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New occurrence of Triassic gymnosperm wood at the Ricker Hills, southern Victoria Land, Antarctica

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ABSTRACT

During the 2016 Antarctic summer season, the fourth Korea Antarctic Geological Expedition (KAGEX IV) investigated the Ricker Hills in southern Victoria Land, Antarctica and collected 33 specimens of fossil wood from an outcrop of Triassic Beacon sandstone in a small basin, Ricker Hills area. Based on anatomical features, four specimens can be identified as belonging to the seed-fern wood *Kykloxylon* sp. (Corystospermales). A specimen is identified as *Agathoxylon* sp. and it is the first report of the genus from the Triassic deposits in Victoria Land, Antarctica. We are able to reconfirm that corystosperm trees were a dominant component of the Triassic forest vegetation in Antarctica, with minor occurrences of *Agathoxylon* trees of yet uncertain affinities from those results. In addition, the new occurrence of *Agathoxylon* at the Ricker Hills also shows us that there is still a shortage of fossil wood studies in Victoria Land.

1. Introduction

Perhaps due to their equivocal position in between southern and northern Victoria Land and partly due to the remote location, the Ricker Hills (RHs) remain one of the least-studied regions of the Transantarctic Basin in southern Victoria Land. Early geological surveys in the region were conducted by New Zealand researchers as a part of the New Zealand Antarctic Research Programme (NZARP) in the 1960s (Skinner and Ricker, 1968a,b). More detailed geological field work was conducted in the 1990s by German, Italian, and American researchers (Wörner, 1992; Pertusati et al., 1998; Capponi et al., 1999; Elliot et al., 1999), resulting also in preliminary reports of Triassic *Dicroidium* leaf fossils at Benson Knob (Capponi et al., 1999). However, no detailed palaeobotanical studies have been conducted in this area yet.

During 2016 Antarctic summer season, the fourth Korea Antarctic Geological Expedition (KAGEX IV) investigated the RHs and collected many plant fossils including *Dicroidium* leaf fossils together with new fossil wood from the Beacon Supergroup sandstone beds (Figs. 1, 2). In this report, we describe the deposit features of the sandstone beds with a suggestion of the depositional environment and present the first systematic description of the fossil wood at the RHs with the brief discussion about the composition and diversity of Antarctic Triassic wood types.

2. Geological setting

The RHs are located at the southern flank of the David Glacier and the south-western part of the Prince Albert Mountains in southern Victoria Land, ca. 180 km south of Jang Bogo Station (Korea), Mario Zucchelli Station (Italy), and Gondwana Station (Germany) at Terra Nova Bay, Antarctica (Fig. 1). Capponi et al. (1999) published a comprehensive review of this area with the geological map, Mount Joyce Quadrangle which recognized four major regional stratigraphic units: (1) the late Cambrian–Ordovician Granite Harbour Intrusives Complex; (2) Permian–Triassic deposits of the Beacon Supergroup; (3) the Jurassic Ferrar Group; and (4) the late Oligocene Ricker Hills Tillite (Capponi et al., 1999). The crystalline basement (Granite Harbour Intrusives Complex) consists largely of coarse-crystalline granite and granodiorite and contains minor diorite and tonalite plutons and dykes (Capponi et al., 1999). It is unconformably overlain by quartzose sandstone and coarse-grained arkosic sandstone of the Beacon Supergroup, although the very contact is not exposed in this area (Ricker, 1964). *Dicroidium* leaf fossils at Benson Knob in the RHs (Fig. 1) indicate that at least part of the Beacon Supergroup deposits in the area is Triassic in age and is correlative with the Section Peak Formation of the Victoria Group further north (Capponi et al., 1999). During the Early Jurassic, the Beacon Supergroup became capped and intruded by the igneous

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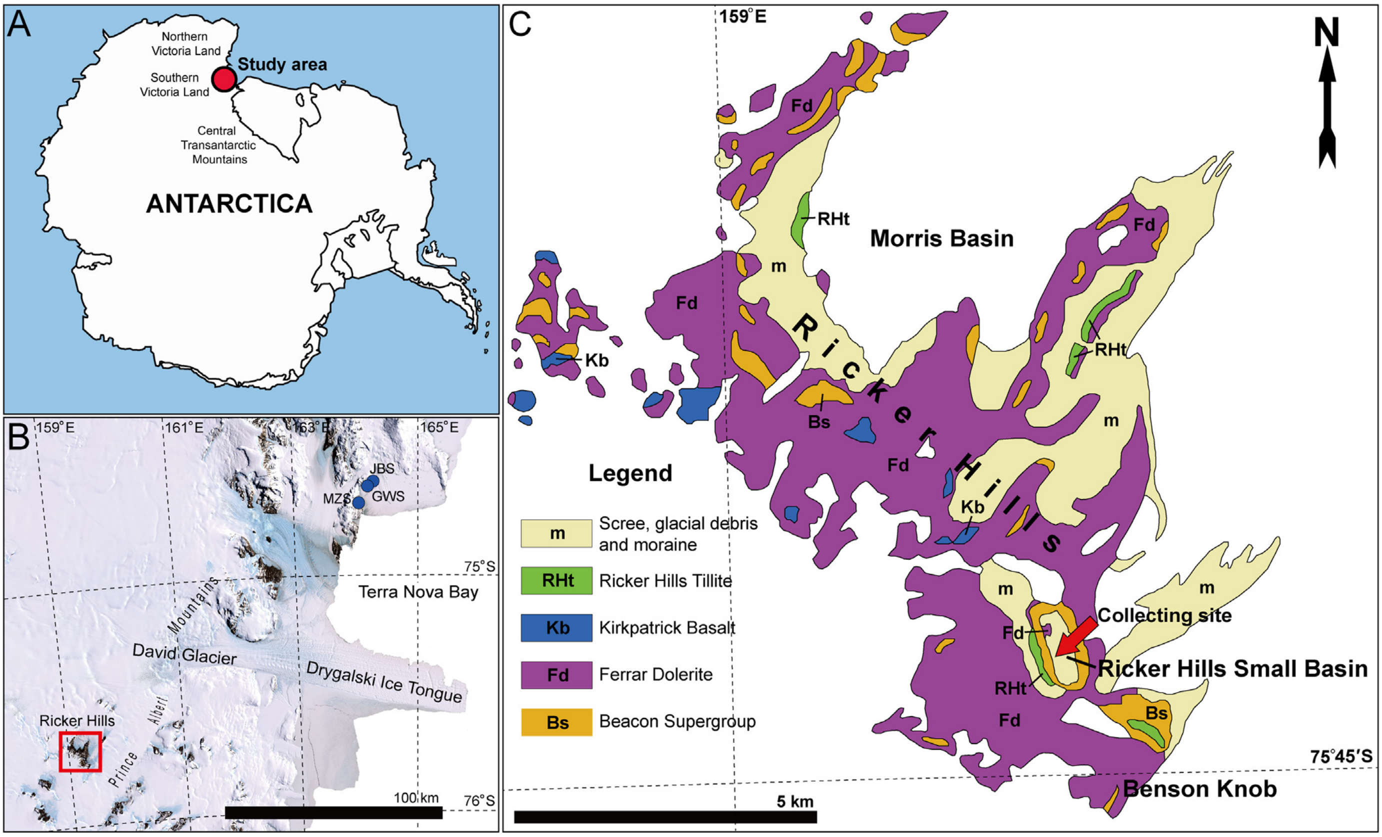


Fig. 1. Geographic and geological map showing the study area and collecting site. (A) Geographic map of Antarctica with study area indicated by red circle. (B) Geographic map of the south-western part of the Prince Albert Mountains in southern Victoria Land, Antarctica with collecting site indicated by red circle (JBS = Jang Bogo Station, Korea; GWS = Gondwana Station, Germany; MZS = Mario Zucchelli Station, Italy). (C) Geological map of the Ricker Hills area with collecting site indicated by red arrow (from Capponi et al., 1999).

Ferrar Group rocks, which mainly consists of lava flows (Kirkpatrick Basalt) and subvolcanic sills and dikes (Ferrar Dolerite). Ferrar Dolerite is the dominant lithofacies in the RHs. The youngest stratigraphic unit is the Ricker Hills Tillite, an up-to-1.5-m-thick bed of glacial diamictite that contains clasts of Ferrar Dolerite and Beacon sandstone floating in a yellowish muddy matrix. The base of the tillite rests directly on top of highly deformed, presumably glaciotectonized Beacon sandstone (Baroni and Fasano, 2006). The Ricker Hills Tillite was previously assumed to be correlated with the Neogene Sirius Group of the Central Transantarctic Mountains; analyses of palynology and clay mineralogy, however, indicate an older, late Oligocene age for the deposit (Baroni et al., 2008).

3. Sedimentological description and interpretation of the Beacon Supergroup

The Beacon Supergroup in the RHs mainly crops out at three localities: Benson Knob, Morris Basin, and the Ricker Hills Small Basin (Figs. 1, 2). The Ricker Hills Small Basin, that is, the fossil wood collecting site in this study is temporarily capitalized to distinguish it from other basins in the RHs. Although these outcrops are poorly exposed due to debris cover, a 70-m-thick succession is measured at the Ricker Hills Small Basin (Figs. 2, 3). The succession consists of thick sandstone beds of the Beacon Supergroup in the lower part and is unconformably overlain by Ricker Hills Tillite (Fig. 4). The Beacon sandstone consists of medium to coarse sandstones with various stream-flow sedimentary features, and can be divided into seven sedimentary facies (Table 1, Figs. 3, 4). The sedimentary facies is overall characterized by: bedform migration of ripples, dunes, and antidunes (Sr, St, Sp, Sh, Sl); the absence of floodplain fine deposits; and the occasional occurrence of sedimentary facies produced by flooding events (Sm, Sch). These altogether indicate the deposition in a sandy-braided-stream (see Table 1 for the abbreviations and Fig. 4 for facies characteristics; Miall, 1978, 2010; Walker, 1983; Collinson et al., 1986; Boggs, 2006). The uppermost 17 m of the Beacon sandstone, beneath the Ricker Hills Tillite, is characterized by various deformation structures (Fig. 4G), presumably resulting from glaciotectonic processes (Baroni and Fasano, 2006). Most fossil wood reported here was found in the uppermost part of the sandstone succession (Fig. 3).

4. Materials and methods

Thirty-three specimens of fossil wood were collected from the Beacon sandstone at the Ricker Hills Small Basin (75°44′1.17″ S, 159°12′ 43.16″ E), Ricker Hills, southern Victoria Land, Antarctica (Figs. 1, 2). Fossil wood occurs mainly in the deformed sandstone in the uppermost part of the section (Figs. 3, 5). Most of specimens are oriented parallel to bedding, indicating allochthonous deposition (Fig. 5). Abundant specimens of fossil wood occur also ex-situ on the moraine hills around the outcrop; however, only those collected in-situ from the outcrop are considered here. The stems range from ca. 4 to 20 cm in diameter and are usually internally carbonized in black color, with only the outer weathered part being silicified in white to gray color.

First, transverse thin-section slides were prepared from each specimen. After observation of transverse section slides, relatively well-preserved specimens were selected for further preparation of radial and tangential thin-section slides. The anatomical description follows the terminology of the IAWA list for microscopic features for softwood (IAWA Committee, 2004). Photomicrographs were taken using an AxioCam HRc attached to a Zeiss Axiophot transmitted-light microscope. Geographic and geological map and the sedimentary logs were made using Adobe Illustrator CS5 and Corel DRAW ver. 17.0.

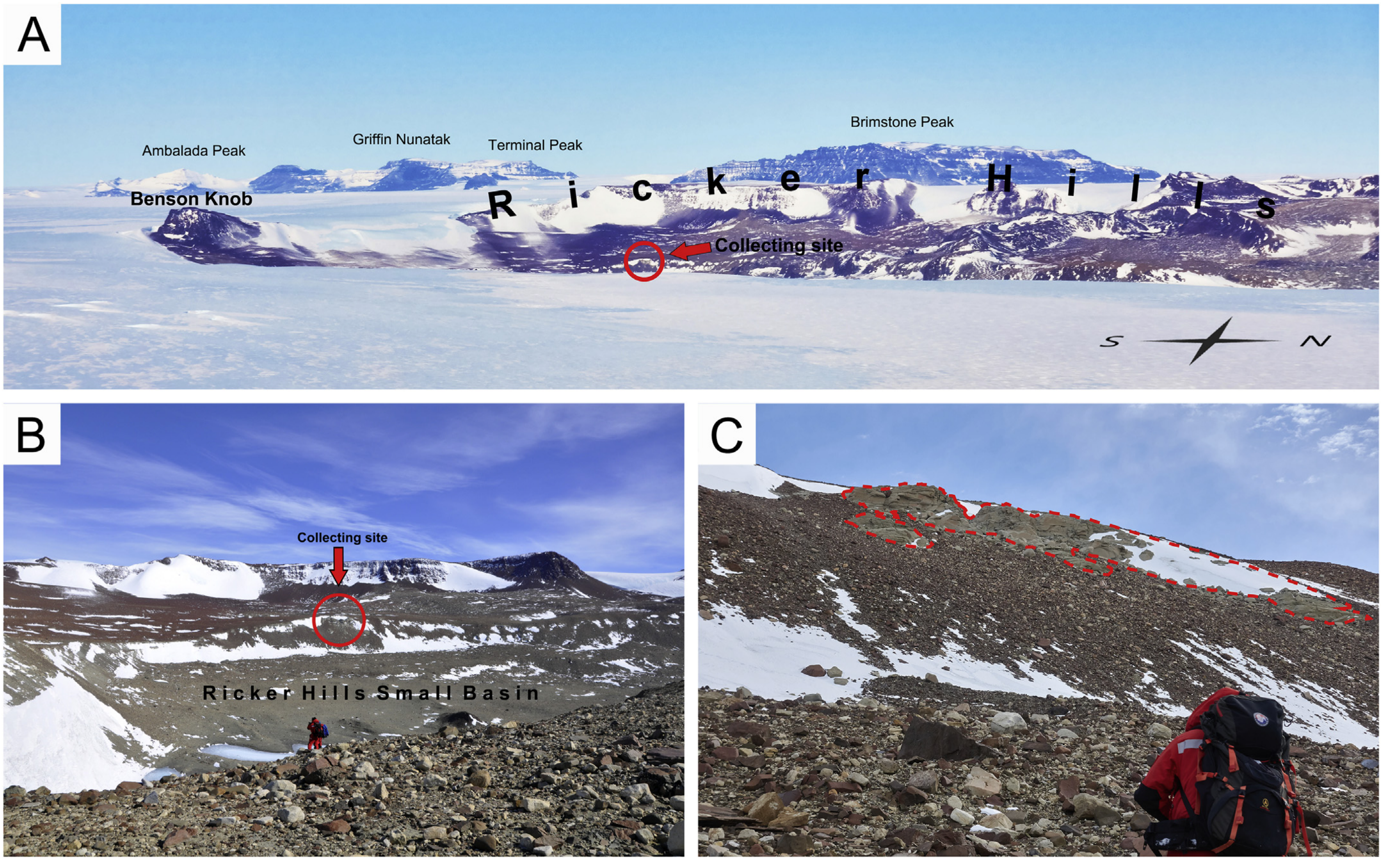


Fig. 2. Photographs of the Ricker Hills area showing the collecting site at the Ricker Hills Small Basin. (A) Aerial view of the Ricker Hills area from the east to the west. (B) The collecting site at the basin. (C) Detailed view of the collecting site. The sandstone outcrop of the basin where the fossil wood occurred (within dotted red line).

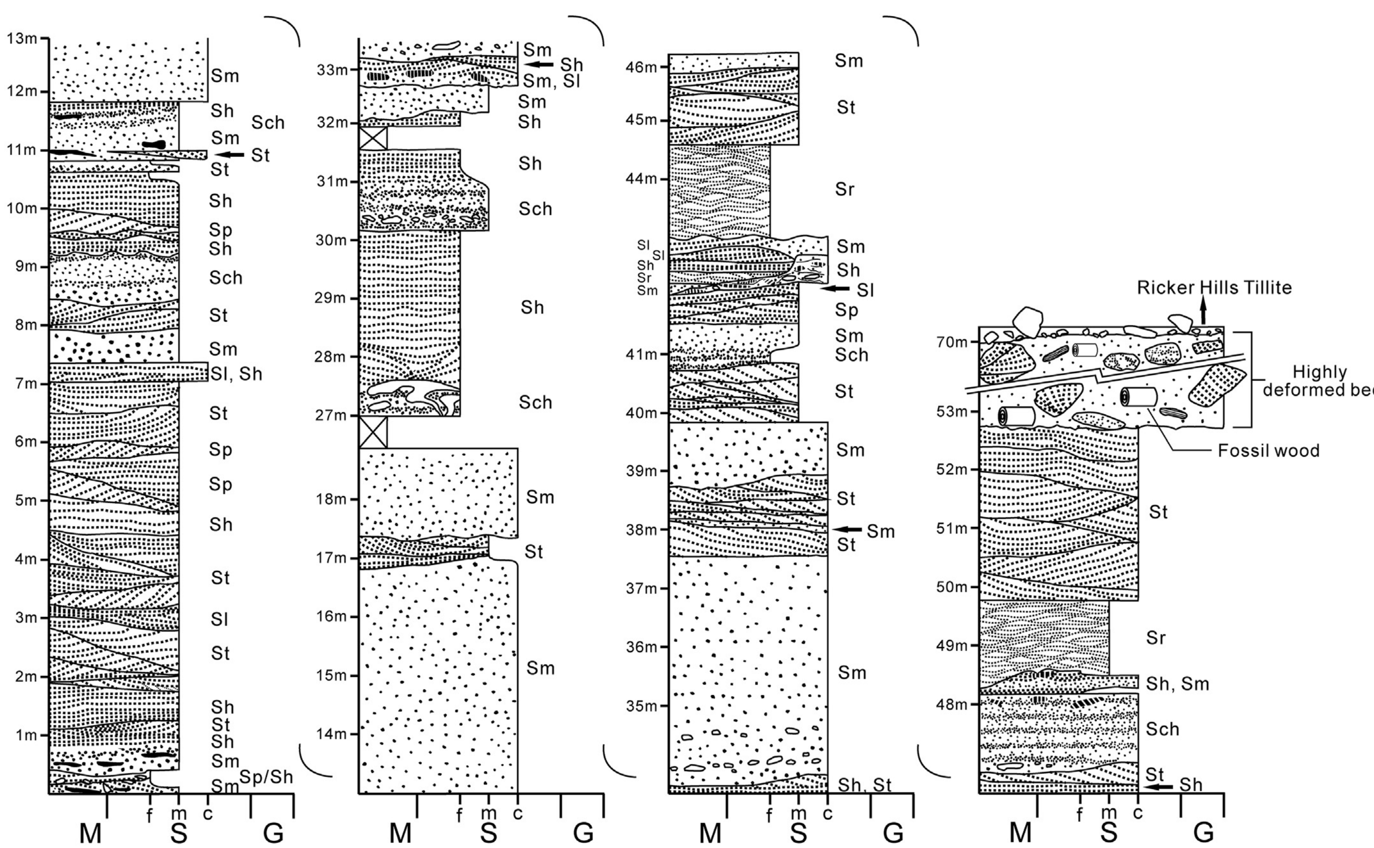


Fig. 3. Sedimentary log of the sedimentary strata at the Ricker Hills Small Basin. Upper part of the sandstone is highly deformed and contains many pieces of fossil wood. (See Table 1 for facies codes. M = mudstone, S = sandstone, f = fine sandstone, m = medium sandstone, c = coarse sandstone, G = conglomerate).

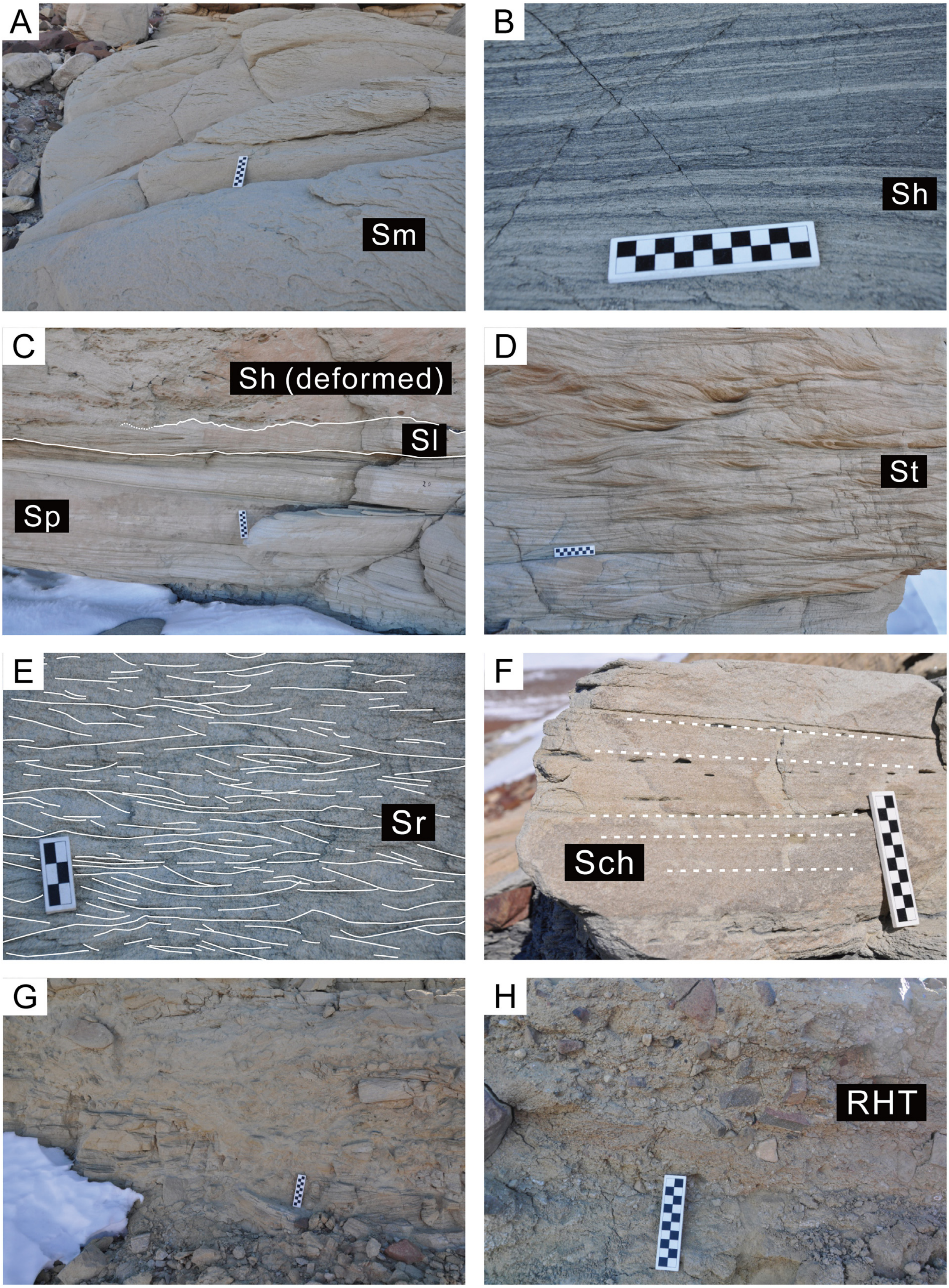


Fig. 4. Outcrop photographs of sedimentary features in the Ricker Hills Small Basin. (A–F) Sedimentary facies of Beacon Supergroup. (A) Massive sandstone (Sm). (B) Horizontally stratified sandstone (Sh) with well-developed lamination. (C) Planar cross-stratified sandstone (Sp, lower part) and low angle cross-stratified sandstone (Sl, middle part). Note that facies 'Sh' in the upper part is deformed. (D) Trough cross-stratified sandstone (St). (E) Ripple cross-laminated sandstone (Sr). (F) Crudely stratified sandstone (Sch), including stratified or imbricated clasts. (G) Highly deformed sandstone at the upper part of the section, containing sandstone clasts of Beacon Supergroup. (H) Ricker Hills Tillite (RHT) unconformably overlying the Beacon Supergroup deposits. All scales in centimeters.

Table 1
Facies description and interpretation of the Beacon Supergroup in the Ricker Hills Small Basin.

Facies	Description	Interpretation
Massive Sandstone (Sm)	Structureless; mostly consist of coarse sandstone occasionally containing pebble to cobble clasts and coalified plant fragments; sharp or erosive base	Rapid fallout deposition from flooding (Walker, 1983)
Horizontally stratified Sandstone (Sh)	Well-developed parallel lamination; fine to medium sandstone; containing coalified plant fragments; soft sediment deformation	Plane-bed flow (Lower or upper flow regime; Miall, 1978, 2010)
Planar cross-stratified Sandstone (Sp)	Medium sandstone; consist of many cross sets; sharp base and top;	Transverse and linguoid (2-D) dunes or sand waves (Lower flow regime; Miall, 1978, 2010)
Trough cross-stratified Sandstone (St)	Medium to coarse sandstone; consist of amalgamated cross sets; occasionally lateral pinch-out	Sinuous-crested and liguoid (3-D) dunes (Lower flow regime; Miall, 1978, 2010)
Ripple cross-laminated Sandstone (Sr)	Fine sandstone; consist of amalgamated ripple cross sets	Ripple (Lower flow regime; Miall, 1978, 2010)
Low angle cross-stratified Sandstone (Sl)	Medium sandstone; more and less 10° angle between bottomset and cross beds	Washed-out dunes or antidunes (Miall, 1978, 2010)
Crudely stratified Sandstone (Sch)	Medium to coarse sandstone; containing coalified plant fragments and imbricated clasts	Rapid deposition from flooding with a little traction sedimentation (Boggs, 2006)

Conventional adjustments of brightness, sharpness, contrast, and saturation of the digital images were made using Adobe Photoshop CS5 and Capture One Express. All specimens and slides are housed in the collection of the Korea Polar Research Institute (Incheon, Republic of Korea) under the accession numbers KOPRIF 20077–20109.

5. Systematic palaeobotany

All 33 specimens of gymnosperm wood studied, only five specimens proved sufficiently well-preserved to allow genus-level identification.

Class: Gymnospermopsida Stewart et G.W.Rothwell 1993

Order: Corystospermales Petriella, 1981

Family: Umkomasiaceae Petriella, 1981

Genus: ***Kykloxylon*** Mey.-Berth., T.N.Taylor et Ed.L.Taylor 1993 emend. Decombeix et al., 2014

Type species: *Kykloxylon fremouwense* Mey.-Berth., T.N.Taylor et Ed. L.Taylor 1993 emend. Decombeix et al., 2014

Kykloxylon sp. (Fig. 6A–I)

Materials: KOPRIF 20078, 20079, 20088, 20108.

Description: Of all specimens studied, KOPRIF 20079 and 20088 are best preserved and have yielded most anatomical information. Growth rings are distinct, but measuring the growth ring width is difficult because many tracheids are crushed and deformed (Fig. 6A). The transition from earlywood to latewood is abrupt. Earlywood tracheids are quadratic, oblong, or circular in transverse section and measure 20–57 × 23–50 μm (mean 39 × 36 μm, n = 50) in radial × tangential diameter (KOPRIF 20079). Resin canals are absent. The presence or absence of axial parenchyma is uncertain because of the poor preservation. Bordered pits on tangential walls of the tracheids are rarely observable, but specimen KOPRIF 20088 shows uniseriate pits (Fig. 6I). The pits are spaced, with a circular outline, and are approximately 8–15 μm in diameter. Rays are uniseriate or partly biseriate, homogeneous, 1–12 or up to 18 cells tall (Fig. 6H). Ray cells are oblong or circular in tangential section, have smooth end walls, and are approximately 23 × 34 μm in tangential × longitudinal diameter. Bordered pits on the radial walls of the tracheids are contiguous, with slightly longitudinally flattened outline, or spaced with circular outline (Fig. 6D, E). The pits are approximately 16–18 μm in diameter. Simple or half-bordered pits are present in the cross-fields with oval outline and are approximately 8–13 μm in diameter (Fig. 6F). There are one to four pits per cross-field in the earlywood, but because of the poor preservation, we cannot exclude the possibility of the presence of much more pits per cross-field. All specimens exhibit unusual parenchymatous tissues in the radial direction, and sometimes these tissues put branches out also into tangential direction (Fig. 6B, C). The pith region is preserved only in specimen KOPRIF 20108, but imperfect preservation of the specimen precludes any detailed anatomical observation.

Remarks: The anatomical features of the specimens, i.e., unusual parenchymatous tissues in both radial and tangential directions, lack of centripetal secondary xylem, somewhat mixed tracheid radial pit arrangements, cross-field pit type, and homogeneous ray system allow assignment to *Kykloxylon*, the fossil wood genus of corystosperm trees in Antarctica (Decombeix et al., 2014; Oh et al., 2016 and references there in). Only two species have been described so far: the type species *Kykloxylon fremouwense* and the recently transferred *K. gordonense* (Del Fueyo et al., 1995; Decombeix et al., 2014). The latter, which was earlier assigned to the separate genus *Jeffersonioxylon* Del Fueyo et al. (1995) is poorly known, and appears to differ from the type species mainly in preservational aspect; it had provisionally been retained as separate species because it occurs associated with *Dicroidium* foliage species that are clearly distinct from those associated with *K. fremouwense*, indicating that the two wood taxa may in fact represent at least two separate biological species. Oh et al. (2016), however, have argued to consider the species synonymous with *K. fremouwense*.

At present, as the lack of accurate information about pith structure and the number of cross-field pits prevents species-level identification of the *Kykloxylon* specimens from the RHs.

Order: Incertae sedis

Genus: ***Agathoxylon*** Hartig, 1848

Type species: *Agathoxylon cordaianum* Hartig, 1848

Agathoxylon sp. (Fig. 7A–G)

Material: KOPRIF 20100.

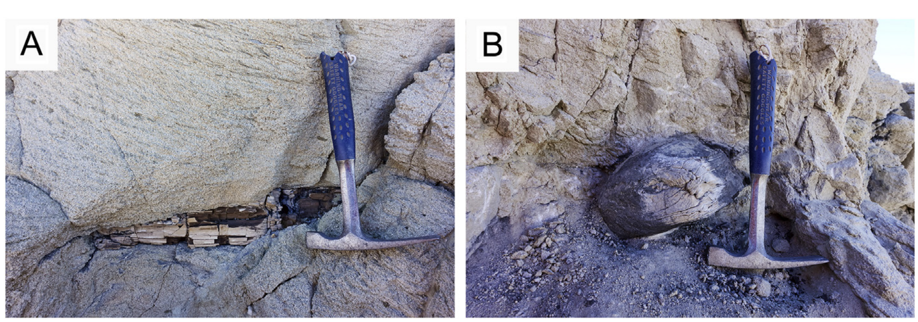
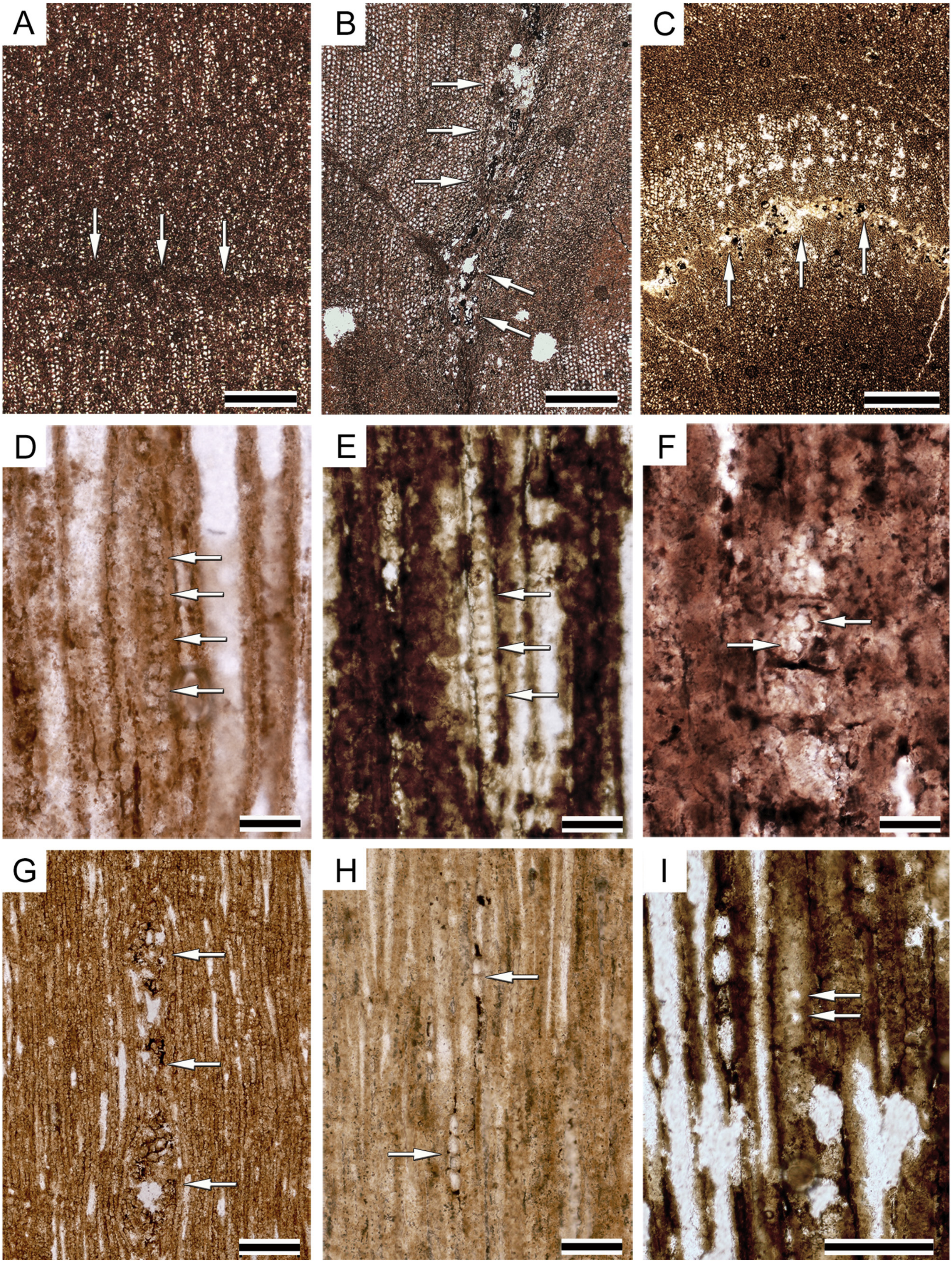


Fig. 5. Field images of fossil wood from the outcrop at the Ricker Hills Small Basin. (A) The embedded fossil wood occurred within the deformed sandstone. (B) Another embedded piece of fossil wood.



Description: Growth rings are both distinct and indistinct (Fig. 7A). As with *Kykloxylon* specimens, growth ring width cannot be measured because many tracheids are crushed and deformed (Fig. 7B). Earlywood tracheids are quadratic, oblong, circular, and thick-walled in transverse section and are 21–47 × 18–44 μm (mean 29 × 28 μm, n = 45) in radial × tangential diameter. Latewood tracheids are notably narrower. Resin

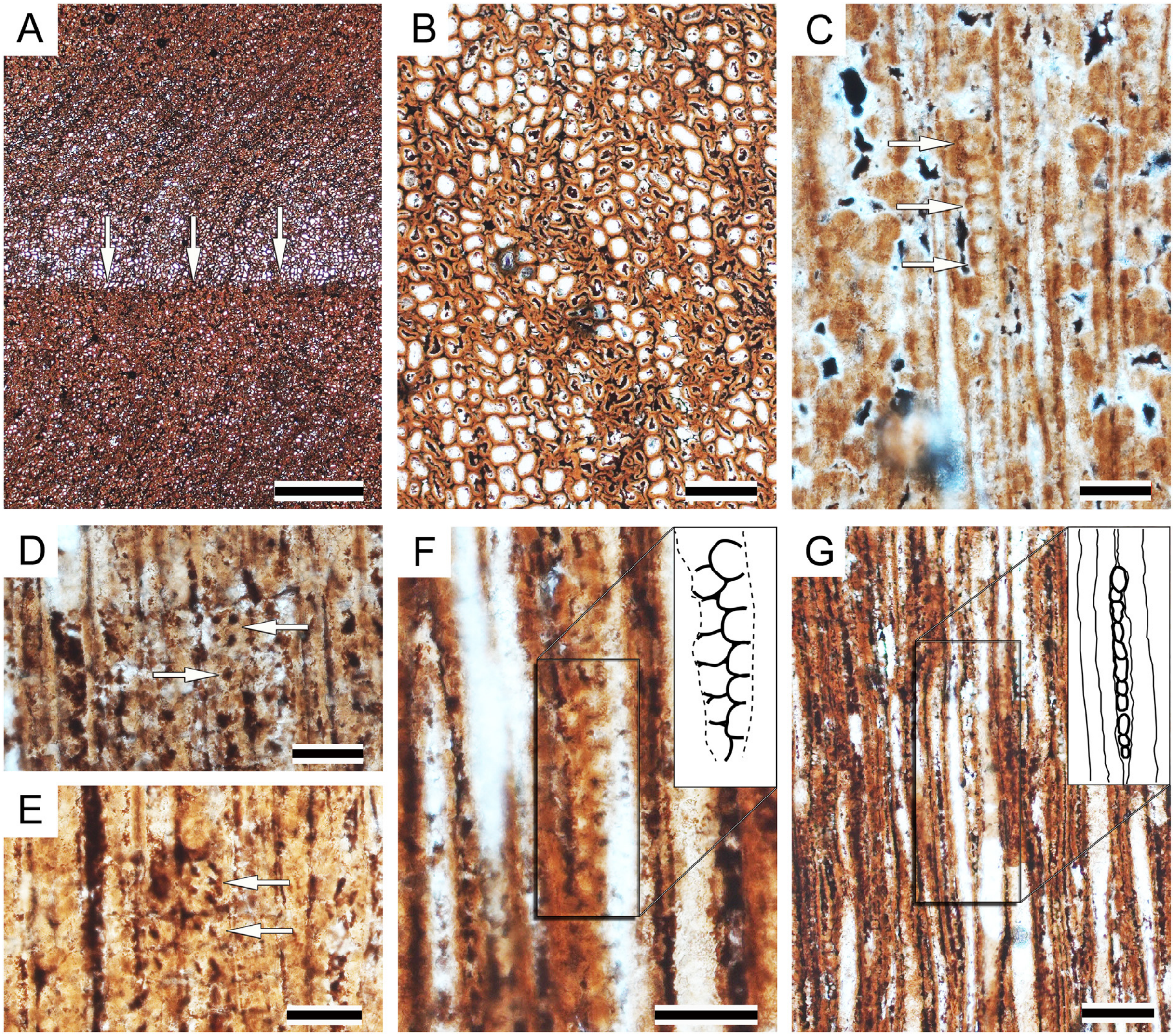


Fig. 7. Photomicrographs showing the anatomical features of *Agathoxylon* sp. from Ricker Hills (KOPRIF 20100). (A) Transverse section showing distinct growth ring (arrows), scale bar = 500 μm. (B) Transverse section showing various forms of tracheids, scale bar = 100 μm. (C) Radial section showing contiguous uniseriate bordered pits on tracheid wall (arrows), scale bar = 50 μm. (D, E) Radial sections showing the cupressoid pits in araucarioid cross-fields (arrows), scale bars = 50 μm. (F) Radial section showing alternate biseriate bordered pits on tracheid wall (in a rectangle and by a line tracing in the upper right corner), scale bar = 50 μm. (G) Tangential section showing homogenous and uniseriate rays (in a rectangle and by a line tracing in the upper right corner), scale bar = 100 μm.

canals are absent, and axial parenchyma is not apparent. Bordered pits on tangential walls of tracheids have not been observed. Rays appear uniseriate and homogeneous; ray cells are oblong and oval in tangential section and are about 17 × 30 μm in tangential × longitudinal diameter (Fig. 7G). Bordered pits on radial walls of tracheids are contiguous, longitudinally flattened and uni- or biseriate, alternate (Fig. 7C, F). The pits are approximately 18–20 μm in diameter (Fig. 7C, F). The cross-fields are of the araucarioid type with one to five crowded, circular to elliptical pits per field, each ca. 11 μm in diameter (Fig. 7D, E).

Remarks: Overall, pycnoxylic homoxylous secondary wood, contiguous and alternate bordered pits on radial walls of tracheids, araucarioid type cross-fields, and uniseriate rays enable assignment to *Agathoxylon* (Philippe and Bamford, 2008). Several types of araucarioid wood have been reported from Antarctica; however, imperfect preservation of the RHs specimen, especially the lack of information on ray height, precludes species identification.

6. Discussion

Up to now, *Kykloxylon* and *Antarcticoxylon* were the only two Triassic fossil wood taxa documented from Victoria Land. However, the occurrence of the latter in the Triassic is uncertain because the precise stratigraphic source unit and age remains unclear (Meyer-Berthaud and Taylor, 1991). From the Antarctic Triassic in general, four pycnoxylic wood species have been reported (Oh et al., 2016), i.e., *Antarcticoxylon priestleyi*Seward (1914), *Kykloxylon fremouwense* Mey.-Berth., T.N.Taylor et Ed.L.Taylor (1993) (including *K. gordonense*; see Decombeix et al., 2014 and Oh et al., 2016), *Notophytum krauselii*

Fig. 6. Photomicrographs showing the anatomical features of *Kykloxylon* sp. from Ricker Hills. (A) Transverse section showing distinct growth ring (arrows), scale bar = 500 μm (KOPRIF 20079). (B) Transverse section showing the unusual parenchymatous tissues in radial direction (arrows), scale bar = 500 μm (KOPRIF 20079). (C) Transverse section showing the unusual parenchymatous tissues in tangential direction (arrows), scale bar = 500 μm (KOPRIF 20088). (D). Radial section showing partly separated, one and two bordered pits on the radial walls of tracheid (arrows), scale bar = 50 μm (KOPRIF 20079). (E) Radial section showing contiguous bordered pits on the radial walls of tracheid (arrows), scale bar = 50 μm (KOPRIF 20088). (F) Radial section showing simple or half-bordered cross-field pits (arrows), scale bar = 20 μm (KOPRIF 20079). (G) Radial section showing the unusual parenchymatous tissues in tangential direction (arrows), scale bar = 200 μm (KOPRIF 20079). (H) Tangential section showing uniseriate rays (arrows), scale bar = 100 μm (KOPRIF 20079). (I) Tangential section showing small bordered pits on the tangential walls of tracheid (arrows), scale bar = 100 μm (KOPRIF 20088).

Mey.-Berth. et T.N.Taylor (1991), and *Rudixylon serbetianum* Bomfleur, Decombeix, Schwendemann, Escapa, Ed.L.Taylor, T.N.Taylor et McLoughlin (2014). Therefore, this new occurrence of *Agathoxylon* at the RHs adds an additional taxon to the composition of Triassic wood types in Antarctica.

Recently Oh et al. (2016) investigated the Triassic wood floral diversity in Antarctica and recognized that the diversity of wood fossils was much lower than that of other plant fossils (e.g., leaf and reproductive organ fossils). They suggested several explanations to this lower diversity: (1) the uniformity of gymnosperm wood anatomy, and hence a low xylological disparity hiding a higher taxonomic diversity; (2) the ecological dominance of corystosperm plants in Gondwana canopies during the Triassic; and (3) much fewer studies of fossil wood compared to that of other plant megafossils (Oh et al., 2016). The lower diversity of wood taxa for the Triassic in Antarctica likely results from a combination of above factors. In any case, the new occurrences of *Kykloxylon* and *Agathoxylon* at the RHs reconfirm that corystosperm plants were the dominant component of Gondwana high-latitude forests during the Triassic period. Moreover, these new occurrences also evidence that more fossil wood study in Antarctica are needed, especially in Victoria Land.

During the Triassic, Gondwana floras were dominated by corystosperms which were the successful successors of glossopterids in the Permian (Anderson et al., 1999). They were the major component of the canopy-forming forest vegetation in Antarctica with other minor components, e.g., the voltzialean conifers (Bomfleur et al., 2013; Oh et al., 2016). Previously, unrecognized *Agathoxylon* trees appear to have constituted additional arborescent elements of the Triassic forest vegetation in Antarctica, even though the affinities of these plants remain so far obscure.

This study demonstrates that our knowledge about the Gondwanan high-latitude vegetation is still fragmentary, and that ongoing palaeobotanical research in Antarctica still promises to yield novel insights into the past vegetation of the frozen continent.

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