Lithostratigraphy, age and distribution of Eocene volcanic sequences on eastern King George Island, South Shetland Islands, Antarctica

Smellie, J.L.[1*], Hunt, R.J.[2], McIntosh, W.C.[3] and Esser, R.P.[3,4]

[1] *School of Geography, Geology & the Environment, University of Leicester, Leicester LE1 7RH, UK [jls55@le.ac.uk]*
[2] *School of Earth Sciences, University of Leeds, Woodhouse Lane, Leeds, LS2 9JT [rjh138@icloud.com]*
[3] *New Mexico Bureau of Geology and Mineral Resources, New Mexico Tech, Socorro, NM, 87801, USA [mcintosh@nmt.edu]*
[4] *now at: Energy and Geosciences Institute, University of Utah, Salt Lake City, UT, 84108, USA [richard.esser@utah.edu]*

Supplementary Information file S3 - Description of the Carruthers Cliff palaeoflora

Introduction

This is a taxonomic account of the poorly-preserved, species-depauperate Eocene (Ypresian) palaeoflora at Vauréal Peak, King George Island (after Hunt, 2001, modified). The angiosperm leaf macrofossils preserved in the Carruthers Cliff flora are described using leaf venation architecture. The leaves are primarily assigned to morphotypes. Although this is only a preliminary study, to aid future comparisons additional examples found at other localities elsewhere on King George Island are indicated (also examined by Hunt, 2001; Hunt and Poole, 2003). Taxonomic affinities of the leaves are discussed where possible. Description of a rare non-angiosperm component of the palaeoflora is also included.

Techniques

Specimens with organic preservation were examined for cuticle using both an Olympus SC-35 (SZH-DA) stereomicroscope with a high objective lens (University of Leeds), and a Leitz microscope, housing a high pressure mercury vapour bulb (100 watts) for fluorescence microscopy (Department of Plant and Animal Sciences, Sheffield University). Ordinary light microscope examination of the specimens revealed no cuticular remains. The preservation is as leaf impressions.

Leaf venation and tooth architecture were drawn and photographed using a stereomicroscope with camera and camera lucida attachments. Photographs were also taken by the University of Leeds Photographic Services using manual and digital SLR cameras. Fossil surfaces were immersed in ethanol and studied with low angle lighting to enhance surface texture.

Descriptive Terminology

Leaf architectural nomenclature used here is based on the Manual of Leaf Architecture (MLA) (Leaf Architecture Working Group, 1999) and Hickey (1973, 1979). Tooth architectural descriptions follow the system of Hickey and Wolfe (1975) and the MLA. The morphotypes have been grouped in a hierarchical fashion based on characteristics of margin type, leaf organisation and lower order venation. Photographs and leaf drawings are used to support morphotype descriptions. Examples of comparable leaf types at other localities on King George Island are also noted, where appropriate. All specimens are held in collections of the British Antarctic Survey, Cambridge, UK.

Size class data are expressed in terms of the Runkiær (1934) definition as modified by Webb (1959) and uses the size class overlays of the Leaf Architecture Working Group (1999). Estimates of leaf area are based on the formula: 'area = *2/3* length x width' (Cain and Castro, 1959), except for leaves with an approximately square lamina, in which case 'area = length x width' was considered to be more appropriate. In most descriptions the percentage of leaves of each size class is stated in addition to the actual number of leaves counted (e.g. Pole, 1993), otherwise the size class range of morphotype is stated. Many of the leaf fossils are incomplete, therefore length, width and area measurements are stated as minimum values or estimated values where reasonable constraint of the original lamina shape is available. Where there is reasonable constraint of the lamina margins, width estimates assume that the lamina is symmetrical and the total width = 2 x half width. Length estimates are more arbitrary and rely on using the trend of the reserved margin to interpret the size and shape of the leaf. Such estimates become increasingly difficult with smaller leaf fragments and are generally inappropriate (or highly subjective) if less than c. 50 % of the original lamina is preserved, unless that fossil fragment comprises a large section of the leaf margin. The large quantity of specimens to be examined in the toothed leaves category has meant that leaf measurements have not been expressed for every specimen, instead some descriptions are based on the most complete specimens preserved. The leaves are listed in the material examined category to give an estimate of the diversity and distribution of each morphotype.

Secondary divergence angles were standardised and defined as the angle between the primary vein and a secondary vein at 50 % of its length. The number and degree of completeness of specimens used to define each morphotype is stated in the description. The degree of completeness is defined as: Small fragment < 50 % of lamina; Large fragment 50 - 75 % lamina; Near complete> 75 % lamina; Complete> 90 % of lamina.

Taxonomic interpretations

The method adopted for taxonomic identifications was based on initial reference to the synoptic key and tooth architectural studies of Hickey and Wolfe (1975) and the Southern Hemisphere fossil literature (biased greatly towards New Zealand and Australia), early works from Seymour Island (Dusen, 1908) and southern South America (Dusen, 1899; Berry, 1928, 1938), and reference texts, such as Klucking (1986; 1987; 1988; 1989; 1991; 1992; 1995), Christophel and Hyland (1993) and Heywood (1998). Reference is also made (by locality and specimen number) to comparable leaf fossil specimens found elsewhere on King George Island and which are described in detail by Hunt (2001) and Hunt and Poole (2003). Modern plant distributions were obtained from Mabberley (1997). In addition, the modern composition of cool to warm temperate Southern Hemisphere forests has also been used as an index for possible plant families and genera that may have been present in Antarctica (e.g. Veblen et al., 1996). This has inevitably been biased, towards *Nothofagus* dominated forests, since *Nothofagus* is a dominant element in the Tertiary fossil record.

Previous macrofossil collections from the Antarctic Peninsula and southern South America generally lack cuticle and tertiary or higher order venation, which are important taxonomic features (Dilcher, 1974). Detailed leaf architecture descriptions are often lacking for that material and the descriptions often lack a sound systematic basis. In addition, detailed modern records of the South American floras are lacking. A solid database of morphological characters is therefore lacking. This is particularly pertinent when describing taxa that have conservative leaf morphologies such as the Lauraceae, Cunoniaceae *(Weinmannia* and *Schizomerieae),* Proteaceae and for the Nothofagaceae, which are extremely difficult to differentiate without cuticle data.

Taxonomy

1. Entire margined morphotypes

Non-lobed

Brochidodromous veined leaves

Morphotype 1A (Fig. S3-1)

Material examined: Vauréal Peak *Large fragment* P2799.2.1,.6.1,.6.2. Other examples on King George Island: Potter Cove impression flora *Small fragment* P.232.17.4.

Differential characters: Elliptic leaves with thick secondaries. Basal secondaries are slightly more acute and irregular than apical secondaries.

Description: Leaf organisation appears simple. Lamina narrow-elliptic, symmetrical. Length est. 94 - 96 mm, width est. 26 - 30 mm, length:width ratio 3.2 - 3.62. Area est. 1629.33 – 1920 mm^2. Microphyll = 4 (100 %). Apex acute convex, apical angle 41° - 55°. Base slightly asymmetrical, acute convex, basal angle 42° - 46°. *Venation* Primary pinnate weak brochidodromous. *Primary* thickness weak to moderate. Course straight. *Secondary* min 5 – 11 (est. 14) pairs of moderate secondaries diverging at a moderate to wide acute 40° - 73° Spacing uniform or increasing basally, divergence angle decreasing exmedially. Course curves abruptly near the margin, joining suprajacent secondary at an acute angle. Strong intersecondaries. *Tertiary* vein category mixed opposite and alternate percurrent, course convex or sinuous, vein angle to primary perpendicular or obtuse, angle increasing basally. *Fourth order* vein category regular polygonal reticulate. *Fifth order* vein category regular polygonal reticulate. Areoles 4 or more sided. *Sixth order* veins are highest order present. Single F. E. V observed to be 2 or more branched. Highest excurrent fifth order. Marginal ultimate venation (?)looped. Leaf rank 3r.

Remarks: There is no whole leaf preservation of this morphotype, although the two leaf fragments preserved on P.2799.6 are very similar in size and morphology and it is tempting to suggest that they are base and apex of the same leaf. The conservative nature of this leaf morphology means that it is comparable to a number of fossil species from South America, such as *Nectandra* spp. (Orlando, 1964; Berry, 1938), *Cassia* L. spp. (leguminosae), *Embothrium* Forster and Forster f., spp., and *Iloffmannia protagaea* Engel., (Proteaceae) (Berry, 1938), *Remijia* DC spp., and *Cephalanthus* L. spp. (both in the Rubiaceae). Of these *Cephalanthus glabratifolius* Berry and *Iloffmania protagaea* have a more acute pair of basal secondaries and opposite branching secondaries, suggesting affinities with the fossil

Rubiaceae and Proteaceae. By reference to modern herbarium material and leaf atlases, the entire margined elliptical leaf type with brochidodromous venation is perhaps the most conservative leaf morphology, occurring in many modern southern temperate families including, but not exclusive to, Lauraceae, Sapindaceae, Winteraceae, Myrtaceae and Proteaceae.

Morphotype 1B (Fig. S3-2)

Material examined: Vauréal Peak *Small fragment* P2799.14.1.

Differential characters: Elliptic leaf with tine secondaries and an acuminate apex.

Description: Leaf organisation appears simple. Lamina (?)wide elliptic, (?)symmetrical. Lamina length min 45 mm, width est. 30 mm, length:width ratio min 1.18: 1. Area 900 mm^2. Notophyll = 1 (100 %). Apex acute, acuminate, apical angle c. 80°. Base not preserved. Petiole not preserved. Margin entire. *Venation* pinnate weak brochidodromous. *Primary* thickness weak. *Secondary* min 7 fine secondaries, diverging at a wide acute angle 60° - 73°, course is curved abruptly, joining suprajacent secondaries at an acute angle, some loops show ramification with tertiary loops. One intersecondary present. *Tertiary* vein category alternate percurrent, course sinuous, obtuse angle to primary vein. Higher order venation not preserved. Leaf rank 2r/3r.

Remarks: The leaf is considered to be entire margined, however the possibility of toothing in the absent basal region of the lamina cannot be excluded. The poor preservation of the specimen does not allow detailed morphological comparisons. An apical fragment of a leaf also with an acuminate apex, fine secondaries and weak brochidodromous venation was described by (Greenwood et al., 2000) from the Neogene Yallourn Clays, Australia, but no taxonomic affinities were suggested. Fine brochidodromous secondaries und acuminate apices are also found in *Anona infestens, Allamanda crassostipitata* Engelhardt and *Ficus patagonica* Berry from the Rio Pichileufu flora of Argentina (Berry, 1938), but increased basal spacing is only present in A. *infestens,* which is also of a similar size. The closest affinities are therefore with A. *infestens* or possibly with the Yallourn Clays specimen.

Eucamptodromous veined leaves

Morphotype 1C (Fig. S3-3)

Material examined: Vauréal Peak *Large fragment* P2799.1.2.

Differential characters: Elliptic to lanceolate leaf with an enrolled margin frequent intersecondary veins and an undulose lamina. Secondary vein course highly variable.
Description: Leaf organisation appears simple. Lamina symmetrical, wide elliptic. Length min 40 mm, width min 24 mm, length:width ratio 1.66:1. Area min 640 mm^2. Microphyll = I (100 %). Apex not preserved, ?convex. Base asymmetrical, acute convex, basal angle 71°. Petiole thickened relative to primary vein. Margin ?entire, although not well preserved. Margins enrolled, lamina undulose. Mineralised leaf has a coriaceous texture. *Venation* pinnate weak eucamptodromous. *Primary* thickness weak. *Secondaries* min 17 moderate secondaries, diverging at moderate acute angle 45° - 60°. Secondaries thin rapidly towards margin and are sometimes branched, spacing irregular, vein angle approximately uniform but lower on sinistral portion of lamina. Weak intersecondaries. *Tertiary* vein category weakly percurrent, angle to primary (?)obtuse.

Remarks: Morphotype 1C is unusual in having an enrolled margin, an undulose lamina, a feature only rarely seen elsewhere in King George Island floras, and irregular vein spacing and branching. The irregular nature of the undulation suggests that it is does not result from plicate vernation, which is usually regular. Inflated intercostal areas are present in the Myrtaceae family (e.g. *Lophomyrtus),* however this leaf lacks (or has not preserved) the intramarginal vein that normally characterises the Myrtaceae. The affinities of the leaf are uncertain.

2. Toothed morphotypes

Leaf organisation appears simple

Leaf lobed

Craspedodromous venation

Morphotype 2A *Nothofagus* sp. 1 (Fig. S3-4)

Material examined: Vauréal Peak *Large fragments* P.2799.1-.3, .5-.6, .8-.11, .13, .15-.18, .20, .22-.23, .26-.28. Other examples: Platt Cliffs (Cytadela) *Small fragment* G.309.15.

Differential characters: Ovate leaves with up to 36 secondary veins diverging at a narrow to moderate acute angle. Secondaries occasional branch abaxially, especially the basal pair.

Description: Lamina organisation appears simple. Lamina lanceolate to ovate symmetrical, length min. 26 - 110 mm, width min. 13 - 40 mm. Microphyll = 15 (88 %), Notophyll = 2 (12 %). Apex acute, apical angle 40 - 51°. Base symmetrical. convex, base angle wide acute 65-78°. Petiole normal, minimum length min. 12 mm width 1.5 mm. Margin serrate. *Venation* pinnate craspedodromous. *Primary* moderate to stout, course straight or slightly curved. *Secondary* minimum 7-18 sub-opposite pairs of secondary veins; narrow to wide acute divergence angle 40 - 60°, uniform or decreasing apically; secondaries are moderate thickness, course straight; secondaries may branch especially in basal pair. Straight non-paired secondary veins. *Secondaries* occasionally branch towards the margin, particularly in the basal pairs. *Tertiary* rare weakly percurrent tertiaries with a moderate acute angle of divergence. No higher order vein detail observed. *Teeth* indentation to midvein c. 1 mm, two orders of teeth, spacing and number of teeth uncertain due to poor margin preservation (74 per cm), tooth shape straight acuminate, (?)rounded sinus, tooth apical angle acute, teeth are simple.

Remarks: The extremely high number of secondary veins and the regular nature of the craspedodromous venation are typical of *Nothofagus subferruginea* (Dusen) Tanai, although the margin is not sufficiently well preserved to determine whether the leaves possess the characteristic double serration. This morphotype also differs in having a larger lamina (length < 110 mm, width < 40 mm). *N. subferruginea* is one of the most frequently described fossil leaf morphologies from King George Island but these associations are generally based on incompletely preserved leaves with little margin preservation, and the leaves often don't conform to Tanai's (1986) description of a leaf with a doubly serrate margin. For example, Troncoso (1986) described craspedodromous leaves with compound teeth with (?)up to four teeth/secondary which he referred to *N. subferruginea* as did Li (1994). At least one of figured leaves is more suggestive of a double serration (Li, 1994), although only a few of the leaves described by Li (1994) conform to the minimum 10 sub-opposite veins (Li, 1994; Tanai, 1986). This morphotype is therefore similar to *N. subferruginea*.

Morphotype 2B *Nothofagus* sp. 2 (Fig. S3-5)

Material examined: Vauréal Peak *Large fragments* P.2799.8, .27.2. Other examples: Cytadela (Platt Cliffs) *Small fragment* G.309.15.

Differential characters: Obovate leaves with frequent branching of the secondary veins and prominent intersecondaries. Margin at least doubly serrate, with up to four teeth/secondary.

Description: Leaf organisation appears simple. Lamina elliptic to obovate, symmetrical. Length min 40 - 55 mm, width est. 30 - 36 mm, length:width ratio 1.33: 1 - 1.53: 1. Area 1222-1621 mm^2. Notophyll = 2 (100 %). Base and apex absent. Apex (?)convex. Base (?)acute convex, midvein 0.75 - 1 mm. Shape ST-ST, ST-CV. Angular sinus, apical angle acute. Principal vein is a secondary or a secondary branch. Course (?)slightly eccentric, apical. Origin direct.

Remarks: These leaves are similar to Morphotype 2A, that is similar to *N. subferruginea,* but differ in having an obovate to elliptic lamina, frequent abaxial branches of the secondary veins and strong intersecondaries and multiple rather than the double serrations of Morphotype 2A.

Non-angiosperm foliage

Family incertae

Fertile fern (Fig. S3-6)

Material examined: Fertile axes Vauréal Peak P2799.12, .19, .21, .24, .26.1, .27. Other examples: Sterile foliage Barton Peninsula P.2145.2. Dragon Glacier flora P.2810.13. P.3001.3Sa/b. Fossil Hill Unit 3 P.3032.82.

Description: Preserved frond length 24 - 27 nun, total length unknown, at least once pinnate. Pinnules 3 - 4 mm long, 2 - 2.5 mm wide, arising at 50° - 70°. Single unbranched midvein. Pinnule margin interrupted by elliptical to reniform structures. 0.5 - 1 mm long, 0.1 - 0.5 mm wide, 0 – 2 elliptical structures present on both the basal and apical margins of the pinnule. Sterile foliage is essentially the same but frond lengths 25 - 55 mm, at least bipinnate. Primary pinnae 39 mm long, 1 mm wide, bearing at least 7 secondary pinnae. Secondary pinnae distichous, 7 - 11 mm apart, arising acutely 35° - 43° (av. 41°) at least 16 mm long. Pinnules 1.9 - 5.2 mm long, 1.9 - 2.6 mm wide, arising at 43° - 66°. Sterile foliage differs only in the lack of elliptic structures. Variable preservation gives the impression of toothing in some specimens.

Remarks: The elliptic structures present on the pinnule margins of Fertile Fern type 1 are probably sori. However, the poor preservation of the specimens prevents discrimination of which lamina surface is exposed. The elliptic structures may be the expression of an object from the reverse side of the lamina. The cupped shape of the pinnules and the similarity in size of the elliptic structures to the receptacles of *Lophosoria cupulatus* Cantrill, suggest that these fronds might be related to *Lophosoria.* However the number of pinnules per pinna is significantly higher in Fertile Fern type 1, which has up to 18 pinnules compared to a maximum of 12 in *L. cupulatus.*

Table S3-1. Taphonomic and environmental interpretations of the Carruthers Cliff plant beds and associated palaeoflora.

Description	Interpretation
Medium to fine grained fluvial volcaniclastic sandstones with a low diversity flora comprising five angiosperm taxa and ferns; many of the slabs are dominated (80 %) by a single nothofagaceous angiosperm morphotype (Morphotype 2A). The leaves are frequently preserved as mats, with poorly preserved overlapping sections of lamina suggesting in-situ decay following deposition.	The abundance of a single nothofagaceous species in these fluvial sandstones can be explained either in terms of: 1). a Nothofagus-dominated local forest environment; 2) by a nearby source of Nothofagus leaves (e.g. a tree overhanging the water body); or 3) as a function of leaf toughness, with such leaves being more durable and less prone to degradation.

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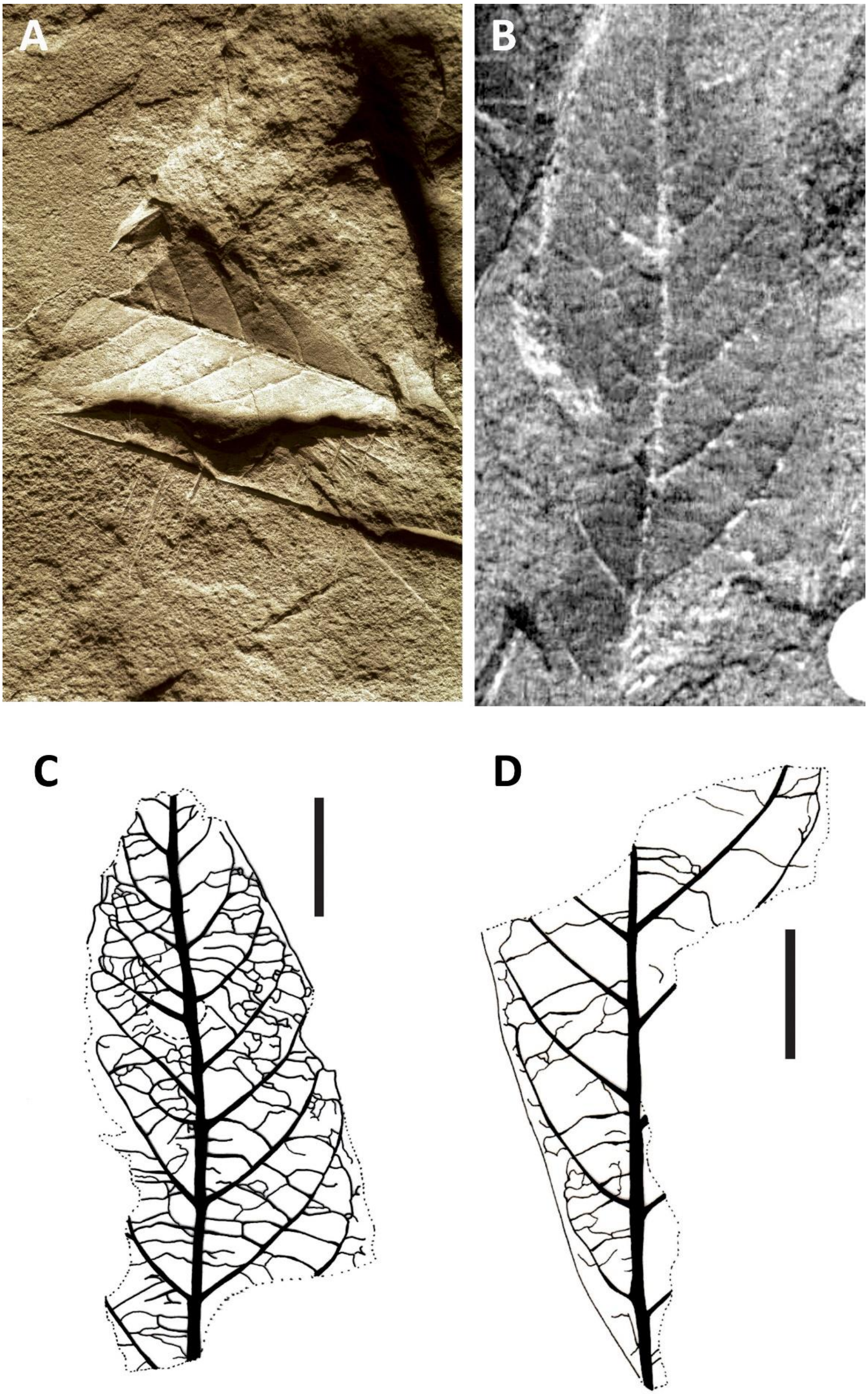

Fig. S3-1 Examples of Morphotype 1A. A - P.2799.2.1; B - P.2799.6.1. C - P.2799.6.1. D – P.2799.6.2. Scale bars 1 cm.

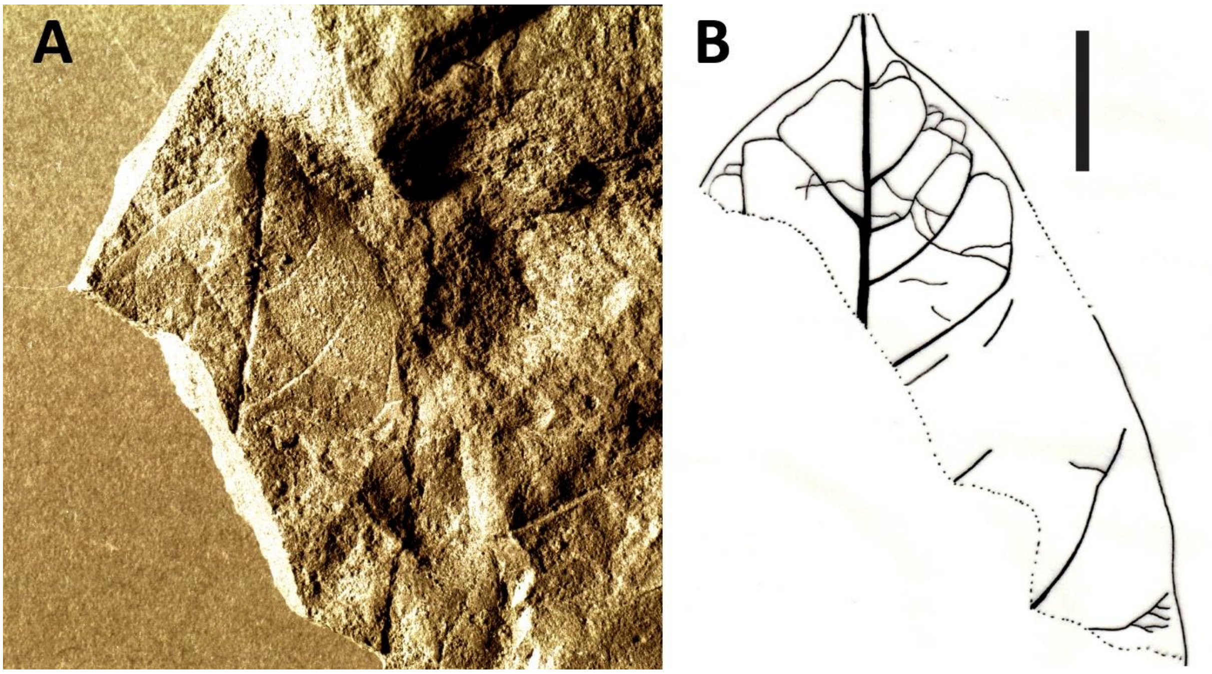

Fig. S3-2 Example of Morphotype 1B. A & B - P.2799.14.1. Scale bar 1 cm.

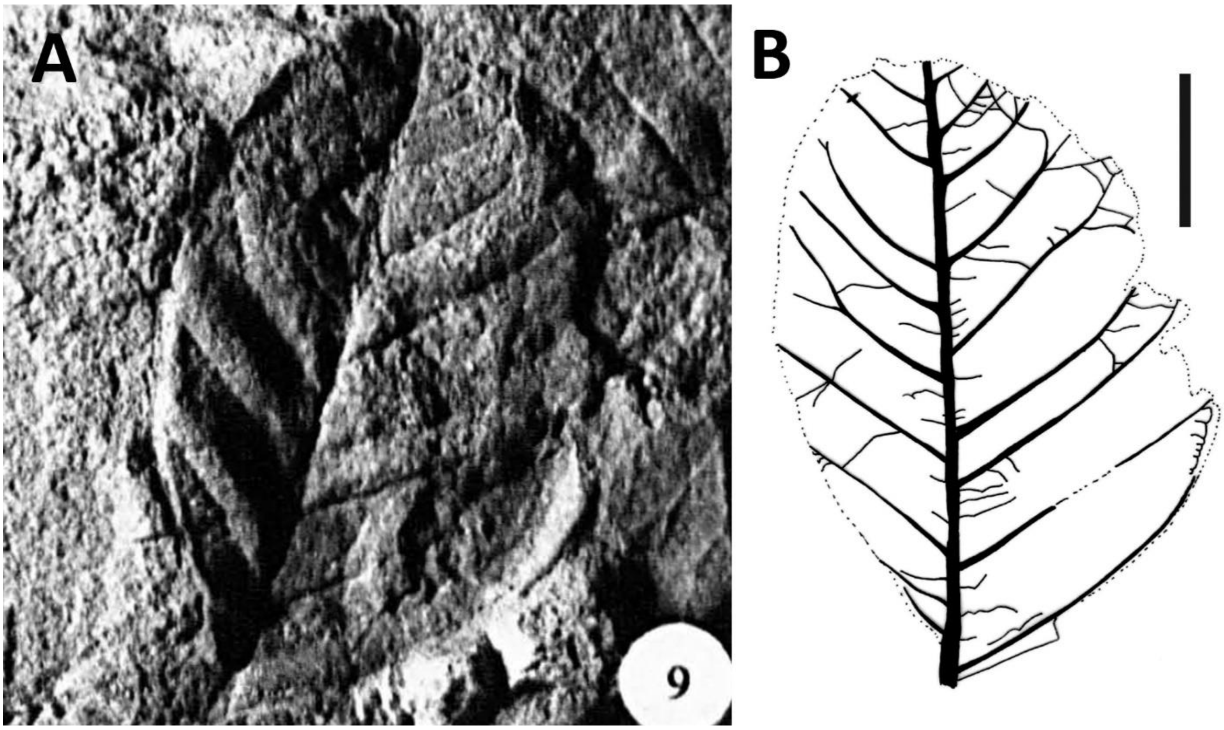

Fig. S3-3 Example of Morphotype 1C. A & B - P.2799.1.2. Scale bar 1 cm.

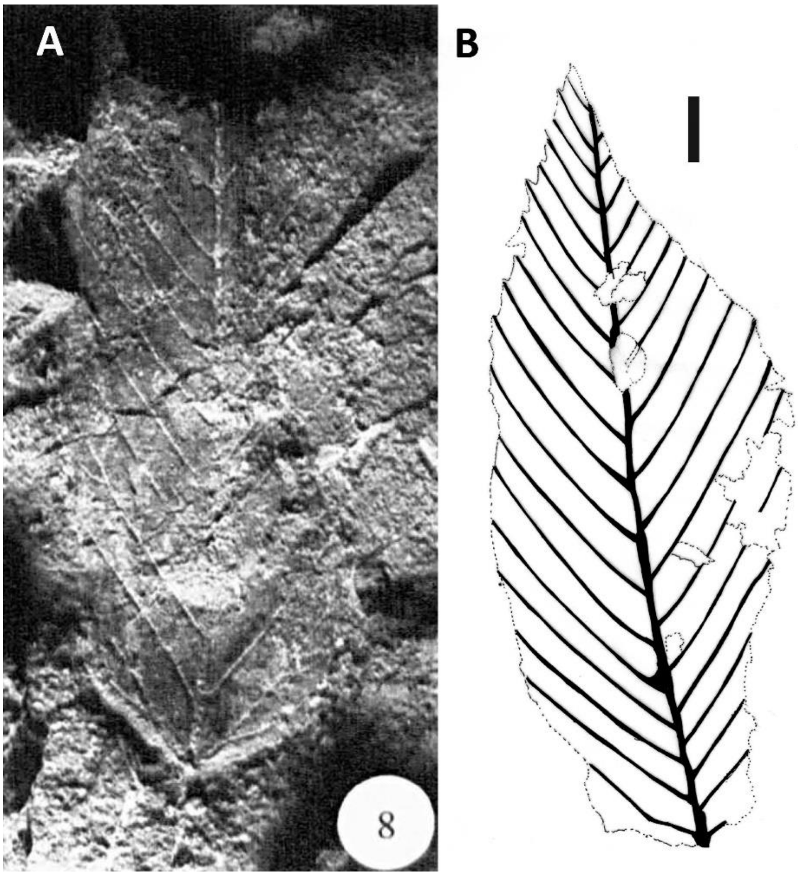

Fig. S3-4 Example of Morphotype 2A (*Nothofagus* sp. 1). A – P.2799.28; B - P.2799.8.1. Scale bar 1 cm.

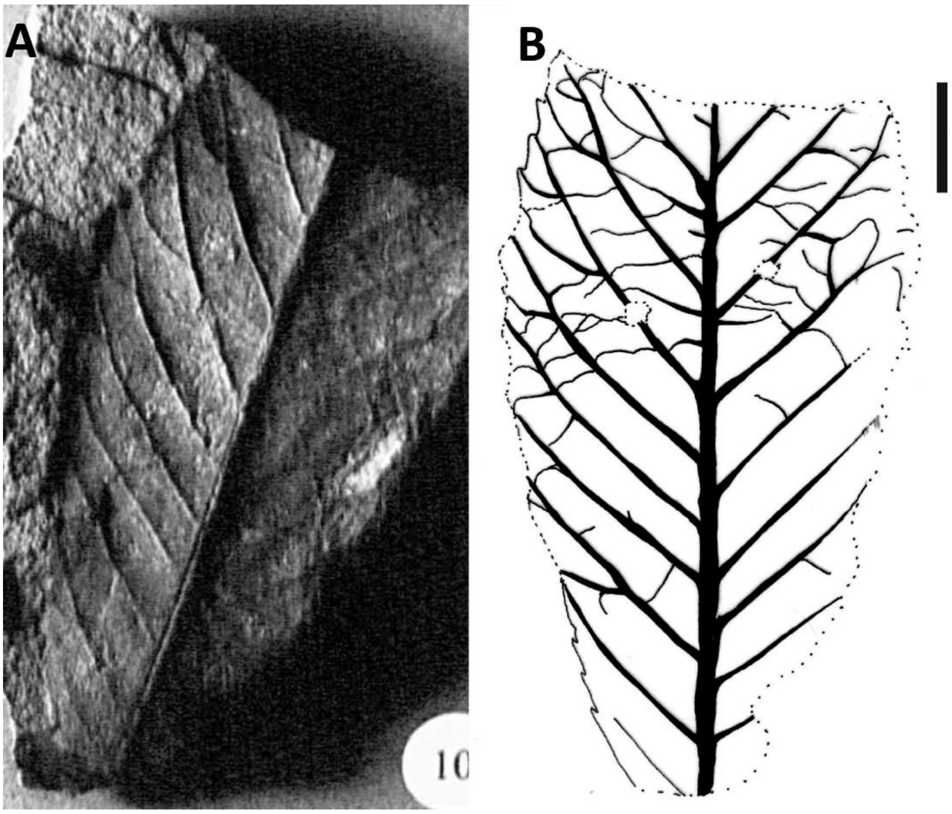

Fig. S3-5 Example of Morphotype 2B (*Nothofagus* sp. 2). A & B - P.2799.8.2. Scale bar 1 cm.

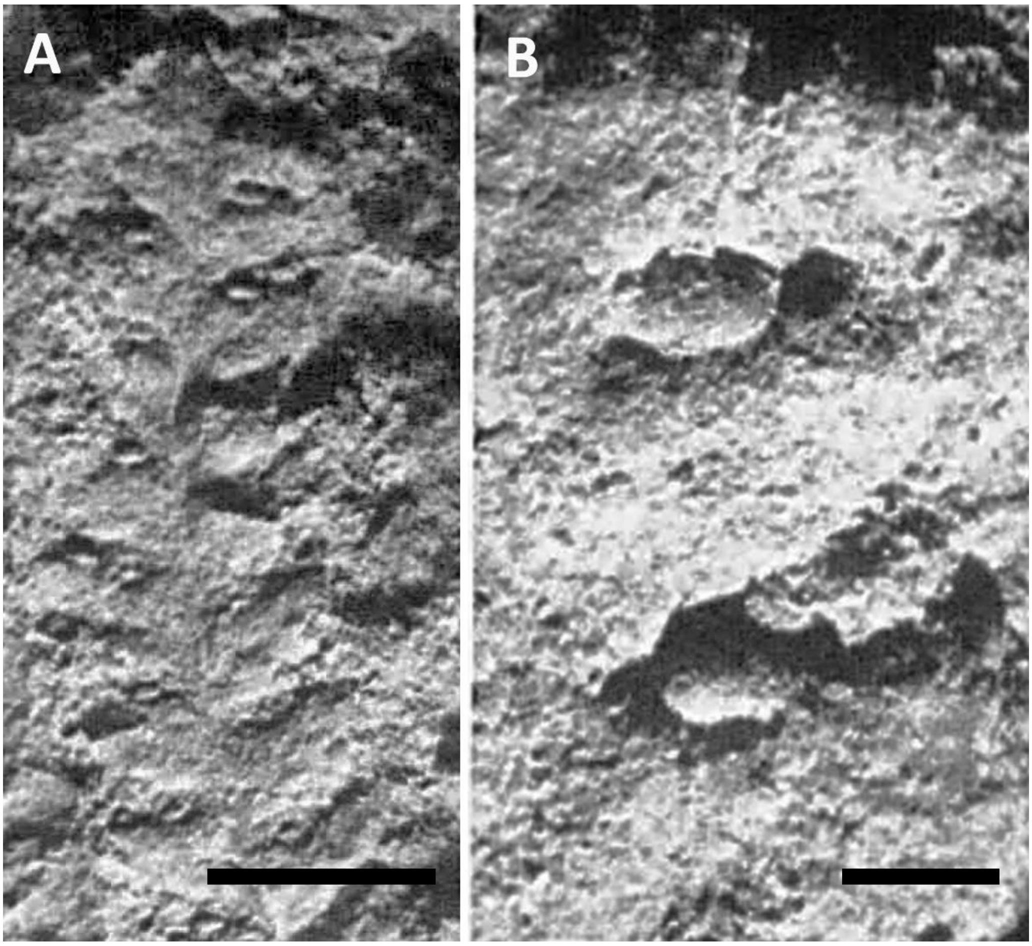

Fig. S3-6 A – Fertile fern morphotype; scale bar 1 cm; B – Detail of probable sori; scale bar 1 mm. Both images of specimen P.2799.19.