TRIASSIC PALAEOSOLS IN THE UPPER NARRABEEN GROUP OF NEW SOUTH WALES. PART I: FEATURES OF THE PALAEOSOLS

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(With 1 Table and 21 Figures)

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Abstract

The sea-cliffs north of Sydney expose a complex of Triassic palaeosols, pedoliths, and sedimentary rocks.

The most obvious and diagnostic features of the palaeosols are fossil roots in place and markedly leached or reddened, relatively massive, clay-rich strata. Associated coaly layers and fossil plant remains in adjacent sediments show varying degrees of decomposition. The *A* horizons of some of these palaeosols have been silicified by plant opal and contain abundant insect, earthworm, and larger animal burrows, cradle knolls, and basket podzols. Many of the palaeosols have well-preserved peds and their upper horizons slake more readily in water than their lower horizons. Their *B* horizons may consist of extensive layers of siderite nodules or red claystone with tubular grey mottles around old root channels.

Less mature palaeosols show some relict sedimentary bedding and ripple marks within their profiles. More mature palaeosols, which appear massive in the field, may show anomalous grainsize variation in thin section, remaining from sedimentary bedding.

Soils can be eroded and deposited as pedoliths. Conglomerates of palaeosol clay pebbles and siderite nodules are easy to recognize as pedoliths. Finer-grained pedoliths have the distinctive mineralogy and some of the small structures, but not the larger structures and field relations, of palaeosols.

Siderite crystals and nodules developed in the gleyed organic and *A* horizons of some of the clayey palaeosols shortly after they were covered by sediment and subsided below base level. With further compaction and dewatering, the ferric-oxide minerals became redder by inverting to hematite, mineralized joints developed in some massive *B* horizons, some peds were accentuated by slickensides, and some root channels and coal cleat were filled with copper minerals.

INTRODUCTION

In the past, geologists seldom had any interest or training in soil science and so have been unable to identify palaeosols in sedimentary sequences. This is especially the case in pre-Cainozoic rocks, as the modifying effects of diagenesis and metamorphism are so poorly known. Nevertheless, over the last 20 years soil features have been increasingly documented from older sedimentary sequences (*e.g.* by Allen, 1959; Batten, 1973; Terrugi & Andreis, 1971; Jensen, 1975; Ortlam, 1971; Chalyshev, 1969; Steel, 1974; Huddle & Patterson, 1961; Woodrow, Fletcher & Ahrnsbrak, 1973). These workers have been slowly establishing criteria for distinguishing the products of soil formation from those of sedimentation, volcanism and diagenesis. In this study of Triassic palaeosols in the sea-cliffs north of Sydney, I develop similar criteria and discuss their implications for palaeoenvironmental interpretation. The classification and reconstruction of these palaeosols in their ancient environment is the subject of a second paper (Retallack, *in press*), in which the palaeosol names used here are defined. As a general rule, mineralogy and geochemistry are the features of palaeosols most susceptible to diagenetic change and should play a subordinate role to detailed field observations, horizons, pedality, micromorphology, and associated fossil floras in the study of older palaeosols.

SOME BASIC TERMS AND CONCEPTS

In non-marine environments, sedimentary materials are subjected to short periods of movement under the influence of gravity, wind, and water, interspersed with long periods of soil formation. Within rock sequences produced in such an environment, the following definitions are useful. A *palaeosol* is an ancient soil, preserved in its entirety or with its upper layers removed, and recognized by the various features of modern soils. *Relict* features of a given palaeosol are those not believed to be caused by processes active during the formation of that

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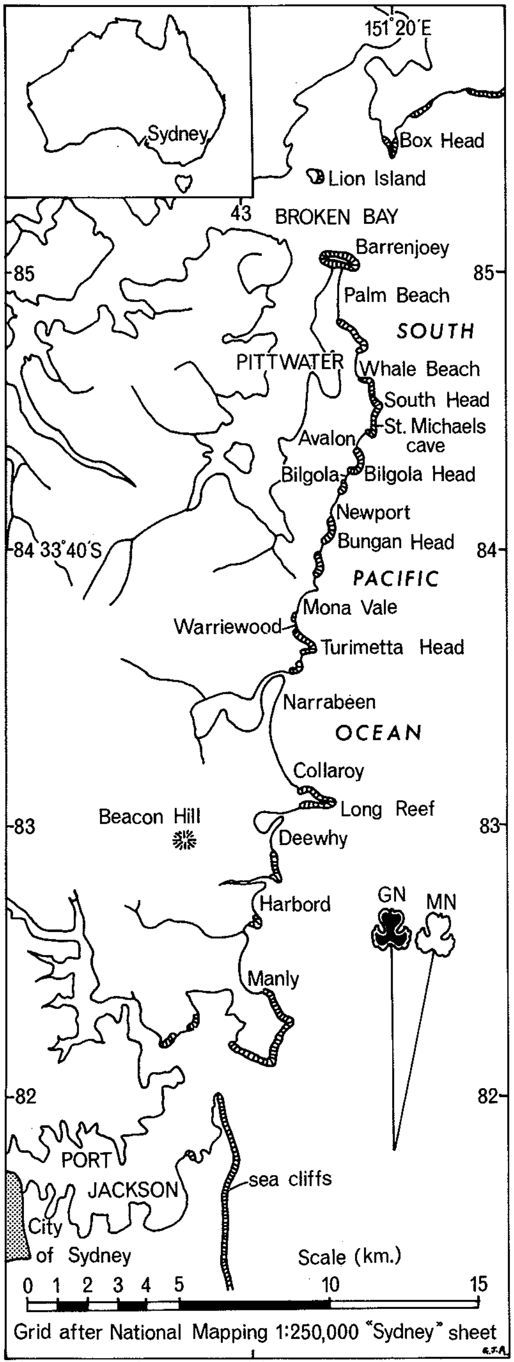

Fig. 1. Mentioned localities in the Pittwater area.

particular soil. *Pedorelicts* are 'features formed by the erosion, transport and deposition of nodules of an older soil material or pedological features of it, or by preservation of part of a previously existing soil horizon within a newly formed horizon' (Brewer, 1964, p. 145). *Sedimentary relicts* are sedimentary structures formed during the deposition of the parent material, which are not completely obliterated by soil-forming processes. Most commonly these are bedding and ripple-drift cross lamination. A *pedolith* (Crook & Coventry, 1967; Gerasimov, 1971) is a bed of transported and deposited soil material, showing sedimentary organization and pedological mineralogy and clast microstructure.

Many of the technical terms I have used here will be unfamiliar to geologists. I have tried to reduce these as much as possible and ask the reader to tolerate them in the same way that pedologists would have to tolerate such difficult jargon as 'strata', 'formation' and 'porphyritic' if they were interested. My descriptive terminology is largely from Brewer (1964), Buol, Hole & McCracken (1973) and Stace *et al.* (1968).

GEOLOGICAL SETTING

Palaeosols in the Triassic of the Sydney Basin have only been briefly mentioned as such by Branagan & Packham (1967), Bunny & Herbert (1971), and McDonnell (1974). Many are exposed in the magnificent sea-cliff exposures of the upper Narrabeen Group between Long Reef and Palm Beach, north of Sydney (Figs 1 and 2). The main results of recent unpublished stratigraphic work on these sea cliffs (Retallack, 1973) are summarized here. The lowest rock unit is the Bulgo Sandstone, exposed on the rock platform at Long Reef. Overlying this is about 18 m of red kaolinitic Bald Hill Claystone. The overlying Garie Formation, up to 7.6 m of drab sandstone and shale, is most conveniently defined on the first and last appearance of a distinctive grey-green lithic or clay-pellet sandstone, consisting of altered volcanic rock (58%), iron-stained sideritic claystone (36%), volcanic quartz (4%), and clay matrix (2%) at Turimetta Head. The overlying Newport Formation, consists of 49 m of interbedded kaolinite-illite shale, quartz-lithic sandstone and polymictic conglomerate, but is mainly sandstone in its upper portion. The base of the Hawkesbury Sandstone may be placed below the lowest, quartzose-sandstone channel deposit with some of the following features: oligomictic quartz-granule conglomerates, cross-sets 1.2 to 3.6 m thick, and extensive convolution of the top- and bottomsets. Retallack (1975) interprets the succession as a sequence of soils (Bald Hill Claystone) slowly drowned (Garie Formation) and covered by deltaic sediments and soils (Newport Formation). The area was finally overrun by the braided streams of the Hawkesbury Sandstone (Conaghan & Jones, 1975).

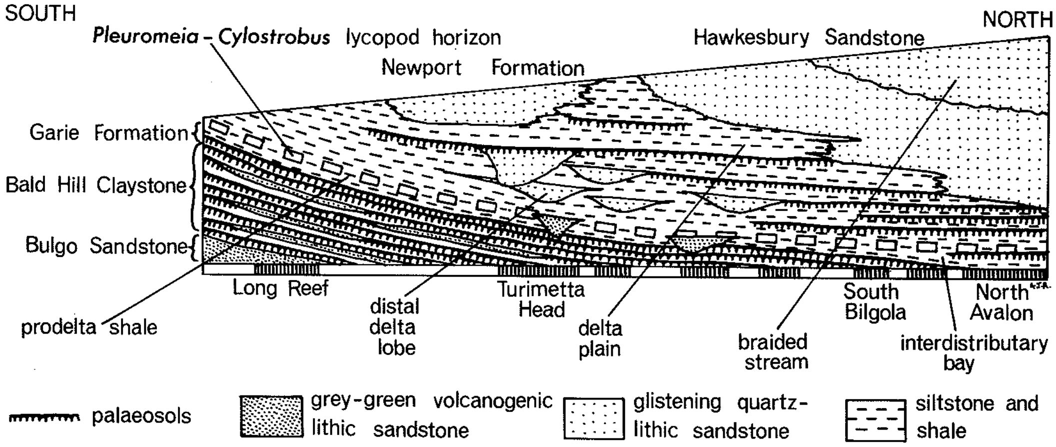

Fig. 2. A schematic palinspastic reconstruction of Triassic sediments exposed in sea cliffs between Long Reef and North Avalon.

FEATURES OF THE PALAEOSOLS

Leaf litter and stick debris

Plant fossil remains found in the upper Narrabeen Group show the whole range of decomposition found in the organic layer of modern soils.

Black carbonaceous shale layers in which there are no recognizable plant fragments suggest very well-humified plant material.

Fossil plants in layers several leaves thick are associated with the Avalon silty clay loam palaeosol. The leaves are ragged and irregularly ferruginized, and shallow scribbling depressions about 3 mm wide cover their surface (Fig. 3). The clumping is probably due to the cementing effect of fungal hyphae, bacteria and slimy masses of decomposed cell cytoplasm (Kononova, Nowalkowski & Newman, 1966). The scribbles are probably traces of degrading organisms. These features are similar to the fermentation layer in organic horizons of modern soils (Bridges, 1970).

Fig. 3. Scribbling trails of leaf-litter organisms in fossil *Dicroidium* leaf (UNEF14607, x1.3).

Ganister surfaces commonly show purple-red limonitized stick debris, radial root systems and rare leaf impressions on their upper surfaces.

Leaf skeletons and naturally macerated plant fragments found in the upper Narrabeen Group could have been formed in the organic horizon of soils. Cuticle and the lignified vascular system are the most resistant of plant tissues to decay (Kononova *et al.*, 1966). However similar macerating effects are produced by the leaching of the sediment, in which the plants are fossilized, either within soils during their formation, by deep weathering associated with post-Triassic lateritization or by weathering in the present outcrop.

Carbonaceous roots

Fossil roots are found as radial groups (Fig. 4) on the upper surfaces of ganister or penetrating the upper horizons of the palaeosols at various angles. Radiating systems of carbonaceous roots are quite distinct from uncommon uncarbonized trace fossils referable to *Glockeria* and *Subglockeria* (Fig. 5, and see Häntzschel, 1975).

Fossil roots are best preserved in siderite nodules and claystone, where they maintain a round cross-section. Typically, the carbonaceous remains of the epidermis and central stele are separated by fine sediment (Fig. 21B). This pattern of root decomposition and infilling with sediment is also found in modern soils (Kononova *et al.*, 1966; Jacot, 1936).

Ganister (sandy eluvial horizons)

Williamson (1967) suggests that the term ganister be limited to sandstone beds less than

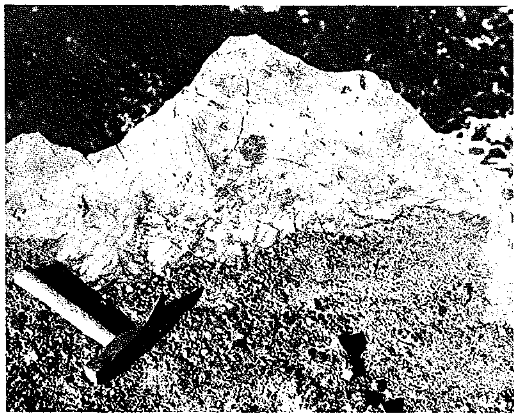

Fig. 4. Radiating fossil roots on ganister surface of Warriewood clay loam palaeosol north of Turimetta trig.

Fig. 5. Numerous specimens of *Subglockeria* and *Glockeria* on overturned slab near South Head.

1.5 m thick, with over 90 percent angular grains, dominantly in the range 0.5 to 0.15 mm (medium to fine sand), with only minimal amounts of organic matter and clay, commonly containing fossil roots and underlying coal seams. Ganister in the Pittwater area is commonly weather resistant, glistening white, very hard, less than 10 cm thick (exceptionally up to 61 cm) and underlies thin cuticle-coal or carbonaceous shale. In thin section, medium sand- to silt-sized grains of clear, high-relief quartz are generally closely packed, but in places float in a matrix of low relief cryptocrystalline quartz (Fig. 6). There are variable amounts of organic matter and only rare heavy minerals, muscovite, and rock fragments. The terms quartzite, silcrete (Stephens, 1971), and grey billy (Browne, 1972) are less appropriate for the Pittwater ganisters as they include a much wider range of composition and texture. Ganisters of the Pittwater area have been previously noted by Raggatt (1938) and David (1950), as quartzites; David (1893) and Culey (1932), as Fontainebleau sandstone; McDonnell (1974), as silcrete and ganister; and Loughnan, Ko Ko & Bayliss (1964), as ganister.

The two key problems in the origin of these ganisters are the purification and concentration of the quartz and the origin of the low-relief cryptocrystalline siliceous matrix.

The cleanness of the ganisters is more likely a result of leaching and argilluviation in a soil profile (see Hallsworth & Waring, 1964), than of persistent sedimentary layering (see Oertel & Blackburn, 1970) or intrastratal solutions during diagenesis. The ganisters form widespread thin layers near the top of the palaeosols. Their upper contact is sharp, but their lower contact more gradational into clayey sediments. Furthermore, ganisters are cleaner in apparently more mature palaeosols; as is shown in the sequence of progressively cleaner ganisters from the Warriewood silty clay loam through the Avalon silty clay loam to the Avalon silt loam palaeosols.

The siliceous matrix and cement of the ganisters was most likely contributed by vegetation, now preserved as an abundant fossil

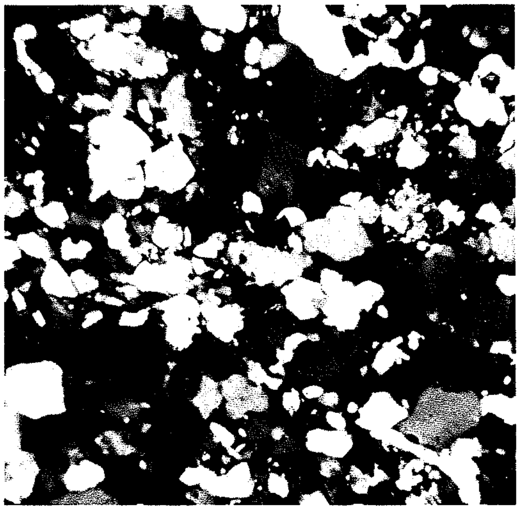

Fig. 6. Thin section of ganister, with a faecal pellet (UNER35292, crossed polars, x60).

flora associated with the palaeosols. Diatoms and siliceous sponge spicules are common components of modern soils, but are unlikely to have occurred in these palaeosols. Diatoms are entirely unknown before the Jurassic and in quantity before the Oligocene (Bold, 1967). The characteristic tubular shape of sponge spicules (see Jones & Beavers, 1963, fig. 1) has not been seen in any of my thin sections of ganisters. As there is no evidence for nearby Triassic volcanism, groundwater would not have had a high enough concentration of monosilicic acid to precipitate silica in the presence of quartz (compare values of Davis, 1964, and Millot, 1970). The texture of the ganisters excludes the possibility of any significant contribution of silica from scattered alkali dolerite dykes in the area, post-depositional solutions or pressure solution at grain boundaries.

Silica is a widespread component of plants (Kaufman *et al.*, 1971; Wilding & Dries, 1971; Scurfield, Anderson & Segnit, 1974) and may reach concentrations of 27.96 percent by dry weight (Blackman, 1968). It is found only in subaerial parts of plants, as opaline silica bodies (phytoliths), as opaline silica encrusting cell walls, epidermis and stomata, or as uncharged $Si(OH)_4$ in solution (Blackman & Bailey, 1971). The pitting in some *Dicroidium* cuticles (Fig. 7, also noted by Frenguelli, 1944) may indicate that they were encrusted by or contained silica phytoliths. However, this is a very uncertain guide to the silica content of fossil plants, as it is evidence of only one type of plant silica and could also be due to poor preservation, rough maceration, or attack by microbes and insects.

Phytoliths are released to the soil by death and burning of the vegetation, from the dung of herbivores, and from airborne dust (Baker, 1959, 1960). Some of the larger aggregates of cryptocrystalline silica deformed about the detrital grains in these ganisters may be faecal pellets of leaf-litter fauna (*cf.* Bal, 1970). In modern soils, phytoliths may reach concentrations of 3.63 percent (Verma & Rust, 1969) in the uppermost horizons, in areas of intermediate drainage underlying vegetation with a high silica productivity (Jones & Beavers, 1964; Witty & Knox, 1964). Isotropic opal is more readily soluble than quartz (Millot, 1970) and so more easily mobilized to form a siliceous cement after deposition.

The Pittwater ganisters were originally clean loose aggregates of phytoliths, faecal pellets, and detrital quartz forming the A_2 or eluvial horizon of palaeosols. Some of the ganisters contain obscure sedimentary relicts but all were more or less profoundly affected by vegetation, argilluviation and soil fauna.


Fig. 7. Weakly macerated cuticle of *Dicroidium* showing rod-shaped pits; after phytoliths(?) (x250 GSNSW Min. Mus. no. MMF13040, frond figured by Walkom, 1925, pl. 28, fig. 2).

The thickness of the A_2 horizon in soils is controlled primarily by the level of the water table and secondarily by the duration of formation (Daniels, Gamble & Nelson, 1967): thin, texturally-mature ganisters indicate a relatively high water table. The absence of carbonate in the ganisters (present as siderite in the lower horizons of some ganister-bearing palaeosols) indicates a neutral to acid pH (Krumbein & Garrels, 1952; Baas Becking, Kaplan & Moore, 1960). The Eh gradient over the ganister was probably quite steep, following the difference between dry soil on top to wetter soil with increasing clay, siderite, and organic matter below.

During diagenetic consolidation of the ganister a little remobilized silica cement could have been added to the ganister from overlying coaly bands and intrastratal solutions.

Ferruginized ganister top (hard-setting surface crust)

The Avalon silty clay loam palaeosol has a ganister with a thin ferruginized surface. The red stain includes some bedded organic material and penetrates to depths of a few centimetres along narrow downward tapering cracks (Fig. 8B), which outline irregular blocks in plan. The ganister of the St Michaels silty clay loam palaeosol is similar but ferruginized to a greater depth. The St Michaels sandy loam palaeosol has light yellowish areas of ganister surrounded by areas of purple mammillated ferruginization (Fig. 8A). Purple and blue hues in ferruginized ganisters mark the mixing of carbonaceous material.

These ferruginous layers were probably formed in the original soil as hard setting sur-

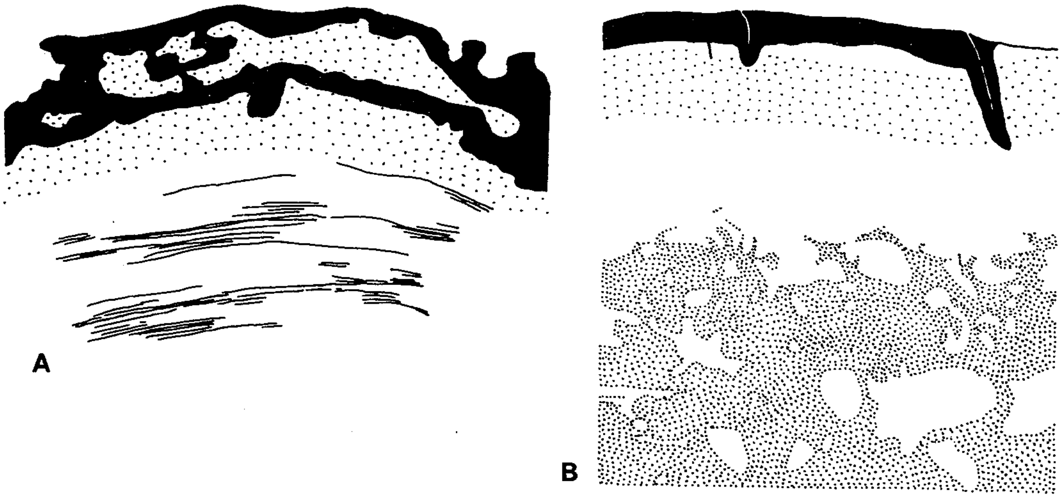

Fig. 8. *Camera lucida* sketches of ferruginized surface crusts (black), at natural scale. A, St Michaels sandy loam palaeosol north of Narrabeen beach (UNER28002), B, Avalon silty clay loam palaeosol north of Avalon beach (UNER27998).

face crusts. They are only formed towards the top of ganisters and extend downwards in desiccation cracks. They are found in apparently well-drained (St Michaels Palaeosol Series and Avalon silty clay loam palaeosol), rather than poorly-drained palaeosols (Warriewood Palaeosol Series and most of the Avalon Palaeosol Series).

The original crust was probably well aerated with a high positive Eh, so the oxidation of iron was encouraged (Krumbein & Garrels, 1952). The iron in the soil was probably yellow or brown goethite or amorphous iron oxide and inverted patchily to limonite and hematite during diagenesis (see Walker, 1974).

Shallow holes in ganister (cradle knolls)

Cradle knolls are craters formed when shallowly rooted trees are knocked down by the wind (Buol, Hole & McCracken, 1973, p. 150). This is a possible explanation for the large rounded irregular holes 15 to 20 cm in diameter on the surface of the thick surface phase of the Avalon silt loam palaeosol on the rock platform just south of St Michaels cave.

Lenticular ganister (basket or egg-cup podzols)

Basket or egg-cup podzols are marked thickenings of the A_2 horizon of soils attributed to the activity of a single plant over several hundred years (Buol *et al.*, 1973, p. 142). The egg-cup podzol variant of the Avalon silt loam palaeosol shows good examples of this throughout its outcrop (Fig. 9).

Ganister metagranotubules (insect krotovinas)

More or less vertical, mostly unbranched, tubular structures of ganister material commonly extend down from ganisters into clayey *B* horizons (Fig. 10). They are metagranotubules in the terminology of Brewer (1964). They are circular or elliptical in cross section and about 5 mm across. In irregular weathered outcrops they may appear to branch or taper (McDonnell, 1974, fig. 19), but I have seen no unequivocal sectioned examples of these features. Some have sparse traces of carbonaceous matter on or near the surface. Broadly similar structures are also seen in non-palaeosol shales and siltstones, also traceable from a sandy interbed or lens. The metagranotubules could be internal moulds after plant roots or burrows.

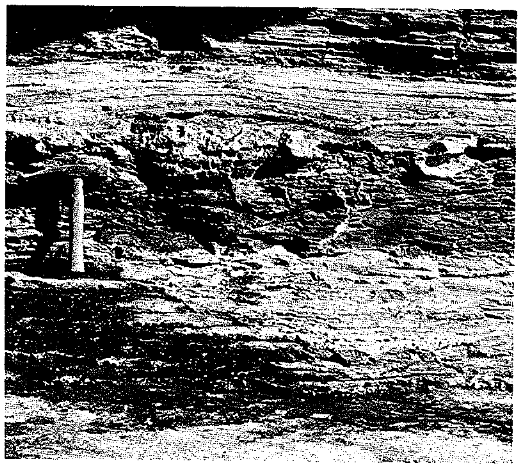

Fig. 9. Egg-cup or basket podzols in ganister of Avalon silt loam egg-cup variant palaeosol near St Michaels cave (hammer handle is 25 cm long).

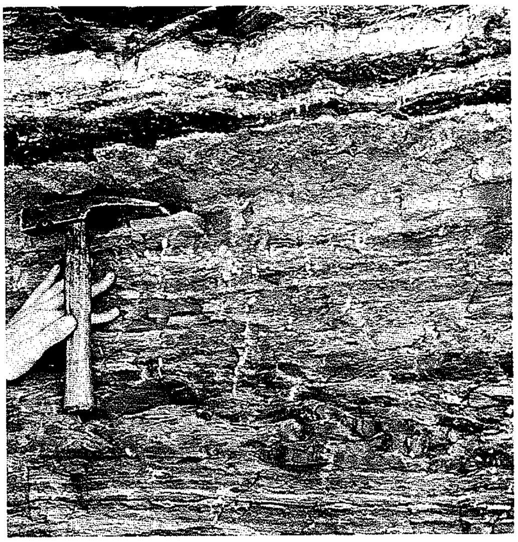

Fig. 10. Ganister metagranotubules in type Avalon silt loam palaeosol 200 m south of St Michaels cave.

McDonnell (1974) and Osborne (1948) interpreted them as root casts. McDonnell mentions carbonaceous films, downward tapering, and branching to support his interpretation. However, all these features are uncommon. Tapering can be simulated by the angle of the tubule to the outcrop face and branching by intersecting tubules. The metagranotubules are quite dissimilar to unequivocal root casts figured by Vossmerbäumer (1969), which have abundant carbonaceous sheathing and lamellae within the tube and a concertina outline owing to the compaction of sediments around the root, hinging on the carbonaceous traces of the stronger lateral roots. The metagranotubules lack the larger diameter, obconical base, regular nodes, and clear vertical striation of equisetalean pith casts, such as the one described from North Sydney by Etheridge (1890).

The upper Narrabeen Group metagranotubules are more likely to be traces of insects, crustaceans, or worms. Crook (1957), Branagan, Packham & Webby (1966), and Gibbons & Gordon (1974) interpret them as worm burrows. Similar burrows are formed on modern estuarine flats by the crustacean *Corophium* (Buller & McManus, 1972). Worms or crustaceans possibly excavated the similar sandstone tubules in well-bedded (non-palaeosol) shale and siltstone of the Newport Formation. These rocks also contain low angle or horizontal sinuous sandstone tubules, commonly associated with superficially similar triradiate and 's' shaped synaeresis cracks (see Conybeare & Crook, 1968; Glaessner, 1969), and a variety of more complex scrapings and burrows. Most distinctive are convex hyporeliefs (*sensu* Seilacher, 1964) or hypichnial ridges (*sensu* Martinsson, 1970) of radiating sandstone tubules in shale, referable to the ichnogenera *Glockeria* and *Subglockeria* (Fig. 5; see Häntzschel, 1975).

However, the metagranotubules of the Pittwater palaeosols are most like the cicada krotovinas of Hughie & Passey (1963). These are burrows made by cicadas, commonly following or associated with the roots on which they feed and filled with material from a higher horizon of the soil profile. Similar burrows are made by other insects (see Bryson, 1939). Insect krotovinas are most abundant in sandy dry soils (Jacot, 1936).

Cicada-like insect fossils of suitable size are known from the eastern Australian Triassic (Riek, 1970). Good examples have been found in the shale lens within the Hawkesbury Sandstone at Beacon Hill, about 228 m stratigraphically above the insect krotovinas in the lower Newport Formation north of Avalon beach (Evans, 1956).

Large ganister orthostriotubules (vertebrate burrows)

Two specimens, probably of a single example of orthostriotubule (*sensu* Brewer, 1964), were found in large boulders of the littoral talus in front of the eastern fence of the fourth house northeast of Avalon beach (Fig. 12). They are elliptical in cross-section, measuring 7 by 12 cm. The slightly radiating fossil roots and flat underside of the slabs, indicates that the tubule was close to the base of the ganister and protruded a little into the underlying clayey horizon. Their size and structure suggests the living burrow of a vertebrate—possibly a lungfish or

Fig. 11. Thin ganister dykes in Avalon silt loam egg-cup variant palaeosol near St. Michaels cave.

Fig. 12. Large ganister orthostriotubule on overturned slab north of Avalon beach.

labyrinthodont such as have been found as fossils on a similar stratigraphic horizon (Woodward, 1890; Cosgriff, 1972).

Cryptotonstein (clayey eluvial horizons)

Cryptotonstein is an indurated, cryptocrystalline, kaolinitic claystone (Bouroz, 1962). In the Pittwater area there are at least two distinct types. Within the Turimetta Palaeosol Series they are light grey-blue or green clays which weather to small interlayered pillows. Within the South Head Palaeosol Series they are hard and grey and weather slightly pink.

Most of the cryptotonstein was probably formed biochemically in soils. Clay crystals cannot be seen in thin section even at 450 magnifications. The clay minerals give a broader and lower peak on an X-ray diffractometer trace than clays lower in the same palaeosol profile or sedimentary rocks nearby (Fig. 13). This is probably due to small crystallite size, poor crystallization, and mixed layering common in the upper horizons of soils (Townsend & Reed, 1971; Mills & Zwarich, 1972). The cryptotonsteins are unevenly indurated; the upper portions disintegrate in tap water more readily than their lower portions, as in modern soils (see Emerson, 1954). The lower contacts of cryptotonstein beds are more gradational than their upper contacts and they contain peds, cutans, tubules and carbonaceous roots.

Detrital grains with relict volcanic texture are associated with the cryptotonsteins of the Turimetta Palaeosol Series (Ward, 1972, pl. 25; Loughnan, 1963, pl. 1, fig. 2); indicating that these palaeosols developed on weathered volcanic material. These volcanics were probably a northern extension of a Permian volcanic ridge, which weathers to a kaolinitic surface soil in the present cool temperate climate (Craig & Loughnan, 1964). These cryptotonsteins were partly formed in place and partly from re-sorted soil materials. Cryptotonsteins of the South Head Palaeosol Series were formed similarly, but with additional contributions from the weathering of granites, durain peats (a source of kaolinite according to Moore, 1968) and kaolinitic rocks (described by Diessel, 1965: Loughnan, 1962, 1970) exposed in the northern and western sourceland of these rocks (see Ward, 1972; Branagan & Johnson, 1970).

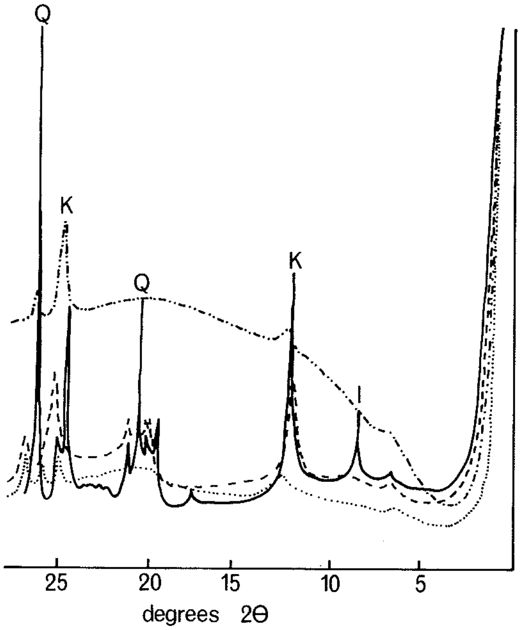

Fig. 13. Upper horizons of palaeosols show less well-crystallized clay and lower iron content (indicated by fluorescence with Cu/Ni radiation). X-ray diffractometer traces using Cu/Ni radiation on a Philips PW 1060/00; mineral interpretation after Loughnan (1963, 1970), Q, quartz; K, kaolinite; I, illite; unbroken line, lower Newport Formation grey siltstone (UNER28033); dashed line, claystone *B* horizon of type Turimetta clay palaeosol (UNER28023); dotted line, claystone A_2 horizon of type Turimetta clay palaeosol (UNER28017); dashed and dotted line, siderite nodule from 0 horizon of type Turimetta clay palaeosol (UNER27992).

Brecciated and oolitic tonsteins are probably pedoliths (*sensu* Gerasimov, 1971). A cryptotonstein-pebble, channel-lag conglomerate crops out at the base of the cliff north of Mona Vale beach. A thin grey claystone with a brecciated base overlies the sandy variant of the Turimetta clay palaeosol for much of the southern end of Turimetta Head southeast wall. The pelletal, brecciated, and oolitic marker beds of the Garie Formation and the Docker Head Claystone Member (described by Loughnan, 1962, 1969,

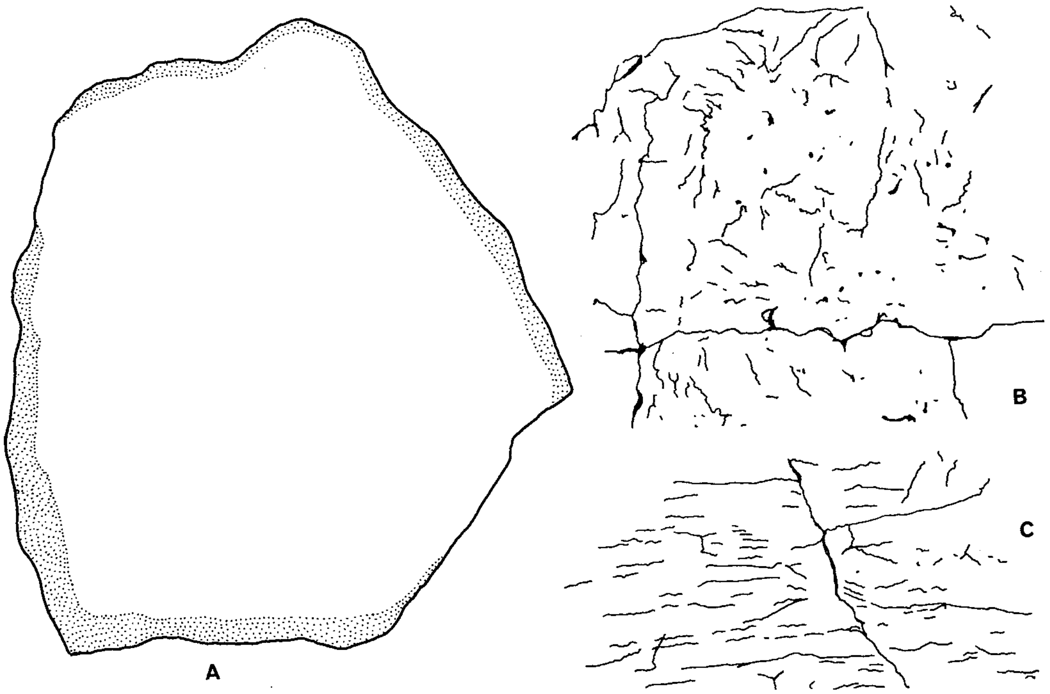

Fig. 14. Fossil soil peds. A, prismatic ped with weak diffusion ferran from the Avalon silt loam palaeosol near South Head (UNER35311, x0.5). B, C, plan and section of thick platy rough faced peds from *A* horizon of the type South Head clay palaeosol (UNER35313, UNER35312, x1).

1970; Loughnan, Goldbery & Holland, 1974) are probably also pedoliths.

Kaolinite can form from other minerals or, at least, is stable in a pH of 4 to 7 where precipitation exceeds evaporation and there is good drainage, with plentiful Al and Si and removal of Ca^{++}, Mg^{++}, Na^{+} and K^{+} ions (Wilson, 1965; Millot, 1970; Carroll, 1958).

Light colour (leaching of clay and humus)

One of the most prominent features of palaeosols in the field is their lighter-coloured upper layers. This is accentuated by modern weathering to produce glistening white ganisters and very light pink, orange, or blue-grey claystone. Fresh rocks are somewhat darker but still lighter than fresh rock lower in the profile. The pale colour was probably produced by leaching of humus and (in ganisters) argilluviation.

Cracking and veining (soil peds)

Most former peds have been obscured by compaction so that the palaeosols appear massive, although claystones may weather to pebble-sized interlayered pillows. The original bedding and sedimentary structures of the palaeosol parent material are gradually destroyed by the bioturbating effect of plant roots, soil organisms, and soil forming processes.

However, some of the palaeosols show beds defined by clear cutans. The following descriptions are based on the terminology of Brewer (1964) and Buol *et al.* (1973).

In the A_2 horizon of the South Head clay palaeosol there are very thick platy rough-faced peds defined by pink-weathering sideritic organo-argillans (Fig. 14C, D). The type Avalon silt loam palaeosol just south of South Head shows incipient coarse prismatic peds, best defined by sparsely ferruginized diffusion sesquans in a 3 cm relict sandy bed (Fig. 3A), but traceable throughout the profile. The ganister dykes (Fig. 11) in the egg-cup variant of the Avalon silt loam also outline a prismatic structure.

The A_2 horizon of the type example of the Long Reef clay shows very coarse subangular blocky peds defined by slickensided argillans. The *B* horizons of similar palaeosols at Long Reef commonly show tesselated pavements and prismatic structure. As the joints are filled with mineral, not soil, material and the microfabric is not related to joint faces, I regard this as a diagenetic development of prismatic structure (*cf.* Roeschmann, 1971).

Fig. 15. Vomosepic porphyroskelic plasmic fabric with fine granular peds defined by ferrans, from B_{3irb} horizon to type Long Reef clay palaeosol (UNER35272b, x25).

Microscopic texture

Sepic plasmic fabric is characteristic of soil (Brewer, 1964), and is found in palaeosols of the Pittwater area (*e.g.* Fig. 15). Further examples of soil microtextures are given in the descriptions of the palaeosol type profiles (available on request).

Crystal and faecal pellet para-aggrotubules (earthworm burrows)

These red tubules appear to be about 7 mm in diameter in a greyish clay matrix. In thin section they have a deeply folded organic margin (Fig. 16). If the involute outer surface of the tubules was the original circumference, the inflated tube was 11 mm in diameter. The clayey matrix follows the margin through these involutions as a vomasepic plasmic fabric. The interior is filled with elliptical faecal pellets up to 1 mm long, which have a very fine flecked appearance under crossed polars and contain no grains coarser than silt grade. Thus the tubules are para-aggrotubules of Brewer (1964). A marked authigenic growth of bladed siderite crystals inward from the margin, has cut across some of the faecal pellets.

This structure (without siderite crystals) is identical with that of modern earthworm burrows (Barley, 1959, pl. 1). The deeply folded margin is due to collapse into internal voids. Earthworms like relatively moist loamy soils and some varieties can even tolerate waterlogging (Svendsen, 1957; Kühnelt, 1961). They have a wide pH tolerance but cannot stand acidity less than pH 4.5 (Murphy, 1953). Calcite secretion from calciferous glands (Lunt & Jacobson, 1944) may have nucleated the authigenic siderite.

Siderite nodules (gleyed illuvial horizons)

Tuberose and ellipsoidal siderite nodules (*sensu stricto* Brewer, 1964) are common in the upper Narrabeen Group. Several lines of evidence indicate that these formed in place and were contemporaneous with soil formation.

1. In places relict sedimentary layering can be traced through the nodules (McDonnell, 1974; Golding, 1955);
2. Siderite nodules may be laterally linked to form extensive thin reticulate horizons (Fig. 17);
3. The nodule horizons are relatively constant in thickness over considerable distances;
4. There is often some draping of sediment around the nodule (Golding, 1955; McDonnell, 1974, fig. 17);
5. Ganister metagranotubules commonly avoid passing through the nodules even to the extent of sidling right around them (McDonnell, 1974, fig. 17), exactly like modern cicada krotovinas (Hughie & Passey, 1963);
6. Carbonaceous rootlets passing through the nodules are more rounded and inflated than elsewhere in the palaeosol;
7. The clay component of the siderite nodules in the *C* horizon of the Turimetta clay sandy variant palaeosol show a similar poorly defined X-ray diffraction trace to cryptotonstein of overlying layers (Fig. 13);
8. The nodules represent the culmination of a down-profile increase in iron content, indi-

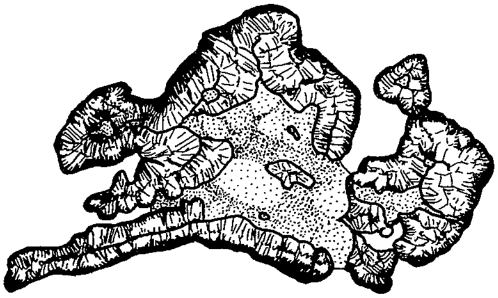

Fig. 16. Cross section of earthworm(?) para-aggrotubule from A_2 horizon of the Turimetta clay slightly eroded phase palaeosol south of Bilgola beach (UNER35320, x10).

Fig. 17. Siderite nodules in type Avalon silt loam palaeosol on rock platform near South Head.

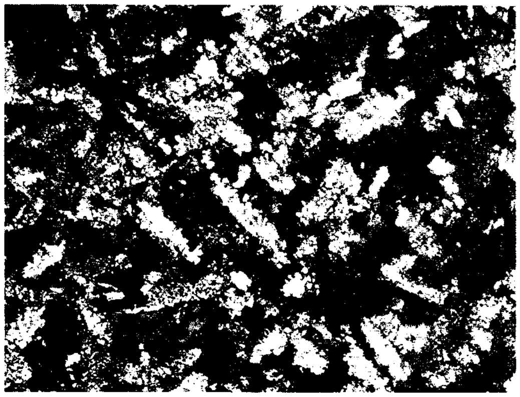

Fig. 18. Siderite rhombs in thin section of siderite nodule from O horizon of type Turimetta clay palaeosol (UNER27992, crossed polars, x70).

cated by the increasing fluorescence of iron with Cu/Ni radiation (Fig. 13; see Zussman, 1967);

9. The siderite nodules are present in the gley palaeosols of the Avalon Series but absent in the essentially similar but probably better drained St Michaels Series.
10. Siderite nodules are found as clasts in channel-lag conglomerates intimately associated with the oldest siderite nodule bearing palaeosols of the Pittwater area (the Turimetta Palaeosol Series in the Garie Formation).

The nodules have a crystic plasmic fabric of siderite rhombs up to fine-sand size (Fig. 18). They have a yellow or green weathered surface when in a carbonaceous shale matrix, as in the *C* horizons of the South Head clay nodule variant palaeosol and the Turimetta clay sandy variant palaeosol. In the Avalon Palaeosol Series the siderite nodules commonly have a reddish brown surface and diffusion ferran, which sometimes also penetrates synaeresis cracks (Fig. 19; *cf.* Franks, 1969; White, 1961). Even more heavily ferruginized nodules may be found as clasts in channel-lag conglomerates of the Garie and Newport Formations.

Calcareous and ferric nodules, commonly formed in modern soils by a fluctuating water table, may be soft after only 30 years but become indurated after a few thousand years (Coleman & Gagliano, 1965). Siderite nodules are less commonly reported from waterlogged soils (Kanno, 1962; Degens, 1965).

It is possible that the sideritic nodules of the Narrabeen Group were originally iron-manganese nodules similar to those described by Drosdoff & Nikiforoff (1953) and that the sideritic composition is due to metamorphic pseudogley (*cf.* Roeschmann, 1971); but the diffusion ferran (Fig. 19) is evidence against this. It is unlikely that diagenetic gleising solutions could have reduced the centre of the nodule without also reducing the ferran through which they passed. The ferran is not due to oxidation in the present outcrop as it is not found on exposed nodules of the Turimetta Palaeosol Series. It appears to have been an original feature; it is better developed in palaeosols which appear to have been better drained and best developed on re-sorted nodules of conglomerates.

In gley soils iron is reduced and transported down the profile by rainfall leachates of fresh leaves, by humidified organic matter, by simple solution at low pH and by iron reducing bacteria (see Bloomfield, 1951, 1964; Hallsworth, Costin & Gibbons, 1953).

Siderite is precipitated in waterlogged soils under various combinations of interdependent conditions; restricted circulation, a low Eh (−0.25 to −0.35 volts), high microbiological activity, neutral to acid pH, zero sulphide activity, and high concentrations of carbon dioxide, biocarbonate and ammonia (Curtis & Spears, 1968). Calcium saturation enhances waterlogging and gleying (Albrecht, 1941), and siderite can form by Fe^{++} in solution acting on calcite.

The siderite nodules probably formed in the original gley soils. In the Avalon Palaeosol Series, horizons of nodules may be taken as marking the zone of former water table oscillation. In the case of the Turimetta Palaeosol Series and the South Head clay nodule variant, the nodules preferentially developed in carbonaceous layers within the *C* horizon, which

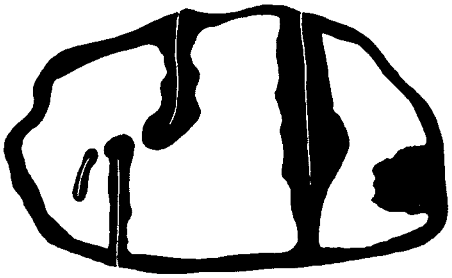

Fig. 19. *Camera lucida* sketch of diffusion ferran on margin and synaeresis cracks of siderite nodule from type Avalon silt loam palaeosol near St Michaels cave (UNER35323, x1).

was sometimes the older organic horizon of an underlying palaeosol.

Siderite crystals (deep gley)

Siderite also occurs as intercalary crystals, spherulites and crystal tubes usually developed within a thin ferri-organan. The spherulitic form (sphaerosiderite *sensu* Williamson, 1967) is generally of the bladed type (*sensu* Spencer, 1925) with only 4 or 5 crystals without zoning and is of medium to coarse sand size. Culey (1932) figures fibrous sphaerosiderite from Narrabeen. In thin section isolated intercalary crystals and spherulites cannot be distinguished from cross sections of tubular crystal aggregates replacing plant roots (*cf.* Deans, 1934), which are also seen in longitudinal sections. Siderite crystals are usually found in grey claystone (cryptotonstein) even where it occurs in reduced zones around plant roots in red mottled horizons (Fig. 20).

Siderite crystals also line the walls of earthworm para-aggrotubules (Fig. 16), where they were formed after the faecal pellets and before compaction unequally convoluted the margin and irregularly ruptured and doubled the even layer of crystals. The rounded shape of siderite within organans, also indicates a very early diagenetic origin. The siderite was probably precipitated below the water table as a deep gley feature of a soil.

Ferruginous layers (iron-enriched illuvial horizons)

The *B* horizons of the Long Reef Palaeosol Association appear red owing to dense staining with hematite, goethite, and siderite (Loughnan, 1963; Loughnan *et at.*, 1964; Goldbery & Holland, 1973). The strongest stain is isotic (*sensu* Brewer, 1964), but lesser stain may redden other plasmic fabrics. In the Turimetta Palaeosol Series the iron-stained *B* horizons are penetrated by vermicular mottles (*cf.* Vermaat & Bentley, 1955) of grey clay around the remains of roots (Fig. 21A, B). The A_2 horizon of the Long Reef clay has diffuse ferruginous mottles and concretions (Fig. 21C). The *B* horizon is heavily ferruginized, with rare lighter vermicular root mottles.

The ferruginized layers were probably formed within the palaeosols or were re-sorted from soils of the source area. In the Long Reef Palaeosol Series some re-sorted component is indicated by red pedoliths in the underlying grey-green sandstones of the Bulgo Sandstone at Long Reef and north of Garie beach. Some formation in place is suggested by diffuse waves of stain associated with mottles and concretions, peds and root channels. In the Turimetta Palaeosol Series the stain is probably wholly in place because it avoids vermicular root mottles, associated red pedoliths are very rare, and iron content increases down profile (represented by increased fluorescence of Cu/Ni x-radiation, Fig. 13).

Iron is leached out of the upper portions of the soil profile, usually in a ferrous form, and moves laterally with groundwater. There is no evidence for the older idea of an upward capillary rise of iron. Red ferric oxide is formed in dry periods and once formed is highly insoluble and unlikely to be reduced by the action of groundwater alone (see Eaton, 1942; Millot, 1970). The iron-oxidation environment was probably one of high positive Eh and acid pH (Baas Becking *et al.*, 1960). The original ferric

Fig. 20. Sphaerosiderite in stelar growth rings of a large fossil root from *B* horizon of the type Turimetta clay (UNER28023, x20, also shown in Fig. 21B).

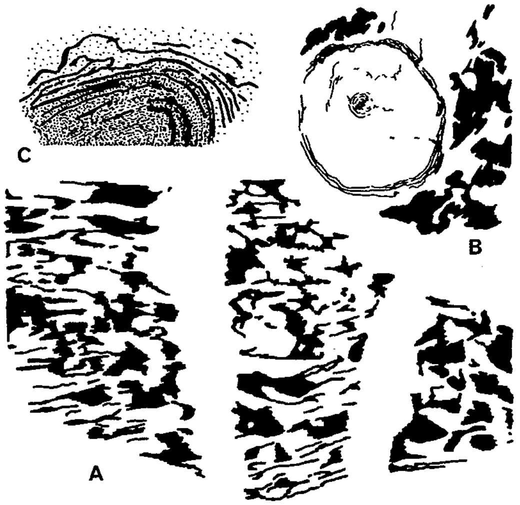

Fig. 21. Ferric plasma separations (black). A, vertical section of grey-green vermicular mottles after plant roots in red claystone *B* horizon of Turimetta clay slightly eroded phase palaeosol south of Bilgola beach (UNER35317, x1). B, horizontal section of fossil root with clay filled cortex from *B* horizon of type Turimetta clay palaeosol (UNER28023, x1). C, diffuse concretion from B_{3irb} horizon of type Long Reef clay palaeosol (UNER-35272a, x2.5).

oxide may have been yellow or brown gel or goethite which inverted to brown or red limonite and hematite during diagenesis (Walker, 1974).

Copper mineralization

Within the Long Reef clay palaeosols of the Bald Hill Claystone, paratacamite and atacamite occur with rare native copper (Branagan & Packham, 1967, p. 38; Goldbery & Holland, 1973, p. 1321; Dolanski, 1975) in the coal cleat of stick debris in lithic sandstone *C* horizons, and in the centre of grey vermicular root mottles of upper *B* horizons. Copper in analyses of the Bald Hill Claystone ranges from 50 to 250 ppm (Loughnan, 1963). In modern soils also, copper is more abundant in clayey than sandy soils (Lundblad, Svanberg & Eckman, 1949), non-calcareous than calcareous soils (Kishik *et al.*, 1973), and soils formed on volcanic rather than quartzose sedimentary materials (Rolt, 1962). Replacement of plant roots and coal cleat, indicates late diagenetic remobilization of the copper from the surrounding claystone.

Geochemistry

The changes in amounts of important soil elements from the Gerringong volcanic source rock, to weathered lithic sandstone and its red and grey palaeosol products, directly parallels the weathering of Gerringong Volcanics today (Table I). They are the usual loss of CaO, MgO, K_2O and Na_2O, and gain in Fe_2O_3 + FeO and Al_2O_3 (Chesworth, 1973). The comparable geochemical maturity of Newport Formation sedimentary rocks also indicates a considerable component derived from soils.

SUMMARY OF DIAGENETIC EFFECTS AND PALAEOENVIRONMENTAL INDICATORS

These palaeosols are very well preserved for their age. The only post-depositional effects I could identify are: crystallization of siderite crystals and yellow-green weathering nodules in older soils when they were the *C* horizons of the overlying soils; progressive later diagenetic reddening of ferric oxide minerals; development of prismatic structure exposed as tessellated pavements and jointing in clayey *B* horizons of Long Reef clay palaeosols; accentuation of peds by slickensiding in clayey A_2 horizons; minor copper mineralization associated with Long Reef clay palaeosols; compaction and dewatering.

The remaining features discussed indicate the conditions at the time of soil formation. These features need to be more widely investigated so that palaeosols can be more confidently identified with modern soils.

Periodically wetter conditions: siderite nodules demonstrably in place; asepic and undulic plasmic fabric; apedal or massive structure; gley colours; more humidified organic matter at the surface.

Periodically drier conditions: red ferric oxide mottles, concretions, nodules, surface crust and diffusion ferrans; sepic plasmic fabric; well developed peds; insect krotovinas: less humidified organic matter at the surface.

Acidic, neutral to low pH: kaolinite; ganister without carbonate; red ferric oxide mottles, concretions, nodules, surface crust, and diffusion ferrans.

Alkaline, neutral to high pH: carbonate (including siderite) nodules; PPF indicated by Northcote & Skene (1972).

Oxidizing, positive Eh: red ferric oxide mottles, concretions, nodules, surface crust, and diffusion ferrans.

Reducing, negative Eh: gley colours; siderite nodules, intercalary crystals, spherulites, and crystal tubes.

Na^+ as the dominant exchangeable cation: surface salt crust; well-developed domed columnar peds in an argillic *B* horizon; PPF indicated by Northcote & Skene (1972).

Table 1

Published chemical analyses for palaeosols and associated sedimentary rocks of the upper Narrabeen Group; averaged for major soil elements of Brewer (1964)

	A	B	C	D	E	F	G	H
Al_2O_3	16.67	15.8	16.3	13.29	28.01	38.64	21.82	9.43
$Fe_2O_3 + FeO$	8.03	9.2	10.7	9.38	14.49	3.55	3.93	3.10
CaO	6.11	6.3	0.9	1.64	0.38	0.84	0.25	0.64
MgO	3.18	3.4	0.3	3.44	0.36	0.29	0.64	0.56
Na_2O	3.70	3.6	0.8	2.44	0.16	0.06	0.10	0.23
K_2O	3.85	4.1	1.1	0.66	0.15	0.05	0.44	2.16
number of analyses	16	1	1	1	4	4	3	1

A, Gerringong Volcanics (Joplin, 1963); B, bottom; and C, top of a modern weathering profile on Gerringong Volcanics (Craig & Loughnan, 1964); D, Narrabeen Group tuffaceous sandstone (Joplin, 1965); E, Bald Hill Claystone, largely red *B* horizon material (Joplin, 1965); F, Garie Formation, largely drab *A* horizon material (Joplin, 1965; Loughnan, 1970); G, Newport Formation shale; and H, sandstone (Joplin, 1965).

Shallower water table: thinner mineralogically mature ganister; contemporaneous siderite nodules of the *B* horizon in place and closer to the surface.

Longer time of formation: less sedimentary relicts; thicker profiles; better differentiated horizons; greater textural maturity within horizons; better developed peds.

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