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The first report of a Campanian palaeo-wildfire in the West Antarctic Peninsula

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ABSTRACT

The analysis of palaeofloras and the related palaeoecological conditions is of great importance for the understanding of past environmental and palaeoclimatic events in Antarctica. At the end of the Cretaceous, subtropical forests developed there because of wet and temperate climate conditions. On the Antarctic Peninsula, which is geologically characterized by a forearc context, volcanic activity caused by tectonics favours the ignition of vegetation fires. In the present study, the occurrence of palaeo-wildfires during the Upper Cretaceous is demonstrated for the Rip Point outcrop on Nelson Island, South Shetland Islands. During Brazilian expeditions to the area, macroscopic charcoal was collected and subsequently analysed under a stereomicroscope and scanning electron microscope (SEM). The charred wood remains were identified as belonging to conifers, which were important components of the Antarctic palaeoflora during the Cretaceous. A review of the data published thus far regarding palaeo-wildfires in the Southern Hemisphere confirms that the charcoal remains analysed here are the first to verify the occurrence of palaeo-wildfires in the upper Campanian levels of the West Antarctic Peninsula.

1. Introduction

Currently, Antarctica composes more than 10% of the total continental area of Earth, making it the fifth largest continent. The greatest portion of Antarctica has been maintained in the Antarctic Polar Circle since the end of the Mesozoic (Lavwer et al., 1991). The modern geographical design of Antarctica and the continents of the Southern Hemisphere have a common history that results from the gradual fragmentation of Gondwana (Tarling, 1988; Dalziel et al., 2000; Boger, 2011). In West Antarctica (WANT), or the Antarctic Peninsula, tectonic plate interactions and subduction processes have been taking place since the Early Mesozoic altering its geographical design during the time (Smellie et al., 1984; Del Valle and Rinaldi, 1993; Hervé et al., 2006).

The fossil record of WANT is distinguished from that of East Antarctica in that it comprises mostly Mesozoic and Cenozoic successions (Birkenmajer and Zastawniak, 1989; Yanbin, 1994; Cantrill and Poole, 2012; Reguero et al., 2013). As a result of the tectonic context and volcanism, the plant fossils of WANT were mostly preserved by sediments originating from fallen ash and surge deposits and the deposition of reworked volcanic grains produced during the breakup and convergence of tectonics plates (Birkenmajer, 2001; Willan and Hunter, 2005; Reguero et al., 2013).

Moreover, because plants are sensitive to climatic and environmental changes, fossiliferous successions are the most helpful for the reconstruction of climatic and ecological changes and events that occurred throughout geological time (Poole and Cantrill, 2006; Francis et al., 2008). One of the most readily preserved forms of the plant fossil record is macroscopic charcoal, which is the product of the incomplete combustion of plant biomass (Goldberg, 1985; Scott, 2010). Although macroscopic charcoal undergoes some shrinkage, resulting in subtle anatomical changes (Jones and Chaloner, 1991; Lupia, 1995), macroscopic charcoal preserves the anatomical and morphological details of fossils very well, and this information can be used in taxonomical and palaeoecological studies (Scott and Damblon, 2010).

Despite the volcanic context of WANT, which may have favoured palaeo-wildfires, studies regarding the macroscopic charcoal record in Antarctica are greatly lacking. For the Upper Cretaceous, only two localities (Eklund, 2003; Eklund et al., 2004; Kvaček and Sakala, 2011) with charred remains and structurally preserved fossil plants have been described in the literature.

Eklund (2003) and Eklund et al. (2004) described charred and structurally preserved plant remains found at the Table Nunatak Formation (Santonian), Kenyon Peninsula, Antarctic Peninsula Eastern margin. Additionally, Kvaček and Sakala (2011) cited the occurrence of charcoalified

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plant mesofossils from the Hidden Lake and Santa Marta Formations (Coniacian/Campanian), James Ross Island; however, they did not provide detailed analyses of those charcoal remains.

Brown et al. (2012) reviewed the occurrence of Cretaceous palaeowildfires on a global scale, only citing the two records by Eklund (2003) and Eklund et al. (2004) for Antarctica. Although the authors illustrated a charcoal assemblage with charred angiosperm reproductive organs for the Antarctic Campanian/Maastrichtian interval on a schematic map (see Brown et al., 2012 — fig. 3c), the references for that occurrence could not be found in that paper.

According to Scott et al. (2014), after the Permian–Triassic boundary fire systems collapsed, which resulted in a reduction of palaeo-wildfire records during the Triassic and Jurassic, the Cretaceous can be considered as a "high-fire" world. However, while charcoal from the Cretaceous period has been extensively described for Eurasian areas (Brown et al., 2012) direct palaeo-wildfire evidence records [charcoal, inertinites in coals or pyrogenic polycyclic aromatic hydrocarbons (PHAs)] for the entirety of Gondwana are scarce (Eklund et al., 2004; Brown et al., 2012).

With that information gap in mind, each new discovery of Cretaceous palaeo-wildfire evidence contributes to the construction of a Cretaceous palaeo-wildfire scenario for Gondwana. In that regard, the present paper reports the first detailed analysis of macroscopic charcoal from the north-western sector of the Antarctic Peninsula and the second analysis of macroscopic charcoal from the Campanian period for all of Antarctica. The charcoal was detected amongst non-charred wood fragments preserved in the basal tuff levels of the volcanoclastic succession exposed at the Rip Point, northeast Nelson Island (Fig. 1).

2. Geological and palaeontological context

Past geological processes are preserved and can be detected in the fossil record from the Lower to Upper Palaeozoic successions from East Antarctica (Bose et al., 1990; Taylor and Taylor, 1990; McLoughlin et al., 1997; Dutra and Jasper, 2010). In WANT areas, the Mesozoic and Cenozoic events are attested (e.g. Dutra, 2004; Cantrill and Poole, 2012; Reguero et al., 2013).

The western South Shetland and Alexander Islands to the West and the eastern James Ross Basin contain a well-known fossil record from the Antarctic Peninsula that consists mainly of plants, vertebrates and various invertebrate groups. Starting from the Jurassic (with uncertain Triassic levels), the fossiliferous succession extends to the upper Miocene, when the ice cover of this sector affected a large area (Falcon-Lang and Cantrill, 2000; Yanbin, 1994; Birkenmajer, 2001; Dutra, 2004; Cantrill and Poole, 2012; Reguero et al., 2013).

Nelson Island, where the material discussed here was collected, is one of the northernmost islands of the South Shetland Island archipelago. It is composed of insular fragments of volcanic origin and was formed in a forearc context at the western margin of the Antarctic Peninsula. The geologic and structural constraints of WANT indicate the influence during the Mesozoic of the subduction process of western Pacific. After the end of Paleogene, by the strike-slip fault systems that result in the drifting apart of the of the South America and the Antarctic Peninsula (Adie, 1964, 1977; Barton, 1965; Birkenmajer, 1981, 2001; Smellie et al., 1984, 2006; Elliot and Fleming, 2000; Hervé et al., 2006).

Like the other South Shetland Islands, Nelson Island is mainly composed of andesitic and intrusive lavas, with a few thin intercalations of volcanoclastic sediments (Elliot, 1988; Birkenmajer, 2001). Palaeontological surveys have shown that the fossiliferous levels are restricted to the northeast part of the Island and occur in an isolated outcrop at Rip Point on the Fildes Strait coast approximately 1.0 km north of the Crulls Brazilian Refuge (62°14′19"S/58°59′0"W). The exposure begins near sea level and extends nearly 10.0 m high. Geological prospecting in the area has shown that similar, but less well-preserved, fossils and intercalations of lava and tuff also occur in levels at an altitude of 200.0 m (Birkenmajer, 1981; Hansen et al., 1988). The Fildes Strait separates Nelson Island from southern King George Island, in which other Upper Cretaceous lithologies are exposed [e.g. Half Three Point (Liu, 1990)]. According to Birkenmajer (1981), the Fildes Strait resulted in faults transversally positioned in relation to the alignment of the South Shetland Islands.

The Rip Point outcrop is composed of dark grey pyroclastic rocks and lavas (tuff and lapilli) with restricted lenses of volcanoclastic grains. Macro- and microfloristic records occur in two horizons (Fig. 2). The

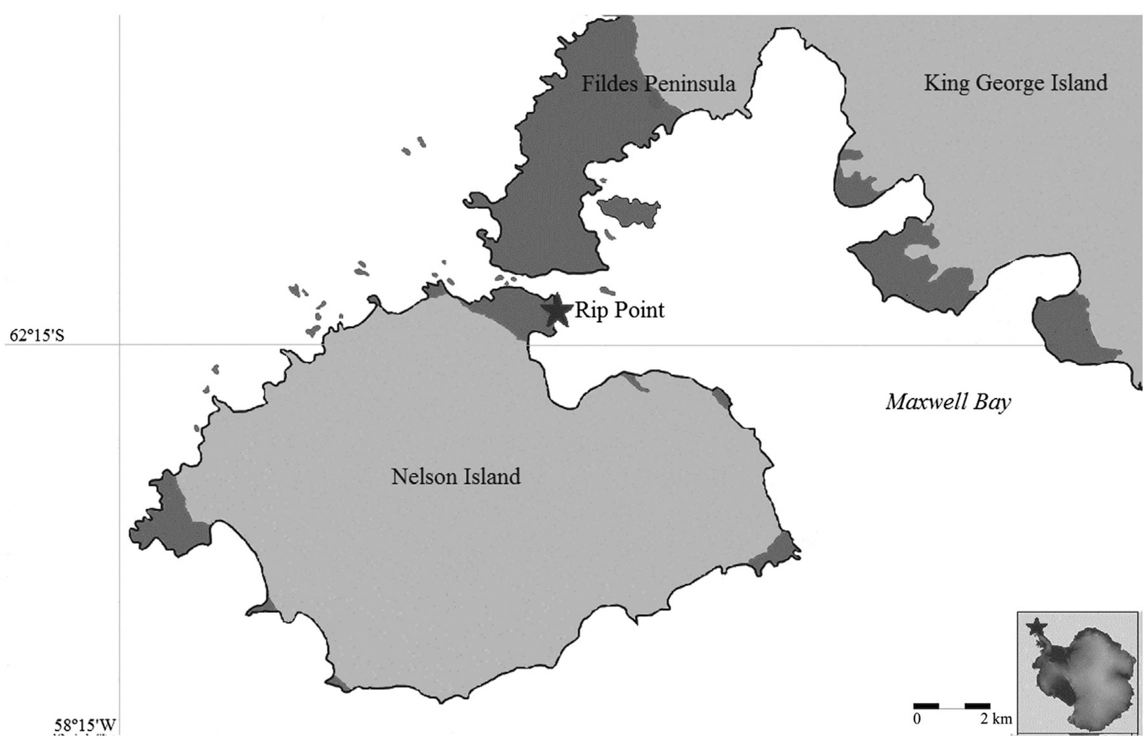

Fig. 1. Simplified map of Antarctica with the position of Nelson Island in relation to the Antarctic Peninsula. The Rip Point locality is indicated by the star on Nelson Island.

macroscopic charcoal described here occurs only in a thin tuff bed directly overlying the breccia deposits at the profile base. The other unique macrofossils in these layers are well-preserved fronds of Dicksoniaceae [*Coniopteris* sp. (Dutra et al., 1996; Trevisan et al., 2012)] and dispersed wood logs. The palynological analysis showed spore and pollen grains of other pteridophytes (e.g. Cyatheaceae), gymnosperms (Araucariaceae, Cheirolepidiaceae and Cycadaceae) and angiosperms, with primitive forms of *Nothofagus* as the dominant component (Bastos et al., 2013). The identification of rare foraminifers in the petrographic sections indicates a near-coast context to the deposition. This is similar to the deltaic and shallow marine environments inferred by Eklund et al. (2004) for the Table Nunatak deposition and those inferred by Kvaček and Sakala (2011) for the Hidden Lake and Santa Marta formations in the East Antarctica Peninsula.

The uppermost plant fossil level of Rip Point contains macro- and microflora and is dominated by primitive forms of *Nothofagus* represented by members of the *Lophozonia* genus, which currently only exist in South America. Impressions of Anacardiaceae and Lauraceae and what is likely Melastomataceae complete the poorly preserved assemblage (Bastos et al., 2013).

The Rip Point microfossil content is comparable to that of the nearby Half Three Point outcrop analysed by Liu (1994). It is also exposed near

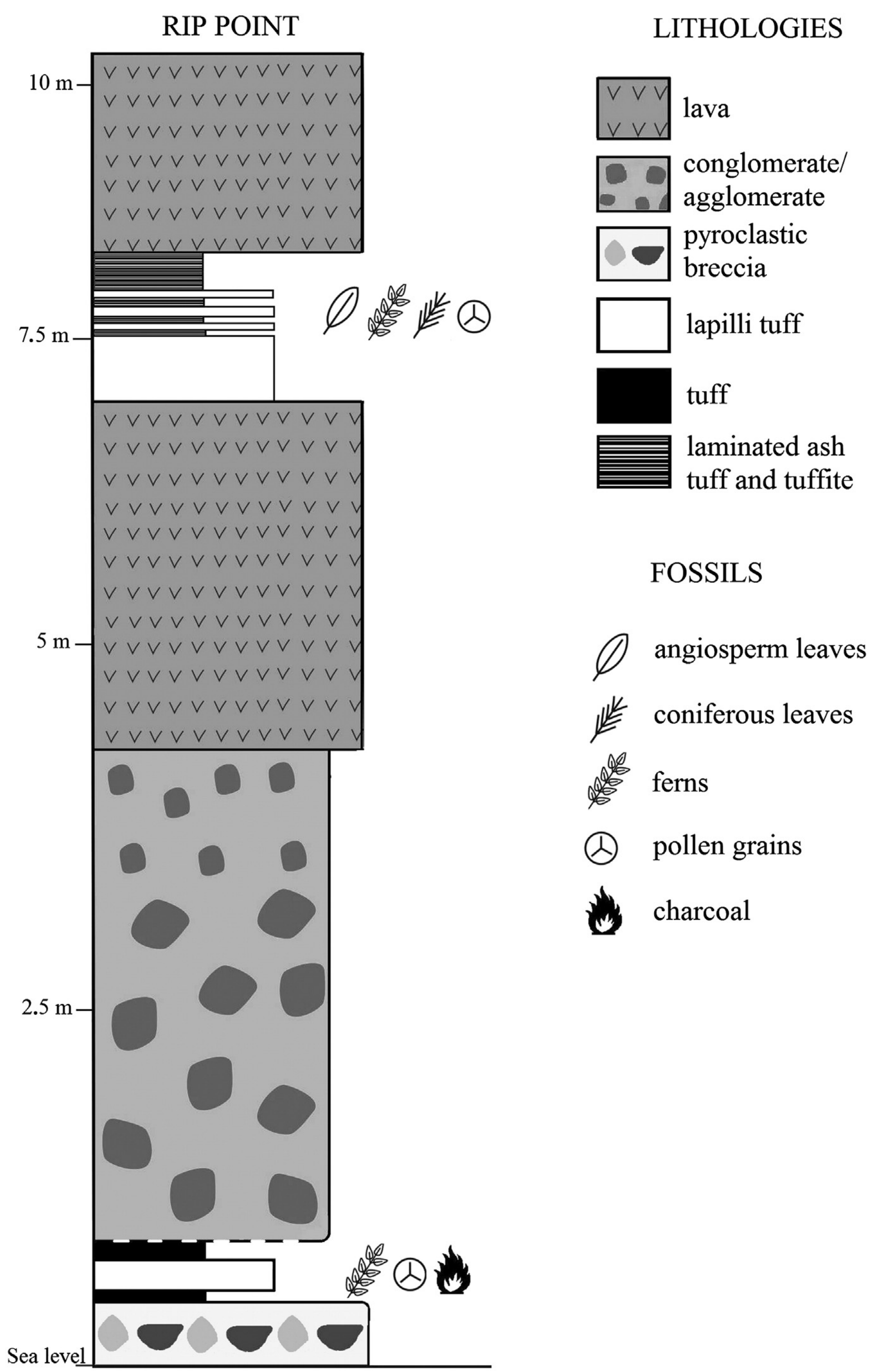

Fig. 2. Rip Point geological section and its main volcanic and volcanoclastic levels, highlighting the two fossil plant beds. The tuff level covering the basal pyroclastic breccia is where macroscopic charcoal studied here was found.
Modified from Bastos et al. (2013).

sea level and is located on southeast King George Island. At this locality, radiometric data from calc-alkaline basalt overlying the fossiliferous tuff levels, which contain palynomorphs, provide a Late Campanian age [Rb/Sr ages between 71–77 Ma (Wang and Shen, 1994)].

3. Material and methods

This study was carried out with samples collected at the Rip Point outcrop during expeditions supported by the Brazilian Antarctic Program (PROANTAR). In the field distinct (partly) charred wood fragments [varying between 19.9–36.3 cm in length and 1.0–2.5 cm in diameter (Fig. 3)] restricted to a thin layer covering the basal volcanic breccia were observed. Considering the difficult logistics, only portions (12 in total) of those fragments could be collected for detailed study.

In the laboratory, the macroscopic charcoal samples were mechanically extracted from the sediment with the aid of a stereomicroscope (Zeiss Stemi 2000-C) with a magnification of 10× and 40×. They were stored in the Antarctic Section of the Earth and Life History Laboratory (LaViGea) at UNISINOS, under the acronym Pbac. The macroscopic charcoal samples were subsequently mounted on standard stubs with LeitC (Plano GmbH, www.plano-em.de) for morpho-anatomical analysis under a scanning electron microscope (SEM-Zeiss EVO LS15) at the *Instituto Tecnológico de Ensaios de Segurança* (ITTFuse) at UNISINOS.

Based on the observed anatomical structures, general taxonomic affiliations were established using the morpho-key provided by Philippe and Bamford (2008). Additionally, hypotheses regarding palaeoecological conditions were constructed based on the new data as well as the existing associated depositional data for the regional context.

4. Results

The collected fragments of 1.0–3.0 mm in width and 1.0–5.0 mm in length had most of the features described by Jones and Chaloner (1991) and Scott (2000, 2010) as typical of macroscopic charcoal [black colour, silky lustre (Fig. 3), well preserved anatomical details (Fig. 4A) and homogenized cell walls (Fig. 4B)].

Tracheids that were 10.0–26.0 μm wide and 50.0–250.0 μm long were observed (Fig. 4C). In radial longitudinal sections, the tracheids showed abietinoid pitting with circular areolate pits in their radial walls, which were uniseriate spaced or, occasionally, contiguous (Fig. 4D, E and F). The cell lumina and surfaces of the cell walls were often impregnated with unidentified minerals (Fig. 4B, F, G and H).

The pits were 7.0–10.0 μm in diameter and had circular or oval apertures that were 3.0–5.0 μm in diameter. Cross-field pits were not observed. In longitudinal tangential sections, the radial system was homogeneous with homocellular, uniseriate, low rays of 7–9 cells in height. The ray cells were triangular in shape at their extremities and rectangular in shape in their centres. They were 8.0–10.0 μm in width and 8.0–16.0 μm in length (Fig. 4G and H).

Only small areas with those anatomical features could be observed due to the compaction of the sediments, which also caused compaction of the wood.

5. Discussion

Although there was an absence of black streaks, which can be related to how the samples were preserved (i.e. impregnation with minerals), all other features characteristic for charcoal as described by Jones and Chaloner (1991) and Scott (2000, 2010), especially homogenized cell walls observed under SEM, were present. This confirms that the woody fragments investigated here correspond to charcoal. Because charcoal is fragile, the occurrence of large pieces indicates that these samples were not transported far (Scott, 2000; Abu Hamad et al., 2012). The stems were 36.3 cm in length, indicating that the macroscopic charcoal deposition at the Rip Point outcrop occurred in an autochthonous context and that these stems represent partly (or superficially) charred logs. High compaction rates have been observed in many localities with fine-grained sediments, such as tuffs (e.g., Marynowski and Simoneit, 2009; Kubik et al., in press); correspondingly, compaction of wood cells occurred after deposition at the Rip Point outcrop.

The volcanic ashes, in which the charcoal was deposited indicate that volcanism was a potential ignition source for the palaeo-wildfires. Based on taphonomic observations, the charred remains indicate a superficial burn of the woody vegetation growing in an area in the direct vicinity of the deposition site (Bastos et al., 2013).

The occurrence of tracheids with well-homogenized cell walls and without cracking of their middle lamella also supports volcanic events as a possible cause of the charcoal formation. Scott and Glasspool (2005) and Glasspool and Scott (2013) conducted experimental studies that simulated the burial of wood in hot volcanic ash

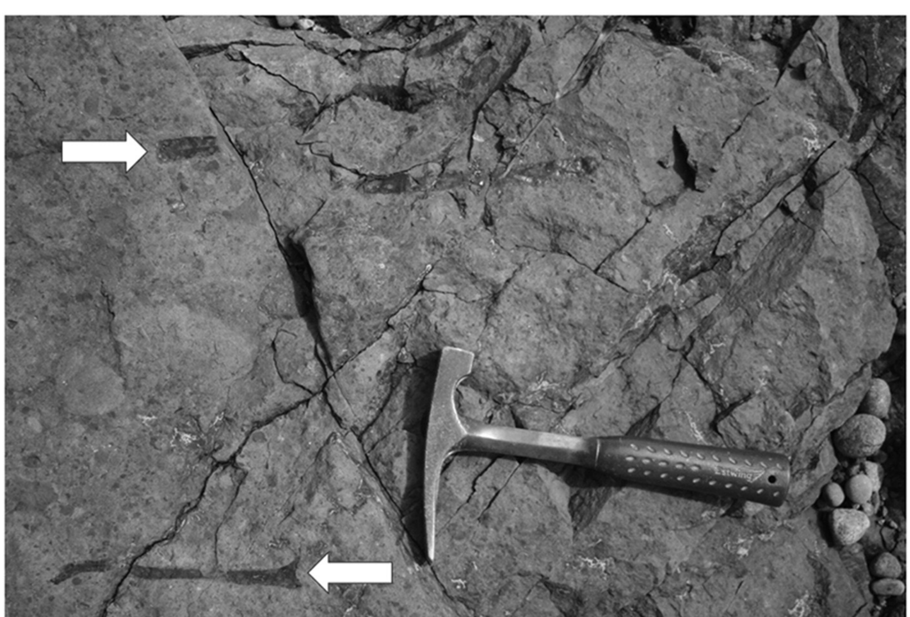

Fig. 3. Aspect and disposition of the macroscopic charcoal fragments in the Rip Point basal tuff level (arrows).

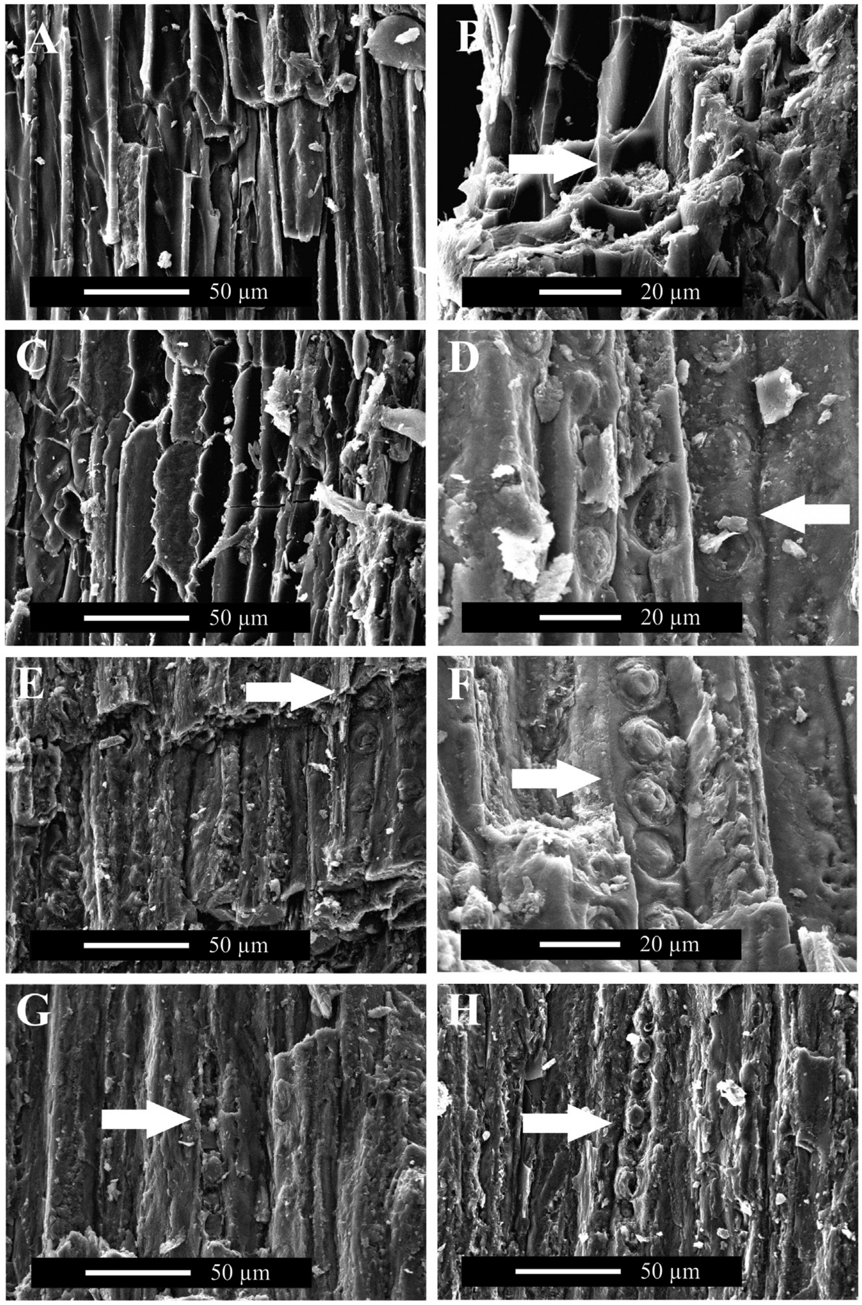

Fig. 4. SEM images of the Rip Point charcoal: A) highly fragmented tracheids; B) oblique view the charred wood with homogenized cell wall (arrow); C) highly fragmented tracheids; D) charred wood in radial longitudinal section showing uniseriate, spaced pits (arrow); E) charred wood in radial longitudinal section showing uniseriate, spaced pits (arrow); F) charred wood in radial longitudinal section showing uniseriate, contiguous pits (arrow); G) charred wood in longitudinal tangential section showing a uniseriate ray that is 7 cells high (arrow); H) charred wood in longitudinal tangential section showing a uniseriate ray that is 9 cells high (arrow).

without oxygen ingress; they found that no cracking occurred along the line of the middle lamella if temperatures were kept constant at 900 °C for 24 h.

According to Wegmann et al. (2014), one of the main effects on the microclimate near the volcanoes is the influx of rain (normally acid rain) during an eruption, which occurs due to the ash particles attracting water droplets. According to Parfitt and Wilson (2008), rainfall generates important episodes of mudflow, which rapidly covers plant, preserving distinct organs and diversity. This concept was proposed by Eklund et al. (2004) for the Table Nunatak Formation. However, the extreme weather conditions during the deposition and consequent transport in mud or other flows can also contribute to the poor preservation of the fragments, as was observed for the Rip Point charcoal.

The charred materials contained tracheids with abietoid pitting and uniseriate rays; thus, the Rip Point macroscopic charcoal has an affinity for coniferous remains. Based on Lüttge et al. (2005) and Philippe and Bamford (2008), the uniseriate, spaced pitting occurring with contiguous pitting in the same sample, confirms the abietoid pattern. However, the overall poor preservation of the material prevented the establishment of a more detailed taxonomic affinity. A coniferous affinity matches with the macro- and microfloristic composition described for the region during the Upper Cretaceous. Those data demonstrated that ferns and non-coniferous seed plants were less present than gymnosperms and that, except for *Nothofagus*, gymnosperms were the dominating woody components of the area (Dutra et al., 1996; Dutra and Batten, 2000; Bastos et al., 2013). Pujana et al. (2014) showed that these conditions did not change in the Early Cenozoic, with conifer woods (with a dominance of

Podocarpaceae) representing 68% of the preserved woody material in the La Meseta Formation beds, at James Ross Basin.

The identification of the oldest known remains of Cupressaceae in the Southern Hemisphere in the same profile at Rip Point (upper fossiliferous level) by Bastos et al. (2013) is also noteworthy. However, the abietoid pitting pattern of the analysed macroscopic charcoal samples occurs in woods of both Podocarpaceae and Cupressaceae (Philippe and Bamford, 2008), preventing a more detailed taxonomic identification.

The macro- and microfloral remains preserved in the two fossiliferous levels of the studied site (Trevisan et al., 2012; Bastos et al., 2013) point to a recovering of the vegetation in the inter-eruption phases, but not with the exact same components.

The data presented here for the western sector of the Antarctic Peninsula, most likely during the Campanian, seems to be related to data regarding other palaeo-wildfires through the end of the Upper Cretaceous in that area. The previously known record, revised by Brown et al. (2012) based on their own data and on a global overview published by Glasspool and Scott (2010), noted the presence of charred plant remains published by Eklund (2003) and Eklund et al. (2004) from Santonian levels of the Table Nunatak Formation in the eastern Antarctic Peninsula. The only other information regarding the occurrence of charcoalified mesofossils was presented by Kvaček and Sakala (2011) and was with regard to the Santonian/Lower Campanian levels of the James Ross Basin, which is also in the eastern flank of the Peninsula. However, those authors did not provide any evidence (e.g. SEM images) to confirm the precisely charcoal nature of their material.

Thus, the charred wood described here, is the first substantiated record of that type of preservation of Late Campanian remains from the entire WANT. It complements previous studies that provided direct evidence for palaeo-wildfires (charcoal and inertinites) during the Cretaceous in the Southern Hemisphere (e.g. Francis and Coffin, 1992; Newman and Newman, 1992; Suggate, 1998; Pole and Douglas, 1999; Passalia, 2007; Martill et al., 2012).

Considering the intense volcanic activity that took place on the western fore arc areas of the Antarctic Peninsula during the Cretaceous, more macroscopic charcoal remains are expected. Thus, the collection of new data and discussions regarding taphonomic biases, fuel shortage and sampling methods (Abu Hamad et al., 2012) must occur before a more detailed picture of palaeo-wildfire occurrence can be drawn for this region and time. In Antarctica, fieldworks are difficult, contributing to the current lack of knowledge regarding the occurrence of palaeo-wildfires, and additional fieldwork with a more explicit focus on this issue will be necessary.

6. Conclusions

Based on the data presented here, it is possible to draw the following conclusions:

(1) the presence of macroscopic charcoal in northeast Nelson Island, the South Shetland Islands, and the Antarctic Peninsula, and, consequently, the occurrence of palaeo-wildfires, is confirmed for the first time in this sector of the Antarctic Peninsula;
(2) the plant fossil level containing macroscopic charcoal is related to the end of the Campanian by correlation (biological and faciological) with the Half Three Point deposits in King George Island;
(3) the macroscopic charcoal remains, which have been preserved by volcanic ash, originated from a wood vegetation that grows not far from the marginal marine area and depositional site;
(4) a coniferous taxonomic affinity can be established for the preserved charred woods;
(5) despite the absence of direct evidence, the autochthonous charcoal deposition and the tectonic context allow to infer that volcanic activity was the major ignition source for the palaeo-wildfires.

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