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Two New Approaches for Reconstructing Fossil Vegetation with Examples from the Triassic of Eastern Australia

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ABSTRACT

A system of classification used by modern phytosociologists can be readily applied to fossil plant associations. A distinctive association name is formed from the name of a characteristic plant in its reference collection. The three-dimensional shape of this fossil plant association can be mapped in rocks, and its range in time, its preferred sedimentary environments, soil types, and likely habit are then open to interpretation. Also, paleosols may be classified using modern soil mapping units. Reconstruction of paleosols often gives a detailed idea of the local physico-chemical environment and the phytogeography of fossil plant associations and some indication of basin topography, tectonics, and paleoclimate. As an example of these new approaches, I reconstruct the environment of the Triassic rocks exposed in the sea cliffs north of Sydney, Australia. Here, Voltziopsetum coniferous forest on grey-brown podzolic (ferrod) soils was succeeded by Dicroidietum zuberi swamp woodland on humic gley (fibrist) soils with a relative rise in water table, which also formed large coastal lagoons. These were reclaimed by lobate deltas, fringed with Pleuromeietum meadows around interdistributary bays, and supporting a Dicroidietum zuberi heath on gleyed podzolic (aquod and ochrept) and alluvial (aquent) soils. Higher within the sequence, grey clay (fluvent) soils of levees in the river floodplain supported a scrubby Taeniopteretum lentriculiformis. No paleosols have been found in the overlying sandstones deposited by braided streams, where the fossil flora is a moderately xerophytic Dicroidietum zuberi xylopterosum.

INTRODUCTION

A multidisciplinary approach is needed for the reconstruction of fossil vegetation. Such studies should consider sedimentary petrography and environments, paleocurrents, paleontology, palynology, and fossil soils as well as the mode of preservation, accumulation, associations, and systematic paleobotany of the fossil plant material. Two of these approaches, previously neglected, are of great value in giving a clear picture of ancient vegetation. These are ecostratigraphy and paleopedology. My preferred classification schemes for these relatively new stratigraphic categories are contrasted with those for other stratigraphic categories in Table 10-1.

ECOSTRATIGRAPHY

There are many approaches for classifying modern vegetation, for example, according to its physical structure, growth type, habitat, community ecology, internal layering or floristic composition (Whittaker, 1973). Of these approaches the classical system of Braun-Blanquet (1932) is still widely applied and most easily adapted for classifying fossil vegetation. According to this system, vegetation is classified into named associations, defined by their floristic composition.

Two schools of thought have run counter to the idea of recognizing and classifying associations. Some workers (such as Curtis and MacIntosh, 1951) observed that association boundaries may be so indistinct that they are impossible to map, and vegetation grades in a continuum from one type to another. Others (such as Johnson, 1972) maintained that "associations" are merely the accidental overlapping of various independent species ranges limited by different and complexly related parameters. Thus, each synecological situation is different and "associations" from different areas cannot be compared as if they were "quasi-organisms."

These objections have done little to undermine continued association analysis of modern vegetation. Fossil associations (Zeigler, et al., 1968) and paleobiogeographic provinces (Whittington and Hughes, 1972; Jell, 1974) have also been widely recognized. As a first order approximation of regional patterns, association analysis of fossil assemblages is most useful. Detailed ordination studies may show a different picture, but such studies are not always practical, particularly with megafossil plants. I believe that the naming, definition, classification, and interpretation of fossil associations should continue, although on a more standardized basis.

The naming system of phytosociologists can be used to derive unique and distinctive names for fossil associations and paleobiogeographic provinces. Association names are formed from the Latin name of a prominent species by addition of the suffix "-etum" to the stem of the genus name and, if more detailed distinction is necessary, by also adding the specific epithet in the genitive case (Braun-Blanquet, 1932). For example, the Dicroidietum odontopteroidium (unitalicized) is a fossil plant association characterized by *Dicroidium odontopteroides*. Associations can be subdivided into smaller units (synusiae) or classified within a hierarchy of larger units (alliances, orders, classes). The alliance (suffix "-ion") could be useful for naming paleobiogeographic provinces.

Fossil plant associations should be based on a type collection. Without such an objective basis, there can be no stability in association nomenclature. Thus, the fossil plant association is theoretically just such, rather than a reconstruction of past communities. It has the same relationship to a modern plant association as a fossil species to a living one or a paleosol to a soil. To express the concept of reconstructed ancient vegetation, I

Table 10.1
Units of various stratigraphic categories (partly after Hedberg, 1975).

Ecostratigraphy	Lithostratigraphy	Paleopedology
alliance	supergroup	association
association	group	series
synusia	subgroup	paleosol
	formation	variant/stage
	member	
	bed	

Geochronology	Chronostratigraphy	Biostratigraphy
eon	eonothem	biozones e.g. assemblage, range, acme, & interval zones.
era	erathem	
period	system	
epoch	series	
age	stage	
chron	chronozone	

have found it convenient to use the fossil association name, some indication of its likely habit, and the past tense. Such theoretically-loose usage is widespread in paleontology, but may prove unacceptable to some workers.

To facilitate further identification of the fossil association, the type collection should be as large and well preserved as possible. It should also be from a narrowly-defined locality, both geographically and stratigraphically.

Quantitative assessment of ecological parameters in fossil plant material is often impractical. Most sampling is non-statistical both in numbers and methodology, given the usual limitations of what can be recognized by the collector, losses during deposition and preservation and the restricted nature of many outcrops. For the purposes of regional ecostratigraphic work, the assessment of associations and their diagnostic species will probably remain largely a judgement of the collector.

Taphonomy is the study of the information lost in a fossil assemblage compared to the former living community from which it was derived. Krassilov (1975) coined a complex nomenclature for the various taphonomic modifications of fossil plant associations. All such interpretive studies should be independent of the naming and definition of fossil associations. Evidence from taphonomy, functional morphology, sedimentary environment, and paleosols are all critical to the interpretation of fossil plant associations. The distinctive differences between associations can often be explained in terms of environmental parameters. From my own studies of fossil plant associations (Retallack, 1977b, d), such parameters as water stress, proximity to the sea, and paleosol type seem to have been important for Triassic fossil plant associations of eastern Australasia.

Synusiae (subunits of associations) are difficult to interpret. In many Triassic plant localities, the abundant remains of pteridophytes, including filicaleans and equisetaleans, may outnumber those of the more constant seed plants. The fossil record of pteridophytes is probably exaggerated because, as in the modern world, they were more abundant near moist depositional environments. In this case, they are better regarded as synusiae of the seed plant association. Nevertheless, distinctive pteridophytic associations also exist, for example, the Pleuromeietum (discussed later).

PALEOPEDOLOGY

The study of fossil soils (paleosols) can give a detailed impression of the ancient biological, geochemical, and hydrologic microenvironment as well as clues to regional paleotopography, paleoclimate, and tectonics of sedimentary basins. Paleosols are often as distinct from each other as the plant associations that helped to form them. The combined study of paleosols and fossil plant associations can give a precise idea of the terrestrial paleoecology of an area. One of the more exciting aspects of additional interpretative paleosol studies is the prospect of documenting the evolution of world soils from abiotic, Precambrian weathered surfaces to the great array of modern soils. This promises to furnish new information on important events in the history of the earth's land surfaces: the evolution of atmosphere, the appearance of vascular land plants, the development of forests, the expansion of grasslands, and the impact of man.

Most modern classifications of soils (Stace et al., 1968; Buol et al., 1973) are highly interpretive. An objective naming system is needed for paleosols. For this purpose, the soil mapping units of the United States Department of Agriculture (Soil Survey Staff, 1951, 1962) are best for several reasons. The names are not interpretive and not dependent on modern soil classification whose criteria cannot always be applied to paleosols or be unequivocally distinguished from diagenetic modifications. A separate name can be given to any particular paleosol. The paleosols can be interpreted at several conceptual levels within the hierarchy of the classification. Finally, the units of classification are already defined and accepted by soil scientists.

By this system, a name is coined from a locality name and a textural term derived by point-counting the grain-size distribution in thin sections of the A horizon, for example, the Avalon silt loam (discussed later). Variants and stages can also be named if a more distinctive name is required. Individual paleosols can also be grouped into series and these into associations, both named after localities.

Because geologists usually do not have training in soil science, the greatest initial problem for paleopedology may be the recognition of paleosols and their relationship to enclosing sedimentary rocks. The most obvious and diagnostic feature of paleosols is evidence of fossil roots in place. There may also be leached or reddened, massive-looking, clay-rich layers; prismatic or blocky jointing; coaly layers; trace fossils; mottles; nodules; or concretions.

The following terms and concepts are useful in understanding the relationships of paleosols in sedimentary sequences. Relict features of a given paleosol are those not believed to have been caused by processes active in the formation of that particular paleosol. Pedorelicts are features formed by erosion and deposition of older paleosols or formed by preservation of parts of older paleosols within the profiles of younger ones. Sedimentary relicts are structures formed during the deposition of the parent material, and not obliterated during formation of the paleosol (Brewer, 1964). These are commonly ripple-drift cross-laminations and bedding. A pedolith is a bed of transported and deposited paleosol material showing sedimentary organization, but pedological mineralogy and clast microstructure (Gerasimov, 1971). Books by Brewer (1964) and Buol et al. (1973) are excellent guides to other, more usual, soil concepts and nomenclature.

The interpretation of paleosols is not easy. The micromorphological nomenclature of Brewer (1964), detailed field observations, point-counting of thin sections for grain-size distribution and X-ray diffraction studies are all helpful. The biggest problem is assessing pH, Eh, and cation exchange capacity of the former soil, data essential to parts of some modern soil classifications. These can only be inferred from soil structures commonly associated with particular geochemical environments or established by the tortuous process of establishing evidence (usually field or thin-section structures) for the original (non diagenetic) mineralogies. The former geochemistry can then be assessed from the mineral-stability fields provided by Krumbein and Garrels (1952) and Baas-Becking et al. (1960).

AN EXAMPLE FROM THE SYDNEY BASIN

As an example of these approaches to reconstructing ancient vegetation, consider this account of Triassic rocks in the sea cliffs between Long Reef and Palm Beach, 15 km north of Sydney, Australia (Figure 10-1).

STRATIGRAPHY

The Triassic rocks exposed in these sea cliffs are an almost flat-lying sequence with local dips of less than 1° to the west and north (Figure 10-2A). These are local anomalies to the regional dip of the Sydney Basin of which they are part. The outcrop pattern in the Pittwater area (Figure 10-1) is best understood as due to extensive erosion of a plateau capped by Hawkesbury Sandstone. Here, I only briefly characterize the formations and give their maximum exposed thicknesses for the Pittwater area. A more detailed treatment is given by Retallack (1973).

The Bulgo Sandstone (uppermost 1 m only exposed at Long Reef, 3 km south of the area mapped in Figure 10-1) is a grey-green volcanogenic sandstone. The Bald Hill Claystone (18 m) consists largely of red, kaolinitic claystone with minor grey-green lithic sandstone. The Garie Formation (7.6 m) is best mapped on the presence of grey-green volcanogenic sandstone, but also contains grey-green, kaolinitic claystone, and claystone breccia with minor, red-claystone intercalations. The Newport Formation (49 m) is a varied unit of polymictic pebble conglomerate, quartz-lithic sandstone, siltstone, and grey kaolinitic-illitic shale. The Hawkesbury Sandstone (255 m) is a glistening, quartz-lithic sandstone with relatively few shale interbeds. The base of the Hawkesbury Sandstone is best placed at the erosional base of the lowest sandstone channel deposit, which has some of the following features: oligomictic quartz-granule conglomerate, cross-sets 1.2

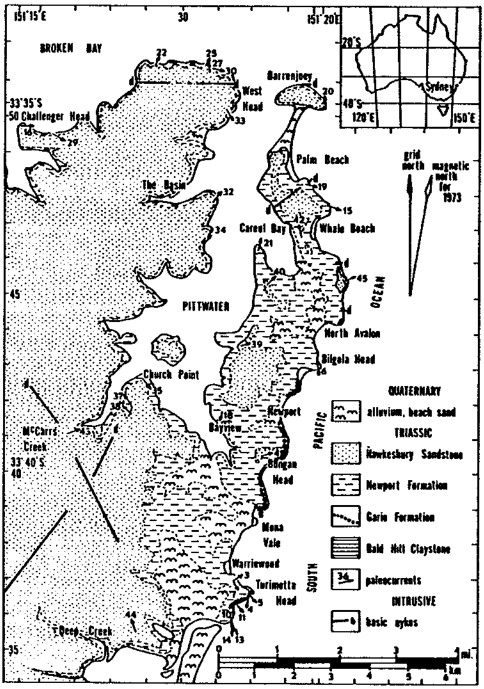


Figure 10-1
A geological interpretation map of the area around Pittwater, New South Wales. Grid after the 1:63,360 "Broken Bay" map sheet.

to 3.6 m thick, and extensive convolution of the top-and bottomsets.

SEDIMENTARY ENVIRONMENTS

The Bald Hill Claystone consists largely of paleosols. However, in the southeast wall of Long Reef (3 km south of the area mapped in Figure 10-1), there are thin sandstone beds and an epsilon cross-set. Similar cross-sets are also seen in plan in the uppermost Bulgo Sandstone in the rock platform at Long Reef as arcuate deposits of interbedded red claystone and grey-green lithic sandstone. Such structures, better exposed and understood in the Newport Formation (Figure 10-3), were probably levees of meandering streams.

Some channel sandstones are found within the Garie Formation at Turimetta Head and north of Mona Vale. Little internal cross-bedding has been preserved by the soft lithic grains. These sandstones are usually asymmetrically lenticular in cross section. The steeper side is probably the cut bank of the original stream, often associated with growth faults of minor displacement (for example, the channel in unit B at Turimetta Head, Figure 10-3). These features suggest that they were deposited by small meandering creeks. Some extensive beds of claystone breccia are also found in the Garie Formation at Turimetta Head. Like the distinctive, normally graded,

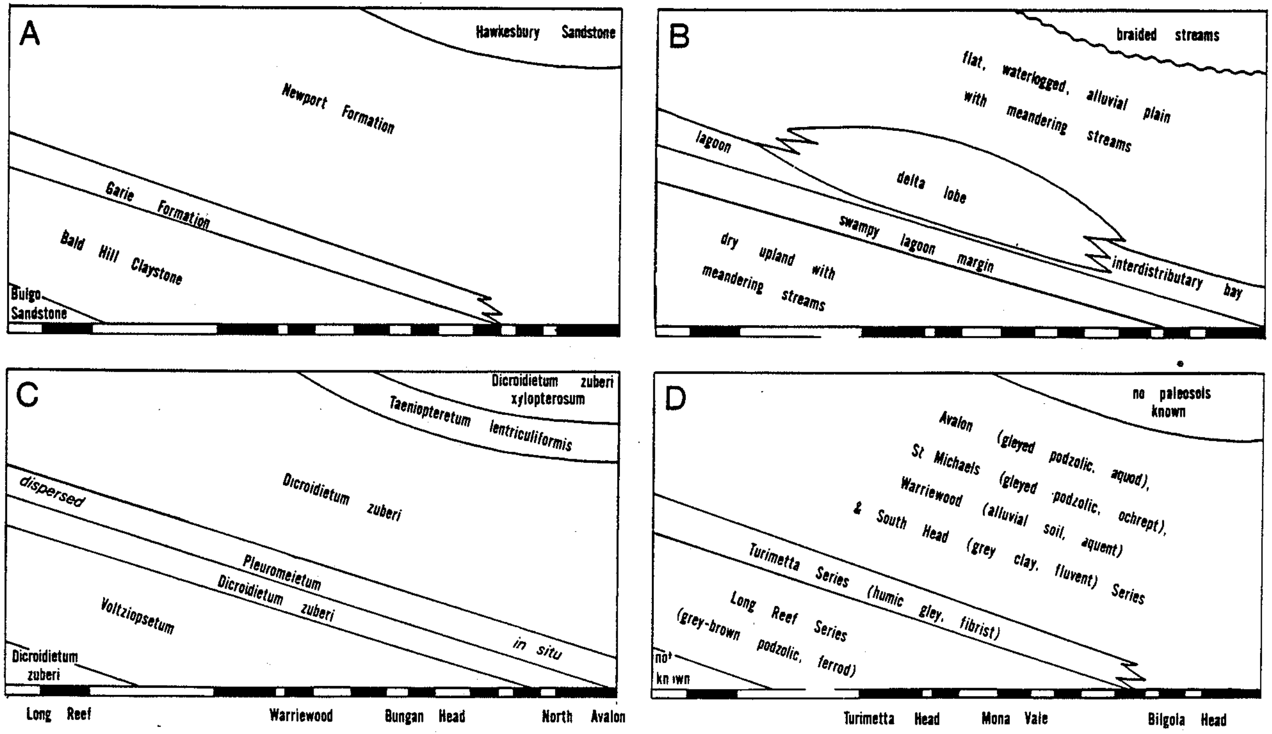


Figure 10-2
Stratigraphy (A), interpreted sedimentary environments (B), fossil plant associations (C), and paleosols (D) on a schematic geological cross section of the sea cliffs from Long Reef (3 km south of the area mapped in Figure 10-1) to Palm Beach. The shaded bar represents the length of the various sea-cliff exposures in this part of the coast.

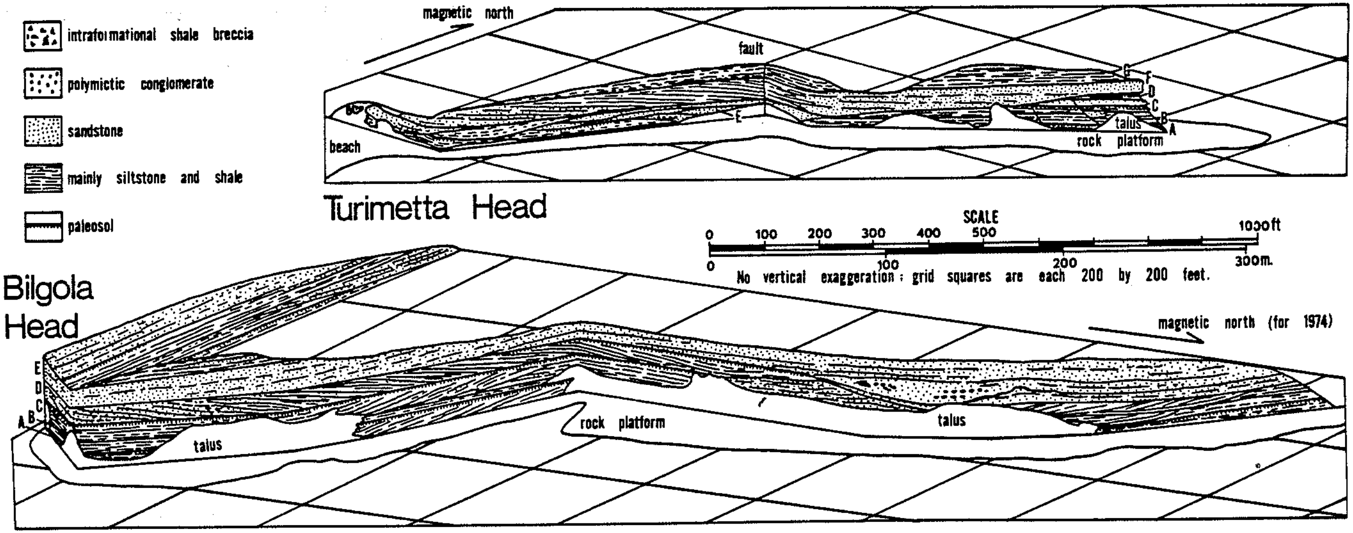


Figure 10-3
Three-dimensional geological sketch of the sea-cliff exposures at Turimetta Head (above) and Bilgola Head (below) showing the lateral transition from levee deposits (large epsilon cross-sets) into sandstone channel deposits (Turimetta Head unit F and Bilgola Head unit D) and into floodplain shale deposits (Bilgola Head unit C).

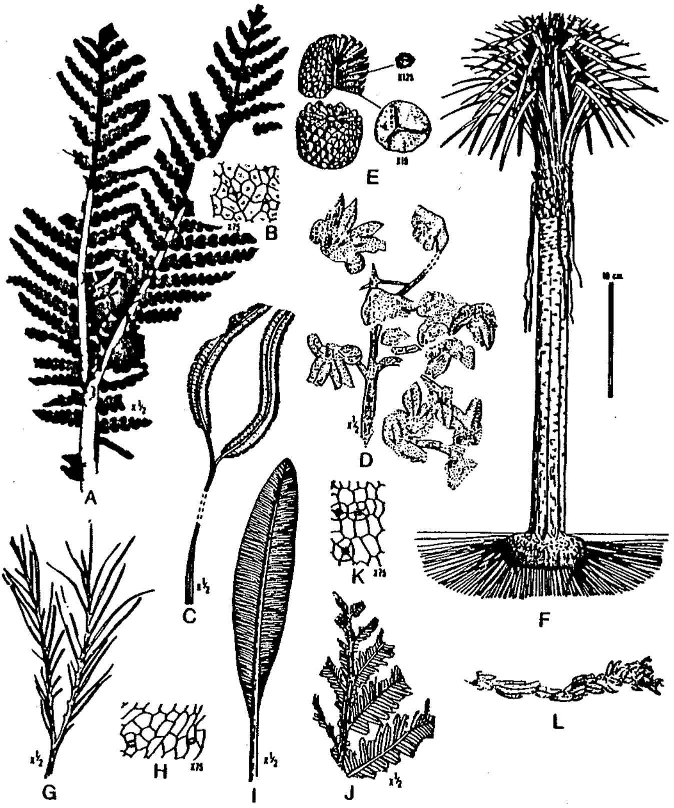
pelletal claystones of the Garie Formation on the south coast of New South Wales (Bunny and Herbert, 1971), these are interpreted as formed by pedolith beaches on a lagoonal shoreface.

The lower Newport Formation shows considerable variation from north to south (Figure 10-2B). At Turimetta Head (Figure 10-3), the outcrop is dominated by channel sandstones that become larger up-section. The shales associated with these channel sandstones contain a diverse *Dicroidium*-dominated flora. However, immediately above the redbeds (unit A at Turimetta Head, Figure 10-3) there is a distinctive unit (B) of evenly bedded, ripple-drift cross-laminated siltstone and shale that contains few plant fossils other than *Cylostrobus* cones (Figure 10-4E) and fragments of *Sigillariophyllum* leaves. Farther north, around Avalon, there are no channel sandstones at a similar stratigraphic horizon, but there is a succession of siltstone and shale interpreted as crevasse splay and floodplain deposits. Most of these contain a *Dicroidium*-dominated flora, but near the base of the section is a thin, poorly-differentiated paleosol overlain by a coaly band formed of abundant, in-place remains of *Pleuromeia longicaulis* (Figure 10-4F). As I have argued in more detail elsewhere (Retallack, 1975), *Pleuromeia-Cyclostrobus* lycopod fossils characterize a large lagoonal deposit formerly bounded to the north by interdistributary bays fringed with thickets of *Pleuromeia*, which scattered its supposed cones (*Cylostrobus*) and leaves (*Sigillariophyllum*) over a large area of the lagoon to the south. This lagoon was infilled by a delta (now exposed at Turimetta Head) similar to modern deltas of the Gippsland Lakes (Bird, 1962). Some authors (Bunny and Herbert, 1971) have argued that this Triassic lagoon was brackish or marine, but the balance of evidence (Retallack, 1975: 5) supports freshwater. This Triassic delta and lagoon have been loosely labelled the Gosford Delta and Narrabeen Lake (Conolly, 1969).

All of the fluvial depositional environments described by McDonnell (1974) from the partly stratigraphically equivalent Gosford Formation north of Broken Bay can also be recognized in the upper Newport Formation. Large outcrops of the Newport Formation (Figure 10-3) show a variety of structures mostly deposited by meandering streams. In-channel deposits consist largely of thick, trough cross-bedded sandstone units with basal lenses of polymictic, pebble conglomerate. Some channel sandstones have steep cut banks eroded into older sediments and associated intraformational shale breccia (Figure 10-3, Turimetta Head unit F, Bilgola Head unit E). Channel sandstones can also be traced laterally into complex units of finely interbedded sandstone, siltstone, and shale (Figure 10-3, Turimetta Head unit F, Bilgola Head unit D). These mixed units can be traced laterally into flat-lying floodplain shale capped by increasingly thick and differentiated paleosols toward the floodplain deposits (Figure 10-3, Bilgola Head unit C). The mixed units consist of interbedded sandstone, siltstone, and shale up to 10 m thick and cross-bedded at angles of 5 to 15° with the toe-sets bending to concordance with the base of the set. In plan, on the rock platform at Bilgola Head, these units appear to be composed of very large, intersecting trough cross-sets. Individual cross-strata may display linguoid or straight-crested, asymmetric ripple marks and occasionally pebbles or intraformational shale clasts. This structure is similar to that widely identified as epsilon cross-bedding (of Allen, 1963) by many authors (Allen and Friend, 1968;

Dodson, 1971; Leeder, 1973). In the Newport Formation, at least, they appear to be largely levee deposits formed of scroll bars (as discussed by Reineck and Singh, 1973), chutes (as defined by McGowan and Garner, 1970), flood-spillover deposits and crevasse splays (like those figured by Hatch et al., 1971). Other horizontally bedded shales and siltstones of the Newport Formation were probably deposited in distal crevasse splays, lakes, ponded floodwaters, and billabongs (oxbow lakes). These floodplain deposits can be differentiated by the various criteria discussed by McDonnell (1974).

From my own observations of the Hawkesbury Sandstone in the Pittwater area, I agree with the interpretation of its depositional environment presented by Conaghan and Jones (1975). From a consideration of flood cycles within the sandstone, these authors envisaged



deposition by a periodically flooding, braided stream of a size and stream power comparable to the modern Brahmaputra River of India.

PALEOCURRENTS AND PALEOTOPOGRAPHY

No paleocurrents could be obtained from the Garie Formation, Bald Hill Claystone, or Bulgo Sandstone in the Pittwater area. However, from the paleocurrents (Ward, 1972) and petrography (Culey, 1938) of these units on the coast south of Sydney, they were evidently derived from a volcanic ridge to the east. These volcanics were petrologically similar to the Permian Gerringong Volcanics on the south coast of New South Wales (Raam, 1969). Magnetic mapping (Ringis et al., 1970; Mayne et al., 1974) of the narrow continental shelf east of Sydney revealed a volcanic basement of considerable topographic relief. This is possibly a twenty-million-year-old buried Triassic landscape in the Permian volcanics (Retallack, 1977b). The present low position of these volcanics in the continental shelf, with respect to their presumed Triassic outwash in the coastal cliffs, may be explained by meridional faulting of the classic rift-margin type.

Trough cross-bedding is widespread in the Newport Formation and Hawkesbury Sandstone. Great care was taken to ensure that all measurements (Figure 10-5) were taken from a single sandstone channel. Direct measurement of the trough axes exposed in plan gave the most reliable paleocurrent readings, but this could also be approximated

Figure 10-4 (at left)
Common plant megafossils of the Pittwater area. A. *Dicroidium zuberi* var. *feistmantelii* (Johnston) Retallack (1977d); a relatively small frond for this species; x1/2; Geology Department, University of New England, Armidale, UNEF13955; from North Avalon (locality UNEL1383). B. Cuticle of *Dicroidium zuberi* var. *papillatum* (Townrow) Retallack 1977d; x75; after Townrow (1957, Figure 11A); from near Derby, Western Australia. C. "*Pterorrachis*" *barrealensis* Frenguelli, 1942, a pair of sporangial heads of the likely microsporophyll of *Dicroidium zuberi;* UNEF13903 from North Avalon (UNEL1385). A similar paired structure was observed by Townrow (1962) in the closely related species, *Pteruchus dubius*. D. *Umkomasia* sp.; dehisced cupules of the likely megasporophyll of *Dicroidium zuberi*; Mining Museum, Geological Survey of New South Wales, MMF17905; from the Newport Formation north of Sydney. E. *Cylostrobus sydneyensis* (Walkom) Helby and Martin 1965; x1; its microspore *Aratrisporites* (X125) and megaspore *Banksisporites* (X19); reconstruction drawn from Retallack (1975). F. *Pleuromeia longicaulis* (Burges) Retallack 1975; size in bar scale; reconstruction drawn from Retallack (1975). G. *Xylopteris elongata* var. *rigida* (Dun) Stipanicic and Bonetti (in Stipanicic, 1957); x12; Australian Museum, AMF18581; from Brookvale. H. Cuticle of *Xylopteris tripinnata* (Jones and de Jersey) Frenguelli, 1943; X75; AMF18590; from Brookvale. I. *Taeniopteris lentriculiformis* (Etheridge) Walkom 1917; X1/2; after Etheridge (1894); from Gosford. J. *Lepidopteris madagascariensis* Carpentier 1935; x1/2; UNEF13853; from Bungan Head (UNEL1417). K. Cuticle of *L. madagascariensis*; X75; UNEF13961; from Mona Vale (UNEL1418). L. *Voltziopsis angusta* (Walkom) Townrow, 1967; X1; after Townrow (1967); from Turimetta Head.

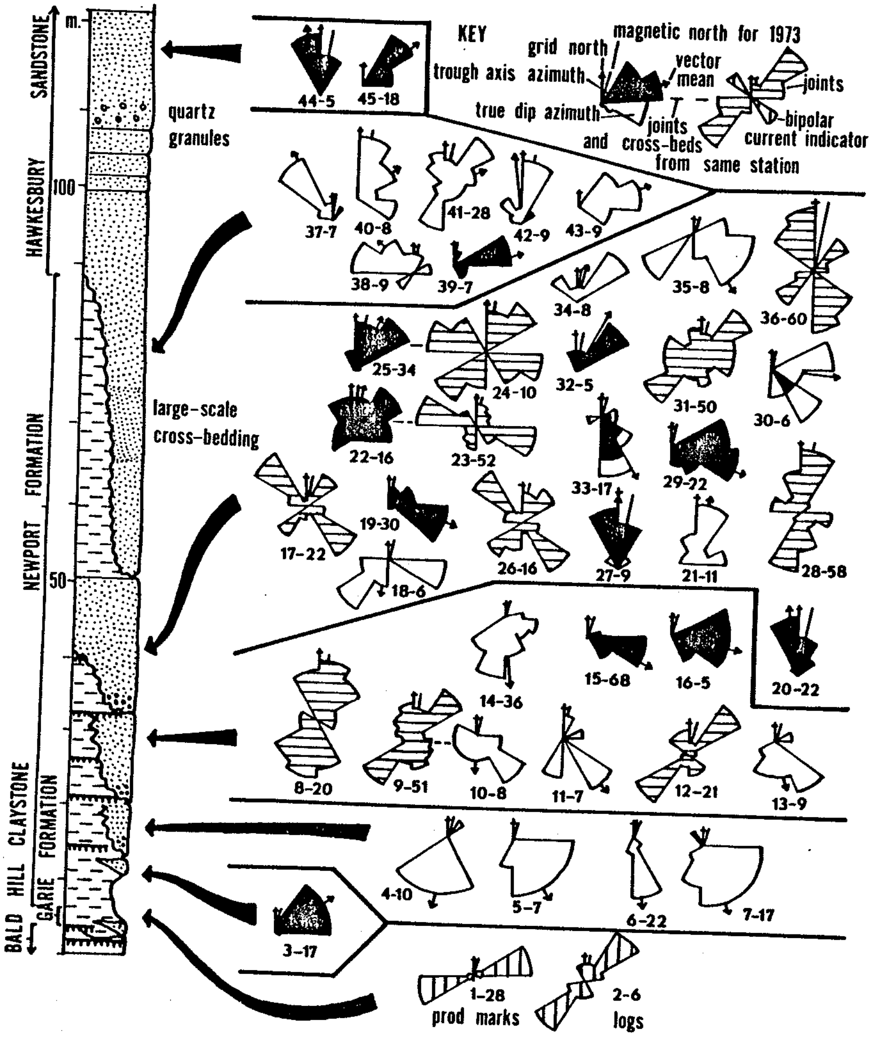


Figure 10-5
Paleocurrents from Triassic rocks in the Pittwater area. Current roses are plotted by 30° class intervals and labelled with a station number that is plotted in Figure 10-1. The number following the hyphen is the number of readings at each station. Lithological key as for Figure 10-3. Further details are given by Retallack (1973). The current rose for station 19 is replotted from that of Ward (1972).

by calculating the true dip of cross-strata from their apparent dip in two intersecting near-vertical faces exposing the same cross-set. I had hoped that the orientation of joints in the sandstones would show some relationship to the elongate axis of channel sandstone and thus to paleocurrent. However, there was no consistent relation

(Figure 10-5). Jointing is probably related to compaction also involving overlying sediments of different geometry.

Paleocurrents of the Newport Formation are largely from the northwest. There is considerable variation in the central deltaic portion of the formation. In some cases (Figure 10-5, stations 22, 25, 27 versus 30, 33 at West Head; stations 4, 5, 6, 7 versus 3 at Turimetta Head), these divergences may be due to distributary branching similar to the Head of Passes in the modern Mississippi Delta. These paleocurrents are in general agreement with findings from studies of pebbles and heavy mineral composition (Culey, 1938; Ward, 1972), indicating that the Newport Formation was derived from hilly terrain of varied geology to the north and west.

My paleocurrent measurements for the Hawkesbury Sandstone are similar to those of Standard (1969) who found a relatively consistent basin-wide direction towards the northeast. The channel sandstone marking the base of the Hawkesbury Sandstone in the Pittwater area forms a major erosional feature trending in the same direction. This channel feature is topographically lowest at Deep Creek and west of Barrenjoey and highest at Bungan and Challenger Heads. This evidence from paleocurrents and paleochannels is also supported by the heavy mineral composition of the sandstone (Standard, 1969), which indicates it was derived from a mixed granitic, metamorphic, and sedimentary sourceland of moderate relief to the southwest.

PALEOPEDOLOGY

The following discussion is a summary of the more interesting conclusions of my detailed studies on Pittwater paleosols (Retallack, 1977a, b, c). The type sections of the various paleosol series are shown in Figure 10-6 and their stratigraphic distribution in Figure 10-2D.

No paleosols can be seen in the small amount of Bulgo Sandstone exposed at Long Reef, but there are several well-preserved profiles at the base of the Bald Hill Claystone there. These Long Reef Series paleosols have a thin, surficial ferruginous layer, commonly with a polygonal cracking (A_1) horizon, overling about 30 cm of grey clay (A_{2cn}). This contains diffuse yellow and orange staining, slickensided lenticular soil peds, and ferric mottles and concretions. The grey clay passes down through a zone of vermicular grey mottles in red claystone (after plant roots, B_{1ir}) into completely red claysandstone (B_{2ir}). The sandstone grains are so soft, coated with clay and heavily oxidized that this may appear more like claystone than sandstone in hand specimen. These paleosols were probably grey-brown podzolic soils in the Australian classification (Stace et al., 1968), ferrods in the North American classification (Buol et al., 1973), and Uf2 in the Northcote (1974) Key. Modern soils of this type are usually well drained and forested. The erosion and redeposition of such paleosols in the upper Bald Hill Claystone appears to have been complex. However, the paleosols show a similar breakdown pattern of upper horizons after immersion in tapwater (slaking as discussed by Emerson, 1954) to that found in modern soils. From the weathering profile at Long Reef, as many as eight superimposed paleosols may form the Bald Hill Claystone there.

Within the Garie Formation, lowermost Newport Formation, and uppermost Bald Hill Claystone, two or three superimposed paleosols

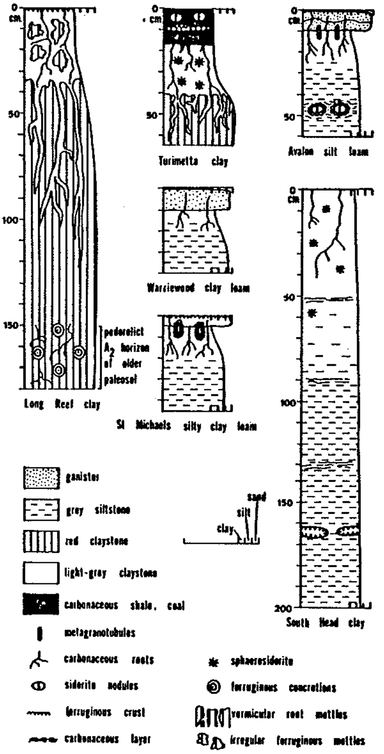


Figure 10-6
Type profiles of paleosols from the Pittwater area (adapted from Retallack, 1977b).

of the Turimetta Series crop out in most of the sea cliffs between Bilgola Head and Long Reef. These have a thick (about 20 cm) organic horizon of clay and fibrous fossil plant material (some of it identifiable) overlying about 15 cm of leached grey claystone (A_{2g}) which in turn overlies about 10 cm of red claystone ($B\&A_{gir}$) with a vermicular mottled contact. Each vermicular mottle is a reduced halo around a fossil plant root that is often preserved in the center. Other plant remains found within the profile include in-place stem bases of the equisetalean *Neocalamites* penetrating the uppermost grey clay and fragments of *Dicroidium zuberi* seeds and large logs in the organic horizon. Burrows, some remarkably like those of modern earthworms, are common in the grey A_2 horizon. Siderite crystals around burrow margins and within fossil roots in the A_2 horizon and siderite nodules in the organic horizon appear to have formed shortly after covering of the paleosol with overlying sediment. These paleosols are identified as humic gleys or fibrists and are of a type not yet subdivided in the Northcote Key. Modern soils of this type form in poorly drained swamplands.

A variety of paleosols are found in the Newport Formation. Most characteristic are the Avalon Series paleosols. These consist of a thin, carbonaceous shale (O) underlain by about 10 cm of ganister (A_2) containing abundant metagranotubules and carbonaceous roots that also penetrate the underlying, leached, grey clay. This clay (B_{2t}) becomes progressively darker and more clearly bedded with depth until a horizon of siderite nodules (B_{3hirg}) at a depth of about 40 cm. Ganister is a strongly outcropping, silicified, fine sandstone. From the evidence of microscopic texture, associated paleosols, plant fossils, and comparison with modern soils, it is likely that the ganisters of the Pittwater area were cleaned as acid, sandy, eluvial horizons of soils and diagnetically silicified by the in-place remobilization of abundant opal phytoliths from the *Dicroidium*-dominated vegetation originally growing in them. Metagranotubules (vertical burrows filled with ganister) were probably excavated by cicada-like insects. They are quite distinct from root casts that contain abundant carbonaceous lamellae and a concertina-like outline due to differential compaction of the tap-root around lateral roots. The best evidence that the siderite nodules are in place and formed at the same time as the paleosol is the rare occurrence of metagranotubules sidling closely around their edges. Geochemically, siderite indicates reducing, relatively alkaline or neutral conditions. The concentration of siderite nodules in layers probably marks a zone of slight humus illuviation and of water table oscillation. The Avalon Series paleosols were probably gleyed podzolics (aquods, Dg3.41). Modern soils of this type form in low-lying sites, intermittently waterlogged. They commonly support heath and coniferous forest, but also some broad-leaf vegetation.

Warriewood Series paleosols consist of ganister (A_2) penetrated by carbonaceous roots, sometimes also metagranotubules, and overlying moderately leached shale (B_t). These immature soils were probably alluvial soils (aquents, Uc2.21). Given time, and perhaps less waterlogging in some cases, these might have developed into soils similar to paleosols of the Avalon Series.

The St. Michaels Series paleosols are similar to those of the Avalon Series, but the St. Michaels Series paleosols have several features indicating drier conditions at the time of formation: ferruginized surface crust and burrows, some ferric mottling throughout the profile, and a lack of siderite nodules. These were most likely gleyed podzolic soils (ochrepts, Dy3.41). These immature paleosols may indicate that yellow podzolic soils or ultisols were formed in the Triassic hinterland to the north and west. Yellow podzolic soils also form on Newport Formation exposures in the Pittwater area today.

Capping many of the large epsilon cross-sets in the middle and upper Newport Formation are the South Head Series paleosols. These consist of leached, pink-weathering, sphaerosideritic claystone, often with a blocky ped structure in the uppermost 40 cm (A_2), overlying layered claystone (AC) with a deep-seated zone of weak iron accumulation at depths of one to two meters. The South Head Series paleosols may originally have been grey clays (fluvents, Uf4.2). In modern river systems, such soils are common on clayey levees.

No paleosols and few overbank shales have been preserved in the Hawkesbury Sandstone in the Pittwater area. Presumably, this is due to exceedingly low subsidence rates during deposition leading to continuous reworking of the floodplain fines by laterally migrating channels.

The various soil series fall within two associations based on the type of parent material. The Long Reef Association, including the Long Reef and Turimetta Series, are paleosols with red B horizons formed on volcanogenic, kaolinitic materials derived from the east. The Avalon Association, consisting of Avalon, Warriewood, St Michaels, and South Head Series, formed on quartz-lithic, kaolinitic-illitic materials from the north and west.

Taking 2,000 years as a reasonable time estimate for developing a mature soil profile (Buol et al., 1973), the Bald Hill Claystone probably contains an accumulated depositional hiatus of at least 16,000 years, and the alluvial plain that formed the Newport Formation probably subsided at a rate of less than a meter every 2,000 years.

No firm paleoclimatic conclusions can be drawn from the study of these paleosols. The dominance of podzolic paleosols is compatible with the evidence of paleolatitude (Smith et al., 1973), growth rings in fossil wood (Burges, 1935), and the moderate diversity of the fossil flora and indicates that the climate was cool temperate.

ECOSTRATIGRAPHY

The Braun-Blanquet phytosociology chart (Figure 10-7) does not show the fossil plant associations organized into fields as clearly as is often the case in studies of modern vegetation. This is because of taphonomic modifications of the original plant associations and the uneven quality of the collections. Some localities were so poor that collections from them could not be assigned to a defined fossil plant association. Nevertheless, the diagram is a convenient summary of otherwise unwieldy data. All these fossil plant associations are defined by Retallack (1977d), so only a short explanation and additional comments are offered here. The stratigraphic distribution of the associations in the Pittwater area is shown in Figure 10-2C. Some of the common plant fossils are illustrated in Figure 10-4.

No megafossils have been found in the highly oxidized Bald Hill Claystone except for burrows and plant roots. However, fossil pollen and spores recovered from the Bald Hill Claystone by Helby (1973) suggest that it was vegetated by conifers rather than pteridosperms. The conifer pollen are similar to those from palynological assemblages found at lower stratigraphic levels in the Sydney Basin. These little known Early Triassic coniferophytic associations are grouped together as the Voltziopsetum. They evidently formed forests because of the type, thickness, maturity and root mottling of the paleosols they produced and the large logs found with remains of this association in underlying formations (described by Baker, 1931; Burges, 1935).

The Pleuromeietum in the Pittwater area is a monodominant association of *Pleuromeia longicaulis* (Figure 10-4F) and its supposed cones (*Cylostrobus sydneyensis*, Figure 10-4E) and leaves (*Sigillariophyllum*). The association shows a differential distribution of plant parts from north to south. To the north at North Avalon where the plants appear to have grown in

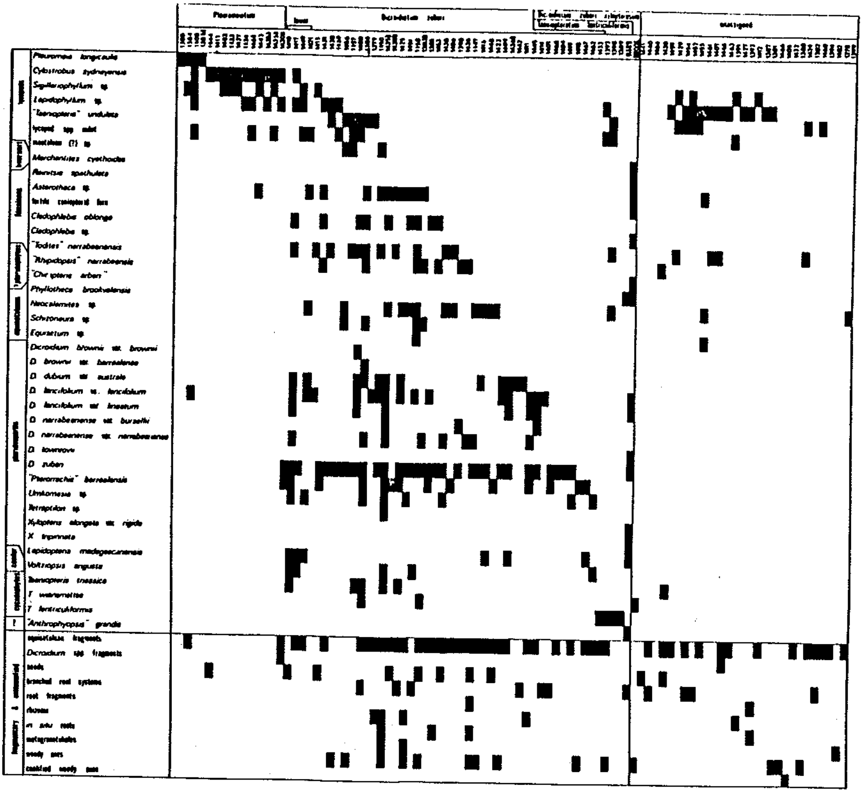


Figure 10-7
Braun-Blanquet phytosociology chart for fossil plant collections from the Pittwater area. Numbered localities are registered with the Geology Department, University of New England, Armidale, New South Wales, and discussed by Retallack (1973). The flora of the Newport Formation and also of Harbord (HARB.) and Brookvale (BROOK.) localities are discussed by Retallack (1977d, microfiche frames G6, G9, G10).

interdistributary bays, *Pleuromeia* is found in a thin coaly layer containing rhizophores, stems, and leafy apices. A little farther south, north of Newport, cones, leaves, bark fragments, and sterile apices are scattered in lagoonal shales. Similar shales, cropping out in most of the cliffs south as far as Long Reef, contain cones and leaves. No rhizophores, stems, bark fragments, or sterile apices are found south of Newport. Presumably these changes are due to the differential distribution of plant parts into the lagoon to the south from stands at North Avalon.

For several localities (Figure 10-7) where the collections were derived from mixed boulders in littoral talus that contained remains of both the Pleuromeietum and Dicroidietum zuberi (localities 1383, 1435, 1436, 1420), I separated the associations on the basis of matrix. However, *Cylostrobus* does occur mixed with pteridosperms and conifers in the lowermost Newport Formation at Bungan Head (locality 1417). Other lycopod remains also occur in several collections of the Dicroidietum zuberi and some unassigned collections. Perhaps these belong to an additional lycopod association. Definition of this association will have to await description of better preserved and more abundant new lycopod material such as that from similar stratigraphic levels north of Broken Bay and in Tasmania (Ash, 1979).

The Dicroidietum zuberi is the most common and widespread association of the Pittwater area. It is a diverse broadleaf pteridosperm association that commonly includes filicalean and equisetalean remains and rarely, lycopods. Within the Newport Formation there are several lines of evidence indicating it was a heath vegetation (Retallack, 1977b). It is intimately associated with paleosols of the Avalon Series, a soil type today commonly supporting heath. Cradle knolls, egg-cup podzols and radiating root impressions found in the ganisters of these paleosols are all small and probably produced by vegetation less than 2 m high. *Dicroidium zuberi* (Figure 10-4A, B) leaves from the Newport Formation have a very thick leaf substance and cuticle (veins are seldom seen in impressions) compared with the same species associated with the same reproductive structures (Figure 10-4C, D) 100 km west of Sydney at Mt. Piddington. Finally, no large fossil logs have been found in the Newport Formation above the basal lagoonal shales.

Figure 10-7 is artifically arranged to show the proportions of localities for the Dicroidietum zuberi that contain equisetaleans, filicaleans, and lycopods. These pteridophytes probably formed synusiae as an understory to the pteridosperms, or perhaps stream or lakeside thickets marginal to the Dicroidietum zuberi.

The Dicroidietum zuberi associated with the Turrimetta Series paleosols is not particularly distinct floristically from the association elsewhere, but is interpreted as quite a different type of vegetation. Large logs have been found lying in the organic horizon of these paleosols indicating that here the association was a swamp woodland. There is also a greater abundance of the conifer *Voltziopsis angusta* (Figure 10-4L) and the pteridosperm, *Lepidopteris madagascariensis* (Figure 10-4J, K) in collections from this stratigraphic level (Figure 10-7, localities 1410, 1417, 1449, 1421). The *Neocalamites* stem bases observed in the uppermost A_2 horizon of Turimetta Series paleosols may have been a successional stage in a hydrosere towards swamp-woodland climax.

No megafossils have been found below the Bald Hill Claystone in the Pittwater area, but the Dicroidietum zuberi occurs in that stratigraphic position north of Garie Beach on the coast south of Sydney and in the north wall of the Skillion, Terrigal, north of Broken Bay (Retallack, in press).

The Taeniopteretum lentriculiformis is characterized by a remarkable abundance of the nominate species (Figure 10-4I). Considering the abundant, slender, branching twigs found in this association, these plants may have had a bushy habit. The association occurs with South Head Series paleosols in the uppermost Newport Formation at North Avalon and was probably a levee vegetation. The Taeniopteretum lentriculiformis has also been found at Gosford north of Broken Bay and at Harbord 5 km south of the mapped area (Retallack, in press).

The Dicroidietum zuberi xylopterosum is known best in the Sydney region from a single locality near Brookvale 4 km south of the mapped area (Figure 10-1). *Xylopteris* and several other narrow-leaved species form relatively xerophytic elements in an association otherwise similar to the Dicroidietum zuberi. These xerophytic elements may have been adapted to drier, sandier, soils low in nutrients. Such modern soils on the Hawkesbury Sandstone, support dry sclerophyll vegetation.

BIOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY

The entire Triassic sequence exposed in the Pittwater area was deposited during the *Dicroidium zuberi* Oppel-zone (of Retallack, 1977d). The Bald Hill Claystone, Newport Formation, and Hawkesbury Sandstone have yielded, respectively, the *Protohaploxypinus samoilovichii*, the upper zonule of the *Aratrisporites tenuispinosus*, and lower zonule of the *A. parvispinosus* palynological assemblages (Helby, 1973). These plant remains are correlated with the late Scythian to early Anisian Stages of the European Triassic largely on the basis of *Pleuromeia* and *Aratrisporites* (Retallack, 1975). *Taeniopteris lentriculiformis* is also abundant within a restricted interval of Anisian marine rocks in the Murihiku Supergroup, New Zealand (Retallack, 1977d).

SYNTHESIS

In describing the likely panorama and processes in the Pittwater area during the Triassic (Figure 10-8), I have paraphrased my earlier work (Retallack, 1977b: 31) with little modification.

From a position high in the sky west of Sydney, the extensive waters of Narrabeen Lake can be seen to be the freshwater northern portion of a large lagoonal system intermittently open to the sea in the south. To the east, low rolling hills rise gradually to scattered plugs of the twenty-million-year-old Gerringong Volcanic Ridge, which separates the lake from the glistening waters of the Eopacific Ocean in the far distance. Sluggish streams drain down to the lake from the crest of the ridge. Their meandering and branching is marked by deep linear shadows through the Voltziopsetum coniferous forest of the low hills and the Dicroidietum zuberi swamp woodland of the lake margins.

These streams are floored by unaltered, grey-green, volcanogenic sandstones. When exposed, these sandstones weather quickly to form the predominantly red, kaolinitic claystone soils of the Long Reef Association. In better drained areas, the clay is strongly oxidized to grey-brown podzolic soils (ferrods) of the Long Reef Series formed under Voltziopsetum coniferous forest. Well-drained conditions prevailed for at least 16,000 years, with very slow subsidence, to form the Bald Hill Claystone.

In lowland areas around the lake, the soft lithic sandstones form clayey gley soils accumulating small thicknesses of peat under Dicroidietum zuberi swamp woodland. Local thickets of *Neocalamites* are trapping sediment as an early stage in the hydrosere toward a woodland climax. The mature soils are humic gleys (fibrists) of the Turimetta Series. With the slow relative rise of the Narrabeen Lake,

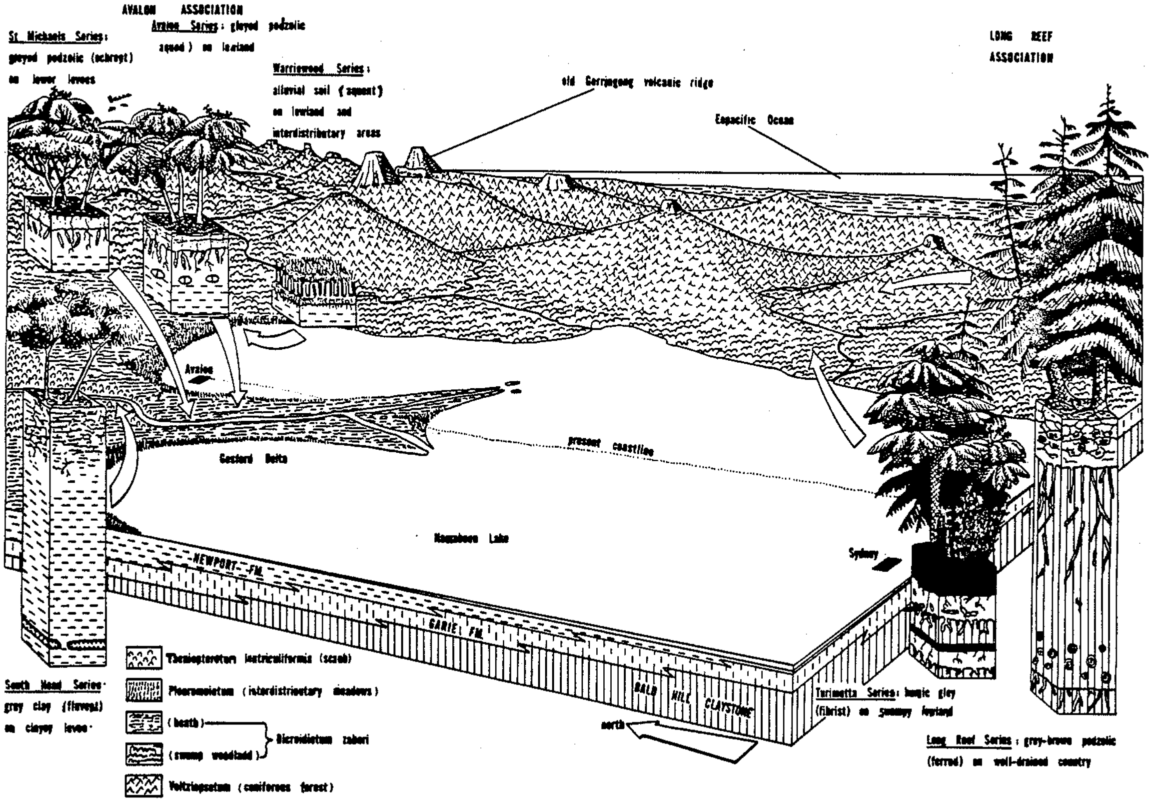


Figure 10-8
Reconstructed environment of the Pittwater area during the latest Early and earliest Middle Triassic (from Retallack, 1977b:30, with permission).

drab clayey sediments and soils of this type came to continuously overlie the Bald Hill Claystone forming the Garie Formation.

At the northern margin of the lake, the Gosford Delta is imperceptibly building southwards concomitant with the slow relative rise of lake level. The delta channels drain a broad river plain extending far to the north. A few hundred kilometers to the north and west hilly country is barely visible on the horizon. This large and geologically varied source terrain supplies quartzose sand and silt and kaolinitic-illitic clay to the delta.

From the air, the Gosford Delta is an interesting patchwork of dark Pleuromeietum meadows in marshy interdistributary bays; light drab-green Dicroidietum zuberi heath on sandy-surfaced soils and bright-green islands of pteridophytes around small lakes and billabongs; all dissected by sinuous ribbons of shining water in clean sandy channels. Beneath the still waters, the lakefloor is predominantly grey clay littered with comminuted plant fragments, but there are lighter-colored sand bars around distributary mouths.

Within the low-lying and sedimentologically active delta, only gleyed and immature soils are formed. Alluvial soils (aquents) of the Warriewood Series are formed under Dicroidietum zuberi heath in lowlands recently covered by flood deposits and under partly submerged Pleuromeietum meadows in interdistributary bays. On older lowlands Dicroidietum zuberi heath grows on more differentiated gleyed podzolic soils (aquods). These have a dry, acid surface, but the water table is almost permanently within a meter of the surface. On slightly more elevated ground also vegetated by Dicroidietum zuberi heath, there are more oxidized gleyed podzolic soils (ochrepts) of the St. Michaels Series. These are immature, but indicate that yellow podzolic soils (ultisols) may have developed on similar parent materials in more inland and better-drained sites.

The southward growth of the Gosford Delta lobes and bay shorelines eventually filled much of the Narrabeen Lake to form the Newport Formation. Slow but steady subsidence of less than a meter every 2,000 years prevailed during the progradation of the Gosford Delta and the final covering of the Gerringong Volcanic Ridge. After a time, subsidence proceeded even more slowly. As a result, the sandy river channels more frequently reworked the shaly floodplain by lateral meandering, so only immature grey clays (fluvents) of the South Head Series supporting Taeniopteretum lentriculiformis scrub on clayey levees are preserved in the geological record.

Subsidence was extremely slow when the Hawkesbury Sandstone was deposited by powerful braided streams from the southwest. These eroded deeply into older sediments and reworked the floodplain to such an extent that few shaly sediments and no paleosols have been preserved. Local billabongs and lakes still supported a lush growth of ferns and equisetaleans, but the sandy, drier, low-nutrient substrate supported a relatively more xerophytic vegetation. This Dicroidietum zuberi xylopterosum is a diverse broadleaf association including several narrow-leaved pteridosperms such as *Xylopteris*.

As in many other regions of prolonged geological study, the broad outlines of this reconstruction had been established by previous research on sedimentary petrography and environments, paleocurrents, paleobotany, palynology and paleozoology. However, most details of this new reconstruction are due primarily to new approaches in studying fossil soils and associations of fossil plants. I hope this brief illustration of the potentials of these approaches will stimulate additional research into their methodology and application elsewhere.

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