to 5 to associated flora. As for palynofacies, PC scores >1 are dominant elements and 0,5 to 1 significant-associated (SM-2).

Diversity (Shannon-Wiener), dominance (Simpson) and equity (Eveness) indexes for palynoflora were calculated using the PAST software (Hammer et al. 2001). An x^2 -test was used for sedimentary organic matter to determine which paleoenvironment was preferred, calculated on the MedCalc software.

RESULTS

Sedimentological and geochemical characterization

The composite stratigraphic profile at President Head Peninsula is ~ 30 m thick, constitutes a fine to medium-grained clastic and volcaniclastic deposit with abundant plant fossils (Fig. 3). Six lithofacies were grouped into two associations, one of clearly clastic origin and the second with volcanic influence.

Within the first 4 m from the base to the top, a clastic layer without volcanic influence constitutes the first facies association, where mudstones without volcanic components predominate. Organic-rich claystone are interspersed in a planar-bedding pattern (Figs. 4a–b) with laminated siltstone to fine-grained quartzarenite, abundant kerogen clasts are observed in these facies (Figs. 5a–b, e–f). To the middle of the pelitic interval, a medium- to coarse-grained graywacke with low angle cross-lamination and abundant subangular to subrounded rhyodacite lithic fragments (Figs. 4a; 5c–d) is intercalated. Massive siltstones are found to the base and to the top of this interval (Fig. 4e).

The second association is characterized by volcaniclastic facies. From ~ 3.9 m upward to ~ 30 m, excluding the regolith-covered intervals which were not recovered, welded fine- to coarse-grained ash tuff, siltstone and lapilli tuff beds are intercalated (Figs. 4c–d, f–i; 5f-p). The tuff levels display well-preserved volcanic components including welded pyrogenic ash forming the matrix, pumice and angular to subangular plagioclase and quartz crystals up to > 3 mm sized, vesicles and oriented volcanic glass shards. Palagonite is observed filling amygdales and as alteration of the matrix glass. Most of the tuff levels are matrix-supported but to the top of the section contains a clast-supported tuffaceous litharenite with pyrogenic crystals as well as subrounded to rounded rhyodacite lithic fragments. In these facies are also present kerogen clasts, as amorphous and as structured grains.

Twenty-seven samples were classified by combining information from the major element whole rock geochemistry (Table I) together with macroscopic and petrographic

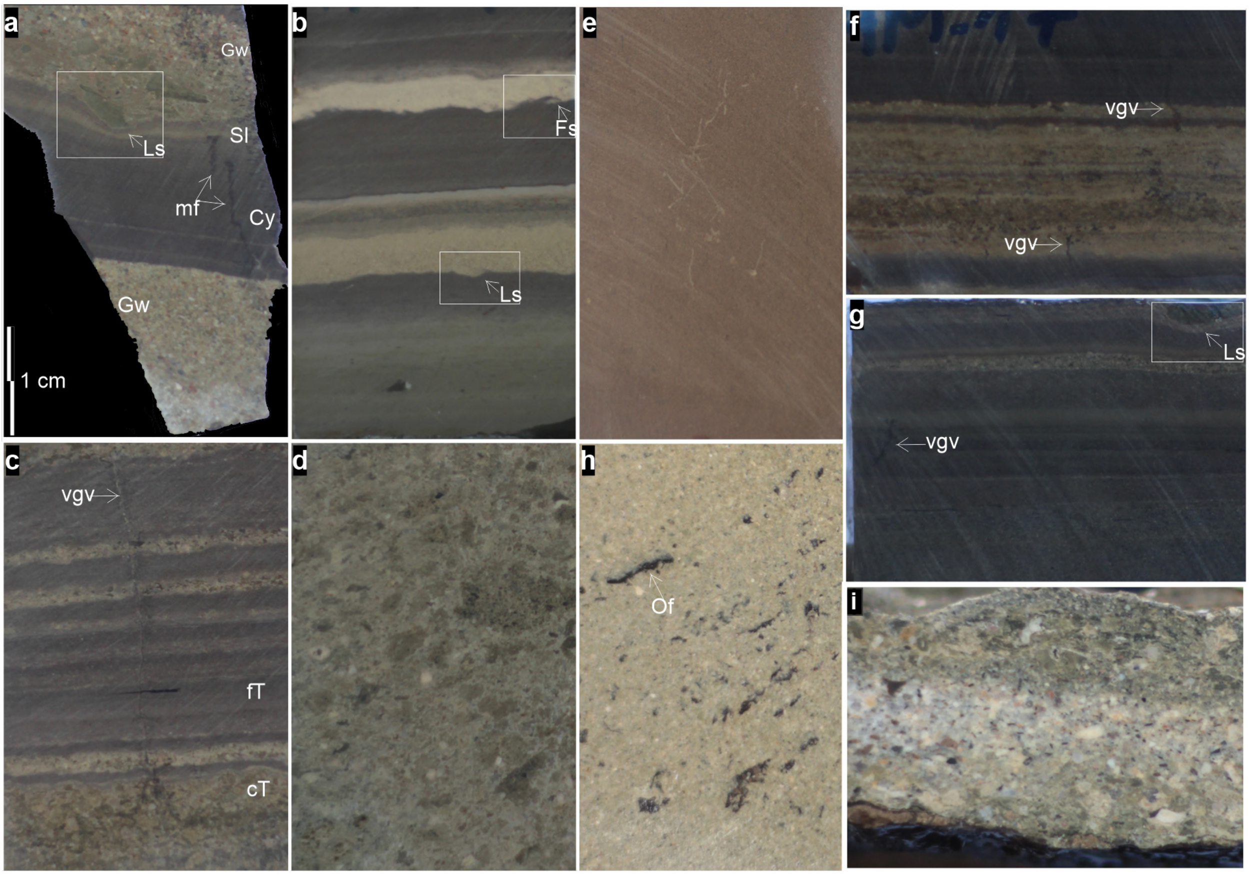

Figure 4. Samples macrophotographs showing the different lithofacies. a) Sample M.5, medium to coarse-grained graywacke (Gw) with interbedded planar laminated claystone (Cy) and siltstone (Sl) levels that are crossing by two microfractures (mf) and to the top an overload structure (Ls) is observed lying on the finer sediments. b) Sample M.7, claystone, siltstone and very fine-grained sandstone interspersed with flame structure (Fs) and Ls. c) Sample M.14, fine (fT) and coarse-grained (cT) ash tuff laminae crossed by a volcanic glass vein (vgv). d) Sample M.14, matrix-supported lapilli tuff. e) Sample M.15, massive siltstone. f) Sample M.17, siltstone laminae with interbedded fine and coarse-grained ash tuff, several volcanic glass veins are crossing these. g) Sample M.23, fine to medium-grained ash tuff interbedded with few siltstone fine laminae. h) Sample M.25, matrix-supported lapilli tuff with abundant black organic fragments (Of). i) Sample M.27, clast-supported tuffaceous litharenite.

information. There are clastic rocks without volcanic influence and volcaniclastic rocks. Sixteen samples correspond to clastic rocks, one sample was classified as a graywacke and is a secondary volcaniclastic rock, and ten samples were identified as primary volcaniclastic rocks. The volatile free-base composition of all the rocks shows they are moderate to highly evolved silicic rocks with SiO_2 values ranging between 58 and 77 wt. %. The igneous classification diagram, based on Irvine & Baragar (1971) and Middlemost (1994), includes just the volcaniclastic rocks, this displays a main group of samples lying within the subalkaline rhyolitic composition with SiO_2 > 66 wt. % and total alkali content (K_2O+Na_2O) between 3.54 and 8.23 wt. % (Fig. 6a). With SiO_2 < 65 wt. %, the subalkaline dacitic graywacke sample M.5 and the tuffs samples M.14 and M.21 are on the alkaline limit of trachy/andesite composition, respectively with a total alkali content of 3.54, 7.73 and 9.06 wt. %. The immobile elements have generally high Al_2O_3 values ranging between 12.36 and 17.11 wt. % and moderate Fe_2O_3 values between 2.43 and 8.63 wt.

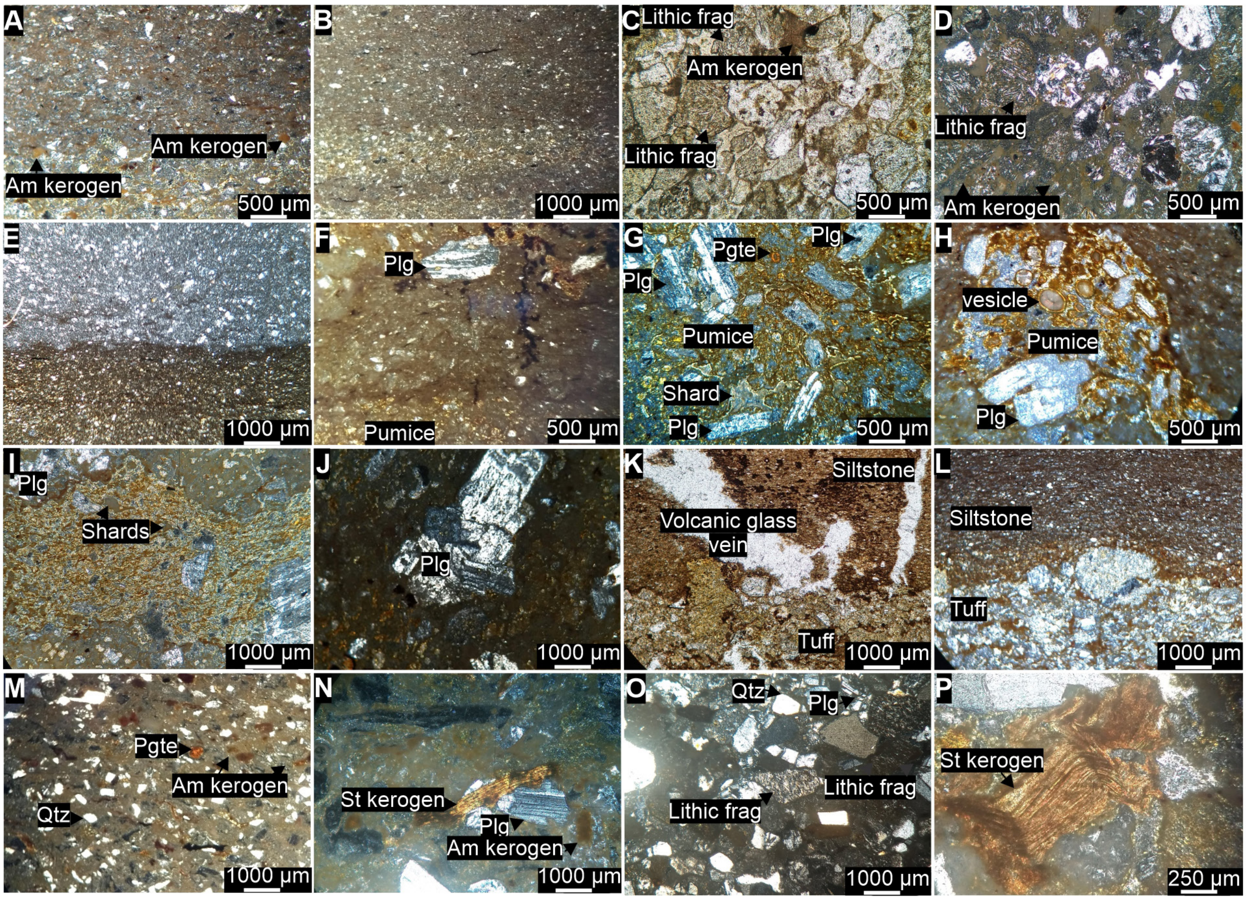

Figure 5. Petrographic photographs showing some details of the microfacies. a–b) Sample M.3, claystone-siltstone laminae under cross polarized light XPL. c–d) Sample M.5, Medium- to coarse-grained grauwacke with abundant rhyodacite lithic fragments, parallel polarized light PPL and XPL, respectively. e) Sample M.7, claystone-siltstone laminae under XPL. f–h) Sample M.13, tuff under XPL, ash matrix with abundant brown kerogen (f), phenocrystals of < 1 mm of plagioclase in pumice (g) showing vesicles (h). i–j) Sample M.14, lapilli tuff, glass, and ash matrix with phenocrystals of > 3 mm of plagioclase under PPL and XPL, respectively. k–l) Sample M.17, siltstone-tuff laminae under PPL and XPL, respectively. m–n) Sample M.25, lapilli tuff under XPL, matrix compound of ash and clastic fine grains with phenocrystals of quartz, plagioclase and oxides, abundant amorphous (Am) kerogen and structured (St) kerogen, and accretionary lapilli filled with palagonite (Pgte) are observed. o–p) Sample M.27, medium- to coarse-grained tuffaceous litharenite under XPL, poor selected and grain supported matrix with sub-rounded to rounded quartz, plagioclase, lithic fragments in welded ash altered to clay minerals (o), structured kerogen (p) grains are abundant as well as amorphous.

% (and the anomalous tuff sample M.14 that has 10.71 wt. %). MgO content is < 3 wt. % in all rocks except the graywacke sample M.5 and the Fe_2O_3-rich tuff sample M.14 (3.10 and 3.63, respectively). CaO content is ~ 2.75 wt. % for graywacke sample M.5 and tuff sample M.24, for the rest of the samples is < 1.76 wt. %. All the rocks present TiO_2 and P_2O_5 values < 1.28 and 0.70 wt.%, respectively.

The tectonic setting plot modified from Bhatia (1983) (Fig. 6b) considers both primary and secondary volcaniclastic and the clearly clastic rocks, it shows a provenance characteristic of arc magmatism, corresponding to a sialic continental arc. Most of the samples fall into these fields, but the graywacke sample M.5 with secondary volcaniclastic grains and the

Table I. Bulk chemical composition of the primary volcaniclastic rocks from Cerro Negro Formation at the President Head Peninsula, Snow Island obtained by X-ray fluorescence (XRF). Major element compositions were recalculated on volatile-free basis and reported in weight percentage (wt. %).

Sample	Rock type	SiO_2	Al_2O_3	TiO_2	Fe_2O_3T	MgO	MnO	CaO	K_2O	Na_2O	P_2O_5
M.27	Tuff. litharenite	67.01	15.83	0.62	4.86	1.70	0.17	1.76	5.56	2.41	0.09
M.26	Tuff	68.72	16.55	0.54	3.56	1.26	0.11	1.49	2.04	5.60	0.13
M.25	Tuff	71.36	14.22	0.63	4.21	0.99	0.11	1.40	1.87	5.11	0.09
M.24	Tuff	74.23	13.83	0.51	3.45	1.51	0.09	2.74	1.45	2.09	0.10
M.23	Tuff	70.95	14.11	0.56	3.57	1.17	0.08	1.24	6.51	1.72	0.08
M.22	Tuff	70.00	13.70	0.72	5.01	1.65	0.17	1.14	5.60	1.88	0.13
M.21	Tuff	64.71	14.86	0.70	7.06	2.41	0.27	0.78	7.62	1.44	0.14
M.20	Non-volcanic	62.90	15.20	0.91	8.39	2.90	0.24	1.53	5.61	2.16	0.15
M.19	Non-volcanic	67.20	13.31	0.71	6.62	2.17	0.21	1.66	5.77	1.89	0.46
M.18	Tuff	76.70	12.36	0.31	2.43	0.62	0.08	0.30	0.97	6.19	0.04
M.17	Tuff	68.63	13.93	0.84	6.03	1.89	0.20	1.12	5.29	1.96	0.11
M.16	Non-volcanic	63.39	15.51	0.78	7.94	2.01	0.24	1.04	7.05	1.91	0.14
M.15	Non-volcanic	64.31	14.78	0.70	7.67	1.99	0.20	0.86	8.00	1.33	0.16
M.14	Tuff	58.62	16.45	1.05	10.71	3.63	0.35	1.32	5.19	2.54	0.15
M.13	Tuff	66.40	14.29	0.79	6.37	2.07	0.18	1.74	5.87	1.91	0.37
M.12	Non-volcanic	66.71	16.23	0.45	5.41	2.14	0.15	1.35	4.55	2.91	0.09
M.11	Non-volcanic	64.92	16.45	0.56	6.22	1.93	0.16	1.01	3.55	5.14	0.06
M.10	Non-volcanic	69.75	13.31	0.58	5.52	1.80	0.16	0.81	6.50	1.49	0.09
M.9	Non-volcanic	66.20	14.36	0.68	7.60	2.31	0.23	0.87	5.10	2.54	0.12
M.8	Non-volcanic	60.80	17.11	0.92	8.51	2.68	0.18	1.22	5.24	3.14	0.20
M.7	Non-volcanic	64.63	17.11	0.49	5.64	2.02	0.16	0.93	5.72	3.23	0.06
M.6	Non-volcanic	62.59	16.88	0.78	7.10	2.56	0.21	1.19	4.37	4.18	0.14
M.5	Greywacke	63.61	14.69	0.90	8.63	3.10	0.26	2.76	3.11	2.25	0.70
M.4	Non-volcanic	61.72	16.41	1.28	8.37	2.19	0.26	1.55	3.42	4.56	0.23
M.3	Non-volcanic	64.83	15.88	0.64	6.96	1.94	0.18	0.81	4.27	4.39	0.10
M.2	Non-volcanic	70.06	13.54	0.55	5.60	1.67	0.15	1.50	3.93	2.92	0.07
M.1	Non-volcanic	68.48	14.19	0.74	6.35	1.96	0.19	1.57	3.74	2.68	0.09

Fe_2O_3-rich tuff sample M.14 fall into the passive margin and oceanic island arc fields.

Palynofacies and Palynology

Palynofacies analysis

Three main groups have been identified along the section, palynomorphs (54.2%), AOM/pseudoamorphous (24.8%), and phytoclasts (21.0%). The Cerro Negro Formation section is dominated by palynomorphs, mainly spores (41.6%), followed by phytoclasts translucent (20.4%), and pseudoamorphous (14.7%) components (Fig. 7, SM-2).

The Principal Component Analysis (PCA) reveals the three palynofacies assemblages in

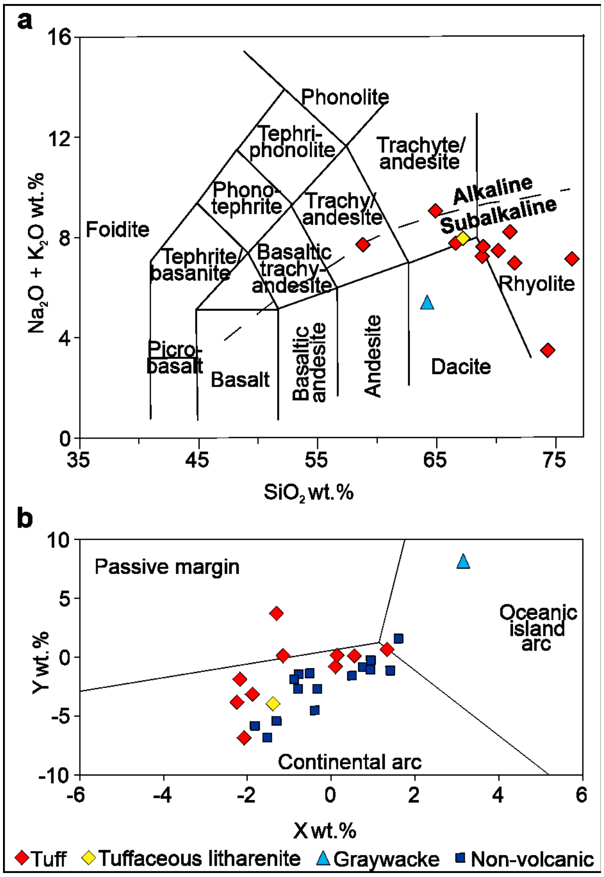

Figure 6. Geochemistry plots a) Total alkali vs. silica (TAS) compositional plot (based on Irvine & Baragar 1971, Middlemost 1994). b) Tectonic setting plot, where X = 0.303 – 0.0447SiO2 – 0.972TiO2 + 0.008Al2O3 – 0.267Fe2O3 + 0.208FeO – 3.082MnO + 0.14MgO + 0.195CaO + 0.719Na2O – 0.032K2O + 7.51P2O5 and Y = 43.57 – 0.421SiO2 + 1.988TiO2 – 0.526Al2O3 – 0.551Fe2O3 – 1.61FeO + 2.72MnO + 0.881MgO – 0.907CaO – 0.177Na2O – 1.84K2O + 7.244P2O5 (based on Bhatia 1983).

the Cerro Negro Formation that are composed of spores (Principal component 1, PC1), pollen grains (PC2), and freshwater algae/AOM (PC3) (Fig. 7). They represent the dominant organic elements; the multivariate model explains 76% of the total variance of the dataset. The vertical distribution of palynofacies assemblages and PCA in the section is presented in Fig. 7. Supporting data on loading, scores, and summary PCA are given in SM-2. The PCA data illustrates the variability of each organic group in the samples analyzed. As revealed in a biplot scatter plot, the samples represent two different groups (square and circle) according to their location in the section (Fig. 8). We observed a separation between the group of palynomorphs and phytoclasts, mostly in the quadrants on the right, associated with the samples M.1 to M.14, and the group of AOM (quadrants on the left) (samples M.15 to M.27) (Fig. 8). The variability and depositional distinction of the groups are confirmed by the chi-square test, being significant for spores (X^2 = 194.9; p<0.0001), pollen grains (X^2 = 15.2; p<0.0001) and AOM + pseudoamorphous (X^2 = 2046.2; p<0.0001).

According to the application of the Q-mode cluster for the palynofacies distribution, and corroborated with PCA data and ecological indexes, it was possible to recognize two palynofacies assemblages (P1 and P2, Fig. 7) which represent different depositional paleoenvironments for the Cerro Negro Formation.

The Palynofacies assemblage 1 (P1) is recognized in the lower-middle portion of the studied section, between samples 1 to 14 (Fig. 7). This palynofacies is dominated by the palynomorphs (66%), with spores (52%; p<0.0001) and pollen grains (14%; p<0.0001); and the phytoclasts (19%) (Fig. 7; SM-2). There is an increase of *Botryococcus* (freshwater algae) to the top, samples 8 to 13 (8.4% to 11.4%), with the exception of sample 11 (3,4%). Pseudoamorphous particles occurs in low percentages in the P1, except for sample 13 (11.45%), and AOM has a high percentage value in sample 4 (44.1%).

The Palynofacies assemblage 2 (P2) is identified among samples 15 to 27, in the middle-upper portion of the Cerro Negro Formation section. In this interval, AOM/Pseudoamorphous particles (43.1%) are dominant (p<0.0001), the palynomorphs decrease significantly (spores with 29.6%; pollen grains with 2.9%; p<0.0001). The phytoclast group is 21.6%, similarly to Palynofacies assemblage 1, where it is 19%. (Fig.

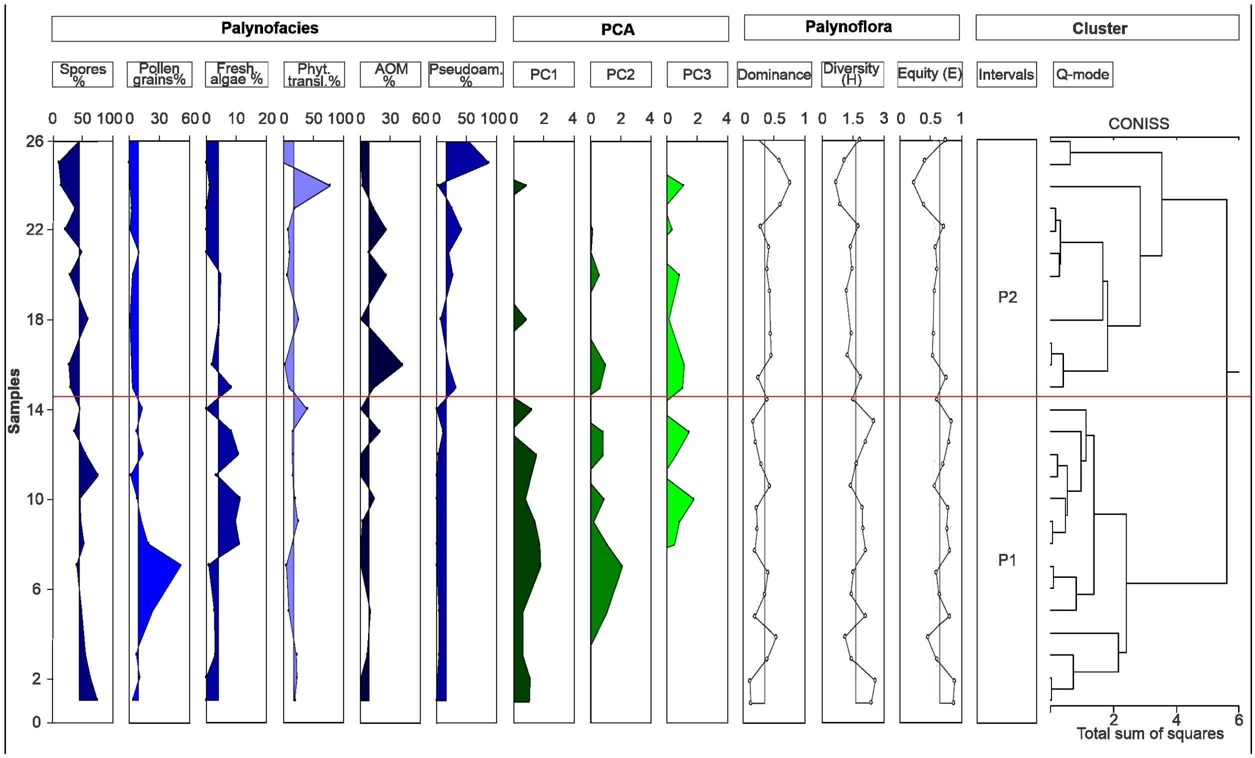

Figure 7. Stratigraphical distribution of palynofacies ratio, Principal Component Analysis (palynofacies) (PCA), palynoflora ecological indexes ratio, and paleoenvironmental intervals (Q-mode cluster).

7), and *Botryococcus* occurs in samples 15 to 20 (2% to 8.4%) in the base of the P2. The chi-square test, in comparison of proportion between intervals, is not significant for phytoclasts (X^2 = 0.018; p = 0.89) or freshwater algae (X^2 = 1.53; p = 0.21). In this interval, the maximum distribution of the PC3 (Freshwater algae/AOM) is inversely correlated with those of the assemblage of spores and pollen grains (PC1 and PC2) (Fig. 7).

Palynological analysis

A total of 43 taxa were identified in Snow Island, including spores, pollen grains, freshwater algae and fungi (Figs. 9–11; SM-1 and SM-3). Ferns, lycophytes and bryophytes are the most abundant with 33 species, followed by conifers with seven species, and others palynomorphs with three elements (algae, fungi and indeterminate palynomorph) (SM-1). Rarefaction curve indicates that several palynomorphs species were recovered and that the sampling was enough (Fig. 12).

Smooth spores included within the suprageneric classification Triletes are the most abundant (47%), and display a high value of standard deviation (sd=23.7), indicating that there is a large variation in the whole section. Despite this, they are dominant in samples 24 to 26. As Cantrill (2000) recorded, in our study many of the smooth spores (Triletes group) specimens could belong to *Cyathidites*, furthemore, bisaccate pollen grains occurs in great percentage but are poorly preserved.

Based on the Principal Component Analysis (PCA) for the palynoflora, it was possible to distinguish three assemblages for Snow Island: *Ischyosporites* (principal component 1, PC1), *Podocarpidites* spp. (PC2) and *Deltoidospora hallii* (PC3). The multivariate model explains 51.45% of the total variance of the dataset (Table II).

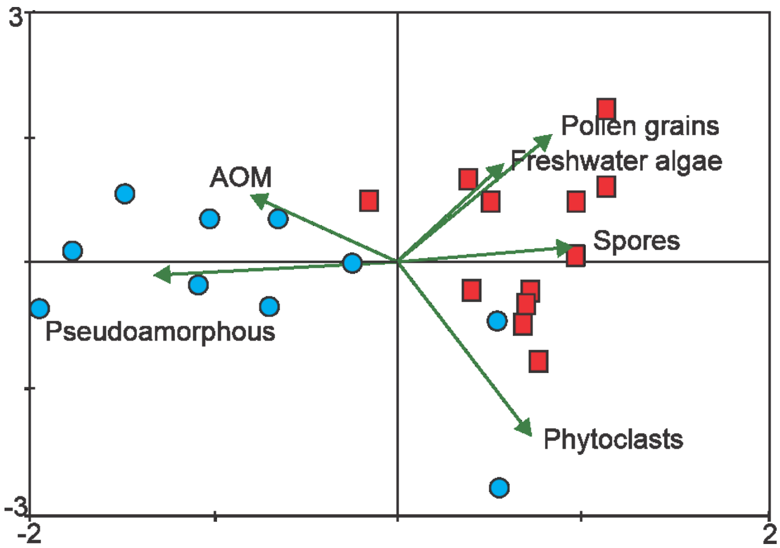

Figure 8. PCA Biplot scatter plot for palynofacies and samples from the Cerro Negro Formation. In squares (samples M.1 to M.14), and circles (samples M.15 to M.27).

The *Ischyosporites* assemblage (PC1) accounts for 23.97% of the total variance of the dataset. This assemblage includes *Foraminisporis wonthaggiensis*, *Cyathidites australis*, *Ceratosporites equalis*, *Biretisporites* spp., *Foveotriletes* spp., *Araucariacites* spp., and *Gleicheniidites senonicus* (Table II). Notably, there is a dominance of spores.

The *Podocarpidites* spp. assemblage dominance (PC2) explains 15.75% of the total variance, also including *Camarozonosporites insignis*, *Callialasporites segmentatus*, Bisaccates pollen grains, *Leiotriletes* spp., *Baculatisporites comaumensis*, *Alisporites biateralis* and *Vitreisporites* spp. (Table II). In PC2 there is a predominance of conifer pollen grains associated with spores. The palynoflora assemblages (PC1 and PC2) together explain 39.72% of the total variance in the section, occurring mainly in interval P1 of Snow Island (Table II). The PC3 is less representative, showing a variance of 11.73% (Table II).

The palynoflora of the Snow Island has mean values of 0.35 for dominance (D), 1.63 for diversity H(S), and 0.65 for equity (E). The lowest mean values calculated for D (0.11 to 0.29) appear in interval P1, and the maximum values above the mean occur in samples 24 to 26 for interval P2, as 0.59 to 0.77 (e.g., Triletes) (Fig. 7; SM-1). The diversity H(S) and equity E both have a general increase of mean values for interval P1, as H = 1.64 to 2.59 and E = 0.70 to 0.88, respectively. These results are positively correlated with the highest record of spores (PC1) and pollen grains (PC2) for interval P1. The H(S) and E generally have low values in the interval P2 (Fig. 7).

DISCUSSION

Paleoenvironmental inferences

The paleoflora of South Gondwana contains widely distributed taxa during the Cretaceous, with a dominance of ferns, conifers and the invasion of angiosperms (Cantrill & Poole 2012). Torres et al. (1995) and Césari et al. (2001) suggest for the Cerro Negro Formation on Livingston Island (South Shetland Islands, Antarctica) a diversity of ferns as indicated by the macroflora compressions, and that the vegetation was influenced by different local habitats. Also, Falcon-Lang & Cantrill (2002) based on megaflora taphonocoenoses analyses defined three dominant-plants communities: podocarp-araucarian-fern forests at lowland floodplains; podocarp-bennettite forests of mid-altitude volcanic cones, and shrubby bennettite-fern,

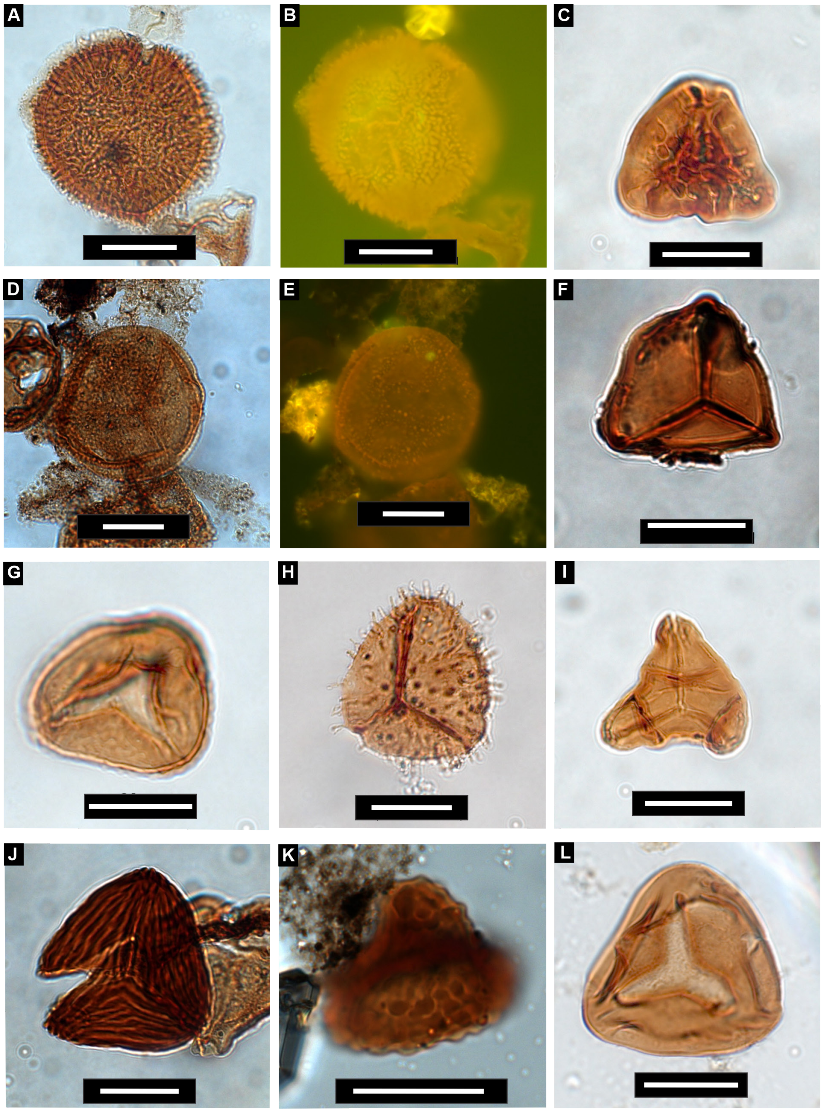

Figure 9. Spores recovered from the Cerro Negro Formation, President Head Peninsula, Snow Island: a–b) *Aequitriradites superspinulosus*, M.12, EF (R27/3), b) fluorescence mode, c) *Antulsporites baculatus*. M.2, EF (Z32/3), d–e) *Baculatisporites comaumensis*, M.7, EF (W28/1), e) fluorescence mode, f) *Biretisporites* sp., M.2, EF (F36/3), g) *Camarozonosporites insignis*, M.14, EF (U29/2), h) *Ceratosporites equalis*, M.1, EF (U28/2), i) *Cibotiumspora jurienensis*, M.3, EF (R27/2), j) *Cicatricosisporites* sp., M.7, EF (G29/3), k) *Converrucosisporites* sp., M.6, EF (X33/2), l) *Cyathidites australis*, M.14, EF (B29/1). Scale bar 20 µm. England Finder (EF).

developed during sustained periods of high frequency basaltic ash falls.

The dispersion of organic matter has been used as a proxy for environmental inferences (e.g., Oboh-Ikuenobe et al. 2005, Quattrocchio et al. 2006, Mendonça Filho et al. 2010, Carvalho et al. 2013, Santos et al. 2013). In our study, a varied distribution of constituents of kerogen were observed, and two palynofacies were recognized according to the depositional environment. For this purpose, a ternary plot of the main palynofacies elements registered in each sample studied is given in Fig. 13.

The variations in the stratigraphic distribution of the two palynofacies assemblages reflect changes during deposition of the Cerro Negro Formation on Snow Island (Figs. 7; 13). The paleoenvironment recognized by palynofacies assemblage 1 indicates a predominance of palynomorphs, represented by sporomorphs, mainly spores of ferns (Figs. 9–11). This assemblage is similar to the macroflora recorded in the Early Cretaceous of the South Shetland Island, Antarctica, for example Osmundaceae and Gleicheniaceae families (Torres et al. 1995, Cantrill 2000, Césari

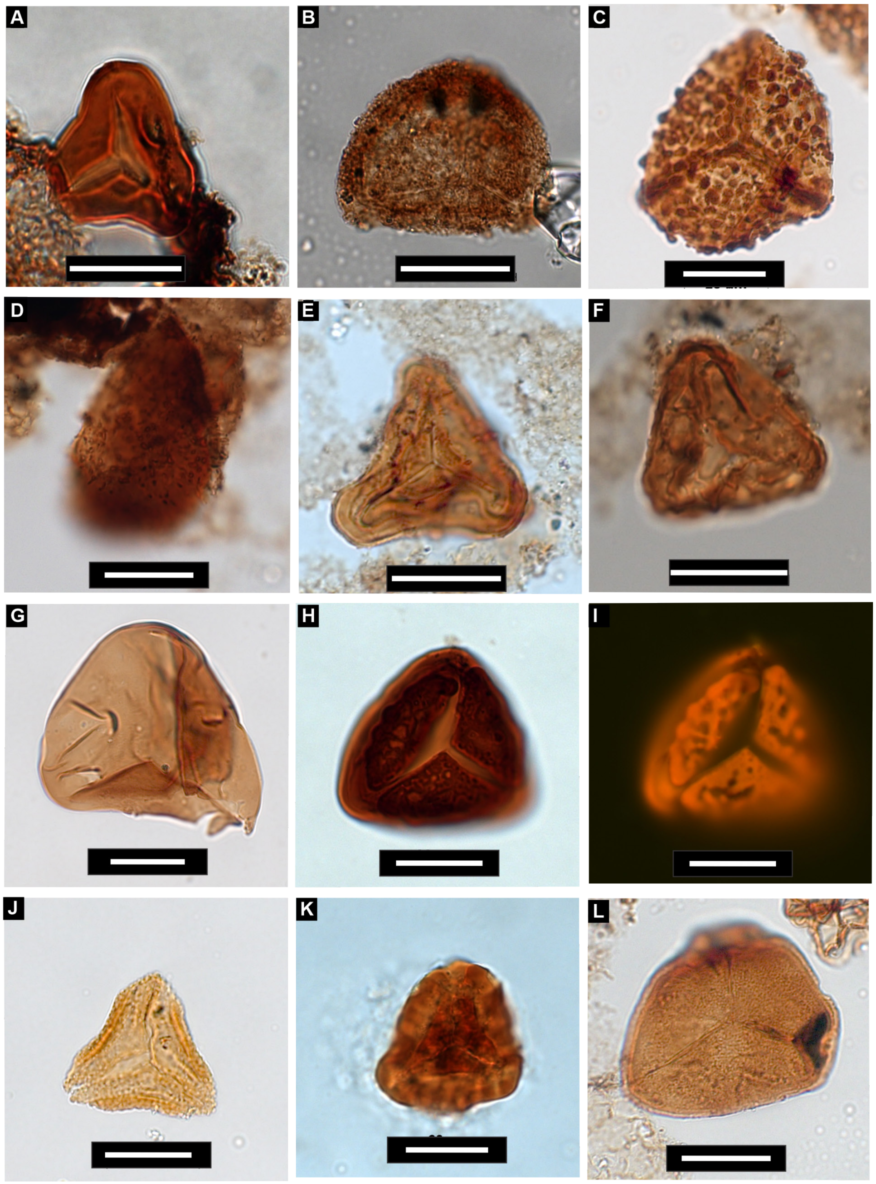

Figure 10. Spores recovered from the Cerro Negro Formation, President Head Peninsula, Snow Island: a) *Deltoidospora hallii*, M.2, EF (L32/2), b) *Densoisporites microrugulatus*, M.6, EF (C37/2), c) *Foraminisporis asymmetricus*, M.1, EF (E33/3), d) *F. wonthaggiensis*, M.1, EF (X27/2), e) *Gleicheniidites senonicus*, M.1, EF (T26/4), f) *Ischyosporites* sp., M.1, EF (B27/1), g) *Leiotriletes* sp., M.14, EF (O29/2), h-i) *Muricingulisporis annulatus*, M.5, EF (W32/1), i) fluorescence mode, j) *Ornamentifera* sp., M.1, EF (H36/1), k) *Polycingulatisporites* sp., M.2, EF (F25/3), l) *Psilatriletes radiatus*, M.1, EF (P32/4). Scale bar 20 µm.

et al. 2001). Fern spores (e.g., *Ischyosporites, Cyathidites* and *Deltoidospora*) and bryophyte spores (e.g., *Aequitriradites* and *Foraminisporis*) observed in the Cerro Negro Formation at Snow Island are very common genera in humid climates, because the fertilization of this plants requires water availability (Tyson 1993, Mendonça Filho et al. 2011, Carvalho et al. 2017) and they are mainly dispersed by water. Gymnosperms (e.g., *Podocarpidites*) occur secondarily in this assemblage suggesting the presence of highlands in the Snow Island region during the Early Cretaceous. Regions with a high percentage of plant spores from total kerogen, suggests an oxidized environment, close to the source of production and redeposition in areas of active fluvio-deltaic origin (Tyson 1993, Mendonça Filho et al. 2011, Carvalho et al. 2013). The oxidized environment is also confirmed in our material (Palynofacies Assemblage 1) by the low occurrence of AOM. The sedimentological and geochemical data support a flooded plain to lacustrine depositional environment associated with Palynofacies 1 interval.

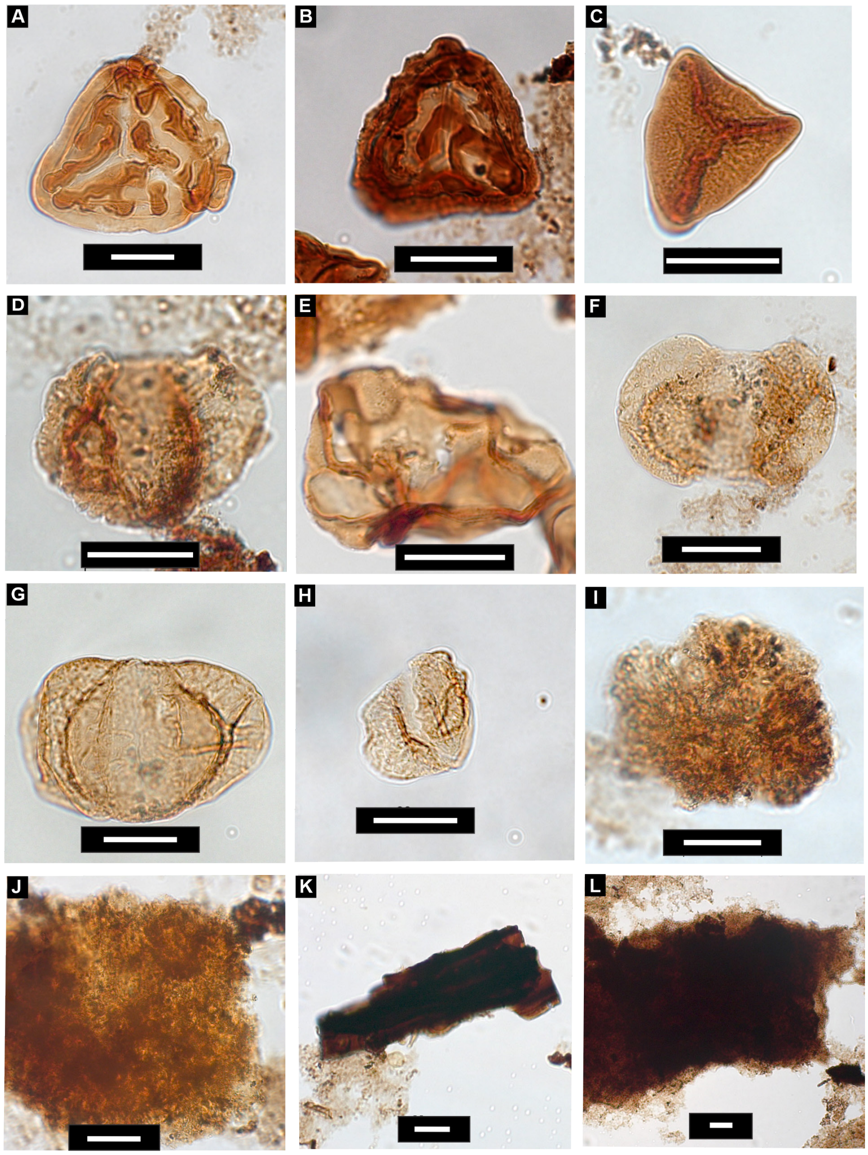

Figure 11. Spores, pollen grains, algae, and SOM recovered from the Cerro Negro Formation, President Head Peninsula, Snow Island. Spores: a) *Sotasporites elegans*, M.14, EF (S41/3), b) *S. triangularis*, M.2, EF (O32/3), c) *Undulatisporites pannuceus*, M.14, EF (S29/4). Pollen grains: d) *Alisporites bilateralis*, M.1, EF (A36/3), e) *Araucariacites* sp., M.1, EF (T26/2), f) Bisaccate, M.14, EF (N29/2), g) *Podocarpidites* sp., M.14, EF (O38/1), h) *Vitreisporites* sp., M.14, EF (Q34/1). Algae: i) *Botryococcus* sp., M.14, EF (H33/1). SOM: j) AOM, M.15, EF (X33/2), k) Phytoclast translucent, M.15, EF (V36/4), l) Pseudoamorphous, M.15, EF (C37/2). Scale bar 20 μm.

Medium- to coarse-grained, moderately sorted graywacke with low angle cross-lamination indicate deposition of reworked volcanoclastic material and thus is not considered a primary volcaniclastic deposit. According to Miall (2006), this type of psammitic facies is deposited within moderate energy fluvial channels that could represent crevasse splays within a flooded overbank transitory to full lacustrine conditions interpreted from fine-grained quartzarenite intercalated with the organic-rich and laminated siltstone to claystone facies. The presence of desiccation cracks suggests that the floodplain was exposed to subaerial conditions. This facies association can be correlated to those from Cerro Negro Formation at Byers Peninsula in Livingston Island described by Hathway (1997) as sandstones, granule-pebble conglomerates and mudstones grouped in the basaltic sandstone facies that indicates deposition from suspension and initially high-energy, waning flows in bodies of standing water and lacustrine turbidite successions. Falcon-Lang & Cantrill (2002) interpreted their sandstone-dominated

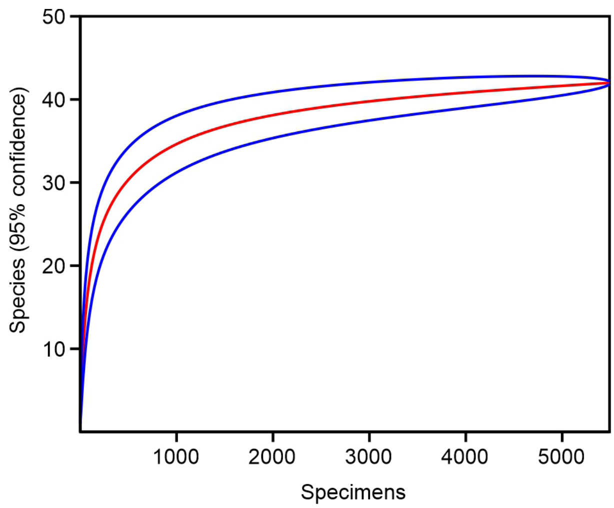

Figure 12. Rarefaction curve with 95% confidence intervals of the palynofloristic species from the Snow Island.

and laminated mudstone facies as having been deposited on low-land fluvial floodplains within half-graben and deposits of large permanent lakes formed during periods when basin subsidence outpaced volcanic sedimentation.

From the ~ 4 m upwards the section, the mudstone-siltstone predominant facies are in part substituted by abundant volcaniclastic content. Primary volcaniclastic materials are directly emitted from a vent and transported through air, water, granular debris or the combination these (White & Houghton 2006). The petrographic investigations of the rocks evidence a high content of pyroclastic fragments that mainly resulted as a direct action of volcanic activity without reworking by sedimentary processes. Moreover, the high percentage of pyroclasts and the rhyodacite content indicate an explosive volcanism. Modern silicic, explosive, steep-sided volcanoes are characterized by ephemeral, high-magnitude eruptions every few hundred years, followed by long periods of quiescence (Cas & Wright 1987). Welded ash and lapilli tuffs recognized in the upper interval of the studied section, are considered as primary pyroclastic fall out into standing ponds between mudstone-siltstone accumulations on an overbank. At Byers Peninsula, Livingston Island, the Cerro Negro Formation follows a middle Valanginian to earliest Aptian erosional hiatus considered to record tectonic or volcano-tectonic uplift, perhaps related to thickening of arc crust by magmatic processes Hathway (1997). At Byers Peninsula, punctuated silicic eruptions in the lower unit of Cerro Negro Formation are suggested by the intercalation of fluvial-lacustrine strata with cool fall/flow pyroclastic deposits (Hathway 1997, Falcon-Lang & Cantrill 2002). The cumulative synsedimentary volcanism was preserved by inter-eruption fluvial-lacustrine deposition favored by differential subsidence within a fault-bounded intra-arc basin (Hathway 1997). The presence of tuffaceous litharenite at the top of our studied section is suggestive of redeposition of unconsolidated tephra by debris flows and flood flows on the volcaniclastic apron, as interpreted by Hathway (1997) at Byers Peninsula, deposition occurred from high-energy, subaerial, waning flows, probably representing overbank flood deposits from adjacent sediment-charged streams.

The ternary graph (Fig. 13) clearly shows the change in paleoenvironment (palynofacies assemblage 2, P2) indicated by high values of AOM/pseudoamorphous material and a decrease of palynomorphs, specially represented by sporomorphs. AOM suggests, even temporarily, conditions of environments with low oxygenation (Mendonça Filho et al. 2011), and environments with low energy (Carvalho et al. 2013). The amorphized material from Snow Island appears to come from aquatic algae, as *Botryococcus* species. This palynofacies presents the pseudo-amorphized material from the biodegradation of plant fragments (Tyson 1995), easily recognized by the diffuse outline of phytoclasts and absence of fluorescence (Fig. 11).

Table II. Principal Component (PC) number, dominant palynomorphs, and associated species with loadings and explained variance in percentage of total variance are given.

PCA	Dominant palynomorphs	Loadings (Load)	Variance %	Associated species	Load
PC1	*Ischyosporites* spp.	0.32	23.97	*Foraminisporis wontahggiensis* *Cyathidites australis* *Ceratosporites equalis* *Biretisporites* spp. *Foveotriletes* spp. *Araucariacites* spp. *Gleicheniidites senonicus*	0.31 0.30 0.27 0.27 0.26 0.26 0.25
PC2	*Podocarpidites* spp	0.28	15.75	*Camarozonosporites insignis* *Callialasporites segmentatus* Bisaccates pollen grains *Leiotriletes* spp. *Baculatisporites comaumensis* *Alisporites bilaterales* *Vitreisporites* spp.	0.26 0.26 0.26 0.25 0.25 0.25 0.23
PC3	*Deltoidospora hallii*	0.39	11.73	*Sotasporites triangularis* *Antusporites baculatus* *Cyathidites minor*	0.37 0.32 0.28

According to Carvalho et al. (2013), this pseudo-amorphization may be related to the oxidation process during particle transport.

In both palynofacies assemblages we observed the occurrence, even non-dominant, of freshwater algae and fungi spores mainly in the transition from palynofacies assemblage 1 to palynofacies assemblage 2. This type of microplankton (*Botryococcus*), according to Mendonça Filho et al. (2011), has been found in lagoon, lake, fluvial and delta facies, or in a freshwater input redeposition area (Tyson 1993, 1995). Therefore, the paleoenvironmental conditions for the Cerro Negro Formation, in the Snow Island, are associated with a system influenced by water bodies. Additionally, we recorded the palynomorphs and elements of SOM are very damaged, possibly due to volcanic influence, as previously pointed out by Cantrill (2000), analyzing cuticular material in the same region.

The whole-rock compositions from the pyroclastic rocks mostly plot in the subalkaline rhyodacite fields of the Total alkali vs. silica (TAS) diagram (Fig. 6a based on Irvine & Baragar 1971, Middlemost 1994), thus corroborating our petrographic interpretation as originated from silicic magmatism and the correlation of the President Head studied interval with the lower unit of Cerro Negro Formation at Byers Peninsula. As with the volcanic rocks, the major element geochemistry of sediments can be used to infer the provenance differences that depend upon the tectonic setting of the volcanism and of the ancient sedimentary basins (e.g., Bhatia 1983). Tectonic plate interactions govern the isostatic movements and composition of source areas, as well as the position of the basin within the plate or the plate boundary and

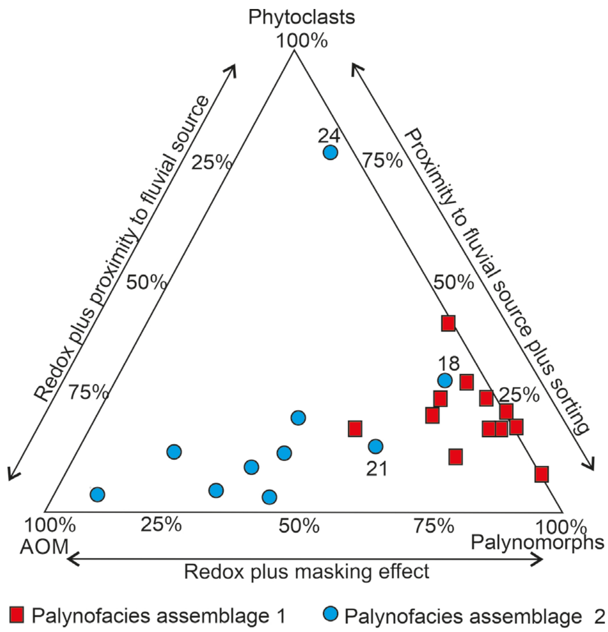

Figure 13. Ternary plot AOM-Phytoclast-Palynomorph based on relative frequency kerogen from Snow Island (Adapted from Tyson 1993, 1995).

four broad tectonic settings for continental and oceanic basins are recognized: oceanic island arc, continental island arc, active continental margin and passive margins (Bhatia & Crook 1986). The melts that rise to feed the volcanism typical of island arcs and active continental margins are generated by the interaction of the subduction zone and the asthenosphere of the mantle (Frisch et al. 2011). Continental island arc and the active continental margin correspond to tectonic settings where oceanic lithosphere is subducted beneath continental lithosphere with the difference that the island arc type is separated from the continental lithosphere by a marine basin behind the volcanic arc; rather, the arc of the active margin is built directly on the adjacent continent (Frisch et al. 2011). Based on this information, we modified the tectonic setting plot of Bhatia (1983) (Fig. 6b) joining the continental island arc and active continental margin fields in one field called continental arc. Most of our samples, including both clastic and volcaniclastic are plotted within the continental arc field, leading to corroborate that the non-marine volcaniclastic Cerro Negro Formation at President Head Peninsula have their provenance of magmatism founded on a sialic basement as proposed by Smellie et al. (1984) for the South Shetland Islands.

The integrated palynological, sedimentological and geochemical data suggests an initial trend deposition in proximal oxide fluvial-lacustrine environment for Cerro Negro Formation in Snow Island, followed by volcaniclastic strata. According to the paleoenvironmental change observed in our data, the intense volcanism on Snow Island played a significant role in the biological history, and the collapse of the flora.

Age based on palynology

The paleoflora of the Byers Group, recorded at the Byers Peninsula, Rugged Island, and at President Head, Snow Island, Antarctica, had previously been suggested to be from the Middle Jurassic (Fuenzalida et al. 1972) to the Early Cretaceous (Philippe et al. 1995, Torres et al., 1995, 1997a, b, Cantrill 1998, 2000, Césari et al. 1998, 1999). Palynological studies of the Jurassic marine sediments (Duane 1997) and those from the Cretaceous continental deposits (Torres et al. 1997a) are supported by radiometric studies from Byers Peninsula (Hathway et al. 1999) indicating an Aptian age for this sequence.

The palynoflora from Snow and Livingston islands, and President Head was correlated with Australia and South American sections, mainly with ones from the Baqueró Formation of Santa Cruz Province, Argentina, in strata no older than Valanginian (Duane 1996, 1997, Torres et al. 1997a). *Interulobites pseudoreticulatus*, *Appendicisporites*, *Foraminisporis wonthaggiensis*, *F. asymmetricus* allow correlation with the *Interulobites–Foraminisporis* Zone and the lower part of the *tectifera–corrugatus* Zone in South America and suggests the correlation with the early–late Aptian *Cyclosporites hughesii* Interval Zone of Australia (Hathway et al. 1999).

The age of the Cerro Negro Formation in Livingston Island was estimated to be 120.3 ±2.2 Ma, 119.4 ±0.6 Ma and 119.1±0.8 Ma using the $^{40}Ar/^{39}Ar$ method (Hathway 1997, Hathway et al. 1999), early Aptian. According to Ugalde et al. (2013), in a study of two groups of U-Pb zircon indicates an absolute age of 116.53 ±0.79 Ma and 109.0 ±1.1 Ma, suggesting deposition on President Head during the late Aptian.

In our study, the palynoflora demonstrates richness in ferns and conifers, that matches with the palynological record of Duane (1996), Torres et al. (1997b), Cantrill (2000), and also shows similarities with Antarctic macroflora (Philippe et al. 1995, Torres et al. 1997b, Cantrill 2000).

The Early Cretaceous geographic distribution of *Sotasporites* and *Muricingulisporis* is restricted to Patagonia and surrounding basins, including Antarctica (Archangelsky & Archangelsky 2006). Therefore, the co-occurrence of spores in this study, such as *Muricingulisporis annulatus*, *Sotasporites elegans*, *S. triangularis*, can be correlated with those occurring in the Austral Basin in Patagonia, Argentina (Archangelsky & Archangelsky 2006). Other taxa, such as *Foraminisporis wonthaggiensis* e *F. asymmetricus* can be compared to the Australian biozones *F. wonthaggiensis* and *Cyclosporites hughesii* (Helby et al. 1987, Hathway et al. 1999), suggesting that the deposition of the Cerro Negro Formation in Snow Island occurred during the Aptian.

Supplementary material

Dataset is available on Zenodo repository (https://zenodo.org/) under the DOI https://doi.org/10.5281/zenodo.5140569.

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REFERENCES

ARCHANGELSKY S & ARCHANGELSKY A. 2006. Putative Early Cretaceous pteridaceous spores from the offshore Austral Basin in Patagonia, Argentina. Cretac Res 27: 473-486. https://doi.org/10.1016/j.cretres.2005.09.001.

BASTIAS J, CALDERÓN M, ISRAEL L, HERVÉ F, SPIKINGS R, PANKHURST R, CASTILLO P, FANNING M & UGALDE R. 2020. The Byers Basin: Jurassic-Cretaceous tectonic and depositional evolution of the forearc deposits of the South Shetland Islands and its implications for the northern Antarctic Peninsula. Int Geol Rev 62: 1467-1484. https://doi.org/10.1080/00206814.2019.1655669.

BHATIA MR. 1983. Plate tectonics and geochemical composition of sandstones. J Geol 91: 611-627.

BHATIA MR & CROOK KAW. 1986. Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. Contrib to Mineral Petrol 92: 181-193. https://doi.org/10.1007/BF00375292.

BIRKENMAJER K. 1994. Evolution of the Pacific margin of the northern Antarctic Peninsula: an overview. Geol Rundschau 83: 309-321. https://doi.org/10.1007/BF00210547.

CANTRILL DJ. 1998. Early Cretaceous fern foliage from President Head, Snow Island, Antarctica. Alcheringa An Australas J Palaeontol 22: 241-528.

CANTRILL DJ. 2000. A Cretaceous (Aptian) flora from President Head, Snow Island, Antarctica. Palaeontogr Abteilung B 253: 153-191. https://doi.org/10.1127/palb/253/2000/153.

CANTRILL DJ & POOLE I. 2012. The vegetation of Antarctica through geological time. Cambridge University Press, New York.

CARVALHO MA, LANA, CC, BENGTSON P & SÁ NP. 2017. Late Aptian (Cretaceous) climate changes in northeastern Brazil: A reconstruction based on indicator species analysis (IndVal). Palaeogeogr Palaeoclimatol Palaeoecol 485: 543-560. https://doi.org/10.1016/j.palaeo.2017.07.011.

CARVALHO MA, RAMOS RRC, CRUD MB, WITOVISK L, KELLNER AWA, SILVA HP, GRILLO ON, RIFF D & ROMANO PSR. 2013. Palynofacies as indicators of paleoenvironmental changes in a cretaceous succession from the Larsen Basin, James Ross Island, Antarctica. Sediment Geol 295: 53-66. https://doi.org/10.1016/j.sedgeo.2013.08.002.

CAS RAF & WRIGHT JV. 1987. Volcanic successions: modern and ancient. Unwin-Hyam, London.

CÉSARI SN, PARCIA CA, REMESAL MB & SALANI FM. 1998. First evidence of Pentoxylales in Antarctica. Cretac Res 19: 733-743.

CÉSARI SN, PARCIA CA, REMESAL MB & SALANI FM. 1999. Paleoflora del Cretácico Inferior de península Byers, Islas Shetland del Sur, Antártida. Ameghiniana 36: 3-22.

CÉSARI SN, REMESAL M & PARICA C. 2001. Ferns: a palaeoclimatic significant component of the Cretaceous flora from Livingston Island, Antarctica, in: VII International Symposium on Mesozoic Terrestrial Ecosystems. Asociación Paleontológica Argentina. Publicación Especial 7, Buenos Aires, p. 45-50.

CRAME JA, PIRRIE D, CRAMPTON JS & DUANE AM. 1993. Stratigraphy and regional significance of the Upper Jurassic-Lower Cretaceous Byers Group, Livingston Island, Antarctica. J Geol Soc 150: 1075-1087. https://doi.org/10.1144/gsjgs.150.6.1075.

DUANE AM. 1996. Palynology of the Byers Group (Late Jurassic-Early Cretaceous) of Livingston and Snow islands, Antarctic Peninsula: Its biostratigraphical and palaeoenvironmental significance. Rev Palaeobot Palynol 91: 241-281. https://doi.org/10.1016/0034-6667(95)00094-1.

DUANE AM. 1997. Taxonomic investigations of palynomorphs from the Byers Group (Upper Jurassic-Lower Cretaceous), Livingston and Snow islands, Antarctic Peninsula. Palynology 21: 123-144. https://doi.org/10.1080/01916122.1997.9989491.

FALCON-LANG HJ & CANTRILL DJ. 2002. Terrestrial paleoecology of the Cretaceous (early Aptian) Cerro Negro Formation, South Shetlands Islands, Antarctica: A record of polar vegetation in a volcanic arc environment. Palaios 17: 491-506. https://doi.org/10.1669/0883-1351(2002)017<0491:TPOTCE>2.0.CO;2.

FRISCH W, MESCHEDE M & BLAKEY R. 2011. Plate Tectonics, Continental Drift and Mountaing Building. Springer. https://doi.org/10.1007/978-81-322-1539-4_14.

FUENZALIDA H, ARAYA R & HERVÉ F. 1972. Middle Jurassic flora from north-eastern Snow Island, South Shetland Islands, in: Adie RJ (Ed), Antarctic Geology and Geophysics. Universitetsforlaget, Oslo, p. 173-180. (Unpublished).

GALINDO-ZALDÍVAR J, JABALOY A, MALDONADO A & SANZ DE GALDEANO C. 1996. Continental fragmentation along the South Scotia Ridge transcurrent plate boundary (NE Antarctic Peninsula). Tectonophysics 258: 275-301. https://doi.org/10.1016/0040-1951(95)00211-1.

GOTELLI NJ & COLWELL RK. 2001. Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. Ecol Lett 4: 379-391. https://doi.org/10.1016/S0956-5663(98)00023-2.

GOTELLI NJ & ELLISON AM. 2011. Princípios de estatística em ecologia. ARTMED, Porto Alegre.

GRIMM EC. 1987. CONISS: a FORTRAN program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Geosciences 13: 13-35.

HAMMER Ø, HARPER DAT & RYAN PD. 2001. PAST: Paleontological statistics software package for education and dat analysis. Paleontol Electron 4: 1-9.

HATHWAY B. 1997. Nonmarine sedimentation in an Early Cretaceous extensional continental-margin ARC, Byers Peninsula, Livingston Island, South Shetland Islands. J Sediment Res 67: 686-697. https://doi.org/10.1306/d4268617-2b26-11d7-8648000102c1865d

HATHWAY B & LOMAS SA. 1998. The Upper Jurassic-Lower Cretaceous Byers Group, South Shetland Islands, Antarctica: Revised stratigraphy and regional correlations. Cretac Res 19: 43-67. https://doi.org/10.1006/cres.1997.0095.

HATHWAY B, DUANE AM, CANTRILL DJ & KELLEY SP. 1999. $^{40}Ar/^{39}Ar$ geochronology and palynology of the cerro negro formation, south shetland islands, antarctica: A new radiometric tie for Cretaceous terrestrial biostratigraphy in the southern hemisphere. Aust J Earth Sci 46: 593-606. https://doi.org/10.1046/j.1440-0952.1999.00727.x.

HELBY R, MORGAN R & PARTRIDGE AD. 1987. A palynological zonation of the Australian Mesozoic. In: Jell PA (Ed), Studies in Australian Mesozoic Palynology. Association of Australasian Palaeontologists, p. 1-94.

IRVINE TN & BARAGAR WRA. 1971. A Guide to the Chemical Classification of the Common Volcanic Rocks. Can J Earth Sci 8: 523-548. https://doi.org/10.1139/e71-055.

ISRAEL LS. 2015. Geología de President Head, Isla Snow, Archipiélago Shetland del Sur, Antártica. Universidad de Chile, 117 p. (Unpublished).

KELLNER AWA, RODRIGUES T, COSTA FR, WEINSCHÜTZ LC, FIGUEIREDO RG, SOUZA GAD, BRUM AS, ELEUTÉRIO LHS, MUELLER CW & SAYÃO JM. 2019. Pterodactyloid pterosaur bones from Cretaceous deposits of the Antarctic Peninsula. An Acad Bras Cienc 91: e20191300. DOI:10.1590/0001-3765201920191300).

MENDONÇA FILHO JG, MENEZES TR & MENDOÇA JO. 2011. Organic Composition (Palynofacies Analysis), in: ICCP Training Course on Dispersed Organic Matter. Porto, p. 33-81.

MENDONÇA FILHO JG, MENEZES TR, MENDONÇA JO, OLIVEIRA AD, CARVALHO MA, SANT'ANNA AJ & SOUZA JT. 2010. Palinofácies. In: Carvalho IDS (Ed), Paleontologia. Interciência, Rio de Janeiro, p. 283-317.

MIALL AD. 2006. The geology of fluvial deposits. Sedimentary facies, basin analysis, and petroleum geology, 4th print ed., The Geology of Fluvial Deposits. Springer-Verlag Berlin Heidelberg GmbH. https://doi.org/10.1007/978-3-662-03237-4.

MIDDLEMOST EAK. 1994. Naming materials in the magma/igneous rock system. Earth Sci Rev 37: 215-224. https://doi.org/10.1016/0012-8252(94)90029-9.

OBOH-IKUENOBE FE, OBI CG & JARAMILLO CA. 2005. Lithofacies, palynofacies, and sequence stratigraphy of Palaeogene strata in Southeastern Nigeria. J African Earth Sci 41: 79-102.

PANKHURST RJ & SMELLIE JL. 1983. K-Ar geochronology of the South Shetland Islands, Lesser Antarctica: apparent lateral migration of Jurassic to Quaternary island arc volcanism. Earth Planet Sci Lett 66: 214-222. https://doi.org/10.1016/0012-821X(83)90137-1

PHILIPPE M, TORRES T, BARALE G & THÉVENARD F. 1995. President Head, Snow Island, South Shetland, a key-point for Antarctica Mesozoic palaeobotany. Comptes Rendus - Acad des Sci Ser II Sci la Terre des Planetes 321: 1055-1061.

QUATTROCCHIO ME, MARTÍNEZ MA, CARPINELLI PAVISICH A & VOLKHEIMER W. 2006. Early Cretaceous palynostratigraphy, palynofacies and palaeoenvironments of well sections in northeastern Tierra del Fuego, Argentina. Cretac Res 27: 584-602. https://doi.org/10.1016/j.cretres.2005.11.012.

SANTOS AS, HELENES J & CARVALHO MA. 2013. Palynofacies evidence of dysoxia and upwelling in the Turonian of the Sergipe Basin, Brazil. Cretac Res 46: 151-165. https://doi.org/10.1016/j.cretres.2013.09.005.

SMELLIE JL, DAVIES RE & THOMSON MRA. 1980. Geology of a Mesozoic intra-arc sequence on Byers Peninsula, Livingston Island, South Shetland Islands. Br Antarct Surv Bull 50: 55-76.

SMELLIE JL, PANKHURST RJ, THOMSON MRA & DAVIES RES. 1984. Stratigraphy, geochemistry and evolution, in: The Geology of the South Shetland Islands. British Antarctic Survey scientific reports, Cambridge, p. 1-85.

SOLARI MA, HERVÉ F, MARTINOD J, LE ROUX JP, RAMÍREZ LE & PALACIOS C. 2008. Geotectonic evolution of the Bransfield Basin, Antarctic Peninsula: Insights from analogue models. Antarct Sci 20: 185-196. https://doi.org/10.1017/S095410200800093X.

TORRES T, BARALE G, MEÓN H, PHILLIPPE M & THÉVENARD F. 1997a. Cretaceous Floras from Snow Island (South Shetland Islands, Antárctica) and Their Biostratigraphic Significance. Antarct Reg Geol Evol Process 1023-1028.

TORRES T, BARALE G, THÉVERNARD F, PHILLIPPE M & GALLEGUILLOS H. 1997b. Morfología y sistemática de la flora del Cretácico Inferior de President Head, Isla Snow, Archipiélago de las Shetland del Sur, Antartica. Ser Científica Ina 47: 59-86.

TORRES T, PHILLIPPE M, GALLEGUILLOS H & HAUK F. 1995. Nuevos descubrimientos de restos vegetales en la Isla Snow, Shetland del Sur, Antartica. Boletín Antart Chil May, 25-28.

TYSON RV. 1993. Palynofacies analysis. In: Jenkins DJ (Ed), Applied Micropalaeontology. Kluwer Academic, Dordrecht, p. 153-191.

TYSON RV. 1995. Sedimentary Organic Matter: organic facies and palynofacies. Kluwer Academic, Dordrecht.

UGALDE R, TERESA T, ISRAEL L, GALLEGUILLOS M, HERVÉ F & FANNING M. 2013. New geological data and paleontological record of President Head Peninsula, Snow Island, South Shetland Islands, Antarctica: a key for the Lower Cretaceous, in: GeoSur2013. Bollettino Di Geofisica Teorica Et Aplicata, Vina del Mar, p. 359. https://doi.org/10.13140/2.1.3959.8724.

VAUGHAN APM & STOREY BC. 2000. The eastern Palmer Land shear zone: A new terrane accretion model for the Mesozoic development of the Antarctic Peninsula. J Geol Soc London 157: 1243-1256. https://doi.org/10.1144/jgs.157.6.1243.

WATTS DR, WATTS GC & BRAMALL AM. 1984. Cretaceous and Early Tertiary paleomagnetic results from the Antarctic Peninsula. Tectonics 3: 333-346.

WHITE JDL & HOUGHTON BF. 2006. Primary volcaniclastic rocks. Geology 34: 677-680. https://doi.org/10.1130/G22346.1

WOOD GD, GABRIEL AM & LAWSON JC. 1996. Palynological techniques processing and microscopy. In: Jansonius J & McGregor DC (Eds), Palynology: Principles and Applications. American Association of Stratigraphic Palynologists, p. 2950.

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