RESEARCH ARTICLE

Wildfires in the Campanian of James Ross Island: a new macro-charcoal record for the Antarctic Peninsula

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Abstract

The Cretaceous "high-fire" period was a global event that reached almost all continental masses during that period in Earth's history. The extensive wildfires directly affected plant communities. Significant palaeobotanical records in the Antarctic Peninsula have been studied from the James Ross Sub-Basin, especially from the Santa Marta Formation. However, there is no described evidence for palaeo-wildfires in the area so far. Here, we present the first occurrence of fossilized macro-charcoal coming from James Ross Island, confirming that palaeo-wildfires occurred in the Campanian vegetation preserved in the Santa Marta Formation. The new charcoal material has a gymnospermous taxonomic affinity, more specifically with the Araucariaceae, which is in accordance with previous palaeobotanical records from James Ross Island. This occurrence adds new information to the construction of the palaeo-wildfire scenario for Gondwana.

Keywords

Charcoal; palaeo-wildfires; Cretaceous; Southern Hemisphere; Gondwana; Cretaceous high-fire

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Abbreviations

LeitC: Latvian Electronic Equipment Testing Centre
PALEOANTAR: Paleobiology and Paleogeography of South Gondwana: Interrelationships between Antarctica and South America (research project)
PbUMCN: Paleobotânica—Museu de Ciências—UNIVATES
SEM: scanning electron microscope

Introduction

Extensive wildfire activity during the Cretaceous "high-fire" period directly affected the plant communities, playing a significant role in palaeoecological changes in different environments (Scott et al. 2014). A compilation for the entire Cretaceous by Brown et al. (2012), as well as numerous additional studies published in recent years (e.g., Manfroi et al. 2015; El Atfy et al. 2019; Lima et al. 2019; Uhl et al. 2019), has demonstrated that fires were frequent and were widespread during this period, reaching both low- and high-latitudinal areas. There is evidence of fire on every continent in the Late Cretaceous, but most of the data come from the Northern Hemisphere (Brown et al. 2012). Analogous "Gondwanan" gymnosperm forests in the Southern Hemisphere periodically burn in places such as Tasmania, New Zealand and Argentina (McGlone et al. 2016; Arzadun et al. 2017; Prior et al. 2018).

During the Late Cretaceous, the Southern Hemisphere was experiencing the final breakup of Gondwana, and continental areas, including Antarctica, became isolated from other portions of the former continent (Boger 2011). The Antarctic Peninsula evolved under intense volcanic activity caused by tectonics, preserving diverse fossil biotas in strata related to ash falls (Birkenmajer 2001; Willan & Hunter 2005; Reguero et al. 2013).

Concerning Late Cretaceous palaeobotanical evidence in the Antarctic Peninsula, significant records have been studied coming from the James Ross Sub-Basin, especially from

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the James Ross Island area, where the Santa Marta Formation crops out (Crame et al. 1991; Poole & Francis 1999, 2000; Poole, Cantrill et al. 2000; Poole, Gottwald et al. 2000; Cantrill & Poole 2005; Poole & Cantrill 2006; Kvacek & Sakala 2011; Leppe et al. 2012; Pujana et al. 2017; Pujana et al. 2018; Pipo et al. 2020). However, no palaeobotanical evidence that palaeo-wildfires reached the vegetation in this area has been described so far, although the region as a whole had favourable conditions for fire, for example, abundant vegetation, the presence of ignition sources and adequate pO_2 levels. The first palaeobotanical evidence that palaeo-wildfires reached Antarctica was reported only recently; it occurred during the Campanian at Rip Point, on Nelson Island (Manfroi et al. 2015). Considering the scarcity of data and taking into account the significance of the evolution of the Antarctic Peninsula for palaeobiodiversity, we present the first occurrence of macro-charcoal coming from the James Ross Island. This record confirms that palaeo-wildfires reached the vegetation during the Campanian in the Santa Marta Formation.

Geological setting and palaeobotanical overview

The James Ross Archipelago is located next to the western tip of the Antarctic Peninsula and exposes a sedimentary succession known as the Marambio Group of the Larsen Basin (Fig. 1). This basin is subdivided into the South and

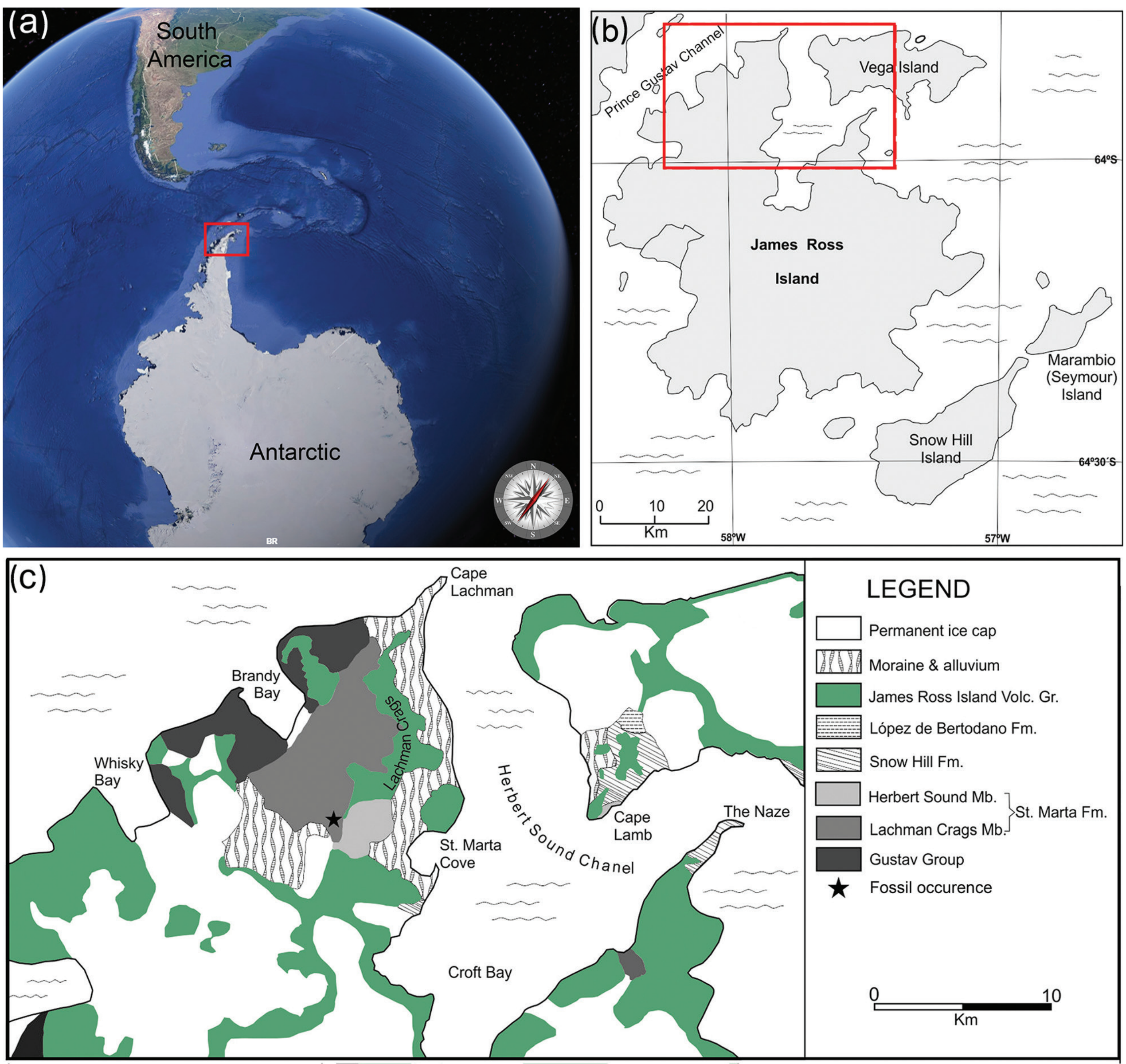

Fig. 1 (a–b) Location of the Antarctic Peninsula and James Ross Island. (c) Geological map of the north-east portion of James Ross Island, showing the geographic location of the studied area with a star.

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James Ross sub-basins (Macdonald et al. 1987). The origin of the James Ross Sub-Basin is attributed to the break-up of Gondwana, and the deposition of a Meso-Cenozoic sedimentary sequence occurs in a backwater system (Hathway 2000). It is one of the thickest and most complete volcano-sedimentary sequences deposited from the Cretaceous to the Paleogene in the Southern Hemisphere (Crame et al. 1996). Lithostratigraphically, it is formed by the Nordenskjöld Formation, the Gustav Group and the Marambio Group (Hathway 2000; Riding & Crame 2002).

The Marambio Group crops out on James Ross, Vega, Humps, Snow Hill, Seymour and Cockburn islands (Crame et al. 1991; Pirrie et al. 1997). These islands represent a progradant system, composed of a variety of sandstones, siltstones and lamites, with high levels of coquinas, deposited under storm conditions on the internal to external platform (Crame et al. 1991). It is divided lithostratigraphically into Santa Marta, Snow Hill Island, Lopez de Bertodano and Sobral formations (Fig. 2).

The Santa Marta Formation (Santonian–Campanian) is the basal unit of the Marambio Group. More than 900 m in thickness, it consists of sandstones, siltstones and argillites intercalated with volcanic tufts and rare coquinas (Olivero 2012). This is interpreted as a sequence of volcanoclastic surfaces deposited in a deltaic environment (Olivero 2012). Locally, at the north-west portion of James Ross Island, the Santa Marta Formation is divided in Lachman Crags and Herbert Sound members (Crame et al. 1991).

The basal Lachman Crags Member has a thickness of approximately 850 m, consisting of mudstones, siltstones and sandstones with rare conglomerates, which are commonly found in its upper part (Crame et al. 1991). Its age comprises the late Coniacian to late Campanian (Crame et al. 1991). The new charcoal material was collected at the top of the Lachman Crags .

The upper Herbert Sound Member was named by Crame et al. (1991) and is 250 m thick, consisting of fine sandstone with cross-stratification and shell coquinas. It is late Campanian–early Maastrichtian in age, based on fossils and strontium isotope dating (Crame et al. 1991; Olivero & Medina 2000).

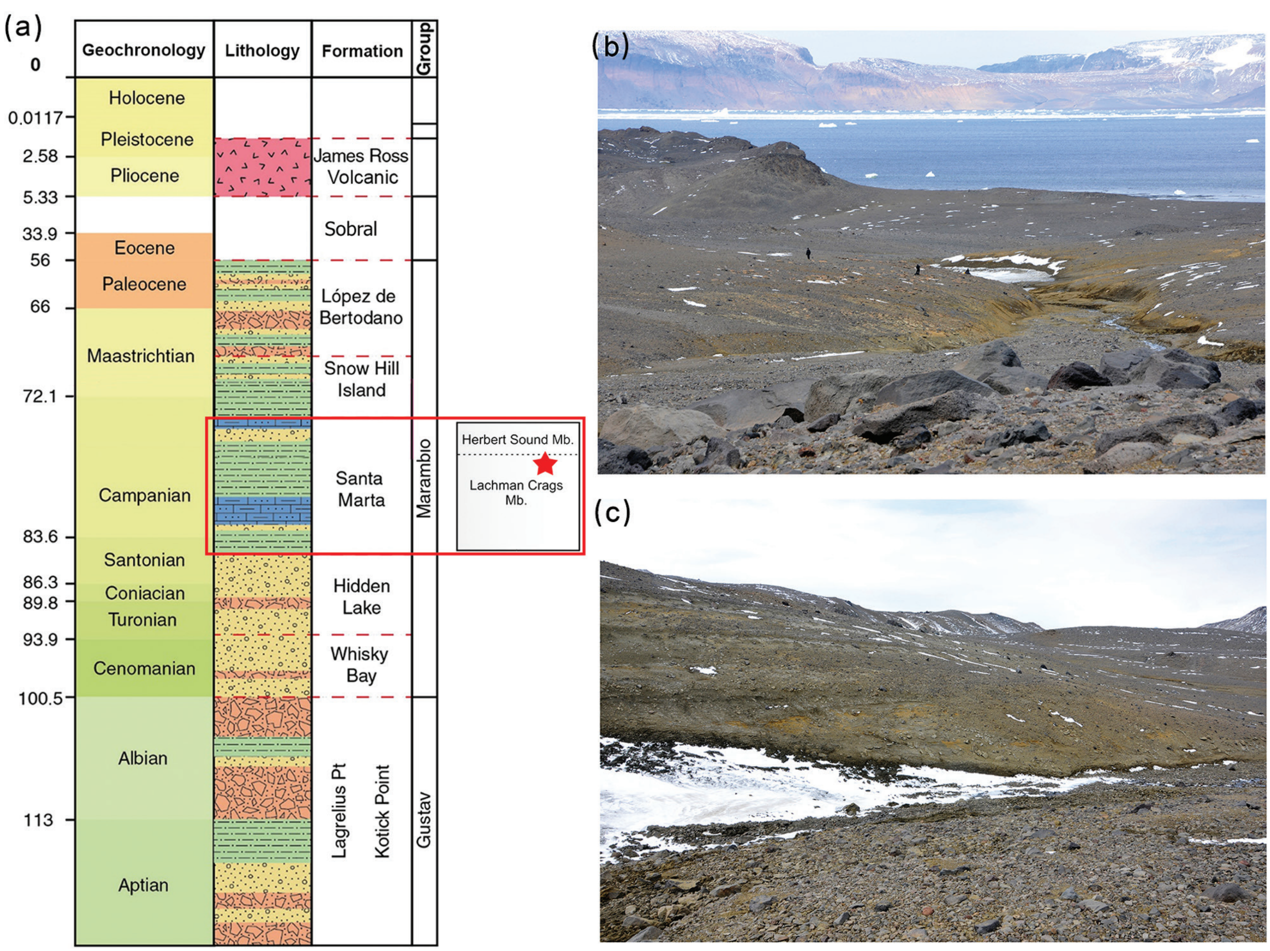

Fig. 2 (a) Stratigraphic chart for the James Ross Sub-Basin. (b–c) Field photograph of the area that hosts the charcoal.

The palaeobotanical record of the Antarctic Peninsula and its adjacent islands is well known from Cretaceous sediments of the back-arc James Ross Sub-Basin (e.g., Svojtka et al. 2009), which are full of fossils (Crame et al. 1991). Fossil wood has been known from these regions since the 1830s, with reports of additional wood localities in the Seymour Island region (Sharman & Newton 1898). The majority of studies that include fossil woods and descriptions of the palaeoflora from the Santa Marta Formation were published in the last decades, especially from James Ross Island. Most of them refer to vegetation not only with a canopy dominated by conifers (Cantrill & Poole 2005; Pujana et al. 2017) but also with an important component of some angiosperms and ferns (Poole & Francis 1999, 2000; Poole, Cantrill et al. 2000; Poole, Gottwald et al. 2000; Kvacek & Vodrázka 2016; Pujana et al. 2018). Some works briefly mention fossil woods but lack anatomical descriptions (e.g., Cantrill & Poole 2005) or mention gymnosperm fossil woods identified only as conifers because of their poor preservation (e.g., Kvacek & Sakala 2011). The prospected area was restricted to the north, north-east, north-western and western portions of James Ross Island, around the localities called Brandy Bay, Lachman Crags, Stickle Ridge and Lost Valley, respectively.

Pujana et al. (2017, 2018) conducted a detailed taxonomical review of fossil wood from different strata of the Santa Marta Formation at the Brandy Bay locality in James Ross Island. Regarding gymnosperms, the authors described a new species, *Cupressinoxylon rotundum*, and also reported the occurrence of *Agathoxylon*, *Phyllocladoxylon antarcticum* and *Cupressinoxylon hallei*, which were previously known for other regions in Antarctica (e.g., Pujana et al. 2014). Also, they point out significant conifer diversity in the Brandy Bay (Pujana et al. 2017). Pujana et al. (2018) described fossil angiosperms from Santa Marta Formation at the same locality, proposing three new species: *Paraphyllanthoxylon antarcticum*, *Weinmannioxylon trichospermoides* and *Cretaceoxylon heteropunctatum*. They also recognized the occurrence of three other angiosperm taxa based on their anatomy: *Laurelites jamesrossii*, *Hedycaryoxylon tambourissoides* and *Eucryphiaceoxylon eucryphioides* (Pujana et al. 2018).

Recently, Pipo et al. (2020) described *Sarcandraxylon sanjosense*, a permineralized stem preserved in marine calcareous concretions from the Campanian (Upper Cretaceous) of James Ross Island, and assigned this fossil to the Chloranthaceae family, relating it to the extant genus *Sarcandra* (Pipo et al. 2020).

Material and methods

The samples presented here were collected from outcrops of the Lachman Crags Member (Santa Marta Formation) in the north-eastern part of James Ross Island. The material was collected along with other fossils that have been recently described (Kellner et al. 2019; Pinheiro et al. 2020; Piovesan et al. 2021) by the PALEOANTAR team, during the fieldwork of the XXXIV Brazilian Antarctic Operation (austral summer 2015/16). Four fragments showing macroscopic features of charcoal (≥2.0 mm, black colour and streak, silky luster [*sensu* Jones & Chaloner 1991; Scott 2000, 2010]) were mechanically extracted from the sedimentary levels for evaluation in the laboratory.

The samples were analysed under a stereomicroscope (Leica M80) and mounted on standard stubs (Plano, Münster, Germany). Subsequently, the material was examined with the aid of a JEOL JSM 6490 LV SEM (accelerator current 20 kV) at the Senckenberg Research Institute and Natural History Museum, Frankfurt.

The ImageJ software was used for anatomical features imaging and measurements. The samples and corresponding stubs are stored in the palaeobotanical collection of the Laboratory of Paleobotany and Biome Evolution, Science Museum, University of Vale do Taquari (Brazil), under the acronym PbUMCN (1181–1184).

Results

The macro-charcoal fragments are 5.0–19.0 mm wide, 7.0–38.0 mm long and 1.0–2.0 mm thick and exhibit slightly abraded edges. Besides the typical macro-charcoal features, the samples are impregnated by a weak yellowish substance that can be visualized without the aid of magnification lenses.

Under SEM, well-preserved anatomical details, including homogenized cell walls, can be observed (Fig. 3a–c). Charcoal is a direct evidence for palaeo-wildfires (Scott 2010), and the presence of homogenized cell walls confirms that the material we studied was charred. In longitudinal section, tracheids show rare uniseriate (Fig. 3d–e) or biseriate alternate pitting (Fig. 3f) consisting of uniseriate pits (Fig. 3e). Rare uniseriate rays, formed by four to seven cells and 150–187 µm in height, are preserved. Cross-field pitting seems to be cupressoid to taxodioid (Fig. 4), but this character is easily disturbed during charring and cannot be used reliably for a taxonomic treatment of woody charcoal. However, all observed characteristics point to a gymnosperm origin (Araucariaceae) of these samples.

Discussion

In the last few years, the need for more information from high-latitude biotas—especially in Antarctica—and their role in the global context of continental drift and plate tectonics have become clearer (Cantrill & Poole 2005). Since the Antarctic plate was close to the South Pole for a

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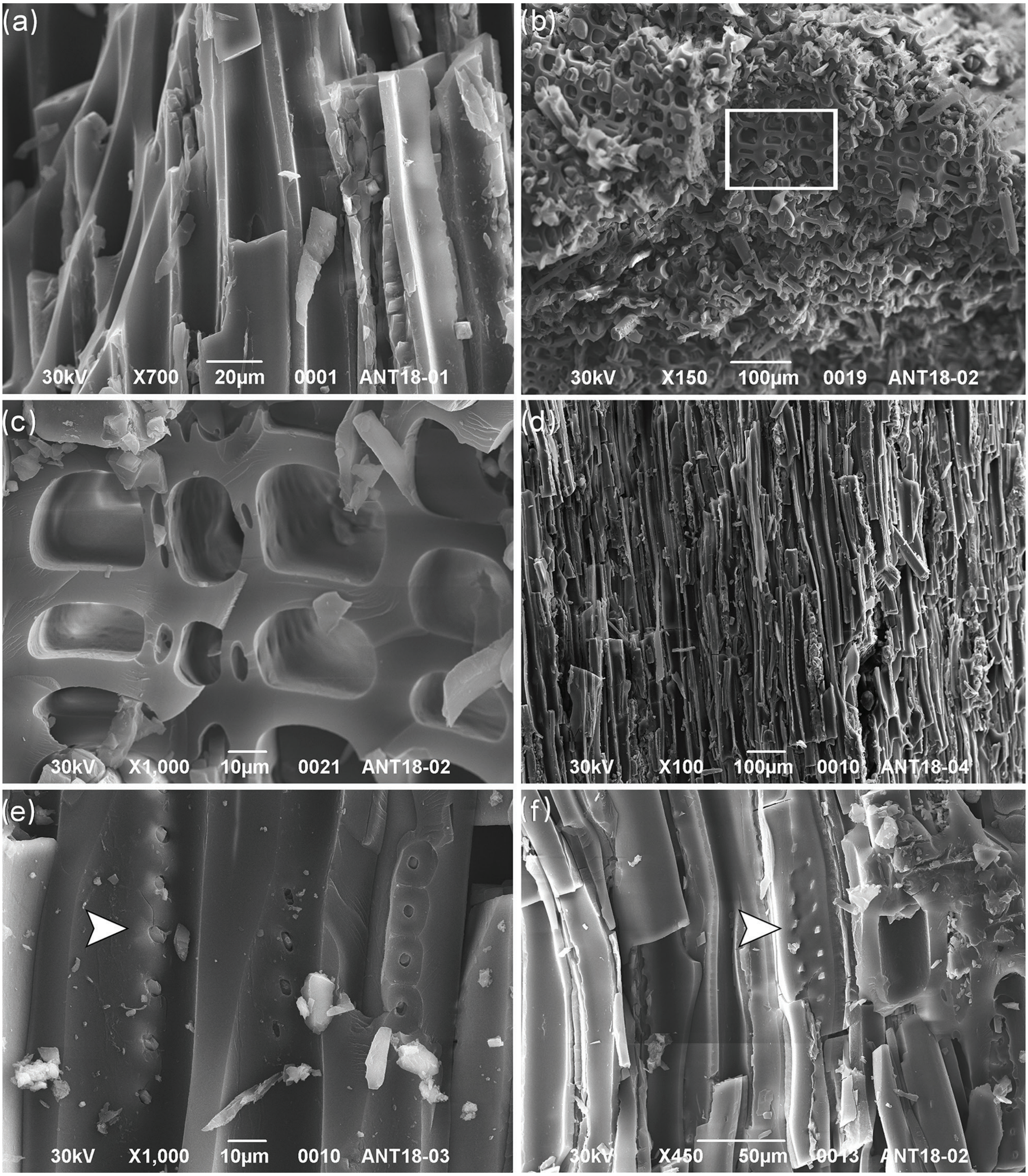

Fig. 3 SEM images of gymnosperm charcoal from the Santa Marta Formation. (a) Homogenized cell-walls; (b) overview of the cross-section; (c) detail of (b) showing the cross-section of the three-dimensionally preserved wood with homogenized cell walls; (d) overview of tracheids in the longitudinal section; (e) longitudinal section showing uniseriate pits; (f) longitudinal section showing alternate pitting.

long geological period, the succession of biotas on this continent over this time sheds light on the physical parameters influencing the evolution of animals and plants (Poole & Francis 2000). Plants are among the organisms most sensitive to changes in environment and climate. Understanding floristic successions is, therefore,

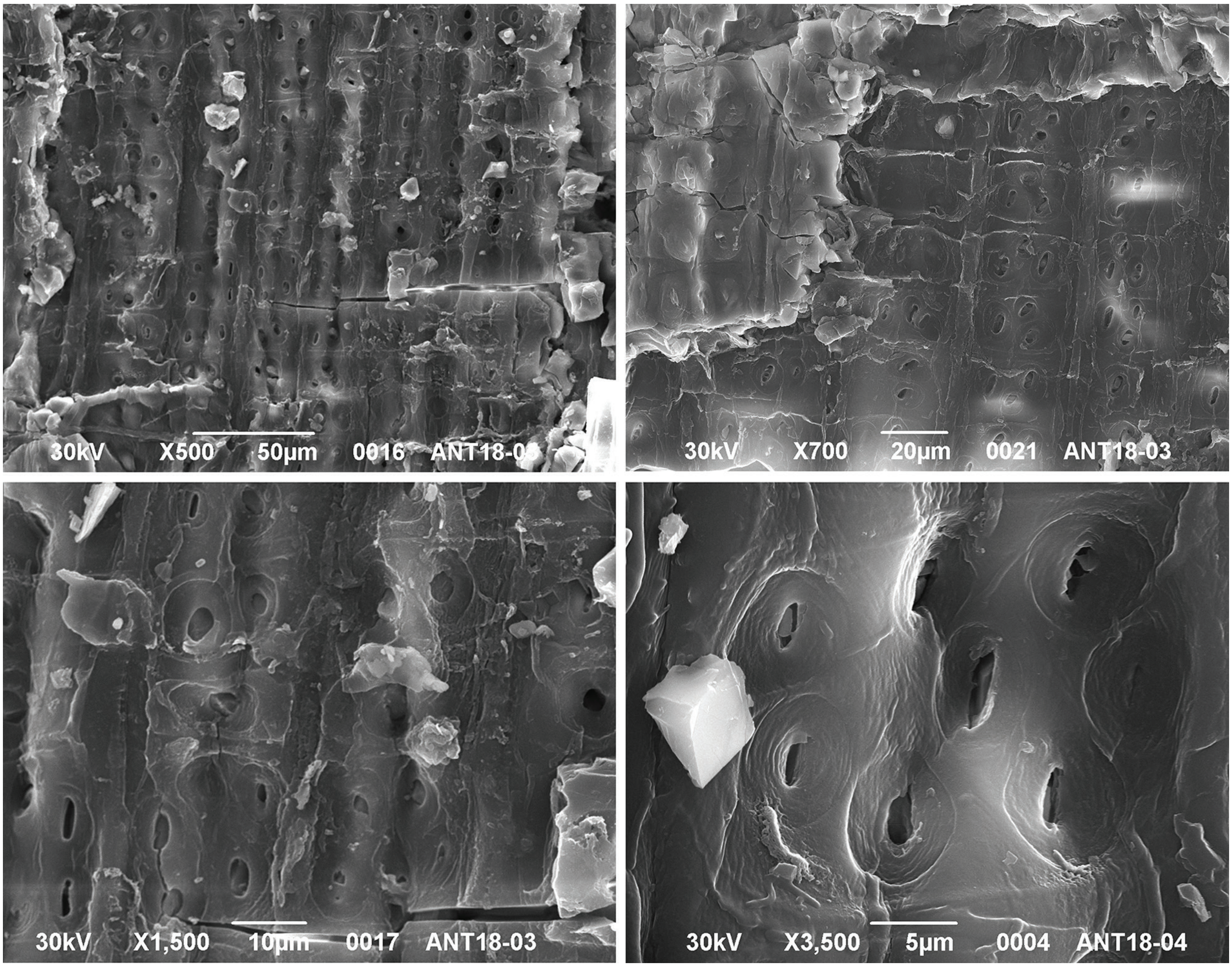

Fig. 4 SEM images of gymnosperm charcoal from the Santa Marta Formation showing cupressoid to taxodioid cross-field pitting.

extremely informative in the reconstruction of climatic and ecological events that occurred over long periods of time (Poole & Cantrill 2006).

In the fossil record, Antarctica had a highly diverse biota sustained by very favourable climate for certain kinds of vegetation in contrast to the modern environment (Poole & Francis 2000; Cantrill & Poole 2005; Klages et al. 2020). This can also be assumed for the Cretaceous, a well-known global "high-fire" period (Scott et al. 2014). Evidence for Cretaceous palaeo-wildfires has been studied all over the globe (Brown et al. 2012; Scott et al. 2014), and charcoal occurrences include high-latitude areas such as Antarctica, which was covered by abundant arboreal vegetation until the Neogene (Leppe et al. 2012). The current latitude of the fossiliferous location presented here is at the northern edge of the boreal forests, which are both coniferous and fire-adapted where lightning is a common ignition source. This shows that fires at this latitude were not necessarily extremely unusual in a warmer, ice-free world.

Oxygen is a prerequisite for the propagation of fire, and its level impacts the flammability (Glasspool et al. 2015) and long-term fire occurrence (Scott & Glasspool 2006). During the Late Cretaceous, the palaeo-atmospheric oxygen level was well beyond 15 or 16%, the lowest range of the "fire window." When the oxygen level is under 16%, it is unlikely to have been more than trivial wildfire activity (Belcher & McElwain 2008). Some experimental data indicate that 16% pO_2 fires will not propagate, no matter how minimal the moisture content of the fuel available (Wildman et al. 2004; Scott & Glasspool 2006; Glasspool et al. 2015). At oxygen levels above 21%, fires will ignite more readily, and at levels exceeding 23%, they become common (Glasspool et al. 2015). The oxygen supply in the Late Cretaceous was sufficient for fires to occur, even for a short duration, during the Campanian.

The natural forest fire—caused by lightning strikes, fireballs, sparks and volcanic activity—was a regular phenomenon throughout geological time (Scott 2000). Antarctica had intense volcanic activity caused by tectonics during the Cretaceous, as suggested by the presence of fossil remains in strata related to ash falls (Birkenmajer 2001; Willan & Hunter 2005; Reguero et al. 2013). It is plausible that volcanic activity ignited the palaeo-wildfire that created the charcoal reported here. Volcanic activity was also the probable cause proposed for charcoal occurring in the Cretaceous deposits on Nelson Island (Manfroi et al. 2015). Furthermore, the deposition of charred wood under coastal marine conditions usually implies severe fragmentation, so the preservation of fragments reaching 38.0 mm in length suggests a parautochthonous origin for the material studied here.

Antarctic palaeofloristic dynamics are essential to understanding the changes that occurred in Southern Hemisphere high-latitude environments during the Cretaceous. An exuberant conifer-dominated vegetation was gradually replaced by an angiosperm-dominated assemblage during the Paleo–Eocene and subsequently by ice sheets during the Neogene (Bond & Scott 2010; Brown et al. 2012; El Atfy et al. 2019). Antarctica experienced palaeo-wildfires in different localities during the Late Cretaceous, as inferred from the meso-charcoal record (Fig. 5). Santonian remains come from the eastern side of the Antarctic Peninsula, at Table Nunatak of the Kenyon Peninsula (Eklund et al. 2004) and from Rip Point, north-east Nelson Island (Manfroi et al. 2015); there are also briefly mentioned, but not described, charcoalified plant mesofossils from the Hidden Lake and Santa Marta formations, of Coniacian/Campanian age, on James Ross Island (Kvacek & Sakala 2011). The new record presented here, from another unit of the James Ross Sub-Basin, represents a significant input to the palaeobotany studies in the area.

Studies related to the anatomy of fossil woods play an important role in understanding the Antarctic palaeofloras and floristic successions that took place in Cretaceous forests, especially related to Gondwana. Forests dominated by conifers are compatible with the

Fig. 5 Reconstruction of palaeo-wildfires in Antarctica during the Cretaceous. Illustration by Maurilio Oliveira (palaeoartist, National Museum, Federal University of Rio de Janeiro).

pollen and macrofloras that have been described from the Santa Marta Formation (Pujana et al. 2017; Pujana et al. 2018). The characteristics of the charcoal samples, such as the shape of the tracheids, with a rare uniseriate or biseriate alternate pitting, supporting a gymnosperm affinity. In addition, the cupressoid cross-field pits are common in Cupressaceae and Taxodiaceae (Richter et al. 2004). However, because these characteristics are easily modified by charring (Gerards et al. 2007), they are not reliable for assigning the fossils to a precise gymnosperm family. Nonetheless, the clear alternate arrangement of the tracheid bordered pits indicates Araucariaceae. This family is also represented by silicified wood taxa. The only other possible wood taxon is *Sahnioxylon*, but it has irregular biseriate bordered pits and scalariform pits on the tracheids, with numerous cross-field pits. Although the identification of the charcoal as gymnosperms is plausible, any specific or even generic assignments cannot be made on the account of the relatively small sample size and limited number of diagnostic features (as observed before by Uhl & Jasper [2018] for charcoal from Germany). Nonetheless, the fossils studied here are relevant for systematic, palaeoecological and biogeographic comparative studies with other fossil assemblages, as Herendeen (1991) proposed.

Conclusions

Each new discovery contributes to the establishment of Cretaceous palaeo-wildfires in southern Gondwana, including Antarctica. In this context, an Araucariaceae taxonomic affinity can be established for the charcoal described here based on the tracheid bordered pits clearly alternately arranged. This macro-charcoal is consistent with wood macrofossils found in the same geological unit. This is the first detailed description of macro-charcoal from the James Ross Island, confirming that palaeo-wildfires reached its vegetation during the Campanian, as preserved in the Santa Marta Formation and observed in other Antarctic areas.

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Disclosure statement

The authors report no conflicts of interest.

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