

Permafrost palaeoclimate of Permian palaeosols in the Gerringong volcanic facies of New South Wales*

G. J. RETALLACK

Department of Geological Sciences, University of Oregon, OR 97403, USA.

Late Permian (early Tatarian, 258 Ma) palaeosols exposed near Kiama and Dapto on the south coast of New South Wales can be recognised from their red colour, clayey and massive texture, and clay-filled root traces. Harvey pedotype palaeosols are within the upper Jamberoo Sandstone Member of the Broughton Formation. Loveleigh pedotype palaeosols are within the basal Kiama Sandstone overlying columnar jointed flows of the Blow Hole Latite Member of the Broughton Formation. Both kinds of palaeosols are strongly ferruginised with little relict bedding, yet they are little weathered and have surprisingly high amounts of feldspar and pyroxene. Both also show deformation of sub-surface layers comparable to the active layer of permafrosted soils. Root traces in these palaeosols are sparse and comparable to those of woody gymnosperms, not chambered like the known roots of *Glossopteris*. Plausible components of the taiga woodland represented by the palaeosols include *Gangamopteris*, cordaites, seed ferns, and equisetaleans. Frigid palaeoclimatic indications from the palaeosols are compatible with a palaeomagnetically determined palaeolatitude of 57–85°S, and thus indicate an equator–pole climatic gradient in the Late Permian generally similar to that of today.

Key words: Broughton Formation, Gerringong volcanic facies, Kiama, palaeosol, permafrost, Permian.

INTRODUCTION

A cold palaeoclimate has been inferred during deposition of Permian rocks of the Sydney Basin for a variety of reasons: dropstones in marine rocks (Herbert 1980a); solifluction flows in beach sands (Gostin & Herbert 1973); glendonite pseudomorphs of ikaite in marine shales (Carr *et al.* 1989); deformation like that of shore ice in tidal flat siltstones (Stutchbury 1989); coal seams interpreted as string bogs (Conaghan 1984; Conaghan *et al.* 1994; Retallack *in press*); and seasonally deciduous fossil plants (Retallack 1999). Such a palaeoclimate is compatible with the high palaeolatitude of this part of Australia during the Permian as revealed by palaeomagnetism and global tectonic reconstructions (Embleton 1984; Scotese & Denham 1988). These various lines of evidence are not, however, sufficiently precise to constrain such variables as equator-to-pole temperature gradients during the Permian, and there remain problems for accurate palaeoclimatic modelling of that period of geological time (Kutzbach & Ziegler 1993; Yemane 1993; Fawcett *et al.* 1994). This paper introduces palaeosols as another line of palaeoclimatic evidence in an attempt to both refine and resolve problems in palaeoclimatic interpretation and modelling.

Ever since Russian studies of soil genesis and geography in the late nineteenth century, climate has been a prominent variable for understanding soil morphology and chemistry at high latitudes (Tedrow 1977). Subsequent polar exploration has revealed a great array of permafrost deformation in soils produced under specific climatic regimens (Washburn 1980; Karte 1983). Many of these climate-sensitive soil and permafrost features can be preserved in palaeosols as ancient as Precambrian and as deformed as greenschist facies metamorphism (Williams 1986; Retallack 1990; Retallack & Alonso-Zarza 1998). This paper aims to

apply this approach to Late Permian (early Tatarian) palaeosols in the Broughton Formation near Kiama and Dapto on the south coast of New South Wales.

GEOLOGICAL SETTING

The Broughton Formation is largely sandstone which interfingers eastward into a local latite (shoshonite of Joplin 1964) volcanic centre. It includes the lower part of the informal Gerringong volcanic facies and has several formally named flow and interflow members (Table 1). Sandstone of the Broughton Formation is dominated by feldspar and volcanic rock fragments, reflecting its volcanic source (Raam 1968, 1969).

Marine faunas of the Broughton Formation, and particularly the Westley Park Sandstone Member, indicate a Late Permian age, or more precisely the *Echinalosia ovalis* brachiopod zone of Runnegar (1980) and the *Echinalosia* spp. nov. (numbers 5 & 6) zones of Briggs (1991). The Broughton Formation is probably about 258 Ma, judging from local radiometric dating (summarised by Veevers *et al.* 1994a). The volcanic flows are in the uppermost part of the Carboniferous–Permian Reversed Magnetozone (formerly Kiaman Magnetic Interval) and its transition into the Illawarra Magnetozone. This transition is dated at 265 Ma and early Tatarian by international calibration of the palaeomagnetic time scale (Menning 1995).

Appendices 1 and 2 [indicated by an asterisk () in the text and listed at the end of the paper] are Supplementary Papers lodged with the National Library of Australia (Manuscript Section); copies may be obtained from the Business Manager, Geological Society of Australia.

Deep burial alteration of the Broughton Formation is mild, perhaps because this volcanic terrain was a positive landscape feature less deeply buried than other parts of the Sydney Basin (Middleton 1993). Overlying Upper Permian to Middle Triassic rocks of the Sydney Basin are as much as 1500 m thick (Stroud 1974; Uren 1974; Bowman 1980; Herbert 1980b). An additional 800 m of overlying Upper Triassic and Lower Jurassic sedimentary rocks has been eroded away. The missing section can be inferred from the shape of diatreme intrusions and the pollen content of their shale clasts (Crawford *et al.* 1980; Branagan 1983) and the vitrinite reflectance and rank of coals of the Illawarra Coal Measures (Diessel 1992; Faiz & Hutton 1993). This 2.3 km of burial would have compacted the palaeosols to some 95% of their former thickness, using a compaction equation (Caudill *et al.* 1997). Thermal modelling of the Sydney Basin gives maximum temperatures of some 170°C (Middleton 1993). Illitisation would be expected under such conditions (Eberl *et al.* 1990), but is not indicated by sharpness of the 10 Å peak on XRD traces of Broughton Formation palaeosols. Their indices of illite crystallinity (Weaver index 1.25, Kübler index $1.7^\circ 2\theta$, Weber index 300) are well short of the anchizone of regional metamorphism (values >2.3, <0.42, <181 respectively: Frey 1987). Laumontite cement indicates zeolitisation (Raam 1968), but is probably hydrothermal–volcanic alteration rather than regional metamorphism. Also found in sandstone of the Sydney Basin is rare dawsonite cement, presumably derived from tectonic degassing of CO₂ (Baker *et al.* 1995). In addition, palaeosols of the Broughton Formation were altered by decomposition of organic matter, gleization (chemical reduction) of iron oxides and reddening by dehydration of iron hydroxides shortly after burial, as is

usual for palaeosols (Retallack 1991). These early diagenetic alterations are indicated by their red hue, drab-haloed root traces and organic-lean clay-filled root traces (Retallack 1990).

Much of the Broughton Formation is thought to have been deposited in beaches, tidal flats and a shallow open-ocean shelf (Bull & Cas 1989). The Kiama Sandstone Member at Mt Pleasant and near Kiama ocean baths has yielded marine bivalves (Raam 1969; Runnegar 1980) and burrows with transverse clayey partitions (backfills) similar to burrows found elsewhere in Permian marine rocks of the Sydney Basin (Pickett 1972). Marine fossils and burrows also are found in the Jamberoo Sandstone Member near Dapto and elsewhere (Raam 1969). Also found is hummocky cross-stratification indicating strong storms during a season of little sea ice (Arditto 1985; Cas & Wright 1987 figure 10.19; Bull & Cas 1989). Yet some sea ice or icebergs were present, judging from large dropstones (Raam 1968; Cas & Wright 1987, figure 10.13; Bull & Cas 1989) and glendonites in the Westley Park and Kiama Sandstone Members (Carr *et al.* 1989). The Blow Hole Latite flows have columnar jointing (rather than pillows) and so cooled on land (Raam 1968; Bull & Cas 1989). Other flows of the Gerringong volcanic facies extended out into the shallow ocean as demonstrated by breccias, pillows and associated soft-sediment deformation of unconsolidated marine sediments (Cas & Wright 1987; Bull & Cas 1989).

The Gerringong volcanic centre was probably an island at first, then a peninsula, within the shallow-marine continental shelf of the southern part of the Sydney Basin during the Late Permian. The volcanics were downfaulted during Cretaceous rifting of the Tasman Sea, but they can still be detected in the continental shelf as a magnetic

Table 1 Formal stratigraphic units in the Gerringong volcanic facies (from Jaquet *et al.* 1905; Raam 1969; Carr 1983).

Unit	Thickness (m)	Remarks
Illawarra Coal Measures		
Pheasants Nest Formation		
Berkley Latite Member	24–35	Two coarsely porphyritic flows
Minamurra Latite Member	up to 37	Glomeroporphyritic flow with phenocrysts of labradorite
Calderwood Latite Member	up to 38	Coarsely porphyritic flow
Five Islands Latite Member		Fine-grained, pillowed flow
Upper Shoalhaven Group		
Broughton Formation		
Cambewarra Latite Member	18–70	Amygdaloidal, red-yellow, finely porphyritic, with labradorite phenocrysts, pillowed flow.
Dapto Latite Member	up to 85	Two porphyritic flows, separated by breccia
Saddleback Latite Member	18–35	Pillowed, coarsely porphyritic flow, with phenocrysts of labradorite and augite
Jamberoo Sandstone Member	55–155	Red and green, volcanoclastic sandstones, with interbedded conglomerates, common marine fossils, Harvey palaeosols in upper part between Cambewarra and Dapto Members
Bumbo Latite Member	9–150	Three coarsely porphyritic columnar jointed flows, with breccia pipes; large phenocrysts of labradorite and small phenocrysts of augite
Kiama Sandstone Member	30–53	Purple-brown volcanoclastic sandstone with rare marine fossils; Loveleigh palaeosol near base.
Blow Hole Latite Member	up to 50	Three pillowed, columnar, microporphyritic flows separated by breccias
Westley Park Sandstone Member	up to 45	Green-grey volcanoclastic sandstone, with locally abundant marine fossils

anomaly (Bradley 1993). Local thickening of the flows is evidence of stratovolcanoes (Raam 1968). Small stratovolcanoes and cinder cones are indicated by the columnar and pillowed flows, and mainly lithic and crystal tuffs (Cas & Wright 1987 figures 3.11, 3.12). These are suggestive of a combination of eruptive styles: Hawaiian, Strombolian, Subplinian and Surtseyan (Cas & Wright, 1987).

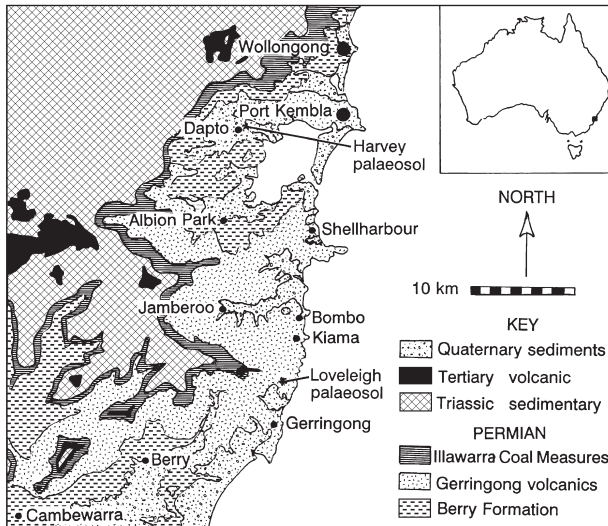


Figure 1 Simplified geological map and location of the Loveleigh and Harvey palaeosols in the southern Sydney Basin, near Dapto and Kiama, New South Wales.

To the west of the volcanoes was initially a shallow sea-way, then a lowland mantled by vitric, crystal and lithic tuffs. The green and red sandstones have palaeocurrents heading northwest along the Permian shoreline, as well as northeast toward the shoreline (Bowman 1980; Ardito 1991; Herbert 1995). Much farther west were low hills of Palaeozoic schists and quartzites (Runnegar 1980). Connection between the north-trending volcanic arc and the northwest-trending mainland probably began as a wave-swept tombolo, then widened into a wave-dominated coast of beach ridges and alluvial lowlands (Bowman 1980; Veevers *et al.* 1994a). Comparable volcanic peninsulas in coastal alluvial plains are the Tertiary volcanic centres near Christchurch and Dunedin, New Zealand (Suggate 1978).

MATERIALS AND METHODS

My search for palaeosols in the Upper Permian Broughton Formation near Kiama and Dapto (Figures. 1, 2) included only large exposures in road cuts and sea cliffs where the rocks were sufficiently free of modern weathering to allow geochemical studies of ancient weathering. Palaeosol profiles were sampled for petrographic and chemical study. Thin sections were counted for 500 points each for separate counts of grainsize and mineral composition using a Swift automatic point counter. Bulk density was determined by the clod method using paraffin. Chemical analyses were from inductively-coupled plasma-fusion for major oxides and X-ray fluorescence for trace elements by Bondar Clegg

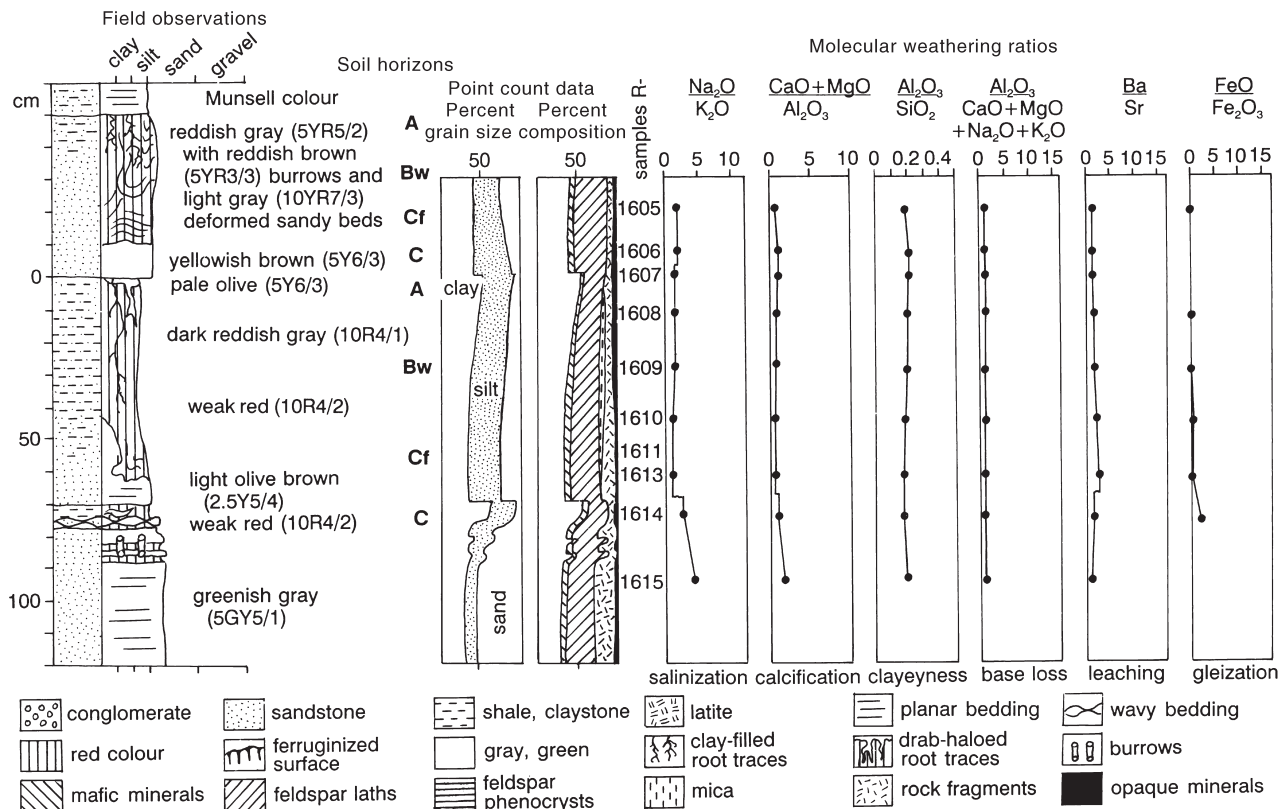


Figure 2 Measured section, Munsell colours, soil horizons, grainsize, mineral composition, organic matter and selected molecular weathering ratios of the Harvey palaeosols from a road cut on highway F6 near Dapto.

Table 2 Description of the Harvey silty clay palaeosol.

Depth (cm)	Horizon	Lithology	Colour	Other features	Micromorphology	Lower contact
+15	-	Silty sandstone	Yellowish brown (10YR5/4)	Root traces filled with dark reddish brown (5YR3/3) claystone; relict bedding reddish gray (5YR5/2) and light gray (10YR7/2); iron stain (sesquans) brownish yellow (10YR6/8) and very dark grayish brown (10YR3/2); non-calcareous	Agglomeroplastic mosaic; volcanic grains have weathering rinds (diffusion sesquans)	Abrupt smooth contact to
0	A	Clayey siltstone	Dark reddish gray (10R4/1)	Root traces up to 4 mm diameter of dusky red (10R3/2) claystone; few root traces with large (15 mm) drab haloes around root traces of pale olive (5Y6/3); manganese stain (mangans) of reddish black (10R2.5/1); grains reddish gray (10R6/1); non-calcareous	Agglomeroplastic inseplic; common ferruginised planes (sesquans) partly after plant fibre	Gradual irregular contact to
-22	Bw	Clayey siltstone	Weak red (10R4/2)	Root traces dusky red (10R3/2); blocky angular peds defined by slickensided clay skins (argillans) of dark reddish gray (10R4/1); iron stain strong brown (7.5YR4/6) and manganese stain (mangans) reddish black (10R2.5/1); non-calcareous	Intertextic inseplic; root traces (paraisotubules) of golden clay; clay skins (stress argillans); volcanic clasts with weathering rinds (sesquans)	Clear irregular deformed to
-44	Cf	Sandy siltstone	Light olive brown (2.5Y5/4)	This layer deformed upwards into dykes, curled fragments and bulbous projections into overlying horizon; few small (3 mm) mottles light olive gray (5Y6/2); scattered iron-manganese stain (mangans) of black (2.5Y2.5/1); non-calcareous	Agglomeroplastic inseplic; fine root traces lined with organic matter and filled with golden clay (paraisotubules with sesquiorganans)	Clear wavy to
-64	C	Medium-grained sandstone and siltstone	Greenish gray (5GY5/1)	Interbeds of dusky red (10R4/2) large (1.5 cm diameter) burrows dusky red (10R3/4), with backfills layering (paraisotubules); non-calcareous	Inseplic intertextic with fine paraisotubules after root traces	Clear smooth to
-88	C	Medium-grained sandstone	Greenish gray (5GY5/1)	Massive to crudely bedded	Granular silasepic; with some remnant pyroxene	

Table 3 Description of the Loveleigh clay palaeosol.

Depth (cm)	Horizon	Lithology	Colour	Other features	Micromorphology	Lower contact
+25	-	Sandstone	Dusky red (10R3/2)	Volcaniclasts reddish brown (2.5YR4/4), very dusky red (10Y3/2) and pale yellow (5Y7/4); large (up to 61 cm) claystone clasts very dusky red (10R2.5/2); non-calcareous	Intertextic skelmosepic; some scoria; volcanic clasts with weathering rinds (sesquans)	Abrupt wavy to
0	A	Clayey, medium-grained sandstone	Dusky red (10R3/3)	Platy to angular blocky peds defined by slickensided dusky red (10R2.5/2) clay skins (argillans); wide (2 cm) drab haloes around stout (3-4 mm) root traces and joints of pale yellow (5Y7/3); fine (1-2 mm) root traces filled with very dusky red (10R2.5/2) claystone; volcaniclastic granules of light gray (2.5Y8/2) and reddish brown (2.5YR4/4) and pebbles (up to 1 cm) of pale yellow (5Y7/3); non-calcareous	Intertextic to agglomeroplastic skelmosepic; with clayey isotropic para-isotubules after root traces; volcanic grains with thin weathering rinds (sesquans)	Gradual smooth to
-35	Bw	Clayey, medium-grained sandstone	Dusky red (10R3/3)	Root traces up to 3 mm diameter of very dusky red (10R2.5/2); clasts light gray (10YR7/2); root traces and joints pale yellow (5Y7/3); non-calcareous	Agglomeroplastic skelmosepic; with isotropic paraisotubules after root traces; volcanic rock fragments with weathering rinds (sesquans)	Gradual wavy to
-112	Bf	Medium-grained sandstone	Dusky red (10R3/3)	Large subhorizontal and near vertical joints with reduction haloes up to 3 cm wide on either side of pale yellow (5Y8/3); relict bedding; rare clay skins (argillans); non-calcareous	Intertextic skelmosepic; volcanic clasts with weathering rinds (sesquans)	Clear wavy to
-148	C	Coarse-grained pebbly sandstone	Weak red (10R4/4)	Crudely-bedded to massive, diffuse mottles strong brown (7.5YR4/6); pebbles up to 2 cm diameter greenish gray (5G5/1), olive yellow (2.5Y6/8) and light gray (5Y7/1); large boulders olive gray (5Y4/2) with weathering rind yellowish red (5YR4/6); non-calcareous	Agglomeroplastic inseplic; latite boulders granular silasepic with mafic phenocrysts weathered to brown clay	Abrupt wavy erosional to
-256	C	Volcaniclastic boulder breccia	Weak red (10R4/2)	Pebbles very pale brown (10YR7/4) and olive gray (5Y4/2); large boulder bluish gray (5B5/1) to dark gray (7.5YR3/1), with vesicle fills strong brown (7.5YR5/8) and weathering rind dark brown (7.5YR3/4); non-calcareous	Granular silasepic; large latite clasts granular silasepic, with matrix of pilotaxitic feldspar laths and large feldspar glomerophenocrysts	

Inc., Vancouver, BC Canada, with ferrous iron from ferrous ammonium sulfate titration and loss on ignition by 4 hours at 600°C (Appendices 1*, 2*). Errors were estimated from

multiple analyses of CANMET SY-3 and CANMET SO-2 for ICP. Error ($\pm 1\sigma$) from ten replicates of R1604 for bulk density is 0.04 g.cm⁻³. Manipulation of the chemical data to

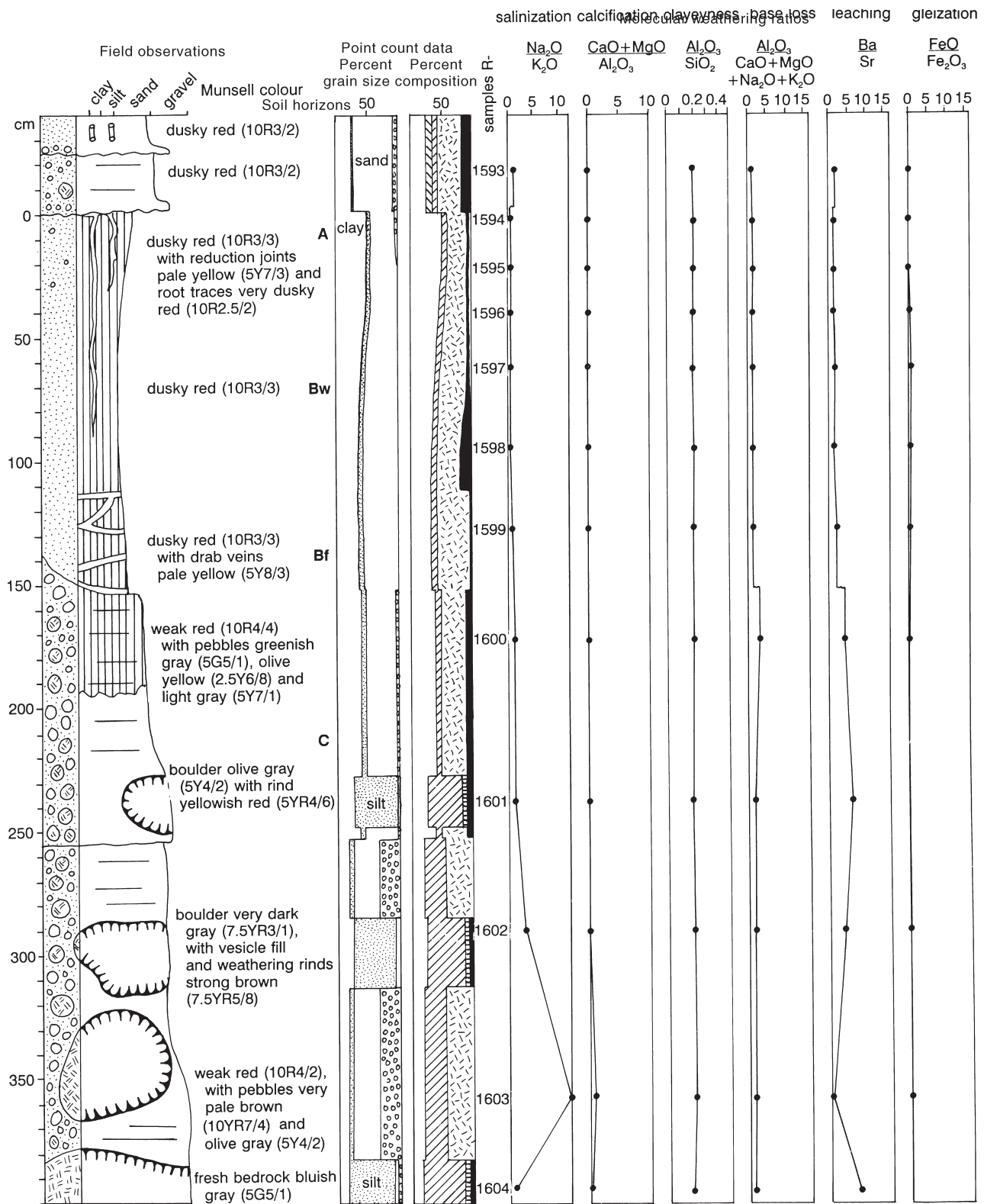


Figure 3 Measured section, Munsell colours, soil horizons, grainsize, mineral composition, organic matter and selected molecular weathering ratios of the Loveleigh palaeosol in a road cut on Princes Highway south of Kiama. Lithological and petrographic key as for Figure 2.

reveal degree of soil formation included calculation of molecular weathering ratios, pedogenic strain and mass transfer (Brimhall *et al.* 1991; Retallack 1997a).

PALAEOSOLS OF THE GERRINGONG VOLCANIC FACIES

Two different kinds of palaeosols were found: Loveleigh and Harvey palaeosols. They are named here as pedotypes (Retallack 1994), and were sampled and described in detail at the localities where best exposed (Tables 2, 3). Two Harvey palaeosols are in the upper Jamberoo Sandstone Member of the Broughton Formation stratigraphically between the Dapto and Cambewarra Latite Members (Bowman 1970) exposed in the western road cut of highway F6 beneath the Harvey Street overpass near Dapto (GR 9817 8071, Wollongong sheet 9029-2-S). The type profile is the lower of two comparable profiles in this outcrop (Figures 1, 2; Table 2). The Loveleigh palaeosol is within the lowermost Kiama Sandstone Member of the Broughton Sandstone where it directly overlies the Blow Hole Latite Member (Bull & Cas 1989) in a road cut of the Princes Highway on the southern flank of Mt Pleasant south of Kiama (Figures 1, 3; Table 3: GR 0228 5657, Kiama sheet 9028-I-S). The same palaeosol would also crop out around Kiama harbour and ocean baths, were it not for construction of those facilities. Red sandstones of the overlying Kiama Sandstone Member may be derived from erosion of this and comparable palaeosols, but contain no recognisable palaeosols in the sea cliffs near Kiama ocean baths, beneath the Bumbo Latite at Bombo Point, or in road cuts along the Princes Highway at Kiama Heights.

Within the Late Permian volcanic coast near Kiama the Harvey palaeosol formed on air-fall tuffs in well-drained floodplains of the coastal plain (delta plain facies of Bowman 1970). The Loveleigh palaeosol on the other hand formed on volcanic sands and gravels mantling a latite flow. Compared with these parent materials both palaeosols show the following clear indications of soil formation.

(1) Root traces filled with dark brownish red clay ramify through the upper part of both palaeosols. In the Loveleigh palaeosol some of these are drab haloed. Root traces indicate that plants grew in these ancient soils.

(2) Clay is increasingly abundant in the surface horizons of both palaeosols, usually accompanied by a concomitant decline in the abundance of volcanic rock fragments, and to a less extent, declining feldspar (Figures 2, 3). This is evidence of weathering of rock fragments and feldspar to clay.

(3) Alkali and alkaline-earth elements, and especially soda, are depleted with respect to alumina (Figures 2, 3), and with respect to parent material. Both Loveleigh and Harvey palaeosols show similar weathering trends, with the Loveleigh more weathered than the Harvey palaeosol (Figure 4). This is a chemical indication of weathering of rock fragments to clay.

(4) Both palaeosols are highly oxidised, red with hematite and with low FeO/Fe₂O₃ ratios compared with parent latite and tuff (Figures 2, 3; also Joplin 1963, 1964). This is a chemical indication of oxidation, probably due to good aeration and drainage during soil formation.

(5) Field, petrographic and chemical variation are all gradational down from the abrupt surface of the palaeosol (Figures 2–4). Gradational boundaries are characteristic of soil horizons.

(6) Unlike enclosing sediments, the palaeosols lack obvious bedding. They show instead a system of veins and clay skins like the peds, cutans and permafrost disruption of soils (Retallack 1990).

PALAEOCLIMATIC INDICATORS IN THE PALAEOSOLS

Both the Loveleigh and Harvey palaeosols show lateral deformation comparable with that produced in the active layer of permafrosted soils (Figure 5). The two successive Harvey palaeosols near Dapto for example show a variety of deformations that lift the drab-coloured sandy basal layer up into the red clayey palaeosol as flame structures, lobes and dykes. These structures are very different from ball-and-pillow structures and load casts (Potter & Pettijohn 1963), in which heavy sandy layers founder into underlying thixotropic clay. Deformation in the Harvey palaeosols shows just the reverse: the sandy material is injected upwards into the overlying clayey material. Furthermore the strong oxidation (low FeO/Fe₂O₃ ratios and red colour)

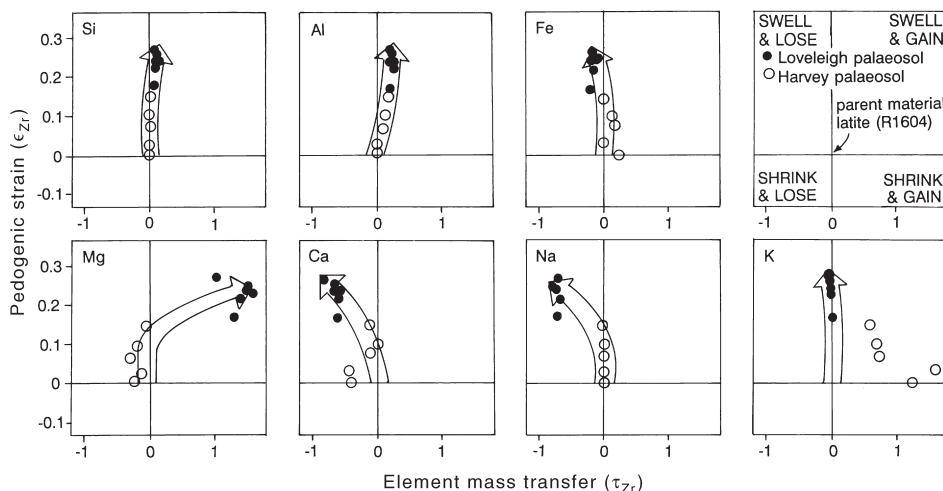


Figure 4 Zirconium-normalised changes in volume (ϵ) and element mass transfer (τ) for Harvey and Loveleigh palaeosols. Parent material composition (at cross-bars) is from the base of each profile (specimens R1614 and R1604 of Figures 2 and 3 respectively). Chemical trends of element depletion (to left) or enrichment (to right) in an overall regime of physical soil dilation (to top) are indicated by arrows.

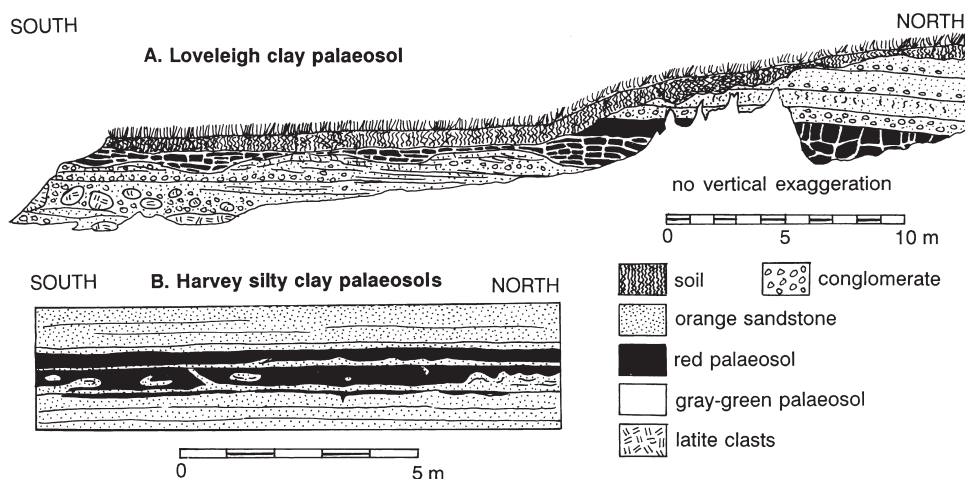


Figure 5 Outcrop sketches of Loveleigh (A) and Harvey (B) palaeosols, showing lateral variation interpreted as deformation created within a permafrost active layer.

of the Harvey palaeosols is an indication of better drainage and drier soils than those prone to load casting or convection (Van Vliet-Lanöe 1991). Load casts, contorted lamination and dyking can also be created by earthquake liquefaction, but such coseismic deformation is more pervasive and irregular than that seen in the Harvey palaeosols (Peterson & Madin 1997). In addition, both palaeosols show comparable deformation confined to their clayey portions and not cross-cutting the lower palaeosol. Coseismic deformation of the upper palaeosol when it was still unlithified would have affected also the lower palaeosol, which was then shallowly buried (Peterson & Madin 1997). Upward bulging subsurface layers are also found in swelling clay soils or Vertisols (Paton 1974), but the Harvey palaeosols show irregularities and liquefaction unlike the shearing of mukgara or gilgai phenomena. Deformation of the Harvey palaeosol is most like frost stirring in the active layer of permafrosted soils (Tedrow 1977; Van Vliet-Lanöe *et al.* 1984; Van Vliet-Lanöe 1985). Expansion of ice in the sandy lower parts of the palaeosol may have caused it to bulge upwards and be pinched off in overlying soil horizons. In other cases there are dyke-like injection features (Figure 5B). This kind of permafrost deformation of subsurface layers is found in climates with a mean annual temperature of less than -1°C , and with a freezing index of $80\text{--}7000^{\circ}\text{C days/year}$ and thawing index $<100\text{--}3700^{\circ}\text{C days/year}$ (Karte 1983; Williams 1986). Such structures not only indicate a frigid temperature regime, but also seasonal freezing and thawing cycles.

At the base of the dark red portion of the Loveleigh palaeosol there is pronounced undulation of the contact between red sandstone and underlying volcanic conglomerate (Figure 5A). Because bedding planes in the sandstone fill and onlap this undulose structure, I interpret it as an erosional feature, probably shallow rills. It is rather the system of bleached sand-lined cracks in the red palaeosol above the undulose top of the conglomerates that resemble the structure of fragipans and ice lenses in permafrosted soils (van Vliet-Lanöe 1985; van Vliet-Lanöe *et al.* 1984). In frigid soils cracks are lined with coarse grains expelled from clayey soil by freezing. Root traces in the Loveleigh palaeosol cut across comparable vertical, drab, sand-lined cracks, indicating that they were not originally indurated like fragipans. No roots were seen to penetrate the basal brickwork-like drab cracks at the base of the

Loveleigh profile. The drab colour of the cracks and red patches between the cracks are interpreted here as early burial alteration features dating back to Permian time, because they weather orange in the present outcrop. In addition, they are more distinct in the contrast between green and red further back in the cliff than the weathered surface. The green-grey stain defining a pattern of red brick-like units is maintained in different parts of the outcrop, where buried by sandstone or where covered directly by the current soil (Figure 5A). Such drab halos are common in palaeosols and are thought to form during shallow and early burial by the microbial reduction of buried organic matter (Retallack 1991). Ice lenses may have collected humus that later decayed to accentuate local cracks with drab halos. Such ice lenses are found within permafrosted soils with mean annual temperatures of less than -1°C (Williams 1986).

Also indicative of a cool and humid climate is the degree of weathering of the profiles. There are lower soda and lime in both palaeosols compared with their parent materials (Figures 2, 3), and compared with unweathered latite (Figure 4). There is also no sign of evaporite or carbonate nodules. Humid weathering is also clear from the mass transfer of sodium and calcium out of these aggrading profiles (Figure 4). These chemical weathering trends are significant, though less marked than in more deeply weathered palaeosols (Retallack & Mindszenty 1994; Bestland *et al.* 1996). Similar trends were found using titanium and zirconium to normalise pedogenic strain. These are all indications of a humid climate, with precipitation well in excess of evaporation. The molecular ratio bases/alumina (B: the inverse of alumina/bases of Figures 2, 3) in the Bt horizons of North American soils can be shown to be related to mean annual rainfall (P in mm) according to the following formula (Ready & Retallack 1996):

$$P = -759B + 1300$$

with correlation coefficient (r) of 0.7 and standard deviation (σ) of ± 174 mm. Using this relationship, both Loveleigh and Harvey palaeosols give a value of 542 ± 174 mm, or roughly 350–700 mm mean annual precipitation. In tropical to warm temperate climates such rainfall regimes include mostly calcareous soils (Yaalon 1983), unless evaporation is checked by very cool temperatures. Non-calcareous soils form in such dry climates in North America north of

the US–Canada border (Birkeland 1984) and in Eurasia north of Israel (Yaalon 1983). To have such humid chemical weathering at such low mean annual precipitation requires the very low evapotranspiration of frigid climates.

Frigid conditions are also indicated by the modest variation in clay abundance and persistence of feldspar throughout both profiles (Figures 2, 3). Down-profile variation in ratios of alumina/silica and alumina/bases are also modest (Figures 2, 3): more modest than for Spodosols, Alfisols and Ultisols of temperate climates (Retallack 1997a). Petrographic and chemical differentiation of these palaeosols is comparable to that found in weakly developed soils of non-frigid climates, yet none of the palaeosols shows relict bedding that would indicate very weak development. In contrast, the palaeosols have been bioturbated and cryoturbated to take on a massive to weakly pedal appearance similar to moderately developed soils of non-frigid climates. Cryoturbation structures like those of the Harvey palaeosols can be created in as little as about 50 annual freeze–thaw cycles, and prismatic structure like that of the Loveleigh palaeosol in 100–1000 cycles (van Vliet-Lanöe *et al.* 1984; van Vliet-Lanöe 1985). This conundrum of massive profiles in sedimentary parent materials yet modest chemical and mineral weathering is also compatible with origin through cryoturbation and slow weathering of frigid climates.

PALAEOCLIMATIC IMPLICATIONS OF PALAEOSOL CLASSIFICATION

Classification of palaeosols in the same way as modern soils facilitates comparison with modern soil-forming environments. There is a problem that some of the criteria for the classification of soils are not fully preserved after burial (Retallack 1991), and need to be approximated by other measures (Retallack 1993). Neither the Harvey nor Loveleigh palaeosols shows a surficial peat, subsurface horizon enriched in clay or carbonate, nor are they deeply weathered chemically or petrographically. Thus only the very weakly to weakly developed soil orders of Entisols and Inceptisols are appropriate using the US soil taxonomy (Soil Survey Staff 1997). In view of the permafrost deformation already outlined the great groups Cryorthent and Cryochrept are most appropriate (Table 4). Classifications, such as the various empirical classifications of Australia (Stace *et al.* 1968; Northcote 1974; Isbell 1993), have roughly equivalent kinds of soils, but lack exact analogues of permafrosted soils. The most useful classifications for finding analogous modern environments to the palaeosols of the Gerringong volcanic facies are the FAO World Map (1974) and polar soil classifications (Tedrow 1977; Bockheim & Ugolini 1990).

Gelic Cambisols comparable to Loveleigh and Harvey palaeosols are found on marine sediments, glacial till and outwash in lowlands to the west of Hudson Bay, Arctic Canada at a latitude of 59–61°N (map units Bx 1-1a, Bx 2-1b of FAO 1975). Nearby Churchill has a mean annual precipitation of 407 mm and mean annual temperature of –7.2°C; there are 52 days above 10°C and July has mean daily temperatures of 12.0°C (Walter *et al.* 1975; Müller 1982).

Gelic Cambisols are also found in Siberia in the alluvial basins of the Vilyui and Amga Rivers at a latitude of 59–65°N (map units Bx 1-1b and Bx 1-2b of FAO 1978a). Vilyuisk has a mean annual precipitation of 226 mm and mean annual temperature of –9.2°C; there are 90 days with temperatures above 10°C, 189 days with temperatures less than –10°C, and July has mean daily temperatures of 18°C (Walter *et al.* 1975; Müller 1982).

In striking contrast, red soils developed on the Gerringong volcanic facies of the Kiama region today are much more deeply weathered and clayey (Craig & Loughnan 1964) than either Loveleigh or Harvey palaeosols. The surface soils can be classified as Acrisols (FAO 1978b), Ultisols (Soil Survey Staff 1997), Red Earths (Stace *et al.* 1968), and Gn2.14 and Gn2.15 (Northcote 1974; Walker *et al.* 1983). Comparable deeply weathered palaeosols (Ultisols) of Triassic age are known to have developed on sandstones eroded from the Gerringong volcanic facies (Retallack 1977, 1997b). The Loveleigh and Harvey palaeosols formed on similar parent materials but are quite distinct from these temperate climate Quaternary soils and Triassic palaeosols.

PALAEOCLIMATIC ZONATION OF INFERRED VEGETATION

Loveleigh and Harvey palaeosols contain stout root traces of woody plants. Many of the root traces are brown, clay-filled and up to 4 mm in diameter. Some of the root traces have a drab (grey-green) halo extending to a diameter of 30 mm. There is also local drab discolouration of the former surface of the palaeosols, but it is discontinuous and thin (<3 cm). Drab discolouration is diffuse and not accom-

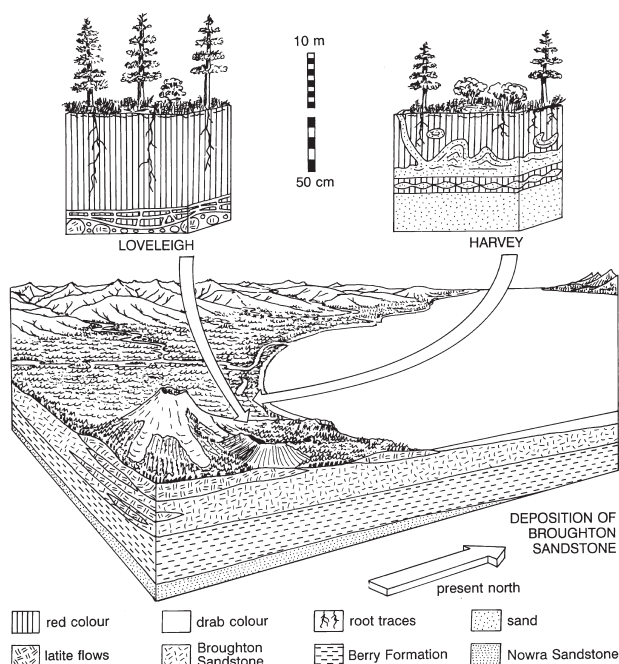


Figure 6 A reconstruction of Permian palaeosols and vegetation in the Gerringong volcanic facies of the Broughton Formation and their palaeogeographic setting.

Table 4 Classification of palaeosols in the Gerringong volcanic facies.

Pedotype	Diagnosis	Old Australian (Stace <i>et al.</i> 1968)	New Australian (Isbell 1993)	Northcote key (Northcote 1974)	US Soil Taxonomy (Soil Survey Staff 1997)	FAO World Map (FAO 1974)	Polar Soils (Tedrow 1977; Bockheim & Ugolini 1990)
Harvey	Red siltstone with clayey root traces, and deformed subsurface sandy layer	Brown Clay	Orthic Rudosol	UF6.51	Cryorthent	Gelic Regosol	Brown Wooded
Loveleigh	Red volcanoclastic sandstone and conglomerate, and with drab and brown root traces	Brown Earth	Orthic Tenosol	UF5.12	Cryochrept	Gelic Cambisol	Brown Wooded

Table 5 Palaeoenvironmental interpretation of palaeosols in the Gerringong volcanic facies.

Pedotype	Palaeoclimate	Ancient vegetation	Ancient animal life	Palaeotopography	Parent material	Time for formation
Harvey	Frigid, with seasonal thaw, humid	Taiga woodland	Insect or spider burrows	Well-drained floodplain	Lithic crystal air-fall tuff	500–1000 years
Loveleigh	Frigid, humid	Taiga woodland	Insect or spider burrows	Well-drained flow tops and colluvial aprons	Volcanic flow breccias and colluvium	1000–5000 years

panied by marked textural differences. Drab mottles are most like microbial reduction (gleization) during early burial of remnant roots and other organic matter (Retallack 1991). The pattern of deeply penetrating, stout root traces and their gleization is compatible with a forested ecosystem of modest size with patchy and limited humus. Together with evidence for permafrost climate, discussed above, this supports a previous speculation (Retallack 1980) that these Late Permian forests were analogues of boreal taiga forests.

Comparable soils of northern Canada (map units Bx 1-1a, Bx 2-1b of FAO 1975) support boreal forest of white spruce (*Picea glauca*) and black spruce (*Picea mariana*), with white birch (*Betula papyrifera*), aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*). In Siberia (map units Bx1-1b, Bx1-2b of FAO 1978a) comparable soils support taiga forest of Dahurian larch (*Larix dahurica*), with Siberian pine (*Pinus sibirica*) and scrub alder (*Alnus fruticosa*). In both places trees are small (6–20 m tall) and well-spaced (Larsen 1989; Nikolov & Helmisaari 1992).

None of these living species extend back to Permian time. Glossopterid floras and palynofloras of the Tomago Coal Measures are of about the same Late Permian geological age as the Gerringong volcanic facies (stage 5a of Kemp *et al.* 1977), but these wetland habitats probably supported a very different flora than the well-drained Loveleigh and Harvey palaeosols. The distinctive chambered roots that characterise the swampland plants with leaves of *Glossopteris* are called *Vertebraria* (Retallack & Dilcher 1988). These are common in underclays to coal seams in the Tomago, Newcastle and Illawarra Coal Measures (Retallack 1980), but were not seen in either the Loveleigh or Harvey palaeosols. Instead the two types of root traces in these palaeosols are (1) fine (2 mm diameter) with copious lateral rootlets, and (2) stout (4 mm or more diameter) and woody with less regular, perpendicular laterals. Comparable root traces have been described from the German Lower Triassic Buntsandstein (Mader 1990), where they were attributed to equisetaleans (type 1) and conifers (type 2).

Both kinds of plants have been found in Upper Permian rocks of the Sydney Basin, and include *Walkomiella australis* (conifer) and *Phyllothea australis* (equisetalean). Nevertheless the stout woody root traces in Loveleigh and Harvey palaeosols show no distinctively conifer or equisetalean features, and could conceivably have been from a variety of plants. Equally likely parent plants for these fossil roots are rufforian cordaites (*Noeggerathiopsis hislopilii*), seed ferns (*Botrychiopsis ovata*) or early glossopterids (*Gangamopteris cyclopteroides*), which are common in Lower Permian periglacial facies of the Sydney Basin and elsewhere (Retallack 1980; McLoughlin & Drinnan 1996). *Gangamopteris* is so common in Lower Permian rocks that it can be taken as the most representative taxon of this ancient taiga (Retallack 1980). The exact nature of vegetation on well-drained permafrosted soils of the Gerringong volcanic facies may never be known, because such environments are not conducive to plant preservation (Retallack 1984). The reconstruction of this vegetation (Figure 6) shows a generalised plant formation, rather than a specific flora.

PERMIAN PALAEOCLIMATE

Palaeocontinental and palaeoclimatic reconstructions for the Permian remain controversial. Palaeomagnetic estimates for the palaeolatitude of the Sydney Basin during Late Permian time vary from 85° with the south pole in central New South Wales (Embleton 1984; Veevers *et al.* 1994b), to 57° with the pole in northern Victoria Land (Powell & Li 1994), and 65° with the pole in or near palinspastically restored terranes of New Zealand off the coast of Antarctica (Scotese & Denham 1988; Scotese & Langford 1995; A. G. Smith for Barrett 1991). Palaeoclimatic modelling and interpretation for the Permian in the Sydney Basin range from warm temperate–subtropical (Loughnan 1991) to cool–cold temperate (Kutzbach & Ziegler 1993) and frigid (Fawcett *et al.* 1994; Barron & Fawcett 1995). The supercontinent of Gondwana creates unreasonably harsh and seasonal Permian palaeoclimatic estimates in many computer models, incompatible with palaeobotanical and other evidence (Taylor *et al.* 1992). These problems of extreme continentality may have been mitigated by clouds or lakes (Yemane 1993) or elevated atmospheric levels of carbon dioxide which altered equator-to-pole temperature gradients (Barron & Fawcett 1995). Also potentially important are soil productivity factors, including soil carbon storage, relative primary/secondary productivity, high albedo and low soil moisture that may have been particularly anomalous in the past (Retallack 1997b). Neither lakes, nor elevated carbon dioxide, nor changed soil productivity are necessary to explain the palaeoclimate of the Gerringong volcanic facies, which from evidence presented here was frigid.

Palaeosols of the Gerringong volcanic facies now allow an unusually detailed view of the palaeoclimate of the early part of the Late Permian on the southeastern coast of the Gondwana supercontinent. They were permafrosted soils of a humid, frigid climate in the taiga forest life zone (Figure 6, Table 5). Such an interpretation is compatible with palaeocontinental reconstructions placing them at palaeolatitudes of 57–85°S. Thus for this part of the Permian the equator–pole temperature gradient, atmospheric levels of CO₂ and soil productivity factors were broadly comparable to those of today.

ACKNOWLEDGEMENTS

I thank J. J. Veevers, R. Morante, B. G. Jones and C. Herbert for useful discussion. Research was funded by NSF grant OPP9315228 and an ARC grant to J. J. Veevers.

REFERENCES

- ARDITTO P. A. 1985. Hummocky stratification as an environmental indicator in the Late Permian Shoalhaven Group. *Proceedings of the Symposium on Advances in the Sydney Basin* **19**, 33–36.
- ARDITTO P. A. 1991. A sequence stratigraphic analysis of the Late Permian succession in the Southern Coalfield, Sydney Basin, New South Wales. *Australian Journal of Earth Sciences* **38**, 125–137.
- BAKER J. C., BAI G. P., HAMILTON J. J., GOLDING S. D. & KEENE J. B. 1995. Continental-scale magmatic carbon dioxide seepage recorded by dawsonite in the Bowen–Gunnedah–Sydney Basin system, eastern Australia. *Journal of Sedimentary Research* **A65**, 522–530.

- BARRETT P. J. 1991. Antarctica and global climatic change: a geological perspective. In: Harris C. & Stonehouse B. eds. *Antarctica and Global Climate Change*, pp. 35–50. Scott Polar Institute and Belhaven Press, Cambridge.
- BARRON E. J. & FAWCETT P. J. 1995. The climate of Pangea: a review of climate model simulations of the Permian. In: Scholle P. A., Peryt T. M. & Ulmer-Scholle D. S. eds. *The Permian of Northern Pangea. Vol. 1. Paleogeography, Paleoclimates, Stratigraphy*, pp. 37–52. Springer-Verlag, Berlin.
- BESTLAND E. A., RETALLACK G. J., RICE A. E. & MINDSZENTY A. 1996. Late Eocene detrital laterites in central Oregon: mass balance geochemistry, depositional setting, and landscape evolution. *Bulletin of the Geological Society of America* **108**, 285–302.
- BIRKELAND P. W. 1984. *Soils and Geomorphology*. Oxford University Press, New York.
- BOCKHEIM J. G. & UGOLINI F. C. 1990. A review of pedogenic zonation in well-drained soils of the southern circumpolar region. *Quaternary Research* **43**, 47–66.
- BOWMAN H. N. 1970. Palaeoenvironment and revised nomenclature of the Upper Shoalhaven Group and Illawarra Coal Measures in the Wollongong–Kiama area, New South Wales. *Geological Survey of New South Wales Records* **12**, 163–182.
- BOWMAN H. N. 1980. Southern coalfield, Upper Shoalhaven Group and Illawarra Coal Measures. *Geological Survey of New South Wales Bulletin* **26**, 10–53.
- BRADLEY G. 1993. Evolution and hydrocarbon prospectivity of the offshore Sydney Basin—NSW/PS10. *Proceedings of the Petroleum Symposium of the Australian Petroleum Exploration Association*, 27–54.
- BRANAGAN D. 1983. The Sydney Basin and its vanished sequence. *Journal of the Geological Society of Australia* **30**, 75–84.
- BRIGGS D. J. C. 1991. Correlation charts for the Permian of the Sydney–Bowen Basin and New England Orogen. *Proceedings of the Symposium on Advances in the Study of the Sydney Basin, Newcastle* **25**, 30–37.
- BRIMHALL G. A., CHADWICK O. A., LEWIS C. J. *ET AL.* 1991. Deformational mass transport and invasive processes in soil evolution. *Science* **255**, 695–702.
- BULL S. W. & CAS R. A. F. 1989. Volcanic influences in a storm- and tide-dominated shallow marine depositional system: the Late Permian Broughton Formation, southern Sydney Basin, Kiama, N.S.W. *Australian Journal of Earth Sciences* **36**, 569–584.
- CARR P. F. 1983. A reappraisal of the stratigraphy of the upper Shoalhaven Group and lower Illawarra Coal Measures, southern Sydney Basin, New South Wales. *Proceedings of the Linnean Society of New South Wales* **106**, 287–297.
- CARR P. F., JONES B. G. & MIDDLETON R. G. 1989. Precursor and formation of glendonites, Sydney Basin. *Australian Mineralogist* **4**, 2–12.
- CAS R. A. F. & WRIGHT J. V. 1987. *Volcanic Successions, Modern and Ancient*. Allen & Unwin, London.
- CAUDILL M., DRIESE S. & MORA C. I. 1997. Physical compaction of vertic palaeosols: implications for burial diagenesis and palaeoprecipitation. *Sedimentology* **44**, 673–685.
- CONAGHAN P. J. 1984. Aapamire (string-bog) origin for stone-roll swarms and associated ‘fluvio-deltaic’ coals in the Late Permian Illawarra Coal Measures of the southern Sydney Basin: climatic, geomorphic and tectonic implications. *Geological Society of Australia Abstracts* **12**, 106–109.
- CONAGHAN P. J., SHAW S. E. & VEEVERS J. J. 1994. Sedimentary evidence of the Permian/Triassic global crisis induced by the Siberian hotspot. *Canadian Society of Petroleum Geologists Memoir* **17**, 785–795.
- CRAIG D. C. & LOUGHNAN F. C. 1964. Chemical and mineralogical transformations accompanying the weathering of basic volcanic rocks from New South Wales. *Australian Journal of Soil Research* **2**, 218–234.
- CRAWFORD E., HERBERT C., TAYLOR G., HELBY R., MORGAN P. & FERGUSON J. 1980. Diatremes of the Sydney Basin. *Geological Survey of New South Wales Bulletin* **26**, 294–323.
- DIESEL C. F. K. 1992. *Coal-bearing Depositional Systems*. Springer-Verlag, Berlin.
- EBERL D. D., SRODON J., KRALIK M., TAYLOR B. E. & PETERMAN Z. E. 1990. Ostwald ripening of clays and metamorphic minerals. *Science* **248**, 474–477.
- EMBLETON B. J. J. 1984. Continental palaeomagnetism. In: Veevers J. J.

- ed. *Phanerozoic Earth History of Australia* pp. 11–16. Clarendon Press, Oxford.
- FAIZ M. M. & HUTTON A. C. 1993. Two kilometres of post-Permian sediment—did it exist? *Proceedings of the Symposium on Advances in the Study of the Sydney Basin, Newcastle* **27**, 221–228.
- FAO 1974. *Soil Map of the World. Vol. I. Legend*. UNESCO, Paris.
- FAO 1975. *Soil Map of the World. Vol. II. North America*. UNESCO, Paris.
- FAO 1978a. *Soil Map of the World. Vol. VIII. North and central Asia*. UNESCO, Paris.
- FAO 1978b. *Soil Map of the World. Vol. IX. Australasia*. UNESCO, Paris.
- FAWCETT P. J., BARRON E. J., ROBISON V. D. & KATZ B. J. 1994. The climatic evolution of India and Australia from the late Permian to mid-Jurassic: comparison of climate model results with the geologic record. *Geological Society of America Special Paper* **288**, 139–157.
- FREY M. 1987. Very low grade metamorphism of clastic sedimentary rocks. In: Frey M. ed. *Low Temperature Metamorphism*, pp. 9–58. Blackie, Glasgow.
- GOSTIN V. E. & HERBERT C. 1973. Stratigraphy of the Upper Carboniferous and Lower Permian sequence, southern Sydney Basin. *Journal of the Geological Society of Australia* **20**, 49–70.
- HERBERT C. 1980a. Evidence for glaciation in the Sydney Basin and Tamworth Synclinal Zone. *Geological Survey of New South Wales Bulletin* **26**, 274–293.
- HERBERT C. 1980b. Wianamatta Group and Mittagong Formation. *Geological Survey of New South Wales Bulletin* **26**, 254–272.
- HERBERT C. 1995. Sequence stratigraphy of the Late Permian Coal Measures in the Sydney Basin. *Australian Journal of Earth Sciences* **42**, 391–405.
- ISELL R. F. 1993. A classification system for Australian soils (3rd approximation). *CSIRO Division of Soils Technical Report 2/1993* (unpubl.).
- JAQUET J. B., CARD G. W. & HARPER L. F. 1905. The geology of the Kiama–Jamberoo district. *Geological Survey of New South Wales Records* **8**, 1–66.
- JOPLIN G. A. 1963. Chemical analyses of Australian rocks. Part 1, Igneous and metamorphic. *Bureau of Mineral Resources Bulletin* **65**.
- JOPLIN G. A. 1964. *A Petrography of Australian Igneous Rocks*. Angus & Robertson, Sydney.
- KARTE J. 1983. Periglacial phenomena and their significance as climatic and edaphic indicators. *GeoJournal* **7**, 329–340.
- KEMP E. M., BALME B. E., HELBY R. J., KYLE R. A., PLAYFORD G. & PRICE P. L. 1977. Carboniferous and Permian palynostratigraphy in Australia and Antarctica. *BMR Journal of Australian Geology & Geophysics* **2**, 177–208.
- KUTZBACH J. E. & ZIEGLER A. M. 1993. Simulation of Late Permian climate and biomes with an atmosphere–ocean model: comparisons with observations. *Philosophical Transactions of the Royal Society of London* **B341**, 327–340.
- LARSEN J. A. 1989. *The Northern Forest Border in Canada and Alaska*. Springer-Verlag, New York.
- LOUGHNAN F. C. 1991. Permian climate of the Sydney Basin—cold or hot? *Journal of the Royal Society of New South Wales* **124**, 35–40.
- MADER D. 1990. *Paleoecology of the flora in the Buntsandstein and Keuper in the Triassic of middle Europe*. G. Fischer Verlag, Stuttgart (2 vols).
- MCLOUGHLIN S. M. & DRINNAN A. N. 1996. Anatomically preserved Permian *Noeggerathiopsis* leaves from east Antarctica. *Review of Palaeobotany and Palynology* **92**, 207–227.
- MENNING M. 1995. A numerical time scale for the Permian and Triassic periods: an integrated time analysis. In: Scholle P. A., Peryt T. M. & Ulmer-Scholle D. S. eds. *The Permian of Northern Pangea. Vol. 1. Paleogeography, Paleoclimates, Stratigraphy*, pp. 78–97. Springer, Berlin.
- MIDDLETON M. F. 1993. Thermo-tectonic influences on the Sydney Basin during the breakup of Gondwana. In: Findlay R. H., Banks M. R., Unrug R. & Veevers J. J. eds. *Gondwana Eight*, pp. 613–622. A. A. Balkema, Rotterdam.
- MÜLLER M. J. 1982. *Selected Climatic Data for a Global Set of Standard Stations for Vegetation Science*. Junk, The Hague.
- NIKOLOV N. & HELMISAARI H. 1992. Silvics of the circumpolar boreal forest tree species. In: Shugart H. H., Leemans R. & Bonan G. B. eds. *A Systems Analysis of the Global Boreal Forest*, pp. 13–84. Cambridge University Press, Cambridge.
- NORTHCOTE K. H. 1974. *A Factual Key for the Recognition of Australian Soils*. Rellim, Adelaide.
- PATON T. R. 1974. Origin and terminology for gilgai in Australia. *Geoderma* **11**, 221–242.
- PETERSON C. D. & MADIN I. P. 1997. Coseismic paleoquaternary evidence in the central Cascadia margin, U.S.A. *Oregon Geology* **59**, 51–74.
- PICKETT J. W. 1972. The ecology of worm populations in the Erins Vale Formation (Late Permian), southern Sydney Basin. *Journal of the Geological Society of Australia* **19**, 313–330.
- POTTER P. E. & PETTJOHN F. J. 1963. *Paleocurrents and Basin Analysis*. Springer-Verlag, Berlin.
- POWELL C. MCA. & LI Z-X. 1994. Reconstruction of the Panthalassan margin of Gondwanaland. In: Veevers J. J. & Powell C. MCA. eds. *Permian–Triassic Pangean basins along the Panthalassan margin of Gondwanaland*, pp. 5–9. *Geological Society of America Special Publication* **184**.
- RAAM A. 1968. Petrology and diagenesis of Broughton Sandstone (Permian), Kiama district, New South Wales. *Journal of Sedimentary Petrology* **38**, 319–331.
- RAAM A. 1969. Gerringong Volcanics. *Journal of the Geological Society of Australia* **16**, 366–368.
- READY C. D. & RETALLACK G. J. 1996. Chemical composition as a guide to paleoclimate of palaeosols. *Geological Society of America Abstracts* **27(6)**, A237.
- RETALLACK G. J. 1977. Triassic palaeosols in the upper Narrabeen Group of New South Wales. Part II. Classification and reconstruction. *Journal of the Geological Society of Australia* **24**, 19–35.
- RETALLACK G. J. 1980. Late Carboniferous to Middle Triassic megafossil floras from the Sydney Basin. *Geological Survey of New South Wales Bulletin* **26**, 383–430.
- RETALLACK G. J. 1984. Completeness of the rock and fossil record. *Paleobiology* **10**, 59–78.
- RETALLACK G. J. 1988. Field recognition of palaeosols. *Geological Society of America Special Paper* **216**, 1–20.
- RETALLACK G. J. 1990. *Soils of the Past*. Unwin-Hyman, London.
- RETALLACK G. J. 1991. Untangling the effects of burial alteration and ancient soil formation. *Annual Reviews of Earth and Planetary Sciences* **19**, 183–206.
- RETALLACK G. J. 1993. Classification of palaeosols: discussion and reply. *Geological Society of America Bulletin* **105**, 1635–1637.
- RETALLACK G. J. 1994. A pedotype approach to latest Cretaceous and earliest Tertiary palaeosols in eastern Montana. *Geological Society of America Bulletin* **106**, 1377–1397.
- RETALLACK G. J. 1997a. *A Colour Guide to Paleosols*. John Wiley & Sons, Chichester.
- RETALLACK G. J. 1997b. Palaeosols in the upper Narrabeen Group of New South Wales as evidence of Early Triassic palaeoenvironments without exact modern analogues. *Australian Journal of Earth Sciences* **44**, 185–201.
- RETALLACK G. J. 1999. Post-apocalyptic greenhouse paleoclimate revealed by earliest Triassic palaeosols in the Sydney Basin, Australia. *Geological Society of America Bulletin* **111**.
- RETALLACK G. J. & ALONSO-ZARZA A. 1998. Middle Triassic palaeosols and paleoclimate of Antarctica. *Journal of Sedimentary Research* **68**, 169–184.
- RETALLACK G. J. & DILCHER D. L. 1988. Reconstruction of selected seed ferns. *Annals of the Missouri Botanical Garden* **75**, 1010–1057.
- RETALLACK G. J. & MINDSZENTY A. 1994. Well preserved Late Precambrian palaeosols from northwest Scotland. *Journal of Sedimentary Research* **A64**, 264–281.
- RUNNEGAR B. 1980. Biostratigraphy of the Shoalhaven Group. *Geological Survey of New South Wales Bulletin* **26**, 376–382.
- SCOTESE C. R. & DENHAM C. R. 1988. *Terra Mobilis: Plate Tectonics for the Macintosh*. Earth in Motion Technologies, Austin, Texas.
- SCOTESE C. R. & LANGFORD R. P. 1995. Pangea and the paleogeography of the Permian. In: Scholle P. A., Peryt T. M. & Ulmer-Scholle D. S. eds. *The Permian of Northern Pangea. Vol. 1. Paleogeography, Paleoclimates, Stratigraphy*, pp. 1–19. Springer-Verlag, Berlin.
- SOIL SURVEY STAFF. 1997. *Keys to Soil Taxonomy*. Pocahontas Press, Blacksburg, Virginia.
- STACE H. C. T., HUBBLE G., BREWER R. ET AL. 1968. *A Handbook of Australian Soils*. Rellim Technical Publications, Adelaide.
- STROUD W. J. 1974. Hawkesbury Sandstone. In: Markham N. L. & Basden H. eds. *The Mineral Deposits of New South Wales*, pp. 499–500. Geological Survey of New South Wales, Sydney.

- STUTCHBURY R. 1989. The early Permian Pebble Beach Formation—deposition in a cold climate. *Proceedings of the Symposium on Advances in the Study of the Sydney Basin, Newcastle* **23**, 101–108.
- SUGGATE R. P. (Editor) 1978. *The Geology of New Zealand*. Government Printer, Wellington.
- TAYLOR E. L., TAYLOR T. N. & CUNEO R. 1992. The present is not the key to the past: a polar forest from the Permian of Antarctica. *Science* **257**, 1657–1677.
- TEDROW J. C. F. 1977. *Soils of the Polar Landscapes*. Rutgers University Press, New Brunswick, New Jersey.
- UREN R. 1974. Narrabeen Group. In: Markham N. L. & Basden H. eds. *The Mineral Deposits of New South Wales*, pp. 490–498. Geological Survey of New South Wales, Sydney.
- VAN VLIET-LANÖE B. 1985. Frost effects in soils. In: Boardman J. ed. *Soils and Quaternary Landscape Evolution*, pp. 117–158. John Wiley & Sons, Chichester.
- VAN VLIET-LANÖE B. 1991. Differential frost heave, load casting and convection: converging mechanisms: a discussion of the origin of cryoturbation. *Permafrost and Periglacial Processes* **2**, 123–139.
- VAN VLIET-LANÖE B., CLOUTARD J.-P. & PISSART A. 1984. Structures caused by repeated freezing and thawing in various loamy sediments: a comparison of active, fossil and experimental data. *Earth Surface Processes and Landforms* **9**, 553–565.
- VEEVERS J. J., CONAGHAN P. J., POWELL C. MCA., COWAN E. J., McDONNELL K. L. & SHAW S. E. 1994a. Eastern Australia. *Geological Society of America Memoir* **184**, 11–171.
- VEEVERS J. J., POWELL C. MCA., COLLINSON J. W. & LÓPEZ GAMUNDI O. R. 1994b. Synthesis. *Geological Society of America Memoir* **184**, 331–353.
- WALKER P. H., NICOLLS K. D. & GIBBONS F. R. 1983. South-eastern region and Tasmania. In: *Soils: an Australian Viewpoint*, pp. 241–250. CSIRO and Academic Press, Melbourne.
- WALTER H., HARNICKEL E. & MUELLER-DOMBOIS D. 1975. *Climate-diagram Maps*. Springer-Verlag, Berlin.
- WASHBURN A. L. 1980. *Geocryology*. Wiley, New York.
- WILLIAMS G. E. 1986. Precambrian permafrost horizons as indicators of paleoclimate. *Precambrian Research* **32**, 233–242.
- YAALON D. H. 1983. Climate, time and soil development. In: Wilding L. P., Smeck N. E. & Hall G. F. eds. *Pedogenesis and Soil Taxonomy. Vol. 1. Concepts and Interactions*, pp. 233–251. Elsevier, Amsterdam.
- YEMANE K. 1993. Contribution of a Late Permian palaeogeography in maintaining a temperate climate in Gondwana. *Nature* **361**, 51–54.

Received 8 September 1997; accepted 6 January 1998

SUPPLEMENTARY PAPERS

Appendix 1 Chemical analyses of palaeosols in the Gerringong volcanic facies.

Appendix 2 Bulk density (g.cm^{-3}) and point count data

(vol%) on the grain size and mineral composition of palaeosols in the Gerringong volcanic facies.