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Palaeosols in the upper Narrabeen Group of New South Wales as evidence of Early Triassic palaeoenvironments without exact modern analogues*

G. J. RETALLACK

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

Early Triassic palaeosols in the sea cliffs north of Sydney are evidence of a cool-temperate, seasonal, humid palaeoclimate. As is typical in such climates, the palaeosols include Ultisols, Inceptisols and Entisols. These ancient soils supported a variety of broadleaf, deciduous and needle-leaf forests, as well as oligotrophic heaths, coastal marshes and vegetation early in ecological succession to colonise disturbed ground. Their fauna of earthworms, crayfish, insects, amphibians and reptiles is now known from a variety of trace fossils. Although many of these palaeosols show evidence of waterlogging and include ganisters, sphaerosiderite and siderite nodules typical of coal measures palaeosols, no coal has been found in this sequence. Other palaeosols are strongly oxidised and were well-drained, and yet were copiously rooted and presumably densely forested. Thus, upland environments were well vegetated by Early Triassic time, if not earlier. The parent material of these ancient soils included fertile volcanic sands and oligotrophic quartz sands. Many of the palaeosols represent times for formation of only hundreds to thousands of years but some formed over tens to hundreds of thousands of years and represent times of very slow sediment accumulation. Several aspects of Early Triassic palaeosols can now be seen as peculiar compared with soils of today. None of the palaeosols are thought to have been Spodosols now common in humid-temperate regions, perhaps because strongly podsolising plants had not yet evolved. A global lack of coal, even in humid wetlands represented by these palaeosols, is an outstanding anomaly of the Early Triassic that has been called the 'coal gap'. The profound chemical weathering of some of these palaeosols is comparable to that of mid-latitude soils (24–38°), and is anomalous compared with soils now at the high latitudes (65–70°) postulated for the Sydney Basin during the Early Triassic. The coal gap and anomalous polar warmth may be legacies of the Permian-Triassic life crisis and ensuing CO_2 greenhouse.

Key words: Narrabeen Group, palaeoenvironment, palaeosol, Triassic.

INTRODUCTION

Twenty years ago I sent off for publication a long manuscript on palaeosols of the sea cliffs north of Sydney. It appeared as two papers (Retallack 1977a, b) that were the beginning of my research career in the relatively new field of palaeopedology. Much has happened since to refine and enlarge the conclusions of those two early papers (Retallack 1990). A good part of this paper enlarges upon their palaeoenvironmental interpretations, which remain little changed. However, one aspect of that early work has bothered me for some time: the classification of the palaeosols using a preliminary version of the US soil taxonomy (Soil Survey Staff 1960) that was soon supplanted with a definitive treatment not available in Australia at the time of writing (Soil Survey Staff 1975). The new classification required additional chemical and petrographic data on some of the palaeosols, presented here for the first time. It can now be established that Ultisols, Inceptisols and Entisols are indeed present, but not Spodosols. This has implications for understanding the fossil record of soils. There are also indications that Triassic soils differed in several ways from those of the modern world, for reasons that may be related to evolution of soils through geological time and unique events at the Permian–Triassic boundary.

GEOLOGIC SETTING AND METHODS

Sea cliffs dividing the popular surfing beaches between Pittwater and Sydney expose Triassic sediments of the Sydney Basin (Figure 1). The geological succession exposed from Long Reef north to Palm Beach includes Bulgo Sandstone, Bald Hill Claystone, Garie Formation and Newport Formation of the upper Narrabeen Group, overlain by plateau-forming Hawkesbury Sandstone (Table 1). The rocks are fossiliferous with fossil plants of the *Dicroidium zuberi* oppel zone (Retallack 1977c, 1980) and palynomorphs of the *Aratrisporites tenuispinosus* palynozone (Helby *et al.* 1987), which indicate a late Early to early Middle Triassic age.

Attention focused on comprehensive resampling of four palaeosols: the type Long Reef clay palaeosol (Retallack 1977b), the type Avalon silt loam palaeosol (Retallack 1977b), the Warriewood sandy loam palaeosol and Avalon loam palaeosol (both new, formerly

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*Tables 7 to 10 [indicated by an asterisk(*) in the text] are Supplementary Papers lodged with the National Library of Australia (Manuscript Section); copies may be obtained from the Business Manager, Geological Society of Australia.

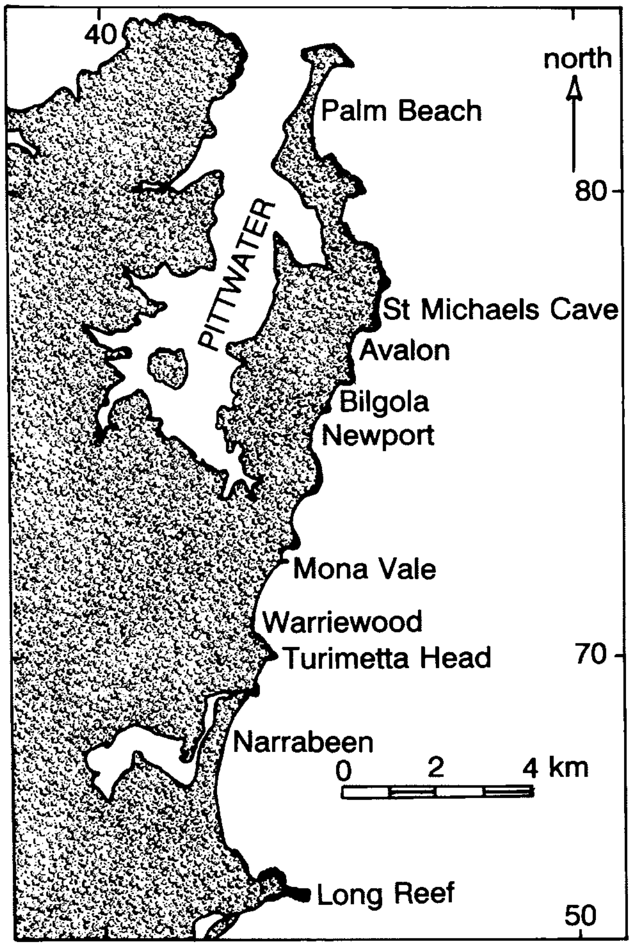

Figure 1 Location of palaeosols in the sea cliffs north of Sydney.

included in Avalon thick surface phase by Retallack 1977b). The profiles were characterised in the field (Figures 2–6; Tables 2–4) with observations on Munsell colour and reaction with dilute acid (following Retallack 1988). Thin-sections were prepared from representative samples and counted for 500 points using a Swift automatic point-counter to determine the distribution of sand, silt and clay (Table 7*) and constituent minerals (Table 8*). Bulk density was determined by the clod method using paraffin. Chemical analyses were determined using atomic absorption, ferric iron by ferrous ammonium sulfate titration, and loss on ignition at 600°C for 4 hours by Christine McBirney at the University of Oregon (Tables 9*, 10*). Organic carbon was determined using the Walkley-Black titration by Don Horneck at Oregon State University (Table 10*). Errors were estimated from 10 replicate analyses of standard rock W2 for atomic absorption analyses, from 50 replicates of a standard soil for the Walkley-Black titration and from 10 replicates of a palaeosol for bulk density (specimen R602 of Retallack 1994). An introduction to soil jargon useful for the study of palaeosols has been published elsewhere (Retallack 1990).

ALTERATION AFTER BURIAL

Palaeosols of the upper Narrabeen Group show clear evidence of three changes commonly altering soils shortly after burial: (i) overall depletion in organic matter: (ii) chemical reduction (gleisation) of oxides during decomposition of organic matter; and (iii) reddening of iron hydroxides by dehydration (Retallack 1991b). These are evident from unusually low organic carbon content, pervasive grey-green mottles around root traces and locally dark red colour (Figures 3–5; Retallack 1977a). Early burial gleisation also included widespread precipitation of siderite nodules and microspherulites (Retallack 1977a; Bai 1988) and local copper mineralisation (Dolanski 1975; Retallack 1977a). These various burial alterations have changed the appearance of what were formerly yellowish-brown to grey soils to the red-green mottled palaeosols of today.

The palaeosols have also been altered by moderately deep burial processes including illitisation, cementation and compaction. The maximum preserved sequence above the Bald Hill Claystone is about 685 m (cumulative from Conaghan 1980; Herbert 1980; Cowan 1993). A sequence of shales some 800 m thick above that, and ranging in geological age to Early Jurassic, can be reconstructed from the shape of erosionally dissected diatremes, and their content of sedimentary blocks with palynomorphs of sequences missing in outcrop (Crawford *et al.* 1980; Branagan 1983) and from vitrinite reflectance of coals and phytoclasts (Diessel 1975; Faiz & Hutton 1993). Both thermal modelling and oxygen isotopic studies of the upper Narrabeen Group indicate maximum burial depths of about 1.2 km and maximum temperatures of 150–160°C (Bai *et al.* 1990; Middleton 1993). Compaction of the palaeosols at this depth can be estimated at about 77% of former thickness using a formula of Sclater & Christie (1980):

$$C = -0.5/[\{0.49/e^{(D/3.7)}\}-1]$$

where C is compaction as a fraction and D is depth in km. Thus the type Long Reef clay palaeosol, now 47 cm thick (to the base of horizon Bt), would have originally been 61 cm thick. Also expected under such conditions of burial are quartz overgrowth cements, seen especially in ganisters of the palaeosols (Retallack 1977a) and also in associated sandstones (Bai 1988). Illitisation also would be expected (Eberl *et al.* 1990) and is quite far advanced with sharp illite peaks on XRD traces and little mixed-layer illite-smectite remaining (Retallack 1977a). In most cases potash is less than 1 wt%, with an anomalously high value of 3.39 due to detrital muscovite (Table 8*), so that bulk composition of the palaeosols was not greatly affected by illitisation. Lack of either muscovite or clay may explain the extremely low potash (Table 8*) and the anomalous soda/potash ratio of the Warriewood sandy loam palaeosol (Figure 3). Salinisation is another possibility, but unlikely considering the very low values of alkalis. Illitisation has, however, brightened the birefringence fabric of these palaeosols. As in other cases (Retallack & Krinsley 1993), this appears to have been a heightening of pre-existing pedogenic birefringent streaks.

Table 1 Stratigraphic summary for sea cliffs between Long Reef and Palm Beach near Sydney.

Rock units	Lithology	Thickness (m)
Hawkesbury Sandstone	Quartz sandstone	lower 213 only
Narrabeen Group		
Newport Formation	Shale and quartz-lithic sandstone	49
Garie Formation	Volcanic sandstone and clay-pellet conglomerate	8
Bald Hill Claystone	Red claystone	18
Bulgo Sandstone	Green volcanic sandstone	upper 2 only

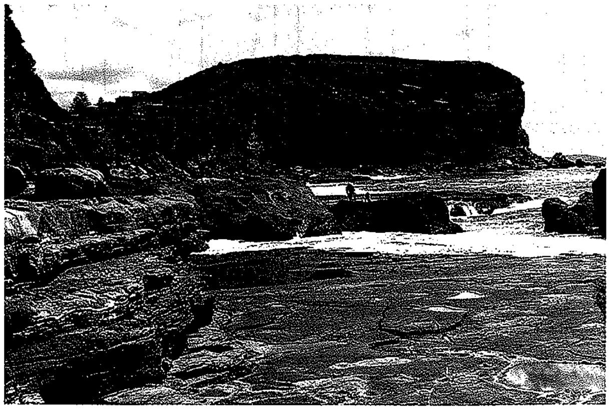

Figure 2 View of rock platform craters and furrows after stumps and logs (foreground) in the surface of the Warriewood sandy loam palaeosol south of St Michaels Cave, Avalon (grid reference 459772 on Mona Vale sheet 9130-I-S). Fisherman on outer platform gives scale.

CLASSIFICATION OF THE PALAEOSOLS

The US soil taxonomy (Soil Survey Staff 1975) made a break with tradition in defining the order Spodosol. Although this soil order includes most of the soils identified as podsols in traditional classifications (Stace *et al.* 1968), Spodosols are defined by the presence of a spodic horizon with subsurface enrichment of iron and aluminium oxides and organic matter (Soil Survey Staff 1975). This can easily be recognised from palaeosols by chemical analysis for iron. In thin-section the spodic horizon is distinctive because of the thick, radially cracked, laminated, opaque coatings to the grains (de Coninck *et al.* 1974; MacPhail 1983; de Coninck & McKeague 1985). Podsol on the other hand is Russian for 'under ash' and refers to the bleached sandy near-surface horizons commonly found in these soils, or albic horizon in the terminology of Soil Survey Staff (1975). Soils with spodic horizons commonly also have albic horizons, and albic soils commonly are also spodic. However, soils with spodic horizons developed in pure quartz sands may have a spodic without albic horizon. More stringent chemical criteria for the amounts of organic matter and iron needed to qualify as spodic (Soil Survey Staff 1975, 1990) has meant that many soils once regarded as podsols are not Spodosols, but Inceptisols. On the other hand, some soils with albic horizons over subsurface horizons that are clayey are better regarded as argillic rather than spodic. Such soils are called podsols or podsolic in traditional classifications (Stace *et al.* 1968) but are now called Alfisols or Ultisols, rather than Spodosols in the US taxonomy (Soil Survey Staff 1990).

Albic horizons of palaeosols are distinct enough to have attracted attention as white layers (Tarnocai *et al.* 1991) and ganisters (Retallack 1977a; Percival 1986; Leckie *et al.* 1989; Gibling & Rust 1992). Ganisters and white layers are unusually pure quartz sandstones commonly penetrated by fossil roots, with an abrupt upper and gradational lower boundary. The quartz-rich composition was created in albic horizons of soils by humid acidic leaching. In addition, phytoliths that accumulated in the soil may have been remobilised during burial to form the characteristic quartz cement of ganisters (Retallack 1977a).

Spodic horizons are equally obvious layers of quartz-rich sand strongly cemented by iron oxides, organic matter or both. Surprisingly few examples of these have been recognised in pre-Quaternary sedimentary rocks, for example in the Upper Eocene (Bartonian) Sables de Beauchamp and Formation d'Ezanville near Paris, France (Pomerol 1964) and the Lower Carboniferous (lower Visean) Cromhall Sandstone of Wales (Vanstone 1991). Sideritic mudstone layers, spherulites and nodules are commonly associated with ganister palaeosols (Retallack 1977a; Gibling & Rust 1982). These are called 'ironstones' and frequently have thick red oxidation rinds in outcrop. There is some question whether these were originally oxidised, but they also would not qualify as spodic horizons as defined by Soil Survey Staff (1990) because of their abundant clay and carbonate, which indicate more alkaline conditions than found in Spodosols.

Triassic palaeosols from north of Sydney certainly have ganisters well enough developed to be regarded as former albic horizons, but none have spodic horizons sufficiently clean of clay or strongly ferruginised to be regarded as Spodosols. The type Avalon silt loam and Avalon loam have thin albic horizons, but no evidence of a spodic horizon (Figures 3,4). Their subsurface horizon of siderite nodules is known to have been an original feature of the palaeosols because, among other lines of evidence (Retallack 1977a), sand-filled burrows sidle around the nodules (McDonnell 1974; Retallack 1990, figure 7.2). These nodules indicate alkaline pH incompatible with a spodic horizon. The Warriewood sandy loam palaeosol has more promise as a potential Spodosol because of its subsurface horizon of brown iron staining

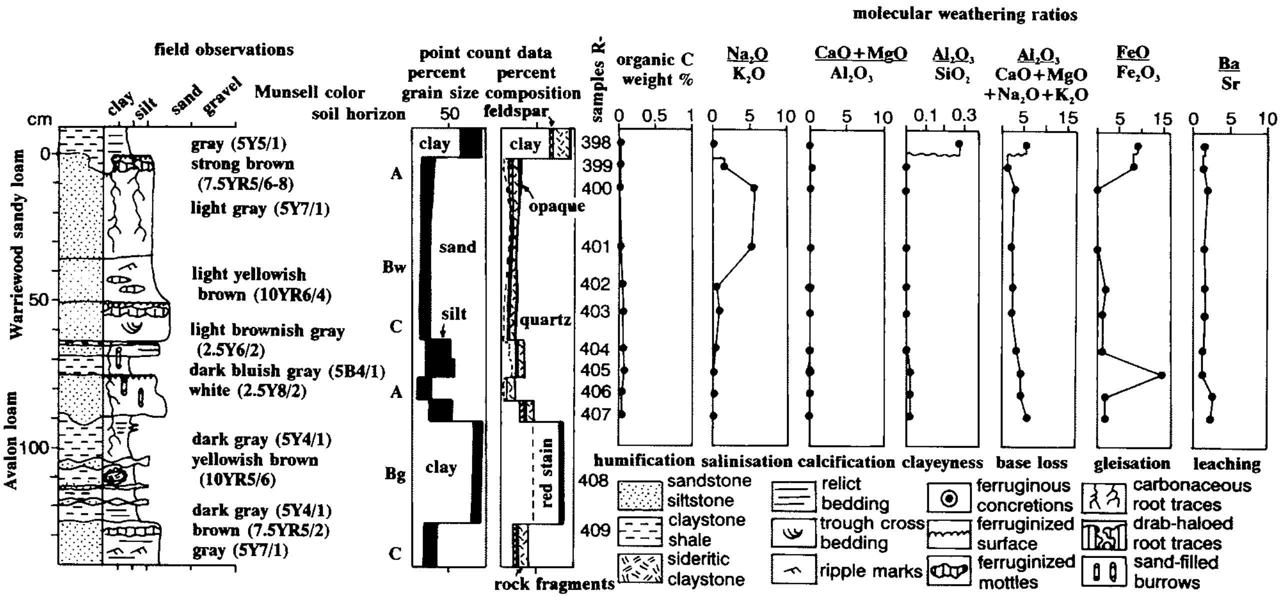

Figure 3 Measured section, Munsell colours, soil horizons, grainsize, mineral composition, organic matter and selected molecular weathering ratios of the Warriewood sandy loam and Avalon loam palaeosols from the rock platform 200 m south of St Michaels Cave, North Avalon (grid reference 459772 on Mona Vale sheet 9130-I-S).

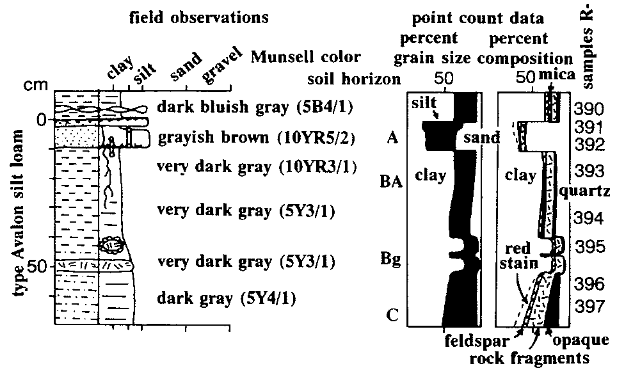

Figure 4 Measured section, Munsell colours, soil horizons, grainsize, and mineral composition of the type Avalon silt loam palaeosol from sea cliff 200 m south of St Michaels Cave, North Avalon (grid reference 459772 on Mona Vale sheet 9130-I-S). Lithological key as for Figure 3.

(Figure 3). However, in both thin-section (Figure 7) and geochemical analysis (Figure 3), this rock is too weakly ferruginised to qualify as a spodic horizon. All these Avalon and Warriewood palaeosols are better regarded as deeply-leached, low-fertility, weakly-developed soils of waterlogged lowlands, such as Quartzipsamments, Aquents or Dystrochrepts (Table 5).

The type Long Reef clay could be regarded as a Spodosol if the ferruginised lithic sandstones deep within the profile were spodic (Figure 5). However, these show much clay and relict bedding, incompatible with a spodic interpretation. Furthermore point counting (Figure 5) and petrographic analysis (Figure 8) reveal a clayey subsurface horizon including laminated clay skins formed by washing down into root holes and cracks (argillic or Bt in terminology of Soil Survey Staff 1975), that is more like that of an Alfisol or Ultisol than a Spodosol. Nevertheless this was a deeply leached acidic soil profile, as indicated by elevated alumina/bases and barium/ strontium ratios and negligible alkaline earth/alumina ratios. This pronounced alteration did not come entirely with parent material eroded from pre-existing soils, because these indices of weathering are significantly more marked in the upper parts of the profiles than in the lower parts. My computation of alumina/bases molecular ratios from subsurface (Bt) horizons of 130 soils of North America (analyses of Marbut 1935; Soil Survey Staff 1975) has shown that values between 2 and 31 correspond to the degree of weathering found in Ultisols, with lower values in Alfisols and values higher than 5 and into the hundreds for Oxisols. The type Long Reef clay differs from Oxisols anyway in its clear argillic horizon with illuviated clay skins (light coloured streaks of Figure 8). Despite significant values of alumina/bases (6–10) in the type Long Reef clay, its thickness (now 47 cm and before compaction probably 61 cm) is not remarkable, and suggests it was an Hapludult.

Even in the light of this new analytical information (Tables 2–4, 7*–10*), pedotype terms, such as Avalon and Long Reef palaeosols, have remained stable, which is why this field-based local descriptive scheme was used. In contrast, evolution of the US soil taxonomy (Soil Survey Staff 1960, 1975, 1990) and my understanding of its application to palaeosols (Retallack 1990), has led to extensive revision of its application to identification of palaeosols of the upper Narrabeen Group (Table 5). Application of such soil classifications to palaeosols is interpretive and is done to assess the meaning of

Table 2 Description of the Warriewood sandy loam palaeosol.

Depth (cm)	Horizon	Rock	Colour	Other features	Micromorphology	Basal contact
+ 22	–	Silty claystone	Grey (5Y5/1)	Relict bedding, non-calcareous	–	Abrupt to irregular
0	A	Fine-grained sandstone	Strong brown (7.5 YR5/6-5/8)	Large cradle knolls up to 45 cm across, root traces 5, 6, 9, 18 cm diameter, log impressions 9.5, 12.5 cm wide; non-calcareous	Unistrial insepic porphyroskelic, with relict bedding and ripple-drift cross-lamination	Gradual to irregular
–6	A	Fine-grained sandstone	Light grey (5Y7/1)	Massive with fine root traces; non-calcareous	Granular silasepic	Gradual to broken
–44	Bw	Fine-grained sandstone brown	Light yellowish (10YR6/4)	Discontinuous streaky sesquans concordant with bedding; non-calcareous; relict cross-bedding 13 cm thick	Granular silasepic with irregular intergranular sesquans	Abrupt to wavy
–64	A	Fine- grained sandstone	Light brownish grey (2.5Y6/2)	Carbonaceous root traces light brownish grey (2.5Y6/2); non-calcareous	Granular silasepic	Abrupt to wavy

Table 3 Description of the type Avalon silt loam palaeosol.

Depth (cm)	Horizon	Rock	Colour	Other features	Micromorphology	Contact
+ 20	–	Shale	Dark bluish grey (5B4/1)	Non-calcareous; prominent lamination, and one ripple train of fine-grained sandstone up to 2 cm thick	Unistrial argillasepic intertextic, with relict laminae and carbonaceous fragments	Abrupt to smooth
0	A	Fine-grained sandstone	Greyish brown (10YR5/2)	Common *Skolithus* isogranotubules, burrows and carbonaceous root traces; relict beds of grey (10YR4/1); non-calcareous	Granular silasepic	Abrupt to smooth
–10	BA	Silty claystone	Very dark grey (10YR3/1)	Common *Skolithus* metagranotubules and carbonaceous root traces; non-calcareous	Unistrial insepic agglomeroplasmic with granular silasepic metagranotubules	Clear to irregular
–40	Bg	Shale with siderite nodules	Very dark grey (5Y3/1)	Nodules ellipsoidal to elongate, 3–4 cm thick, with thick (5 mm) neosesquan on surface and penetrating septarian cracks; some relict bedding; weakly calcareous	Unistrial insepic agglomeroplasmic with nodules calciasepic porphyroskelic with thick isotic neosesquan	Clear to irregular
–55	C	Shale	Dark grey (5Y4/1)	Relict bedding; weakly calcareous	Unistrial insepic agglomeroplasmic, common relict laminae	Gradual to smooth

palaeosols within the context of all that is known about soils of today. Especially valuable in this regard is the classification of the Food and Agriculture Organisation of UNESCO (FAO 1974, 1975, 1978a, b), which can now be applied to palaeosols of the upper Narrabeen Group (Table 5). Acrisols of the Bald Hill Claystone and Garie Formation are similar to soils of humid eastern Australian coastal terraces from Gladstone in Queensland to Wollongong in New South Wales (map unit Ao 96-1/2b of FAO 1978b). A soil profile from near Kiama, New South Wales (Craig & Loughnan 1964) is chemically very similar to the Long Reef clay palaeosol but somewhat less deeply weathered. Comparable suites of soils also are found near Whangarei in the North Island of New Zealand (map unit Ao 98-3c of FAO 1978b), in northern Alabama, Georgia and South Carolina, USA (FAO 1975) and in

Table 4 Description of the type Long Reef clay palaeosol.

Depth (cm)	Horizon	Rock	Colour	Other features	Micromorphology	Contact
+ 25	–	Siltstone	Dark reddish brown (5YR3/2)	Sparse drab-haloed root traces greyish green (5G5/2) and slickensided sesquiargillans strong brown (7.5YR5/6); non-calcareous; relict bedding	Isotic to insepic agglomeroplasmic, relict laminae	Abrupt to irregular (especially around burrows)
0	A	Silty claystone	Light olive grey (5Y6/2)	Root traces olive (5Y5/3); blocky angular peds defined by slickensided sesquiargillans strong brown (7.5YR5/6); non-calcareous	Mosepic porphyroskelic with common laminated argillans and isotic nodules	Gradual to wavy
–12	Bt	Claystone	Dark olive grey (5Y3/2)	Common woody root traces of ground colour; scattered round to irregular mottles and sesquiargillans dusky red (2.5YR3/2), defining blocky subangular peds; non-calcareous	Clinobimasepic porphyroskelic with laminated argillans and isotic nodules	Gradual to wavy
–32	Bt	Clayey siltstone	Dark reddish brown (5YR3/2)	Abundant drab-haloed root traces greenish grey (5GY5/1); non-calcareous	Clinobimasepic agglomeroplasmic with laminated argillans in root channels and isotic nodules	Gradual to irregular
–47	BC	Clayey siltstone	Dark reddish brown (5YR3/2)	Common drab-haloed root traces as above; non-calcareous	Clinobimasepic to skelmosepic porphyroskelic, large areas isotic, with laminated argillans in root holes	Gradual to wavy
–74	BC	Clayey sandstone	Dark reddish brown (5YR3/2)	Sparse drab-haloed root traces as above; non-calcareous; common relict bedding	Unistrial mosepic agglomeroplasmic, isotic in areas, obscure relict bedding	Gradual to smooth
–90	C	Clayey sandstone	Dark reddish brown (5YR3/2)	Non-calcareous; massive to bedded	Unistrial insepic agglomeroplasmic, and isotic	Abrupt to wavy
–114	A	Silty claystone	Dark reddish brown (5YR3/3)	Common ferric concretions 1–2 cm diameter of ground colour; root traces and sesquiargillans also oxidised; non-calcareous	Unistrial insepic to isotic agglomeroplasmic, with common opaque concretions	Gradual to wavy

Korea and southern Japan (FAO 1978a). Sassafras soils of the eastern United States (Marbut 1935; Markewich *et al.* 1990) are similar to the type Long Reef clay, although better developed and on less clayey parent materials. It is more difficult to find soils and soilscapes analogous to the palaeosol association of the lower Newport Formation because Dystric Cambisols (map code Bd), Fluvisols (Jd) and Gleysols (Gd), are now widely associated with Histosols (O) and Podsols (P), which are conspicuously absent from the Newport Formation. Oligotrophic heathlands of the Myall Lakes region of New South Wales (map unit Ph 7-1 of FAO 1978b) and of southeastern Tasmania (Ph 11-1c) are landscapes with many similarities to that envisaged during deposition of the lower Newport Formation, but both include Histosols and Podsols not found in the Newport Formation. Oligotrophic humid landscapes lacking these soils are at high altitude and latitude in tectonically active landscapes unlike the coastal lagoonal environment envisaged for the Newport Formation: for example, in coastal terraces and hills of Westland, Southland and Otago provinces of New Zealand (map units Bd3-2c, Bd3-2bc, Bd54-1ab of FAO 1978b), in hill country of New York and Pennsylvania, USA (Bd3-abc, Bd3-2c, Bd23-2b, Bd20-2b, Bd20-2abc, Bd20-2a of FAO 1975), hilly Quebec and British Columbia, Canada (Bd3-1b, Bd3-2a of FAO 1975), Siberian riversides (Bd3-2ab, Bd36-1ab, Bd36-2b of FAO 1978a) and the Korean east coast (Bd3-2b of FAO 1978a). Although these comparisons may have some value for reconstructing former vegetation and climate, the soilscape represented by palaeosols of the Newport Formation lacks an exact modern analogue.

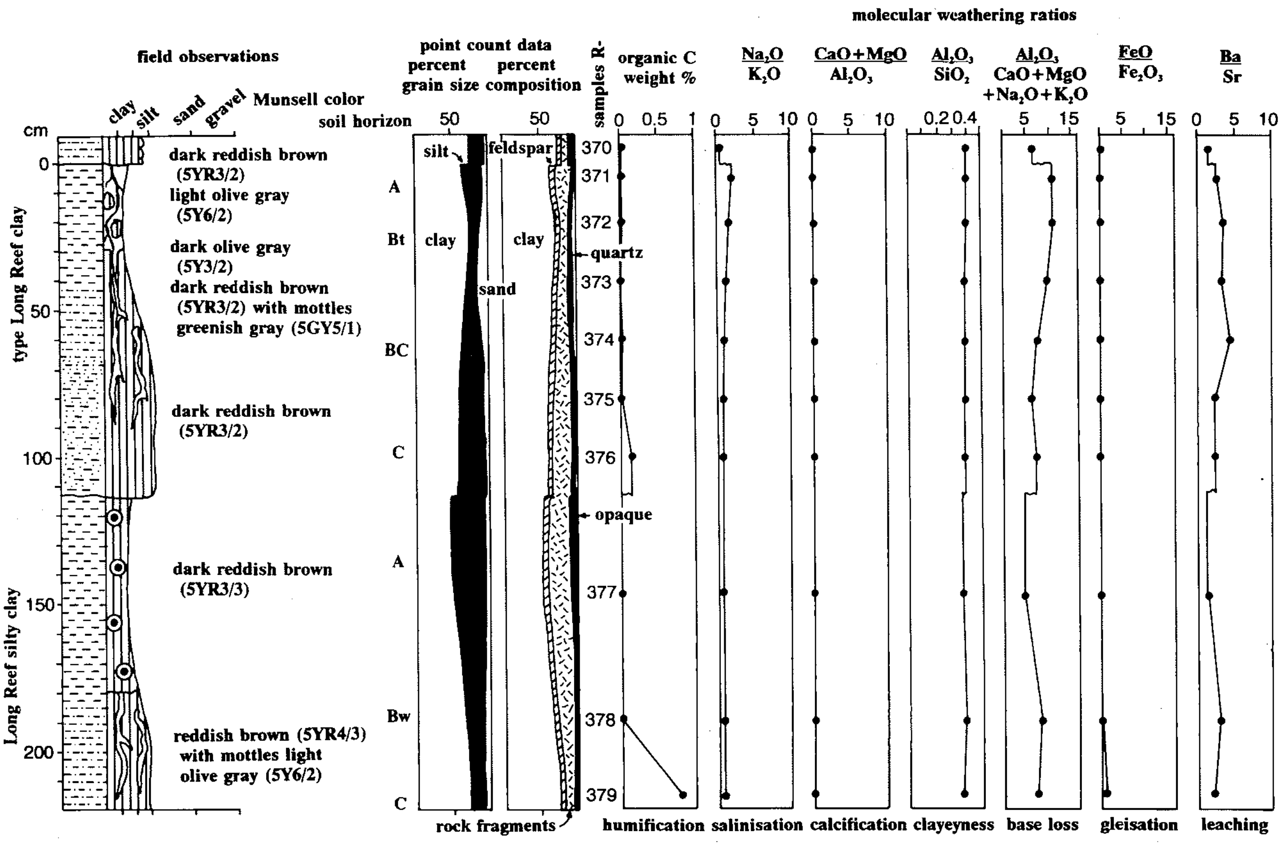

Figure 5 Measured section, Munsell colours, soil horizons, grainsize, mineral composition, organic matter and selected molecular weathering ratios of the type Long Reef clay palaeosol immediately above rock platform southwest of the point at Long Reef (grid reference 439649 on Mona Vale sheet 9130-I-S). Lithological key as for Figure 3.

PALAEOCLIMATIC IMPLICATIONS

Humid cool-temperate climate has been inferred from Early Triassic palaeosols of Queensland (Jensen 1975), New South Wales (Retallack 1977b) and Antarctica (Barrett & Fitzgerald 1986). Indications of a rainy climate come from the low content of alkalis and alkaline earths, both in absolute value and compared with parent materials represented best by the lowest horizons of the palaeosols (Figures 3–5, Table 9*). All the palaeosols are non-calcareous and thus pedalfers in the sense of Marbut (1935) indicating rainfall in excess of at least 600 mm (Yaalon 1983). The molecular ratio bases/alumina (B) of 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 equation on two Bt samples of the type Long Reef clay gives mean annual rainfall of 1233 and 1221 ± 174 mm and for the Bw horizon of the Warriewood sandy loam gives 889 and 984 ± 174 mm; roughly 1050–1400 mm for the Long Reef clay at the base of the Bald Hill Claystone and 700–1150 mm for the Warriewood sandy loam within the Newport Formation. This kind of difference between the two stratigraphic levels is compatible with the abundance of pedogenic siderite in the Newport Formation, indicating alkaline groundwater, whereas siderite is missing from gleyed palaeosols and root traces in the underlying Bald Hill Claystone.

There also is evidence of climatic seasonality in palaeosols of the Newport Formation and Bald Hill Claystone. Concentrically zoned ferruginous concretions indicate conditions of wet chemically reducing conditions for transportation of iron alternating with dry oxidising conditions (Retallack 1977a). Concentric banding can also be seen in clay skins within root channels of the type Long Reef clay palaeosol (Figure 8), where illuviated silt layers resemble those formed around root channels during spring thaw of snow-covered soils (van Vliet-Lanoë 1985). The silty layers alternate with laminae of clay, presumably filtered by summer vegetative cover and a reactivated rhizosphere. Varve-like graded bedding also was seen in thin-section of shales associated with the type Avalon silt loam, Avalon loam and Warriewood sandy loam palaeosols. These are evidence that seasonally snowy conditions persisted during deposition of the Bald Hill–Garie–Newport succession. Seasonality of the kind found in cool temperate climate is also supported by abscission scars on the petioles of the fossil

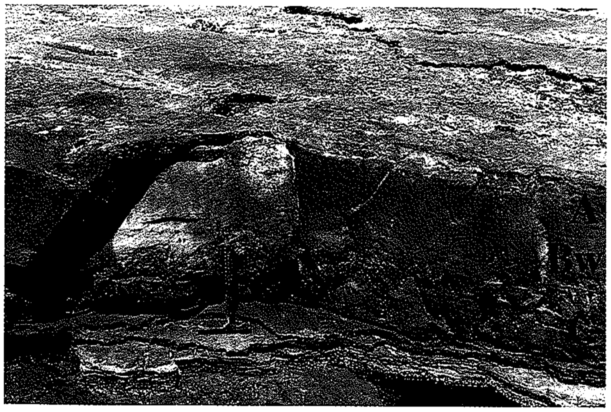

Figure 6 Warriewood sandy loam palaeosol, showing weakly ferruginised subsurface horizons and relict bedding in rock platform south of St Michaels Cave, Avalon. Interpreted soil horizons are labelled to the right. Hammer for scale.

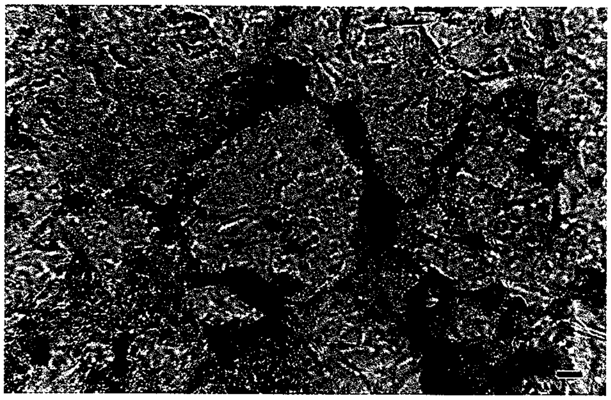

Figure 7 Photomicrograph of incomplete ferruginisation (dark grain-rimming stain) in subsurface (Bw) horizon (specimen R402) of Warriewood sandy loam palaeosol south of St Michaels Cave, Avalon. Scale bar (lower right) is 10 mm.

seed ferns *Dicroidium zuberi* indicating that they were deciduous (Figure 9), and pronounced growth rings in fossil wood of conifers (Baker 1931; Burges 1935).

All the palaeosols of the upper Narrabeen Group are thin compared with tropical soils, but better developed than soils of frigid climates. The palaeosols lack pedogenic calcite which is common in seasonally dry soils and palaeosols (Retallack 1991a). The siltans within clay skins are evidence that the hostile season was instead cool, and probably snowy. Ball-and-pillow structures and clastic dykes of the Newport Formation and tesselated pavements of the Bald Hill Claystone (Osborne 1948; Crook 1957) do not have any distinctive features of permafrost deformation (cf. Washburn 1980). The tessellated pavements are similar to patterns of jointing found in fragipans of North American forest soils (Soil Survey Staff 1990). Fragipans are avoided by roots, their cracks are filled with silty material and are often bleached, and in thin-section show angular grains and common cementing bridges (Payton 1983). None of these features were seen in Long Reef palaeosols, supporting instead interpretation that these are tectonic joints from unloading of deeply buried clayey horizons (Retallack 1977a). A cool temperate climate may explain distinctive features of fossil plant assemblages in the upper Narrabeen Group: relatively low diversity, especially of ginkgoes and cycadophytes, and dominance by *Dicroidium zuberi*, rather than *D. hughesi* characteristic of coeval vegetation in formerly subtropical parts of the Gondwana supercontinent (Retallack 1995c).

Despite all this evidence and agreement among many investigators that during the Early Triassic the Eopacific rim of the Gondwanan supercontinent had a humid cool temperate climate (Jensen 1975; Retallack 1976; Barrett & Fitzgerald 1986), there are still advocates of hot and seasonally dry Triassic palaeoclimate in this same region (Loughnan 1991). Calcareous red palaeosols of seasonally dry, monsoonal, subtropical climates of Early Triassic age are known, but they are in Germany (Ortlam 1971; Mader 1990; Weber 1993), which was at low palaeolatitudes at that time. A part of the trouble is the persistent myth that redbeds form in hot deserts (Russell 1928; Walker 1967), an idea that overlooks the abundance of laterites (McFarlane 1976) and red soils such as Oxisols and Ultisols in humid regions (Soil Survey Staff 1990). Indeed, the red centre of Australia (Ollier 1991) and Painted Desert of Arizona (Kraus & Middleton 1987) are coloured that way by palaeosols remaining from humid palaeoclimates of the past (Miocene and Triassic in age respectively). Soil formation in deserts is so sluggish that both soils and sediments remain close in colour and texture to their basement rocks, which is grey in many deserts of North America, the Middle East and central Asia (Birkeland 1984).

Another misconception is that redbeds are characteristic of the Early Triassic everywhere, just as in central Europe. Drab coloured palaeosols of the Wombarra Shale and Newport Formations of the Narrabeen Group of New South Wales have siderite nodules, sphaerosiderite and ganisters (Retallack 1977a, 1980) like palaeosols of Euramerican Carboniferous coal measures thought to have formed in humid climates (Percival 1986; Gibling & Rust 1992). There are also redbeds with palaeosols of Permian (Steel 1974; Loope 1988) and Middle to Late Triassic age (Hubert 1977; Kraus & Middleton 1987; Sereno *et al.* 1993). Redbeds and palaeosols form in both wet and dry climates where water-tables are low enough to allow oxidation (Retallack 1990) and redness can be enhanced by diagenetic dehydration of ferric hydroxides (Retallack 1991b). Such conditions were not limited to Early Triassic time.

A final misconception is that deeply weathered kaolinitic to bauxitic clays are restricted to tropical regions (Loughnan 1991). Extreme base-leaching of clays can occur in hydrothermal vents independent of climate (Rinehart 1980). In soils, it is more a reflection of abundant water and free drainage, and is aided by, but not dependent upon, warm temperatures (Birkeland 1984; Taylor *et al.* 1992).

Table 5 Identification of Triassic palaeosols of the upper Narrabeen Group.

Pedotype	Diagnosis	Old Australian (Stace *et al.* 1968)	New Australian (Isbell 1993)	Northcote key (Northcote 1974)	FAO Map (FAO 1974)	US taxonomy (Soil Survey Staff 1990)
Avalon	Silicified sandstone surface over shale with siderite nodules	Gleyed Podsolic	Stratic Rudosol	Dd3.41	Dystric Fluvisol	Fluvaquent
Long Reef	Grey silty claystone surface with mottled contact to red clayey subsurface	Grey-Brown Podsolic	Brown Kurosol	Dr5.11	Orthic Acrisol	Hapludult
South Head	Grey claystone with root traces and sphaerosiderite	Grey Clay	Chernic Tenosol	Uf6.13	Dystric Gleysol	Haplaquept
St Michaels	Yellow to orange claystone with root traces	Gleyed Podsolic	Orthic Tenosol	Gn3.41	Gleyic Cambisol	Dystrochrept
Turimetta	Carbonaceous shale surface, over green-grey claystone with red subsurface mottles	Humic Gley	Redoxic Hydrosol	Uf6.62	Humic Gleysol	Humaquept
Warriewood	Bedded sandstone with root traces	Siliceous Sand	Arenic Rudosol	Um1.21	Dystric Fluvisol	Quartzipsamment

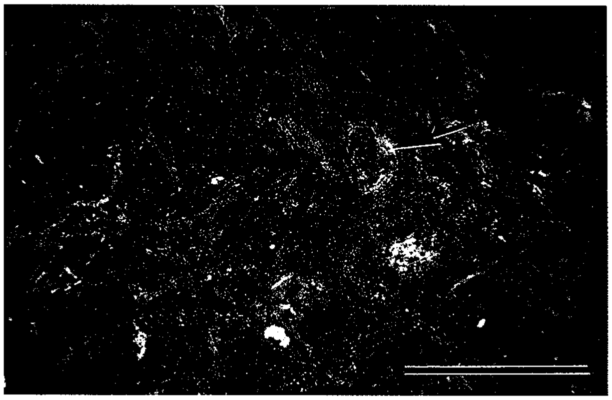

Figure 8 Photomicrograph of concentric fill of root hole (at arrow) and clinobimasepic porphyroskelic plasmic fabric (scattered white streaks) in clayey subsurface (Bt) horizon (specimen R372) of the type Long Reef clay at Long Reef. Scale bar (lower right) is 1 mm.

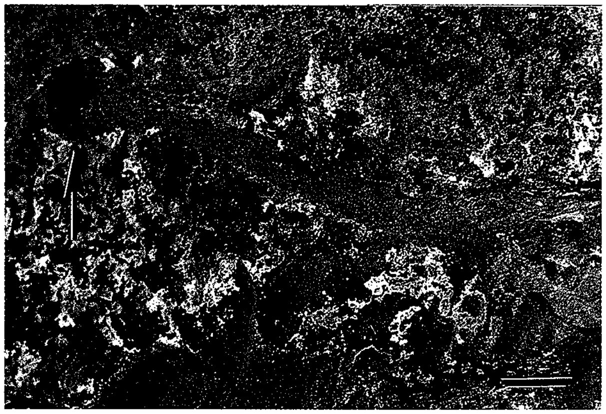

Figure 9 Callused abscission scar (arrow) at the base of the petiole of the fossil seed fern *Dicroidium zuberi* from the Newport Formation (University of New England specimen UNEF13927). Scale bar (lower right) is 1 cm.

Palaeoclimatic inferences from generalisations about rock colour and mineral composition have not fared well. They have been re-assessed here within the context of the whole suite of pedogenic characteristics of palaeosols. Detailed studies of palaeosols such as those reported here are showing that there was considerable regional variation in climate and soils during Triassic time.

FORMER VEGETATION

The large, clay-filled, drab-haloed root traces and clear subsurface horizon of clay accumulation (Bt) of the Long Reef clay palaeosols are evidence of forest vegetation. Comparable modern soils support oligotrophic forest (Retallack 1977a; FAO 1975, 1978a, b). Woody vegetation also is in evidence for the type Avalon silt loam from carbonaceous woody root traces, but no tree-sized roots or logs were seen there, and the reconstructed shallow water-table indicated by horizons of siderite nodules, would have restricted plant growth. Vegetation of these soils would have been comparable to coastal heaths of the Myall Lakes region of New South Wales (Retallack 1977). There is evidence for vegetation of greater stature, probably pole woodland, in the surface of the Warriewood sandy loam palaeosol. Radial stump impressions on this rock platform are up to 45 cm in diameter and include roots measured at 18, 9, 6 and 5 cm in diameter (Figure 2; Table 2). Fossil log impressions on this surface were measured at 9.5 and 12.5 cm in width, which equals the former diameter of the cylindrical trunk according to Walton's (1936) compaction theory. Vegetation of this palaeosol can be envisaged as a tree island or hammock within extensive lagoon-margin heathlands represented by more common Avalon palaeosols.

Many palaeosols of the upper Narrabeen Group preserve fossil leaf litters as evidence of the floristic composition of their original vegetation. From such evidence, volcaniclastic slopes of an eroding volcanic arc to the east were forested by conifers such as *Voltziopsis angusta* in well-drained Long Reef palaeosols, but by a mixed forest of conifers with *Dicroidium zuberi* on Turimetta palaeosols of lagoon-marginal swamps (Retallack 1977b, figure 10). Quartzose sediments of lagoon margins supported marshes of *Cylostrobus sydneyensis* on Warriewood palaeosols. Deltaic flats of this northern quartzose terrain supported woody heath of *Dicroidium zuberi* on Avalon and St Michaels palaeosols, and levee-top scrub of *Taeniopteris lentriculiformis* on South Head palaeosols.

This palaeosol-based reconstruction of 20 years ago (Retallack 1975, 1977b) now needs little alteration. Cowan (1993) has questioned evidence for conifers in the Bald Hill Claystone, but they are common as megafossils in the upper Bald Hill Claystone and Garie Formation (Retallack 1981) and an outlier of the conifer-dominated *Protohaploxypinus samoilovichii* palynozone is clearly shown in the Bald Hill Claystone within cross-sections of the Narrabeen Group by Helby (1970, 1973). Nevertheless, two points need modification: the tree hammocks for some Warriewood palaeosols discussed above, and reinterpretation of the fossil lycopsid *Cylostrobus sydneyensis* as a plant of salt marsh, rather than mangal. Marine influence of these former lagoonal marshlands has been confirmed by discovery of fossil clams (Grant-Mackie *et al.* 1985) and trace fossils, including *Diplocraterion* (Naing 1993). Earlier dubious claims of fossil foraminifers, holothurian sclerites and coralline algae (Crespin 1938; Conolly 1969; Packham cited by Helby 1970) continue to be mentioned as evidence of marine influence in the Narrabeen Group (Herbert 1993b), but remain unsubstantiated by publication. My discussions with the authors and inspection of the sites have convinced me that they are all misinterpretations of ferruginised sphaerosiderite (discussed by Retallack 1977a), which can appear chambered in thin-section. Although *Cylostrobus sydneyensis* has stems up to 3 cm in diameter, permineralised plants comparable to *Cylostrobus* have little more woody tissue than herbaceous plants (Snigirevskaya & Srebrodolskaya 1986; Roselt 1992). It was thus a herbaceous salt marsh plant, rather than a mangrove. Because of its distinctive cones the name *Cylostrobus sydneyensis* is more appropriate for whole plants than *'Pleuromeia longicaulis'*.

In terms of modern vegetation biomes (Walter 1985), the fossil flora of the Bald Hill–Garie–Newport succession corresponds to the cool temperate humid forest zone. Soils comparable to the Long Reef clay palaeosol in North America (map unit Ao31-2ab of FAO 1975) support mixed forests of deciduous angiosperms such as hickory (*Carya*) and evergreen conifers such as pine (*Pinus*), with local bottomland swamps of bald cypress (*Taxodium*) and tupelo (*Nyssa*). Similarly in Korea and Japan (Ao84-2/3b of FAO 1978a) such soils support floristically diverse forest of deciduous angiosperms and evergreen conifers. In New Zealand, comparable soils (Ao98-3c of FAO 1978b) support mixed podocarp–hardwood forest. In Australia (Ao96-1/2b of FAO 1978b), they support heath and wet sclerophyll forest. These analogous modern soilscapes are found at latitudes of 24–30°, in contrast to the Early Triassic palaeolatitude of 85°S (Embleton 1984) to 65°S (Scotese & Denham 1988; Barrett 1991). There is less of an anomaly between the latitudes of 32–63° indicated by soils comparable to palaeosols in the Newport Formation (FAO 1975, 1978a), but these palaeosols are waterlogged, weakly developed and do not have exact modern analogues, so are relatively weak evidence for a palaeoclimatic anomaly. Palaeosols of the Bald Hill Claystone indicate more clearly the spread of cool temperate biome to palaeolatitudes of as high as 70°, which is a distinctive feature of Early Mesozoic palaeoclimates also inferred from fossil floras (Zeigler *et al.* 1993).

Long Reef palaeosols of the Bald Hill Claystone provide evidence for vegetation of upland environments, where they were oxidised above the water-table. They are strongly bioturbated and show clayey subsurface horizons similar to soils today formed under closed canopy forest vegetation. This evidence thus falsifies the view that upland environments were not vegetated until the advent of angiosperms (Beard 1989; Retallack 1991c). Palaeosols provide evidence of extensive upland forests by at least Late Carboniferous time (Retallack 1990, 1995b; Retallack & Germán-Heins 1994).

FORMER ANIMAL LIFE

Palaeosols of the upper Narrabeen Group are rich in trace fossils of a variety of soil animals. *Skolithus* burrows created by cicada-like root-feeding insects are abundant in Avalon palaeosols, and comparable trace fossils are widespread also in Early Triassic palaeosols of Antarctica (Fitzgerald & Barrett 1986; Miller & Collinson 1994). Siderite-lined burrows filled with faecal pellets in the Turimetta palaeosols at Bilgola remain the oldest fossil record of earthworms (Retallack 1977a), although there are rumours and some likelihood of Devonian examples and a body fossil very similar to an earthworm in Ordovician marine rocks (Morris *et al.* 1982). Vertebrate burrows attributed to lungfish or labyrinthodonts in Avalon palaeosols (Retallack 1977a) were more likely produced by therapsid reptiles, now represented by footprints in the Narrabeen Group (Naing 1993) and known to have been able to burrow since Permian time (Smith 1987). Thus there were a variety of animals in addition to fish and labyrinthodonts known as body fossils in shales and fluvial conglomerates of the Newport Formation and laterally equivalent Terrigal Formation (Retallack 1980).

A variety of burrows also has been found in Long Reef palaeosols of the Bald Hill Claystone (Figure 10). Although these redbeds have been interpreted as marine

(Conolly 1969; Naing 1993; Herbert 1993a, b) their diverse trace-fossil assemblage includes no definitively marine forms, and much evidence such as fossil root traces (Figures 8, 10) that they were soils. Some burrows in Long Reef palaeosols were the work of crayfish, which have been found fossilised within them (Naing 1993) and so are the oldest known examples of crayfish, earlier within the Triassic than examples recently described from the Chatham Group of North Carolina (Olsen 1977) and Chinle Formation of Arizona (Hasiotis & Mitchell 1989). Crayfish commonly burrow to the water table in floodplain soils today (Hasiotis & Bown 1992). Other burrows in Long Reef and Turimetta palaeosols of the Bald Hill Claystone and Garie Formation are shallow scrapes that may be the work of amphibians or reptiles, and narrow burrows like those of insects and worms (Naing 1993). The biology of palaeosols that can be inferred from their trace fossils is a promising direction for future research.

PALAEOTOPOGRAPHY

Long Reef and Turimetta palaeosols were oxidised and have deeply penetrating root traces indicating free drainage. Their volcanic sand parent materials indicate formation on a volcanic upland that was overwhelmed by coastal lagoons and quartzose alluvium from the west. The highly dissected ancient landscape of volcanic plugs originally inferred from palaeomagnetic data (Retallack 1977b) has now been confirmed with models of seismic data (Bradley 1993). Lagoon-margin bottomlands accumulated sediments onlapping the old volcanic edifice and included Avalon, Warriewood, St Michaels and South Head palaeosols, which are thin and have shallow horizons of siderite and common carbonaceous root traces and fossil leaf litters indicative of waterlogging. These conclusions (of Retallack 1977b) remain little altered by subsequent systematic studies of basin geometry and palaeocurrents (Cowan 1993).

Confirmation of marine influence for the carbonaceous lagoonal siltstones comes from a suite of trace fossils including *Diplocraterion* (Naing 1993). There is comparable evidence for another marine highstand from trace fossils including *Rhizocorallium* in grey siltstones and sandstones at stratigraphic levels high in the Newport Formation, above the palaeosols described here (Naing 1993). As already mentioned, the suite of trace fossils from the upper Bald Hill Claystone regarded as marine by Naing (1993) is here interpreted as a soil assemblage. Another trace fossil assemblage with *Helikospirichnus* (*'Glockeria'* and *'Subglockeria'* of Retallack 1977a), between those with *Diplocraterion* and *Rhizocorallium* is regarded here as aquatic, but not marine-influenced. Thus the Bald Hill Claystone to Newport Formation interval includes one major and a second minor marine incursion, not the four postulated by Naing (1993). Redbeds and palaeosols of the Bald Hill Claystone at Long Reef are highly oxidised and include numerous well-drained palaeosols (Figure 5). Palaeosols also are common in the Bald Hill Claystone in sea cliffs around Garie Beach south of Sydney. Palaeosols also dominate the stratigraphically equivalent Wentworth Falls Claystone on Nullo Mountain in Wollemi National Park and in Boggy Swamp, along the Putty road, both in the northwest Sydney Basin, as well as in the Camden Haven Claystone near Laurieton, New South Wales. These widespread red, oxidised palaeosols represent a time of the lowest local water-tables in the Sydney and Lorne Basins during the Early Triassic. There are other red palaeosols in the stratigraphically lower Patonga Claystone near Forresters Beach and in Murrays Run DDH1 drill core, and in the Stanwell Park Claystone near Coalcliff. These represent two additional periods of low base-level between the late Early Triassic Bald Hill Claystone (Helby 1973; Retallack 1977b) and the Permian–Triassic boundary (as currently dated by Claoué-Long *et al.* 1991; Renne & Basu 1991; Campbell *et al.* 1992; Morante *et al.* 1994; Renne *et al.* 1995; Retallack 1995a). Thus the Bald Hill Claystone and equivalent units can be correlated with deep erosional discontinuities below the Solling Folge of the German Buntsandstein, and the Patonga and Stanwell Park Claystones correspond to lesser discontinuities above the Detfurth and Volpreihausen Folge of this classic Early Triassic sequence (Aigner & Bachmann 1992). By this reasoning, the Garie and basal Newport Formation with *Diplocraterion* represent late Scythian marine transgression, and *Rhizocorallium* trace fossils of the upper Newport Formation represent an earliest Anisian transgression. This is a different sequence-stratigraphic correlation than that of Cowan (1993) and Naing (1993) who place the Anisian–Scythian boundary

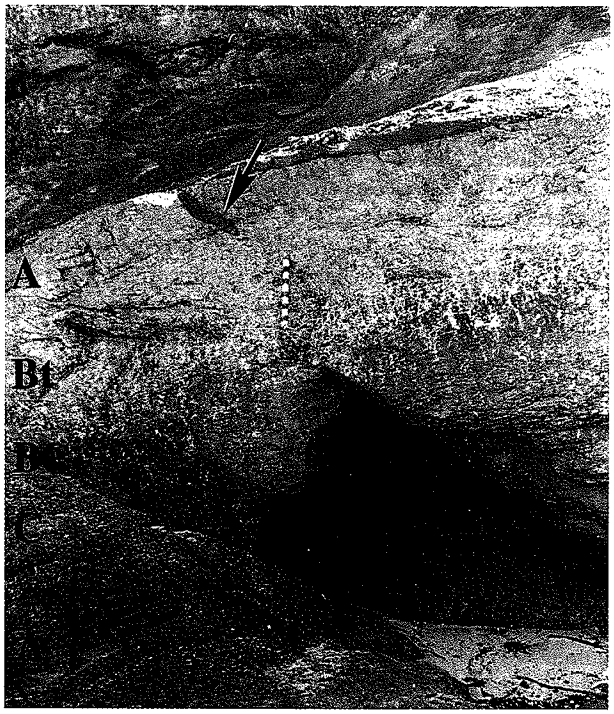

Figure 10 Shallow burrow (at arrow) in the surface of the type Long Reef clay palaeosol at Long Reef. Interpreted soil horizons are labelled at left. Scale graduated in inches.

at the base rather than high within the Newport Formation. By the correlation favoured here all the palaeosols described are late Scythian or latest Early Triassic in age.

PARENT MATERIALS

Palaeosols of the upper Narrabeen group formed on two distinctly different parent materials: (i) volcanic sands derived from an eroding volcanic upland to the east; and (ii) quartz sands and illitic mud derived from the craton to the west (Cowan 1993; Veevers *et al.* 1994). Quartz-rich sediments are poor in plant nutrients and prone to podsolisation by acid-generating plants rich in phenolic compounds, such as heathland shrubs and needle-leaf conifers (Fisher & Yam 1984). Palaeosols of the quartzose Newport Formation have remained sandy, but a similar humid climate created clayey palaeosols in the volcaniclastic Bald Hill Claystone and Garie Formation.

TIME FOR FORMATION

The time over which each palaeosol formed can be estimated from the degree to which pre-existing bedding was obliterated and from comparison with Quaternary soils of known age (Retallack 1990). Viewed in this way, palaeosols of the Newport Formation are very weakly developed (Warriewood and Avalon palaeosols) to weakly developed (St Michaels and South Head palaeosols), whereas those of the Bald Hill Claystone and Garie Formation are moderately developed (Long Reef and Turimetta palaeosols). Ultisols on till of humid (900–1050 mm mean annual precipitation), cool-temperate Ohio and Pennsylvania formed clayey subsurface (Bt) horizons comparable to those of the type Long Reef clay in about 40 000 years (Lessig 1961; Levine & Ciolkosc 1983). A variety of chronofunctions for comparable soils of the eastern United States (from Markewich *et al.* 1990) can be used to assess time-for-formation of the type Long Reef clay palaeosol as 22 000 years (using precompaction solum thickness of 61 cm), 47 000 years (using precompaction argillic horizon thickness of 45 cm), 56 000 years (using 17 $g.cm^{-2}$ clay accumulation with respect to parent material), 4000 years [using per cent, not molecular, ratio $(Fe_2O_3 + Al_2O_3)/SiO_2$ in Bt] and 200 000–500 000 years (using hue of 5YR). The last two estimates are unreasonable because of the felsic composition of the soils, different from the latitic parent volcanic sand of the palaeosols, and because of burial reddening of the palaeosols (Retallack 1977a, 1991b). Estimates of 20 000–60 000 years are reasonable. On the other hand, Inceptisols and Entisols like palaeosols of the Newport Formation represent only thousands to tens of years of soil formation (Walker & Butler 1983). Soils of humid Westland in the South Island of New Zealand have subsurface (Bw) horizons 58 cm thick and some ferruginisation after 18 000 years (Ross *et al.* 1977). This is development in excess of that for St Michaels palaeosols which may represent about 10 000 years. Elsewhere in Westland soils have subsurface (Bsg) horizons 42 cm thick after 1500 years (Smith & Lee 1984), and such a span of time for formation is reasonable for comparably developed Avalon palaeosols. Other palaeosols in the Newport Formation can be interpolated between and below these estimates down to only a few growing seasons for well bedded palaeosols such as the Warriewood pedotype.

These comparisons have implications for rate of sediment accumulation in the upper Narrabeen Group, because sedimentary events are temporally insignificant (days and weeks) compared with times for soil development (thousands to millions of years). The Bald Hill Claystone which is 18 m thick at Long Reef includes at least eight successive Ultisol palaeosols of comparable development to the type Long Reef clay, and these represent depositional hiatuses totalling as much as 480 000 years and long-term sediment accumulation rates of 0.04 $mm.y^{-1}$. In contrast the 15 m sequence of palaeosols in the Newport Formation north of Avalon, with nine palaeosols (Retallack 1977b), represents only about 33 200 years of soil formation for a long-term sediment accumulation rate of about 0.5 $mm.y^{-1}$. The Bald Hill Claystone north of Garie Beach, the Patonga Claystone at Wamberal Point and Wyrrabalong Head, and the Widdin Brook Conglomerate at Coxs Gap also include common moderately developed red palaeosols, whereas palaeosols of the Wombarra Shale near Coalcliff, the Bulgo Sandstone near Royal National Park, the Terrigal Formation near Terrigal and Avoca, and the Dooralong Shale in Frazer State Park are drab and weakly developed like those of the Newport Formation. Thus the redbeds or 'chocolate shales' of the Narrabeen Group represent more geological time than the grey shaly and quartzose sandy parts of the sequence.

PECULIARITIES OF THE EARLY TRIASSIC PEDOSPHERE

Comparison of Triassic palaeosols with soils of today was appropriate during initial studies because there was little else to compare. Similarly the first primitive land plants were initially compared with the specialised living fern *Psilotum* (Stewart & Rothwell 1989) and the first dinosaur teeth were compared with those of living iguanas (Benton 1990). There are now sufficient palaeosols known to suspect that some of these Triassic palaeosols were dinosaurs in the sense of soils that have no exact modern analogues. Early Triassic palaeosols certainly were not unique because of their red colour, as already discussed, but were peculiar for their weakly developed spodic horizons, lack of peat (that would become coal) and significant soil formation at very high palaeolatitudes.

Especially odd is the lack of spodic horizons in palaeosols of the upper Narrabeen Group. Spodosols are common under oligotrophic heath and conifer vegetation in humid cool-temperate climatic regions today, but the fossil record of Spodosols is very sparse indeed (Retallack 1990). Evidence of leaching, podsolising, acidic soil formation can be discerned from chemical data on Late Devonian palaeosols (Retallack 1985) and from fossil albic horizons (ganisters) in Carboniferous strata (Percival 1986; Gibling

& Rust 1992). However, only a single spodic horizon has been reported from Carboniferous strata (Vanstone 1991) and other examples are insufficiently ferruginised to qualify (Retallack 1990), as in the case of the Warriewood sandy loam described here. In Carboniferous strata there are also common palaeosols with an albic horizon over a subsurface horizon of siderite nodules (Retallack 1995b) like the type Avalon silt loam palaeosol. The Carboniferous siderites include well preserved stigmarian rootlets (Mader 1990) as indications that the nodules were part of the original soil. There is a geochemical conundrum here of acidic leaching of the surface in close proximity to alkaline groundwater. Siderite nodules are known in peats and underclays of modern swamps (Ho & Colman 1969) but I have been unable to find any modern example of a sandy surfaced soil with little litter and a shallow horizon of siderite nodules comparable to palaeosols of the Triassic (Retallack 1977b) or Carboniferous (Percival 1986; Mader 1990; Gibling & Rust 1992). One way out of this conundrum is to postulate less effective podsolisation then than now, perhaps because of less acidic phenolic compounds or less active chelating compounds produced by plants. Many of these podsolising compounds are known to be useful in deterring insect attack of plants, and their effectiveness may well have increased through time as they co-evolved with increasingly resistant insects (Swain & Cooper-Driver 1981). These distinctive sandy sideritic palaeosols may represent an early stage in the evolution of oligotrophic vegetation and soils.

No coal is found anywhere in the world in Early Triassic rocks (Retallack *et al.* 1996b), a profound anomaly comparable to the lack of Early Triassic corals and coral reefs (Flügel 1994). Lack of coal in the Narrabeen Group is especially puzzling because palaeosols of the Wombarra Shale and Newport Formation include such distinctive lithologies as ganisters, sphaerosiderite, siderite nodules and tonsteins (Retallack 1977a, 1980) that are common in Carboniferous coal measures (Percival 1986; Gibling & Rust 1992). As shown here, palaeosols of the Newport Formation formed in coastal bottomlands with high water-table in a humid palaeoclimate at high palaeolatitudes and presumably low evapotranspiration (Table 6). Such conditions encourage peat accumulation today (Moore & Bellamy 1974). Furthermore, the estimated rate of sediment accumulation for the Newport Formation of 0.5 mm.y^{-1} is within the range now favouring peat accumulation (Falini 1965; Retallack 1990). Palaeosols of the upper Narrabeen Group thus falsify explanations of the coal gap as due to low sea-level or arid climate. The role of plant extinction in the coal gap is indicated by the redefined Permian–Triassic boundary, coincident with the last coals and their distinctive glossopterids and ruflorian and voynovskyan cordaites in the Sydney Basin of Australia and Kutznetsk Basin of Siberia (Retallack 1995a) and the very different vegetation of coals when they reappear in the Middle Triassic (Retallack *et al.*, 1995b). Thus the Early Triassic pedosphere was peculiar in lacking peaty soils or Histosols, for the first time since their origin in the Devonian (Retallack 1990), probably because of extinction of peat-forming plants at the Permian–Triassic boundary.

Comparisons of Triassic palaeosols of the Bald Hill Claystone and Garie Formation are strongest with soils of North America, Japan, New Zealand and Australia currently at latitudes of 24–38°. However, palaeomagnetic estimates place the Sydney Basin at high palaeolatitudes during the Early Triassic, although specific estimates vary from 85°S with the pole in central New South Wales (Embleton 1984) to 65°S with the pole in terrains including New Zealand offshore from Antarctica (Scotese & Denham 1988; A. G. Smith cited by Barrett 1991). Ultisol palaeosols with mid-latitude affinities like those of the upper Narrabeen Group are also known from the lower Feather Conglomerate in southern Victoria Land (Barrett & Fitzgerald 1986; Retallack *et al.* 1995a), which was probably at a palaeolatitude of about 70°S (Embleton 1984; Scotese & Denham 1988; A. G. Smith cited by Barrett 1991). Following any of these estimates, palaeosols indicate a palaeoclimate during the Early Triassic warmer than today. Furthermore, this climatic warming set in abruptly at the Permian–Triassic boundary. Several latest Permian coals have floor rolls of sideritic claystone (Agrali 1987, 1990), interpreted by Conaghan *et al.* (1994) as evidence of string bogs (palsamires), which today form in Finland at latitudes of 68–70°N (Ruuhijärvi 1983). My own examination of these structures has convinced me that these are not fossil palsas, but mud-bottom flarks of another kind of string bog called aapamires, which form a distinctive peatland to the south in Finland at latitudes of 63–67°N (Ruuhijärvi 1983). The latest Permian palaeolatitude of the Sydney Basin was not appreciably different from that for the Early Triassic (Scotese & Denham 1988; A. G. Smith cited by Barrett 1991). Thus for the Late Permian, both palaeosols and palaeomagnetism indicate similar palaeolatitudes, but for the Early Triassic, palaeosols indicate much more warmth than palaeomagnetism. One explanation for this anomaly is a carbon dioxide greenhouse resulting from massive oxidation of organic carbon implied from dramatic isotopic lightening of $\delta^{13}C$ in organic matter at the Permian–Triassic boundary in the Sydney Basin and other marine and non-marine sequences throughout the world (Morante *et al.* 1994). The nature of the catastrophe ushering in this palaeoclimatic shift could have been massive volcanic eruptions (Conaghan *et al.* 1994) or bolide impact (Hsü & McKenzie 1990). Explanation of Early Triassic warm polar climates will remain controversial (Erwin 1994), but existence of this anomaly is becoming better established as palaeosols of Late Permian and Early Triassic age are studied in more detail.

From the perspective now provided by other palaeosols, those of the upper Narrabeen Group can be seen to be peculiar in some ways compared with soils today. As outlined above these peculiarities may be reflections of early stages in animal–plant chemical co-evolution of oligotrophic ecosystems, and of Permian–Triassic extinction of peat-forming plants and ensuing global greenhouse. Such a view of these palaeosols was not possible 20 years ago when they could only be compared with soils of today. Enough palaeosols are now known that the dinosaurs among them can be recognised. A history of soils on Earth can be recounted from the beginning, rather than reconstructed from its ending.

Table 6 Palaeoenvironmental interpretation of Triassic palaeosols of the upper Narrabeen Group.

Pedotype	Palaeoclimate	Former vegetation	Former animals	Palaeotopography	Parent material	Time for formation (years)
Avalon	Humid, seasonal, cool-temperate	Coastal heath dominated by *Dicroidium zuberi*	Burrows of cicada-like insects	Lagoon-margin lowlands	Quartzose alluvium	500–2000
Long Reef	Humid (1050–1400 mm mean annual precipitation), seasonal, cool-temperate	Conifer forest dominated by *Voltziopsis angusta*	Burrows of insects, crayfish, amphibians and reptiles	Toeslopes of old volcanic ridge	Volcaniclastic sands	20 000–60 000
South Head	Humid, seasonal, cool-temperate	Scrubby woodland dominated by *Taeniopteris lentriculiformis*	Burrows of insects	Levees of coastal streams	Quartzose alluvium	2000–5000
St Michaels	Humid, seasonal, cool temperate	Woodland	Burrows of insects	Coastal floodplain	Quartzose alluvium	5000–10 000
Turimetta	Seasonal	Swamp woodland with horsetails *(Neocalamites)*, conifers *(Voltziopsis angusta)* and seed ferns *(Dicroidium zuberi)*	Burrows of insects and earthworms	Swamps marginal to coastal lagoon	Volcaniclastic sands	5000–15 000
Warriewood	Humid (700–1150 mm mean annual precipitation)	Coastal heath and woodland dominated by *Dicroidium zuberi*; also local salt marsh of	Burrows of cicada-like insects and reptiles	Lagoon-margin coastal lowland	Quartzose alluvium	5–100

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