Carboniferous Fossil Plants and Soils of an Early Tundra Ecosystem

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Siltstones with fossil root traces and surface mats of fossil plants in the mid-Carboniferous (Westphalian or 310–312 Ma) Seaham Formation near Lochinvar, New South Wales, represent ancient soils of tundra ecosystems. Formerly well-drained paleosols show deeply-penetrating root traces, ferruginous nodules, freeze-thaw banding, and earth hummocks (thufur), but little evidence of mineral weathering. These paleosols also preserve leaf fragments of the seed fern Botrychiopsis plantiana. *Formerly poorly-drained paleosols show tabular root systems, partly decomposed mats of the horsetail* Dichophyllites peruvianus, *and parent material of varved shale. Comparable soils are widespread in tundra regions of the northern hemisphere today. The paleosols show greater organic matter content than polar desert soils and much less weathering than soils of polar woodland. Shrubs or prostrate woody plants are represented by slender compressed fossil logs, but these are a less reliable guide to ancient ecosystem type than the paleosols because scattered small trees are found throughout the modern tundra belt. These fossil soils and plants are the most geologically ancient record of tundra vegetation known.*

INTRODUCTION

Tannatt William Edgeworth David, pioneering Australian geologist and Antarctic explorer, is best known for establishing that Permo-Carboniferous rocks in the Hunter Valley of New South Wales were formed during a great glaciation much older than the "Drift" of Europe. The idea had been debated inconclusively since 1866 (David, 1887), but it was not until David's studies of the Seaham Formation of the Hunter Valley that such an ancient glaciation gained widespread acceptance (David, 1907; Süssmilch and David, 1920; Percival, 1985). This was a dramatic inference of global change to come from studies of deeply weathered conglomerates and shales in the open fields and woodlands of this warm temperate region. His interpretations of fluvioglacial conglomerates, tillites, striated pebbles, and dropstones in varved shales were subsequently confirmed (Walkom, 1913; Osborne, 1922a,b, 1925, 1927; Browne, 1927; Nashar, 1964; Hamilton et al., 1975; Nashar et al., 1976) and extended to include observations of striated glacial pavements (Osborne and Browne, 1921; Herbert, 1980), depauperate glacial floras (Morris, 1975, 1980, 1985; Gould, 1976; Kemp et al., 1977; Retallack, 1980), and distinctive cold-water faunas (Glaessner, 1957; Roberts et al., 1995a). Permo-Carboniferous glacial deposits were subsequently discovered elsewhere in Australia and in other Gondwanan countries, and

played an important role in developing theories of continental drift (du Toit, 1937; Herbert, 1980; Crowell and Frakes, 1971a,b; Crowell, 1983).

Problems remain concerning the paleoenvironment of these historically important glacial deposits. The Seaham Formation has been interpreted as alpine glacial outwash (Crowell and Frakes, 1971a,b, 1975; Dickins, 1985; Crowell, 1995), whereas a continental ice cap is indicated by paleoclimatic modelling (Crowley, 1994) and stratigraphic hiatuses (Veevers, 1984; Powell and Veevers, 1987). There are also problems with the distinctive fossil flora of the Seaham Formation, which has been difficult to correlate internationally, in part because of its periglacial paleoecological setting (Retallack, 1980; Lacey, 1983; Morris, 1985; Archangelsky et al., 1980; Archangelsky, 1987). These questions are addressed by reexamination of fossil plants and soils at one of T.W.E. David's classical Hunter Valley localities of the Seaham Formation.

GEOLOGICAL SETTING AND AGE

Early this century, Professor David and his students dug a long trench on the northwest flank of a prominent hill (grid reference 5583 8242 on Greta 9132-I-S 1:25,000 sheet) on Windermere property between Winders Hill and Lochinvar in the central Hunter Valley of New South Wales (Fig. 1). This is the "Hawes Creek" locality of Walkom (1934) and the "Hut Hill" locality of Browne (1927), but neither of those place names are recognized on recent topographic maps. Nor should the locality be called "David's Cut" following local usage, because another excavation in marine rocks near Maitland is known by the same name (Nashar, 1964). The trench near Lochinvar is now partly filled by slumping and exposes only 1 m of siltstone of the Seaham Formation intermittently along its 200-m length. Some 4 m of section (Fig. 2), including levels also exposed in the trench, can be examined in gullies at its western end (grid reference 5572 8242 on Greta sheet). The unit of cherty siltstones and shales in the trench and gully is 30 m thick (Browne, 1927). It overlies a thick rhyolitic flow and underlies volcanic agglomerate that forms the crest of the hill. The whole sequence dips 22° SW with a strike azimuth of 162°.

The fossil-plant-bearing trench is in the upper part of the Seaham Formation, 530 m stratigraphically above local granodiorite basement, and 150 m below the base of the overlying marine Lochinvar Formation (Browne, 1927; Osborne, 1949; Retallack, 1980). The fossil flora is thus older than earliest Permian, likely for large shells of *Eurydesma*, drift leaves of *Gangamopteris*, and a palynoflora with striate bisaccate pollen (*Protohaploxypinus* or stage 2 assemblages of Kemp et al., 1977) in the Lochinvar
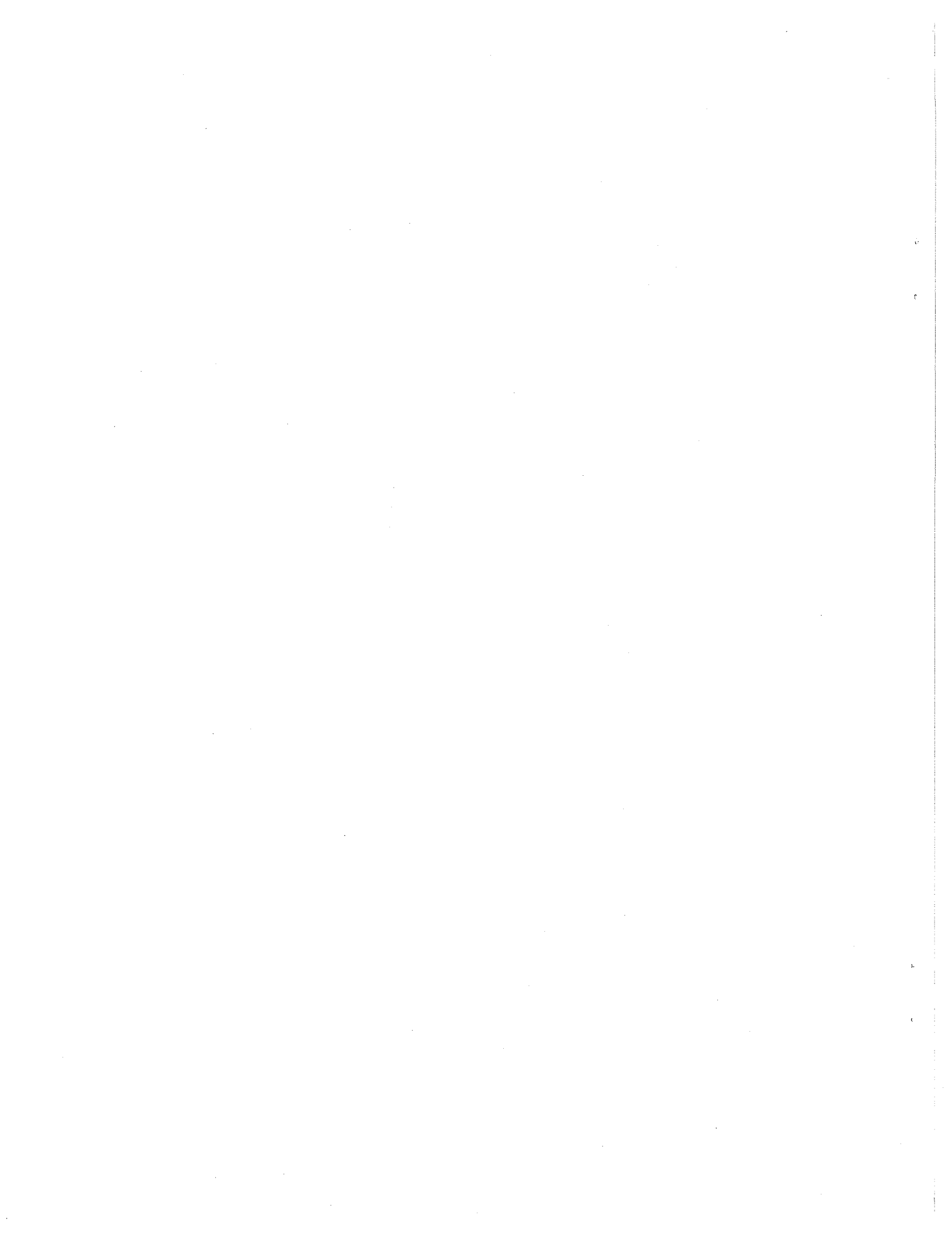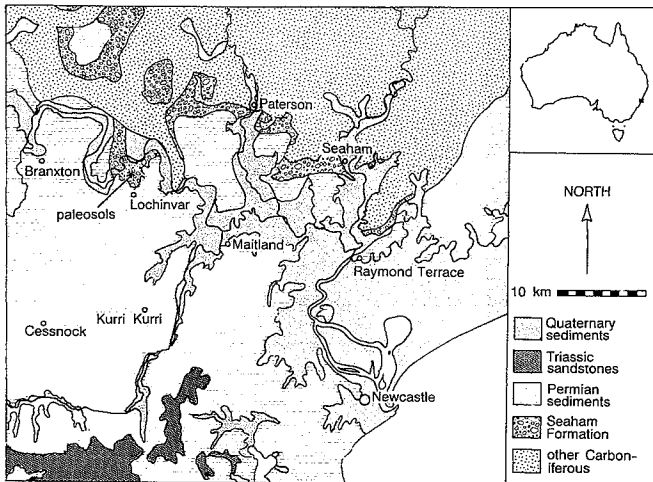
FIGURE 1—Fossil plant localities near Lochinvar, and other mentioned localities in the Hunter Valley, New South Wales. Distribution of the Seaham Formation is from Osborne (1925, 1927) and Nashar (1964; Nashar et al., 1976).

FIGURE 2—Sequence of Carboniferous paleosols in the Seaham Formation near Lochinvar, New South Wales. Scale for degree of development is from Retallack (1990, 1997b) and hue from a Munsell color chart.

Formation. The fossil flora from the trench is also younger than early Carboniferous (Visean-Namurian), because of correlation of fossil floras dominated by *Nothorhacopteris* (formerly "*Rhacopteris*"; see Archangelsky, 1982) in underlying formations with marine rocks bearing the brachiopod *Levipustula levis* to the northeast (Morris, 1975, 1980, 1985). From such broad age constraints a late Carboniferous age (late Pennsylvanian or Missourian-Virgilian of North America or Westphalian-Stephanian of Europe) has been inferred for the *Potonieisporites* or stage 1 palynoflora of the Seaham and other glacial formations of Australia (Kemp et al., 1977; Jones and Truswell, 1992) and Argentina (Lopez-Gamundi et al., 1994). However, an earlier Late Carboniferous age comes from recent radiometric dating of volcanic rocks in the Seaham Formation: a high-precision zircon age of 310.6 ± 4 Ma from the tuff overlying the fossil plant locality near Lochinvar, and another of 312.2 ± 3.2 Ma from a tuff in glacial facies of the Seaham Formation near Paterson (Roberts et al., 1995b). An age of 310–312 Ma corresponds to the Desmoinesian-Atokan of North America or Westphalian B-C of Europe (Roberts et al., 1995a). A Late Carboniferous (Namurian-Westphalian) age for glacial deposits of the Seaham Formation and maximal glaciation in eastern Australia and southern South America is indicated by the first appearance of striated stones in shales with goniatites (e.g., such as *Cravenoceras kullatinense*), a drop in diversity of Gondwanan brachiopods after the *Rhipidomella fortimuscula* brachiopod zone, the first appearance of endemic Gondwanan marine fauna of the *Marginirugus barringtonensis* and *Levipustula levis* brachiopod zones, and the last appearance of oolites at similar stratigraphic levels (Powell and Veevers, 1987). It is also compatible with evidence for a long gap in time between the deposition of the Seaham and Lochinvar Formations, including local angular unconformities (Roberts et al., 1995b) and a marked change in tillite clast composition from granites, aplites, and vein quartz in the Seaham Formation to diorite, gabbro, and andesite in the Lochinvar Formation (Browne and Dun, 1924).
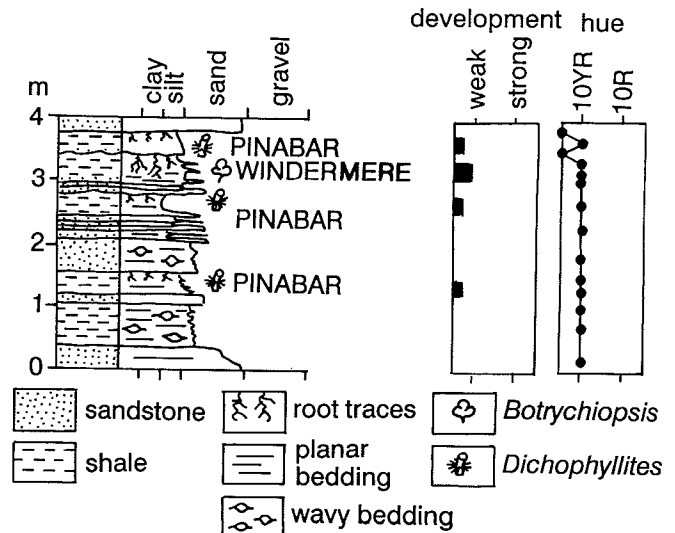
The Seaham Formation accumulated within an Andean-style volcanic arc built on Paleozoic schists and quartzites of the Lachlan Fold Belt (Roberts and Engel, 1987; Veevers et al., 1994). Volcanic rock compositions include andesite, dacite, rhyodacite, and rhyolite (Wilkinson, 1971) like those of stratovolcanoes and calderas in the Cordillera of North and South America today (Cas and Wright, 1987). Paleocurrents in coarse-grained fluvial deposits of the Seaham Formation indicate northerly to easterly directions of flow (van Brakel, 1970; Nashar et al., 1976). A striated pavement indicated ice movement toward N 15° W (Osborne and Browne, 1921). Pebbles of quartzite containing brachiopods typical for the Lambie Group (Devonian) come from far to the southwest (Browne, 1927). So do the granitic clasts in tillites of the Seaham Formation, which are more abundant than volcanic clasts of local derivation in all but a few localities immediately above striated pavements on volcanics (Osborne and Browne, 1921; Browne and Dun, 1924; Osborne, 1925; Browne, 1927). In addition to glaciers and gravel-bed rivers, this ancient landscape also included lakes accumulating varved shales and dropped pebbles (Süssmilch and David, 1920). Paleomagnetic measurements on the Seaham Formation indicate a paleolatitude of 70°S, comparable to modern Victoria Land, Antarctica (Powell and Li, 1994).

FOSSIL PLANTS

Although a large number of plant fossils have been collected from the Seaham Formation near Lochinvar over the years, the flora lacks diversity and is poorly preserved (Retallack, 1980). The fossil plants are all impressions in cherty siltstones and shales, leached of organic matter to a white or orange color. There are only two species: one a seed fern and the other an equisetalean (Fig. 3).
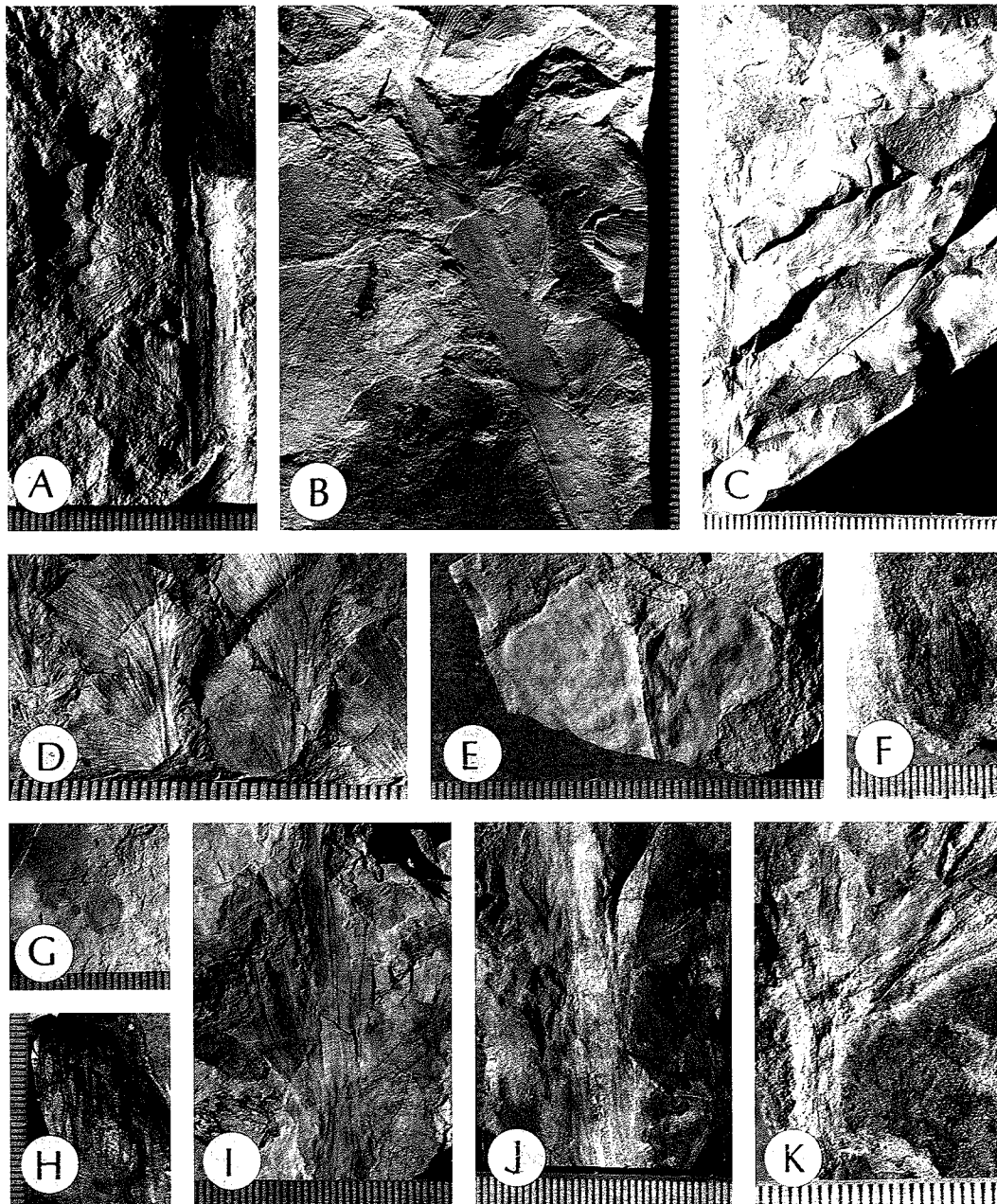
FIGURE 3—Carboniferous fossil plants from near Lochinvar. (A-D) *Botrychiopsis plantiana,* leaf fragments. (E) Bract-like leaf of a seed fern. (F) Ovulate cupule of a seed fern. (G) Seed of a gymnosperm. (H) Seed fern stem with dictyoxylon cortex. (I-K) *Dichophyllites peruvianus.* Specimens in the Australian Museum, Sydney F91472b (A); F91476 (B); F78274 (C); F91481 (D); F91483 (E); F91482 (F); F91474a (G); F91475b (H); F91473a (I); F91484 (J); F91477 (K). Scales within each frame are graduated in mm.

Botrychiopsis plantiana (Carruthers) Archangelsky and Arrondo 1971

Fernlike leaves from near Lochinvar can be identified as the seed fern *Botrychiopsis plantiana* (Carruthers) Archangelsky and Arrondo 1971. The same plant is probably represented by fossil bracts (Fig. 3E), cupules (Fig. 3F), gymnosperm ovules (Fig. 3G), and stems with rhomboidal scars (Fig. 3H). These stems are not lycopsids, as previously thought (Retallack, 1980), but pteridosperm stems with a dictyoxylon-cortex (Retallack and Dilcher, 1988). The helically-arranged diamond-shaped markings of these stems are defined by plant fiber, and lack the parichnos and other details of lycopsid leaf cushions. A single specimen (Australian Museum specimen F91478) of an 82-mm-wide gymnospermous woody trunk also was found. This is interpreted as the original diameter following Walton's (1936) compaction hypothesis. A small tree or shrub is compatible with the size of some of the stout woody root traces seen in the paleosols yielding remains of *Botrychiopsis plantiana.*

Attribution of ovulate cupules and branching microsporophylls to *Botrychiopsis,* and, thus, its interpretation as a seed fern rather than progymnosperm is supported by

close association of comparable remains in other parts of the Gondwana supercontinent. Microsporophylls and bracts are found associated with *Botrychiopsis plantiana* and equisetalean fragments in the Italia Road Formation near Raymond Terrace, New South Wales (Nashar et al., 1976). Comparable cupules and bracts are found in association with fronds of *Botrychiopsis valida* in a low-diversity assemblage, including equisetalean fragments, in Hellyer Gorge, Tasmania (Gould, 1976). Ovulate and pollen organs also have been attributed to *Botrychiopsis* in South Africa (Anderson and Anderson, 1985) and Argentina (Artabe et al., 1987), but these African and Argentine fossils are less certainly linked to the leaves because of the diversity of associated remains. Comparable discoveries now indicate that many of the Gondwanan Carboniferous fernlike leaves, including *Nothorhacopteris* (formerly "*Rhacopteris*") and *Fedekurtzia* (formerly "*Sphenopteridium*", in part), were seed ferns rather than progymnosperms (Archanglesky, 1981a; Vega and Archangelsky, 1996; Erwin et al., 1994).

Both cupules and seeds associated with *Botrychiopsis plantiana* (Fig. 3F-G) are similar to those of Carboniferous lyginopterid seed ferns, such as *Calathopteris heterophylla* (Retallack and Dilcher, 1988) and *Austrocalyx jejenensis* (Vega and Archangelsky, 1996). Thus, it is unlikely that *Botrychiopsis* was ancestral to Triassic corystosperms, such as *Dicroidium* (contrary to Artabe et al., 1987; Archangelsky, 1996), which are reproductively more like seed ferns such as *Callospermarion* than like lyginopterids (Retallack and Dilcher, 1988). Lyginopterid affinities also rule out *Botrychiopsis* as an ancestor of glossopterids, as suggested by Morris (1975), because glossopterids also had a *Callospermarion*-like reproductive system (Retallack and Dilcher, 1988).

Dichophyllites peruvianus (Gothan) Morris 1985

Other beds of the trench near Lochinvar have abundant horsetails, with fleshy leaves and leaf sheaths that obscure the nodes (Fig. 3I-K). Decorticated specimens show ribs continuing through the nodes. The narrow, terete leaves dichotomize outwards. Most of the specimens from near Lochinvar are poorly preserved in compressed mats that make it difficult to see details. Nevertheless, these remains are comparable with *Dichophyllites peruvianus* (Gothan), a sphenopsid common and widespread in Carboniferous nonmarine rocks of the Hunter Valley region (Morris, 1975, 1980, 1985). This was probably a hollow, fleshy, herbaceous plant adapted to waterlogged habitats, as its roots and stems form tabular mats in several carbonaceous, clayey paleosols (Fig. 2). It was fleshier than other Gondwanan Permian-Carboniferous horsetails with finer, more rigid fibers in the stem, and more rigid and splayed leaves, such as *Phyllotheca, Paracalamites, Sphenophyllum, Austroannularia, Lelstotheca,* and *Barakaria* (Feruglio, 1951; Maheshwari, 1974; Retallack, 1980; Archangelsky, 1981b; Rigby, 1993; Cuneo et al., 1993).

The foliage *Dichophyllites peruvianus* was probably produced by the same plant as the cone *Burdekinia multiseptata* (Holmes, 1993, 1996), which has files of quadrilocular markings similar to sporangiophores of the British Early Carboniferous Archaeocalamitacean cones *Pothocites,* es-

pecially *P. grantonii* (Boureau, 1964). Because the sporangiophores are less prominently stellate in *Burdekinia* than in *Pothocites,* the two genera are best retained, at least until discovery of more informative material. Leaves are missing from the type specimen of *Burdekinia,* but the stalks of *Burdekinia* have well-spaced ribs and diffuse nodes, commonly deformed by compression, as in *Dichophyllites peruvianus*. Both *Pothocites* and *Burdekinia* have been compared to chambered leaves of aquatic herbs (Boureau, 1964; Holmes, 1993, 1996), but both make a more substantial impression than associated equisetalean leaves and stems.

Other Comparable Gondwanan Floras

Depauperate fossil floras with *Botrychiopsis* similar to the one near Lochinvar have been found in the Seaham Formation at Cranky Corner, New South Wales (Retallack, 1980; McClung, 1980; Briggs and Archbold, 1990), and in the Wynyard Tillite in Hellyer Gorge, Tasmania (Clarke and Banks, 1975; Banks and Clarke, 1987). Both the Wynyard Tillite and Seaham Formation have yielded *Potonieisporites* or stage 1 palynofloras (Kemp et al., 1977). Both palynoflora and megaflora at these two localities represent a nadir of diversity compared with fossil floras of younger and older geological age. This depauperate flora may represent a time of maximal glaciation, though its use as a biostratigraphic marker is compromised by this strong paleoenvironmental influence that peaked in different places at different times (Foster and Waterhouse, 1988).

Botrychiopsis has a long stratigraphic range. Also sharing *Botrychiopsis* are plant assemblages in the Italia Road Formation near Raymond Terrace (Helby, 1967; Morris, 1975; Nashar et al., 1976) and in the Isaacs Formation south of Buladelah (Morris, 1975; Holmes, 1993, 1996). In both cases, there is evidence of more diverse vegetation from megafossils, pollen, and spores (Helby, 1967; Holmes, 1993). More substantial vegetation also is indicated by coal seams and large fossil logs (up to 154 mm wide) at the locality near Raymond Terrace, unlike the weakly carbonaceous rocks with small trunks near Lochinvar. The floras at Raymond Terrace and Buladelah are probably Early Carboniferous in age and predate the Seaham Formation. *Botrychiopsis* also may have ranged into diverse floras of Permian age in Queensland, although some fossils previously identified to this genus have been assigned to *Bergiopteris* (Rigby, 1993; McLoughlin, 1995).

Botrychiopsis also is long ranging in Argentina. Low-diversity plant assemblages with *Botrychiopsis* are in the Formación Nueva Lubecka on the Estancia La Casilda, Patagonia (Archangelsky and Cúneo, 1981), in the Formación Arroyo Totoral of the Sierra de los Llanos, La Riója (Cúneo, 1984, 1986), in the Formación Rio Peñón near Jagué, La Riója (Carrizzo and Azcuy, 1995), and in the Formación Trampeadero of the Sierra de Ambato, La Riója (Archangelsky, 1978a). None of these floras are as depauperate as that of the Lochinvar locality, and they range in age from Late Carboniferous to Early Permian (Archangelsky, 1987; Cúneo, 1996). A low-diversity palynoflora dominated by *Potoniesporites* and *Lundbladispora* also is found in Argentina, but within only a small part of the overall range of *Botrychiopsis* (Archangelsky et al., 1980;

TABLE 1—Description of the type Windermere and Pinabar pedo-types.

+ 30 cm, coarse-grained tuffaceous sandstone; dark bluish gray (5B4/1), with crystals weathered to white (10YR8/1) and yellowish brown (10YR5/6); noncalcareous; abrupt smooth contact to

0 cm (3.8 m in Fig 2), **A horizon of type Pinabar paleosol**, siltstone, grayish brown (10YR5/2), abundant rhizomes of *Dichophyllites peruvianus*; noncalcareous; gradual smooth contact to

−15 cm, AC horizon, siltstone, dark greenish gray (5G4/1), common rhizomes and roots of *Dichophyllites* of grayish brown (10YR5/2); noncalcareous; gradual smooth contact to

−40 cm, C horizon, siltstone, white (10YR8/1); scattered roots and relict bedding, local iron stain (sesquan) yellowish brown (10YR5/8); noncalcareous; abrupt smooth contact to

−50 cm, **A horizon of type Windermere paleosol**, silty claystone, white (10YR8/1); with woody root traces up to 4 mm diameter of dark yellowish brown (10YR4/6); fragments of *Botrychiopsis plantiana* leaves; local iron stain (sesquans) yellowish brown (10YR5/8); noncalcareous; gradual smooth contact to

−20 cm, C horizon, interbedded fine-grained sandstone and siltstone, light gray (10YR7/1); with prominent bedding; local iron stain (sesquans) yellowish brown (10YR5/8); noncalcareous

López-Gamundi et al., 1994). *Botrychiopsis* is found in diverse floras of underlying formations with *Nothorhacopteris,* and in overlying formations with *Gangamopteris* and *Glossopteris* (Archangelsky, 1971, 1978b, 1984; Rocha Campos and Archangelsky, 1985; Archangelsky and Archangelsky, 1987). *Botrychiopsis* has not been reported from Carboniferous floras of India (Pal and Chaloner, 1979), but in both South Africa and India *Botrychiopsis* is a minor component of diverse Permian floras (Chandra, 1974; Anderson and Anderson, 1985).

Dichophyllites peruvianus is similarly widespread in earlier Carboniferous floras dominated by *Nothorhacopteris* and other seed ferns in both South America and eastern Australia (Morris, 1985; Archangelsky, 1987). It has not yet been recorded in Permian rocks.

A long-standing problem for Australian fossil floras of this age has been the lack of conifer megafossils (Retallack, 1980), because associated palynofloras are dominated by conifer grains of *Potonieisporites* (Poort and Veld, 1997). Conifers may be represented by small leaves described as lycopsids (*Lycophyllum morrisiae*) from the Seaham Formation near Paterson (Lacey, 1983). These tiny, coriaceous leaves have deeply sunken stomates with thickly cutinized rims, more like those of conifers than lycopsids. Conifers have long been known from fossil floras of comparable age in Argentina (Archangelsky, 1978a,b; Carrizo and Azcuy, 1995).

PALEOSOLS

The 4-m section of Seaham Formation exposed in the trench and gully near Lochinvar includes four thin and weakly developed paleosols of two distinct kinds, or pedotypes, named for nearby homesteads (Fig. 2, Table 1). Windermere paleosols are sandy, weakly carbonaceous and have deeply penetrating woody root traces. Pinabar paleosols, on the other hand, are carbonaceous with mats of rhizomes. Both pedotypes are non-calcareous and preserve bedding little mixed by root traces or other soil-building processes.

Alteration after Burial

The paleosols were substantially altered during burial and compaction, and then by deep weathering in outcrop. These modifications need to be considered before proceeding further with their paleoenvironmental interpretation.

Coal and phytoclast reflectance in early Permian and Carboniferous rocks around the Lochinvar dome is modest ($R_{o\ max}$ = 0.71–0.82%: Diessel, 1975), probably because of late Paleozoic uplift of this structure (Herbert, 1997). Like the nearby late Permian coal measures with comparable reflectance, this area was buried about 2 km and heated to temperatures of about 170°C (Middleton, 1993). The paleosols are now cherty and well indurated, presumably because of silica released by illitization, devitrification of volcanic shards, and zeolitization expected at such depths of burial (Frey, 1987; Retallack, 1997a). Illitization is a plausible explanation for the potash-rich but lime-poor composition of shales of the Seaham Formation (Osborne, 1925). Compaction at such depths would be about 95% of their former thickness (using equation of Caudill et al., 1997). Compaction may explain the flattened root mats of the Pinabar pedotype and concertina-like deformation of formerly vertical root traces in the Windermere pedotype.

The paleosols are surprisingly light colored and lacking in organic matter considering the abundance of fossil plant impressions. These deposits were probably originally gray and chemically reduced like other parts of the Seaham Formation (Osborne, 1925), although the Windermere paleosol has deeply penetrating root traces and ferruginous nodules indicative of a moderately oxidized soil of probable brownish original color (Retallack, 1997b). Permian cherty varved shales from near Cobbora, N.S.W. also are white and contain red and yellow leaves of *Glossopteris* (Retallack, 1980; Rigby and Holmes, 1981). Much of the leaching and reddening of these Carboniferous and Permian shales may be due to deep weathering during the late Mesozoic and Cenozoic (Schmidt and Ollier, 1988; Ollier and Pain, 1996). This and the relatively weakly developed nature of the paleosols renders chemical study unpromising.

Thin Graded Laminae in Pinabar Paleosols

Pinabar paleosols include bedding unmixed by tabular root systems. Most of these beds are thin (2–3 mm) laminae that are normally graded from silt to clay. They represent a parent material to the paleosols, little altered by plant growth.

Such varved bedding is well known in the Seaham Formation near Seaham and Paterson in what are widely interpreted as proglacial lake deposits because of their trace fossils and dropped pebbles (Süssmilch and David, 1920; Osborne, 1925; Caldenius, 1938; Fairbridge, 1947; Glaessner, 1957; Rattigan, 1967; Crowell and Frakes, 1971a,b). A case has been made (Coombs, 1958) that the layers represent sorting of airfall tuffs settling through standing water. Evidence against this interpretation includes simple grading from silt through clay, constant thickness (2–5 mm) of thousands of consecutive varves, and rarity of fresh shards and crystals in the varves (Osborne, 1922b).

Varved shales of the Seaham Formation are identical in mineral composition, texture, and scale to late Permian
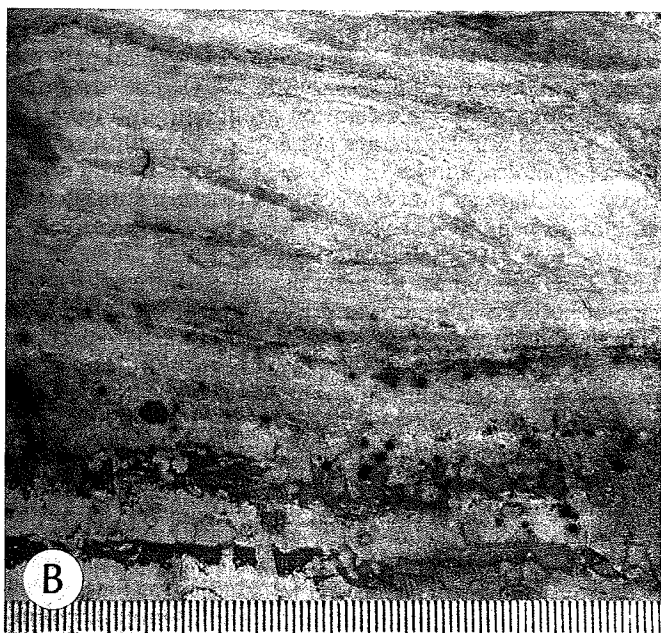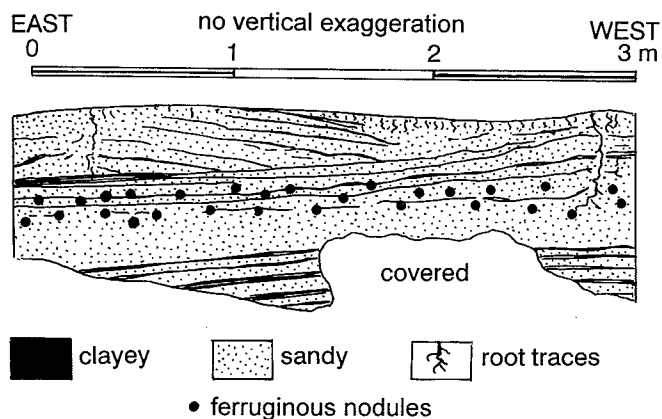
FIGURE 4—Outcrop (A) and sawn slab (B) of Windermere paleosol (3.3 m in Fig. 2) in the Carboniferous Seaham Formation near Lochinvar, New South Wales. The central outcrop is sketched in Figure 5. The slab is at the transition zone between inversely-graded planar features interpreted as freeze-thaw banding in the upper part of the profile and varved-shale of parent material with burrows lower within the profile. The outcrop is 1 m high and the scale on the slab is graduated in mm.

FIGURE 5—Field sketch of root traces and planar features interpreted as freeze-thaw banding and varves in the Windermere paleosol, near Lochinvar (from outcrop of Fig. 4A).

varved shales near Cobbora and elsewhere in the Mudgee district, N.S.W. (Dulhunty and Packham, 1962; Rigby and Holmes, 1981). The late Permian varved shales are richly fossiliferous with *Glossopteris* leaves in rafts at the top of the coarse (spring outwash) part of the varve (Retallack, 1980). Callused abscission scars and growth rings in associated fossil wood also indicate that *Glossopteris* was seasonally deciduous (Anderson and Anderson, 1985; Retallack and Dilcher, 1988). This is paleobotanical evidence that the Permian varved shales represent an annual cycle of silty spring outwash followed by summer and early winter settling of finer sediment before the winter freeze. It is likely that the Carboniferous varves also were annual (Caldenius, 1938).

Varves in parent material of Pinabar paleosols are well preserved. Plant growth may have been limited in its ef-

fectiveness to destroy them by at least three factors. First, tabular root systems and carbonaceous mats of monodominant, herbaceous, carbonaceous fossil plants are evidence for waterlogging at depth, because roots cannot respire in stagnant groundwater (Retallack, 1980, 1997c). Second, there may have been a limited time for plant growth. Soils like Pinabar paleosols represent less than 100 years of plant growth under the worst of conditions (Retallack, 1997b; Bockheim, 1994). Third, plant growth was probably limited by a short, cool, growing season, as is apparent from the varves, together with other evidence for periglacial conditions (Herbert, 1980).

Microdeformation and Dome Structures

There are planar features comparable to bedding in Windermere paleosols also, but these differ markedly from varved shales found within Pinabar paleosols and also lower within parent material of the Windermere paleosol. The planar features outline domes and are reverse graded. The domes are best exposed in an outcrop near the upper end of the trench (Figs. 4, 5), but can be found at various points along its 200-m length. The amplitude of the domes is about 20 cm and their wavelength roughly 2.5 m. Their lateral symmetry and irregularities in spacing are indications that they are broadly hemispherical structures, rather than linear corrugations intersected normal to their strike. Planar features are reverse graded within the domes (Fig. 6A), unlike normally graded varves found in undomed lower parts of the same paleosol (Fig. 6B). The planes are disrupted by root traces (Figs. 5, 6A) and burrows (Fig. 4B), and also by extensive wedge-shaped microdeformation (Fig. 6A, B). The Windermere paleosol has deeply penetrating root traces (Figs. 4A, 5) that reach some 55 cm below the top of the paleosol at the top of the mounds, but only about 30 cm between the mounds (Fig. 5). This paleosol is spotted with small (2–4 mm) ferruginous nodules, which have very diffuse margins in thin section (Figs 4B, 6C). It also has narrow sand-filled vertical burrows, which are most obvious lower in the profile in the ferruginous nodule zone where the burrows disrupt normally graded varves of the parent material (Fig. 4B).
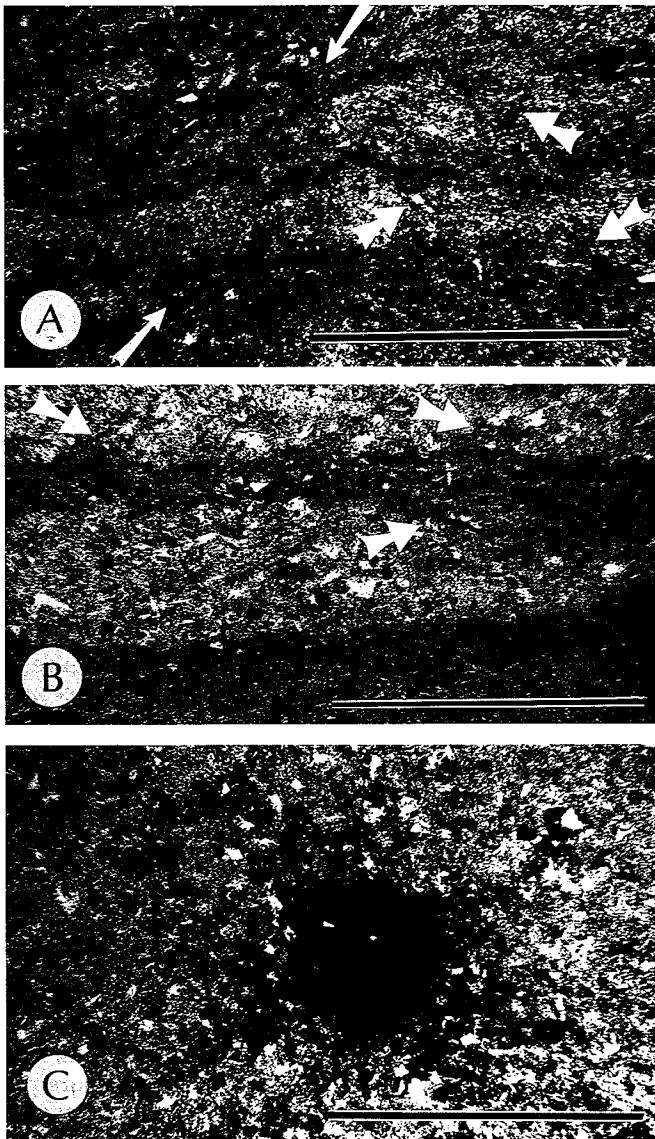
FIGURE 6—Petrographic thin sections of the mid-Carboniferous Windermere paleosol, all cut vertical to bedding and oriented right way up. (A) Clay-filled root trace (between long white arrows) and microdeformation (at 3 short white arrows, and elsewhere) of inverse-graded beds, interpreted to be due to ice disruption, in upper part of profile. (B) Microdeformation (at 3 short white arrows and elsewhere) of normally-graded varves, interpreted to be due to ice-disruption, in lower part of profile. (C) Ferruginous nodule with diffuse margins, formed in place within lower part of profile. All are from the paleosol at 3.3 m in the trench near Lochinvar. Scale bars all 1 mm.

Inversely graded and domed planar features of Windermere paleosols are unlike any known deformation of varved shales in the Seaham Formation (Süssmilch and David, 1920; Rattigan, 1967; Nashar et al., 1976). The mounds were probably not small eolian dunes building around local bushes. Their planar features are much thinner than climbing translatant cross-stratification of eolian dunes (Hunter, 1977), and the reverse grading has a clayey lower and markedly coarser top, rather than a smooth increase in sandy grain size upwards found in eolian reverse grading. Equally puzzling is the pervasive microde-

formation. It is much less through-going than microfaulting and jointing, and more widely wedge-shaped and less sinuous than tension gashes. Also unlike tectonic microdeformation, these features are restricted to specific beds (Fig. 4). Unlike tension gashes, these features are filled with sediment, rather than quartz or calcite. In some cases, brittle disruption of a bedding plane passes laterally into ductile deformation zones. The Windermere paleosol is silty and lacks the distinctive deformation of Vertisols (mukkara structure of Paton, 1974). Thus, the microdeformation is unlikely to be due to shrinking and swelling of clays (Nettleton et al., 1983). Root traces are not pervasive or stout enough to have created these domed planar-banded features.

These enigmatic planar and microdeformational features make better sense if the domed structures of the Windermere paleosols are interpreted as earth hummocks (thufur) produced by frost heave in a periglacial paleoclimate (Washburn, 1980; Bockheim, 1994). The low-angle disruptions are like deformation around ground ice. Silty clastic dikes and layers are similar to those filling a system of frost cracks like that found in permafrost. Freeze-thaw banding is a platy to crinkly structure superficially similar to bedding (Beskow, 1947; Fox, 1983; Van Vliet-Lanoë et al., 1984; Van Vliet-Lanoë, 1985). Such an inferred environment is also compatible with the silty grain size of both Windermere and Pinabar paleosols, because clay formation is suppressed in frigid climates. Earth hummocks today form at temperatures of <3°C and in climates with a freezing index of 700–3800°C days/yr and thawing index of 500–3000°C days/yr (Karte, 1983). Although they can be found in climates with a mean annual temperature as warm as 6°C, they are most common in tundra environments (Washburn, 1980).

Preservation of freeze-thaw banding in the upper part of the Windermere paleosol and varved shales in the lower part imply biota ineffective in bioturbation, as for the Pinabar profile. Unlike the Pinabar profile, however, the Windermere paleosol was not thoroughly waterlogged. Deeply penetrating root traces and ferruginous nodules with diffuse margins as if formed in place are at depths of 50 cm from the surface of the mounds. The sand-filled burrows are simple, tubular in shape, and 2–3 mm in diameter, with a massive, unstructured fill, and can be referred to the ichnogenus Skolithos (Alpert, 1974). These burrows are more prominent where cutting across shaley parts of varves (Fig. 4B), but also continue upwards to the surface. Because of this, the burrows are more likely to have been made by millipedes, insects, or spiders than by aquatic burrowers of the parent material. Nothing like them has been recorded among the ichnofauna of lacustrine facies in the Seaham Formation (Glaessner, 1957; Nashar et al., 1976). For the Windermere paleosol, preservation of bedding and banding is more likely due to a short time of formation and biota limited by a short, cool growing season.

Comparable Soils

Paleosols of the Seaham Formation can be identified in classifications of soils in order to find comparable modern landscapes (Table 2). Both Windermere and Pinabar paleosols are similar to weakly developed soils, such as Alluvial Soils of Stace et al. (1968) or Rudosols of Isbell

TABLE 2—Classification of paleosols in the Seaham Formation.

Pedotype	Diagnosis	Old Australian (Stace et al., 1968)	New Australian (Isbell, 1993)	Northcote key (North-cote, 1974)	U.S. Soil taxonomy (Soil Survey Staff, 1997)	FAO World Map (FAO, 1974)	Polar soils (Tedrow, 1977; Bockheim & Ugolini, 1990)
Pinabar	Gray carbonaceous silt-stone with a root mat of horsetails	Alluvial soil	Stratic Ru-dosol	Um1.41	Cryaquent	Gelic Gleysol	Meadow Tundra Soil
Windermere	Bedded siltstone and shale with angular bedding dislocations and deeply penetrat-ing root traces	Alluvial Soil	Arenic Rudo-sol	Um 1.21	Cryorthent	Gelic Rego-sol	Upland Tundra Soil

(1993), but Australian soils include no good parallels for indications of frigid climate found in the paleosols. In the U.S. Taxonomy (Soil Survey Staff, 1997), both pedotypes fall within the order Entisols. Microdeformation and dome structures interpreted here as frost-induced allow classi-fication of Windermere paleosols as Cryorthents. Tabular root traces and partly humified mats of fossil plants in the Pinabar paleosols are evidence of waterlogging and clas-sification as Aquents.

In the classification of the Food and Agriculture Orga-nization of UNESCO (FAO, 1974) these paleosols are most like Gelic Gleysols and Gelic Regosols. Throughout Asia, these two soil types are found under tundras in the far north, but presently are associated with Histosols (FAO, 1978, 1981). There are no coals (Histosols) known in the Seaham Formation. A closer match is with soils of the Ca-nadian Northwest Territories and Arctic Archipelago, spe-cifically on the coast east of the Mackenzie Delta, the Dis-trict of Keewatin west of Hudson Bay and Baffin, Somer-set, and Southhampton Islands (map units Rx2–1a, Rx2–1b, Gx3–1a, Gx3–2/3a of FAO, 1975). These are frigid tundra regions. Baker Lake in the District of Keewatin, Canadian Arctic, has a mean annual temperature of −11.9°C, with winter temperature of −32.9°C, July tem-peratures of 10.7°C, and mean annual precipitation of 208 mm (Müller, 1982).

Also helpful are the less formal classifications of polar soils of Tedrow (1977), Ugolini (1986), Campbell and Cla-ridge (1987), and Bockheim and Ugolini (1990). Paleosols of the Seaham Formation are most like soils of the tundra life zone. Their degree of rooting, organic accumulation, and mineral weathering is greater than in Polar Desert Soils but less than in Bog Soils, Brown Forest Soils, and Podzols of boreal woodlands. Such paleosols have eluded

discovery in the Seaham Formation where only two kinds of tundra paleosols have been found (Fig. 7, Table 3).

Paleosols of the Seaham Formation are a more secure guide to its ancient vegetation than fossil plants. A fossil woody stem 82 mm in inferred diameter (Australian Mu-seum specimen F91478) could be taken as evidence of tai-ga rather than tundra ecosystem. However, Tedrow (1977) points out that isolated small trees and clumps of trees dot the tundra. Furthermore, cushion plants and prostrate shrubs of tundra can have stout woody axes (Francis and Hill, 1996). From the pole southward, there are five sepa-rate markers for the forest-tundra transition separated by hundreds of kilometers. The prehistoric tree line is repre-sented by isolated stumps of dead trees and shrubs prob-ably dating to the early Holocene. Equatorward of that is the limit of species such as *Salix arctica* that are usually trees, but in so frigid a climate grow only to prostrate shrubs. Equatorward of that is the tree line, an imaginary frontier joining the poleward limit of scattered small trees. Equatorward of that again is the physiognomic forest line of small trees relatively closely spaced, and finally the tim-ber line of a substantial forestry resource. The difference between these various treelines has plagued interpreta-tions of Pliocene periglacial environments (Francis and Hill, 1996; Hill et al., 1996). Even though some of these tree lines reflect dramatic paleoclimatic fluctuations of the Neogene, such variable paleoclimates also are document-ed for the Late Carboniferous and Early Permian (Ziegler et al. 1997; Klein, 1992; West et al., 1997). The limit of prostrate woody tree species is now close to the ecotone be-tween tundra and polar desert. The physiognomic forest line and timberline are at the transition from tundra soils to Brown Forest and Podzolic soils. Paleosols of the Sea-

TABLE 3—Paleoenvironmental interpretation of paleosols in the Seaham Formation.

Pedotype	Paleoclimate	Former vegetation	Former animals	Paleotopography	Parent material	Time for formation (years)
Pinabar	Humid, seasonal	Horsetail (*Dichophyl-lites peruvianus*) marsh	Not known	Seasonally water-logged depres-sions	Alluvial silt-stone	10–100
Windermere	Humid, frigid, seasonal	Seed fern (*Botrychiop-sis plantiana*) tun-dra	small burrows (milli-pede, insect or spi-der)	Sandy, eolian ridges	Alluvial silt-stone	10–100
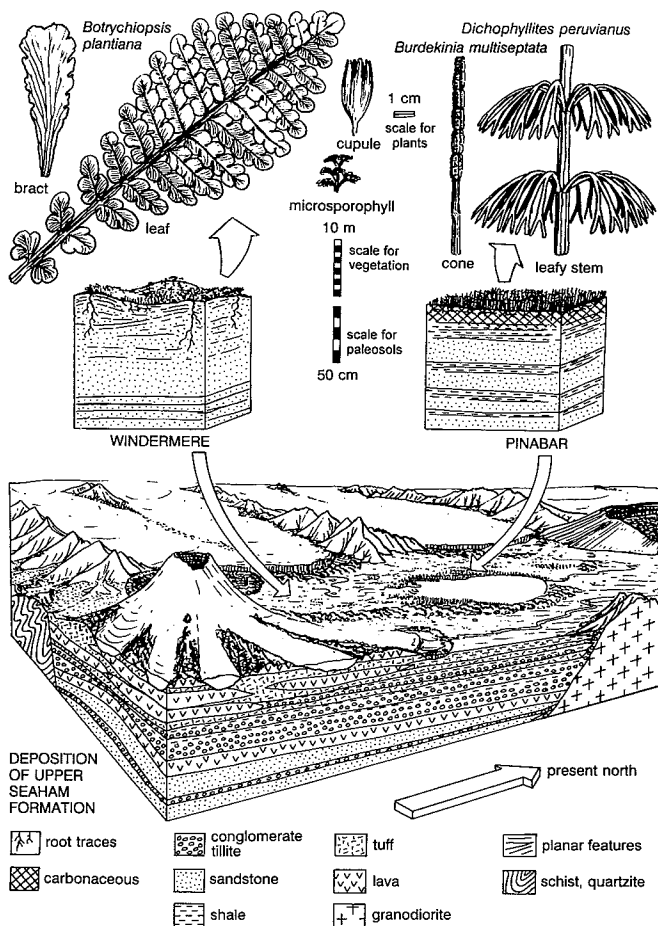
FIGURE 7—A reconstruction of tundra soils and vegetation near Lochinvar during the Carboniferous. The different central scales are for soil profiles (cm, below) and for vegetation (m, above). Fossil plant reconstructions are all to same scale (upper center).

ham Formation are most like tundra soils between these bounds.

ORIGIN OF TUNDRA ECOSYSTEMS

Fossil plants and soils from the Seaham Formation near Lochinvar represent the oldest known example of a tundra ecosystem during the Late Carboniferous (Westphalian or 312–310 Ma: Roberts et al., 1995b). Of broadly comparable age are low-diversity *Botrychiopsis* assemblages at Cranky Corner, New South Wales (Retallack, 1980), and Hellyer Gorge, Tasmania (Clarke and Banks, 1975), but in both places mapping indicates a younger relative geological age than for the assemblage at Lochinvar (Briggs and Archbold, 1990; Banks and Clarke, 1975). As already discussed, both *Botrychiopsis* and *Dichophyllites* range back into more diverse floras of underlying formations in both Australia (Retallack, 1980; Holmes, 1993, 1996) and South America (Archangelsky, 1984, 1987). *Botrychiopsis* tundra vegetation thus was created by loss of most associated plants, rather than by evolution of distinctive new plants.

The origin of Carboniferous tundra may have been comparable in many ways to the origin of the modern tundra

flora. Arctic willow (*Salix arctica*) and dwarf birch (*Betula nana*) are low-growing woody plants of Arctic tundra, commonly the only woody plants, but they also grow to greater stature in diverse boreal forests further south (Bliss, 1981; Tedrow, 1977). Their tolerance of frigid conditions is greater than that of other woody plants whose northward limit is further south. Similarly, *Botrychiopsis* was a component of Carboniferous austral forest ecosystems of the *Nothorhacopteris* flora, but was able to persist further south during climatic deterioration intolerable to other plants (Retallack, 1980). The other plant of this ancient tundra, *Dichophyllites peruvianus,* formed marshes and may have been ecologically comparable to water sedge (*Carex aquatilis*) and cotton grass (*Eriophorum angustifolium*) of Arctic tundra (Bliss, 1981). *Dichophyllites peruvianus* also is common in geologically older Carboniferous forest floras (Morris, 1975, 1980).

Once paleoclimate ameliorated, *Botrychiopsis* persisted into diverse forests of the Permian with *Gangamopteris* and *Glossopteris* (Archangelsky 1971, 1978b, 1984; Chandra, 1974; Anderson and Anderson, 1985; Archangelsky and Archangelsky, 1987). *Dichophyllites,* however, was replaced in the Permian by a variety of other horsetails such as *Phyllotheca.* Such patterns in time can be inferred to reflect a pattern in space of forests thinning out polewards to *Botrychiopsis* tundra for much of the Late Carboniferous.

Such strong ecological control of the depauperate zone of *Botrychiopsis* leaves and *Potonieisporites* pollen means that these have limited biostratigraphic utility (Foster and Waterhouse, 1988). Biostratigraphic zonation of this interval using pollen, spores, and megafossil plants is better based on sequences remote from the ice in Queensland (Jones and Truswell, 1992) or Argentina (Archangelsky, 1987), rather than in the Hunter Valley.

Such a view of this ancient tundra ecosystem supports the idea that tundra vegetation reflects differing tolerances of plants to frigid conditions (Archibold, 1995). Presumably, this would have been the case with the oldest woody plants of the Devonian (Retallack, 1997b) and it is possible that communities analogous to woody tundra will be discovered more ancient than the Late Carboniferous example documented here.

Tundra is best defined as dwarfed, cushionlike or shrubby, woody vegetation of frigid climates (Bliss, 1981; Archibold, 1995). Thus, I do not think that cold-adapted communities older than woody plants should be called tundra. Early frigid ecosystems of microbes, non-vascular plants, and vascular cryptogams may be better called microbial earths, polsterlands, and brakelands, respectively (Retallack, 1992).

An apparent difference between this ancient tundra and modern tundras is the lack of known fossil lichens and mosses in the Seaham Formation. Lichens have a fossil record at least back to the Devonian and perhaps Precambrian (Retallack, 1994; Taylor et al., 1995). Mosses are well known from high paleolatitude vegetation of Permian age (Neuburg, 1960; Anderson and Anderson, 1985; Smoot and Taylor, 1986; Ignatov, 1990). These can be indistinct fossils and their apparent absence may reflect lack of preservation, recognition, collection, or description.

Evidence presented here for a periglacial paleoclimate and tundra ecosystems makes it unlikely that Carboniferous glaciation in the Hunter Valley was merely an al-

pine glaciation (as argued by Dickins, 1985, among others). The alpine glaciers of Alaska, Kamchatka, Chile, and New Zealand all descend to elevations where there are forests growing on soils thicker, more deeply weathered, and better developed (Podzols, Podzoluvisols and Histosols of FAO, 1974, 1975, 1978) than any of the paleosols seen in the Seaham Formation. Tundra paleosols and plants of the Seaham Formation are evidence of periglacial conditions not far removed from sea level. In such a climatic regime it is likely that observed glacial valleys (Herbert, 1980) were merely feeders through the mountains for an extensive continental ice cap like that of Antarctica or Greenland, as inferred on stratigraphic grounds by Banks and Clarke (1987), Powell and Veevers (1987), and Veevers (1984). The Seaham Formation probably represents outwash of a major continental ice cap (Fig. 7).

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