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# Highly productive polar forests from the Permian of Antarctica

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ABSTRACT

Two stratigraphically closely spaced bedding planes exposed at Lamping Peak in the Upper Buckley Formation, Beardmore Glacier area, Antarctica contain abundant *in situ* stumps (n = 53, n = 21) and other plant fossils that allow reconstruction of forest structure and biomass of *Glossopteris* forests that thrived at ~75° S paleolatitude in the Permian. Mean trunk diameter is 14 and 25 cm, corresponding to estimated mean maximum heights of 12 and 19 m. Basal areas are 65 and 80 $m^2$ $ha^{-1}$. The above ground biomass was calculated using allometric equations for *Ginkgo biloba*, yielding biomasses of 147 and 178 Mg $ha^{-1}$. Biomass estimates based on comparison with biomass of modern forests with equivalent basal areas are higher (225–400 Mg $ha^{-1}$). The amount of above ground biomass added each year (annual net primary productivity), based on biomass estimates and growth rings in silicified plant material from the Buckley Formation nearby, is poorly constrained, ranging from ~100–2000 g $m^{-2}$ $yr^{-1}$.

Compared to modern forests at all latitudes, the Permian forests have high basal areas and high biomass, exceeded in both only by forests of the U.S. Pacific northwest and *Sequoia* forests. The estimated range of productivity (ANPP) is within that of many very productive modern forests. The Lamping Peak forests' basal areas and calculated biomass are also larger than younger high paleolatitude fossil forests except for Arctic Cenozoic forests. The presence of these highly productive fossil forests at high paleolatitude is consistent with hothouse conditions during the Late Permian, prior to the eruption of the Siberian flood basalts.



## 1. Introduction

*In situ* stumps representing fossil forests provide information about forest structure, biomass and productivity that is not recorded in plant macrofossils or microfossils (*e.g.*, Francis, 1991; Mossbrugger et al., 1994; Williams et al., 2003, 2009; Thorn, 2005; DiMichele and Falcon-Lang, 2011; Rößler et al., 2012). Because forest characteristics are controlled by environmental factors including temperature, precipitation, soil type, and nutrient availability, they contribute to the reconstruction of paleoclimate, particularly if the paleogeographical settings of the fossil forests are well constrained (*e.g.*, Creber and Chaloner, 1985; Taylor et al., 1992; Francis et al., 1993; Williams et al., 2009). High latitude forests are of special interest, as forests in these regions are especially sensitive to climate change. Ancient high paleolatitude forests give insight into forest distribution, structure, and carbon cycling during periods of greenhouse, icehouse, and hothouse conditions and during transitions between climate states (Kidder and Worsley, 2010).

Numerous well-described Mesozoic (*e.g.*, Jefferson, 1982; Pole, 1999; Cúneo et al., 2003; Thorn, 2005); and Cenozoic (*e.g.*, Basinger et al., 1994; Williams et al., 2003, 2009) forests document prolific forest growth at high latitudes and constrain paleoclimate during these periods. For example, high southern latitude Jurassic fossil forests in New Zealand have high biomasses that reflect warm to cool temperate conditions with high seasonal rainfall (Pole, 1999; Thorn, 2005; Williams, 2007). Relatively warm climates at northern high latitudes existed into the Cretaceous, as evidenced by large logs, *in situ* stumps, and floral composition (Parrish and Spicer, 1988; Spicer and Herman, 2010). However, tree height and density decreased toward the end of the Cretaceous as the climate cooled (Spicer and Chapman, 1990). Polar warmth reached its zenith in the Paleocene to early Eocene, promoting the development of *Metasequoia* forests at high northern latitude, with biomasses several times those of modern lower latitude temperate forests (Williams et al., 2003). Cooling during the Oligocene–early Miocene resulted in replacement at northern polar latitudes of the deciduous

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*Metasequoia* with pines and reduction of forest biomasses to those characteristic of modern temperate forests (Williams et al., 2008; Taggart and Cross, 2009). With continued cooling modern boreal forests were established.

In contrast to the numerous high-latitude Mesozoic and Cenozoic age fossil forests, the only Permian polar *in situ* fossil stumps previously described are from the same unit and same area as the Lamping Peak forests: the Buckley Formation of the Central Transantarctic Mountains (Mt. Achernar, Graphite Peak, Mt. McIntyre; Wahl Glacier; Taylor et al., 1992; Taylor et al., 1997; Taylor et al., 2000; Taylor and Ryberg, 2007; Gulbranson et al., 2012; 2014). The growth of these trees at ~75° south latitude on floodplains of braided stream systems implies a vastly warmer climate. In addition to stumps, the Buckley Formation in this area contains permineralized wood with growth rings, leaves, and permineralized peat, augmenting paleoclimate information and providing a wealth of information about the floristic composition and plant anatomy (*e.g.*, Taylor et al., 1992, 2000; Cúneo et al., 1993; Pigg and Taylor, 1993; Taylor and Ryberg, 2007; Decombeix, 2010; Ryberg and Taylor, 2013; Gulbranson et al., 2014).

The previously described stumps in the Buckley Formation proved that sizable trees grew at polar latitudes during the Permian, but the small number at each site (<16) precluded reconstruction of the forest with sufficient confidence to allow comparison with other ancient or modern forests.

The two closely spaced Lamping Peak forests discovered in 2003 differ from previously described Permian forests in the large number of stumps exposed on horizontal bedding planes (LP1 = 53 stumps; LP2 = 21 stumps).

The purpose of this study was to describe the fossil plant material at Lamping Peak, to reconstruct the attributes of the Lamping Peak forests (tree height, spacing) and their forest structure, to estimate the biomass and yearly productivity of the forests, to compare them to younger high latitude fossil forests and to modern forests, and to explore the paleoclimate implications.

## 2. Setting

### 2.1. Geologic, paleogeographic, paleoenvironmental and paleoclimatic contexts

The Permian fossil forests occur in the Buckley Formation near the top of Lamping Peak (S 84°12.6″; E 164° 40.7″) in the Beardmore Glacier area (Fig. 1). At the time, the Beardmore area was well within the southern polar circle, probably at a latitude higher than 70° S (Powell and Li, 1994; Lawver et al., 2008; Isbell et al., 2012).

The Buckley Formation is part of a thick Lower Permian to Lower Jurassic sedimentary sequence deposited in a subsiding foreland basin (Collinson et al., 1994). During the Jurassic the sequence was intruded by sills (Ferrar Dolerite) generated during the break-up of Gondwana.

The Permian sequence consists of: 1) glacigenic, primarily glacial marine and glacial lacustrine deposits recording Gondwanan glaciation (Pagoda Formation, Isbell et al., 1997; 2001; 2008); 2) shale and interbedded sandstone deposited in a large post-glacial lake or series of lakes filled by deltaic sediments (Mackellar Formation and lowermost Fairchild Formation, Miller and Isbell, 2010); 3) cross-bedded sandstone lacking plant fossils deposited in braided stream channels (bulk of Fairchild Formation, Barrett et al., 1986); and sandstone, siltstone, shale and coal deposited in braided stream systems (Buckley Formation, Isbell, 1990; Isbell et al., 1997; Gulbranson et al., 2012, 2014). The amount of plant material and the thickness and extent of coal increases upward within the Buckley Formation. Trees, particularly in the Buckley sediments deposited in the Late Permian, grew on vegetated bars, levees, crevasse splays, and lake margins.

The Permian succession in the Beardmore Glacier area of the Central Transantarctic Mountains reflects a transition in the Permian from icehouse to greenhouse to hothouse conditions (*e.g.*, Kidder and Worsley, 2004, 2010; Shi and Waterhouse, 2010). The Pagoda Formation records the Late Paleozoic Ice Age and the Mackellar and Fairchild Formations were deposited as the climate warmed in response to rising $CO_2$ levels

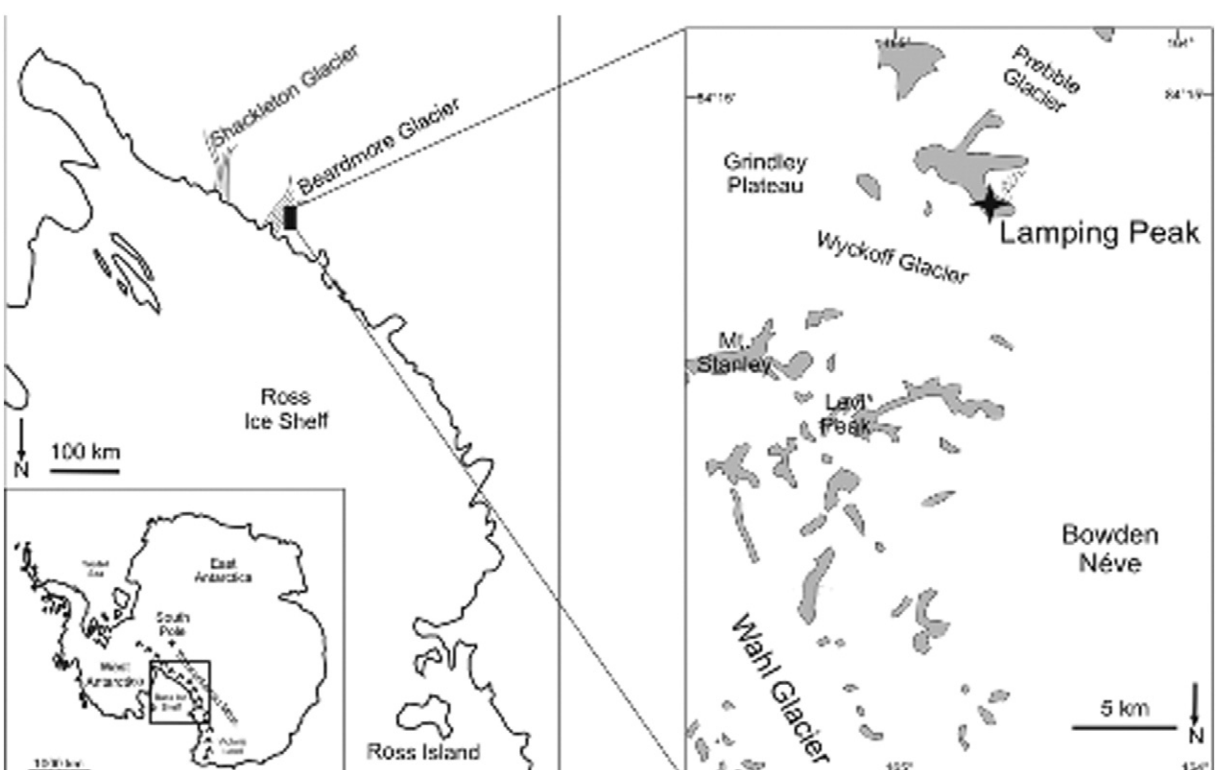


**Fig. 1.** Location of Lamping Peak (S 84°12.6″; E 164° 40.7″) site of large Permian fossil forests (LP1 and LP2) in the Beardmore Glacier area, Central Transantarctic Mountains.