LATE PERMIAN FORESTS OF THE BUCKLEY FORMATION, BEARDMORE GLACIER AREA, ANTARCTICA

By

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To my brother, Adam, and my parents, Mary and Dean, for their loving encouragement

and rational perspective

and

To my bright nephew, Alexander, who always has something interesting to say

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CHAPTER I

INTRODUCTION

Flat-lying upper Paleozoic-lower Mesozoic sedimentary rocks crop out throughout the entire length of the Transantarctic Mountains, but are exceptionally thick (4 km) and well exposed in the Beardmore Glacier area (BGA). This sequence is dominated by Permian through Jurassic siliciclastic rocks deposited in diverse continental environments intruded by Jurassic diabase sills (Elliot, 1975; Barrett et al., 1986). The geologic importance of these rocks was first demonstrated by Robert Scott's field party, that in 1912 collected *Glossopteris* leaves from the BGA, providing Alfred Wegner and subsequent workers with paleobotanical evidence that Antarctica linked with other southern hemisphere continents (Wegner, 1915; Seward, 1917).

The upper Paleozoic-lower Mesozoic sedimentary rocks consist of glacial deposits (Lindsay, 1970; Barrett et al., 1986; Miller, 1989; Isbell et al., 1997) successively overlain by lacustrine (Isbell and Macdonald, 1991; Miller and Collinson, 1994; Miller and Isbell, in review) and fluvial deposits (Barrett et al., 1986; Isbell, 1991; Isbell and Macdonald, 1991; Taylor et al., 1991; Taylor et al., 1992) that record amelioration of the climate (Collinson, 1997), even though the paleolatitude remained high (>70°S; Smith et al., 1981; Lawver et al., 2004). The sequence has yielded a vertebrate fauna from the Triassic that includes amphibians, therapsids, and other reptiles (Kitching et al., 1972; Colbert, 1982; Hammer, 1990) and from the Jurassic that includes dinosaurs (Hammer and Hickerson, 1994). Silicified plant material has allowed reconstruction of plant morphology on a cellular level (Taylor and Taylor, 1990; Pigg and Taylor, 1990; Pigg, 1990; Taylor et al., 1991; Taylor et al., 1992; Pigg and Taylor, 1993; Taylor et al., 2000) and comparison of floras and conditions before and after the end-Permian mass extinction (Retallack, 1995; Taylor et al., 2000); in fact, this sequence may contain a nearly unbroken record of the Permian-Triassic transition in a continental setting (Collinson et al., in press). Discovery of a limited number of *in situ* stumps demonstrated that sizeable trees were present by the Permian (Taylor et al., 1992), and occurrence of many (99) stumps in the Upper Triassic (Cúneo et al., 1993) documented the existence of forests by that time. The floral and faunal evidence combined with information from paleosols (Collinson, 1997; Retallack and Krull, 1997; Retallack, 2001) indicate a polar temperate climate that warmed into the Triassic and is incompatible with a severely seasonal climate suggested by climate models (Retallack G.J. et al., 1998; Gibbs et al., 2002; Benton and Twichett, 2003). A recent model that includes atmospheric, terrestrial, oceanic, sea-ice, geographic, and topographic data has narrowed the gap between reconstructed climate models and paleobotanical evidence (Kiehl and Shields, 2005).

Presence of thick upper Permian coals and domination of the plant flora by *Glossopteris* in the BGA implies that forests of *Glossopteris* trees flourished in the Late Permian, but previously not enough *in situ* stumps were found to reconstruct with confidence the characteristics. During the 2003-2004 austral summer, 74 *in situ* stumps were discovered in two horizons separated by one meter at one locality in the BGA, and 13 *in situ* stumps were discovered in another. The stumps constitute the largest known Permian fossil forest, one which grew at very high paleolatitude. The objectives of this study were to: (1) characterize the Late Permian forests preserved in the Buckley Formation and compare them to modern forests and other high-paleolatitude fossil forests, (2) identify the mode of preservation of the fossil stumps, (3) document the distribution of associated transported plant debris of diverse sizes and infer taphonomic processes, and (4) constrain the paleoenvironmental setting of the Upper Buckley Formation by integrating fossil forest and paleosol characteristics and taphonomic and sedimentological data with observations of modern forests in potentially analogous environments.

CHAPTER II

GEOLOGIC SETTING

Stratigraphy

The Transantarctic Mountains (TAM) stretch across the continent of Antarctica from the Weddell Sea to northern Victoria Land and divide the East Antarctic Craton from the accreted terrains of West Antarctica (Barrett et al., 1986). Flat lying rocks were displaced by high-angle faults and differentially tilted fault blocks during tectonic extension in the Mesozoic. Mesozoic folds and thrust-faults are absent (Gunn and Warren, 1962; Robinson and Splettstoesser, 1984). The TAM uplift commenced in the Cenozoic and continues until today at the rate of 90 m Ma^{-1} (Gleadow and Fitzherald, 1987). The Beardmore Glacier is one of the large outlet glaciers that press through the TAM as it moves from the Polar Plateau to the Ross Ice Shelf (Figure 1).

In the Beardmore Glacier area (BGA), four kilometers of Devonian through Triassic (Beacon Supergroup) and Jurassic (Ferrar Group) rocks are exceptionally well exposed (Barrett, 1986). The Beacon Supergroup consists of continental sedimentary rocks that dip shallowly to the south-southeast and is interspersed with dolerite sills of the Ferrar Group that were intruded during the break-up of Gondwana (Elliot, 1975; Barrett et al., 1986). This sequence records the depositional, paleoclimactic, and basinal history during 90 million years that included the last major icehouse to greenhouse transition and the end-Permian extinction (Barrett, 1986; Isbell and Miller, 2001).

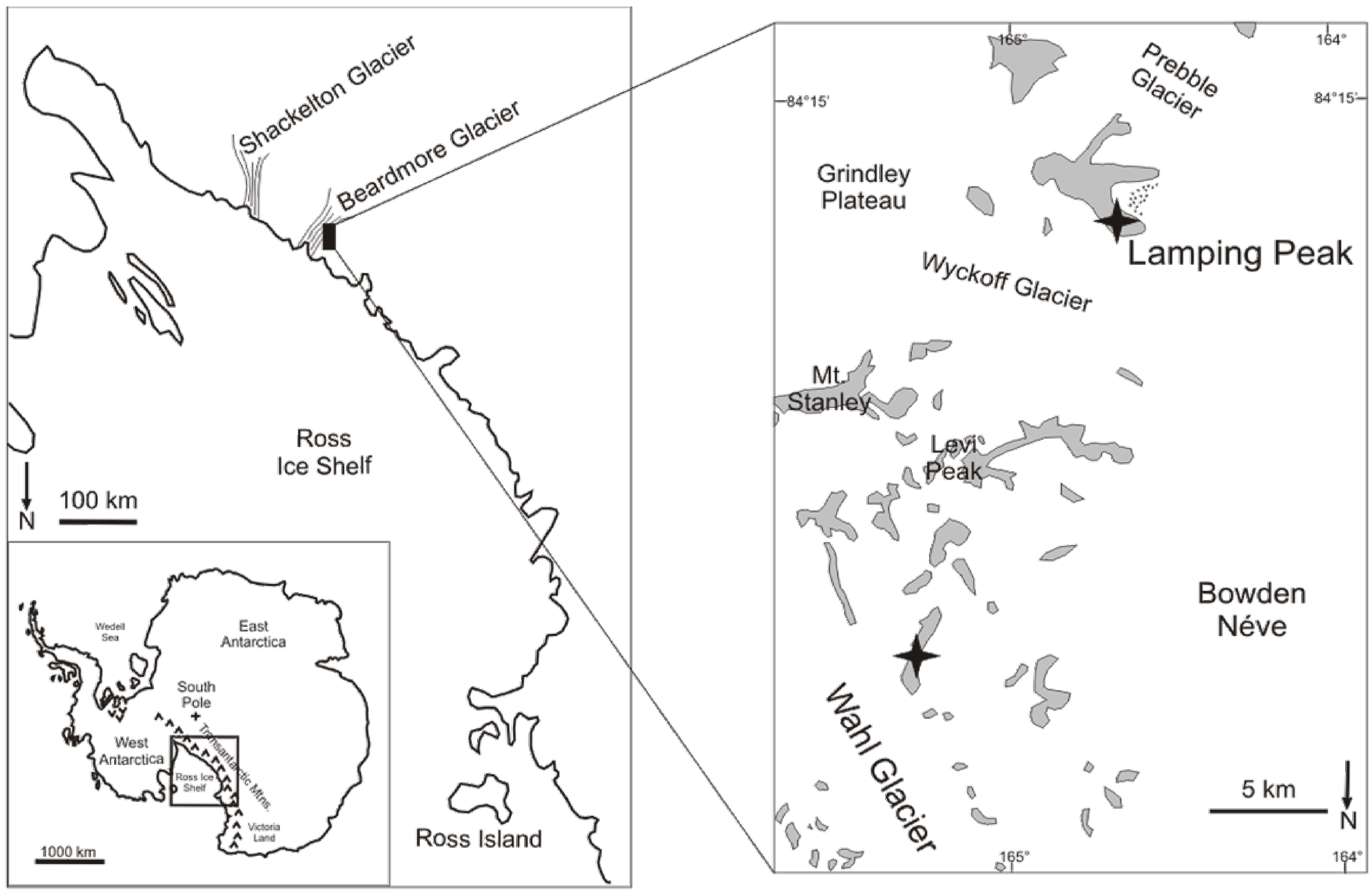


Figure 1. Lamping Peak and Wahl Glacier field sites (marked with star) in the Beardmore Glacier area, central Transantarctic Mountains. Ross Ice Shelf map is enlarged from box in Antarctica continent map (modified from USGS, 1988; USGS, 1965).

Permian through Triassic rocks of the BGA are organized into the following units from oldest to youngest: Pagoda, Mackellar, Fairchild, Buckley, Fremouw, and Falla Formations (Table 1). The Permian Pagoda Formation is up to 400 meters thick and represents glacial, glaciolacustrine, and glaciofluvial deposits associated with glacial advances and retreats (Lindsay, 1970; Barrett et al., 1986; Miller, 1989; Isbell et al., 1997). Powell and Li (1994) interpreted the Early Permian paleolatitude as 80-90°S for the BGA. The concept of a large ice sheet blanketing Antarctica with its spreading center near the CTM during the Late Carboniferous and Early Permian was modified by Isbell et al. (2003) who interpreted the glaciers of the Pagoda Formation to be much smaller; complete ice cover was not attained even during the final glacial advance. Biotic communities populated lakes when conditions were favorable (Isbell et al., 2001).

Glacial deposits of the Pagoda Formation grade into the post-glacial deposits of the Permian Mackellar Formation. The Mackellar Formation, also deposited at 80-90°S (Powell and Li, 1994), consists of a 60 to 140 meter coarsening upward succession of sandstone and shale (Barrett et al., 1986; Miller and Collinson, 1994). These sediments are interpreted as turbidites. Streams traversing braided outwash streams delivered cold, sediment-laden water to the Mackellar Lake/Inland Sea that generated turbidity currents (Isbell and Macdonald, 1991; Miller and Collinson, 1994; Miller and Isbell, in review). The Mackellar Formation is overlain by trough cross-bedded sandstones and minor shales of the Fairchild Formation that were deposited at a similar paleolatitude on the braid plain between the retreating ice sheet and Mackellar inland sea (Barrett et al., 1986); the braided stream channel and overbank deposits eventually filled Mackellar Lake/Inland

Table 1. Characteristics of upper Paleozoic through lower Mesozoic units in the Beardmore Glacier area (modified from Isbell and Miller, 2001)

	Unit	Thickness[1] (m)	Lithology	Paleobotany	Depositional environment	Paleoclimactic	Paleolatitude[36] (°S)
Late Triassic	Falla	0-242	Volcaniclastic sandstone and carbonaceous shale[1].	Diverse Dicroidium flora[12]; frost damage in wood[13].	Low sinuosity streams[1].	Humid warm to cold (?)	70-80
Early to Middle Triassic	Fremouw	630	Alternating volcaniclastic sandstone and shale[1,2,3,4,5]. Upper member: Carbonaceous with coal beds[1,2,3,4,5]. Lower and middle members: Non-carbonaceous; paleosols throughout[1,2,3,4,5].	Upper member: Diverse *Dicroidium* flora[12]; fossil forest[15]; frost damage in wood[13]. Lower member: Rooted paleosols[14].	Low sinuosity braided streams [1,33,3].	Upper member: Humid warm to cold (?). Middle member: Semi-arid warm (?). Lower member: Cool temperate to warm (?) and humid.	70-80
Early to Late Permian	Buckley	750	Alternating sandstone (quartzitic to arkosic in the lower member and volcaniclastic in the upper member), siltstone, shale, and coal[1,6]. Lonestones in lower member[7,8].	*Glossopteris* forests[15,16,17,18], leaf mats, coalified stems, logs, *Vertebraria* , and small roots[1,19,20,21,22,23,24,25], seeds[26]; silicified wood without frost damage[19]. Paleosols throughout[4,5]. Mosses[27]. Ferns[28]. Fungi[29].	Fluvial coal measures; low sinuosity braided streams with channel, floodplain, levee, and crevasse splay deposits[6,33,3,34]. Meandering streams[1].	Upper member: Temperat humid seasonal. Lower member: Cold humid seasonal.	75-80
Early Permian	Fairchild	130-250	Massive quartzitic to arkosic sandstone with rare shale lenses[1].	Leaf impressions and coalified stem detritus[1]. Low diversity of palynoflora[30,31].	Post-glacial: Low sinuosity braided streams, filling of Mackellar lake/inland sea[1,6].	Cold post-glacial	80-90
Early Permian	Mackellar	60-140	Coarsening upward succession of sandstone and shale[9].	Low diversity of palynoflora[30,31].	Post-glacial: Mackellar lake/inland sea, turbidite sequences of lacustrine and crevasse splays[33,9,32].	Cold post-glacial	80-90
Early Permian to Late Carboniferous	Pagoda	0-440	Interbedded quartz dominated diamictite, sandstone, siltstone, and shale[10,1,11].	Low diversity of palynoflora[30,31].	Glacial: fluvial and lacustrine deposits from advancing and retreating ice sheet [10,1,11,35,7].	Cold glacial	80-90

References: [1]Barrett et al., 1986; [2]Vavra et al., 1981; [3]Collinson et al., 1994; [4]Horner and Krissek, 1991; [5]Krull and Retallack, 2000; [6]Isbell, 1991; [7]Isbell et al., 2001; [8]Isbell et al., 2001; [9]Miller and Collinson, 1994; [10]Lindsay, 1970; [11]Miller, 1989; [12]Taylor and Taylor, 1990; [13]Taylor et al., 2000; [14]Retallack and Krull, 1997; [15]Cúneo et al, 2003; [16]Taylor et al., 1992; [17] Taylor et al., 1997; [18]Kneppath et al., 2004; [19]Taylor et al., 1991; [20]Pigg, 1990; [21]Francis et al., 1993; [22]Cúneo, 1993; [23]Pigg and Taylor, 1993; [24]Francis et al., 1994; [25]Kneppath et al., 2005; [26]Taylor and Taylor, 1987; [27]Smoot and Taylor, 1986; [28]Galtier and Taylor, 1986; [29]Stubblefield and Taylor, 1986; [30]Kyle and Schopf, 1982; [31]Askin, 1998; [32]Miller and Isbell, in review; [33]Isbell and Macdonald, 1991; [34]Flaig, 2005; [35]Isbell et al., 1997; [36]Powell and Li, 1994

Sea (Barrett et al., 1986; Isbell, 1991; Powell and Li, 1994). Leaf impressions and coalified stem detritus are preserved within the Fairchild Formation and foreshadow the abundance of plant debris and thick coal beds of the Upper Permian Buckley Formation. The upper contact with the Buckley Formation is gradational.

The Buckley Formation is approximately 750 meters thick and is characterized by *Glossopteris*-bearing, fluvial deposits including channel sandstones and fine-grained floodplain deposits and coals (Barrett et al., 1986; Isbell, 1991; Isbell and Macdonald, 1991; Taylor et al., 1991; Taylor et al., 1992). The sandstone composition of the lower member of the Buckley is quartzitic to arkosic, whereas, the upper member is volcaniclastic (Barrett et al., 1986; Isbell, 1991). The Buckley Formation was interpreted initially as recording meandering stream deposition (Barrett et al., 1986), but has since been reinterpreted as low sinuosity braided stream deposits with associated channel, floodplain, levee, and crevasse splay deposits (Isbell, 1991; Isbell and Macdonald, 1991; Collinson et al., 1994; Flaig, 2005). Dropstones in the lower member indicate cold humid seasonal climate (Isbell et al., 2001; Isbell et al., 2003; Isbell and Miller, 2001), and the presence of coal (Barrett et al., 1986; Isbell, 1991) and *Glossopteris* leaves suggest a temperate and humid seasonal climate during deposition of the upper member (Isbell and Miller, 2001). The BGA was located at 75-80°S during deposition of the Buckley Formation (Powell and Li, 1994).

The transition from the Permian Buckley Formation to the Triassic Fremouw Formation in Antarctica includes the Permian-Triassic boundary (252 ± 1 Ma; Bowring and Erwin, 1998; Mundil et al., 2004). The largest known extinction occurred at this time; 90% of marine species and 70% of terrestrial species became extinct (Erwin, 1994;

Retallack, 1995). The boundary between the Buckley and Fremouw Formation has been interpreted both as conformable and disconformable (Retallack, 1998; Isbell et al., 1999). Collinson et al. (in press) present compelling evidence that complete sections across the boundary may be preserved in the CTM, particularly in the Shackleton and Beardmore Glacier areas. *Glossopteris* wood, *in situ* tree stumps, roots, leaves, and palynomorphs common in the Upper Permian succession disappear at the boundary and are replaced in the Triassic by small root casts and minimal plant debris (Collinson et al., 1994; Retallack, 1995; Retallack and Krull, 1997; Collinson et al., in review). Coals disappear at the boundary and do not re-appear until the upper member of the Fremouw Formation (Veevers et al., 1994). The boundary marks a change from peaty, immature paleosols of the Permian to deeply weathered paleosols of the Triassic (Collinson, 1997; Retallack and Krull, 1997; Retallack, 2001).

The Fremouw Formation is approximately 650 meters thick and consists of three informal members: a lower member dominated by large channel-fill sandstones that are volcaniclastic in composition and interbedded with non-carbonaceous mudstones, a middle fine-grained unit with redbeds and many paleosols, and an upper sand-rich member. Tetrapods, including *Lystrosaurus* and other components of the South African vertebrate fauna, as well as their burrows are abundant in sediments of the lower Fremouw Formation (Colbert and Kitching, 1977; Barrett et al., 1986; Hammer, 1990; Isbell and Macdonald, 1991; Collinson et al., 1994; Miller et al., 2001). The upper Fremouw Formation contains *Dicroidium* flora including an *in situ* fossil forest with 99 stumps on two surfaces (Taylor and Taylor, 1990; Cúneo et al., 2003); there is evidence for frost damage in the wood (Taylor and Taylor, 1993; Taylor et al., 2000). Climates for the lower, middle, and upper members of the Fremouw in the BGA are interpreted as cool temperate to warm and humid, semi-arid warm, and humid warm to cold respectively (Isbell and Miller, 2001) and the paleolatitude ranges from 70-80°S (Powell and Li, 1994).

The Fremouw Formation has a disconformable contact with the Upper Triassic Falla Formation which has a thickness of 0-282 meters (Barrett et al., 1986) and a paleolatitude between 70-80°S (Powell and Li, 1994). Volcaniclastic sandstones and carbonaceous shales with diverse *Dicroidium* flora of the Falla Formation are interpreted as deposited by high paleolatitude, low sinuosity streams (Barrett et al., 1986; Taylor and Taylor, 1990; Taylor et al., 1992).

Paleobiology and Climate

The barren post-glacial terrain of the BGA in the Early Permian was replaced by a landscape vegetated with *Glossopteris*-dominated forests in the Late Permian. This forested Permian landscape at a paleolatitude similar to its modern latitude contrasts with the modern polar desert mountains, glaciers, and ice sheets that lack macroscopic plants and animals (Francis et al., 1990; Taylor et al., 1992). Today, Lamping Peak (S 84° 12.6″; E 164° 40.7″) and Wahl Glacier (S84° 5.7″; E 165° 19.9″) study areas are isolated exposures of rock surrounded by glacial ice. The most recent paleolatitude projection for the Late Permian Beardmore Glacier area is at ~73°S (Figure 2; Lawver et al., 2004). This is consistent with earlier reconstructions putting the area at ~74°S (Smith et al., 1981) and ~66°S (Powell and Li, 1994). The location today at ~84°S is only ~10° south of the inferred Permian paleolatitude, even though there is no evidence in the Upper

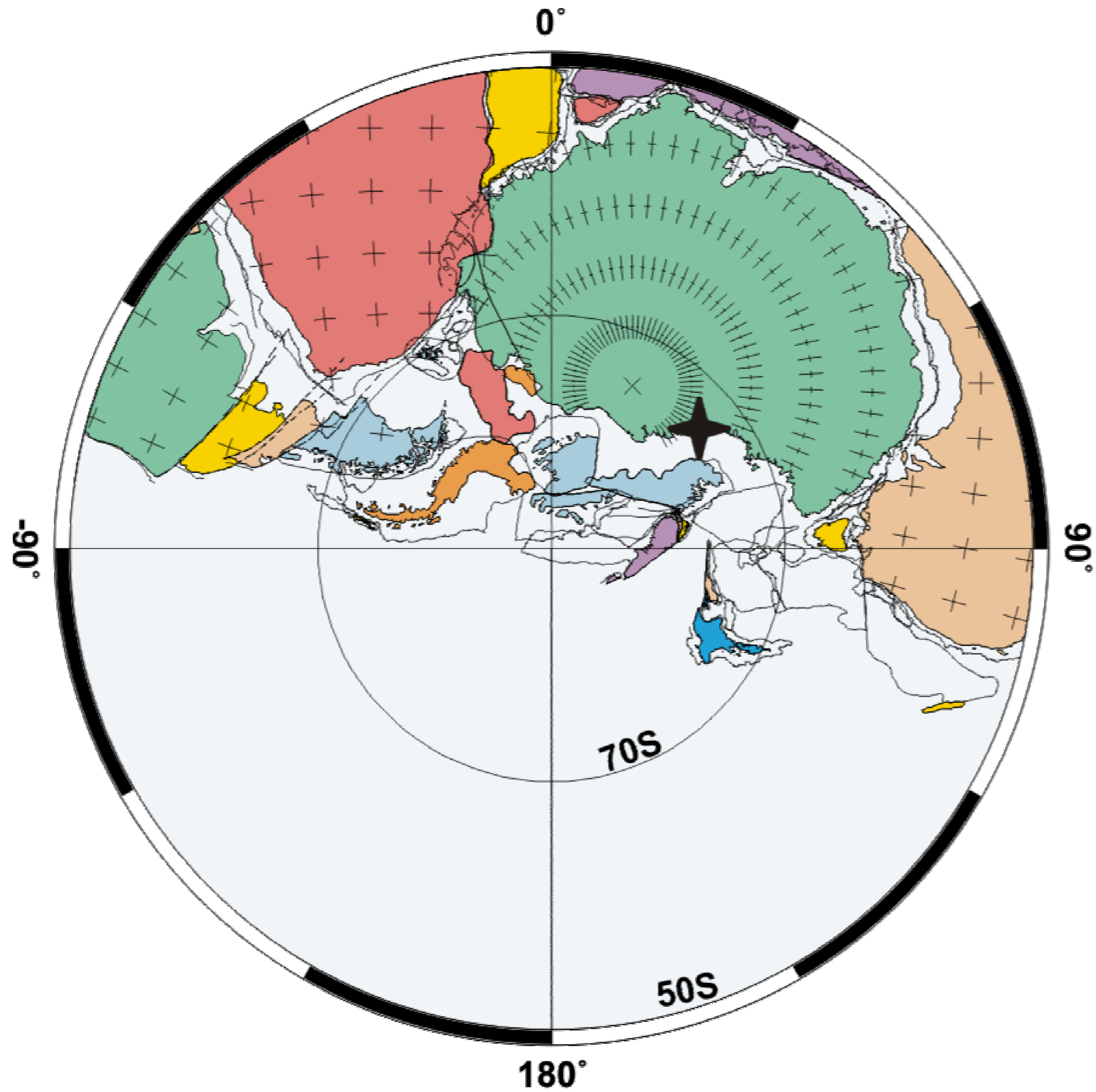


Figure 2. Gondwana in the Late Permian (250 mya). Star represents the location of the Beardmore Glacier area at ~75 degrees south paleolatitude (modified from Lawver et al., 2004).

Buckley Formation of ice (Isbell et al., 2003; Flaig, 2005) and *Glossopteris* trees inhabited the land during the Late Permian (Cúneo et al., 1993; Taylor et al., 1992).

A seasonal temperate humid Late Permian paleoclimate in the BGA and elsewhere in the TAM can be inferred from the plant fossils. Remains of Glossopteridales (seed ferns; Barrett et al., 1986; Taylor and Taylor, 1987; Pigg, 1990; Taylor et al., 1991; Francis et al., 1993; Cúneo, 1993; Pigg and Taylor, 1993), Bryophyta (mosses; Smoot and Taylor, 1986), Filicales (ferns; Galtier and Taylor, 1986), and Fungi (Stubblefield and Taylor, 1986) are preserved in permineralized peat (Taylor et al., 2000), and coals over a meter thick are also abundant (Barrett et al., 1986; Isbell, 1991; Collinson, 1997). Based on the abundance of leaves and a few *in situ* stumps, previous workers inferred that extensive dense *Glossopteris* forests survived dark, cold polar winters and frequent inundation of rivers (Taylor et al., 1992; Francis et al., 1993; Francis et al., 1994; Taylor et al., 2003). Growth rings in wood from *Glossopteris* stumps at Mount Achernar in the BGA indicate that the trees were juvenile. Latewood is the part of a tree ring that develops during the winter months and early wood develops during the summer months of a year. In silicified *Glossopteris* wood, the latewood is typically only a few cells thick implying dormancy in the winter and the mean thickness of earlywood is 4.5 mm implying rapid growth in the spring and summers (Taylor et al., 1992). No frost damage is found in Late Permian wood of the BGA; however, areas of thicker and denser wood than normal known as false rings are found (Taylor et al., 1992). This botanical evidence clearly demonstrates that the climate in the BGA was not frigid during the Late Permian.

Climate models suggest that global surface temperatures, including the polar regions, were elevated in the Late Permian (Retallack, 1995; Chumakov and Zharkov, 2003). Early and Middle Permian mean summer and winter temperatures based on climate models are about -2°C and -30°C (respectively) for a mean annual temperature of about -14°C (Gibbs et al., 2002). Previous paleoclimate models of the Late Permian yield polar surface temperatures that are too low to be consistent with the presence of forests with large deciduous trees, with recovered palynomorphs, or with peaty paleosols (Kiehl and Shields, 2005; Retallack et al., 2003; Taylor et al., 1992). In order to reconcile model-fossil discrepancies, Kiehl and Shields (2005) recently modeled the climate of the latest Permian (251 Ma) and incorporated atmospheric, terrestrial, oceanic, sea-ice, geographic, and topographic data. In their model they varied CO_2, CH_4, and N_2O concentrations and identified high CO_2 levels as the most significant factor in producing warm conditions at polar regions. According to Kiehl and Shields's model, latest Permian mean seasonal surface air temperatures for the BGA in the austral winter was between -25°C and -10°C, the mean temperature for the austral summer is ~20°C, and the mean annual temperature is ~1°C. These model temperatures are consistent with the fossil plants.

CHAPTER III

TREE AND FOREST CHARACTERISTICS

Glossopteris

The seed fern *Glossopteris* is a gymnosperm that flourished in Gondwana during the late Paleozoic before becoming extinct at the end of the Permian. Fossilized *Glossopteris* occurs in Antarctica, Australia, South America, Africa, and India (Schopf, 1970; Gould et al., 1977; Stewart and Rothwell, 1993; Pant, 1999); its widespread distribution provided early and compelling paleobiogeographical evidence for the existence of a large southern continent (Gondwana). Gymnosperms are defined as having naked seeds during pollination. The *Ginkgo biloba*, with its broad deciduous leaves, is the modern gymnosperm most similar to *Glossopteris* (Harlow et al., 1996); conifers are more abundant gymnosperms. Both the *Glossopteris* and the *Ginkgo* have apparent and unique properties with regard to tree size, seed characteristics, female fructifications, leaf appearance and attachment, and deciduous habit (Pant, 1999). Gymnosperms share deciduous characteristics including similarities [such as yellowing (inferred for *Glossopteris*), loss of leaves, and differentiation of early and late wood (Plumstead, 1958)].

Reconstructions of the *Glossopteris* tree from the various Gondwanan continents such as Australia, South Africa, India, and Antarctica are generally quite similar (Figure 3). Variation is most likely a function of incomplete preservation of the trees and subtle

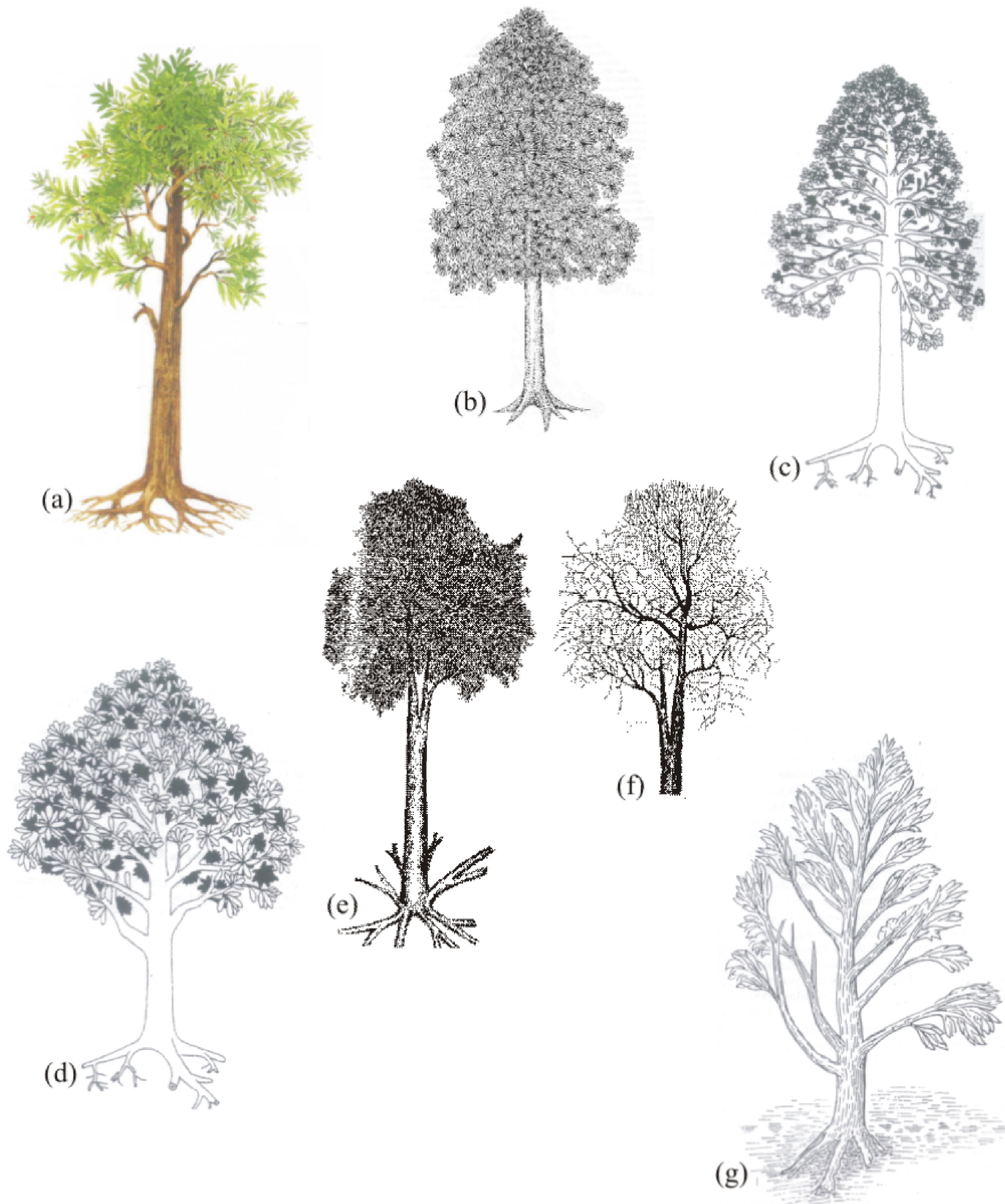


Figure 3. Reconstructions of the *Glossopteris* from various parts of Gondwana: (a) Australia (White, 1998), (b) Australia (Stewart and Rothwell, 1983), (c) Australia (Gould et al., 1977), (d) South Africa (Gould et al., 1977), (e) India (summer), (Pant, 1999), (f) India (winter), (Pant, 1999), (g) Antarctica (Schopf, 1970).

differences among species (Table 2). The crown shape defines the overall shape of the tree, and most *Glossopteris* reconstructions have crown shapes that range from rounded to conical. One exception is the Australian reconstruction by Stwart and Rothwell (1983). Their reconstruction is slightly more columnar. The columnar crown may be a better model for *Glossopteris*, particularly Antarctic species, because in modern environments, columnar crowns are more efficient at absorbing light and shedding snow which is needed at high latitudes and elevations (Kuuluvainen and Pukkala, 1989). The organization of leaves on the tree is similar to the *Ginkgo* (Pant, 1999); each *Glossopteris* reconstruction has leaves attached as clusters to the branch apex. Roots of the reconstruction are generally depicted as lateral extensions from the trunk.

Stumps of *Glossopteris*

During the 2003-2004 Antarctic field season, 87 stumps of *Glossopteris* were discovered in three separate stratigraphic horizons of the Upper Permian Buckley Formation in the Beardmore Glacier area. The stump horizon at Wahl Glacier contains 13 stumps (Figure 4); the exposure of the stump bearing horizon is narrow (~3 m wide) and it is likely that more stumps are preserved, but not exposed. The stumps are rooted in paleosols overlain by massive sandstones and the horizon with 13 stumps is less than 200 m below where Flaig (2005) places the Permian-Triassic boundary. A single stump also occurs in a horizon ~100 m below the boundary. Bedding plane exposures of the two stump horizons at Lamping Peak are more extensive. The upper stump horizon, here referred to as Lamping Peak 1, contains 53 stumps and a horizon one meter below, here referred to as Lamping Peak 2, contains 21 (Figure 5). Another single stump exists at

Table 2. Summary of various author's reconstructions of *Glossopteris* from Australia, South Africa, India, and Antarctica. Crown shape is described using Oliver and Larson (1996), leaf attachment are described using terminology of Pant (1999), branches and roots are described as direction of growth from tree trunk, and limb position (phyllotaxy) is described using terminology of Wilson (1984).

	Australia[a]	Australia[b]	Australia[c]	South Africa[c]	India[d]	Antarctica[e]
Crown shape	round	conical, columnar	conical	conical, round	round	conical
Leaf attachment	apial clusters	apial clusters	apial clusters	apial culsters	apial clusters	apial clusters
Branches	wound upward	straight outward	curved downward	straight upward	wound upward	curved upward
Limb position	alternate	opposite	opposite	alternate	alternate	opposite
Roots	lateral	lateral	lateral	lateral	lateral	slanted

([a]White, 1998; [b]Stewart and Rothwell, 1983; [c]Gould et al., 1977; [d]Pant, 1999; [e]Schopf, 1970)

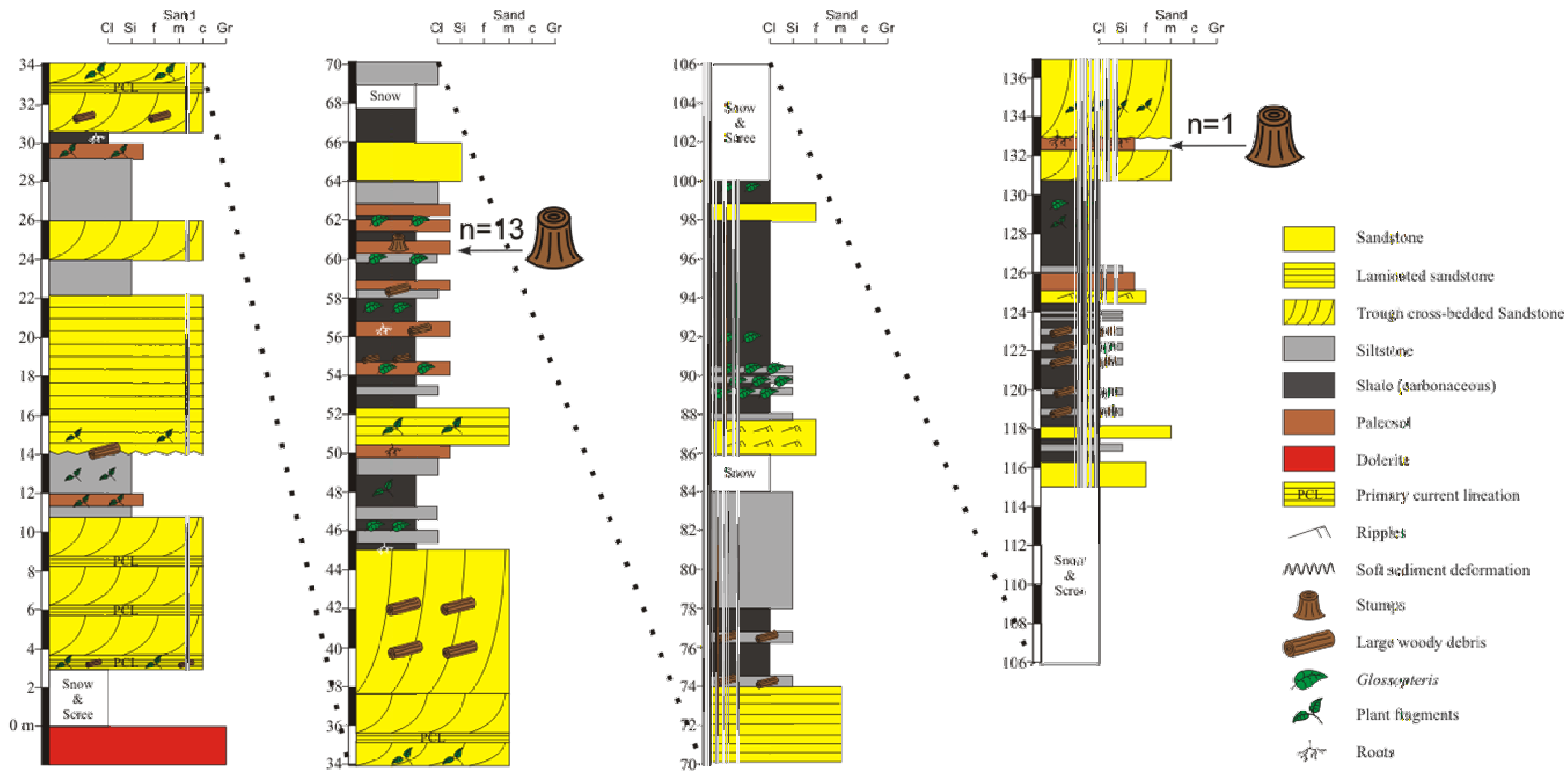


Figure 4. Stratigraphic section of the Late Permian, Upper Buckley Formation at Wahl Glacier. Alternating units of sandstone, siltstone, shale, and paleosols are interpreted as a braided stream system that includes floodplain and crevasse splay deposits (Collinson and Isbell, 1986; Isbell and Collinson, 1988; Isbell, 1991; Isbell and Macdonald, 1991; Flaig, 2005). Plant material of *Glossopteris* is preserved within these deposits as well as 14 stumps. The number of stumps in each horizon is indicated by "n."

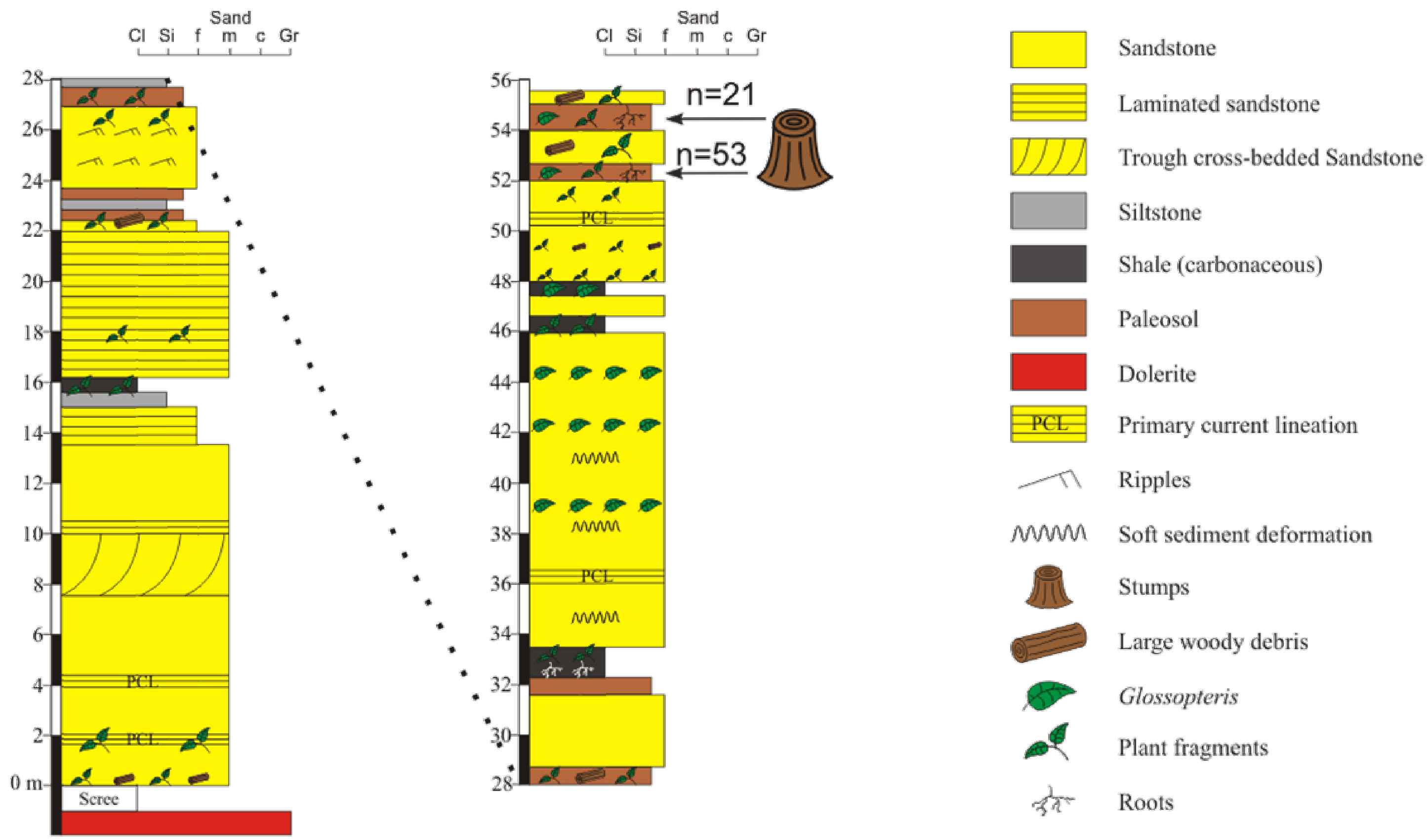


Figure 5. Stratigraphic section of the Late Permian, Upper Buckley Formation at Lamping Peak. Alternating units of sandstone, siltstone, shale, and paleosols are interpreted as a braided stream system including floodplain and crevasse splay deposits (Collinson and Isbell, 1986; Isbell and Collinson, 1988; Isbell, 1991; Isbell and Macdonald, 1991; Flaig, 2005). Plant material is preserved throughout the section and includes two stump horizons in the upper part of the section. The lower stump horizon with 53 stumps is referred to as Lamping Peak 1; the upper horizon with 21 stumps is referred to as Lamping Peak 2.

Graphite Peak in the Beardmore Glacier area slightly below (~15 m) where Retallack and Krull (1997) place the Permian-Triassic boundary. Wahl Glacier and Lamping Peak stumps are interpreted as *in situ* because they are surrounded by fossil leaf mats and have roots radiating outward. The leaf mats consist of stacked impressions of *Glossopteris* leaves (Figure 6). Whole leaves are rare (Figure 7). Coalified roots (Figure 8) or root impressions (Figure 9) radiate shallowly outward from the stumps into surrounding rock indicating a high water table. Laminations in the surrounding rock are well developed and undisrupted implying minimal soil development (Figure 10). These immature paleosols most closely resemble modern inceptisols which are described as poorly developed soils with preservation of residual laminations and large root traces; they are commonly alluvial in origin (Retallack, 1990; Horner and Krissek, 1991; Retallack, 1995; USDA, NRCS, 1999; Retallack, 2001; Bridge, 2003). Root traces at Lamping Peak are a maximum of 157 cm long and 9 cm wide near the trunk.

The abundance of *in situ* stumps allowed for reconstruction of the attributes of the Permian forests using modern forestry techniques. Tree height was estimated from tree diameter and density was determined from tree distribution. Basal area can be calculated using tree diameter and density. Integration of this information with the interpretations of tree shape generates a picture of the Permian forests.

Tree height

Application of forestry techniques to the *Glossopteris* forests at Lamping Peak and Wahl Glacier required determination of maximum tree height which can be estimated from diameter at breast height (d.b.h.), or the diameter at approximately two meters

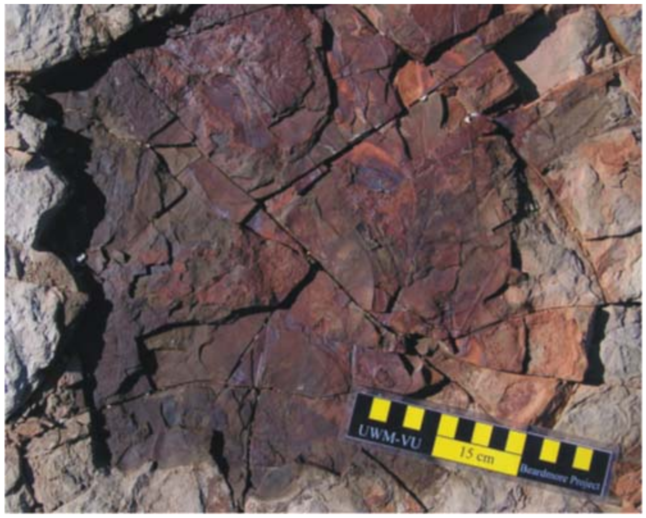


Figure 6. Leaf mat overlying paleosol at Lamping Peak. Scale bar equals 15 cm.

Figure 7. *Glossopteris* leaf with pinnate veins extending from the central rib. This sample is ~10 cm long and is located at Lamping Peak.

Figure 8. Profile of a slicified stump with coalified roots within a paleosol at Wahl Glacier. This stump is approximately 20 cm in diameter.

Figure 9. Top view of a stump in the lower of the two stump horizons at Lamping Peak (Lamping Peak 2). Roots radiate outward from the stump, which is approximately 25 cm in diameter.

Figure 10. Vertical view of paleosol at Lamping Peak. Bedding is visible within the soil horizon, and disruption caused by soil forming processes is absent; the paleosol is immature.

above the ground line (Niklas, 1994). Most stumps of fossil forests do not stand two meters high, so the diameter at ground line is used instead. This is the case at Lamping Peak and Wahl Glacier where stumps have little to no relief. Mean ground line diameters are 20.9 cm at Lamping Peak 1, 39.2 cm at Lamping Peak 2, and 25.6 cm at Wahl Glacier. One problem with using diameter at ground line instead of d.b.h. is that trees flare at their bases; therefore, ground line diameters will yield larger values for height.

D.b.h. for modern species can be calculated using a regression equation developed by McClure (1968) if the diameter and height above ground that the diameter was measured is known. The equation is based on the tapering and root flare trends of 55 modern tree species in the southeastern United States. The coefficients for this equation vary among species due to differences in tapering, and because *Glossopteris* is extinct, d.b.h. for trees of Lamping Peak and Wahl Glacier was calculated using the ground line (zero relief) diameter of each stump and the coefficients each of the 55 species listed. Calculations of d.b.h. from the 55 species were then averaged for each stump (Figure 11). From the average d.b.h., maximum heights were calculated using another regression equation developed by Niklas (1994). The average maximum tree height using the d.b.h. was 14.6 m at Wahl Glacier, 11.7 m at Lamping Peak 1, and 18.9 m at Lamping Peak 2, and the average maximum tree height using ground line diameters was 19.2 m at Wahl Glacier, 15.4 m at Lamping Peak 1, and 24.6 m at Lamping Peak 2.

Forest density

Stand density, the number of trees per unit area, was a feature determined for each fossil forest at Lamping Peak and Wahl Glacier in order to compare to other modern and

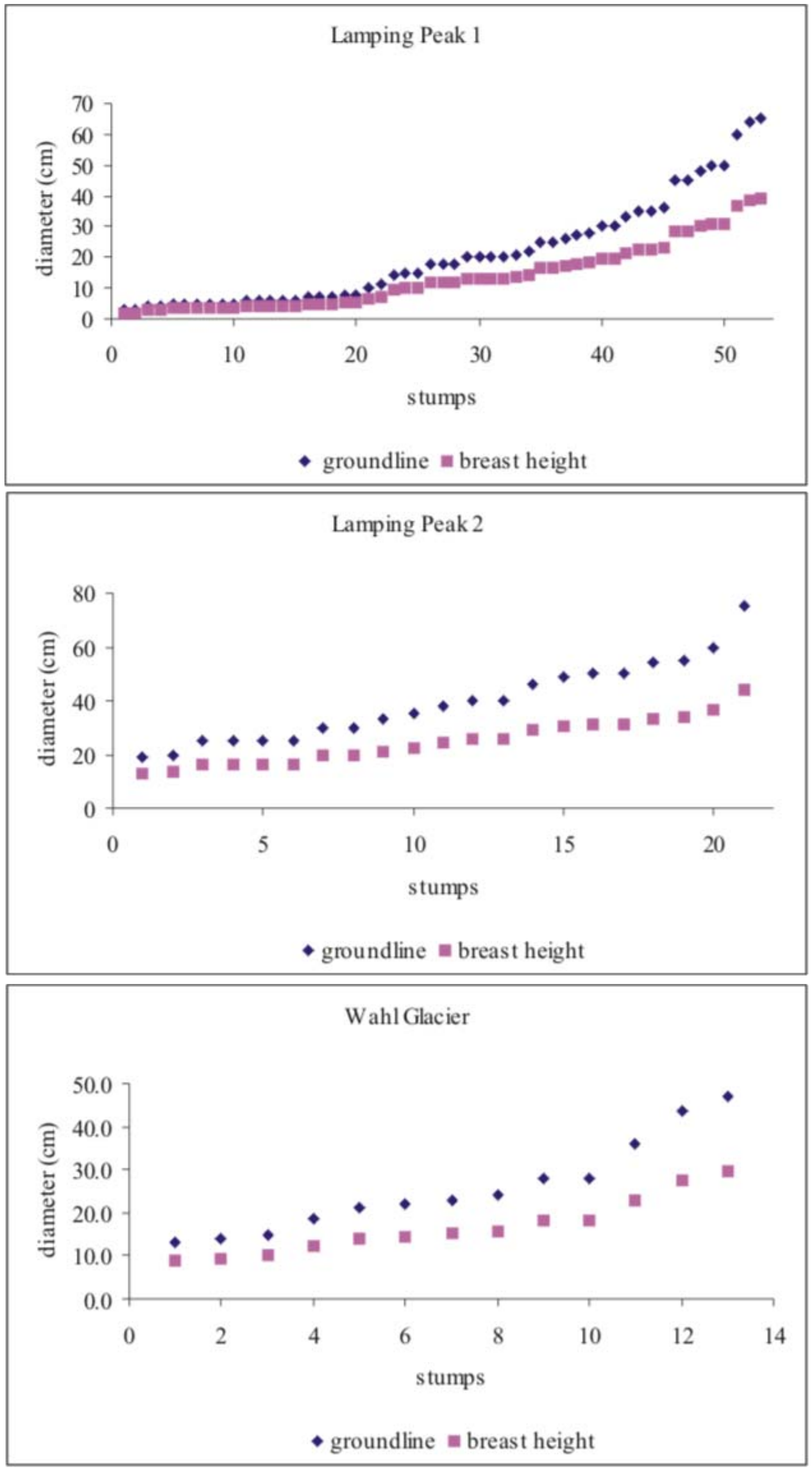


Figure 11. Comparison of diameters measured at ground line to diameters calculated at breast height for Lamping Peak 1, Lamping Peak 2, and Wahl Glacier. Largest stumps are most affected by the calculation.

fossil forests (Jefferson, 1982; Creber, 1990). Distance between each stump was measured from center to center, and direction was obtained by using point and compass. The fossil forest was plotted to scale using field measurements (Figure 12).

One method used to determine stand density was the point-centered quarter (pcq) method described by Cottam and Curtis (1956). This method quantifies the spatial location of trees in quadrants defined by arbitrary points along transects within a forest (Figure 13). It is used by workers describing other fossil forests in the BGA (Taylor et al., 1991; Cúneo et al., 1993; Cúneo et al., 2003) and is the most statistically sound density calculation by modern forestry standards (Cottam and Curtis, 1956; Mitchell, 2005); however, there are inconsistencies with the pcq method observed in this study.

Calculated densities varied depending on the distances between points and on the orientation of the transect line through the forest. One 30 m transect yielded a stand density of 1372 trees/hectare (t/ha) when the interval of measurement was 10 m and 1773 t/ha when the interval was 5 m. Two other 30 m transects through the same forest but at different locations, with intervals of 5 m, yielded densities of 2116 t/ha and 2556 t/ha. The difference in stand density values for Lamping Peak 1 is almost 1200 t/ha. At Lamping Peak 2, the calculated density from two 30 m transects are 1055 t/ha for 5 m intervals and 1225 for 10 meter intervals. Wahl Glacier transects were 190 m and yielded densities of 405 t/ha for 10 m intervals and 573 t/ha for 20 m intervals. Such variability in densities determined using the pcq method may be a concern when comparing Lamping Peak and Wahl Glacier forests to both modern forests and other fossil forests.

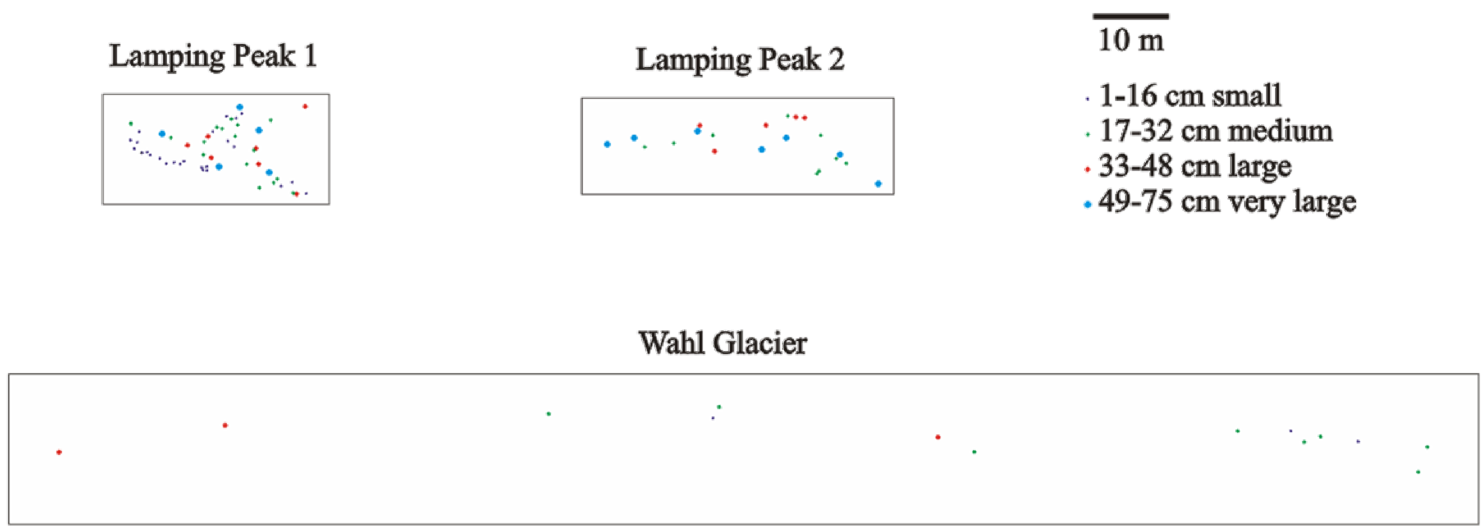


Figure 12. Distribution of *Glossopteris* stumps on bedding planes at Lamping Peak and Wahl Glacier. Diameters are divided into four diameter categories, small, medium, large, and very large.

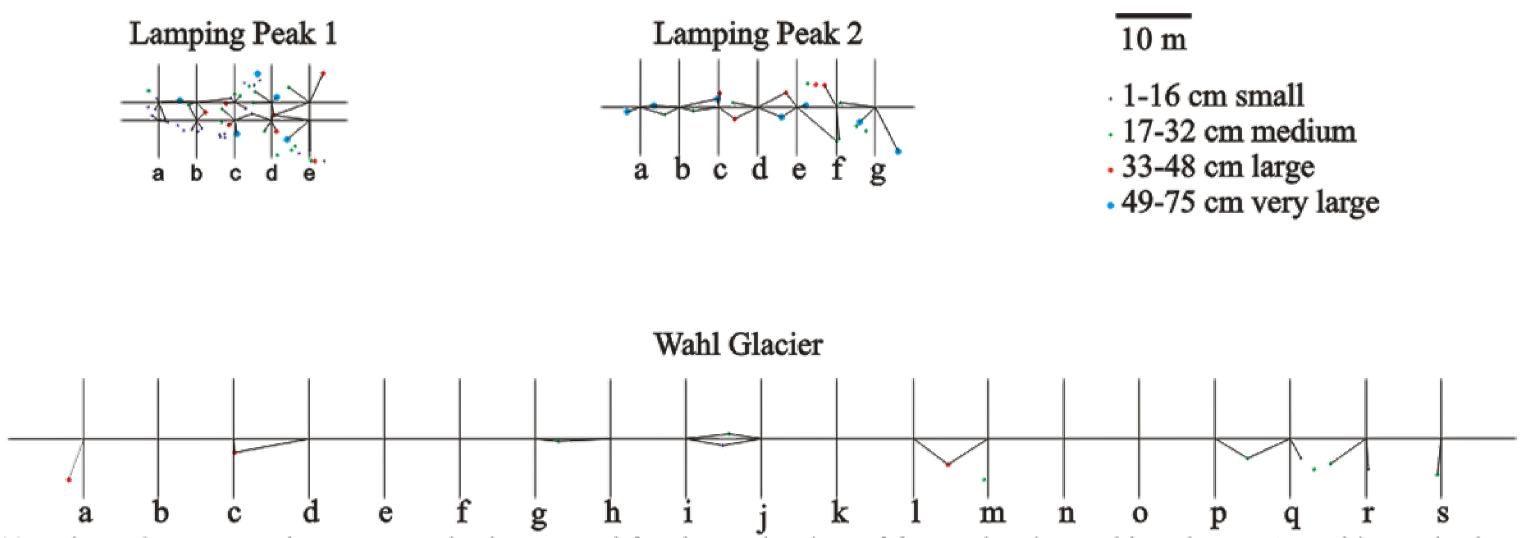


Figure 13. The point-centered quarter method was used for determination of forest density and basal area. For this method a grid is placed over the forest plots from Lamping Peak and Wahl Glacier to produce quadrants. The distance from each intersection (represented by lower case letters) to the nearest tree in each quadrant is measured and averaged to calculate forest density (Cottam

The following are average densities calculated using the pcq method: Lamping Peak 1 is 1954 t/ha, Lamping Peak 2 is 1140 t/ha, and Wahl Glacier is 489 t/ha.

Densities of other high-latitude fossil forests were calculated using a second technique that simply divides the number of *in situ* stumps in a forest by a given area and converts the density to t/ha (Jefferson, 1982; Creber, 1986; Francis, 1991; Basinger et al., 1994; Greenwood and Basinger, 1994; Pole, 1999; Falcon-Lang et al., 2001). This density calculation coupled with the pcq calculation potentially yields more credible density values for forests at Lamping Peak and Wahl Glacier.

The number of stumps in each fossil forest at Lamping Peak and Wahl Glacier are known, but the boundaries are not clearly defined; therefore, the areas of the fossil forests are not precisely known. To define the boundary, I used a technique based on distances to the nearest neighbor. The distance between each stump and its nearest neighbor was measured and averaged to determine an average forest area. Average distances between nearest neighbors were 1.1 m at Lamping Peak 1, 2.0 m at Lamping Peak 2, and 8.4 at Wahl Glacier. These averages were then used as a radius to draw a circle around each stump and define the perimeter of the fossil forest. The calculated perimeter for all three forests closely resembled the perimeter of the exposed bedding surface. The total number of trees in each forest was divided by forest area to produce the stand density. Density for each forest using areas determined by nearest neighbors is as follows: Lamping Peak 1 with 3056 t/ha, Lamping Peak 2 with 1229 t/ha, and Wahl Glacier with 38 t/ha.

To determine possible the upper and lower limits of forest areas, longest and shortest distance between nearest neighbors were used. These limits constrain density values by calculating the perimeters and defining the largest and smallest likely values of forest area. The density of Lamping Peak 1 is between 0.3 m and 4.9 m, Lamping Peak 2 is between 0.5 m and 5.1 m, and Wahl Glacier is between 1.8 m and 22.2 m.

Results of density calculations are summarized in Figure 14. The point-centered quarter method generates stand density values for fossil forests at Lamping Peak and Wahl Glacier within the limits of densities calculated using areas defined by nearest neighbor distances. The range of density values at Lamping Peak 1 is broader than that at either Lamping Peak 2 or Wahl Glacier, but the relative difference is biased at Wahl Glacier. The difference may be an artifact of exposure. Whereas Lamping Peak 1 stumps are exposed on a broad bedding plane, exposure of the Lamping Peak 2 horizon is narrower, and exposure of Wahl Glacier is ~3 m wide.

Average density of all estimates from both methods are 2505 t/ha for Lamping Peak 1, 1185 t/ha for Lamping Peak 2, and 263 t/ha for Wahl Glacier. Stand density of the Lamping Peak 1 forest may be greater than that of the other forests because many stumps at Lamping Peak are smaller in diameter. Tree density decreases as a forest maturity increases in modern forests. In other words, young forests have many small diameter trees, but as the forest matures over time, the number of trees diminishes while the size of the trees increases. Tree density is forest-age dependant, but total basal area per hectare is not, allowing comparison of forests of differing, or unknown, maturities (Oliver, 1981).

Basal area

Basal area is the total cross-sectional area of trees at breast height in a forest per unit area (Cottam and Curtis, 1956). Basal areas for the fossil forests at Lamping Peak

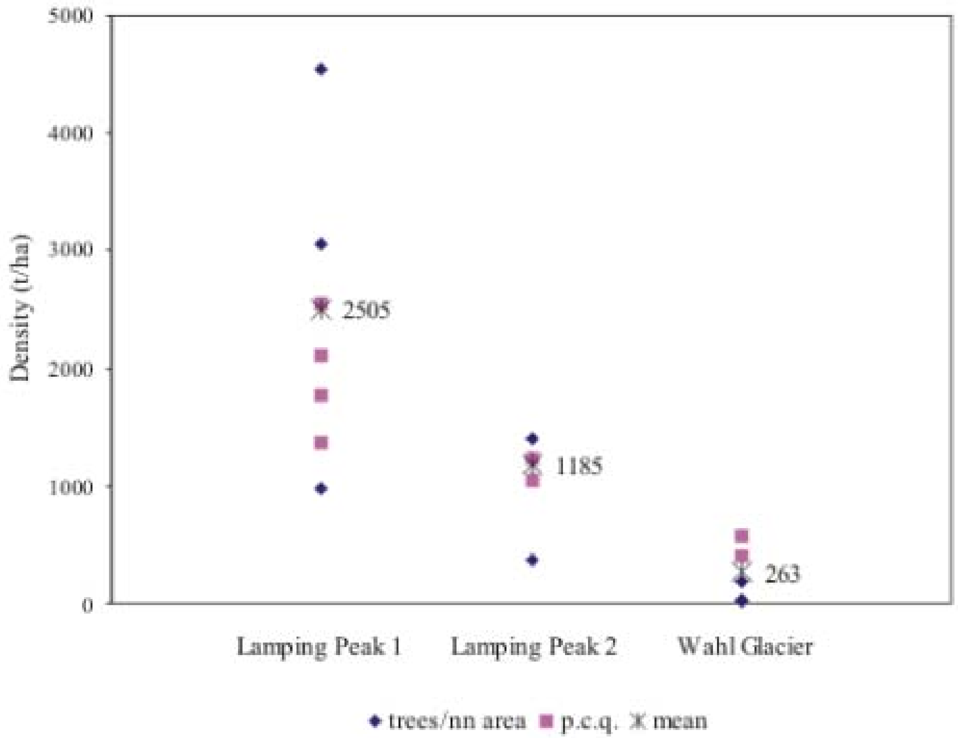


Figure 14. All forest density calculations from various transects with the point-centered quarther method (squares) and different densities calculated from areas determined by the nearest neighbor (nn; diamonds). Mean value for each forest is indicated with a star and labeled with the value.

and Wahl Glacier were calculated using calculated tree diameters at breast height and measured ground line diameters for total forest areas estimated by the pcq method and the nearest neighbor technique (Figure 15). As expected, ground line measurements had larger basal areas at Lamping Peak and Wahl Glacier because of root flare. Lamping Peak forests have a greater range of basal areas, particularly for diameter at ground line. The forest at Lamping Peak 2 has the highest average basal area of the three.

Analysis of stump distribution

Information about stand maturity and health for both modern and fossil forests can be identified using ages and sizes of individual trees, the distribution of trunk diameters, density, and basal area. Tree age is recorded as the number of growth rings which is also proportional to tree size, and more specifically, the trunk diameter. Diameter is a more practical measure of age since in living trees, rings are concealed within the trunk and in fossil stumps, rings are unclear. One stump in the Lamping Peak 2 forest has 26 growth rings preserved. However, most stumps at Lamping Peak do not have preserved rings because the stump has weathered from the surrounding rock. Growth rings in stumps from Wahl Glacier are apparent, but the number is indeterminate due to the homogeneous nature of permineralization.

Forest maturity in modern environments can be assessed by the distribution of tree diameters within a stand (Figure 16). Trees in younger stands are smaller and have little variation in size, but as a stand matures, individuals will die-off and the open space will accommodate new growth; therefore, trees in older stands often have a wider range of sizes (Oliver, 1981; Deal et al., 1991; Oliver and Larson; 1996). As in modern forests,

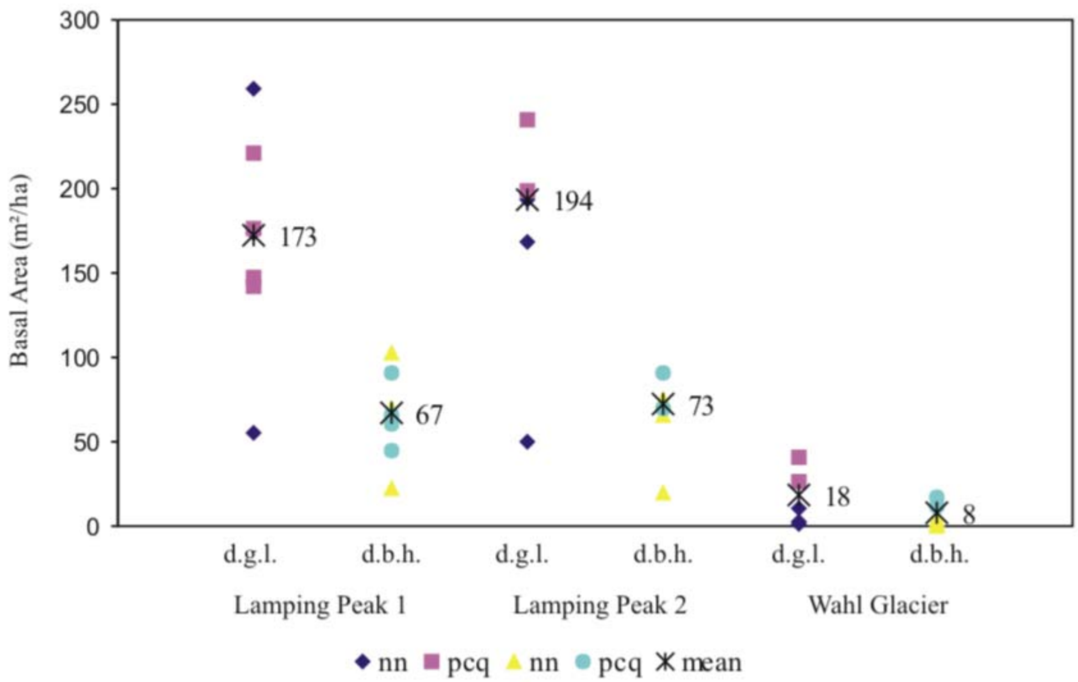
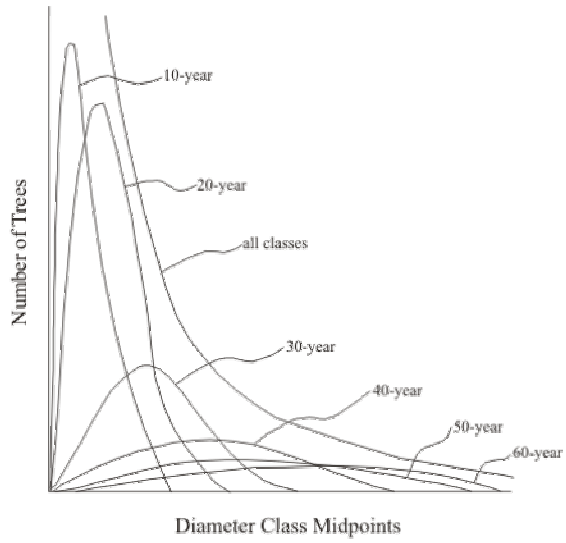
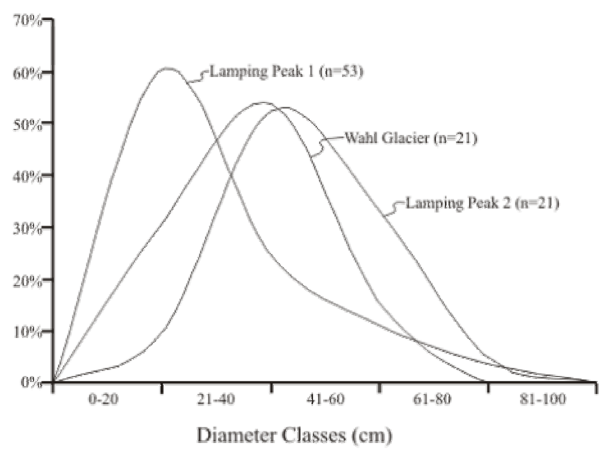


Figure 15. Basal areas from point-centered quarter (pcq) method areas using diameter at ground line (d.g.l.; squares) and diameter at breast height (d.b.h.; circles), and from nearest neighbor (nn) areas using d.g.l. (diamonds) and d.b.h. (triangles). Mean values of each category is indicated with the star and labeled with the value.



(a)



(b)

Figure 16. Distribution of tree diameters within stands. (a) Ideal distribution of tree diameters for different aged stands (Oliver and Stephens, 1977; Deal et al., 1991; modified from Oliver and Larson, 1996). (b) Distribution of stump diameters at ground line for Lamping Peak 1, Lamping Peak 2, and Wahl Glacier. "n" is the total number of stumps in each fossil forest.

distribution of stump diameters may give information about the maturity of fossil forests. Stump diameters at ground line range from 3 to 65 cm at Lamping Peak 1, 19 to 75 cm at Lamping Peak 2, and 13 to 47 cm at Wahl Glacier. The forest at Wahl Glacier appears younger than both forests at Lamping Peak because the maximum tree diameter is lowest. However, assessing maturity of the two Lamping Peak forests is more difficult (Figure 16). Even though 60% of the trees in the Lamping Peak 1 forest are less than 20 cm in diameter and the distribution of diameters resembles a younger forest than Lamping Peak 2 and Wahl Glacier, the Lamping Peak 1 forest includes trees larger than Wahl Glacier and almost as large as Lamping Peak 2 implying that the forests at Lamping Peak 1 and 2 are similar in maturity. The skewed distribution of tree-diameter at Lamping Peak 1 may be the product of a disturbance during the succession of the forest (Oliver, 1981; Deal et al., 1991; Oliver and Larson; 1996).

Comparison to modern forests

To better understand the paleoenvironments of fossil forests at Lamping Peak and Wahl Glacier, density and basal area were compared to those of modern forests in different ecosystems at different lattitudes. Forest density and basal area vary widely in extant forests; values for Lamping Peak and Wahl Glacier forests are within the range of these modern forests.

Density and/or basal area values of modern forests, as well as these of Lamping Peak and Wahl Glacier forests are given in Figure 17. The modern forests for which data are available have densities ranging from 200 t/ha (Bartsch et al., 2002) to 3012 t/ha (Norokorpi, 1997) and basal areas ranging from 16.6 m^2/ha (Golet et al., 1993) - 251.4

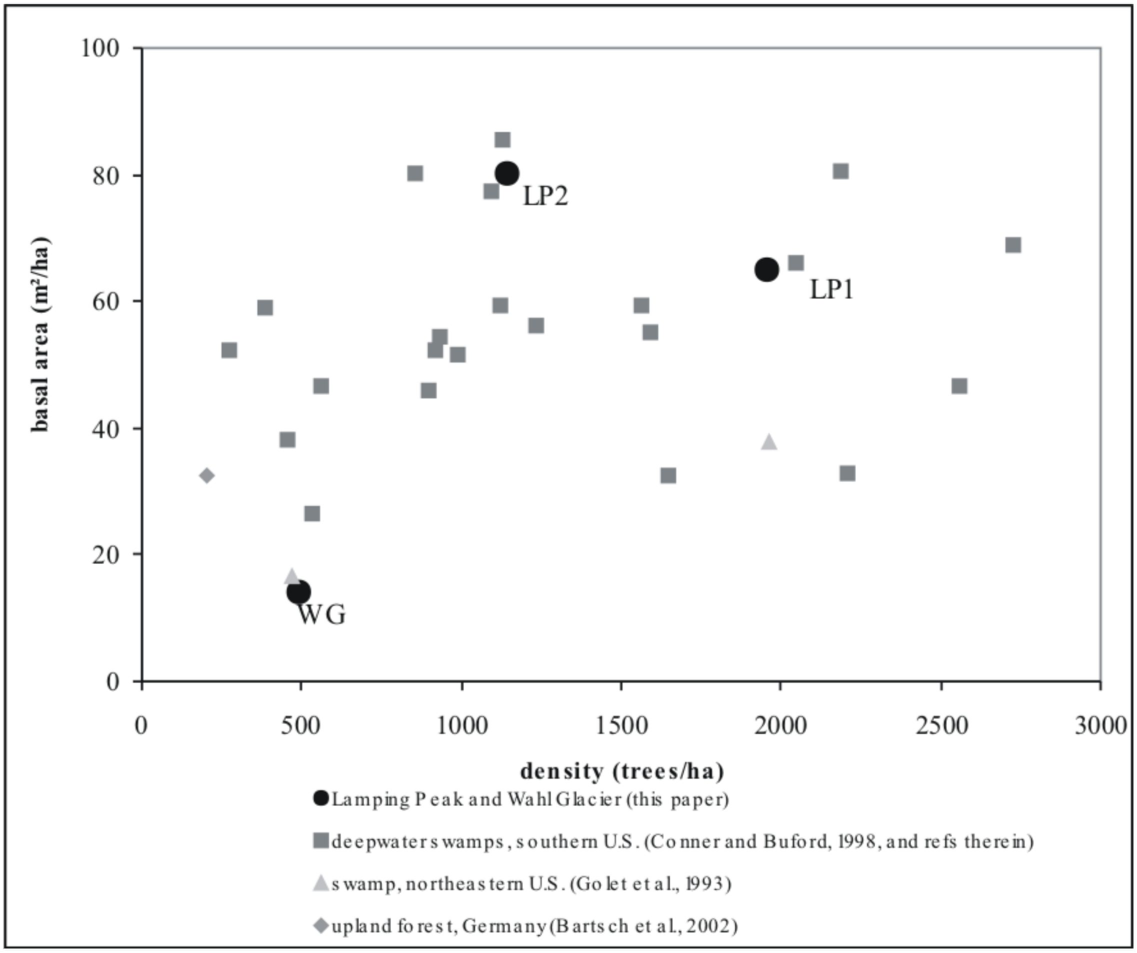


Figure 17. Comparison of density and basal area of Lamping Peak (LP1 and LP2) and Wahl Glacier (WG) forests to selected modern forests.

has a particularly low basal area of 14.1 m^2/ha. This may be a function of the narrow (~3 m) bedding plane exposure.

Comparison of density and basal area of fossil forests to modern forests are hindered by lack of standardized procedures. For example, some studies consider only overstory (Stout and Marion, 1993, and refs. therein) while others include overstory as well as one year old saplings (Norokorpi, 1997). Sharitz and Mitsch (1993, and refs. therein) and Dunwiddie et al. (1994) also report basal area values that exclude d.b.h. (diameter at breast height) less than up to 10 cm. Lowest d.b.h. for fossil forests at Lamping Peak 1, Lamping Peak 2, and Wahl Glacier are 2.1 cm, 12.6 cm, and 8.7 cm, respectively. Also, dead trees cannot be identified in fossil forests, and thus are not excluded from the living populations as they are in most studies of modern forests. Dunwiddie et al. (1996) determined basal area for six types of forests from the eastern United States and included both living and dead trees. Dead trees ranged from 2-35% of the basal area of the entire population of living and dead trees. In two other studies, 0.12% of an upland forest from Germany was dead (Bartsch et al., 2002), and 4% of a wet pine flat forest from North Carolina was dead (Brinson and Rheinhardt, 1998). These factors, along with other inconsistencies, must be considered when comparing density and basal area values.

Densities and basal areas of forests in deepwater swamps of the southern U.S., swamps of the northeast U.S., and upland areas of Northwest Germany were plotted in a stocking chart with Lamping Peak and Wahl Glacier forests (Table 3). Stocking charts are graphs of stand density versus basal area and are used by foresters to gage a stand's productivity for maintaining optimal wood production (Martin and Ek, 1990). Though

Table 3. Density and basal area (B.A.) of Lamping Peak and Wahl Glacier forests compared to selected modern forests.

Forest type	Location	Density stems/ha	B.A. m^2/ha	Comments	References
floodplain (?), fossil	Lamping Peak 1, Antarctica	1933	65.1	d.b.h.	this paper
	Lamping Peak 2, Antarctica	1140	80.2	d.b.h.	
	Wahl Glacier, Antarctica	480	14.1	d.b.h.	
deepwater swamp	Southern U.S.	2730	59.0	trees	Conner and Buford, 1998, and refs. therein
		916	52.4	trees	
		2210	32.8	trees	
		2050	66.1	trees	
		748	251.4	trees	
		988	51.7	trees	
		1094	77.5	trees	
		1127	85.5	trees	
		1588	55.0	trees	
		2558	46.6	trees	
		1120	59.2	trees	
		909	46.0	trees	
		1644	32.5	trees	
		856	80.2	trees	
		1500	59.3	trees	
		n/a	138.1	trees	
		2186	80.4	trees	
		271	52.3	trees	
		530	26.6	trees	
		454	38.0	trees	
		387	59.1	trees	
		1238	56.2	trees	
		939	54.5	trees	
		560	46.7	trees	
deepwater swamp	Big Thicket, TX, U.S.	n/a	138.1	d.b.h. ≥ 4.5 cm	Sharitz and Mitsch, 1993, and refs. therein
	Barataria Bay, LA, U.S.	n/a	44.0	d.b.h. ≥ 2.5 cm	
	Okefenokee Swamp, GA, U.S.	n/a	71.1	d.b.h. ≥ 4.0 cm	
	Alluvial Swamps, SC, U.S.	n/a	44.7	d.b.h.	
	Dismal Swamp, VA, U.S.	n/a	59.8	d.b.h.	

Table ModDenBA, Continued

Forest type	Location	Density stems/ha	B.A. m^2/ha	Comments	Reference
swamp	Northeastern U.S.	470	16.6	trees	Golet et al., 1993
		1960	37.8	trees	
		250	6.7	only shrubs	
		91000	8.2	only shrubs	
peatland, virgin	South Finland	3012	n/a	includes saplings	Norokorpi, 1997
		2882	n/a	includes saplings	
	Southern North Finland	2001	n/a	includes saplings	
		1518	n/a	includes saplings	
	Central North Finland	1546	n/a	includes saplings	
		1139	n/a	includes saplings	
	Northern North Finland	1558	n/a	includes saplings	
		751	n/a	includes saplings	
lowland	Central and North Florida, U.S.	1456	27.8	only overstory	Stout and Marion, 1993, and refs. therein
	Central and North Florida, U.S.	1218	11.9	only overstory	
bottomland, old-growth	Horseshoe Lake, IL, U.S.	n/a	36.7	d.b.h.	Sharitz and Mitsch, 1993, and refs. therein
bottomland, secondary-growth	Horseshoe Lake, IL, U.S.	n/a	30.5	d.b.h.	
bottomland	Big Thicket, TX, U.S.	n/a	23.1	d.b.h. > 4.5 cm	
	Dismal Swamp, VA, U.S.	n/a	38.3	d.b.h.	
	Sandy Alluvial Swamps, SC, U.S.	n/a	36.4	d.b.h.	
	Red Water River Swamps, SC, U.S.	n/a	34.2	d.b.h.	
floodplain	Virginia, U.S.	4474	31.2	only shrub and understory	Brinson and Rheinhardt, 1998, and refs. therein
	North Carolina, U.S.	12550	14.7	only shrub and understory	
floodplain adjacent to river	Cache River, AK, U.S.	120	n/a	trees	Foti, 2001
floodplain frequently flooded		175	n/a	trees	
slightly elevated		122	n/a	trees	
elevated		407	n/a	trees	
upland		116	n/a	trees	
excessive drainage		34	n/a	trees	
upland	Northwest Germany	200	32.5	includes sparse understory	Bartsch et al., 2002
upland, old-growth	Adirondack Park, N.Y., U.S.	n/a	42.4	trees	Dunwiddie et al., 1994
		n/a	37.2	trees	
		n/a	27.7	trees	
		n/a	30.6	trees	
	Massachusetts, U.S.	n/a	21.8	d.b.h. > 10 cm	
		n/a	43.2	d.b.h. > 10 cm	

there is no apparent trend with the either modern or fossil forests, Lamping Peak and Wahl Glacier forests plot among the modern forests. Comparisons could be made with more confidence if more data were available, and, if identical procedures were used. However, it is very clear that the Permian high-latitude forests were equally as dense and had basal areas as large as modern forests in diverse settings.

Comparison to other high-latitude fossil forests

Few Permian forests have been recorded, particularly at high-latitude. The only other Permian high-paleolatitude forests of which we are aware are in Antarctica at Mount Achernar, McIntyre Promontory, and Mount Piccioto. Lamping Peak and Wahl Glacier are two additional locations hosting Permian, high-latitude forests (Table 4). The forests preserved at Lamping Peak have the earliest (~250 mya) and largest number of stumps (74 in two horizons) at high-latitudes (~75°S) ever documented in the southern hemisphere. A Late Permian polar forest at Mount Achernar is recorded with 15 stumps, too few to yield meaningful forest characteristics. Regardless, mean stump diameters at both Lamping Peak and Wahl Glacier are larger in diameter, and therefore, the trees are taller and more mature (Cúneo et al., 1993; Taylor et al., 2003). Trees in the Alexander Island fossil forest are the tallest recorded from any of these fossil forests. However, the forest was significantly younger (mid-Cretaceous), the climate warmer, and the forest located at lower paleolatitude than the Beardmore Glacier area forests, so it is not surprising that the trees were larger (Francis, 1991; Basinger et al., 1994; Greenwood and Basinger, 1994; Figure 18).

Table 4. Selected high-paleolatitude forests.

	Lamping Peak 1	Lamping Peak 2	Wahl Glacier	Mt. Achernar[1]	Gordon Valley[2]	Curio Bay[3]	Alexander Island[4]	Axel Heiberg Island[5]
Location	Antarctica	Antarctica	Antarctica	Antarctica	Antarctica	New Zealand	Antarctic Penninsula	Arctic Canada
Paleolatitude (°)	~75 S	~75 S	~75 S	~75 S	~68 S	~66 S	~70 S	~77 N
Age	Late Permian	Late Permian	Late Permian	Late Permian	Middle Triassic	Middle Jurassic	mid-Cretaceous	early Tertiary
Paleoenvironment	floodplain (?)	floodplain (?)	floodplain (?)	floodplain	levee/floodplain	floodplain	floodplain	swamp
Number of stumps	53	21	13	15	99 (on 2 surfaces)	725	86	-
Mean diameter (cm)	20.9	39.2	25.6	11.4	27.8	16.3	8 to 22	27.4
Estimated height (m)	15	25	19	10	20	14	30	-
Density (trees/ha)	2505	1185	263	2134	274.12	552	568	1136
Basal area (m^2/ha)	173	194	18	65.8	20.83	16	-	80.8
Preservation	magnetite/mold	magnetite/mold	silica	silica	silica	silica/sandstone	silica	mummified

Modified from Cúneo et al., 2003

[1]Cúneo et al., 1993; Taylor et al., 1992

[2]Cúneo et al., 2003

[3]Pole, 1999

[4]Jefferson, 1982; Creber, 1986; Falcon-Lang et al., 2001

[5]Francis, 1991; Basinger et al., 1994; Greenwood and Basinger, 1994

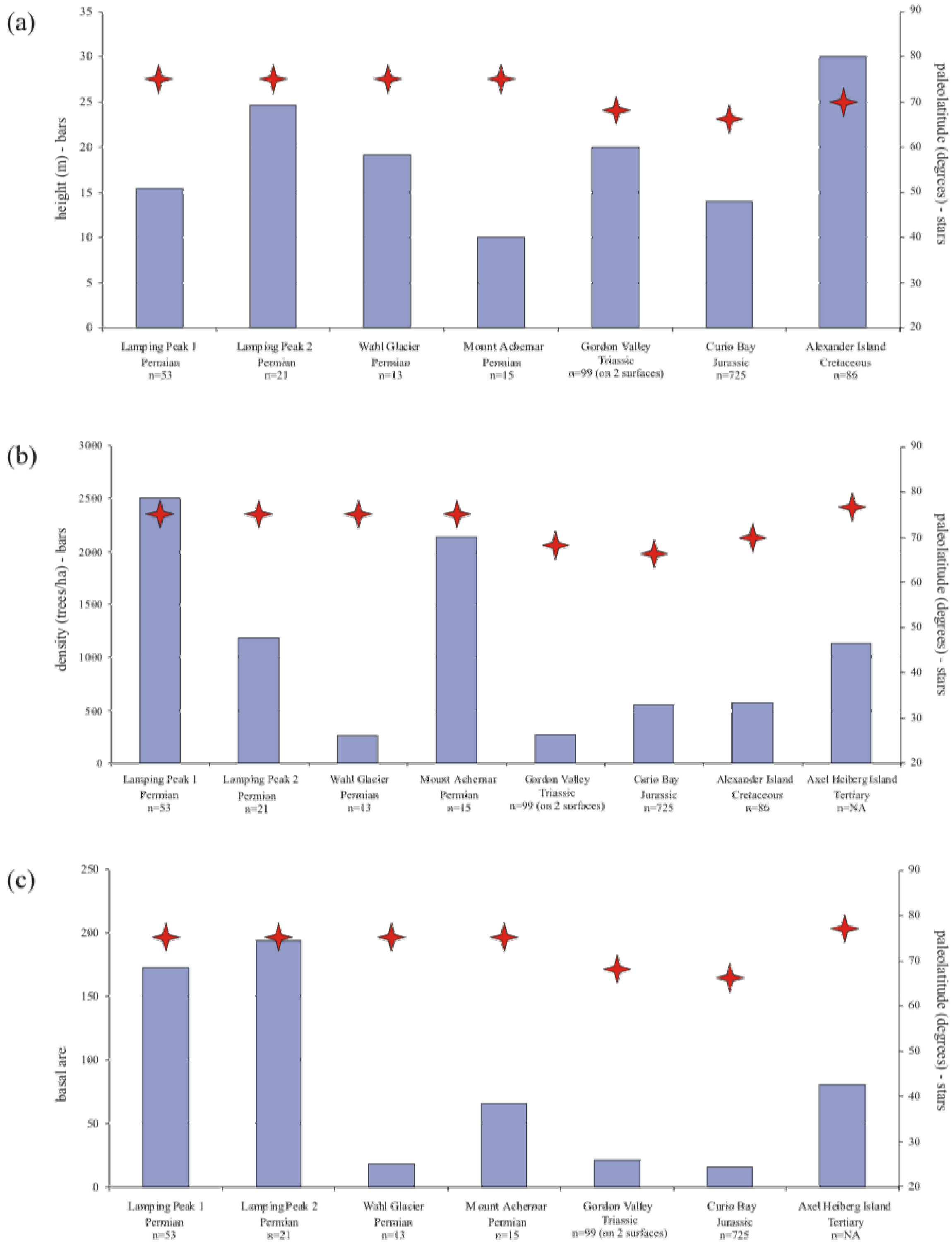


Figure 18. Comparison of (a) tree height, (b) density, and (c) basal area of high latitude forests.

The Lamping Peak 1 forest is denser than other Permian high paleolatitude forests and most similar to the density of Mount Achernar (Cúneo et al., 1993; Taylor et al., 2003; Figure 18). However, stumps of Mount Achernar forests are only a little over half (~55%) as large in diameter. Exposure at Lamping Peak 2 and Wahl Glacier are linear and may preclude observations of high densities. Alternatively, the density of Lamping Peak 2 and Wahl Glacier forests may be lower because they have large trees that require more space.

Comparisons of diameter may be more meaningful for fossil forests as it is for modern forests. Basal areas of the forests at Lamping Peak are larger than those of any other described fossil forests, including those that are younger such as in the Cretaceous (Figure 18) or that grew at lower latitudes. Compared to other described fossil forest, Lamping Peak forests are composed of large trees and have among the highest densities and highest basal areas.

CHAPTER IV

TAPHONOMIC PROCESSES

Taphonomic processes refer to the chemical, biological, or physical factors affecting the remains of an organism after death. They include decomposition, post-mortem transport, burial, compaction and diagenesis. These processes can be used to constrain paleoenvironments. The taphonomy of three types of plant material at Lamping Peak and Wahl Glacier including (1) stumps, (2) roots, leaves, and indistinguishable bits, and (3) large woody debris was analyzed.

Stump taphonomy

Methods

Field observation indicated preservation by replacement and possibly permineralization by an unknown dark mineral. To identify the mineralogy, samples from stumps at Lamping Peak and Wahl Glacier were analyzed using the following geochemical methods: X-ray diffraction (XRD) to identify minerals, energy dispersive spectroscopy (EDS) attached to a scanning electron microscope (SEM) to constrain composition, and X-ray absorption near edge structure (XANES) spectroscopy to determine the oxidation state. XRD analysis uses the reflection of X-rays dissected onto a sample at set angles. The reflection is detected to create a pattern of peaks at angles characteristic of the substance. Each mineral's XRD signature depends on the spacing between planes of atoms in the crystal lattice. XRD results were complemented by EDS analysis which obtained compositional data from the stump material in the form of spectra. The spectra consist of peaks at characteristic energies for each element and essentially ordered by atomic number. EDS detects electrons emitted from activated atoms on the surface of a sample when inundated with an electron beam from the SEM. Sample preparation for this analysis entailed creating a polished epoxy mount which was coated with carbon to better conduct electrons off the mount's surface. In conjunction with the EDS, SEM imaging was used to observe the topographic features of samples at a submicron scale. High energy electrons are produced by the SEM and the sample scatters the electrons to generate the image. XANES uses X-rays to energize electrons within the samples which excites them into an unfilled orbital at a specific energy corresponding to the oxidation state of the targeted element. This produces the "edge" on the spectrum (Gunter et al., 2002). Spectra of the sample can be compared to known spectra of particular minerals to identify the minerals within the sample.

Results

Stumps at Wahl Glacier are permineralized by silica (Figure 19) which is confirmed by XRD (Figure 20) and EDS (Figure 21) analysis. Stumps in the other previously reported Antarctic fossil forests are also preserved by replacement and permineralization by silica (Francis et al., 1994; Taylor et al., 1991; Jefferson, 1982; Jefferson, 1987). In contrast, the Lamping Peak stumps are permineralized by magnetite (Figure 22). This is consistent with XRD analysis that indicates the existence of an iron oxide (Figure 23). The EDS spectrum also has iron and oxygen peaks (Figure 24). XANES analysis was used to determine the oxidation state of iron in the sample and the

Figure 19. Silicified stump at Wahl Glacier with juvenile wood at the pith, asymmetrical tree rings, and a flared root base. This stump stands ~20 cm from the surrounding bed and is ~20 cm wide.

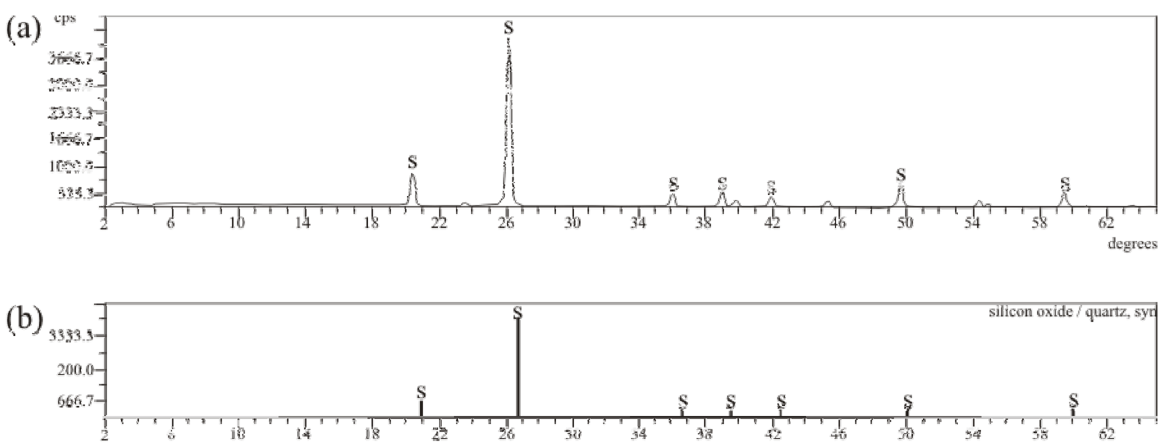


Figure 20. (a) XRD spectrum of Wahl Glacier stump sample and (b) standard quartz peaks. The peaks of the Wahl Glacier sample, match the quartz signature. Peaks labeled with "s" correlate to peaks for synthetic silicon oxide/quartz, used as a standard.

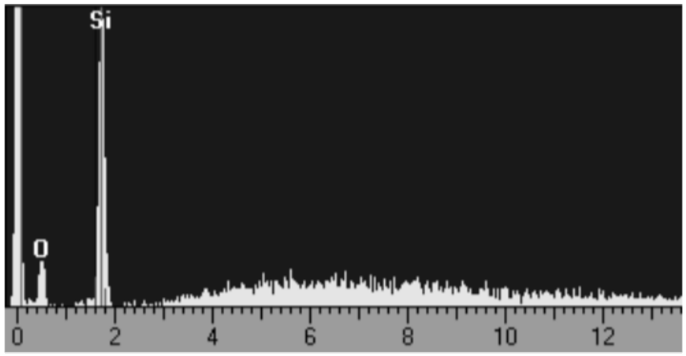


Figure 21. Energy dispersive spectrum of Wahl Glacier stump sample. Peaks correlate to silicon and oxygen to indicate replacement of wood by quartz (SiO_2).

Figure 22. Partially weathered stump from Lamping Peak that is replaced by magnetite and ~25 cm in diameter. There are 26 rings in this stump indicating that the tree was at least 26 years old.

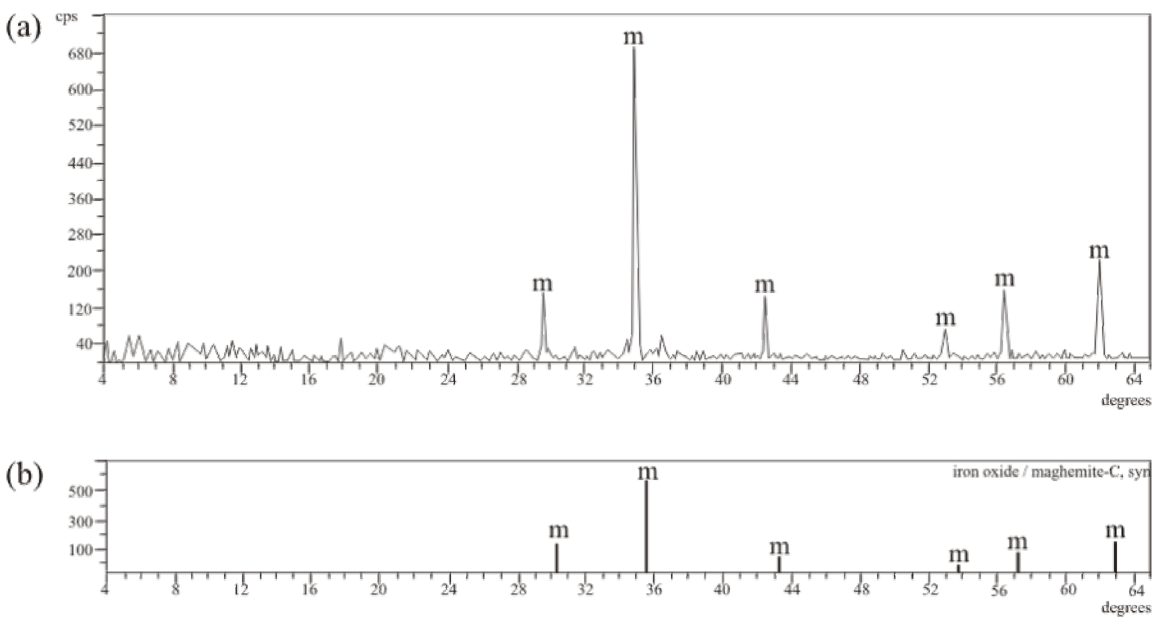


Figure 23. (a) XRD pattern of Lamping Peak stump sample and (b) standard maghemite peaks. Peaks labeled with "m" correlate to peaks for synthetic iron oxide / maghemite-C, used as a standard. Since oxidation states of minerals are undetectable in this method, the mineral could also be magnetite, which has a very similar crystal lattice.

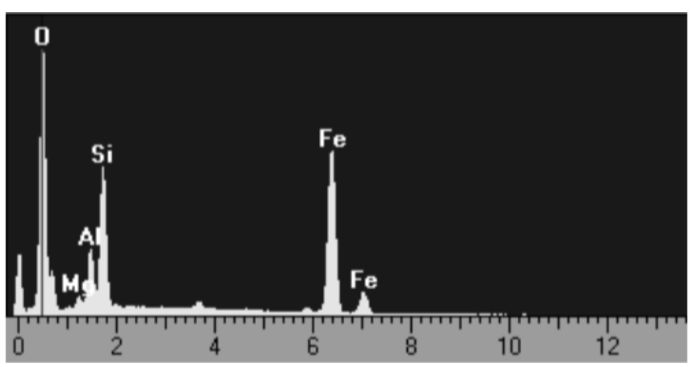


Figure 24. Energy dispersive spectrum of the tree ring sample from Lamping Peak. Major peaks correlate to iron and oxygen to indicate replacement of wood predominantly by magnetitie or maghemite (Fe_2O_3). The presence of magnesium, silicon, and aluminum indicate replacement by more than one substance.

spectrum matched the signature of magnetite (Figure 25). Magnetite probably replaced the organic matter during the Jurassic. The most likely source was iron-rich fluids associated with diabase sills (Figure 26) intruded during the Jurassic break-up of Gondwana (Fleming et al., 1995; Fleming et al., May1997; Marsh and Zieg, 1997). Magnetite is less resistant to weathering than the surrounding sandstone, so stumps at Lamping Peak often form topographic depressions (Figure 27). One stump depression at Lamping Peak contained a white powder which was determined by analysis to be the zeolite laumontite (Figure 28) from XRD (Figure 29) and EDS (Figure 30). The formation of laumontite is likely the result of low-grade metamorphism or diagenesis (Gill, 1957; Perkins, 1998).

Distribution of macerated debris

Macerated plant debris is preserved in the Upper Buckley Formation in the Beardmore Glacier area. The indistinguishable bits of wood and leaves are preserved as coal and impressions (Figure 31). To determine the abundance of this macerated plant debris, unbiased by size or type, the bedding plane plant index (BPPI), similar to bedding plane bioturbation index (BPBI), was applied. BPBI is a semi-quantitative, pattern recognition method for assessing the amount of bioturbation on bedding planes (Miller and Smail, 1997), but the same protocol can be used for assessing abundance of plant material. The category corresponding to the abundance of plant material was recorded for each observation. Categories are as follows: for BPPI=1, there is no plant material; BPPI=2, up to 10% of area is covered by plant material; BPPI=3, 30 to 40% of bedding plane is covered; BPPI=4, there is 40 to 60% coverage; and BPPI=5, 60 to 100% of the

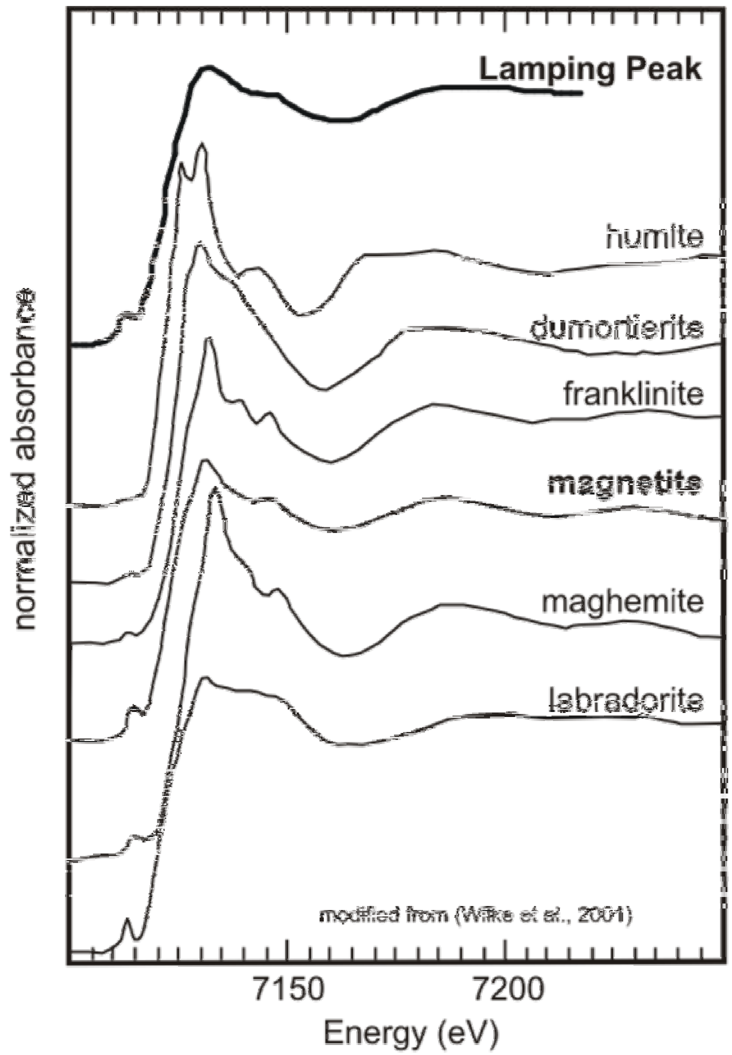


Figure 25. Fe K-edge XANES for spectra of various minerals (Wilke et al., 2001) and stump sample from Lamping Peak. The spectrum of stump sample from Lamping Peak best resembles the spectrum of magnetite #1; therefore, the oxidation state of the stump sample from Lamping Peak is in the form of magnetite rather than maghemite which are not distinguishable by XRD or SEM- EDS analysis.

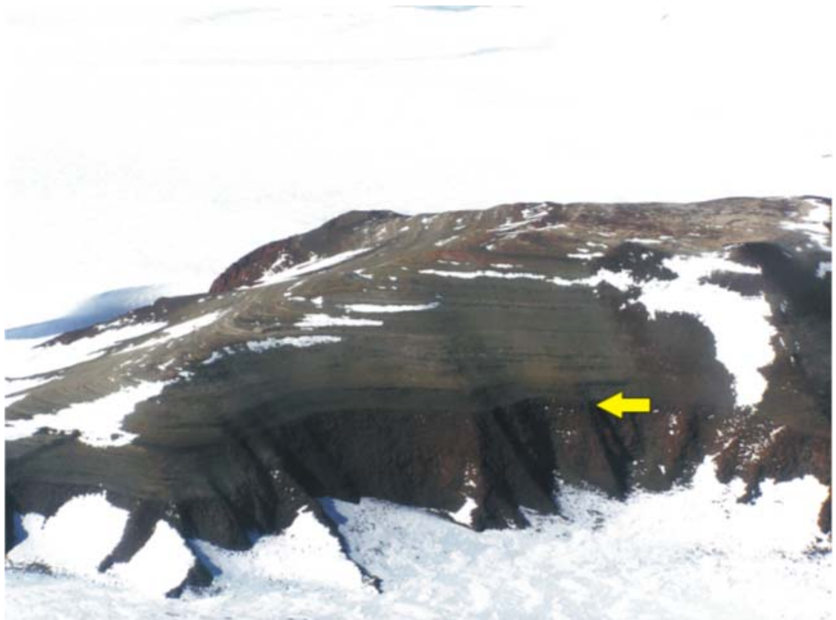


Figure 26. Aerial view of Lamping Peak. Diabase sill occurs at the base of the sedimentary sequence. The magnetite in the fossil stumps may have been formed by reactions between the organic matter and hydrothermal fluids related to sill emplacement. The arrow indicates the contact between the sill and the sedimentary sequence.

Figure 27. Lamping Peak 1 stump, ~40 cm in diameter, preserved as a cast.

Figure 28. Sample of powder collected from stump center at Lamping Peak.

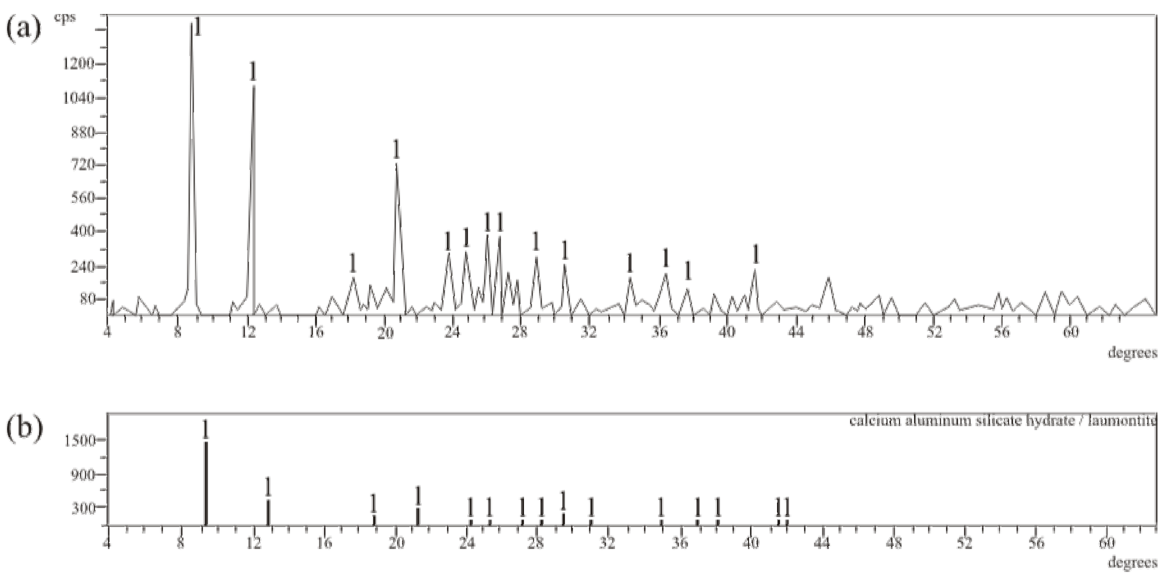


Figure 29. (a) XRD spectrum of powder sample from Lamping Peak and (b) standard laumontite peaks. The peaks of the Lamping Peak sample match the laumontite signature. Peaks labeled with "l" correlate to peaks for calcium aluminum silicate hydrate (laumontite).

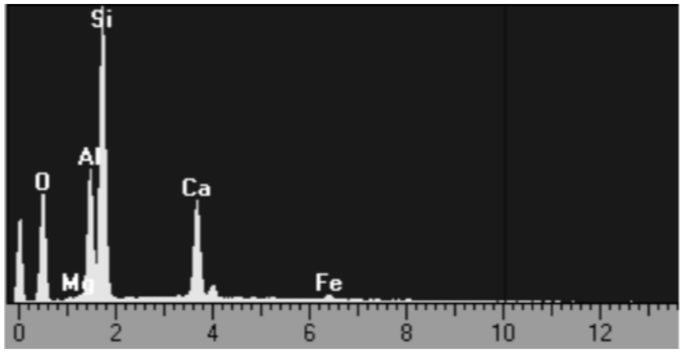


Figure 30. Energy dispersive spectrum of the residual powder sample from the center of a fossil stump from Lamping Peak. Major peaks are oxygen, aluminum, silicon, and calcium and correspond to the mineral laumontite ($Ca[Al_2Si_4O_{12}]$•4H2O.

Figure 31. Indistinguishable plant material preserved as coal at Wahl Glacier.

bedding plane covered by plant material. Observations were made on the bedding surfaces sufficiently well-exposed to allow assessment of BPPI including 40 bedding surfaces at Wahl Glacier and 18 bedding surfaces at Lamping Peak.

Abundance and distribution of plant bits were documented throughout the stratigraphic sequence at Wahl Glacier and Lamping Peak (Figure 32). Over 50% of the 958 observations indicated at least some preserved plant material (BPPI > 1). Readings from the Lower Permian portion of the Buckley Formation exposed at an outcrop ~10 km from Wahl Glacier were also recorded; there, very little plant material is present. Of 273 observations, only about 10% had a small amount of plant material (Figure 33). The paucity of plant debris was consistent with lack of larger plant fossils. There were no stumps and very few logs in the lower Permian, indicating insufficient number of trees to supply the environment with debris.

Large woody debris (LWD) and orientation

Large pieces of wood, here referred to as large woody debris (LWD), are preserved in fluvial deposits of the Buckley Formation in the Beardmore Glacier area. Most of the LWD is preserved as impressions in sandstones overlying paleosols. Wood grain and knots are preserved in these impressions (Figure 34).

Five horizons bearing plant material occur at Lamping Peak, and dimensions of 125 pieces of wood preserved in these were recorded. Both large (65 cm wide) logs and small (1 cm wide) stick and twig wood fragments are present, but because more large pieces were measured, the maximum diameter is a more meaningful measure for comparison of LWD than average diameter. The maximum diameters of fragments in

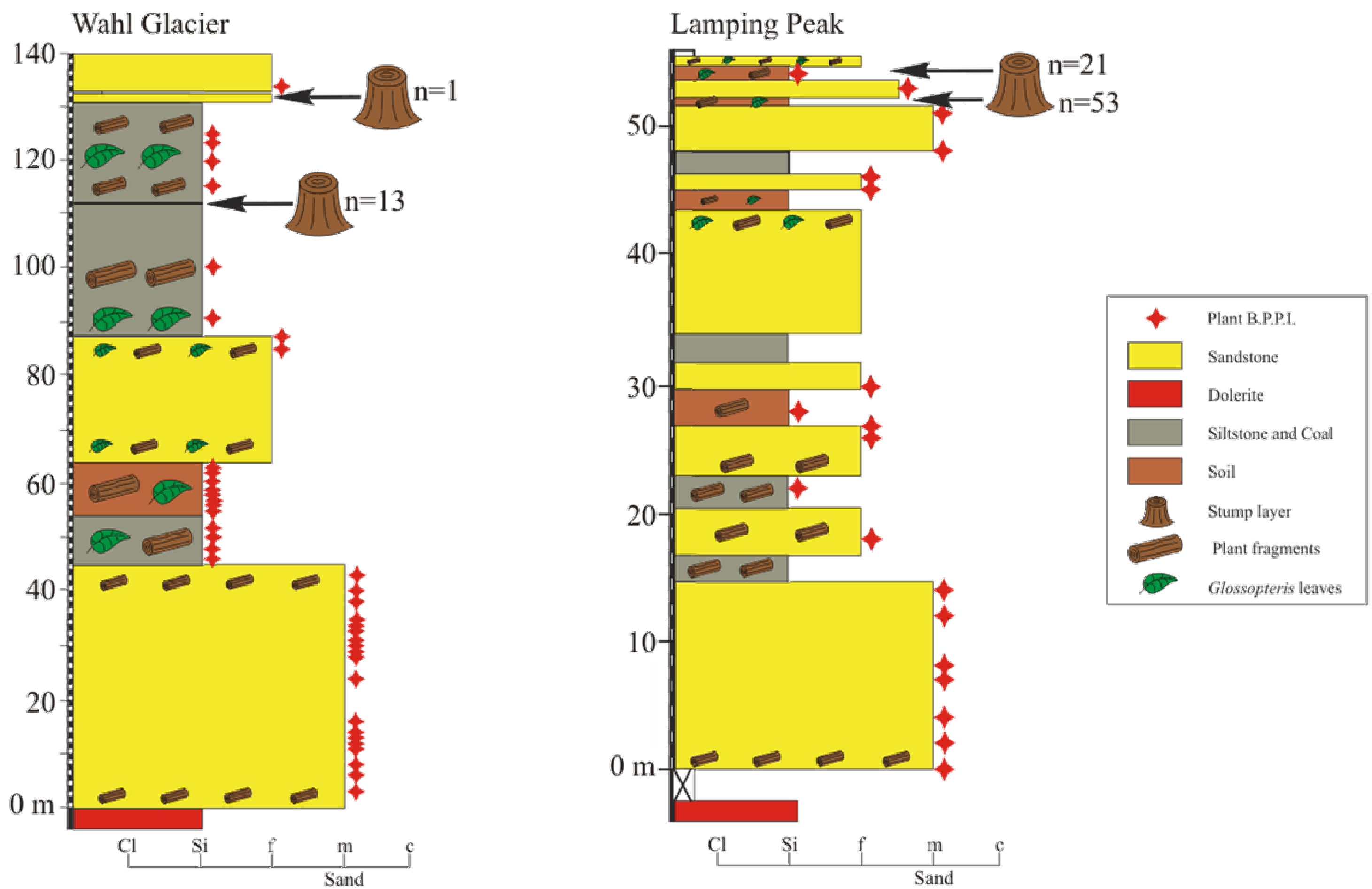


Figure 32. Generalized stratigraphic sections from Wahl Glacier and Lamping Peak where plant material abundance was observed. Stars indicate horizons where abundance of plant material was semi-quantitatively assessed using bedding plane plant index (BPPI).

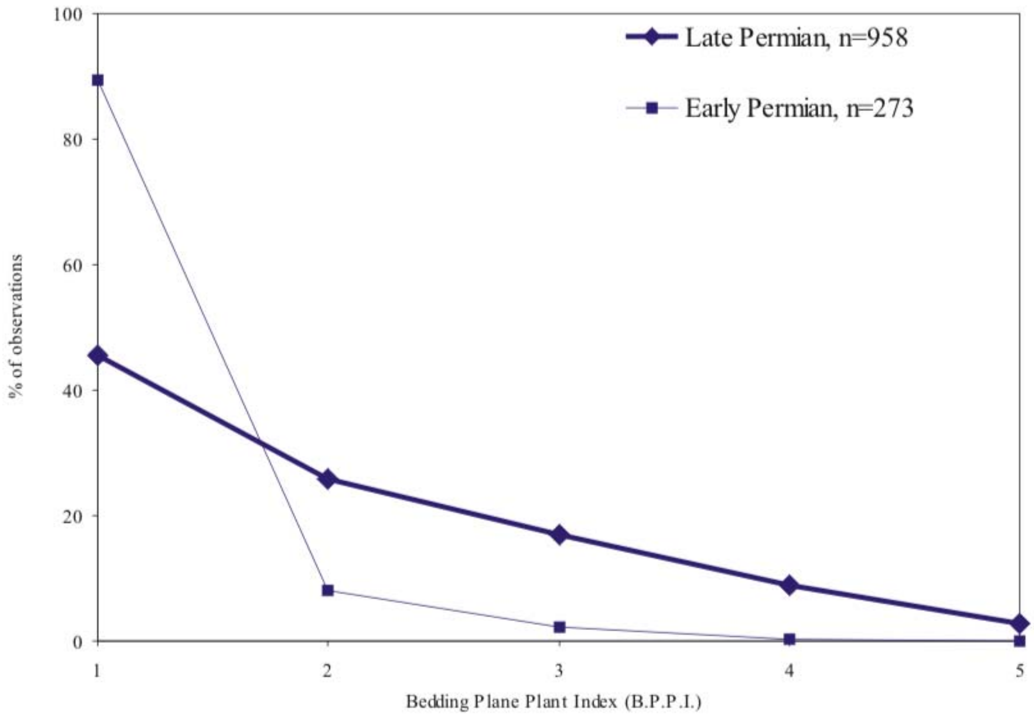


Figure 33. Distribution of abundance of plant material observed in Late (thick line) and Early (thin line) Permian parts of the Buckley Formation. BPPI=1 represents no plant material on bedding surfaces and BPPI=5 represents 60 to 100% of plant material cover over an area. Based on over 1000 observations, there is very little plant material in the early Permian compared to the late Permian. In over 50% of the observations from the Permian, the bedding plane had at least some preserved plant material.

Figure 34. Log impression from Lamping Peak with knots and wood grain preserved.

LWD-bearing horizons are greatest near the horizons with stumps (Figure 35). This distribution shows that LWD is clustered stratigraphically near their presumed source despite the absence of most attached branches and root stocks on the LWD. Branches and root stocks are not missing because of differences in preservation since smaller woody debris is preserved among the LWD. Trees probably snapped from their bases rather than uprooting with their root stocks because fossil stumps remain rooted in paleosols. Wind or flowing water are two likely processes that could strip LWD of branches and cause a tree to snap from its base (Franklin et al., 1987).

In addition to measurements of size, orientations of 38 LWD on three surfaces near the top of the section at Lamping Peak were measured (Figure 36). Trends in orientations for each may reflect paleocurrent direction (Figure 37). In each rose diagram, there was a dominant trend. There were no physical sedimentary structures from which paleocurrent data could be obtained (Flaig, 2005).

Model of a braided river with LWD

To determine the significance of the orientation trends in LWD at Lamping Peak, model logs were systematically introduced into a braided stream in a scaled stream table and their orientations were observed. The stream table, 4 by 8 feet, was filled with 400 pounds of medium quartz sand (Figure 38). The sand was saturated with water and the braided river was produced by tilting the table surface 14 degrees and dispersing the water input over chert cobbles. The open-ended runoff allowed for the channel to remain somewhat natural and unconfined. A braided river was modeled because LWD of the Buckley Formation was preserved within braided stream deposits (Collinson et al., 1994).

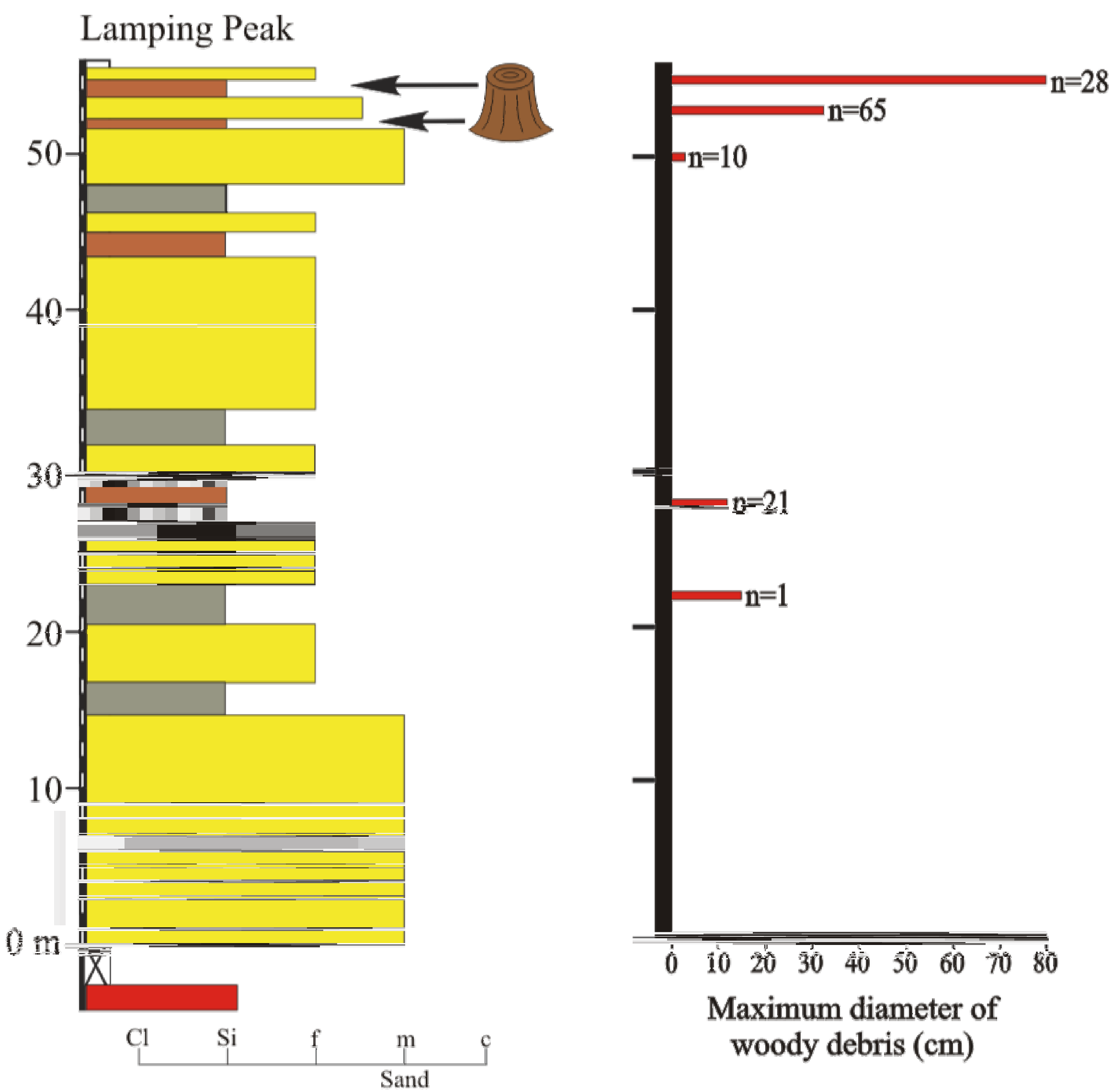


Figure 35. Stratigraphic location of large woody debris (LWD) at Lamping Peak in the Upper Permian. Length of red lines signifies the maximum diameter of LWD and "n" is the number of logs measured at each log bearing horizon. Larger woody debris was measured more often than smaller woody debris; therefore, maximum diameters are the best way to compare.

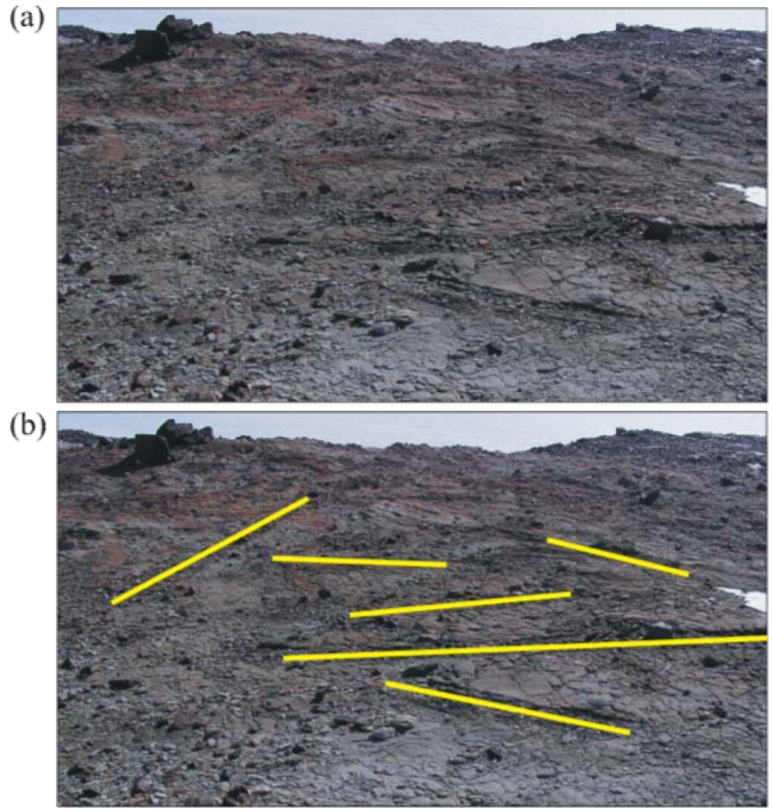


Figure 36. (a) Large woody debris littered on the surface of sandstone overlying the upper stump horizon at Lamping Peak. (b) Outline of large woody debris.

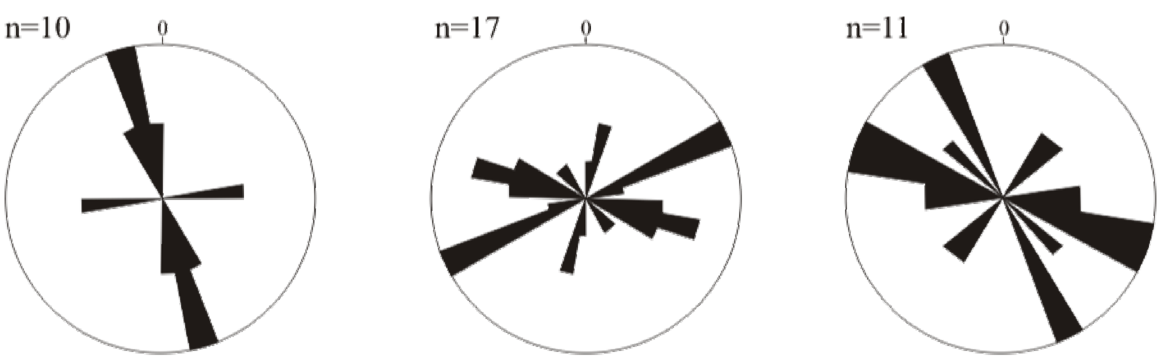


Figure 37. Trends in the orientations of 38 fossil logs in three sandstone surfaces above the upper stump horizon at Lamping Peak. Each rose diagram has a dominant trend.

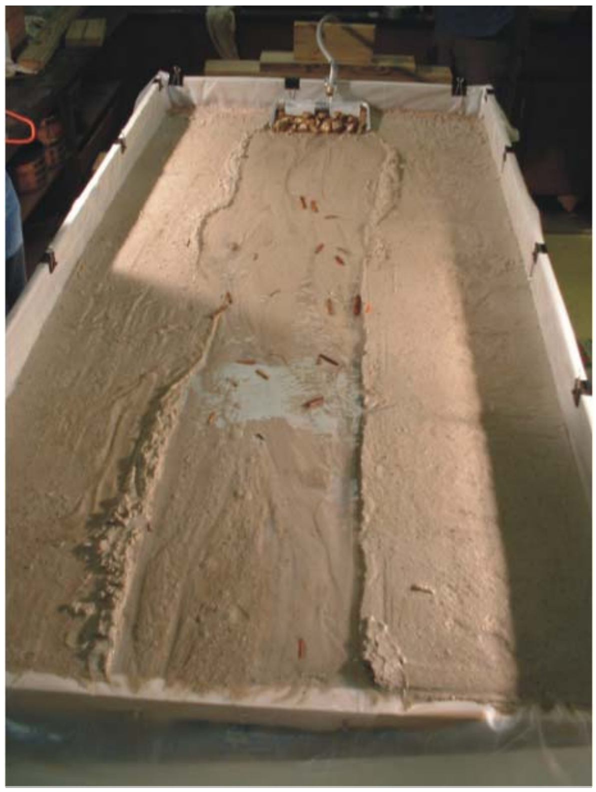


Figure 38. Stream table model of a braided river with scaled dowels representing large woody debris. Dowels were placed in the flow of water to determine how the water would change their orientation. Trends of the orientations were analyzed in relation to flow direction.

Because the average aspect ratio of Lamping LWD was nine to one, the LWD was modeled with dowels cut to aspect ratios of ten to one and five to one.

Six trials were performed for this experiment. Before each trial, the channel was equilibrated for five minutes by allowing water flow over sediment with no dowels. Once equilibrated, 30 water-saturated dowels were added in increments of 10 at three minute intervals. The dowels were placed in the channel at the headwater perpendicular to flow. Trials were run according to the dowel diameter size categorized as small (0.35 cm), medium (0.45 cm), large (0.65 cm), and very large (0.85 cm) and two trials contained a combination of the sizes. After 20 minutes, the water flow was stopped and the orientations were measured.

Orientations from each trial were plotted as rose diagrams. Results indicate that orientations were controlled by direction of channel flow, placement of wood in channel, and size of woody debris with respect to depth and width of channel. Dowel size relative to channel width and depth was the primary control of orientation in these experiments. Trails for small, medium, and large dowels aligned parallel to the flow of water; very large dowels aligned with the direction of placement in the channel, perpendicular to flow (Figure 39). For trials with mixed dowel sizes, the orientations were controlled by the discharge rate (Figure 40). Both mixed trials have the same number of LWD from each size category, but the trend in orientation for the first trial is perpendicular to the flow of water while the second trial is parallel. The difference can be attributed to the second trial having a higher discharge rate than the first; the flow was sufficient to move the large dowels and orient them parallel to flow.

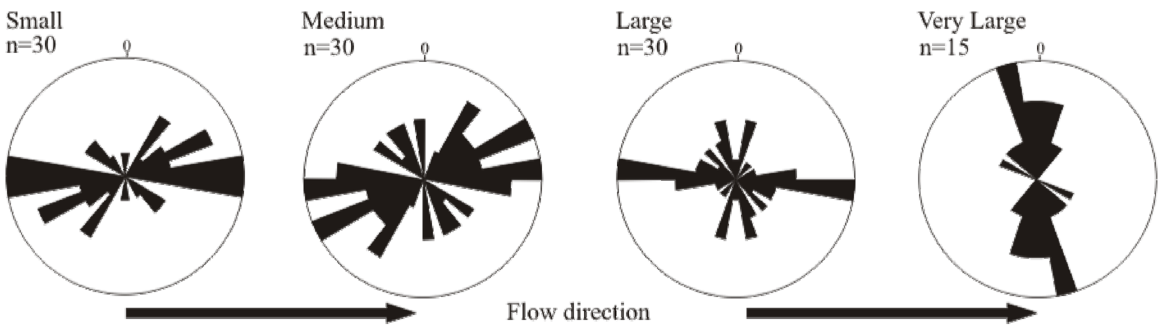


Figure 39. Trends in the orientations of small, medium, large, and very large dowels in stream table trials. Arrow represents the flow direction of water in the channel.

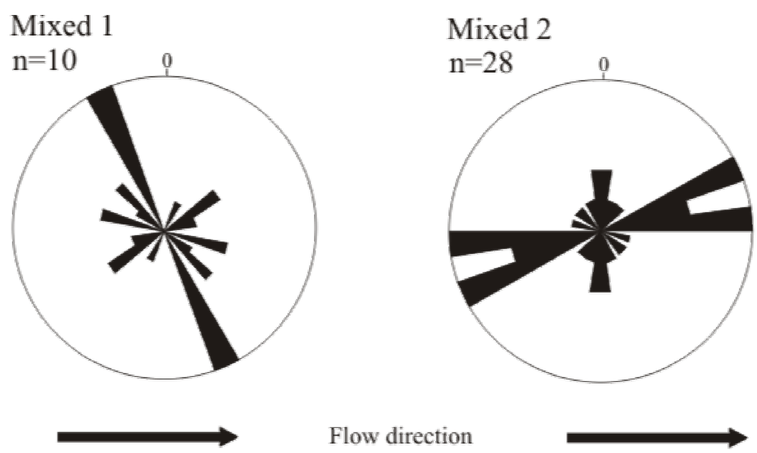


Figure 40. Trends in the orientations of mixed sizes of dowels in stream table trials. Arrow represents the flow direction of water in the channel.

Synthesis: LWD in a braided river

Previous field studies in the alignment of LWD in modern environments demonstrated that alone they cannot be used as an indication of paleocurrent direction in sedimentary sequences (Gastaldo, 2004). The results of the stream table experiments support this conclusion. There are dominant trends in orientations of LWD at Lamping Peak, and there are dominant trends in orientations of modeled LWD in stream table experiments. When the rate of flow was sufficient in the stream table experiments, the dowels oriented parallel to the flow direction. However, in cases where the rate of flow was insufficient to pick up and transport dowels (only in very large dowels), the dowels remained perpendicular to flow. The LWD at Lamping Peak has been transported as indicated by the paucity of branches; therefore, based on stream table experiments with parallel orientations of dowels when transportation has occurred, the logs are likely to be oriented parallel to the paleoflow.

Summary

Stump taphonomy, distribution of macerated debris, and orientation of large woody debris at Lamping Peak and Wahl Glacier all yield paleoenvironmental information. Stumps are replaced by silica and magnetite, and the difference in replacement is likely the result of magmatism associated with the break-up of Gondwana. Macerated plant debris is more common in the Upper Buckley, where stumps, LWD, and leaves are abundant in some horizons, than in the Lower Buckley where LWD and leaves are rare and stumps are absent. Based on stream table experiments modeling orientations of LWD and previous studies, LWD is probably oriented parallel to flow.

CHAPTER V

INTERPRETATION OF ENVIRONMENT

Analysis of information collected about the preserved plant material at Lamping Peak and Wahl Glacier in the Beardmore Glacier area (BGA) allows identification of characteristics required of potential paleoenvironments. These requirements are (1) presence of forests with tall (~20 m) trees, high densities (up to ~2000 t/ha), and high basal areas (~175m^2/ha) within the ranges of modern mature forests in humid temperate zones, (2) poorly developed paleosols characterized by well defined laminations, (3) high water table determined from shallow roots within the paleosol, (4) preservation of leaf mats surrounding stumps, and (5) concentration of LWD (LWD) and, to a lesser extent, small macerated debris, near fossil forests. Environments that meet these criteria include vegetated bars within a braided river system and protected wetlands such as a swamps or bogs.

Wisconsin River

Because the Buckley Formation contains *Glossopteris* stumps preserved in what was once sediment of a braided river system (Collinson et al., 1994), I investigated a modern braided stream. The Wisconsin River has sand bars vegetated with trees (Figure 41) and they are stable for up to 40 years, as can be inferred from the tree size (Mumphy, personal communication). To compare modern and Permian forests, the same treatment of the point-centered quarter method used to calculate forest density and basal area for

Figure 41. Aerial view of vegetated bars of the Wisconsin River near Madison, Wisconsin in May. Flow direction is from left to right.

Permian forests at Lamping Peak and Wahl Glacier was applied to forested sand bars and banks of the Wisconsin River west of Madison, Wisconsin. Three 30 m transects with 5 m intervals were mapped. Both living and dead *in situ* trees were included in the sample set because distinction between living and dead trees is not possible in fossil forests. The forests of the banks and sand bars have an average diameter at breast height of 19 cm, density of 2624 trees/ha, and basal area of 111 m^2/ha; ~9% of the trees were dead. These values are comparable to Lamping Peak 1 (20.9 cm, 2505 trees/ha, 173 m^2/ha) and Lamping Peak 2 (39.2 cm, 1185 trees/ha, 194 m^2/ha). Large woody debris (LWD) is also found within the Wisconsin River. In the channel, LWD is oriented parallel to direction of flow and along the banks, LWD is oriented sub-perpendicular to flow (Figure 42). The orientations of LWD in the Wisconsin River are similar to measurements of Lamping Peak and stream table experiments. Also, soils of the bars are entisols (Hanson et al., 1968) and have relict bedding similar to the paleosols of Lamping Peak and Wahl Glacier (Figure 43).

Cedarburg Bog

Another setting that is potentially analogous to that of the Permian forests in the Buckley Formation are freshwater wetlands that are infrequently disturbed by channelized flow. Frequent disturbances would prohibit a development of a mature forest with large trees. The Cedarburg Bog in Cedarburg, Wisconsin, a freshwater wetland, was investigated in this study. The point-centered quarter method was applied to the forest at the Cedarburg Bog to determine density and basal area. Two 20 m transects with 5 m intervals were performed. Averages are 16 cm for diameter at breast

(a)

(b)

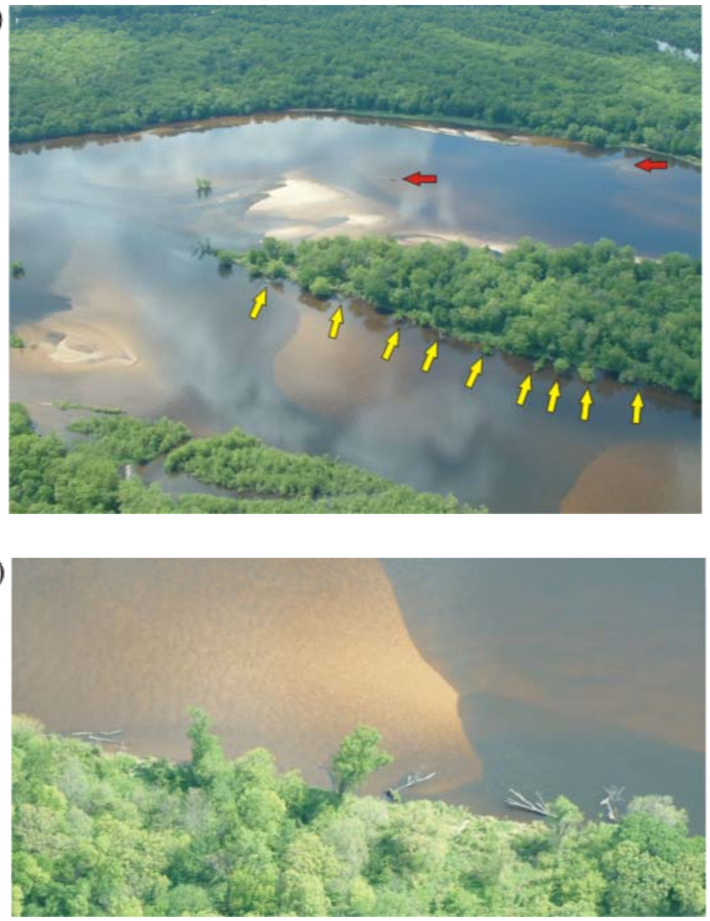


Figure 42. Wisconsin River vegetated sand bars near Madison, Wisconsin. (a) The dark arrow indicates large woody debris along bank; the light arrows indicate large woody debris in the channel. (b) Large woody debris in the channel along the bank viewed up close. Generally, the large woody debris within the channel is oriented with the flow of the channel, and newly fallen trees along the banks are oriented perpendicular to flow.

Figure 43. Soil profile of a vegetated sand bar in the Wisconsin River. Soil horizon A is thin and overlies medium sand with relict bedding. This is similar to characteristics of the soils that stumps are rooted in at Lamping Peak and Wahl Glacier.

height, 5978 trees/ha for density, and 399 m^2/ha for basal area of which 12% of the trees were dead. These averages include stumps as well as trees. LWD in bog environments is often found uprooted near its source because there is in insufficient flow to erode and transport the logs. Uprooted trees with their root stocks were common in Cedarburg Bog. In contrast, no logs with attached roods were observed in the Buckley Formation. This, in addition to absence of bark and branches on the LWD at Lamping Peak implies that the Permian LWD was, unlike Cedarburg Bog trees, subject to significant transportation. Wetlands commonly are sites of peat accumulation (Mitsch and Gosselink, 1993, p. 32) that would be recorded in the stratigraphic record as coal. However, at Lamping Peak and Wahl Glacier, the deposits that most resemble coal are thin beds of coaly shale. Thus, wetlands do not provide a satisfactory modern analogue for the setting of the stump-bearing horizons of the Buckley Formation.

Summary

The Wisconsin River and Cedarburg Bog are all similar to characteristics of the vegetation at Lamping Peak and Wahl Glacier. Trees in forests of braided rivers and wetland environments commonly have shallow roots that resemble stumps at Lamping Peak and Wahl Glacier. Forests in both environments investigated in this study have basal areas within the limits of forests at Lamping Peak and Wahl Glacier, but in the braided river setting the trees are not as large as in the Permian forest. This probably reflects episodic disturbance of the forest by channel migration. LWD is present in both the Wisconsin River system and the Cedarburg Bog, but root stocks are usually attached to the trunks in LWD of wetland environments. Plant debris among trees in braided river systems and wetland environments are similar; however, braided rivers have more macerated material than wetland environments. Since the forests at Lamping Peak and Wahl Glacier lack substantial coal beds, peat-producing environments would not be a good analogue. Each of the modern environments is comparable to the ancient environments, but the braided river is a better model for the ancient environment.

CHAPTER VI

CONCLUSIONS

(1) *In situ* tree stumps are preserved in three horizons in the Permian Buckley Formation at two locations, Lamping Peak and Wahl Glacier, in the Beardmore Glacier area, central Transantarctic Mountains. Two horizons within 1 m of each other at Lamping Peak contain 53 and 21 stumps. In the Late Permian, this area was located at ~73°S, a latitude similar to that of today.

(2) Late Permian high-latitude *Glossopteris* forests from Lamping Peak and Wahl Glacier have tree size, forest density, and basal areas of trees comparable to those of modern forests in humid temperate settings and of other high-latitude fossil forests. Lamping Peak and Wahl Glacier forests had more trees, larger trees, higher densities, and greater basal areas than other Permian and (some) younger forests at high-latitudes.

(3) Roots radiating out from stumps are shallow, implying a high water table; this is consistent with the occurrence of *Glossopteris* in facies recording wetland deposition. Stump-bearing paleosols are immature, and retain laminations.

(4) The modern Wisconsin River, a braided stream, has vegetated bars with forests that are comparable in terms of forest density and basal area to the forests in the Buckley Formation. Tree sizes on the modern vegetated bars are smaller than in fossil forests and

may reflect a shorter time since a disturbance event. A wetland (bog) setting analogous to the Cedarburg (WI) Bog is less likely for the fossil forests because (1) the fossil logs were stripped of branches and roots during transportation, but transportation in bogs typically is not sufficient to do this and (2) organic matter occurs only in thin discontinuous layers at Lamping Peak and Wahl Glacier, but typically accumulates to form peat layers in wetlands.

(5) Stumps at Lamping Peak were permineralized and replaced by magnetite, probably associated with intrusion of the Jurassic dolerite sills. Macerated plant debris is preserved as compressions and coaly material, and is more abundant in the stump-bearing Upper Permian part of the Buckley Formation than in the Lower Permian Buckley that lacks stumps and has few logs. Large woody debris is preserved as impressions that have preferred orientations. Paucity of attached branches and root stocks indicate the large woody debris was transported. In stream table experiments, transported model logs oriented parallel to the flow direction. Therefore, trends in orientations of fossil large woody debris is likely to indicated direction of paleoflow.

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