Upland swamps (dells) on the Woronora Plateau, N.S.W.

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You are worthy, O Lord our God, to receive glory and honour and power, for you created all things and by your will they existed and were created.

Revelations 4:11

UPLAND SWAMPS (DELLS)

ON THE WORONORA PLATEAU, N.S.W.

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This thesis, and the research reported therein, has not been submitted for a degree to any other university or institution. Except where otherwise indicated, it is my own original work.

ABSTRACT

The surface of the Woronora Plateau, in the southern Sydney Basin, coincides with the top of the Triassic quartzose Hawkesbury Sandstone. It is etched by broad, shallow valleys which are the headwaters of deep gorges. These upland valleys are sediment-choked, swampy and treeless. They resemble the 'dellen' (dells) described by early German geomorphologists, and the 'dambos' of southern Africa.

On the Woronora Plateau dells occur at 450-550 m elevation, in an area with 1300-1600 mm annual average rainfall, mean annual temperature of 17°C and an annual average excess of rainfall over evaporation of about 850 mm. They occupy between 2% and 9% of the catchments of streams dissecting the plateau, being most extensive and most numerous where the Hawkesbury Sandstone is least deeply dissected.

Erosion of the plateau supplies a sandy detritus to the dells. Because the streams in the dells have small catchment areas and gentle gradients, they do not flush all the sand into the lower valleys and gorges; thus, sediment accumulates. Sediment washed into the dells is differentiated during overland transport. On the sideslopes, the sediments are characteristically coarse-medium sands with low organic content. In the valley axes, the organic content rises very abruptly (to more than 10% organic carbon) and the sediments are fine-grained.

The waters of the dells are acidic and are low in dissolved oxygen, organic carbon and silica. The vegetation is dominantly sedgeland with some heath. It is differentiated in patterns which reflect

sedimentary and hydrological variations within the dells. Some of the dells display linear patterned ground which resembles that found in fens in the Boreal zone. The patterns are reinforced by biotic factors (particularly vegetational differentiation and crayfish activities) but appear to be initiated by slow, near-surface flow of saturated sediment.

Basal dates of sediments in the dells span at least 17,000 years. As they are not clustered, sedimentation in the upland valleys has not been triggered by any single, regionally-effective environmental change. Indeed the old sediments closely resemble those which are presently accumulating, which indicates that environmental change since the late Pleistocene has not been dramatic. It is suggested that the sediments now infilling the dells are the most recent accumulations in valleys which are episodically flushed when intrinsic geomorphic thresholds are reached. Fires followed by severe storms probably trigger these erosional events.

CONTENTS

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CHAPTER ONE: INTRODUCTION

> '... two valleys will be carved out of the upland at the same time, one a cañon receding from the face of the fault or flex, and one a broad and shallow valley formed headward of the cañon growth.'
>
> Andrews, 1911, p.130.

> '... two essentially different parts of the drainage system stand opposed to one another: (a) the main trunks which are entrenched in the scarplands .. (b) the ramifications which lie on the high surfaces of such peneplanes near the sources of the streams.'
>
> Penck, 1924, transl. 1972, p.185.

This thesis concerns the 'ramifications', the 'broad and shallow valleys' developed on gently sloping uplands. The forms described from southwestern Germany by Penck, and from southeastern Australia by Andrews, typify plateaux in many parts of the world. German geomorphologists, following Schmitthener (1925), usually call such phenomena <u>dellen</u> (Hettner 1928; Louis and Fischer, 1979; Penck, 1924) but Mackel (1974) adopts the local word <u>dambos</u> to describe those on the Zambian plateau. It is unfortunate that the English equivalent of <u>dellen</u>, i.e. 'dells', refers to small, usually wooded valleys whereas the shallow upland valleys here in question are typically sediment-choked and swampy, and therefore treeless. Yet it is difficult to find an alternative term. There are approximate equivalents in the botanical literature, such as 'fen' or 'valley swamp' or 'sedgeland', but not in the Anglo-saxon or the French geomorphic literature. In fact, although Gregory and Walling (1973) discuss them, such valleys are not mentioned in other specialist works on fluvial geomorphology such as Leopold et al (1964) or Morisawa (1968). Nor are they described in detail in standard French works on climatic geomorphology (Tricart and Cailleux, 1972) or on sandstone terrain (Mainguet, 1972). In this study, therefore, I shall follow the translators of Penck's and Hettner's early accounts and use the word dells to describe the swampy headwater valleys on plateaux.

The area investigated here is the Woronora Plateau, which forms part of the southern rim of the Sydney Basin in New South Wales. Triassic and Permian strata outcrop in this area. The plateau surface coincides with the surface of the Triassic formation, the Hawkesbury Sandstone. The sediments infilling the dells on the plateau are Quaternary in age, yet the plateau was uplifted no later than the mid-Oligocene (R.W. Young, 1977). Thus the dells on the Woronora Plateau present a record of sediment accumulation upstream of deep gorges, of Quaternary deposition on an early Tertiary erosion surface, of swamp development amidst dry sclerophyll forest. These seemingly paradoxical circumstances provide the catalyst for this investigation, which aims

i) to define the contemporary geomorphic processes acting in the dells.

ii) to assess the environmental stability of the dells.

iii) to postulate a theory for the origin and development of the dells.

These aims are pursued sequentially within the thesis. Firstly the position of the dells in the landscape and their relationship to the region's climate are examined (Chapter 2). Secondly, their geomorphic and ecological interrelationships are studied, with respect to the type of sediment and the processes of accumulation (Chapter 3), the flow of water and its effect on subsurface weathering (Chapter 4), and the response of the vegetation to varying sedimentary and hydrological patterns (Chapter 5). The development of patterned ground in some dells illustrates the interdependence of soils, hydrology and vegetative cover (Chapter 6). It will be clear from these discussions that the processes affecting the swamps are active today for the dells are not relict features undergoing degradation. Contemporary sediments are compared with those buried several thousand years ago in order to infer previous sedimentary processes and to examine the environmental stability of the dells (Chapter 7). Finally, the origin and development of dells on the Woronora Plateau are interpreted both in the light of local field evidence and in the context of theories concerning the evolution of dells elsewhere (Chapter 8).

Although the dells occupy less than 10% of the area of the Woronora plateau, their treeless sedge-dominated vegetation resembles the communities found extensively on organic swampy terrain elsewhere. Moore and Bellamy (1973, p.152) remark that tussock sedge communities are

> 'so frequent on the surface of mires that it is difficult to believe that they have not existed in the past [yet] they have gone unrecognised in stratigraphical studies.'

Since most of the geomorphic literature on the dells was written more than fifty years ago, there is clearly scope for re-examining theories about their origin and developments.

In this thesis I shall look at the dells holistically. There will be a strong emphasis on their geomorphic development, but this will be within the context of the other inter-related factors of climate, vegetation and environmental disturbances. Because of their kinship, both geomorphic and vegetational, with similar phenomena elsewhere in the world, the relationships elucidated for the Illawarra dells have far more than local relevance.

CHAPTER TWO: THE DISTRIBUTION, REGIONAL SETTING AND CLIMATIC ENVIRONMENT OF THE DELLS.

The Woronora Plateau lies south of Sydney between the Illawarra escarpment near Wollongong and the Nepean River. It is dissected by 5 major streams - Woronora River, O'Hares Creek draining to Georges River, Cataract River, Cordeaux River and Avon River. These streams change in valley form in a similar way to the rivers flowing from the dells of southwestern Germany:

> 'Near their mouths they are canyon-like and accompanied by rocky walls ...; upvalley they rapidly become narrower, as [they] rapidly gain in gradient ...; all at once they widen out into gently sloping, shallow troughs, this taking place as soon as the scarp-forming stratum, and the longitudinal break of gradient associated with it, have been crossed.'
>
> Penck, 1924, transl. 1972, p.186.

Hence the dells are plateau phenomena and do not extend down into the gorges. This is so on the Woronora Plateau, as it is in Germany (Penck, 1924) and Zambia (Mackel, 1974). In the Blue Mountains west of Sydney, however, swamps with similar soils and vegetation 'hang' like curtains down very steep valley sides, in addition to occupying troughs on the plateau surface (Holland, 1974).

The surface of the Woronora Plateau is not horizontal but rises from an elevation of 100 m along the Nepean River to 300 m at the crest of the Illawarra escarpment near Coal Cliff, and to 550 m near Robertson (Fig. 2.1). Taylor (1923) called this surface the Nepean Ramp. The major streams flow to the northwest down the fall of the ramp, away from the coast, and enter the Nepean-Hawkesbury system which finally discharges to

LOCATION MAP

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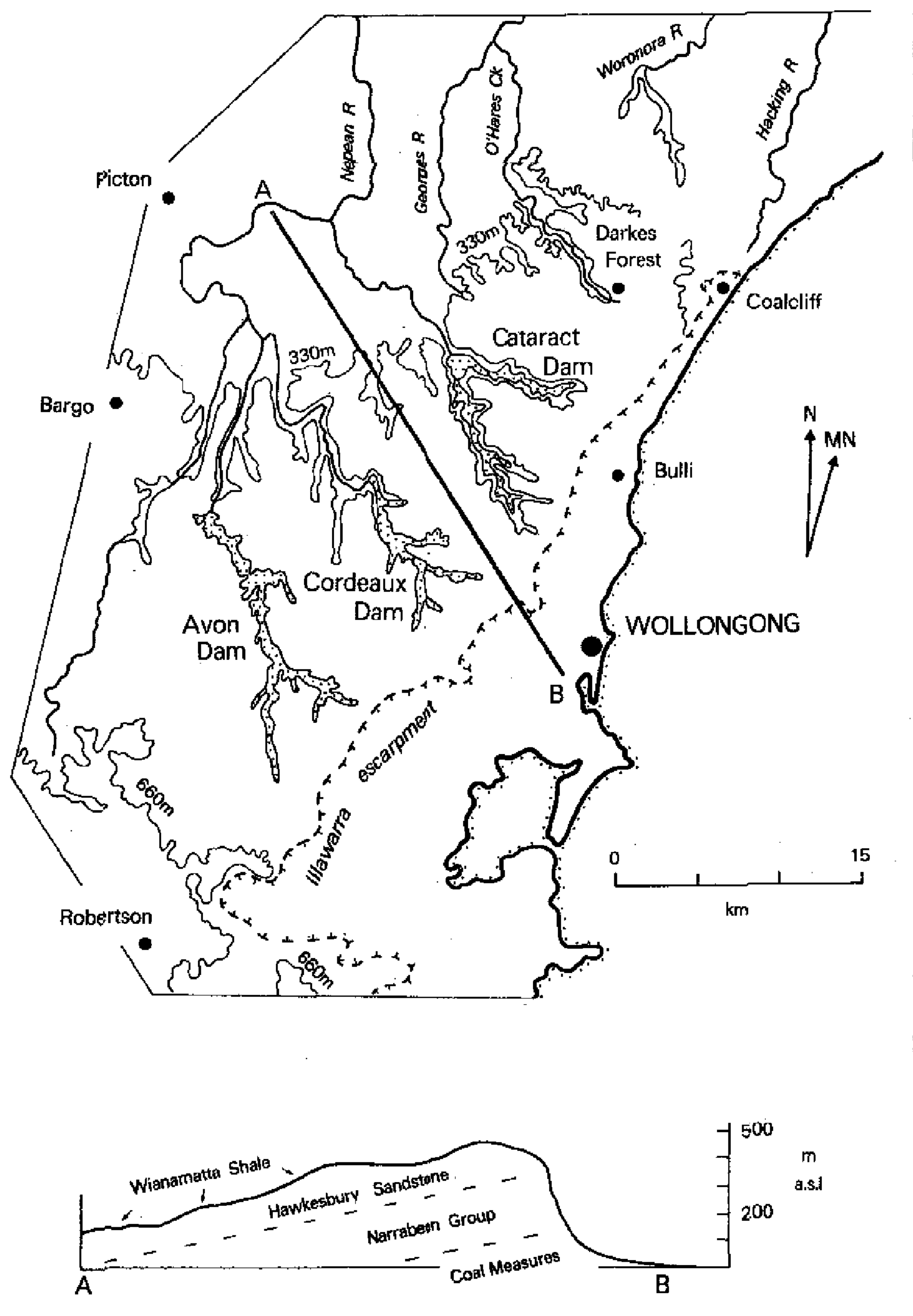


the sea some 100 km north of Wollongong at Broken Bay. In doing so, the streams follow not only the ramp-like topographic surface but also the dip of the Hawkesbury Sandstone. The top of this formation coincides closely with the topographic surface and dips to the northwest at an average slope of less than 1° over 15-20 km (Young and Johnson, 1977). All the dells on the ramp lie on the Hawkesbury Sandstone. They have not developed either on remnant patches of the overlying Wianamatta Shale, or in areas where the Bulgo Sandstone of the underlying Narrabeen Group is exposed. Hence, the spatial association between the dells and the Hawkesbury Sandstone is due not solely to the occurrence of both at the plateau surface, but in some part to the character of the Sandstone itself.

The Hawkesbury Sandstone

The Hawkesbury Sandstone, which is Triassic in age, is highly quartzose. It is comprised of medium-coarse, poorly sorted, quartz grains with secondary quartz-siderite cement, clay matrix and minor accessory minerals (Standard, 1969). Both its lithology and its bed dimensions are variable. Conaghan (1980) distinguishes three facies:

- facies of quartzose crossbedded sandstone
- massive facies of more clayey and less frequently crossbedded sandstone
- mudstone facies of grey-black laminated mudstone.

Occurrences of the mudstone facies are typically 0.3-5 m thick but those of the sandstone facies may be up to 10 m thick and several tens of metres long.

TABLE 2:1. BORELOGS OF THE HAWKESBURY SANDSTONE FROM LOCATIONS WITHIN DELLS.

a) Dept. Main Roads bore, near Sublime Pt

0-2.1 m	soft sandy clay
2.1-7.8 m	white soft medium-grained sandstone
7.8-11.0 m	white hard medium-grained sandstone with thin clay joints
11.0-14.0 m	grey medium-grained hard sandstone

Base of drillhole.

b) A.I.S. Wongawilli No.18, at 6R Swamp.

0-5.5 m	soil and weathered sandstone
5.5-15.8 m	light coloured, coarse sandstone
15.8-16.9 m	grey shale with many thin sandstone bands
16.9-18.7 m	medium-grained sandstone with carbonaceous-micaceous partings
18.7-21.6 m	grey shale with numerous thin sandstone bands
21.6-27.9 m	light coloured, coarse sandstone
27.9-28.8 m	dark grey shale
28.8-67.9 m	light grey coarse grained sandstone
67.9-70.0 m	dark grey shale with many sandstone beds
70.0-75.9 m	light grey coarse sandstone

Base of Hawkesbury Sandstone.

c) Wongawilli No. Bs(c) (Reynolds, 1978, Fig. 20), Drill hole Swamp.

It is tempting to suggest that dells on the Hawkesbury Sandstone could be due to mudstone facies impeding drainage. Buchanan (1980) notes 'puggy material' below valley swamps on the Hawkesbury Sandstone plateau north of Sydney, and Holland (1974) related hanging swamps in the Blue Mountains to emergence of seepage where slopes intersect the Wentworth Falls Claystone member within the Grose Sandstone formation. However, the mudstone facies constitutes less than 5% of the Hawkesbury Sandstone, and knickpoints below dells on the Woronora Plateau show only occasional, minor and discontinuous mudstone outcropping within the sandstone. Moreover, detailed borelogs which are available for three dells show no shales or claystones within 15 m of the surface (Table 2:1). Vertical drainage is impeded by the sandstone, not the mudstone, facies.

As Mainguet (1972, p.101 and 105, my translation) notes:

> 'the heterogeneity of sandstone, the alternation of strata of varying permeability, its lenticular structure and the presence of fissures of variable depth and opening create a complex pattern of internal circulation. Because permeability is greater along bedding planes than vertically through individual beds, flow from sandstone often emerges as pellicular flow, i.e. from two-dimensional, non-point sources, often close to summits and as dictated by planar or sloping surfaces of low permeability.'

These general comments apply well to the Hawkesbury Sandstone. On the Woronora Plateau, aquifers have been struck, in boreholes, at a number of different levels above any general regional water table, their flow systems being horizontal with minimal vertical movement (Reynolds, 1978). In the 10-20 m deep cuttings through

Hawkesbury Sandstone ridges exposed for 20 km along the Sydney-Wollongong expressway, seepage emerges in no apparent pattern, usually along bedding planes, rarely above mudstone lenses, often within a few metres of ridge-tops. It may continue for a week or more after rain, implying considerable local storage and slow flow rates in the rock mass. Thus the sandstone facies themselves, regardless of the occurrence of mudstone lenses, restrict vertical seepage into the rock mass from the plateau surface. The Hawkesbury Sandstone provides a surface of low permeability, a surface which contributes to the development of swampy conditions in the upland valleys. As the surface is more deeply dissected and the Hawkesbury Sandstone is less extensive in the southern part than in the northern part of the study area, it is not surprising that dells occupy smaller percentages of the catchment areas of the Avon and Cordeaux Rivers than of the northern streams.

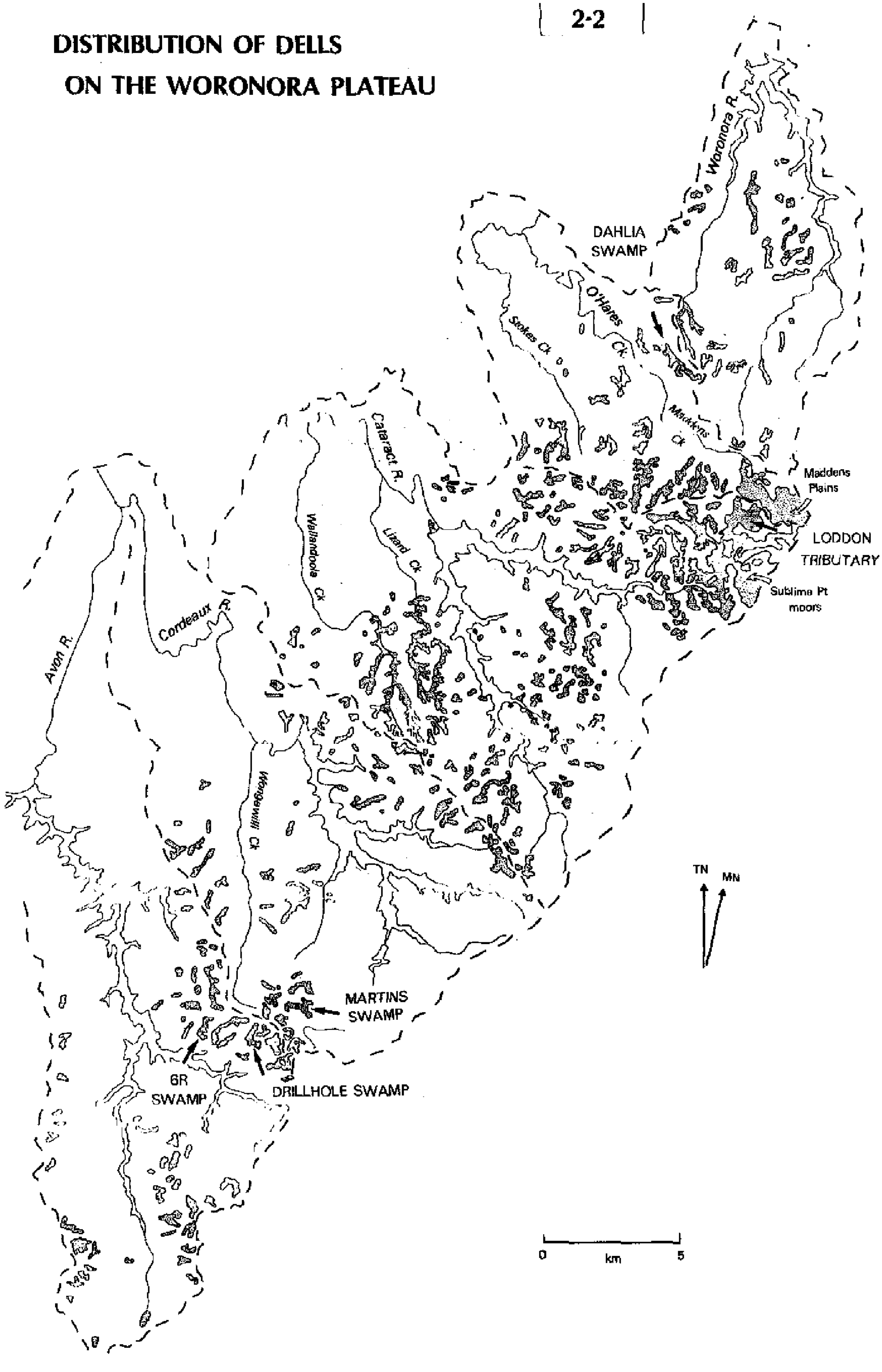
The distribution of the dells.

The distribution of the dells was taken from forestry maps, held by the Metropolitan Water Sewerage and Drainage Board, which showed open swamps. It was checked and supplemented using 1951, 1:17000 aerial photographs. Recent geological maps (1974, 1:50,000) and colour aerial photographs (1977, 1:20,000) were available for Cataract and Cordeaux catchments. From plans of the Southern Catchment (MWSDB 1":20 chains, 20 ft contour interval), slope angle, aspect and local relief (from the nearest divide or prominent bench to the floor of the nearest major stream) were measured on a 40 chain grid over all plateau areas above the gorges. Size, slope angle, aspect, drainage density and elevation data for the dells were taken from the same maps. In calculating catchment areas, the areas occupied by the dams which have been built in all the gorges except for O'Hares Creek, were excluded.

The dells on the Woronora Plateau are comparable in size to those described from Germany by Schmitthener (1925) and from Zambia by Mackel (1974). The most extensive dell is in Cataract River catchment along the Loddon River and its tributaries. Called the Sublime Point moors by Davis (1941), this area is 2.5 km across its widest part and has several arms which are 2-3 km long and 300-500 m wide. It is linked across the watershed to another dell 3 km long and 1.5 km wide on Maddens Creek in O'Hares Creek catchment. These two areas are known locally as Maddens Plains. Most other dells are less than 1 km long and 200 m wide but those on Lizard Creek and Wallandoola Creek, in Cataract catchment, are 5 km long (Fig. 2:2).

Cataract catchment not only contains the largest individual dells on the plateau, but has a greater percentage of its area occupied by dells than have the other catchments (Table 2:2). Dells are far more numerous (123) than in the other catchments of similar size, Cordeaux (47) and Avon (61). They occupy 9% of the catchment's area, compared with 2.3% and 3.1% respectively in Cordeaux and Avon catchments. The two smaller northern catchments, Woronora and O'Hares, have similar numbers of dells (31 and 26 respectively) but, because that along Maddens Creek is so large, 8.1% of O'Hares catchment but only 3.1% of Woronora catchment is occupied by dells.

DISTRIBUTION OF DELLS ON THE WORONORA PLATEAU



As we have noted earlier, the dells occur only on the plateau surface where the Hawkesbury Sandstone outcrops; they do not extend into the gorges. These facts largely account for the differences in the distributions across the five catchments.

TABLE 2:2. COMPARISON OF DELL AREAS IN DIFFERENT CATCHMENTS.

	Woronora	O'Hares	Cataract	Cordeaux	Avon
Catchment area (ha)	7 290	7 510	18 580	15 440	14 350
% of area occupied by dells	3.8	8.1	9.0	2.3	3.1
No. of dells	31	27	124	47	61
% of area where H.Ss outcrops	100	100	89	68	85
Av. local relief (m)	97	80	65	110	125
% slopes 10°	77	93	88	68	75

Cataract River has the largest catchment area and Hawkesbury Sandstone outcrops over 89% of it. Slopes within the catchment are very gentle, 88% being less than 10°, and relatively short, as average local relief is 65 m. Hence the prominence of the dells there is not surprising. Hawkesbury Sandstone outcrops throughout O'Hares Creek and Woronora catchments, the difference with respect to dells being due to the gentler (93% <10°, average local relief 80 m) slopes in O'Hares Creek. The two large southern catchments, Cordeaux and Avon, are deeply dissected. Their average local relief exceeds 100 m and only 75% of the measured slopes were

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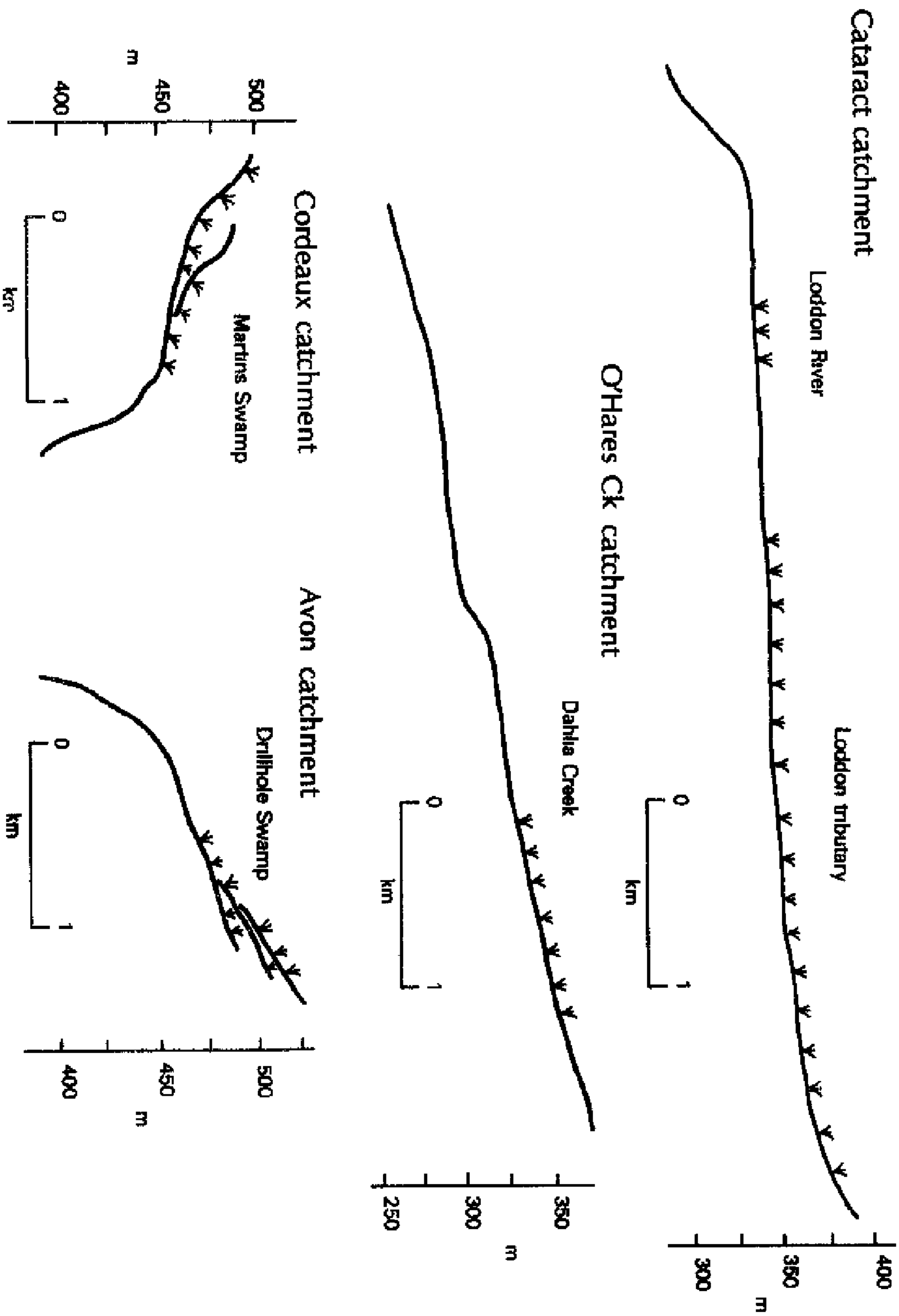
STREAM LONG PROFILES



gentler than 10°. The Hawkesbury Sandstone has been breached extensively in Cordeaux catchment.

The importance of slope form is illustrated further in Figure 2:3, which shows longitudinal profiles of selected dells. Those for Martins Swamp, in Cordeaux catchment, and Drillhole Swamp, in Avon catchment, show very clearly the sudden break of slope at the base of the Hawkesbury Sandstone, with the dells perched above steep-floored gorges. In Cataract catchment, the section through the Sublime Point moors shows the very gentle slope of this part of the plateau and again the dells perched above a distinct break of slope. The knickpoint at O'Hares Creek is even less prominent, and the dells are confined to the upper reaches despite gentle slopes on Hawkesbury Sandstone downstream. We shall return to this last point when discussing regional climate later in the chapter.

Figure 2:3 is misleading however, as it suggests that the gradients of the dells, as well as of the regional slopes, are steeper in the more dissected catchments. This is not so. Dell gradients, measured down their long axes, are similar in Cataract and Cordeaux catchments, with about ⅓ (33% in Cataract, 32% in Cordeaux) having slopes of 4.1-8.0°, about ½ (54% and 50%) having slopes of 2.1-4.0°, and the remainder having slopes less than 2°. Furthermore, drainage densities are lower in Cordeaux catchment (mean of 4.16 km/km^2 for 26 subcatchments of 0.03-4.30 km^2) than in Cataract catchment (mean of 5.70 km/km^2 for 27 subcatchments of 0.13-2.53 km^2), and there is a corresponding difference in the relationships between stream length and drainage area:

in Cataract, $L = 5.248\ A^{1.0087}$ ($r^2 = 0.933$, $n = 32$, $p<0.01$)

in Cordeaux, $L = 4.306\ A^{1.1989}$ ($r^2 = 0.914$, $n = 33$, $p<0.01$).

The swampy sediments in the dells are accumulations within an existing stream network. It is unlikely that they themselves influence the pattern of that network, for there is no significant correlation between the drainage density of the subcatchments and the percentage of their areas occupied by swampy dells ($r = 0.304$, $n = 27$, $p>0.05$ for Cataract, $r = 0.045$, $n = 26$, $p>0.05$ for Cordeaux; subcatchments with zero area of dells being omitted).

The differences in the extent of the dells in the catchments reflect the varying availability of gently-sloping Hawkesbury Sandstone surface.

The position of the dells.

In keeping with their plateau location, most of the dells lie within first- or second-order valleys (Table 2.3). They are not however always confined to the valley floors, but sometimes lie on benches or steep valley sides. Schmitthener (1925, p.5) commented that because of the similarity in appearance of slope dells (Hangdellen) and flat dells (Flachdellen) in Germany, the same principle of formation must apply to both. The Illawarra dells can be classified, using the division of Holland (1974), into valley-floor and valley-side swamps. Even if valley-floor swamps have lobes which extend up onto adjacent benches, they are called valley-floor swamps in this study. Buchanan (1980) however calls these features 'composite swamps'.

TABLE 2:3. COMPARISON OF DELL POSITION AND SIZE IN DIFFERENT CATCHMENTS.

	Woronora		O'Hares*		Cataract*		Cordeaux		Avon	
Area occupied by dells (ha)	282		360		1176		340		429	
No. of dells	31		26		123		47		61	
% of dells in valleys of	by no.	*by area*	by no.	*by area*	by no.	*by area*	by no.	*by area*	by no.	*by area*
1st order	25.8	*16.2*	44.0	*22.6*	30.0	*9.5*	32.6	*22.1*	11.7	*8.0*
2nd order	67.7	*80.4*	36.0	*27.8*	43.2	*27.7*	47.8	*55.6*	73.3	*73.2*
3rd & 4th order	6.5	*3.4*	20.0	*49.7*	26.8	*62.7*	19.6	*22.2*	15.0	*18.8*
% of dells which are valley-floor swamps	64.5	*70.1*	65.4	*79.4*	58.5	*75.2*	65.2	*75.5*	78.3	*80.6*
% of dells										
<3.3 ha	35.5	*7.5*	34.6	*5.8*	46.3	*9.2*	46.9	*12.9*	26.2	*9.0*
3.4-6.5 ha	12.9	*8.5*	11.5	*4.3*	22.0	*11.3*	17.0	*12.1*	37.7	*25.4*
6.6-13.0 ha	35.4	*36.4*	23.1	*16.2*	13.0	*13.2*	21.3	*33.6*	21.3	*27.1*
13.1-26.0 ha	9.7	*19.1*	11.5	*19.2*	13.8	*27.8*	12.8	*25.5*	14.8	*38.5*
>26.0 ha	6.5	*28.5*	19.2	*54.5*	4.9	*38.4*	2.1	*15.8*	-	-
No. of dells with open channel	4		4		20		9		5	

* This analysis excludes the extensive dell of Maddens Plains-Sublime Point moors. This dell occupies 246 ha in O'Hares Creek catchment and 486 ha in Cataract catchment.

Valley-side swamps are most common in Cataract catchment where the slopes are short, gentle and benched. Even here they do not extend continuously from the valley-floors up steep ridges; they overlap a watershed only in a narrow link to Maddens Plains. They differ in this respect from many mires in the Northern Hemisphere (Moore and Bellamy, 1973) and from the structurally similar 'button-grass' plains of Tasmania (Jackson, 1968). About ⅓ of the swampy treeless areas in O'Hares, Woronora and Cordeaux catchments are best classified as valley-side features, but in Avon catchment the long steep slopes discourage moisture and sediment accumulation on the valley sides.

In all catchments, most of the dells are small and there are no obvious trends in their size distributions (Table 2:3). Given their location in first- and second-order valleys, their smallness is not surprising. Only 22% of valley-floor dells have any open channel. When present, a channel extends only a short way upstream of the dell exit or consists of a few discontinuous pools. Most of the dells, particularly those less than 6.5 ha in area, are devoid of any open channel and none has an open channel bisecting it throughout its length. In these small, sediment-choked, gently-sloping valleys, stream power is not sufficient to excavate and maintain a continuous, open channel. Yet the swampy nature of the dells demonstrates a humid local climate

The climatic environment of the dells.

We noted earlier that the dells on O'Hares Creek were confined to the upper reaches of streams even though gentle sandstone slopes exist at lower elevations downstream. It is clear also from Figure 2:2 that the dells occur on the higher parts of the plateau near the Illawarra escarpment. Rainfall is higher in the eastern area, and the annual average precipitation (for 1931-60) is 1500-1600 mm/year along the escarpment crest but drops to only 1000 mm/year along the Nepean River (A. Young, 1976). Since temperature declines at higher elevations, the effect of higher rainfall near the escarpment is enhanced by lower evaporation.

In Table 2:4, climatic data are given for four stations. Wollongong lies on the coastal plain below the Illawarra escarpment and has similar elevation and rainfall to the Nepean River further west. Mt. Keira Scout Camp is on the escarpment but is representative of the rainfall and temperature conditions on the eastern edge of the plateau. The Tasmanian station - Waratah -lies within the area mapped as 'button-grass' plain in Davies (1965). It is added for comparison with the Illawarra stations because its peaty shallow valleys are similar to those characterising the Illawarra.

In summer at Wollongong, estimated average evaporation exceeds the average rainfall and only between April and July does Pr-Ev (precipitation minus evaporation) have an appreciable positive value. The estimated annual effective rainfall at Wollongong is a mere 44 mm (Table 2.4). At Mt. Keira Scout Camp, Pr-Ev is positive for all months. The average annual rainfall is about 700 mm higher than at Wollongong but, because of lower evaporation, the estimated effective rainfall is 840 mm higher.

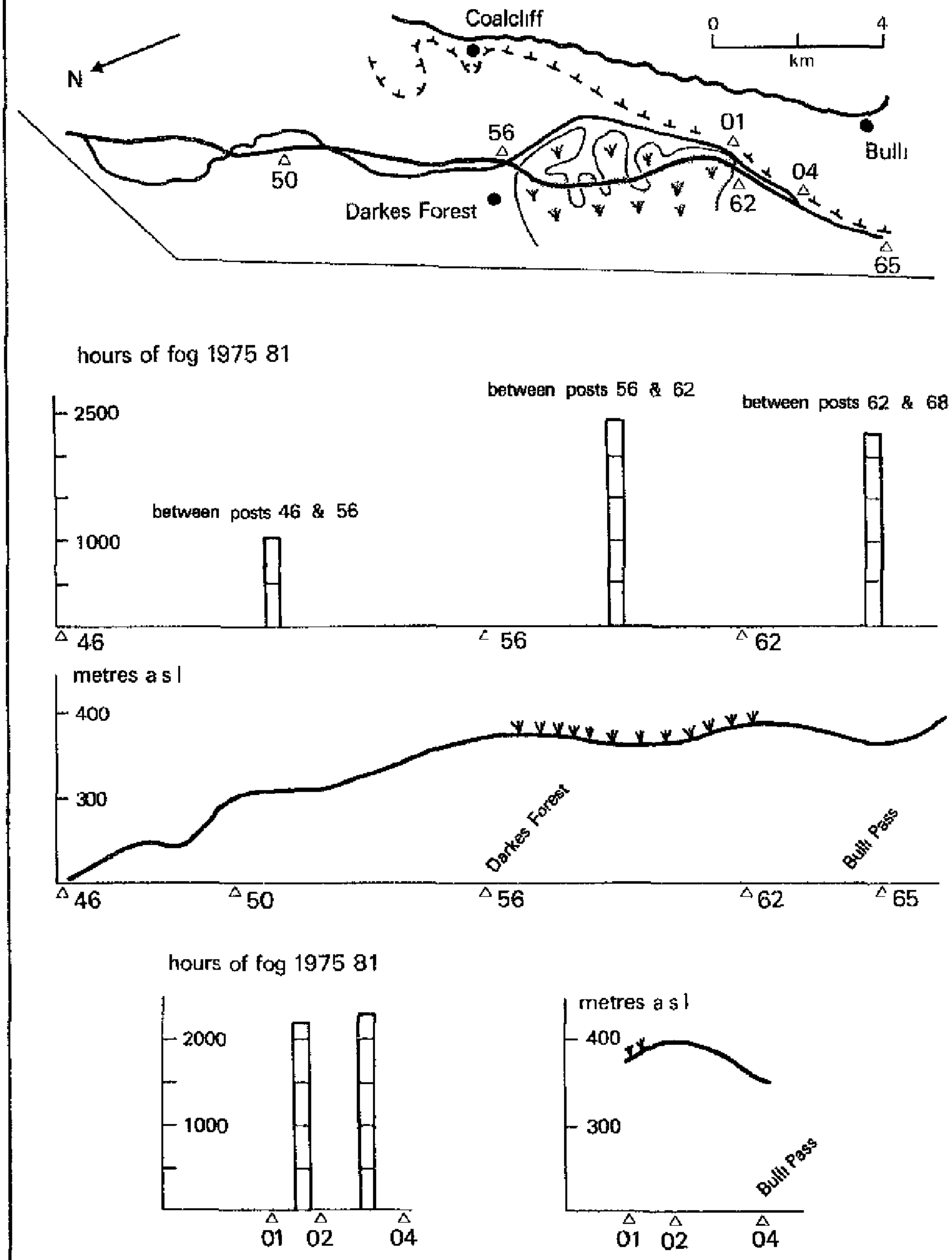
TABLE 2:4. PRECIPITATION-EVAPORATION, ILLAWARRA AND WESTERN TASMANIA.

Evaporation (*Ev*) estimated by Q_s (0.02 RT + 0.9-R) and Q_s = T/4.1-0.048A, multiplied by days per month, where R = relative humidity, T = average mean daily temperature and A = empirical constant (Linacre, 1969). Data from Handbook of Climatic Averages (1969) and for *MKSC*, by courtesy of Mrs D. Walsh.

Annual effective rainfall is high also at both the Tasmanian stations, where there are no months with an appreciable moisture deficit. In terms of moisture availability therefore, the climate of the higher areas of the Woronora Plateau is like that of the button-grass regions of south-west Tasmania. It is not surprising that the Illawarra dells are restricted to the eastern part of the plateau and absent from the lower drier parts near the Nepean River.

Further confirmation of the interrelationship between landscape, climate and dell distribution on the Woronora Plateau comes from analysis of fog records along the F6 expressway through the Maddens Plains area. Since 1975 the Department of Main Roads has kept records of the times when 'fog hazard' lights were used on the expressway between Bulli Pass and Waterfall (Fig. 2:4). The fog is due not to advection but to interception of low cloud cover formed by orographic lift over the escarpment. Fog extends therefore only a few kilometres west of the escarpment, as it disperses when the air is free to drain off into the gorges. Fog hazard lights were used for some part of 436 of the 2191 days between October 1975 and September 1981 (inclusive). Where the plateau is quite flat between Bulli Pass and Darkes Forest, over 2000 hours of fog occurred in this 6-year period, but where deep valleys cut into the plateau further north, only 1000 hours of fog were recorded. Along the Bulli Pass to Darkes Forest stretch, the number of hours of fog was slightly higher (2408 hours) where the expressway cuts across the dells (posts 56-62) than where it cuts through forested ridges near Bulli Pass (posts 62-68, 2257

FOG OCCURRENCE, MADDENS PLAINS - SUBLIME PT MOORS



hours) and where the highway skirts the eastern edge of the Sublime Point moors (posts 01-04, 2273 hours). Fog condensing on the vegetation can augment the rainfall in the Maddens Plains area. Perhaps too, the wet and possibly cooler ground encourages atmospheric condensation. Whatever the causal links, the swampy terrain and the frequency of fog appear to be related.

The overall significance of regional climate

Precipitation need not exceed evaporation in all months or even annually in order for moisure to accumulate and for swampy areas to develop. Ivanov (1981) regards mires as zonal phenomena and distinguishes three zones:

- a zone of excess moisture, where mires may be situated on divides and interfluves as well as on terraces and floodplains.
- an intermediate zone of unstable moisture, where average precipitation minus evaporation is less than 100 mm/year, and mires are pine-Sphagnum communities.
- a zone of deficient moisture, where annual precipitation minus evaporation is negative and mires occur only in depressions where surface and subsurface inflow, rather than rainfall, provides their water supply.

The range of climatic environments in which mires develop is illustrated by the climatic diagrams in Figure 2:5. Both the Hudson Bay lowlands and the northern Finland mires have less humid, even though colder, climates than the Illawarra dells Yet, as will be shown in Chapter 6, the microtopographies

2·5

CLIMATIC DIAGRAMS FOR MIRE TERRAIN

after Sjors 1959

after Moore and Bellamy 1973

after Walter *et al*, 1975

after Gellie 1980

of the three areas are closely akin. The similarity of the climatic data for Mt. Keira and Cape Sorrell (see Table 2.4) demonstrates that the latitudinal climatic influences can be simulated by altitudinal changes. This is noted in fact by Ivanov who comments that the zonal pattern, outlined above, breaks down in mountainous and upland terrains.

> 'The orographical peculiarities of a locality affect mire formation, both through the climatic conditions they create and through the direct effect of its relief.'
>
> Ivanov, 1981, p.8.

The dells in the Illawarra are akin geomorphically to features on plateaux elsewhere in the world - for example, Germany and Zambia. In terms of effective rainfall, of course, these areas may be similar to southeastern Australia. But their climatic histories have been markedly different. The dells must be therefore either convergent forms in the different areas or analogous forms whose development is not primarily governed by regional climate.

The close interrelationships discussed in this chapter between the present landscape and climate on the Woronora Plateau and the distribution of dells across it, imply that the dells did not form under now-defunct geomorphic or climatic conditions. The dells are probably neither relicts where 'present processes do not develop them any more but on the contrary contribute to their destruction' nor extrazonal survivals which formed under past conditions but 'continue to evolve in the same way, even if it is slower' (Tricart and Cailleux, 1972, p.145). It is towards the contemporary processes, particularly those affecting stream competency, that we must look first in order to understand the origin and development of the Illawarra dells.

SUMMARY

- Like the dells of southern Germany and Zambia, the dells in the Illawarra occur on plateaux.
- They only occur where the Hawkesbury Sandstone outcrops. This formation has very low vertical permeability and contains horizontally-flowing aquifers at many levels.
- The dells are most numerous and most extensive where the Hawkesbury Sandstone surface of the plateau is little-breached, where slopes are gentle and average local relief is low.
- Most of the dells are small (<13 ha), occur in first- or second-order valleys, and occupy valley-floors rather than benches on the valley-sides.
- They occur where precipitation substantially exceeds evaporation, at the high eastern side of the plateau. With respect to effective rainfall, climate here resembles the 'button-grass' areas of Tasmania.
- In the Maddens Plains area, fog is common near the dells.
- The interrelationships among the dells, the landscape and the climate suggest that the dells are contemporary phenomena.

1. Martins Swamp. Note the abrupt margin of the dell, the deep green seepage zone, the sand washed in from a road to the right of the photo, the Melaleuca thicket in the top right adjacent to eucalypt forest, the pools. M1 transect is at the base of the photo, M2 across the neck where the dell branches upstream.

2. Pools on the Loddon River. Flow is from the base to top of photo. Dating site is just below the upstream crossing. Note the gentle slopes, the groves of trees within the dell, the narrow channel between the pools, the minor valley lacking a channel that enters from the top left.

3. From M1 towards M2, Martins Swamp. Note the large-leafed Banksia robur and the curved wands of Gymnoschoenus sphaerocephalus.

4. The pool at M1 transect. Note the tall shrubs along this wet area.

CHAPTER THREE: THE ACCUMULATION AND CHARACTER OF THE SEDIMENTS.

> 'Any surface feature which reduces ... the competency of the [moving] water body to a level where sediments are no longer carried by traction can constitute a template for peat formation.'
>
> Moore and Bellamy (1973, p.9)

Stream competence depends on gradient, depth of flow and flow velocity. On all these counts, the competence of the dells must be low. They are headwater valleys lying on a gently-sloping plateau, they have small discharges, they lack continuous open channels, and they are well-vegetated. Since the detritus supplied to them is derived from medium-coarse quartzose sandstone, the accumulation of sandy sediment in the upland valleys can be expected. As Moore and Bellamy note, peat accumulation in such a site is likely also. The waterlogged sediments are poorly aerated; in consequence, partially decayed organic matter accumulates.

The swampy organic-rich soils of the dells and the associated treeless sedge-dominated vegetation are indirect consequences of the geomorphic setting. Nevertheless the ecological processes acting within the dells both influence mineral sedimentation and of course contribute biogenic sediment. The dells thus provide a record of the interplay of geomorphic and ecological processes.

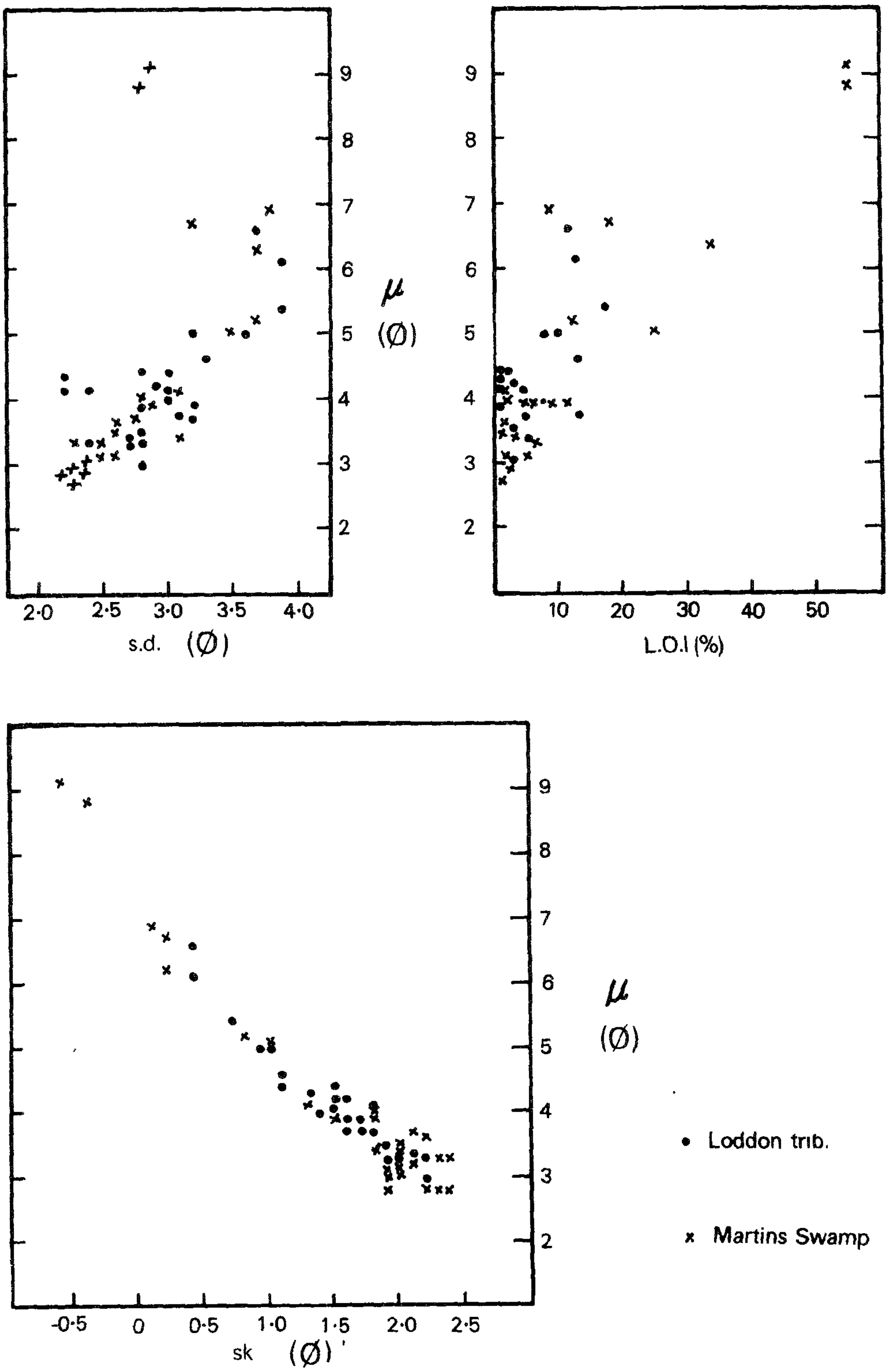
The characteristics of the dell sediments.

The sediments infilling the shallow valleys on the Woronora Plateau are derived either from weathering of the underlying

CLASSIFICATION OF DELL SEDIMENTS

after Folk, 1974

CHARACTERISTICS OF DELL SEDIMENTS



Hawkesbury Sandstone surface, or from erosion of the surrounding ridges. As these ridges are predominantly Hawkesbury Sandstone also, with only minor patches of Wianamatta Shale, the sediments are dominated by medium-coarse quartzose sand. Because their environment is swampy, the sands are darkened by varying amounts of humic substances. They contain variable quantities of silt and clay; it will be argued later that a lack of mineral fines distinguishes transported sands from those formed by in-situ weathering.

Generally the sediments are muddy or silty sands (Fig. 3.1) which are very poorly sorted and highly skewed. The coarsest sediments are better sorted than the finer sediments but are also more highly skewed and have a variable organic content (Fig. 3.2). The finest sediments are silty clays with very high organic contents.

The highly organic fine-grained sediments lie along the valley axes and may be 3-4 m deep. They rest on firm bedrock rather than above a gradational weathered zone, and they are Quaternary deposits (Table 3:1). On the sideslopes of the dells, the sediments are sandy and are 0.5-2 m deep in most places. Along the forest margins, the depth of sediment rarely exceeds 1 m. The present groundsurface of the dells is usually smoothly sloping except for microtopographic variations, but it may bear little relationship to the underlying bedrock surface.

The classification of dell sediments.

The variable and sometimes very high organic content cannot be excluded from any classification of the dell sediments,

TABLE 3:1. RADIOCARBON AGES OF MATERIAL LYING ON BEDROCK IN VALLEY-FLOOR DELLS.

*R.W. Harden (1967)

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yet organic matter is removed before standard sedimentological analysis and description is undertaken (Folk, 1974). On the other hand, classifications of organic sediments focus on peats with minimal non-organic material and on their pedological rather than their sedimentological properties (Buol, Hole and McCracken, 1973). Duchaufour (1970) distinguishes tourbe (peat) with little mineral matter from anmoor with considerable incorporated mineral matter, but again is concerned with pedological processes. In this study however, both the organic content and the grainsize distribution of the mineral fraction are used to classify the unconsolidated sediment in the dells.

It may be noted that several pedological terms could be applied to the sediments. They were mapped in the Atlas of Australian Soils simply as organic (O) soils and yellow earths (Gn. 2.2) (Northcote, 1966). They resemble those of the poor fen environments of the Monaro (Costin, 1954) and the button-grass moorland of Tasmania (Nicolls, 1957; Stace et al., 1968), which may be described as peaty podzols (Stace et al., 1968).

To classify the sediments in the dells, samples were taken at 0.5 m depths on transects across a tributary of the Loddon River in Cataract catchment and across Martins Swamp in Cordeaux catchment. The depth of sampling was chosen as it lay below the surface root mat but consistently above firm bedrock. The moisture content, pH, loss on ignition, total iron oxide content, colour and grainsize parameters (by method of moments) were determined for 49 samples. One site, M2/13 at Martins Swamp, was excluded because the soil depth was only 0.1 m. The same parameters were determined for 5 samples from 0.5 m depth across the forest-swamp ecotone at the Drillhole Swamp in Avon catchment and for 13 samples of buried sediment (up to 4 m below the surface), also from the Drillhole Swamp. Methods and results are given in Appendix I.

Using loss on ignition values (L.O.I.) (as a surrogate for organic carbon content) and grain size parameters, the samples were grouped by clustering on the basis of correlation coefficients. Use of a discriminant analysis programme (Nie, 1975) led to minor re-grouping. Because L.O.I. was dominant in distinguishing between groups, there is some overlap between groups C and D apparent in Figure 3.3. Nevertheless according to the analysis, 87.9% of cases were grouped correctly and the groups were significantly different (Box's M statistic, $p < .001$).

pH was not used in the clustering process because it

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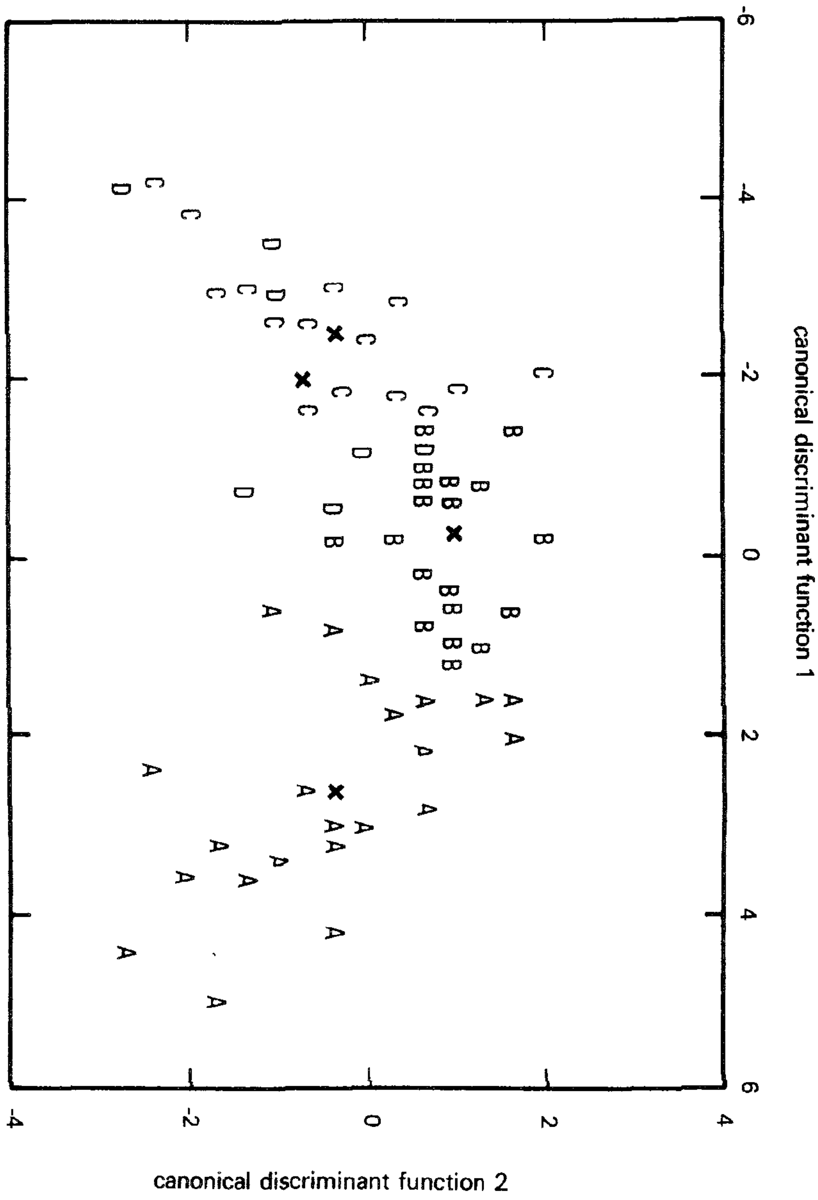
TERRITORIAL MAP OF SEDIMENT GROUPS



varied between, rather than within, the two main sites. At the Loddon tributary it ranged from 3.6-4.5 and at Martins Swamp from 4.7-5.3. Iron oxide content was not used because it was high in two quite separate environments - the permanently waterlogged organic sediments and the sediments characterising the driest slopes of the dells. Loss on ignition (L.O.I.) was used since it was quicker to determine than organic carbon (C_{org}). In addition to loss on ignition, organic carbon was determined for 55 samples by the modified Walkley-Black dichromate oxidation method; the relationship between the two parameters is linear.

$$C_{org} = 0.142 + 0.344 \text{ L.O.I.} \qquad r^2 = 0.939, \; p < 0.005.$$

The slope of the regression is significantly different from zero but the intercept value is not (method after Griffiths, 1967). Hence the loss on ignition values are due to destruction of organic material and are not enhanced by loss of water from clays or by decomposition of carbonates.

Four groups of sediments were distinguished:

Group A: <u>Organic fines</u>.

These are black, wet sediments with a greasy feel, high silt/clay content and less than 50% coarse-medium sand. Their organic content is high (L.O.I. 8-64%, C_{org} 3-22%).

Group B: <u>Organic sands</u>.

These are dark, grey-brown to black, moist sediments with discrete grains of clean sand amidst dark, humified organic matter. They have little silt/clay but appreciable coarse-medium sand (50-75%). Their organic content is lower than for the organic fines (L.O.I. 2-6.5%, C_{org} 0.5-2.8%).

Group C: Grey-brown sands.

These sediments have little silt/clay and appreciable coarse-medium sand (64-70%) but less organic matter than the organic sands (L.O.I. 1.1-5.4%, C_{org} 0.7-1.3%), so they are lighter in colour. They are often moist.

Group D: Sandy yellow earths.

These sediments have a thin (10-30 cm), very dark grey surface horizon but below this are yellow, red or brown. They have relatively high clay contents (24-36%), low coarse-medium sand fractions (30-50%), and low organic contents (L.O.I. 1.3-2.5%). Clay content and the degree of mottling increase with depth.

The yellow earths (Group D) are in situ residual soils, although slopewash may have added sediment to their upper horizons. They are highly organic in their surface horizon but otherwise typical of yellow earths weathered on the Hawkesbury Sandstone. Their in situ formation is shown by their high clay contents and by the gradational changes in their profiles. The remaining groups appear to be largely depositional. The organic sands (Group B) and the grey-brown sands (Group C) contain less silt-clay and considerably more coarse-medium sand than do the yellow earths. They are distinguished from one another by their different organic contents and resulting difference in colour. The organic fines (Group A) often have a very low mineral content and could be described as peat. What little mineral material is present, is very fine-grained, so this group is separated from groups B and C on the basis of texture as well as of organic content.

SEDIMENT CHANGES IN THE DELLS

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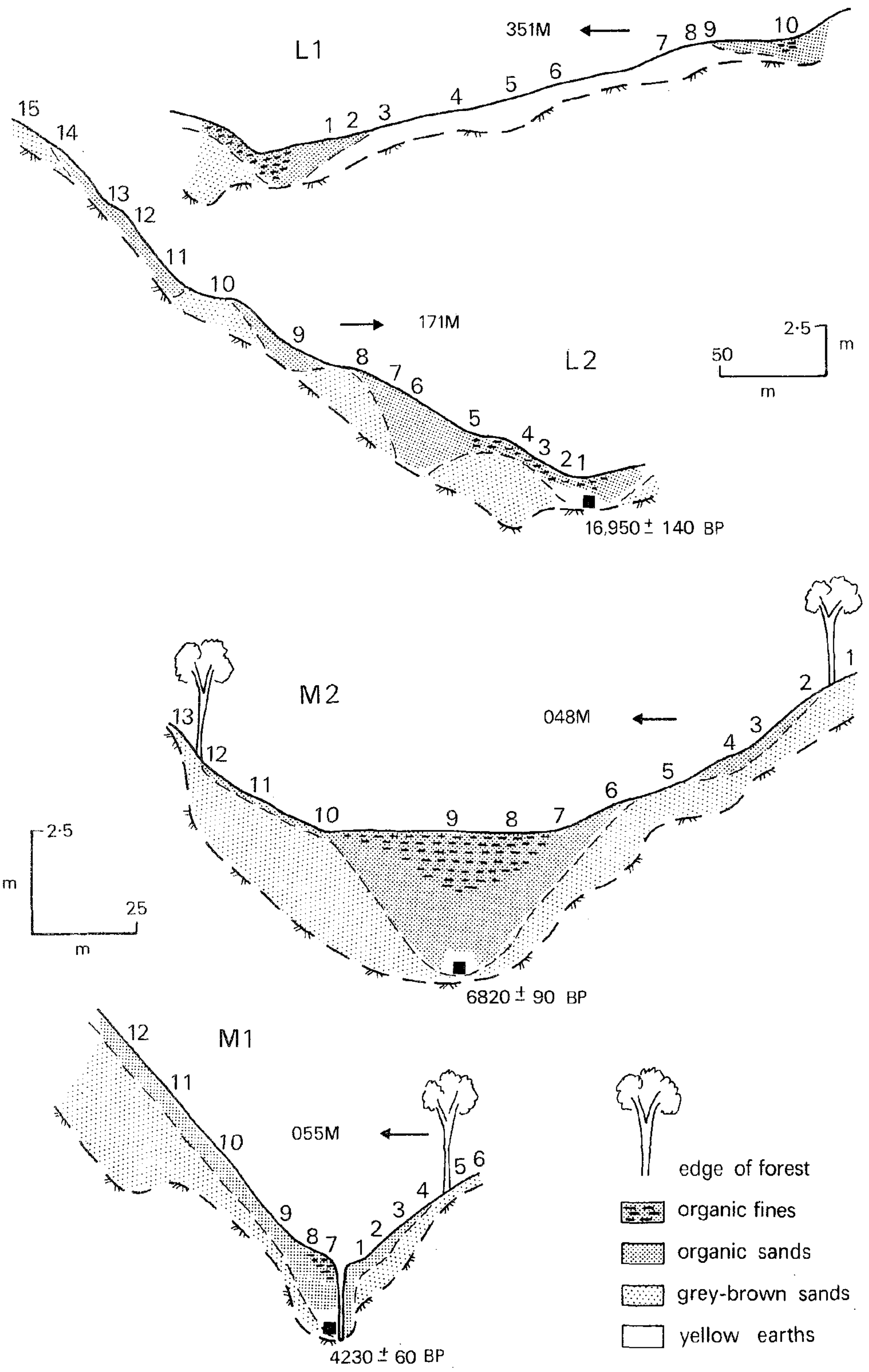


The distribution of sediment types.

As the 4 sediment types could be readily distinguished in the field, their distribution along the transects could be plotted from augered profile data (Fig. 3.4).

Organic fines (Group A) are limited in extent, not merely across the valleys but with depth. They reach to bedrock at Maddens Plains but not at either of the Martins Swamp transects. They are set within wedges of organic sand along permanently wet valley axes. Their organic content is highest close to the surface, where presumably the peat is still forming. For example, in the centre of the upstream Martins Swamp transect (at M2/9), the loss on ignition values are 63% at 0.1 m, 50% at 1.0 m and 20% at 1.75 m, but drop to only 6.4% in the organic sands at 2 m and 4% at 3.4 m.

The organic sands (Group B) lie directly on firm bedrock below the valley axes. There is no gradation into soft weathered material above the bedrock surface. Although the underlying sandstone is pale, it is cohesive. It rings when struck, and resists penetration by a power auger, though the upper few centimetres can be gouged out with a hand-operated bucket auger. Group B sediments also extend across the sideslopes, particularly where these are long and south-facing (L2 transect; M1/7-12). On the sideslopes they often form a surface horizon 20-50 cm deep. They may reach to bedrock where the sediments are shallow (L2/9,11-12), where tributary seepage zones cut across the slope (L1/10) and where former channel positions or tributary seepage zones are intersected by the transects (L2/6).

The grey-brown sands (Group C), which may range in colour from pale grey to very dark grey brown, also lie on firm bedrock. Like the organic sands and unlike the yellow earths, their profile, and show no consistent increase in clay content or in cohesiveness with depth. When wet, they may be sloppy and difficult to retain on the auger even directly above the bedrock surface. They are the most extensive sediments in the sections studied, although they are usually masked by surface horizons of organic sands (note particularly M1/10-12; M2/10-12; L2/3-5; L2/8).

The yellow earths (Group D), typical of the relatively dry, north-facing sideslope of the Loddon tributary, are less common. These and other similarly clayey gradational residual soils appear to characterise only the extensive dells of Cataract catchment, for example at Maddens Plains and Wallandoola Creek. They occur on sideslopes which do not have a permanently or even frequently high water table.

Sedimentary processes within the dells.

> 'Given a supply of heterogeneous detritus, an extremely consistent succession of sediment types differentiates downhill, with distally decreasing surface slopes, as transporting power and turbulence decline.'
>
> Moss and Walker (1978, p.81).

Shallow overland flow, the transporting process dealt with by Moss and Walker, characterises the dells because they lack channels and are densely vegetated. Their sediment supply is certainly heterogeneous, as it comes from weathering and erosion of the Hawkesbury Sandstone which is itself variable. As Standard (1969, p.412) notes:

> 'The Hawkesbury Sandstone is composed of relatively discontinuous layers of highly cross-bedded quartz sandstone; it has an argillaceous matrix and a secondary quartz-siderite cement. It is moderately to poorly sorted ... The grain size varies from fine to very coarse, medium to coarse grains being the most common ... pebbles are usually found scattered randomly ... or in thin layers 2.5-5 cm in thickness.'

The sediment derived from the Hawkesbury Sandstone is thus largely medium-coarse quartz sand with some clays.

Moss and Walker (1978) point out that in overland flows, even if they are only a millimetre or so deep, moving debris separates into suspended and bed-loads. Most silt/clay-sized material, both organic and inorganic, travels quickly as suspended load and is not incorporated into the interstices of coarser hillslope sediments. In the dells, small plant fragments are also carried in suspension for considerable distances and are winnowed out of the denser sands. Where turbulence wanes, when a flatter slope is reached or when fluid energy is dissipated by the plant cover, redeposition of fine-grained material occurs rapidly and often in high concentrations. There is a marked textural break, accompanied by a sudden lowering of slope gradient, between the hillslope deposits of clean sand and the finer deposits downslope.

Hence the abrupt fining of the mineral fraction in the valley axes appears to be caused by sudden redeposition of the suspended load of inflowing slopewash. The break between the organic fines and the organic sands is marked by an abrupt rise in silt-clay content and drop in the coarse-medium sand fraction (Table 3:2). (Compare for example L2/6 organic sand with L2/5 organic fines, and M1/9 organic sand with M1/8 organic fines.)

TABLE 3:2. CHARACTERISTICS OF THE DELL SEDIMENTS, LODDON TRIBUTARY AND MARTINS SWAMP.

Site L1/	1	2	3	4	5	6	7	8	9	10					
Sedt group	B	B	D	D	D	D	D	D	D	A					
Mean (ø)	3.1	3.2	2.9	3.0	3.4	3.1	3.3	3.1	3.4	5.6					
% co-med sand	52	49	51	53	52	45	31	32	31	20					
% silt/clay	25	26	24	28	36	30	33	27	27	52					
L.O.I.	5.1	3.6	1.6	1.8	1.7	1.3	1.1	1.8	2.5	11.8					
Site L2/	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Group	A	A	A	A	A	B	B	B	A	B	B	A	B	B	C
Mean (ø)	4.4	5.1	4.0	4.0	3.6	2.7	2.7	2.5	2.9	2.3	2.4	2.7	2.0	2.3	2.3
% co-med sand	44	36	43	46	48	69	69	67	65	70	68	64	76	73	66
% silt/clay	43	52	42	37	34	19	20	19	22	17	16	20	13	18	14
L.O.I.	17.7	13.2	9.7	8.3	13.2	5.1	5.0	3.2	8.0	2.0	5.8	13.4	3.4	2.7	1.8
Site M1/	6	5	4	3	2	1	7	8	9	10	11	12			
Sedt Group	C	C	C	C	C	C	A	A	B	B	B	B			
Mean (ø)	1.8	1.7	1.8	1.8	2.1	2.1	5.9	4.2	2.9	2.4	3.1	2.5			
% co-med sand	66	70	69	68	66	67	24	48	63	69	57	67			
% silt/clay	10	9	11	11	14	16	64	38	24	19	27	18			
L.O.I.	1.7	1.4	1.1	1.4	5.4	2.7	9.7	13.1	5.5	3.4	2.5	2.9			
Site M2/	1	2	3	4	5	6	7	8	9	10	11	12			
Sedt Group	C	C	C	B	C	C	A	A	A	A	B	B			
Mean (ø)	2.3	2.3	2.3	2.6	2.3	2.3	5.3	8.1	7.8	2.9	2.9	3.0			
% co-med sand	64	66	64	62	68	69	23	4	4	67	58	55			
% silt/clay	15	15	14	15	12	13	55	91	91	22	19	18			
L.O.I.	1.4	2.1	2.2	2.3	1.7	2.3	34.0	55.6	55.8	12.0	6.5	2.5			

The coarse-medium sands which characterise groups B and C appear to correspond to the 'coarse bare bed stage' of Moss and Walker's classification. They are apparently deposited from the 'rheological layer' of overland flows, a layer of saltating (bouncing) particles moving almost like a viscous fluid over the slope. On the sideslopes of dells, after heavy rains, sand does move over the bare ground, between individual plants, in flows only a few millimetres deep.

In the dells, the mineral detritus is separated into sideslope sediments dominated by medium-coarse sand, and very fine-grained sediments along the valley axes and tributary seepage zones. This distinction is illustrated well on the L2 (Loddon tributary) transect (see Fig. 3:4). Although the sediments high on the slope at L2/9 and L2/12 were grouped with the organic fines (Group A) because of their high loss on ignition values, their grain size distributions are only slightly finer than those of the nearby organic sands (Group B) at L2/8, 10, 11, 13. At the tributary seepage zone (L1/10) however the sediments are both organic and fine-grained, like those along the valley axis (L2/2).

The separation of the heterogeneous sediment is encouraged by the vegetation pattern within the dells. On the sideslopes there is open ground between individual shrubs and sedge tussocks, where water can flow quite freely. Along the valley axes, however, vegetation is much denser. Water flowing downstream carves occasional runnels a few decimetres deep and wide, but inflowing slopewash must weave a tortuous path through a dense mass of sedge tussocks, fern fronds, shrubs and small ground-cover species. It inevitably slows and loses its ability to transport its load. In a more open channel system much of the fine suspended load would be carried well downstream, but in the dells it is added to the sedimentary mass. Its deposition maintains the gentle gradient of the valley axis and thus encourages further deposition.

Organic sediment accumulation.

The dropping of the suspended load from overland flows deposits small plant fragments and organic debris as well as mineral silt and clay in the seepage zones. Organic content of the soils, as indicated by loss on ignition, rises as sharply as silt/clay content in the organic fines. For example, L.O.I. soars from 2.3% at M2/6 to 34% only 10 m further downslope at M2/7. This was the most dramatic rise recorded but L.O.I. more than doubles at each transition from organic sands to organic fines (Table 3.2). This difference is partly of sedimentary origin but is due also to the interplay of wetness, grain size and organic decay.

The humic materials which darken organic soils are acidic, chemically complex polymers which have lost the definitive characteristics of compounds such as proteins or lignins (Kononova, 1966). Their cation exchange capacity is comparable with that of clays (Campbell, 1978). They accumulate in soils which are usually or permanently wet, because of the anaerobic conditions which prevail there. Oxygen diffuses far more slowly in wet soils (at less than 1×10^{-5} cm^2/sec) than through the voids of dry soils (about 2×10^{-2} cm^2/sec) (Armstrong, 1978). The net rate of decomposition of dead vegetation is low because anaerobic respiration releases less energy, and anaerobic bacteria assimilate carbon less efficiently than their aerobic counterparts (Gambrell and

Patrick, 1978). Also the larger soil organisms such as worms and mites avoid wet acidic soils (Barratt, 1966).

Since the soils of the dells are clearly saturated most frequently along the valley axes and tributary seepage zones, organic accumulation in the soils is most pronounced in these zones. As the humic content of the sediments increases, so does their water-holding capacity. Because they are fine-grained, their pore spaces are small and discontinuous so they are not as free-draining as the sandier sideslope deposits. Thus the organic content was highest in the centre of the upstream Martins Swamp transect (M2/7-9) where even flood flows are not confined but spread across a densely vegetated, flat valley floor and where the mineral fraction of the soils is very fine-grained (up to 90% silt/clay).

The feedback relationships among the sedimentary processes.

The dells have a low competence to transport debris yet they are supplied with a predominantly sandy load. Hence:

- the sandy detritus is not flushed through the dells into the gorges.
- the sedimentary mass traps runoff during low flows as well as seepage, because of the lack of an efficient channel.
- the resulting swampy conditions encourage the development of a hygrophilous treeless vegetation.
- the sedges, which grow in closely-spaced tussocks, slow down runoff and bind the sediment, further discouraging the preservation or development of open continuous channels.

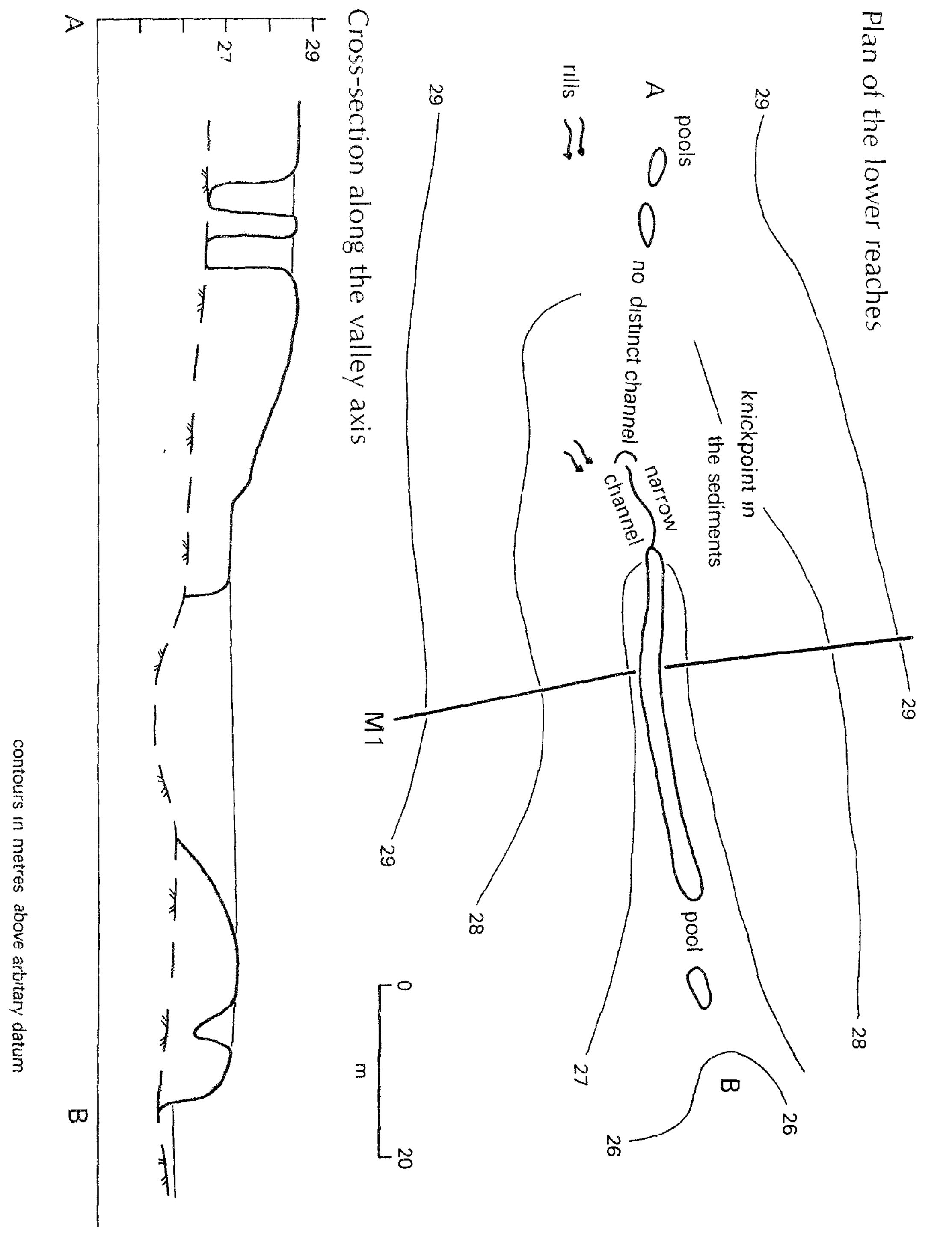
- the overland flow separates the sediment into sandy sideslope deposits and much finer and more highly organic sediments along the valley axes.
- the finer-grained sediments lie in zones of almost permanent saturation. Hence, organic accumulation, due to slow vegetative decay, is greater than on the drier, more freely-draining sideslopes.
- the increasing organic content further enhances the water-holding capacity of the soils.
- the greater density of vegetation along the valley axes discourages sand transport and enhances the probability of deposition of fine-grained sediment.

Thus the mineral sediment is separated into coarse sideslope deposits and fine valley-floor deposits. The greater accumulation of fine organic detritus in the valley-floors than on the sideslopes accentuates the fine-grained nature of the valley-floor sediments.

The effect of sediment type on channel form.

Given the dominantly sandy load supplied from the surrounding ridges, channel forms characteristic of sand-bed streams might be expected in the upland valleys. Such streams would be wide, shallow and braided, yet the few channels which occur in the dells are narrow, deep and discontinuous. Elongated pools (up to 50 m long, 2-5 m wide and 3 m deep) with bedrock floors are linked by extremely narrow and shallow winding passages (less than 0.5 m wide, 0.2-0.3 m deep) or by areas where the vegetation separates sheet flow into multiple rills which barely

STREAM FORM, MARTINS SWAMP



etch the underlying sediments (Fig. 3.5). Since streams move sand only when fast and/or turbulent flow rolls and saltates the grains, significant sand transport downvalley through the dells seems unlikely. Indeed, shear distribution in deep narrow channels is such as to minimise bedload transport. The almost bare floors of the pools (which would be ideal traps for moving sand) and the fine-grained sediments along the valley axes show that significant bedload transport of saltating sand does not occur. In fact, even after 18 months, no sand had accumulated behind a small weir constructed in a dell on the Budderoo Plateau, 50 km south-west of Wollongong (M. Melville, pers. comm., 1980). Sand which washes into the dells from the surrounding ridges is almost entirely incorporated into the organic and grey-brown sands on the sideslopes. The small amounts of sand which must reach the pools over long periods of time are apparently within the competence of the stream to remove.

Streams whose banks are cut in fine-grained sediments tend to have narrow and steep-sided channels. In the dells, the cohesiveness of the sediments is increased by their organic content and probably by the roots of plants. Smith (1976) found that sediment with 16-18% by volume of roots and a 5 cm deep root mat for bank protection had far more resistance to erosion than did comparable fine-grained sediment without vegetation. Live roots are found to depths of several metres in the organic fines adjacent to the pools of the dells; the surface root mat is not easily broken even by a sharp spade.

The problem is not to explain the persistence of the pools - and in no catchment did they change their position, number or extent as seen on aerial photographs between 1951 and 1977 -

but to explain how they originally formed. Presumably they formed, when the dells were initiated, as scour pools (note the form of the bedrock floor of the long pool in Fig. 3.5); since then their sides have grown upwards as the organic fines have accumulated. Because the sedgelands have no species which grow out over deep open water, the pools do not close across the surface and become infilled by the 'terrestrialisation' sequence of hydroseral succession (reviewed by Moore and Bellamy, 1973). As shear stress in narrow deep channels is greater on the banks than on the bed, sediment overhanging and encroaching into the pools may be eroded during floods. This would explain why such channels are found predominantly in large (>6.5 ha) dells, where the discharges and resulting bank shear stress are high enough to maintain an open channel.

Movement of sediment after fires.

Since the vegetation of the dells so strongly affects sediment deposition, changes in sedimentary processes can be expected when the dell surface is bared by fires. In the adjacent forests, litter cover and small plants are usually largely consumed and many tree crowns may be burnt. The groundsurface is therefore more exposed to rainsplash, overland flow is less impeded than when litter or plants disrupt it, and erosion and sediment transport consequently increase. Adamson *et al.* (1982) notes also that fires cause splitting and physical weathering of exposed sandstone in the forest, creating loose sediment which is then available for transport downslope. Movement of sediment from the ridges into the dells is most likely after fires; such movement is not however dramatic.

On the ridges, the slopes are stepped, broken by low sandstone outcrops, and typically covered by only a few decimetres of soil. Hence the supply of sediment available for transport into the dells is limited and discontinuous. In the Loddon R. catchment in October 1981, severe fires, followed within a week by a rainfall of 116 mm in 3 days, caused very little sand transport into or across the dells. Small terracettes of debris are often seen along the forest margins after fires, but these may be only partly due to washing of sediment into the dells from the forest. In the Loddon catchment in October 1981, the terracettes were most common in parts of the dell, adjacent to the forest, which had been covered by heath rather than by sedgeland. Burnt twigs and leaf fragments from the shrubs were washed a few metres downslope and accumulated to form dams of burnt litter. These terracette-like features were a few millimetres high, a few centimetres across and up to a metre long. They were efficient traps for the little sand which was moving and also in some cases for seed released from the shrubs. They did not form in areas where there were few shrubs because the burnt sedges and rushes left only very fine burnt fragments which seemed to be packed down on the surface, perhaps by raindrop impact.

Certainly, within the dells, fires do not expose a loose, sandy surface. The dense mat of fibrous roots binds the upper few centimetres; the surface may also be annealed by burnt algal scum. Fires are unlikely to be hot enough to incinerate the humic material in the organic sands and fines. Orioli and Curvetto (1978) suggest that humic polymers are not destroyed until the soil temperatures reach 300°C. Under fuel reduction and medium slash burns, surface temperatures may reach 90–500°C but temperatures only 1 cm below the soil surface fall to 50–130°C (Humphreys and Craig, 1981). Although there is considerable dry fuel at ground level in the dells, the lack of woody slow-burning fuel and the wetness of the surface suggest that temperatures may be lower than in the forests (cf. Beadle, 1940). In fact, where there is no dry ground fuel along the seepage lines, mosses and shrubs may survive green and unburnt even when the sideslopes are severely burnt.

It may be that very intense rainfalls soon after fires could trigger erosion in the dells, particularly if the root mat is breached on relatively dry and sandy sideslopes. Sand transport into and across the burnt surface, although not dramatic, is probably faster than across the vegetated dells. But there is no evidence for greatly accelerated rates of transport in these environments after severe fires and moderate rainfalls.

Conclusion.

Although geomorphic processes largely explain the initiation of sedimentation in the upland valleys, the development of swampy conditions and the resulting ecological relationships greatly influence the sedimentary characteristics of the dells. Geomorphic processes largely account for the major changes in sediment type but these processes are affected by the vegetation. There is also an overprint of organic accumulation, noticeable particularly in the distinction between organic and grey-brown sands, which is clearly due to hydrological factors and to vegetation changes. Once sedimentary accumulation begins,

> 'water and vegetation appear to be equally valuable, interdependent factors. The former activates the marsh process and creates conditions for the accumulation of partially decomposed organic matter, and the latter serves as material for the formation of peat, obstructs the free flow of water ... and enhances the accumulation and holding of water in the peat layers.'
>
> P'yavchenko, 1976, p.4.

The influence of water and vegetation on the development of the Illawarra dells is the subject of the following two chapters.

SUMMARY

- The sediments infilling the dells provide a record of the interplay of geomorphic and ecological processes.
- They are predominantly sandy, with variable fines and variable organic content, but are derived essentially from the Hawkesbury Sandstone.
- Classification using organic content and grain-size distribution yielded four groups - organic fines, organic sands, grey-brown sands, yellow earths.
- Organic fines occur in seepage zones and down the valley axes, where they are actively accumulating. They lie within wedges of organic sands but the organic sands extend over the sideslopes. The grey-brown sands and yellow earths underlie the wetter and drier sideslopes respectively.
- The changes in sediment type can be explained by fractionation of the sandy detritus supplied to the dells, during transport by overland flow.

- Medium-coarse sand is transported as bedload and redeposited on the sideslopes. Fines are transported in suspension, winnowed from the sands and deposited suddenly at the gentle slope along the valley axis.
- Fine organic debris is carried in suspension also and deposited with the mineral fines.
- Organic matter accumulates in the sediments because they are wet and thus poorly aerated so vegetative decay is relatively slow.
- There is a feedback relationship between slope position, sediment type, wetness and organic accumulation.
- The channel form in the dells is influenced by the sedimentary pattern. There is little evidence of sand transport downvalley and the fine, cohesive, rootbound sediments maintain steep-sided and narrow - even if discontinuous - channels in some dells.
- The dense surface root mat appears to protect the exposed surface of the dells after severe fires. No pronounced acceleration of sediment movement after fires and subsequent moderate rainfalls was observed.

CHAPTER FOUR: WATER TABLE MOVEMENTS IN RELATION TO ORGANIC ACCUMULATION, WATER CHEMISTRY AND WEATHERING.

Organic material accumulates and is preserved in the dells because the sediments are usually saturated. This interruption of the carbon cycle is not, however, the only consequence of water-logging, because poor aeration also affects the chemistry of the interstitial water itself. Hence the average position and fluctuations of the water table influence the alteration of mineral sediment and of the underlying bedrock as well as the accumulation of humic material.

This chapter aims to:

i) examine the changes in the position of the water table, across a typical dell, in response to rainfall variations

ii) relate these changes to the accumulation of organic matter in the sediments

iii) examine the chemistry of the water

iv) briefly evaluate the effects of chemical weathering both on transported sediments and on the underlying bedrock.

Studies of the Zambian dambos (Balek and Perry, 1973) indicate that the dambos supply a considerable part of surface runoff from their catchments, even though they occupy only 5-10% of the total catchment area. Given the high soil moisture contents and relatively deep soils of the Illawarra dells, in comparison to the forested remainder of the catchments, these dells probably also contribute a major portion of runoff from their catchments. While defining the dells' hydrological characteristics may be essential if the catchments are to be soundly managed, it is a less important task for this study, where the aim is to understand the dells' formation and maintenance as geomorphic features. Furthermore, to measure both the hydrological and chemical balance of the dells fully enough to estimate rates of weathering and erosion was a project beyond the feasible limits of this work. Hence the investigation of water table movements and water/sediment chemistry was designed to elucidate the processes, rather than the rates, of organic accumulation and chemical weathering.

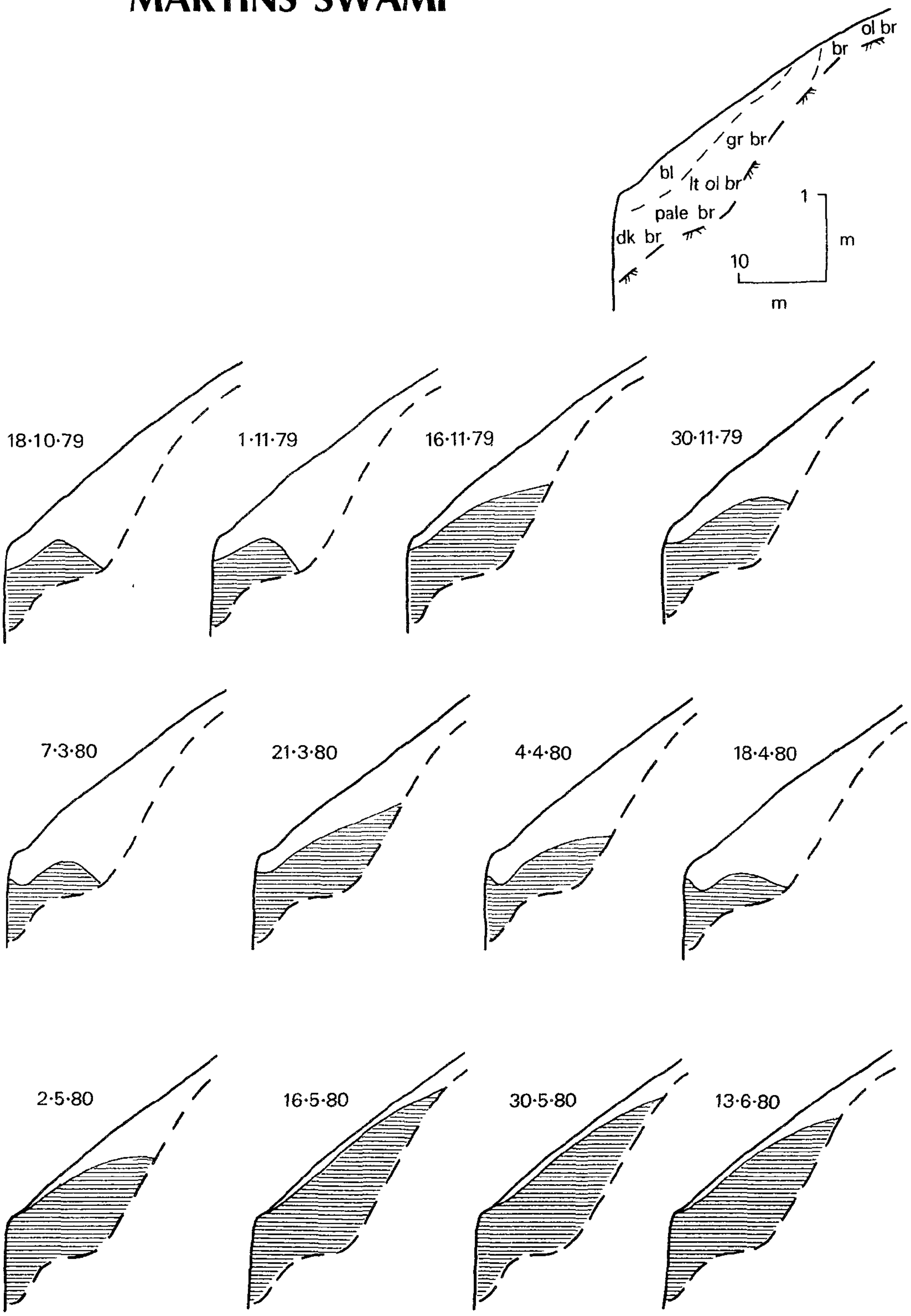
The position and movement of the water table.

During wet weather, the water table in the dells reaches the groundsurface in the valley axes, in tributary seepage zones, and on sideslopes where bedrock is shallow. Even on steep sideslopes underlain by deep sediments, it usually rises to within 10-20 cm of the groundsurface. If rainfall is prolonged, the water table may continue to stand close to the surface for a week or more after the rain stops. Yet this high water table is localised within the dell sediments. In immediately adjacent forested areas, standing water is rarely found in holes augered through the soils to bedrock.

The position of the water table was measured fortnightly at Martins Swamp between M1/1 and M1/6 from October 1979 until July 1980. Details of water levels are given in Appendix 2. The period of measurement was one of low rainfall conditions; rainfall at the nearest station (Cordeaux Dam, 5 km to the southwest) was 994 mm, only 73% of the average total for the months from October to July.

4·1

WATER TABLE FLUCTUATIONS, MARTINS SWAMP



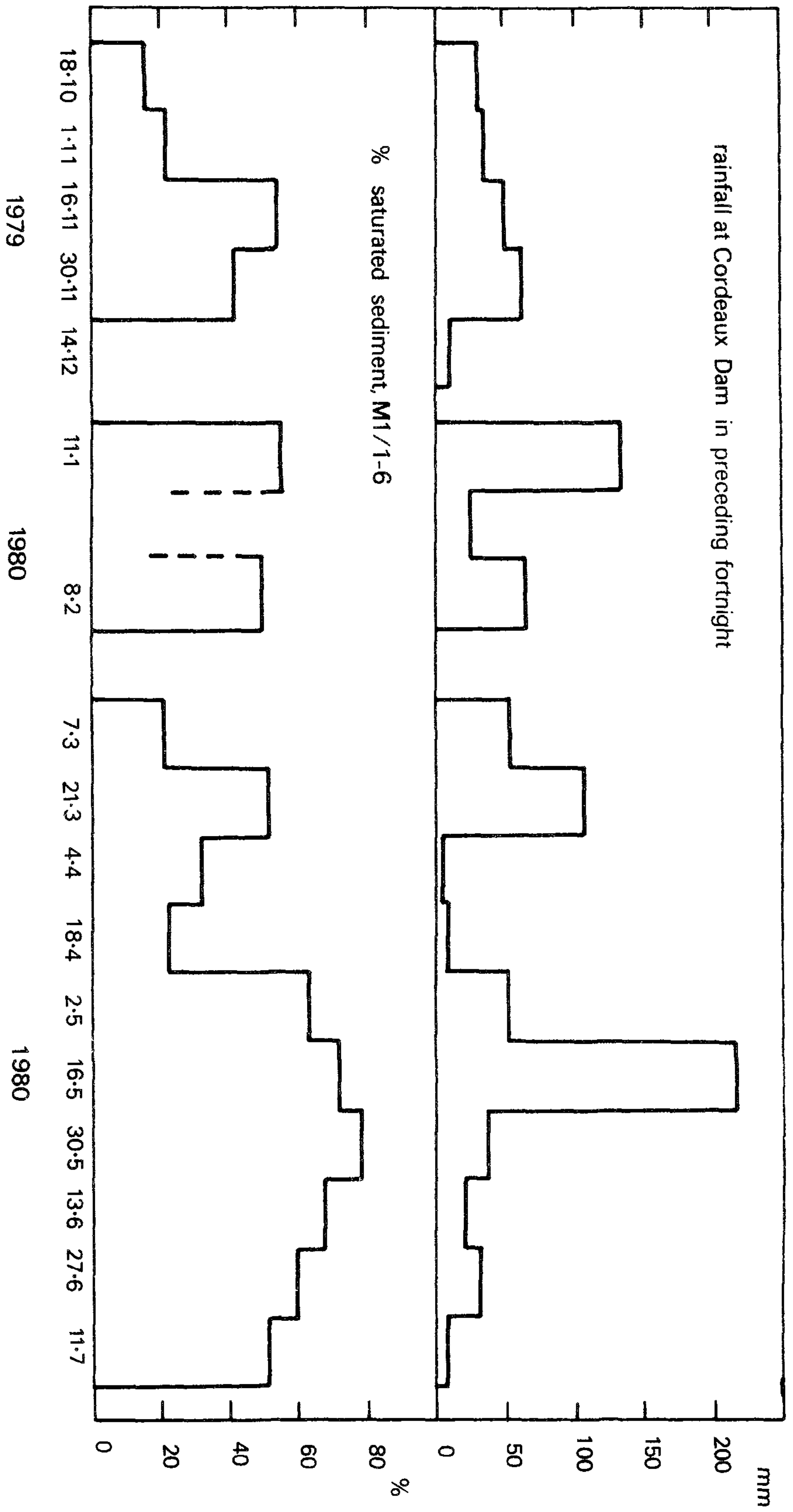
shaded sections show the portion of the profile between the water table and firm bedrock

The water table remained within 30 cm of banktop in the pool by M1/1 throughout the measurement period, even when all the auger holes were dry. At the far end of the transect, in the forested part (M1/5,6), no standing water was found (Fig. 4.1). Between these two extremes, as could be expected, the water table was highest and fluctuated least near the valley axis, standing water being found at M1/1 and M1/2 on all but one occasion. Nearer the dell margin at M1/3 and M1/4, a water table above bedrock was found on only 60% of measurement times. Thus, in the terms defined by Melville and Fitzpatrick (1982), M1/1-2 is a 'lowland wet area' where water is available to satisfy potential evaporation, M1/5-6 is an 'upland dry area' where saturated conditions at the surface are intermittent and short-lived, and M1/3-4 is an 'intermediate area'. Figure 4.1 suggests that on this transect, recharge of the water table occurs by inflow down the valley axis. Seepage downslope is insufficient to raise the water table rapidly near the dell margins.

By assuming constant levels across the slope on a 1m wide transect between M1/4 and the pool, the volume of saturated sediment between the water table and bedrock was compared with the total volume of sediment between the groundsurface and bedrock. The graph of percentage volume of saturated sediments within the dell is a muted trace of the plot of fortnightly rainfall (Fig. 4.2). This is in accord with the more detailed findings of Melville and Fitzpatrick (1982). These authors are able to relate fortnightly readings of precipitation and evaporation, over a 33-month period, in a model that gives close agreement

WATER TABLE CHANGES v. RAINFALL

4·2



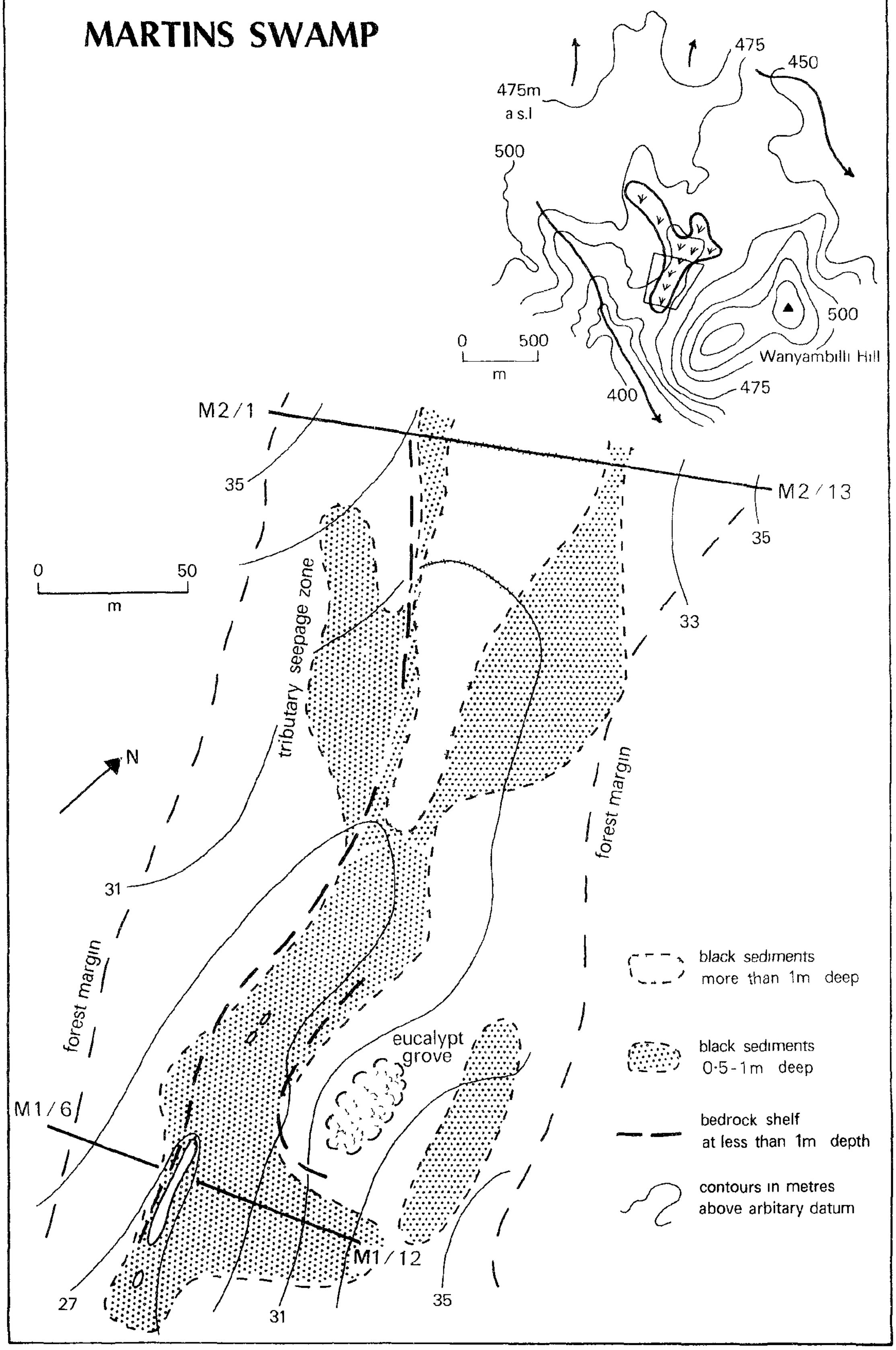
with measured discharge from two catchments on the Budderoo plateau.

Organic accumulation in relation to water table position.

Although all the sediments at 0.5 m depth along the M1/1-6 transect are grey-brown sands (see Chapter 3), the surface horizon of organic-rich sediment varies considerably upslope (see Fig. 4.1). Near the pool, where the water table is usually high, the black surface horizon is 0.4 m deep, loss on ignition values being 15-35% near the surface but only 5% at 0.5 m. Further upslope, where the water table is lower, the black horizon thins and the near-surface L.O.I. falls to 7.5%. In the forested part (M1/5,6), where no standing water was found, the surface horizon is thin (0.1 m) and grey, with little organic content (L.O.I. 3.5%).

The greatest depth of organic accumulation in the downstream reach of Martins Swamp, as shown by the depth of black organic fines and organic sands, occurs where the dell is broad and the sideslopes are very gentle, along M2 transect (Fig. 4.3). Here the water table is close to the surface over a wide zone along the valley axis. The sediments are fine-grained and highly organic. Since they are also poorly aerated, decay of deposited organic material is slow. Their organic fraction dominates their mineral fraction, with L.O.I. values reaching 55-64% at 10 cm depth between M2/7 and M2/9. Near M1 transect, where the sideslopes are steeper and the valley bottom is narrower, the organic horizon is thinner (0.1-0.5 m).

ORGANIC SEDIMENT DISTRIBUTION, MARTINS SWAMP



If a high water table is maintained on sideslopes by downslope seepage, organic material accumulates in the sediment. For example, the organic sands extend upslope to 35 m above arbitary datum where seepage from Wanyambilli hill flows into Martins Swamp, whereas on the gentler and more dissected opposing hillside, they extend only to 28 m above arbitary datum on the M1 transect. However, where a tributary seepage zone enters from the drier north-east facing slope, breaching the shallow bedrock shelf, again the organic surface horizon is 0.5-1 m deep (see Fig. 4.3).

In short, the accumulation of organic material in the soil depends on the average height and the fluctuations of the watertable in the sediments. It is appropriate now to look in detail at the degree of aeration of the interstitial water in the sediments and thence at the expected processes of chemical weathering of the sediments and underlying bedrock.

Chemical properties of water in the dells.

When water table levels were measured along M1/1 to M1/6, between October 1979 and June 1980, field measurements of temperature, acidity (pH) and dissolved oxygen content (D.O.) were made at 5-10 cm below the water surface. Samples of water were collected for laboratory analysis of organic carbon content (C_{org}). Field measurement of pH was essential because laboratory analyses made only a few hours after collection on samples in full, well-sealed plastic bottles gave values which were less variable, and 0.5-0.8 pH units higher, than the corresponding field values. Although the degree of aeration of sedimentary environments is often measured by redox potential (Eh), Langmuir (1971, p.614) comments that 'measurement of Eh should be considered only if D.O. (dissolved oxygen) is below the limits of detection (0.01 ppm)'. In the Illawarra dells, D.O. was rarely below 1 mg/l (1 ppm). Field D.O. values were converted to percentage saturation values, assuming an altitude of 1200 feet (365 m). Details of analyses are given in Appendix 2. Recently Berner (1981) has proposed a geochemical classification of sediments using D.O. and hydrogen sulphide (H_2S) content rather than the traditional Eh/pH scheme. He regards Eh as difficult to measure truly and pH as too invariate. Certainly pH did not vary greatly in the samples taken at Martins Swamp. H_2S was not determined but it was certainly too low to be detected by smell.

The waters of the dells are acidic, ranging from 3.7 to 5.6 pH units (Table 4.1). pH was lowest in the sediments because carbon dioxide released by microbial activity was trapped in the standing water in the auger holes. In the pool and, even more noticeably, at the exit of the dell where the stream flowed over bedrock, the pH was slightly higher.

Dissolved oxygen contents also were highest in the exit stream, somewhat lower in the stiller pool and lowest in the sediments. The lowest values, with a mean of 27.9% of saturation, occurred at M1/2 and it may be remembered that organic content of the surface horizon (L.O.I. of 34.9% at 10 cm depth) was higher here than at any other position on the transect. Dissolved oxygen contents are highest and most constant where the water table is

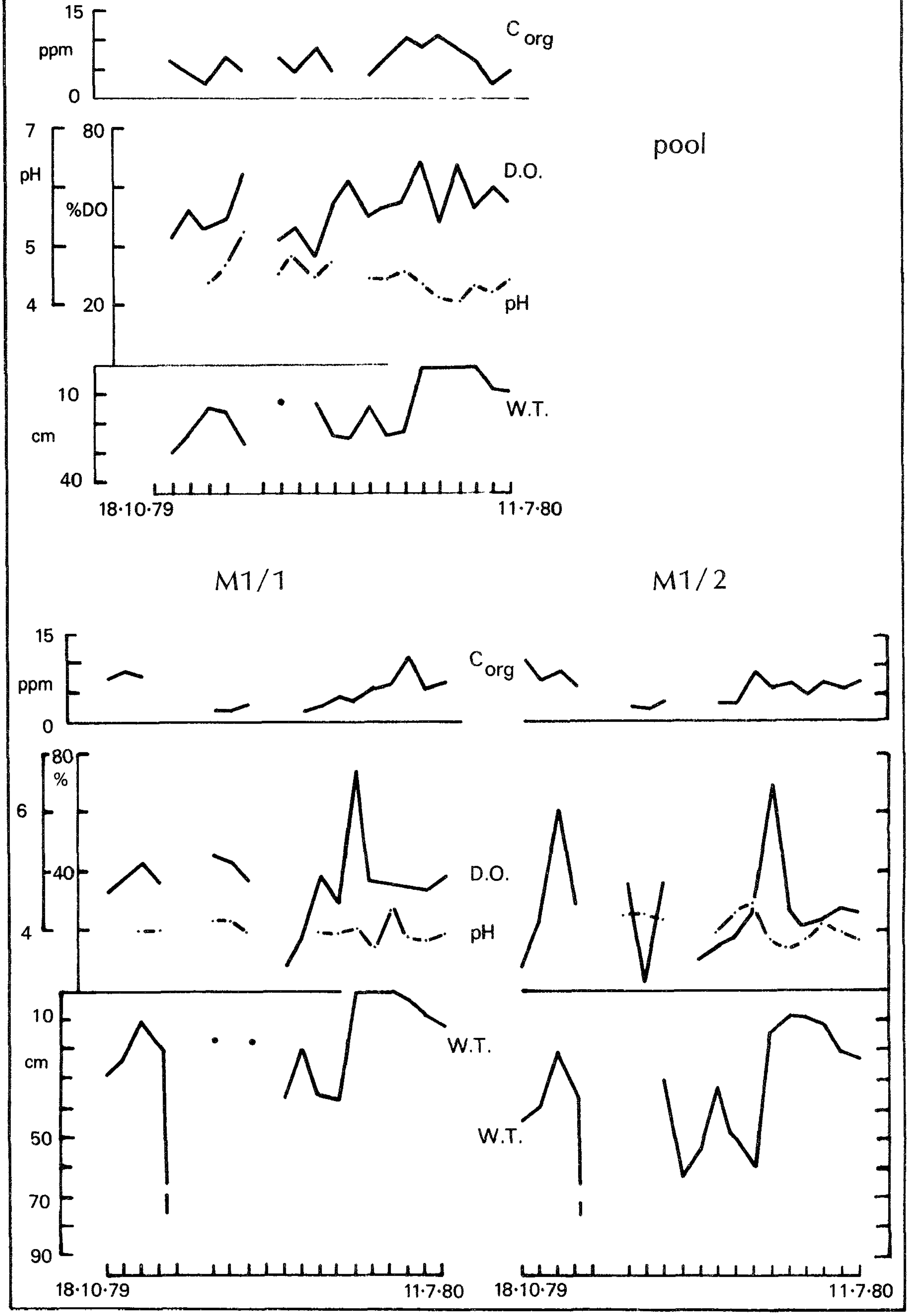
TABLE 4.1. CHEMICAL PROPERTIES OF WATER FROM MARTINS SWAMP. OCTOBER 1979 TO JULY 1980.

	Exit	Pool	M1/1	M1/2	M1/3	M1/4
pH						
range	4.2-5.6	4.1-5.3	3.7-4.5	3.7-4.7	3.7-4.3	3.8-4.3
mean	4.7	4.5	4.0	4.2	4.0	4.1
number of readings	16	16	14	14	10	9
Dissolved oxygen (% saturation)						
range	54-94	37-70	9-75	7-71	12-81	16-72
mean	69.4	53.9	37.1	27.9	38.3	40.1
number of readings	19	19	17	17	11	9
Organic carbon (ppm)						
range	2.5-10.7	2.7-11.2	2.2-11.5	3.1-11.4	2.9-9.1	4.6-10.5
mean	5.7	6.7	5.7	6.3	6.2	6.4
number of readings	16	18	15	16	9	6
Silica (ppm, 18.4.80-11.7.80)						
range	1.4-4.3	1.0-4.1	1.0-4.0	1.2-4.1	1.9-4.0	0.7-4.5
mean	2.7	2.9	2.7	2.8	3.1	2.9
number of readings	7	7	7	7	6	5

usually high because gaseous exchange with the atmosphere can occur readily (Fig. 4.4). In the pool, D.O. of the surface water ranged from 37-70% of saturation, but in the sediments, D.O. fell to less than 10% of saturation when the water table dropped 20 cm or more below the groundsurface.

Despite the considerable variation in dissolved oxygen levels, the organic carbon contents of the waters were surprisingly and uniformly low compared with results reported elsewhere. On the Georgia coastal plain in the U.S.A., streams which are acidic (pH 3.8-5.9) and poorly oxygenated (D.O. 55-85% of saturation),

WATER CHEMISTRY , MARTINS SWAMP



have C_{org} levels of about 23 ppm (Beck et al., 1974). In Belorussia, the average C_{org} content varies with the swampiness of the catchment. 43% of the Yaselda River's catchment is swampy and mean organic carbon content of the stream is 28.1 mg/l, while the corresponding values for the Pripet River are 33% and 27.4 mg/l and for the Neman, are 15% and 15.2 mg/l (Kovalev et al., 1974). On the basis of these data, C_{org} levels of 10-20 mg/l were expected for the waters of Martins Swamp, with higher values associated with lower D.O. readings. But organic carbon contents of the dell waters ranged only from 2.5-11.5 ppm. They did not correlate well with the rises and falls of the D.O. values, and were no higher in the sediments than in the better-aerated open waters (Fig. 4.4).

Silica contents also were consistently low (0.7-4.5 ppm) at Martins Swamp. Siever (1962) quotes values of 14-25 ppm SiO_2 for peat waters and Mitchell (1975) contends that silica dissolves more rapidly in anaerobic than aerobic soil conditions. Nonetheless, low concentrations are reported for swampy areas - 2.5-9 mg/l in Georgia, U.S.A. (Beck et al., 1974) and 1-2 mg/l in Belorussia (Kovalev et al., 1974) - as well as for temperate sandstone terrain - 3.2-5 mg/l in the Vosges, France (Mainguet, 1972). Near the study area, on the Hawkesbury Sandstone plateau near Robertson, mean values of 3-12 mg/l were reported by Johnson and Johnson (1972). The highest readings obtained by them were from catchments including some shale or basalt outcrops, while the lowest were from sandstone catchments including areas of swampy dell.

The low and invariate silica contents in the waters of

Martins Swamp do not necessarily imply that silica is immobile in the dells. Silica may be sorbed onto soils or amorphous iron/aluminium hydroxides even at very low concentrations (Harder and Flehmig, 1970), or may be taken up by plants. Many sedges (Cyperaceae) and grasses (Gramineae) accumulate intracellular bodies of silica which persist in the soil as opal phytoliths when the plants decay (Baker, 1959). Unfortunately, although Australian sedges (for example, species of Baumea) contain such silica bodies, no ecological work has been done on the source or cycling of the silica (K. Wilson, pers. comm., 1981).

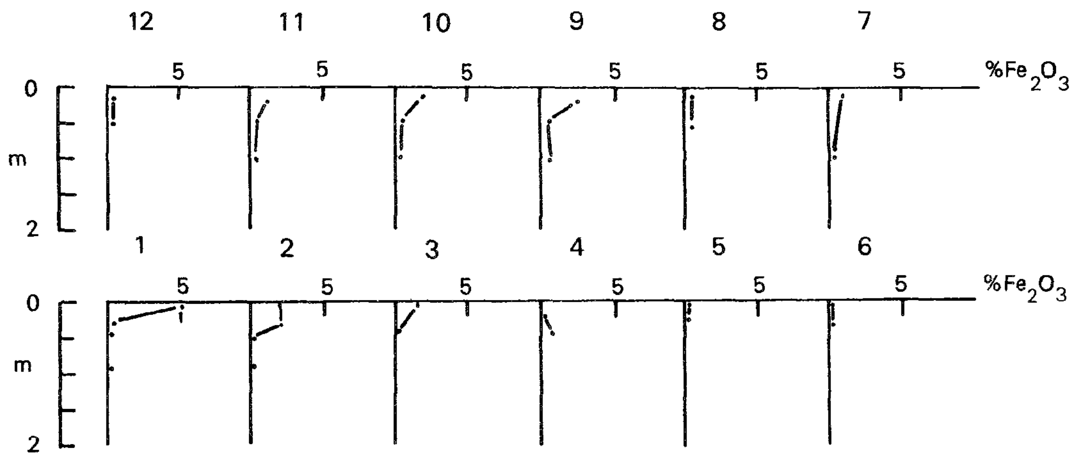
Studies on the Budderoo Plateau demonstrate that cation and anion concentrations in similar environments are low also. Greater variation in anion (Cl^-, SO_4^{2-}) concentration was found in rainfall than in outflow from the dells (E. Fitzpatrick, pers. comm., 1980). The soils and soil waters in the same area had very low concentrations of nutrients (Ca, Fe, K, Mg, Mn, Na), because the cations were locked in the living and dead vegetation (Mirlieb, 1978). Hence the low concentrations of organic carbon and silica in the dell waters at Martins Swamp may be due more to efficient retention within the nutrient cycles than to immobility of the chemical species. This certainly seems to be so with respect to iron.

Mobilisation of iron in the dells.

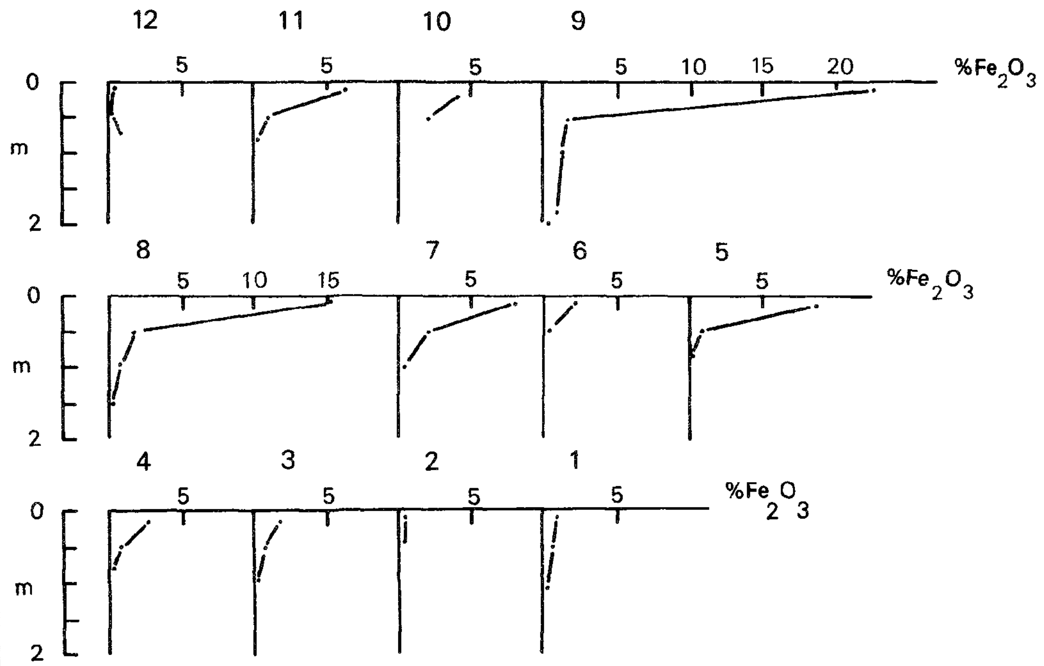
The top decimetre of the organic-rich sediments in the Illawarra dells have extremely high concentrations of iron oxides - often 1-3%, and up to 20%, of dry weight expressed as Fe_2O_3 (Fig. 4.5).

IRON CONTENT
v. DEPTH OF SEDIMENT

M1 transect



M2 transect



The concentrations drop very abruptly with depth, although in deep organic fines (for example M2/9), values of 1-2% persist for up to 1 m below the groundsurface. Tubular sheaths of orange iron (III) oxide, a few millimetres long, which form around the roots of some plants, account for the high, variable iron contents near the groundsurface. Similar sheaths characterise many plants which grow in swampy conditions, because the plants pump oxygen into their roots to sustain respiration (Gambrell and Patrick, 1978; Jones, 1971). In the zone immediately adjacent to the roots, therefore, there is enough oxygen to oxidise mobile iron (II) cations and cause precipitation of iron (III) oxides or hydroxides.

Iron is mobilised as Fe^{2+} in acidic environments even under moderately oxidising conditions (Buol et al., 1973). Organic acids can then form stable and soluble complexes with this reduced iron (Duchaufour, 1970; Jackson et al., 1978). Although Duchaufour (1970) suggests that iron oxides sorbed onto clay or humus do not affect soil colour, uniformly grey soils usually denote permanently saturated conditions whereas mottled sediments are associated with fluctuating water tables (van Breeman and Brinkman, 1976). In the Illawarra dells, iron is either locked into vegetative material near the surface or leached out of the sediments. Iron oxide contents of the sediments at depths of a few decimetres are usually less than 0.3% (of dry weight), whereas the subsoils of the forested areas have much higher values - 0.83% at M2/1, 0.36% at M1/6, 0.7-4.5% at L1/3-9.

No iron determinations were made on the waters from

Martins Swamp. The leaching of iron from the dells is demonstrated clearly, however, by the slimy orange floc which often is precipitated from their exit streams during low flows. Crerar et al. (1979) comment that precipitation of similar material, 'bog iron' containing up to 30% $Fe(OH)_3$, is probably due to bacterial rather than inorganic oxidation of dissolved iron. Floc collected from the Drillhole Swamp contained 20% insoluble (in IN HCl) material (mainly sand) and iron equivalent to 62.9% ferric hydroxide ($Fe(OH)_3$). This latter value corresponds closely to that determined for similar floc by Buchanan (1980), who notes that algae and iron bacteria are associated with the precipitate. Iron is removed in solution from the dell sediments by the acidic and poorly aerated waters. This leaching of iron is the most apparent mechanism by which the bedrock underlying the dells is weathered.

Weathering of bedrock below the dells.

It was noted in Chapter 3 that the sediments of the dells are predominantly transported. Only on the drier, north-facing slope of the transect across the Loddon tributary, did the organic surface horizon overlie weathered sandstone. The sediments between L1/3 and L1/9 (see Fig. 3.4) have high clay contents associated with considerable fine-medium sand. Unlike the transported material, they have not been sorted into dominantly coarse or very fine sediments; they increase in clay content, and in the degree of mottling, with depth. Even though there is an abrupt change to firm, white and orange mottled sandstone at approximately 1.5 m depth, the sediments between L1/3 and L1/9 are clearly

SEDIMENT CHANGES, 6R SWAMP

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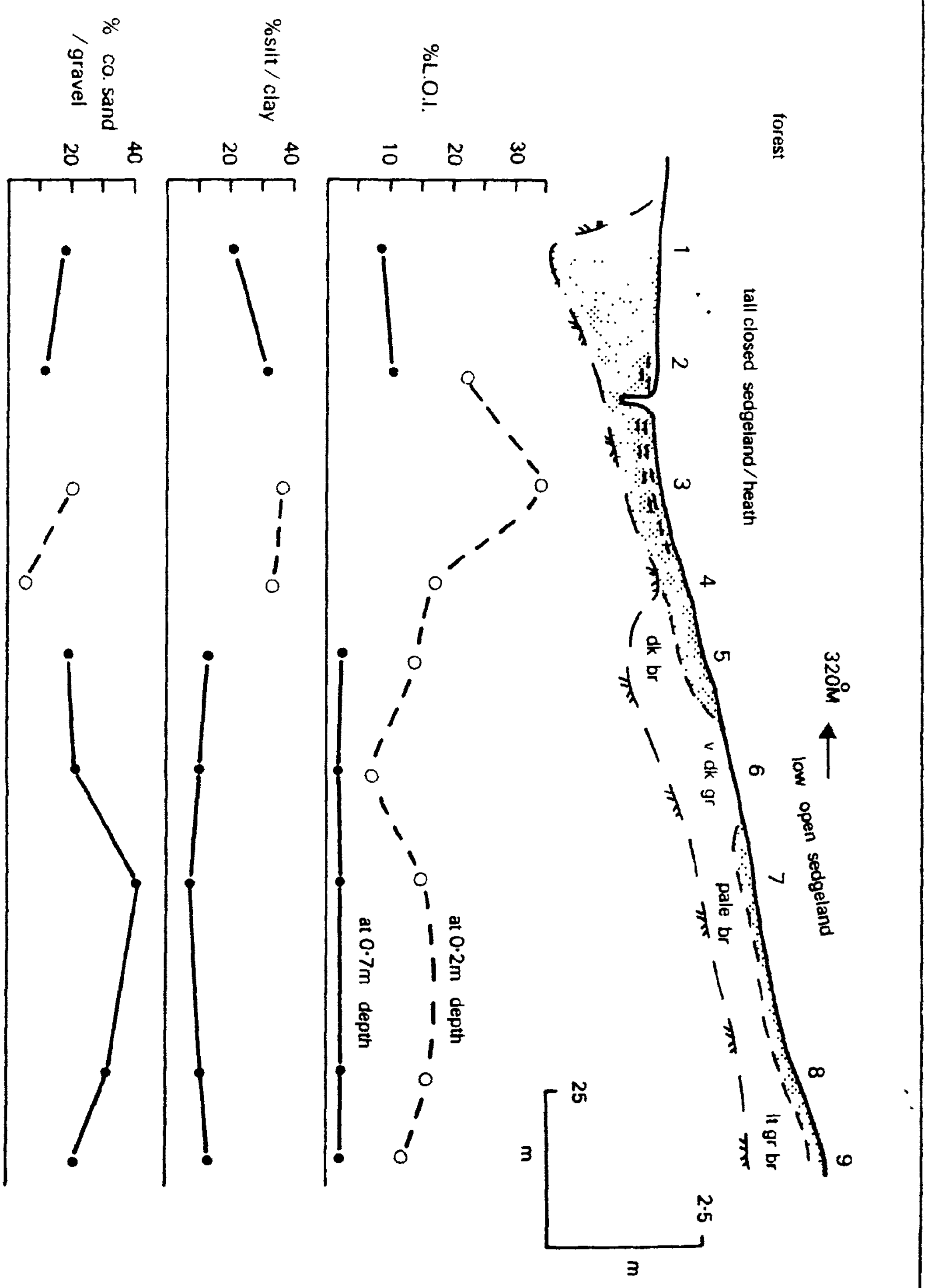


weathered in-situ. At other sites on the Sublime Point moors, an organic surface horizon up to 50 cm thick overlies silty or clayey sand which becomes more clayey and more mottled with depth, reaching weathered mottled sandstone at 1-2 m.

The difference between transported and residual sediments is well illustrated at 6R Swamp in Avon catchment. Here, a shallow bedrock ridge separates transported organic sands and organic fines from residual brown sands with an organic-rich surface horizon (Fig. 4.6). As the western end of the transect is enclosed by a shallow bedrock ridge less than 0.5 m deep, there is no bedrock channel which could have transported the sediments between 6R/5 and 6R/9. The high gravel-coarse sand contents, allied with about 10% silt-clay fraction, indicate in-situ weathering. Although the dell sediments are dominantly transported, especially along the seepage zones where they are deepest, in-situ weathering can provide 1-2m of unconsolidated residual sediment on the sideslopes.

Where the sediments infilling the dells are transported rather than weathered in-situ, there is an abrupt transition from the transported sediments to firm sandstone beneath them. This underlying sandstone is almost invariably white, or orange-white mottled. Occasionally fibrous roots or dark humic matter penetrate along bedding laminations, bleaching the adjacent rock. The sandstone retains its cohesiveness and sedimentary structures such as bedding laminations, so it is weathered not by disintegration or alteration of the major minerals but by leaching of the cement. Although the cement is siderite ($FeCO_3$) in fresh rock, it oxidises in near-surface exposures. As noted earlier, the acidic and poorly aerated waters of the dells readily dissolve and transport iron compounds.

Sediment-water interrelationships.

The data given in this chapter add detail to the feedback relationships described in Chapter 3. Low dissolved oxygen contents in the sedimentary mass account for high organic contents. The constantly high water tables along the valley axes reinforce the poor aeration in these zones due to the fine-grained and highly organic nature of the sediments. To account for the distribution of iron oxides in the sediments, however it is necessary to consider not only sediment-water interactions but also nutrient cycling associated with the vegetation.

While the data given relate to low flow conditions, the chemistry of flood runoff from the dells is probably little affected by sediment-water relationships. Flood runoff rides over the high water table of the dells and moves rapidly down the channel, giving little opportunity for interaction with the underlying soil. Indeed, where the sedges and ferns grow densely along the valley axes, floods bend the plants to form a hydrodynamically smooth bed of entangled vegetation which may be 20-30 cm above the soil surface.

Clearly the vegetation influences sedimentation in the dells because of its effects on overland flow. It is the source of organic sediment, as well as being an important influence on sediment chemistry. In the following chapter, we will examine the interrelationships between the vegetation and the variations in sediment type and hydrological characteristics.

SUMMARY.

- The water table's position and the type of sediment are related. The water table is highest and most constant where the sediments are most organic.
- The percentage volume of sediment that is saturated at any time varies directly with the rainfall of the preceding fortnight.
- The dell waters are acidic (pH 3.7-5.6) and low in dissolved oxygen (less than 70% saturation), in organic carbon (2.5-11.5 ppm) and in silica (0.7-4.5 ppm). The low values for C_{org} and SiO_2 may be due to efficient nutrient cycling.
- Iron is mobile but is retained in highly organic sediments as small tubular sheaths on roots. Floc precipitated from the streams emerging from the dells had an iron content equivalent to 63% $Fe(OH)_3$.
- In-situ weathering of bedrock does occur, for example on the north-facing slope of the Loddon tributary and at 6R Swamp. Such weathering appears to be due usually to mobilisation of iron oxides from the underlying sandstone.

CHAPTER FIVE: VEGETATION.

Organic terrain is usually classified into mires fed by rainfall and terrestrial inflow (rheotrophic mires) and mires fed only by precipitation (ombrotrophic mires) (Kulczynski, 1949; Moore and Bellamy, 1973). Close correspondence between the sources of water and the vegetation has been demonstrated both for regional distributions of mires (Daniels, 1978) and within individual mires (Sjors, 1963; Proctor, 1974). In the Illawarra dells, the movement and average water level influence edaphic conditions (see Chapters 3 and 4) and thence, as we shall see in this chapter, the patterns of vegetation. But the vegetation also affects the movement of water both directly and via its influence on sedimentary patterns. The aims of this chapter are:

i) to define the vegetation types which characterise the various ecotopes within the dells

ii) to relate the changes in vegetation to the prevailing hydrological and sedimentological conditions

iii) to provide a basis for relating relict sediments to the probable vegetation cover under which they accumulated. As Moore and Bellamy (1973) commment, tussock sedge communities occur frequently in present-day mires yet have gone largely unrecognised in stratigraphic studies of organic sediments.

The vegetation of the dells in relation to mire vegetation elsewhere.

The dells are dominated by coarse sedges (members of the Cyperaceae family) and rushes (members of the Restionaceae family). These plants usually grow in tussocks up to 1.5m high. Low shrubs, the most obvious being members of the Proteaceae and

Myrtaceae families, grow densely along drainage lines and on some sideslopes, but more usually are scattered. There are very few trees except for isolated individuals near the dell margins and small groves in relatively well-drained parts of the dells. Structurally therefore the dell vegetation ranges from closed sedgeland, through more open sedgeland/herbfield, to heath (Specht et al., 1974).

Given the swampy organic terrain, the treeless and sedge-dominated vegetation is not surprising; similar vegetation characterises rheotrophic mires in many other parts of the world. The dambos of south-central Africa support grasslands (Loudetia spp.) and are surrounded by broad-leafed savanna. However, in the wettest dambos, where a humic topsoil overlies the sandy sediment, the grasses are replaced by sedges (Werger and Coetzec, 1978). Tussock sedge-grassland (mainly Schoenus spp.) occupies poorly-drained areas of inland south-west Papua-New Guinea, abutting abruptly against savanna (Melaleuca-Banksia-Grevillea spp.) or dry evergreen forest (Paijmans, 1976). Sedges (Carex spp.) dominate organic terrain on Gough Island (Holdgate, 1961), in parts of Britain (Proctor, 1974) and in the Pripet River area of the U.S.S.R. (Regel, 1947; Kulczynski, 1949; Kovalev et al., 1974). In New Zealand, however, restionaceous rather than cyperaceous swamps have developed (Campbell, 1964; Ruscoe, 1975).

Sedgelands and heath also characterise freshwater swampy terrain in many parts of New South Wales - the New England Plateau (Millington, 1954), the Hornsby Plateau north of Sydney (Buchanan, 1980), the Blue Mountains (Holland, 1974), the Budderoo

TABLE 5.1 SPECIES FOUND AT 5 OR MORE TRANSECT SITES.

Species	No.*
Gymnoschoenus sphaerocephalus	1
Chorizandra sphaerocephala	2
Leptocarpus tenax	3
Lepidosperma longitudinale	4
Xyris operculata	5
X. ustulata	6
Lepyrodia scariosa	7
Restio complanatus	8
Lepidosperma forsythii	9
Ptilanthelium deustum	10
Empodisma minus	11
Schoenus brevifolius	12
Xanthorrhoea	13
Banksia robur	14
B. oblongifolia	15
Leptospermum juniperinum	16
L. lanigerum	17
Melaleuca squarrosa	18
Hakea teretifolia	19
Baeckea linifolia	20
Epacris paludosa	21
Isopogon anemonifolius	22
Sprengelia incarnata	23
Phyllota phylicoides	24
Platysace linearifolia	25
Dampiera stricta	26
Patersonia	27
Goodenia bellidifolia	28
Selaginella uliginosa	29
Lindsaea linearis	30
Drosera binata	31
D. spathulata	32
Villarsia exaltata	33
Haemodorum corymbosum	34
Gleichenia dicarpa	35
Tetrarrhena juncea	36
Eucalyptus	37

* identification number in Fig. 5.1.

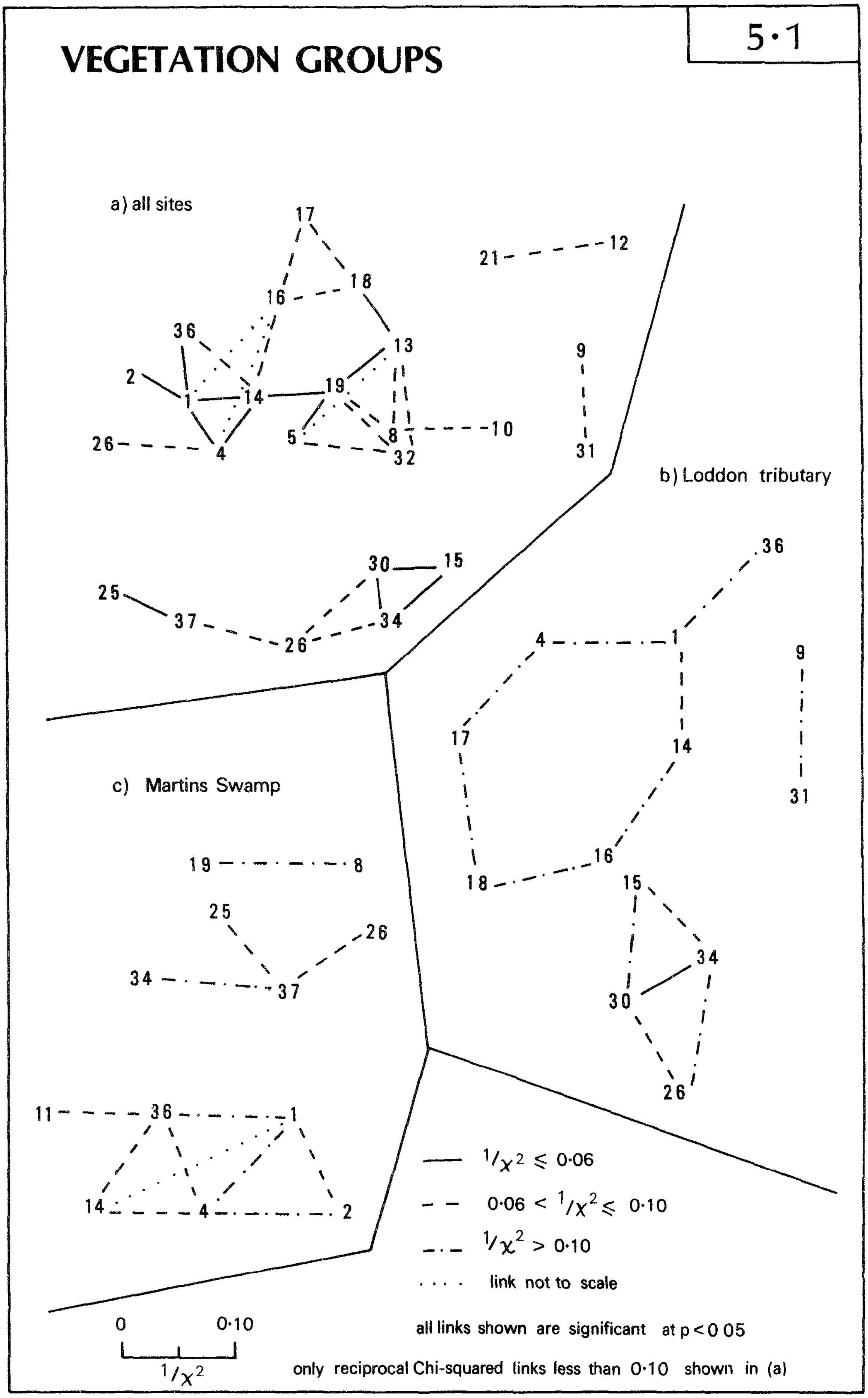
For details of botanical names, see Appendix 3.

area near Kiama (Burrough *et al.*, 1977), the coastal peninsula at Jervis Bay (Ingwerson, 1976) and the plateau developed on Nowra Sandstone near Ulladulla (A. Young, 1981). In Tasmania, sedgeland is widespread on the western side of the island (Davies, 1965; see Fig. 2.5). Thirty of the 44 species listed for swamps on the Hornsby Plateau by Buchanan (1980) and 30 of the 59 species listed for closed-heath at Budderoo by Burrough *et al.* (1977) were observed during the course of this investigation on the Woronora Plateau dells. *Gymnoschoenus* species, usually *G. sphaerocephalus*, are a major constituent of all the sedgelands mentioned above.

Species composition of the dell vegetation.

As the purpose of vegetation sampling was to relate changes in vegetation to variations in the substrate, all species within 1-metre radius of the sediment sampling sites at Maddens Plains (L1 and L2 transects) and Martins Swamp (M1 and M2 transects) were recorded. Species which occurred in 10% or more of sites are listed in Table 5.1. A complete list is given in Appendix 3. Although Appendix 3 is not an exhaustive list of the species which are found in the dells, it includes the most commonly-occurring plants.

The species listed in Table 5.1 were grouped, using the reciprocal Chi-square (χ^2) value as a distance measure for all pairs of species which had significant ($p<0.05$) mutual occurrence (Fig. 5.1). When the data from all 50 sampling sites were used, most of the associated species were linked at $p<0.05$ level. Note, however, that some statistically significant links are



5·1
VEGETATION GROUPS
a) all sites
b) Loddon tributary
c) Martins Swamp
17
18
16
21
12
36
13
9
2
1
14
19
26
4
5
8
32
10
31
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25
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36
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25
26
34
37
11
36
1
14
4
2
$^1/\chi^2 \leqslant 0{\cdot}06$
$0{\cdot}06 < {}^1/\chi^2 \leqslant 0{\cdot}10$
$^1/\chi^2 > 0{\cdot}10$
link not to scale
0
0·10
$^1/\chi^2$
all links shown are significant at p < 0 05
only reciprocal Chi-squared links less than 0·10 shown in (a)

based on the species' common occurrence at so few sites that the links cannot be considered ecologically significant. For example, the links between Drosera binata (31) and Lepidosperma forsythii (9), and between Schoenus brevifolius (12) and Epacris paludosa (21), are based on both species being present at only 4 sites in each case. Note also that species which are almost ubiquitous may not be significantly linked to any other species by the Chi-square procedure. Two rushes - Leptocarpus tenax (3) and Empodisma minus (11) - which were found in 41 and 44 respectively of the 50 sites are cases in point.

The grouping procedure was repeated using Chi-square values obtained for the Loddon tributary and the Martins Swamp data separately (Figs. 5.1b, 5.1c). Again, there were apparent links - between (9) and (31) at Loddon tributary, and (8) and (19) at Martins Swamp -which could not be considered ecologically significant. However, at both dells, there were also two groups which could be related to the sedimentological/hydrological variations across each transect.

For the Loddon tributary there was:

- a group of moisture-tolerant species - the sedges Gymnoschoenus sphaerocephalus and Lepidosperma longitudinale; the shrubs Banksia robur, Leptospermum juniperinum, Leptospermum lanigerum and Melaleuca squarrosa; the grass Tetrarrhena juncea.
- a group with no sedges or grasses but comprised of one shrub Banksia oblongifolia, and three hemicryptophytes Dampiera stricta, Lindseae linearis and Haemodorum corymbosum. B. oblongifolia is typically tolerant of alternating flooded/dry conditions.

For Martins Swamp, the groups were similar:

- Gymnoschoenus sphaerocephalus, Lepidosperma longitudinale, Banksia robur and Tetrarrhena juncea, plus the sedge Chorizandra sphaerocephala and the rush Empodisma minus.
- Dampiera stricta and Haemodorum corymbosum, plus trees or saplings of Eucalyptus species and the hemicryptophyte Platysace linearifolia.

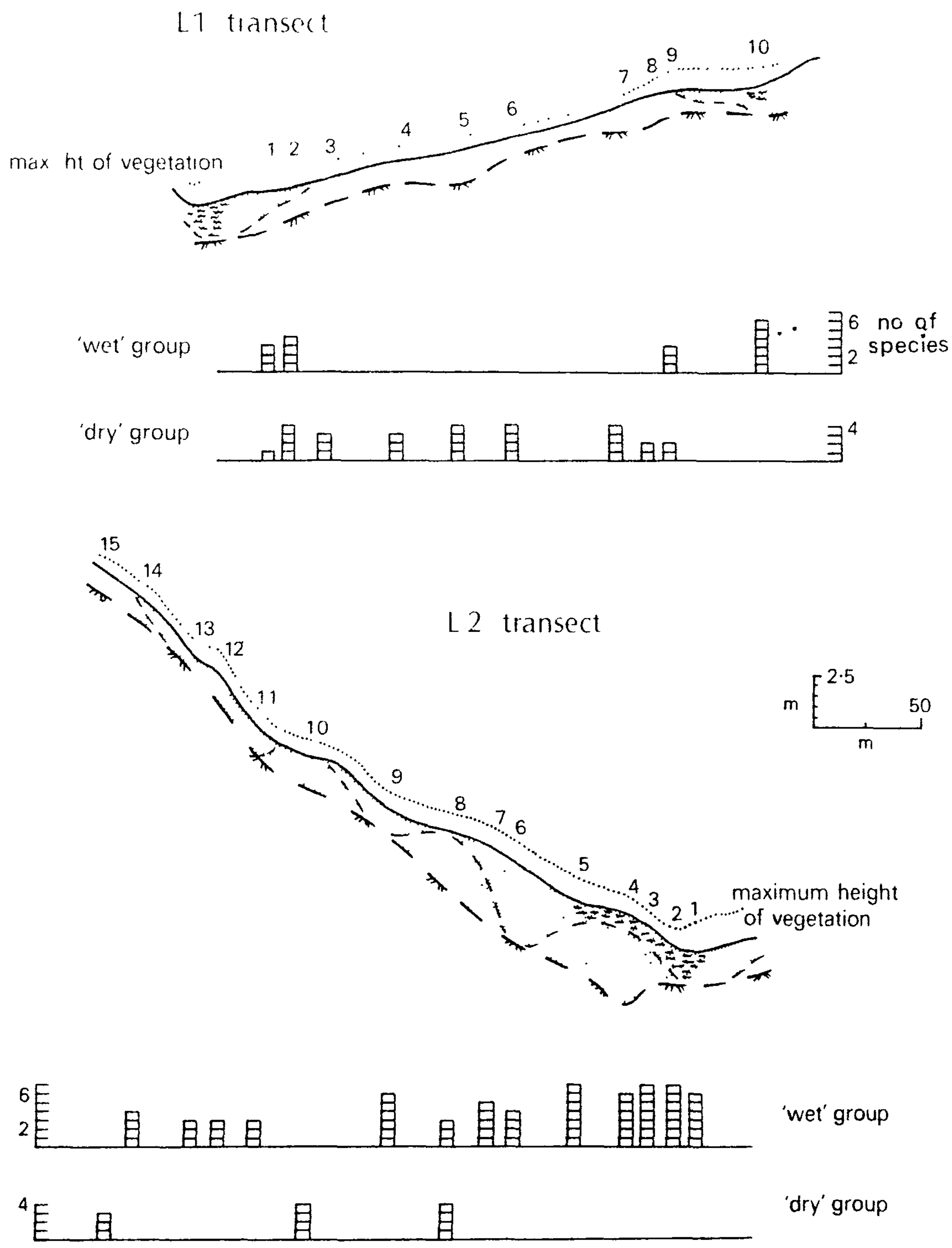
The relative importance of these groups across the transects is illustrated in Figures 5.2 and 5.3, with the group of sedges and hygrophilous shrubs being marked 'wet' and the second group, 'dry'. The diagrams show the number of species from each group recorded at each site, and the transect stratigraphy.

The vegetation's response to environmental conditions is clear, as the floristic groups differentiate the sites in a pattern similar to that defined by the sediment groups. Broadly speaking, the 'wet' group species occupy the organic sands and organic fines whereas the 'dry' group species occupy the grey-brown sands and yellow earths. Species of the 'wet' group were most fully represented on the Loddon transects where organic fines occupy the valley axis (L2/1-5) and a tributary seepage zone (L1/10). In contrast, none of this group was found on the grey-brown sands near the top of the slope (L2/15), near a small eucalypt grove (L2/10) or on most of the yellow earths of the north-facing slope (L1/3-8). At these sites, the 'dry' group species were well-represented. On the organic sands which cover most of the L2 transect, species of the 'dry' group were absent but some members of the 'wet' group were found.

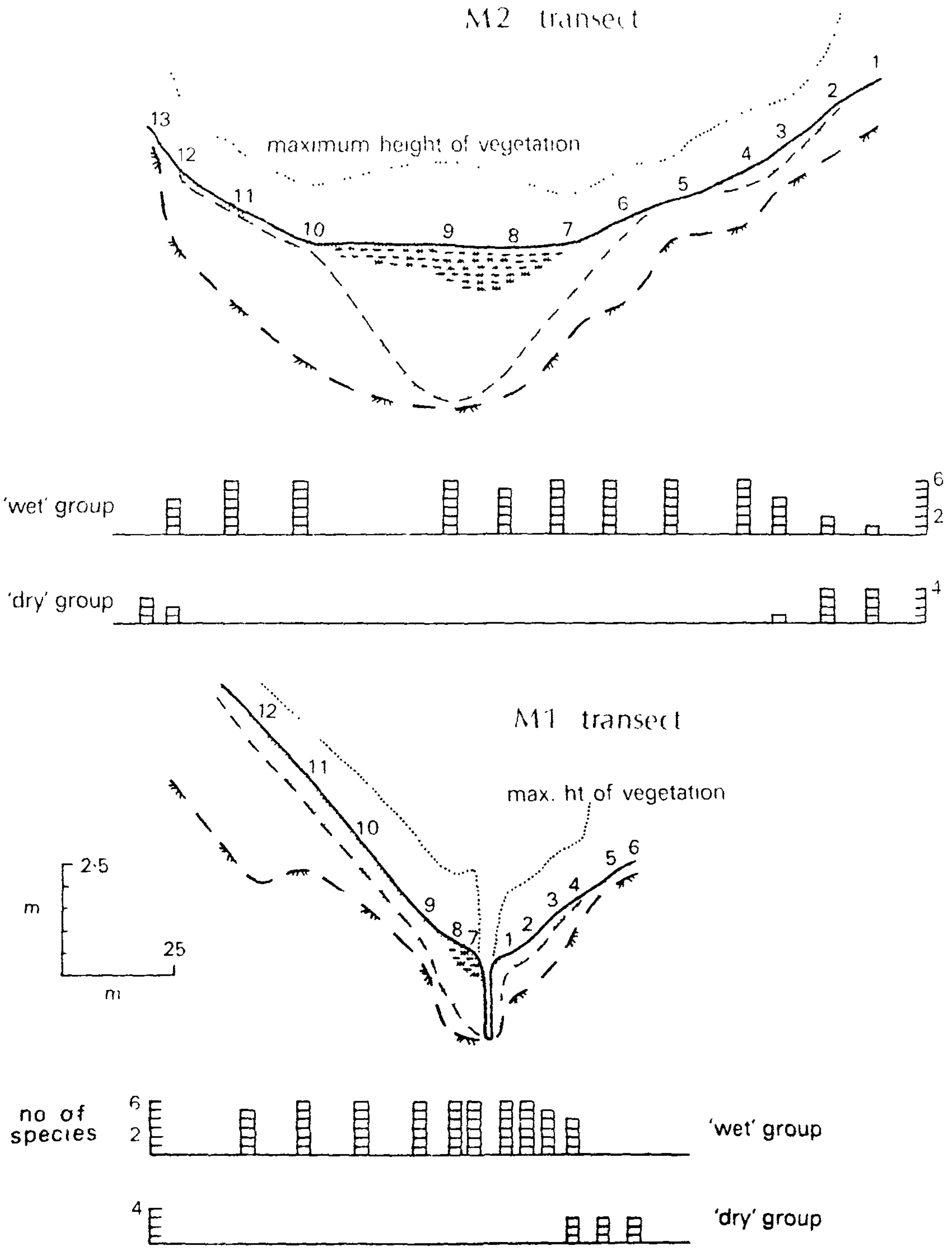
The pattern at Martins Swamp is consistent with that at

5·2

VEGETATION AND SEDIMENT CHANGES, LODDON TRIBUTARY



VEGETATION AND SEDIMENT CHANGES, MARTINS SWAMP



the Loddon tributary. Sedimentological contrasts at Martins Swamp are less marked, as no yellow earths occur and the organic-rich sediments are widespread. Thus the vegetation groups distinguish the dell proper from the dell-forest margin, rather than marking changing ecotopes within the dell. The moisture-tolerant species were most fully represented on the organic fines but also were found without any 'dry' group species on organic sands and at 4 sites (M1/2 and 3; M2/5 and 6) on grey-brown sands.

This does not imply that vegetation in Martins Swamp is unresponsive to environmental changes; presence/absence data alone do not fully describe the vegetation patterns. Along channels and seepage zones, the plants are closely spaced even at ground level, whereas on the sideslopes, bare ground is easily seen between sedge tussocks and individual shrubs. The vegetation is higher in the wetter zones, as well as apparently being more dense. The maximum height of the vegetation is greatest on the organic fines along the valley axes. Where sediments are most organic on the sideslopes, the vegetation is taller than on adjacent sandier sediments (see Figs. 5.2 and 5.3).

The causes of vegetational patterns in the dells.

It is clear that vegetational changes in the dells mirror sedimentological, and thus hydrological, changes. Kulczynski (1949) considers that hydrology, via its effects on edaphic conditions, determines the vegetation of mires. Ingram (1967) emphasises that nutrient supply to the plants depends on the nutrient concentration of the mire waters and also on the rates of flow. At one Scottish mire, flow rate in the water tracks was

$2x10^{-3}$ cm/day but in the mire expanse was only $8x10^{-5}$ cm/day (Ingram, 1967). Since the cation exchange capacity of the highly organic sediments in the water tracks (i.e. the valley axes and seepage zones) is likely to be higher than that of the sideslope sediments, nutrient availability should be higher in the zones where flow concentrates than on the sideslopes where flow may diverge. Certainly the vegetation of the dells is most luxuriant in the valley axes and tributary seepage zones.

The effects on vegetation of changes in sediment and hydrology are particularly well-demonstrated at 6R Swamp (see Fig. 4.6). The organic fines along the channel on the eastern side support closed-sedgeland. Moisture-tolerant shrubs (such as Banksia robur, Melaleuca squarrosa and Leptospermum juniperinum) up to 2.5m tall stand among tussocks of Gymnoschoenus sphaerocephalus and Lepidosperma longitudinale, densely inter-twined with Empodisma minus and Gleichenia dicarpa. This association ends abruptly at the shallow bedrock ridge between 6R/3 and 6R/4. The remainder of the transect (6R/5-9) is occupied by sedgeland which is almost devoid of G. sphaerocephalus and has an appreciable component of less moisture-tolerant species such as Haemodorum corymbosum, Sprengelia incarnata and Banksia ericifolia. The vegetation is lower, rarely more than 1m. There is therefore an abrupt contrast between the tall closed-sedgeland in the zone where flow is most constant, and the lower sedgeland where the water table is generally lower.

Mirlieb (1978), working in the Budderoo area, found that concentrations of nutrients (Ca, Fe, Mg, Mn, K, Na) in the above-ground parts of plants in closed-sedgeland were higher by factors of 3 to 8 than similar concentrations in an adjacent area of open sedgeland. Yet the nutrient concentrations in the soil water of the two areas differed only slightly, while nutrient concentrations in the soils (15-20cm depth) of the two areas differed by factors of less than 3. Mirlieb (1978) suggests that nutrients returned to the soil have very short residence times there. These data confirm the assumption made in the previous chapter that iron and other nutrients do not move freely in the dell waters; as in many other plant communities, the nutrients are largely locked into the store of living vegetation and organic debris.

The stability of the dell boundaries.

Given the close correspondence of vegetation and sediment types, the often-abrupt changes in the sediments between the dells and the adjacent forest suggest that the dell boundaries do not fluctuate rapidly. Yet peatlands in the U.S.A. (Heinselman, 1963), Finland (Lahermo *et al.*, 1977) and New Zealand (Campbell, 1964) have extended across formerly forested areas by the process of paludification. This process involves the extension of the margins of swampy terrain by continued localised rises in the water table. Ivanov (1981) suggests that paludification around mires in the U.S.S.R. is continuing and irreversible. Such paludification usually involves replacement of swamp forest (Heinselman, 1963; Campbell 1964) rather than of sclerophyll forest such as that around the dells.

In the Illawarra dells, there is no evidence for paludification. At no site was buried wood found in a growth position.

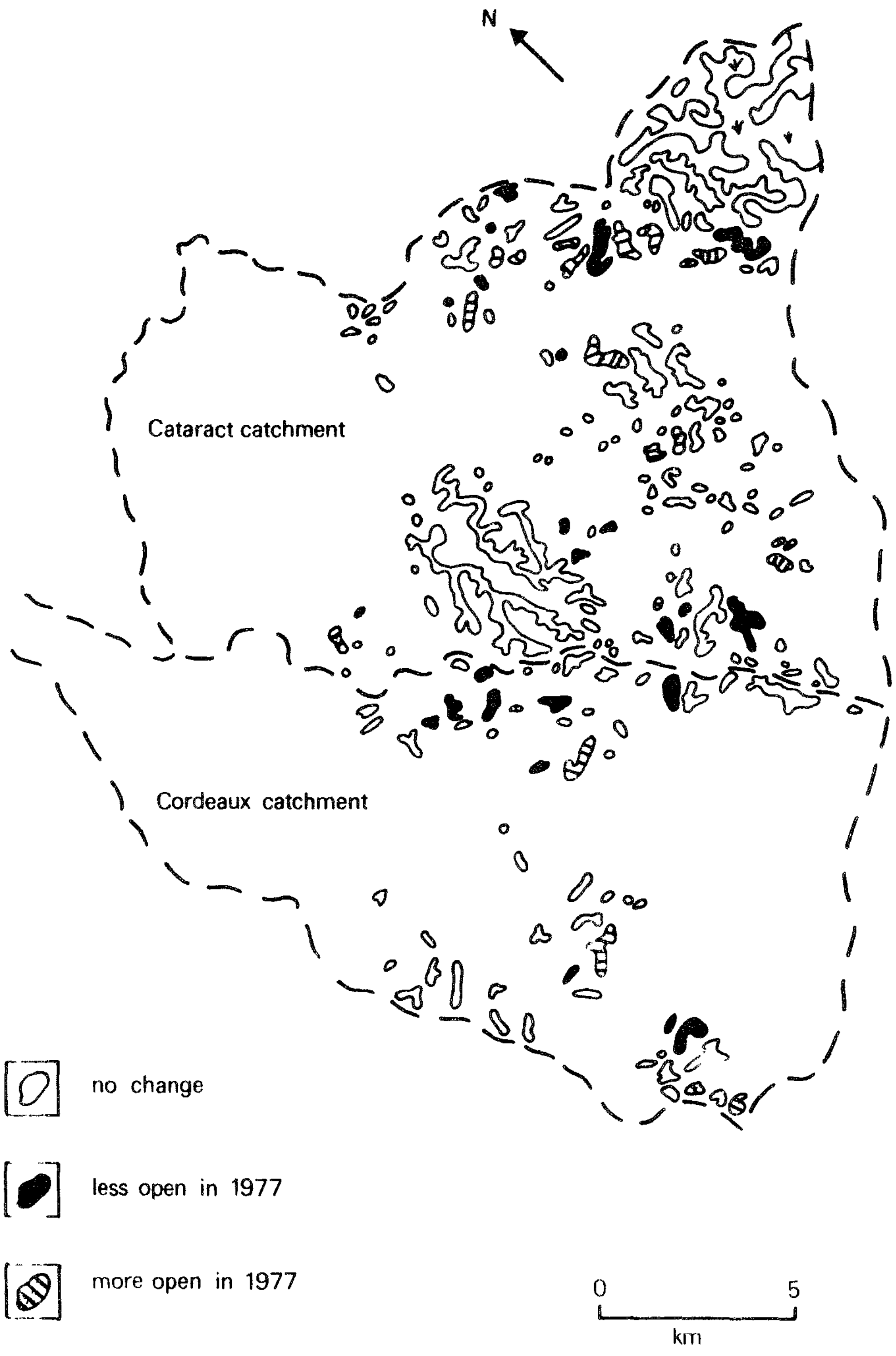
Even where 100m long sections from the dell surface to bedrock were available (at the Drillhole Swamp and at Porters Creek near Ulladulla) and in the channels cut near the F6 expressway through the Maddens Plains area, the few pieces of buried wood that were exposed lay horizontally and appeared to be branches rather than stumps. No wood was struck in any of the sediment sampling holes. As wood is well-preserved in poorly aerated sediments there has been no apparent encroachment of the dells onto the forest since the dell sediments accumulated.

Certainly, there has been no extension of the dells in the short-term. The dells of Cataract and Cordeaux catchments were compared, using aerial photographs flown in 1951 and 1977. In that 26-year period, the dell boundaries were stable. There was no significant contraction or extension of the margins; indeed, even isolated trees along the margins were usually identified on both sets of photographs. The stability of the margins weighs against the possibility of extension of the dells either by paludification or by repeated burning.

Jackson (1968) contends that the sedgelands of southwestern Tasmania have been extended beyond their edaphic limit by repeated fires. These sedgelands are structurally similar to those of the Illawarra and share some common species (such as <u>Gymnoschoenus sphaerocephalus</u>, <u>Leptocarpus tenax</u>, <u>Gleichenia dicarpa</u>, <u>Restio complanatus</u> - see Kirkpatrick, 1977; MacPhail and Shepherd, 1973). Unlike those on the Woronora Plateau, they often extend uninterrupted from valley-floors up steep slopes, occupying very shallow (less than 0.3m) organic soils above quartzite bedrock and overlapping low watersheds. The Illawarra dells are adjacent

CHANGES IN THE DELLS
1951 v. 1977

5·4



to dry sclerophyll eucalypt forest, whose ability to regenerate after fires is well proven; the sedgelands of Tasmania are often adjacent to Nothofagus rainforest (Kirkpatrick, 1977), whose ability to regenerate after fires is the subject of considerable dispute (Mount, 1979; MacPhail, 1980; Bowman and Jackson, 1981).

The effects of fires within the dells.

While fires do not appear to affect the extent of the dells on the Woronora Plateau, they may affect the vegetation within the dell boundaries. Wardle (1980, p.225) comments that in New Zealand:

> 'the wider extent today of meadows dominated by rhizomatous sedges ... largely results from burning ... In their virgin state, the swamps have a large shrub content.'

Similarly, Bowman and Jackson (1981) suggest that, in Tasmania, frequent burning reduces the shrub component and encourages conversion of heath to sedgeland. Gellie (1980) points out that regeneration patterns on the Tasmanian moorlands are influenced also by the time of firing and the fire intensity. Records of fires on the Woronora Plateau, held by the M.W.S.D.B., are not detailed enough to allow reconstruction of the fire histories of individual dells, particularly since fires do not uniformly incinerate the sedgelands. Comparison of the dells on the 1951 and 1977 aerial photographs does however demonstrate changes in the vegetation which may be the result of varying fire histories. Of the dells in Cataract and Cordeaux catchments, 18% were obviously more open in appearance in 1977 than in 1951, while an equal percentage (by number) had become more shrub-dominated and less open in appearance (Fig. 5.4).

Dells which became more, or less, open are sometimes close together but are also scattered among areas where no change, or the opposite trend, was apparent. Certainly there were no discernible regional trends, so that the changes observed were presumably due to endogenous changes (such as life cycle variations) or to exogenous changes (such as fire) whose activity had been sporadic.

The effect of fires on shrub-dominated swamp is well illustrated by the area just downstream of the Drillhole Swamp. The 1977 photographs showed a substantial increase in the area of sedgeland since 1951. When inspected in 1980, blackened dead and fallen eucalypts, and abundant small shrubs, indicated that this area had been previously covered by wet heath with small groves of eucalypts. It may have burned in 1976, as did the Drillhole Swamp. The Banksia ericifolia seedlings, despite their variable height (0.5-1.5m), consistently have 5 whorls, indicating 5 years of growth since germination. Near many of the burnt eucalypts, suckers have grown up. However, the effects of sedimentary and hydrological patterns are still clear. The vegetation changed abruptly from Gymnoschoenus-Lepidosperma closed-sedgeland where seepage emerged over shallow bedrock to lower and more open Leptocarpus tenax sedgeland with many shrub seedlings on convex slopes, to Chorizandra-Gymnoschoenus closed-sedgeland with many Banksia robur in a seepage hollow. While fire has, for the time being, removed the above-ground parts of most of the shrubs and trees from this swamp, the effect is not likely to be permanent. Certainly there is no evidence for alteration of the forest-dell boundary. Both on the margins and within the dell, the hydrological and sedimentary variations are closely linked to vegetation changes.

Within the dells, even very wet organic sediments can be colonised by dense thickets of moisture-tolerant shrubs which virtually eliminate the sedges. Species such as Melaleuca squarrosa, Viminaria juncea and Banksia robur appear to compete very effectively with the sedges, once they become well-established. For example, in the northeastern arm of Martins Swamp, a thicket developed of Melaleuca squarrosa up to 6m tall, with a closed canopy and sparse understorey (of Bauera rubioides and Schoenus melanostachys). The ground was covered with a dense mat of Melaleuca leaves, the sediments were black organic sands and shallow rills flowed through the thicket in wet weather.

The thicket was to some extent protected from fire. Whereas its groundsurface had wet, poorly aerated fuel, the dead leaves around tussocks in the adjacent sedgeland provide continuous, dry, well-aerated fuel through which a fire could travel rapidly. However the edges of the thicket had been partly collapsed by wind. When Martins Swamp was burnt in June 1982, a small outlying thicket was completely burnt and fire penetrated the main thicket. Eighty percent of the thicket suffered at least severe crown scorch. If the area is burnt again within a few years (either as a result of fires penetrating from the adjacent unburnt forest or after the sedgeland has regenerated sufficiently to burn again), then complete destruction of the thicket seems likely. Such destruction would not of course preclude re-establishment of a similar thicket from seedlings.

It seems, therefore, that frequent burning of the dells may reduce the moisture-tolerant shrub component of the vegetation, thus encouraging the development of sedgeland rather than heath.

But since both sedge and shrub species can effectively colonise the wet and highly organic zones within the dells, such a change will not necessarily affect the geomorphic and hydrological processes operating within the dells.

Conclusions

There are obvious similarities between the vegetation of the dells studied here and that of rheotrophic mires elsewhere in the world. The dells are occupied by treeless sedgeland. Within the dell ecosystem or biogeocenose (Troll, 1966; Walter, 1973), variations in hydrological conditions and substrate are reflected by changes in the pattern of vegetation. In contrast to the Northern Hemisphere mires however, the dells are not spreading across formerly forested areas. Nor do repeated fires apparently cause the forest surrounding the dells to retreat, although burning may alter the shrub component of the dell vegetation. The vegetation of the dells is closely related to the edaphic and hydrological conditions, lending support to the conclusion of earlier chapters - that the dells are forming under present conditions.

SUMMARY

- The vegetation of the dells ranges from closed-sedgeland to heath, trees being largely absent. Structurally therefore it resembles the vegetation of rheotrophic mires elsewhere.
- Grouping of presence/absence data defined two vegetational groups. The first group, comprised of moisture-tolerant shrubs and sedges, occupies organic fines and organic sands. The second group, comprised of a shrub and hemicryptophytes, occupies the drier grey-brown sands and yellow earths.
- Vegetation is most luxuriant along the valley axes and tributary seepage zones, apparently because of greater nutrient availability in these zones.
- There is no evidence that the dell margins have expanded at the expense of the surrounding forest during the period in which their sediments have accumulated. No buried stumps were found, and from aerial photographs the dell boundaries have been observed as essentially stable at least over a 25 year period. Paludification is not an important process.
- Nor have the boundaries apparently been extended as a result of repeated burning. However the fire regime may affect the shrub component within the dells.
- Vegetational changes within the dells are closely related to variations in hydrological and edaphic conditions.

5. Melaleuca thicket, Martins Swamp (see Photo 1), from M2/3 after a fire in July 1982. Most of the thicket is badly scorched. Note also the burnt 1-2m high shrubs in the valley axis (centre of photo).

6. A terracette of charred plant fragments within a burnt part of the Sublime Pt moors. Note that it is in an area where shrubs are common, that there is minimal sand build-up behind it. Initial regeneration occurred preferentially along the terracettes rather than in the flatter ground behind them. The pen is 15mm long.

7. The Loddon tributary, after a fire. Note the patterned ground in the dark wet zones, contrasting with the light-coloured patches of forest along rock outcrops. The bright green below the cut channel is due to re-growing Chorizandra sphaerocephala.

8. Furrows in Loddon catchment. Note the bareness of the furrows in contrast to the ridges, the near-vertical furrow sides, the burnt shrubs and sedge tussocks on the ridges. These furrows are narrower, compared with the ridges, than is usual.

CHAPTER SIX: PATTERNED GROUND.

The interplay between topography, hydrology and vegetation which has been described at the macroscale across the plateau (Chapter 2) and at the mesoscale across individual dells (Chapters 3-5), may be seen equally well at the microscale. Microtopographic variation, in the form of linear patterned ground oriented across the slope, is associated with variation in hydrological and vegetational patterns. Thus the patterned ground forms a 'micro-ecotope' (cf Troll, 1966) or 'microtope' (Ivanov, 1981) within the larger ecosystem or 'biogeocenose' (Walter, 1973) of a dell. Studying the development of the patterned ground introduces a new factor in the processes operating in the dells - that of faunal activity; it bears also on the historical-stratigraphic interpretations to be made in the following chapters, as similar patterned ground has been attributed to processes operating in very cold environments (e.g. Tricart, 1970).

The form and distribution of the patterned ground.

In the Illawarra dells, the pattern is composed of ridges and furrows, which approximately parallel the slope contours. The ridges, which are 30-250cm wide, extend across the slope for up to 10m before fusing to enclose elongate lenticular furrows. These furrows are of similar width to the ridges; their floors are usually 10-30cm, rarely more than 50cm, below the ridge tops. On the ridges, graminoid species (usually *Gymnoschoenus sphaerocephalus*, *Lepidosperma longitudinale* and *Xanthorrhoea* sp.) dominate, but shrubs (such as *Banksia robur* and *Hakea teretifolia*) are scattered among the

6·1

RIDGE - FURROW PATTERNS, LODDON CATCHMENT

from 1961 Cumberland
Series 1:13,000 photos

(b)

from Coledale 1:10,000 orthophotomap;
contours in metres a.s.l.

ridge-furrow patterns
from 1:8150 photos, courtesy BHP P/L

tussocks. In contrast, the furrows are sparsely vegetated. Chorizandra sphaerocephala and a few small aquatic plants (notably Villarsia exaltata) are often the only vascular species occupying a furrow. Indeed up to 50% of the furrow floor may be bare, except for algae.

The patterning is best seen from the air and after the dells have been burnt. Unfortunately the aerial photographs on which it could be easily seen (1961 1:13,000 Cumberland series) cover only the northeastern corner of Cataract catchment (Fig. 6.1a). There it is best developed on the Sublime Point moors, along the Loddon River. No patterning was seen in the smaller dells immediately to the west. However it is not confined to the Loddon catchment; it occurs also in the southern arm of the Drillhole Swamp, the northeastern arm of Martins Swamp and in a dell which overlaps the Avon-Cordeaux watershed 1km south of the Drillhole Swamp. McElroy (1951) identified ridge-and-furrow topography, which he termed 'contour trenches', at Maddens Plains and also on the Nowra Sandstone plateau near Ulladulla, on the Dorrigo plateau in northern N.S.W. and on the Monaro Plateau between Kiandra and Mt Kosciusko (see also Costin, 1954, Fig. 156).

Within the Loddon catchment, ridge-and-furrow patterning is absent from the main stream channels, from steep slopes, from slopes broken by numerous bedrock outcrops and from very broad gentle interfluves (Fig. 6.1b). It is predominantly found in tributary seepage zones, where the flow of water is concentrated but is insufficient to create an open channel. Furrowed slopes abut sharply against smooth slopes, but may have the same or even slightly steeper gradients. Certainly they are not always gentler than adjacent smooth slopes even though profiles for the Maddens Plains area drawn by McElroy (1951) might imply that this is so. The gradients involved are very low, usually 2-3° and not more than 5°.

Theories concerning the origin of patterned ground.

The ridge-and-furrow systems in the dells closely resemble the patterned fens of the Hudson Bay lowlands in Canada (Sjors, 1961), the Lake Agassiz region of Minnesota (Heinselman, 1963; Glaser et al., 1981), and alpine Colorado (Vitek and Rose, 1980). A similar microtope characterises vast areas of ombrotrophic mires in the Boreal zone, these areas being termed aapamires or string-bogs (Sjors, 1961; Lahermo et al., 1977; Moore and Bellamy, 1973; Walter, 1977; Ivanov, 1981).

Many studies on patterned mires in the Northern Hemisphere envisage some role for frost action or frozen ground in association with mass movement to explain the formation of the microtopography. Hamelin (1957) is most explicit in this, commenting that

> 'the pattern [of string bogs in Labrador, Canada] was established during the cold period which preceded the present drier period ... we can envisage the pattern coming: firstly, from localised tearing of the skin of the mire, due to differential thickening of ice lenses; and secondly, from solifluction ... [it is] a form inherited from a past period which was colder than the present day. Without a previous cold period, the relief of the bogs of the subarctic zone would be no different from the uniform landscape of those in temperate areas.'
>
> (Hamelin, 1957, p.105; my translation).

Allington (1961) however attributes the Labrador string bogs to frost action and meltwater inundation, without presupposing permafrost. Heinselman (1963) also comments that permafrost is not essential for pattern development, since the patterned fens of Minnesota are currently forming. The action of frost and meltwater are again thought to be the major causes. Vitek and Rose (1980), working in alpine Colorado, propose a polygenetic origin for patterned fen, involving probable solifluction over existing permafrost, frost action, differential sedimentation and erosion, piping and variable growth of vegetation.

Other workers attribute the patterning to the interplay of hydrology and vegetation. Indeed, Ivanov (1981) argues that the hydrological equilibria in mires require that a strip-like pattern of vegetation develop. He suggests that constancy of water table level for a given community is achieved by changes in the proportion of furrows (where hydraulic conductivity is obviously high) and ridges (where hydraulic conductivity is much lower), these changes being determined by the necessity to maintain a constant average rate of seepage through the various parts of a mire. This explanation clearly begs the question of the origin of the microtopography which provides the disparate environments on which the different vegetation communities have developed. A less extreme view is taken by Boatman et al. (1981), who propose that flooding along the line of the contours causes extension of presumably random irregularities on the mire surface. Similar proposals are made by Sjors (1963), by Walter (1977) and by Glaser et al. (1981). Flooding leads to the death of species which occupy the formerly better-aerated ridges; once a bare floor is established on the extended furrow, corrosive oxidation (i.e. rapid breakdown of organic debris due to the well-oxygenated shallow film of water over the furrow floor - Sjors, 1963) may lead to cessation of peat formation in the furrow and thence to maintenance of the ridge-furrow relief. Glaser et al. (1981) suggest further that the formation of ridges may be due partly to the string-like growth habit of some plants.

Despite the variety of mechanisms proposed, there are two important points of consensus among most workers. First, the patterned ground occurs in parts of the mire where flow of water is concentrated. Second, the ridge-furrow systems are contemporary phenomena which must be accounted for by processes that are operating today (see particularly Moore and Bellamy, 1973). These points are clearly established by Glaser et al. (1981). They note that drainage ditches in the Red Lake peatlands of Minnesota are effective in lowering the water table in only the upper few centimetres of the mire, yet even this limited effectiveness has led to the almost complete disappearance of the ridge-furrow pattern in some areas. Not only is the patterning of the Minnesotan mires dependent on hydrological factors, but its development apparently is associated with the characteristics of the near-surface horizons of the mire.

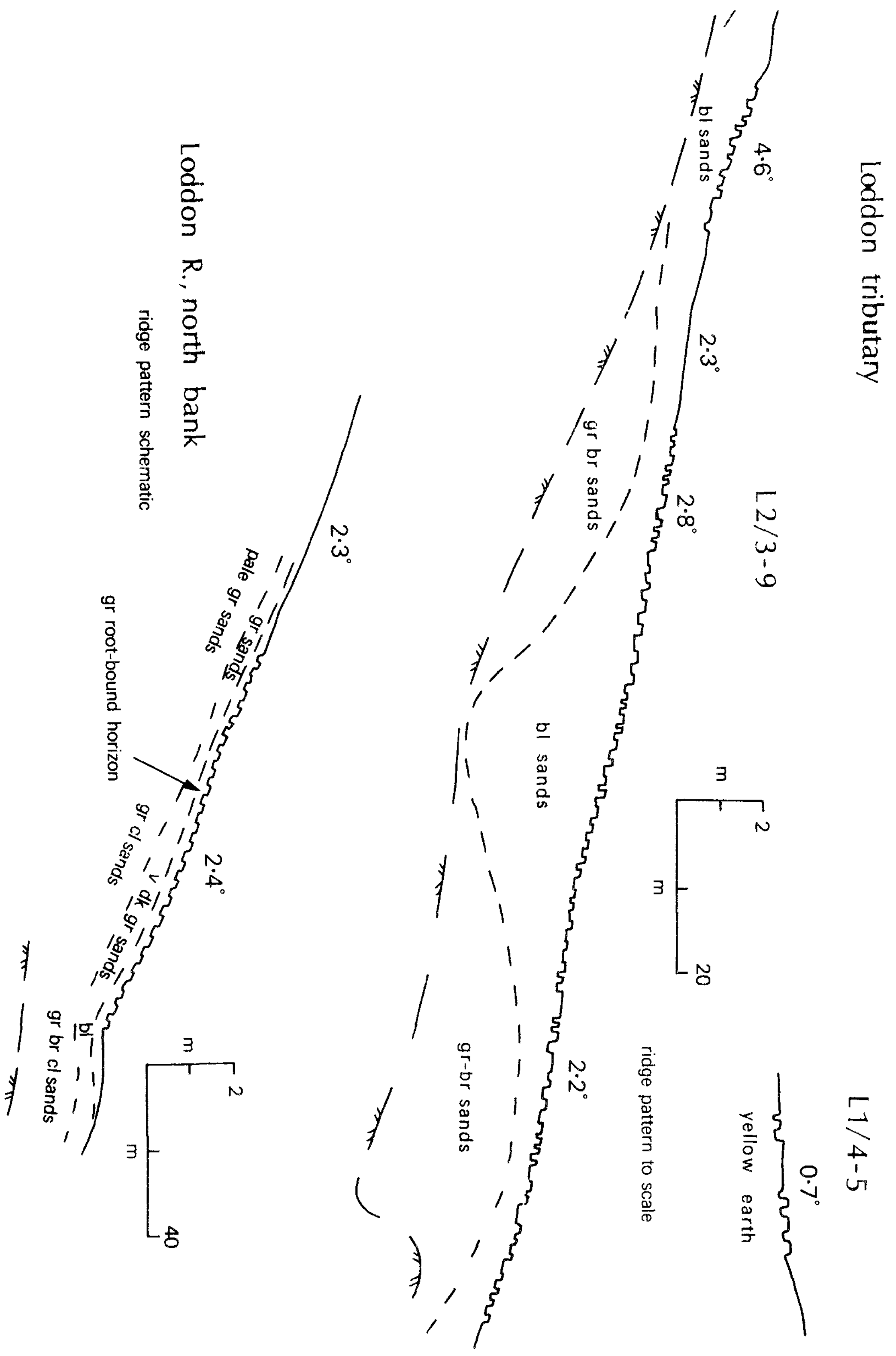
The origin of the patterned ground in the dells.

If the patterning in the Illawarra dells is a contemporary phenomenon, then frost action and/or gelifluction (soil flow over permafrost) are not possible causes. And the patterning is apparently still forming. At the Loddon tributary it has formed on sediments no older than 17,000 BP and at Martins Swamp on sediments no older than 6,800 BP. It is consistently associated with the zones of seepage concentration, particularly in tributary seepage zones (cf. the 'water tracks' of Boatman _et al._, 1981 and Glaser _et al._, 1981) or where seepage emerges at the base of slightly steeper slopes. Certainly there is no reason to suggest that the microtope is relict, nor even that it is a 'survival' formed under colder conditions but able to maintain its development under the present climate (Tricart and Cailleux, 1972).

The ridges and furrows have only shallow surface expression; they are not related to variations in the subsolum. Hence they are genetically unlike the morphologically similar linear form of gilgai (cf. McElroy, 1951). There were no consistent differences in the soil profiles characterising adjacent smooth and patterned slopes. For example, at the Loddon tributary transects, the depth of organic-rich sediments and the depth to firm bedrock varied considerably below patterned ground (Fig. 6.2a). A smooth section between L2/8 and L2/9 was underlain by shallower but otherwise similar sediments to those below furrows between L2/4 and L2/5. Beside the Loddon River also, the soil profiles of the smooth and furrowed slopes were similar. In both the smooth and the furrowed slopes, the top 20cm was a loose tangle of roots in dark grey sand. From 20-60cm approximately, there were very dark grey or black organic sands, massive and compact (specific gravity 2.52) in the furrowed area but friable and loose below the smooth slope (S.G. 1.70). Below the organic sands were clayey sands (S.G. 2.6), which became more clayey with depth and merged at 200cm or more into stiff pale weathered sandstone. The difference in the colour of these clayey sands - pale grey below the furrowed slope, mottled pink/orange/grey below the smooth slope - reflects the wetter environment of the furrowed slope. While the rate of

6·2

RIDGE - FURROW CROSS-SECTIONS, LODDON CATCHMENT



organic accumulation may be higher in this wetter ecotope, the processes of mineral sediment accumulation do not appear to differ between the smooth and the patterned ground.

It is possible also to eliminate shear failure as a mechanism of formation. Organic sands from the Loddon catchment were analysed in a reversing shear box by Dr R. Blong, Macquarie University. They yielded residual shear strength parameters of:

$$\text{cohesion, } c'_r = 3.24 \text{ N/cm}^2$$

$$\text{angle of shearing resistance, } \phi'_r = 21°$$

for field densities of 1760 Kg/m^3. The slopes were analysed assuming an infinite straight slope of $\beta = 4°$ with seepage at and parallel to the surface, according to Chowdhury (1978, p.89):

$$F = \frac{c}{\gamma\ z\ \sin\beta\ \cos\beta} + \frac{\gamma'}{\gamma}\ \frac{\tan\phi}{\tan\beta}$$

This yielded a factor of safety, F, of 2.55 whereas slopes which are unstable with respect to shear failure have F values of approximately 1. This is not surprising as no evidence for shear planes was seen in auger holes or soil pits dug in the patterned ground in the Loddon area.

Nevertheless the concept of pattern development by enlargement of random irregularities (Sjors, 1963; Boatman et al., 1981) is difficult to reconcile with the rhythmic regularity of the pattern. Boatman et al. (1981) also propose that extensive flooding of the mire could lead to establishment of patterning. In the Illawarra dells, sheetwash after fires does create small arcuate terracettes of burnt debris. Yet these terracettes are only a few centimetres high, a few decimetres apart and a metre or so long. They are therefore an order of magnitude smaller than the ridge-and-furrow systems. Furthermore, they are largely confined to relatively dry, heath-covered parts of the dell (see Chapter 5) whereas the ridges and furrows occupy the sedge-dominated water-tracks. And soil pits dug through the ridges showed no core of burnt plant fragments around which sediment had accumulated.

It seems likely that the patterned ground is the result not of deposition from sheetwash but of solifluction. Solifluction was proposed as the prime cause of patterning on Maddens Plains and other similar areas in southeastern Australia by McElroy (1951); it was accepted as a major factor in pattern development also by Vitek and Rose (1980). Indeed the common features of areas for which ridge-furrow topography is described are:

- saturated sediment on gentle, poorly-drained slopes
- treeless vegetation with shallow root systems.

Both these features imply low resistance to soil movement, since porewater pressures must be high and the sediments are not strengthened by deeply-penetrating root systems. Although shearing apparently does not occur, slow movement of the sediments under the influence of gravity is the most likely cause of the microtopographic variation. Once the microtopography is established the disparate microenvironments of the furrows and the ridges are colonised by varying flora and fauna. The interrelationships between the biota and their physical micro-environment encourage the preservation and perhaps the amplification of the microrelief.

Vegetation and faunal activity in the microtope.

As mentioned earlier, the vegetation of the ridges differs from that of the furrows. Percentage cover and probably species diversity is greater on the ridges than in the furrows. Shrub species are very rarely found in the furrows, except where their roots are exposed in the furrow walls. Similar differentiation of vegetation is found in the patterned fens of the Northern Hemisphere. There too, the ridges are well-vegetated, often with low shrubs, whereas the furrows are sparsely occupied by monocotyledonous plants (Sjors, 1961, 1963; Slack *et al.*, 1980). Water level was the main factor influencing this differentiation in the Canadian fens (Slack *et al.*, 1980). Given that the sediments of the ridges do not differ from those of the furrows in the Illawarra dells, water level, perhaps via its influence on aeration, is probably the main factor here also. Because the sediments are not very permeable, there is only very slow percolation through the floor of the furrows or through the intervening ridges. Hence the furrows will store water for a week or more after rainfall, even if the water table for the slope is a metre or so below the surface.

The wet environment of the furrows is favoured by a small crayfish, *Euastacus kierensis* Riek (kindly identified by Dr P. Greenaway of the University of New South Wales). It inhabits the sedgelands rather than the streams of the plateau (Lawson, 1978), particularly the patterned ground rather than drier smooth sideslopes. Entrances to its burrows are usually in the furrows, but sand excavated from the burrows is piled up in a cone around an outlet on a ridge. Even where the crayfish have been recently active, ejected sand is not found around holes on the furrow floors. *Euastacus kierensis* feeds mainly on detritus and plant material (Lawson, 1978), as do the species which inhabit the button-grass plains of Tasmania (Lake and Newcombe, 1975; Suter and Richardson, 1977). One of the Tasmanian species, Parastacoides tasmanicus, which is confined to the wet plant communities and does not enter dry heath-sedgeland, also burrows preferentially in pools. Indeed Gellie (1980) proposes a symbiotic relationship between the crayfish and the Gymnoschoenus tussocks.

A survey of their activity along and near the L2 transect demonstrated that the crayfish in the Illawarra dells move considerable quantities of sediment. An $0.25m^2$ grid was placed every 20 paces along the transect and along another line diagonally across patterned ground nearby, giving a total of 35 observations. Nine debris cones were found along these transects. They ranged in weight from 300-1500g, and the mean value for debris built up in this way on the ridges was $730g/m^2$. In the furrows, there were numerous burrow entrances. The number of these ranged from 1 to 8 within the grid, the average yielding a value of 9 holes per square metre. Since most of the cones were unvegetated and clearly recent, the annual rate of activity may be far higher than this value. However even a rate of $730g/m^2$ per year is comparable with rates of bioturbation in the nearby sclerophyll forest, where Humphreys (1981) recorded $133g/m^2$/year for earthworms and $841g/m^2$/year for one species of ant. Indeed, the crayfish replace these animals as bioturbators, since worms are rarely found in the patterned ground and ants' nests on the ridges are predominantly of plant fragments rather than sediment.

Furthermore, the role of crayfish seems to be important in the preservation and the deepening of the furrows. Roots of growing shrubs are often exposed on the sides of the furrows, indicating that there has been erosion of the ridge and/or lowering of the furrow floor. Wind or wave erosion is inconceivable in such small features, especially as they are usually well sheltered by the vegetation. Sjors (1963) proposed that the floors of furrows were lowered by corrosive oxidation, commenting that the sparseness of vegetation in the furrows means that most of the organic debris is readily-decayed algal remnants. This may be so, but more obvious mechanisms in the Illawarra dells involve the net transport of material from burrows under the furrows to cones on the ridges and the subsequent collapse of abandoned burrows.

A similar role has been proposed for the maintenance of terraces on periglaciated slopes in Colorado due to the action of pocket gophers (Thorn, 1978) and for erosion of solifluction lobes in the Yukon by arctic ground squirrels (Price, 1971). However, none of the work on ridge-furrow patterns in the Northern Hemisphere mentions zoological influences, while Vitek (pers. comm., 1981) confirms that there are no crayfish, large ant colonies or burrowing rodents in the patterned fens of alpine Colorado. The crayfish encourage the preservation and probably the deepening and extension of the furrows by their burrowing activities; these activities may also account for the similarity of the sediments underlying adjacent ridges and furrows and for the absence of flow deformation structures. Differentiation of vegetation in the microtope may be reinforced by crayfish feeding preferentially on sedge rhizomes in and beside the furrows, and by ants inadvertently seed planting in their nutrient-rich mounds on the ridges.

Davis (1941) tentatively suggested that the furrows could have been initiated by the burrowing of the crayfish. Certainly Haantjens (1969) has shown that faunal burrowing (by giant earthworms in New Guinea) can cause patterning of the ground surface. But this is not the case in the Illawarra dells. The few crayfish burrows found on smooth slopes were all oriented downslope, not along the contours. Although the crayfish favour wet seepage zones within the dells, not all these zones are patterned. In Martins Swamp, for example, there is abundant evidence of crayfish burrowing, and of collapse of burrows, in very wet areas which have no regular microtopography. Thus the crayfish appear to exploit a microtope whose origin, as demonstrated by its widespread occurrence in organic terrain, is determined neither by climatic (cf. Hamelin, 1957) nor vegetational (cf. Ivanov, 1981) factors.

Conclusion

At the microscale, the ridge-and-furrow microtope displays similar inter-relationships between sediments, water movement and vegetation to those demonstrated for the dells as a whole, with the added important dimension of zoological influences. Because the patterned ground occurs in areas of seepage concentration and thence relatively high and constant water levels, its sediments are more organic than those of adjacent smooth slopes. The vegetation responds very clearly to the alternative micro-environments provided by the waterlogged furrows and the better-drained ridges. These inter-relationships, like those at the broader scale, are self-reinforcing. Clearly the ponding of water in the furrows and the exclusion of coarse transported sediment reinforces the wetness of the patterned ground and the impermeability of its sediments. The dense vegetation binds and protects the ridges from rainsplash or wind erosion. There may well be differential rates of evapotranspiration and organic accumulation between the two micro-environments, but no data are available to estimate this.

It is suggested here that the patterned ground in the dells is due to slow creep of saturated organic sediments near the groundsurface. The differentiation of vegetation is thus a response to the disparate microenvironments provided by the patterned surface, rather than a prime cause of the patterning. Furthermore, while flooding along the contours may occur, it would extend and reinforce -rather than create - the pattern. The suggested mechanism does not imply that the pattern is a survival initiated under once-colder climates; the mechanism proposed for patterning in the Illawarra dells is due to the wetness of the environment, not to slipping over a frozen subsolum.

SUMMARY

- Patterned ground, comprised of linear ridges and furrows oriented along the contours, characterises some of the dells on the Woronora Plateau, especially in the Loddon River catchment.
- Similar patterning is found in fens (rheotrophic mires) and in extensive ombrotrophic mires in the Northern Hemisphere. It is attributed by various authors to frost action, meltwater inundation, vegetational influences or to localised flooding.
- The patterning on the Woronora Plateau is apparently contemporary and not related to past cold climates. It may be a near-surface feature, but does not appear to originate as strings of sheetwash debris.

- Although shear failure is not involved, the microrelief seems to form as a result of solifluction in zones of high water table and seepage concentration.
- As in patterned fens elsewhere, vegetation grows sparsely in the furrows whereas the ridges are well-covered, often with shrubs as well as sedges and rushes.
- Crayfish appear to move considerable quantities of sediment from below the furrows onto the ridges, building up the ridges and causing collapse and extension of the furrows. Bioturbation may also destroy deformation structures due to the flow of the sediments.
- The vegetation and the fauna thus exploit favourable micro-environments created by the microtopographic variation. In so doing, they reinforce the microrelief.

CHAPTER SEVEN: THE STABILITY OF THE DELLS AS AGGRADING SYSTEMS.

The dells are aggrading under present conditions. Very little of the sediment from the forested ridges is transported through them; even suspended load appears to be largely trapped in the densely-vegetated valley axes. However there is no evidence for significant expansion of the boundaries as the sediment accumulates, even though the basal ages of the sediments indicate that dells have characterised the Woronora Plateau for at least 17,000 years. And the dells are not immune from erosion; rapid contemporary erosion at disturbed sites, and the character of some relict deposits, bear witness to this fact. The stability of the sediments is clearly related to the vegetation cover, the absence of continuous open channels and the cohesiveness imparted to the sands by sticky moist humic material. In this chapter, we shall look at the stability of the dells with respect to erosion, in both the short-term and throughout their development.

The concept of stored hydraulic adjustment potential.

> 'An important consequence of erosional-depositional surfaces being vegetated is that overland flows passing across them entrain very little sediment. Such surfaces may remain unresponsive to changes such as uplift for long periods ... We refer to this condition as "stored hydraulic adjustment". In the case of a landscape where stored hydraulic adjustment potential has increased, the advent of fire, climatic change, or human activities represents a time of reckoning in geological terms.'
>
> Moss and Walker, 1978, p.125.

Although applied to landscapes by Moss and Walker (1978), the concept of stored hydraulic adjustment also applies well to individual sedimentary bodies such as those in the dells. Certainly, there are external forces which could trigger change in the dells. Regional climates may have varied considerably since the late Pleistocene (*cf* Bowler et al., 1976; Kershaw, 1981); Aborigines moving onto the plateau during the Holocene may have altered fire regimes and thence sedimentation rates (Hughes and Sullivan, 1981); wildfires and intense storm events are features of contemporary environmental conditions. Nevertheless, as Schumm (1979) has argued, even major external forces do not necessarily cause adjustment in the landscape. Erosion in some fluvial systems occurs only after a geomorphic threshold, intrinsic to that system, has been exceeded. Hence, as Young and Nanson (1982) demonstrate for the streams of the Illawarra coastal plain, abrupt changes in the sedimentary pattern may be due not to Pleistocene/Holocene climatic changes but to intrinsic geomorphic thresholds. Such thresholds, Schumm (1979) suggests, may be governed by relationships between drainage basin area and valley slope, between armouring of the channel floor and sediment discharge, or between tractive force in the channel and biomass of vegetation on the valley floor.

There are, by analogy with the relationships described by Schumm, several ways in which the dells studied here could become inherently unstable:

- by aggradation to a level well above the bedrock surface near the knickpoint at the dell exit; such aggradation would provide a bank of fairly easily-trenched material at the locus of flow (energy) concentration.
- by higher sedimentation rates in the upstream reaches than near the exit, due to the inefficient transport of sediment

through the dells. This would lead to an increase in the slope of the groundsurface in the valley axis.

- by more rapid deposition near the forest margins than in the valley axis, leading to an increase in the slope of the valley sides and thence to greater tractive power of overland flow.
- by a rise in the groundsurface in the upstream reaches of the dells and on the dell margins, leading to deeper watertables and thus to less organic sediments, less dense vegetation and greater erosion potential in these areas.

Low-frequency, high-magnitude events do not always trigger major changes within river systems (Dury, 1977). Nor do fires in the dells bare an easily-eroded groundsurface (see Chapter 5). While the dells may have considerable stored hydraulic adjustment potential, this potential may not be realised until a critical intrinsic threshold has been reached and until a major external event causes that threshold to be exceeded.

The pattern of contemporary erosion in the dells.

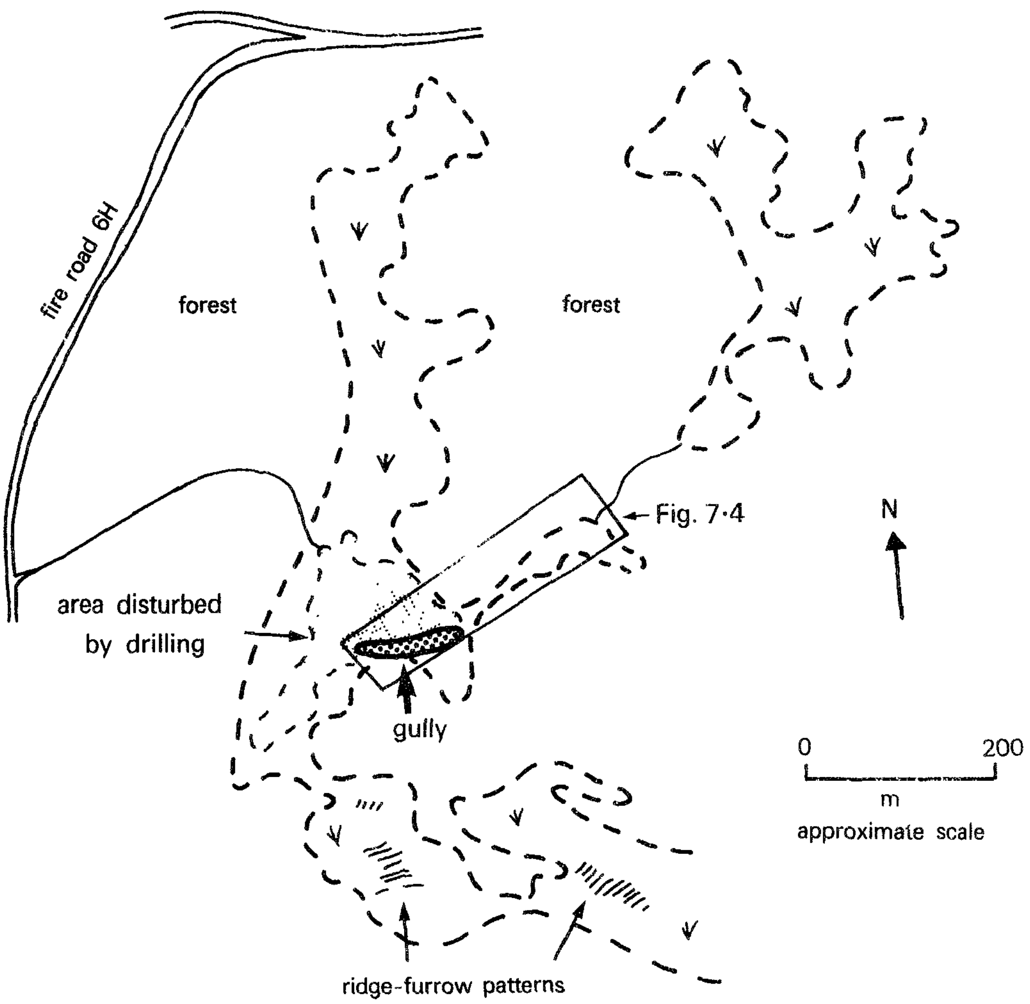
While contemporary erosion in the dells is largely due to human interference, it does demonstrate that the dell sediments can be rapidly eroded and that erosion will continue once an open channel is established. In the Loddon River and Maddens Creek catchments, channels were cut through the dells in order to allow rapid drainage downstream of the F6 expressway. These channels are up to 200m long and 5-10m wide; they are cut to bedrock through up to 4m of organic sediments. As noted earlier, in undisturbed dells, only fine suspended load and minimal sands are transported down the valley axes. In the newly-cut, bedrock-floored channels near the expressway, flow rates are increased so that blocks of sandstone a few decimetres across are moved, and sand and sandstone pebbles are readily transported. It is not surprising therefore that the artificially cut channels remain open unless they are blocked by large slugs of sand derived from bank erosion. Slumping of the sediments has created amphitheatres up to 10m in diameter in the channel walls. Drying-out of the bank sediments, due to the localised fall of the water table from the groundsurface to bedrock, reduces the sediment's cohesion, while piping leads to knickpoint retreat up tributary seepage zones.

Erosion of the channels near the expressway has not been dramatic, but at the Drillhole Swamp in Avon catchment, some 8,250m^3 of sediment was eroded in less than 3 days in March 1978. The gully at the Drillhole Swamp was 100m long and 10-25m wide (Fig. 7.1). Had it not been confined headward, on one wall and on its floor by sandstone bedrock, an even larger gully may have been cut during the flood. Blocks of sediment 1m long and 0.5m across were undercut and tumbled downstream. As the blocks broke up in the turbulent flow, the fine organic fraction was separated and removed as suspended load. However the cleaned sand and some small logs were dumped only 30m downstream. Erosion at the site was triggered by several factors:

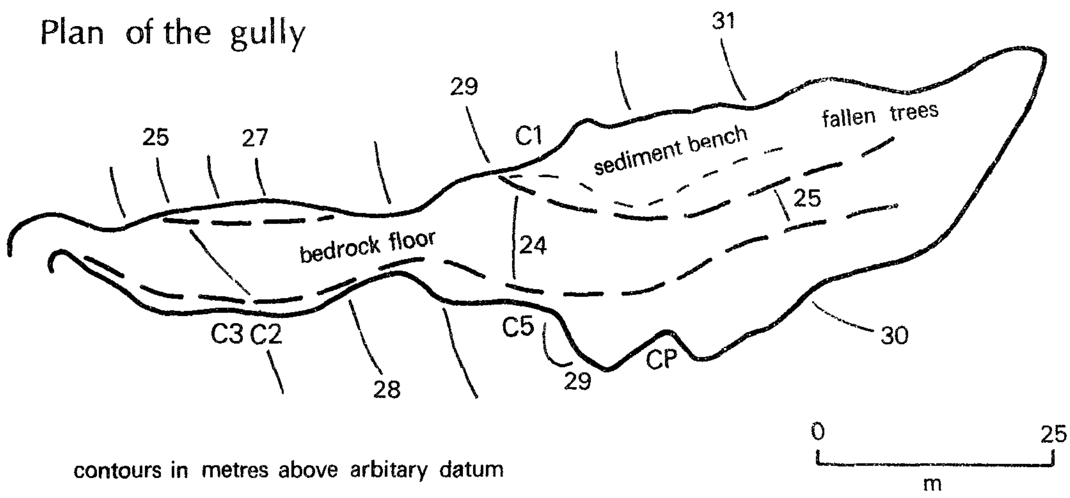
- the area near the mouth of the gully had been stripped of its shallow (<1m) soil and vegetation cover during drilling operations (see Reynolds, 1978). This provided the initial knickpoint in the sediments, from which the erosion proceeded.
- a small dam about 2m deep had been constructed upstream to provide water for drilling. This dam was in place before

7·1

GULLYING AT THE DRILLHOLE SWAMP



Plan of the gully



contours in metres above arbitary datum

C1=profile location

the gully was eroded (G. Nanson, pers. comm., 1978) but there was no sign of it afterwards. Presumably it failed during the flood, releasing a sudden rush of water which began the scouring of the gully.

- the water table and subsurface drainage pattern at the Drillhole Swamp had been altered by mine subsidence. Extraction of two coal seams below the area had caused up to 2.4m of subsidence, creating surface strains of about 2.0mm/m tension and 1.5mm/m compression and leading to considerable cracking of the sandstone on the plateau surface (Kapp, 1980). In 1978 I observed that the water table in open drillholes at the site was at least 8m below the surface, i.e., 3-4m below the bedrock surface in the gullied area. Since subsidence occurred largely before 1970, the sediments had been drying out due to increased vertical seepage for about 8 years before the gully was eroded, although drying-out of the sediments had doubtless been exacerbated by the low rainfalls in 1975-1978. As a consequence of the lowering of the water table, flood flows no longer rode over a high water table but could scour down to bedrock (see Chapter 3).

Once a channel is cut, it erodes rapidly to bedrock. Increased flow velocities maintain the open channel, while slumping and piping extend the eroded area. Changes in vegetation patterns are also likely in the long-term, due to the localised lowering of the water table (cf Glaser _et al._, 1981). As the Drillhole Gully example shows, erosion of the dell sediments can be severe and rapid. Yet the flood which caused the erosion was not catastrophic. Its return period, measured with respect to flow at Avon Dam, was between 20 and 50 years (M.W.S.D.B., pers. comm., 1982). The return period of the associated 24-hourly rainfall was even shorter. At Upper Avon pluviometer, 589.1mm fell between 19 and 21 March, 1978. The 24 hourly fall of 256.9mm on 20 March has a return period of only about 2 years on the plateau. Indeed 24 hourly falls of over 400mm have occurred 6 times in the area since 1890, while a fall of 550mm/day has a return period of only 50 years (Young and Johnson, 1977).

Furthermore, extremely wet conditions can very abruptly succeed drought periods (Dury, 1980) when the water table can be several metres below the dell groundsurface or even below the bedrock base (see Chapter 4). Hence, under natural conditions, the combination of severe fires to bare the surface and a catastrophic storm following a prolonged drought could create conditions similar to those prevailing at the Drillhole Swamp in early 1978.

Stratigraphic details of relict sediments exposed in the gully.

As well as demonstrating how rapidly the dells can be eroded, the gullying at the Drillhole Swamp provided a continuous, long section through relict sediments. These are largely medium-coarse sands with variable organic content, although small slabs of sandstone form basal gravels of limited extent, and infilled relict channels contain pebbly clean sands intercalated with copious charred plant fragments (Fig. 7.2). The sediments began to accumulate about 11,700 B.P. (Table 7.1). I have argued elsewhere that they did so under geomorphic and vegetational conditions which were very similar to those currently prevailing (Young, 1982).

STRATIGRAPHY OF THE GULLY AT THE DRILLHOLE SWAMP

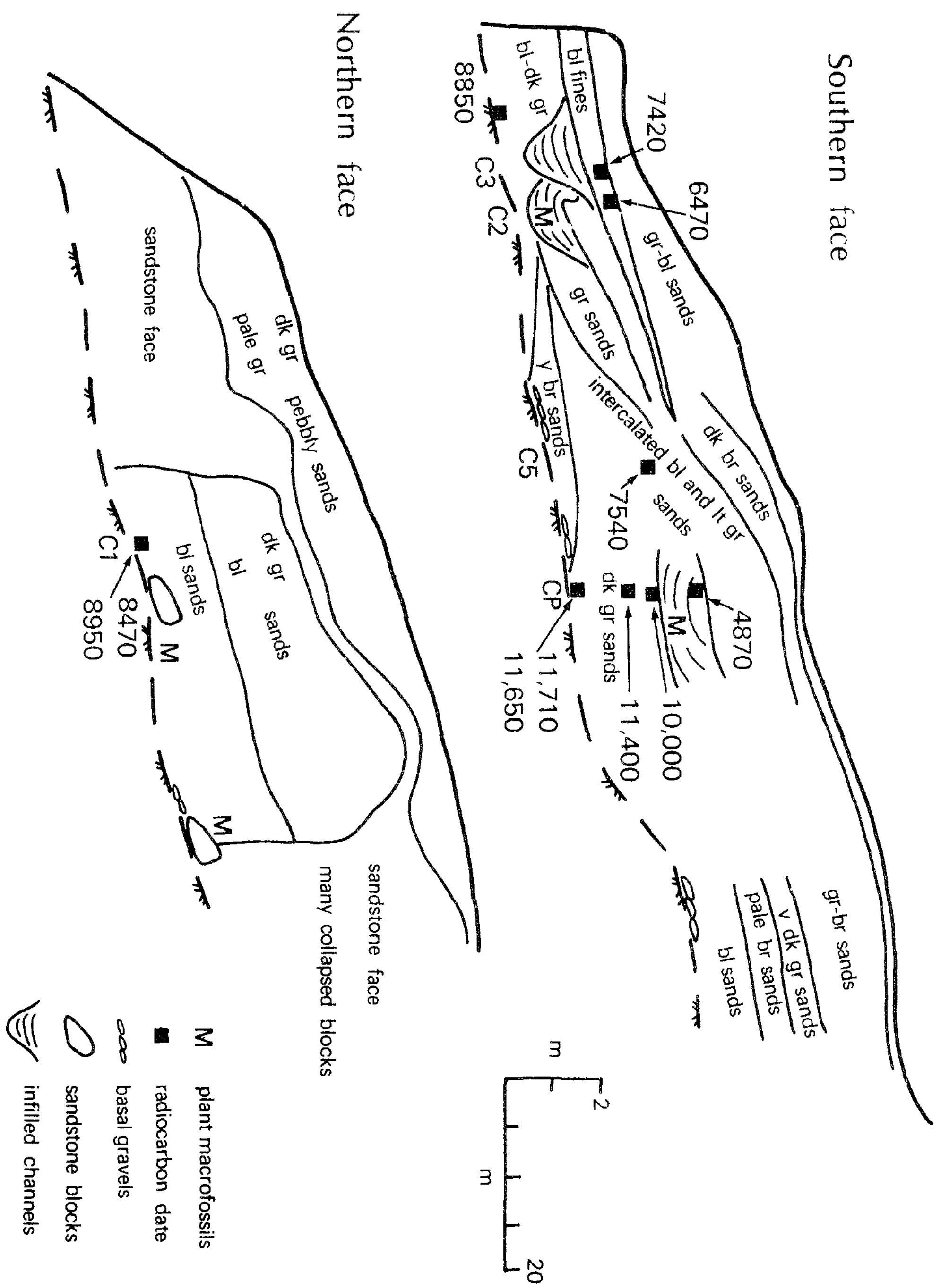


Table 7.1. RADIOCARBON AGES OF SEDIMENTS EXPOSED BY GULLYING AT THE DRILLHOLE SWAMP.*

Location	Age (Years B.P.)	Material	Lab. no.
C1 3.80 m	8,950 ±130	wood	SUA 1070
C1 3.80 m	8,470 ±130	carbon	SUA 1071
C2 1.00 m	6,470 ±110	org. fines	SUA 1074
C3 0.95 m	7,420 ±140	org. fines	SUA 1075
5m d/s of C3, directly above bedrock	8,850 ±190	wood (*Exocarpus cupressiformis*)	SUA 1072
C5 2.65 m	7,540 ±110	org. fines	SUA 1076
CP 2.30 m	4,870 ±110	carbon	SUA 1482
CP 2.90 m	10,000 +1000 -900	carbon	SUA 1483
CP 3.62 m	11,400 +1100 -1000	carbon	SUA 1484
CP 4.65 m	11,710 ±280	carbon	SUA 1339
CP 4.65 m	11,650 ±170	wood	SUA 1073

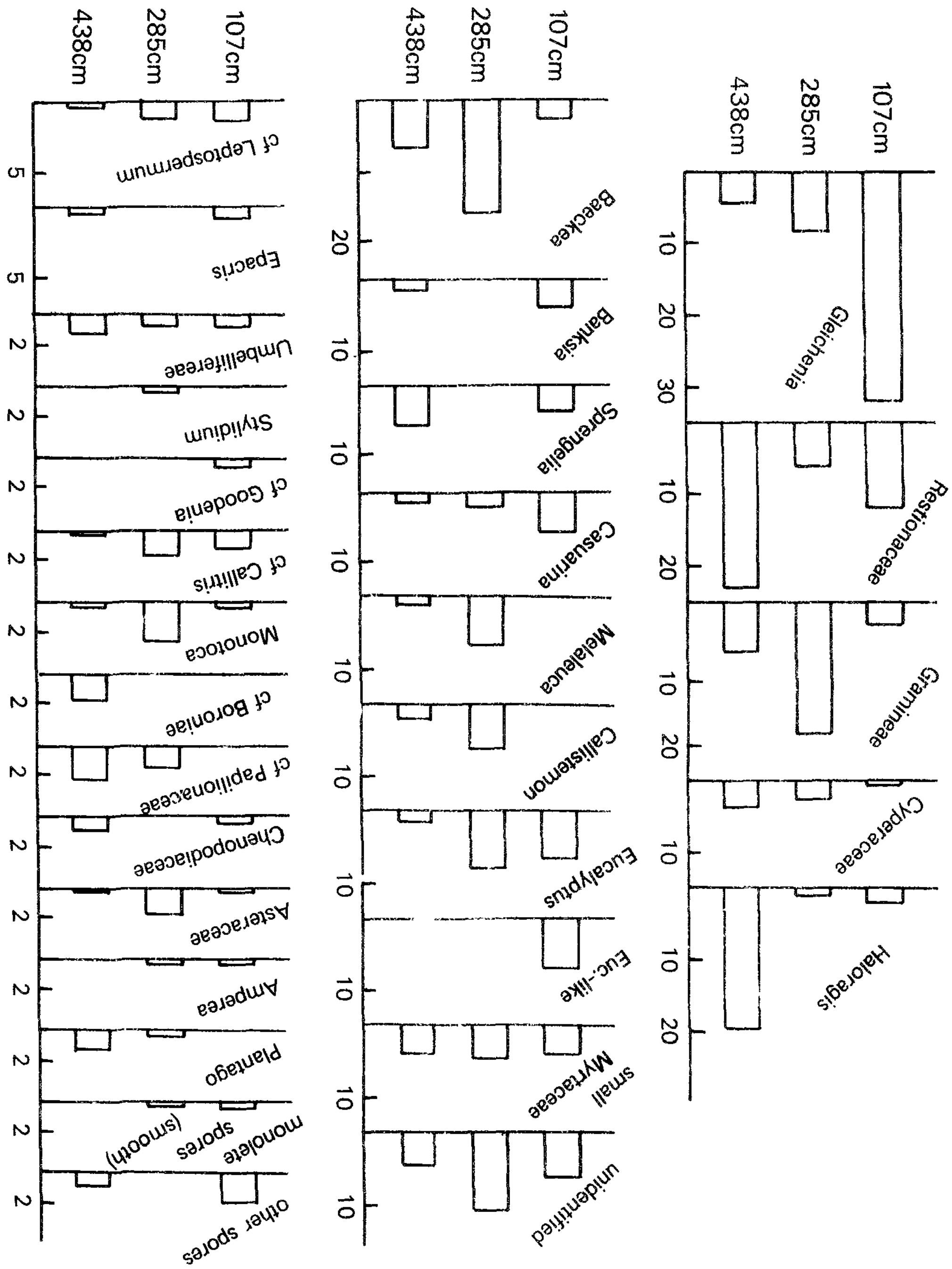
* See Fig. 7.2 for sample locations.

The relict sediments are very like those presently accumulating in the dells here and elsewhere on the plateau. Thirteen samples, taken from 3 profiles along the gully (C1, C2, C5 - see Fig. 7.2), were analysed for grainsize parameters and loss-on-ignition, then grouped by discriminant analysis with the modern (0.5 m depth) sediments from Martins Swamp and the Loddon tributary (see Appendix 1 for sedimentological details). Each of the 13 samples fell into one of the 3 categories of transported sediment determined earlier (see Chapter 3); 7 were classed as organic fines, 4 as organic sands and 2 as grey-brown sands. Furthermore, plant macrofossils (leaves and fruit) caught in sediments dated at approximately 8500 B.P. (near C1) and approximately 4,900 B.P. (at CP) belong to species which presently grow on the Woronora Plateau. These include

- Eucalyptus sieberi and bloodwoods, probably E. gummifera, which grow on the forested ridges surrounding the Drillhole Swamp. These macrofossils were found in sediments both at CP and near C1.
- scribbly gums (E. racemosa or E. sclerophylla), which are common along the dell margins or in groves within the dell. The uncertainty about species may be due to the fact that scribbly gums are undifferentiated on the Woronora Plateau (J. Mowatt, pers. comm., 1982). These macrofossils were found at CP and near C1.
- peppermints (E. piperita ssp piperita approaching ssp urceolaris), and tea-tree (Leptospermum sp. comparable to L. flavescens) which are presently widespread on the plateau. These were found in the channel infill at CP.
- stringy barks (perhaps E. oblonga or E. globoidea) and sheoaks (Allocasuarina littoralis); which are also widespread on the plateau. These were found in the older organic sands just above bedrock near C1.
- Banksia ericifolia (cones found near C1) and Banksia serrata (leaf fragments at CP and cones near C1) which 'match modern specimens from the Central Coast region quite well' (A. George, pers. comm., 1982).

  (Identification of macrofossils were kindly done by Dr L. Johnson, Royal National Herbarium, Sydney and Dr A. George, Bureau of Flora and Fauna, Canberra, and of wood by Dr K. Bamber, N.S.W. Forestry Commission).
- Eucalyptus wood and Banksia ericifolia cones were also found in the channel infill at C2 profile.

PERCENTAGE POLLEN DIAGRAM, CP PROFILE



genera with counts less than 0·5% and in one sample only are not shown

sample depths in cm below groundsurface (profile depth is 468 cm)

approx. ages: 107cm - less than 4000BP; 285cm - 10,000BP; 438cm - 11,500BP

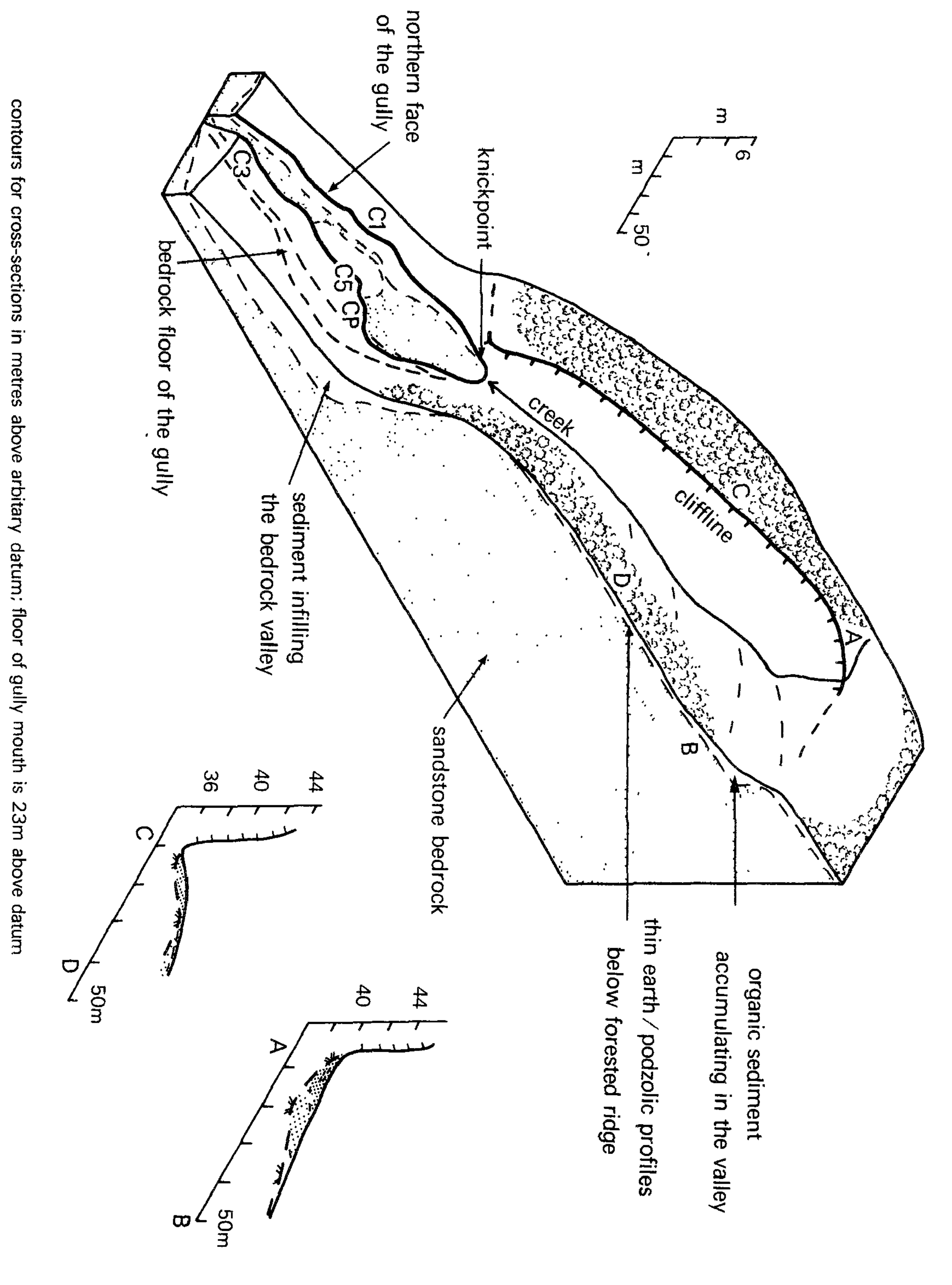
Preliminary pollen analyses, generously supplied by Dr A. Martin of the University of Sydney, also show that the species associated with sediments at CP profile (see Fig. 7.1) are similar to those in the dells today. Most of the pollen at 3 locations in the profile - 107 cm, 288 cm and 438 cm below the groundsurface - is from families or genera which comprise the present dell vegetation (Fig. 7.3), the presence of Eucalyptus and Casuarina pollen being explained by the nearness to the site of patches of dry sclerophyll forest.

Indeed a modern analogue of the sedimentary pattern exposed in the gully can be seen immediately upstream. The sediments shown in Fig. 7.2 accumulated in, and filled, a small asymmetric valley with a bedrock cliff along one side (the northern face) and a 5m-high knickpoint at the head. Above the now-exhumed knickpoint, a similar valley is found (Fig. 7.4). Where the stream flows, at the base of the cliffed northern side, the sediments are usually saturated and thus are organic-rich. Because the stream flows in a distinct, even though overgrown, course, there is little opportunity for organic fines to accumulate (such fine sediments characterise zones where flow spreads over a broad zone, for example at the centre of the M2 transect at Martins Swamp - see Fig. 3.4). The organic sands are shallower towards the forested ridge as the sediments change to grey-brown sands or in-situ yellow earths. Organic sands supporting sedgeland also occupy and overlap the gentle slope at the head of the valley. Hence it is possible to envisage the waterfall being buried as the valley is infilled.

The sediments exhumed in the gully show comparable

7·4

BLOCK DIAGRAM OF THE GULLY, DRILLHOLE SWAMP



patterns. Against the former cliff (the northern face), the sediments are dominantly very dark grey or black whereas those opposite are more variable. Note that the only large lens of organic fines (C2/C3) (see Fig. 7.2) corresponds to the level of the top of the sandstone face opposite. Thus the fines accumulated after the valley had been infilled to the top of the cliffed northern side, when flow downstream was no longer concentrated linearly and when flow from beyond the northern side of the valley no longer tumbled over a cliffline. The basal gravels are clearly relicts of a time when the channel in the gully was open, as it is now that the sediments have been re-excavated. They are tabular pieces of sandstone with intermediate axes ranging from 2-26cm and averaging 5cm. Since these gravels are moved by flows in the present gully, the contrast between gravels and the overlying sands represents a change in sediment supply and in channel form, rather than in hydrological balance or climatic regime. At this site therefore it seems that the sediments accumulated, largely between 11,700 B.P. and 4,870 B.P., and under conditions hydrologically and vegetationally similar to those of today. The lack of young sediment may be attributed to dispersal of flow when the now-exhumed valley had been infilled, some time later than 4,870 B.P.

Sedimentation at the site was occasionally interrupted, as the relict infilled channels show. In the infilled channels (see Fig. 7.2), there is an abrupt change from medium-coarse sands with variable humic content, to clean pebbly coarse sands which are finely inter-laminated with charred plant fragments. Flood flows cascading over the sandstone face on the northern edge of the gully, before the valley was completely infilled, probably caused the channel erosion. Certainly the absence of organic staining on sand grains and the coarseness of the sediment indicate deposition from flood flows, apparently following soon after fires which provided copious charred plant debris. The channels are not contemporaneous; that at CP was dated at 4870±110 B.P., while that at C2/C3 was cut some time between 8,850 and 7420 B.P.

The contemporary erosion of relict sediments exposed at the Drillhole Swamp clearly shows

- that the sediments in the dells can be rapidly and severely eroded once the surface is breached and an open channel is established
- that such channels cut rapidly down to bedrock, particularly if the water table is well below the groundsurface
- that partial flushing of the sediments has occurred in the past, apparently after fires have removed vegetation cover.

The rates of sedimentation in the dells.

On the basis of the stratigraphic section at the Drillhole Swamp, I have suggested that the sedimentary processes operating in the dells have not changed significantly in the past 12,000 years. Indeed, there has been no consistent change even in the mean rates of sedimentation (Table 7.2). The most rapid rate determined was 80cm during the past 290 years, near large pools on the Loddon River, while the slowest mean rate was in the far older (17,000 years) sediments on the Loddon tributary a few kilometres further upstream. Between these extremes, however, sedimentation rates did not vary greatly. They were of the same order of magnitude (0.1 - 1.0mm/year) and the faster rates were not associated with the younger sediments.

Mean rates can also be calculated for 5 sites in the Blue Mountains, recorded by Stockton and Holland (1974). Although the basal ages range from 4,110 to 17,050 B.P., the rates were 0.1 - 0.3mm/year in all cases. A site in the Porters Creek dell on the Nowra Sandstone plateau (A. Young, 1981) yielded a mean rate of 0.7mm/year over the past 2950 years. Rates of sedimentation have apparently been similar throughout the dells of the southern and western Sydney Basin, and throughout the late Pleistocene-Holocene period.

Table 7.2. MEAN RATES OF SEDIMENTATION IN THE ILLAWARRA DELLS.

* Harden, 1967

Surprisingly perhaps, these vertical rates of accumulation do not differ greatly from the few available data for rates in areas where mires have expanded laterally over wide areas. Lahermo *et al*. (1977) show sections several hundred metres long, through Finnish mires, in which forest has been replaced by *Sphagnum*, *Carex* and *Bryales* open mire during the past 8,800-4,500 years. Accumulation of 1 - 4.6m of peat at 11 sites has occurred at an average rate of 0.2 - 0.6mm/year. For the Minnesota peatlands, Glaser *et al*. (1981) suggest that 1-3m of peat has accumulated in the past 4,000 years across an area 80km by 15km. No specific profile data are given by Glaser *et al*, but the single value quoted by Heinselman (1963) - 85 inches since 4360 B.P. - is equivalent to 0.5mm/year. Thus the depths of organic sediment and the mean rates of accumulation at these Northern Hemisphere sites are similar to those in the dells.

The stability of the margins of the Illawarra dells, compared with the apparent extensive paludification of the other areas, may be due to differences in topographic slope, since the sections given by both Lahermo *et al* (1977) and Heinselman (1963) show that peat accumulated on slopes that were consistently gentler than 1°. At the Loddon tributary and Martins Swamp, bedrock underlying the dell sediments on the measured transects slopes at 2-7°; furthermore, the forested ridges often rise more steeply than the dell surface.

Conclusions

Under most conditions, the dells are stable aggrading systems. Sedimentation began in some dells about 17,000 years ago (e.g. at the Loddon tributary); it is continuing today (e.g. at the Loddon River). Indeed there is no evidence either in the transects at the Loddon tributary and Martins Swamp, or in the long section exposed at the Drillhole Swamp, for significant changes in the processes or the average rates of sedimentation since the late Pleistocene. Unlike the mires of the Northern Hemisphere, the dells apparently have stable boundaries; this difference may be due to the steeper bedrock slopes of the dells, although clearly climatic factors, vegetational effects and sediment supply may also be significant.

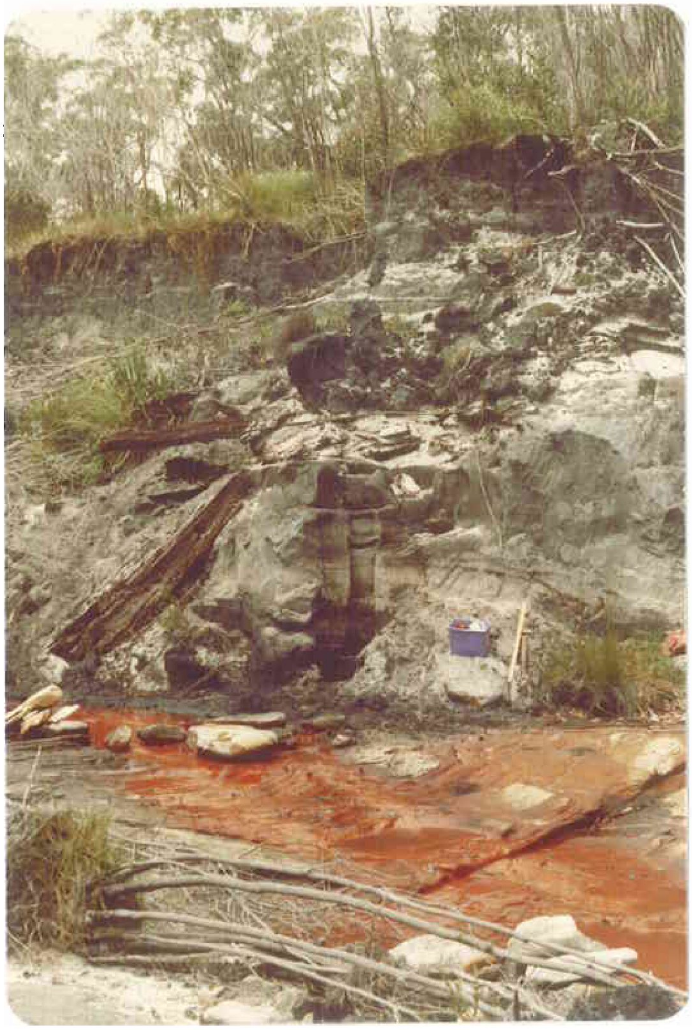
Nevertheless at least partial flushing of the sediments has occurred. Once the surface is breached by a flood flow, there is rapid erosion to bedrock, particularly when the water table is well below the groundsurface. Such erosion is clearly more likely after fires when the surface is unprotected, and the flow of water is unchecked, by the vegetative cover. Yet, as noted earlier (see Chapter 5), erosion does not necessarily follow fires. Nor does a major flood cause erosion regionally or even at all parts of a single dell. Thus, as Moss and Walker (1978) point out, well-vegetated surfaces have considerable potential for rapid hydraulic adjustment which may be triggered by fires, climatic events or human interference. It seems however that the dells, like other fluvial systems (Schumm, 1979), may remain stable until an intrinsic threshold is reached and erosion is triggered by an external environmental perturbation such as fire and a subsequent flood.

SUMMARY

- Under most conditions, the dells are steadily aggrading systems. As they are well-vegetated and because they can be dramatically affected by fires, climatic events and human interference, they have considerable stored hydraulic adjustment potential. Adjustment may not occur however until some intrinsic erosional threshold is reached.
- Contemporary erosion demonstrates that rapid cutting to bedrock, and maintenance of an open cut channel can occur. The most dramatic example, which occurred at the Drillhole Swamp in 1978, was due to disturbance of the vegetation, to lowering of the water table (mainly as a result of mine subsidence) and to bursting of a small dam. However similar erosion can be envisaged under natural conditions.
- Relict sediments at the Drillhole Swamp, which include pollen and plant macrofossils, indicate no major environmental change at that site since 12,000 years B.P.
- Average rates of vertical accretion in dells on the Woronora Plateau resemble those of dells in the Blue Mountains and, surprisingly, in the Northern Hemisphere mires. The stability of the dell boundaries, *vis-a-vis* the Finnish and Minnesotan mires, may be due partly to the steeper bedrock slopes of the dells.

9. The head of the gully at the Drillhole Swamp, 20/3/1978. Note the logs which have fallen in, the slumping of the walls. The bare sticks above the far walls show that the area had been recently burnt. The retreat of the gully was halted here by a sandstone knickpoint on the exhumed bedrock channel.

10. The gully, looking upstream, 20/3/1978. Note the sandstone outcropping on the left hand (northern) side, the fallen blocks of organic sands on the southern wall, the turbulent flow covering the gully floor.



1. CP profile, Drillhole Swamp gully. Note the black-grey basal sands (10,000-12,000 BP), the logs buried in white coarse sands above (4870 BP) (masked by fallen blocks of organic sand), the organic sands in the top metre. Note the orange iron-rich floc on the bedrock floor of the gully.

12. The gully, looking upstream from the mouth, as in Photo 10. Note the blocky peat in the upper section of the southern wall, the iron-rich floc staining the firm bedrock floor, the basal gravels and yellow-brown basal sands at the upstream end.

13. Banksia ericifolia and B. serrata cones, from organic sands 0-0.7m above bedrock, 15m upstream of Cl.

14. Eucalypt fruit and B. serrata leaf fragments from the channel infill at CP. Scale is actual size.

CHAPTER 8. THE ORIGIN AND DEVELOPMENT OF THE DELLS.

In the preceding chapters, the dells are viewed largely as contemporary features within the landscape. Their distribution is related to present topography and climate (Chapter 2); the varying characteristics of their sediments are determined by active sedimentary and hydrologic processes (Chapters 3 and 4); their vegetation patterns reflect varying physical conditions both at the mesoscale (Chapter 5) and at the microscale when patterned ground occurs as a result of localised solifluction (Chapter 6). Further, it has been shown that accumulation and episodic erosion of sediment during the past 11,700 years can be explained without recourse to altered environmental conditions (Chapter 7). Dells in Germany and Zambia have also been seen as contemporary features (Schmitthener, 1925; Penck, 1924, transl. 1972; Mackel, 1974), with Schmitthener (1925) suggesting that they have characterised the plateaux of southern Germany since the Tertiary. However, while the Woronora Plateau was uplifted no later than the Oligocene (R. Young, 1977), the oldest sediments dated in the Illawarra dells are late Pleistocene in age. We must therefore consider the assertions of many European geomorphologists (e.g. Mainguet, 1972; Klatkowa, 1965; Louis and Fischer, 1979) that dells were formed by periglacial processes during the Pleistocene. If this were so, dells would be survivals, in the sense defined by Tricart and Cailleux (1972), which formed under periglacial climates but are able to maintain their form under present conditions. In this chapter, therefore, we shall review these conflicting theories concerning the formation of dells while proposing a probable origin and sequence of development for those on the Woronora Plateau.

Quaternary tectonic and climatic change on the plateau.

Under early chronologies for landform development in the Sydney Basin, the discrepancy between the age of the dells and the age of plateau uplift was slight. Dells were seen as the remnants of mature streams developed on a peneplain, that peneplain having been upwarped only in the late Tertiary (Taylor, 1923). This view is reiterated by Browne (1969) who describes the plateau as a Miocene peneplain, dissected by shallow valleys etched after a minor Pliocene uplift and by deep gorges cut after major Plio-Pleistocene uplift. However, the dating of basalts on the plateaux and nearby coastal plain in the southern Sydney Basin forced the revision of this chronology and the acceptance of a much earlier age for uplift (R. Young, 1978).

While conceding that uplift occurred no later than the mid-Tertiary, Ollier (1979) also appears to imply a role for tectonic change in the formation of dells. He suggests that streams on the Woronora Plateau were beheaded by loss of land to the east of the Illawarra escarpment; yet, as we saw in Chapter 2, this cannot have been so, since the stream lengths and drainage areas are closely related to each other. Ollier emphasises loss of gradient by backtilting elsewhere along the Great Divide. In fact, with a few exceptions (such as the Nepean River's course near Penrith), most of the drainage networks in the southern and western Sydney Basin are structurally and lithologically controlled (Holland, 1974; R. Young, 1978). Those in the Illawarra flow down the Nepean Ramp, with even the divides between the Georges, Woronora and Hacking Rivers following local changes in the dip of the Hawkesbury Sandstone. Thus there has not been significant backtilting on the Woronora Plateau. Indeed, many dells lie on easterly-flowing tributaries (see Fig. 2.2) which would have had their gradients increased, not decreased, had backtilting occurred. And changes in the trunk streams could hardly have influenced dells which lie in headwater valleys above high knickpoints.

Thus, in the absence of evidence for Quaternary tectonic change on the plateau, let us consider the possible effect of Quaternary climatic change. Mainguet (1972) asserts that shallow upland valleys whose floors are only slightly incised by minor channels, characterise

> all sandstone areas which have known or now experience periglacial climatic phases.
>
> Mainguet, 1972, p.146.

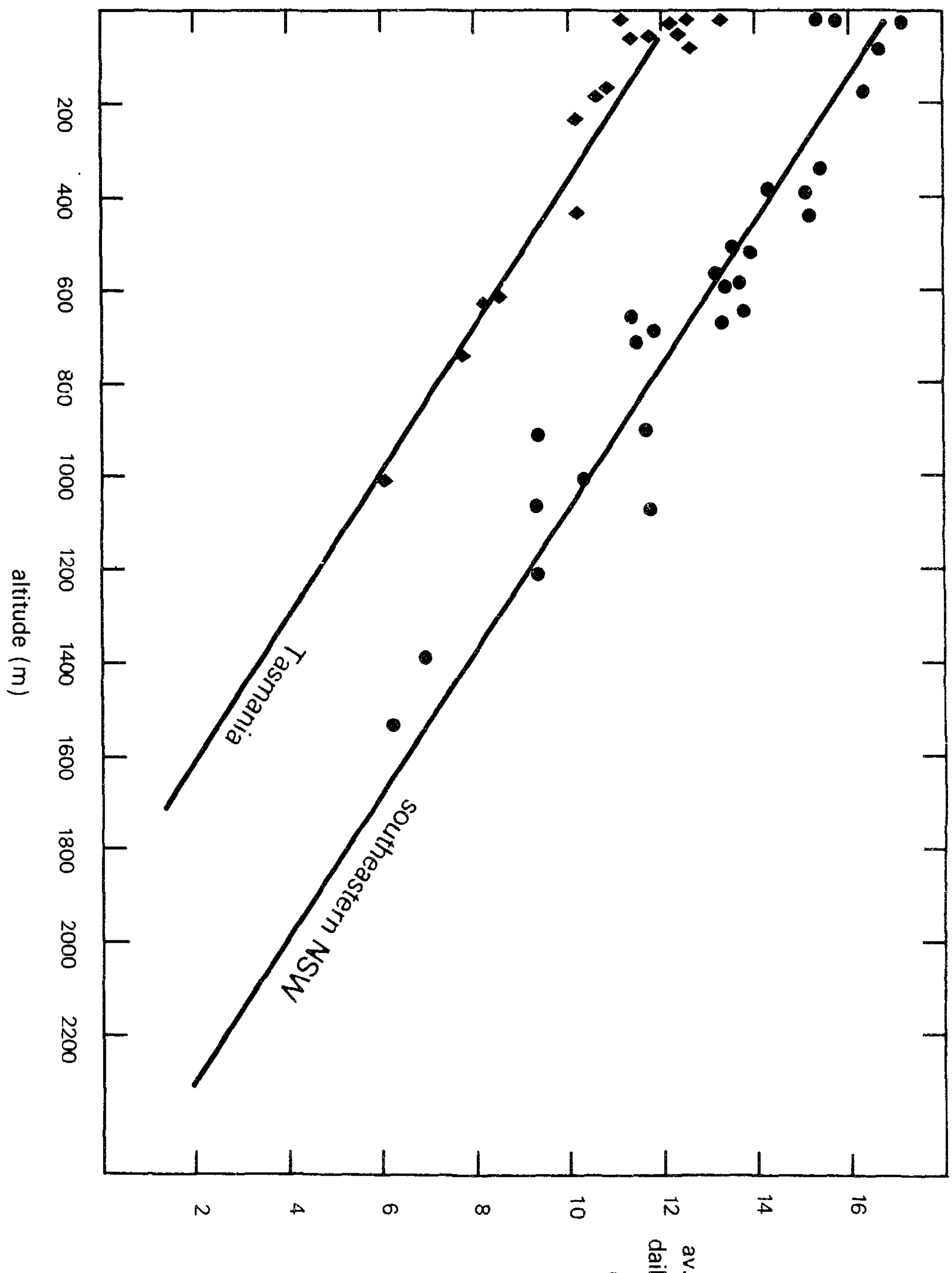
Curiously enough, she then comments that the lack of channels is due to the high porosity of the underlying sandstone. Yet her detailed descriptions of such valleys in the Vosges mountains, her term for the valleys ('les aires spongieuses'), and accounts of the same area by Soons (1958), make it clear that these low order streams are typically swampy. Gregory and Walling (1973) also attribute dells to shrinkage of the drainage network, grouping the dells with climatically or tectonically formed dry valleys. But although devoid of continuous channels, the dells are not dry valleys, as some of the workers quoted by Gregory and Walling - notably Penck (1924, transl. 1972) and Schmitthener (1925) make very clear:

> 'Scarcely any of the valley-heads on, for example, the peneplanes and flattish country of the Central German Rise shows a trace of a stream bed with either permanent or intermittently flowing water. Such depressions, normally wide troughs but often narrow gutters, are usually marshy even when the gradient is not particularly gentle ... Swampiness is the direct result of the accumulation of detrital material.'
>
> Penck, 1924, transl. 1972, p.109 & 114.

As well as emphasising reduced discharge since the Pleistocene, Klatkowa (1965) suggests that dells (vallons en berceau) on planation surfaces in Poland are infilled by relict sediment. He attributes sedimentation to pronounced rill erosion under periglacial conditions. Similarly, Louis and Fischer (1979) maintain that dells in humid mid-latitudes typically formed under Pleistocene periglacial climates, although they propose gelifluction (soil flow over frozen subsoil) as the major process.

On the Woronora Plateau, however, periglacial processes would not have operated even during the coldest phase of the Pleistocene. A fall of 6-10°C below present temperatures has been proposed for alpine areas during the maximum cold phase (Galloway, 1965; Caine and Jennings, 1968; Coventry, 1976). The fall on the Woronora Pleateau is likely to have been identical, despite the region's lower elevation (300-550m), as Figure 8.1 demonstrates. At present, there is a close correlation between average mean daily temperature and altitude in south eastern Australia (Fig. 8.1). The regression equations describing the relationships for southern New South Wales (east of 148°E, 34-37°S) and for Tasmania differ only in intercept, their slopes being identical. Since the differing latitudes of these areas roughly simulate the probable shift of climatic belts during the Pleistocene, then the

TEMPERATURE VARIATION WITH ALTITUDE, S-E AUSTRALIA



relationship between temperature and altitude in N.S.W. during Pleistocene presumably paralleled the present regression line. Thus average mean daily temperatures on the plateau probably fell from 14.5°C to 8.5-4.5°C, the temperatures now experienced at elevations of 1300-1900m. At such elevations, periglacial activity even at the highest altitudes is hardly dramatic (see, for example, Jennings, 1981) and shallow upland valleys are swampy and often sedge-dominated (see, for example, Holland, 1974). Thus, as Galloway (1965) suggested, periglacial solifluction may have reached the higher rims of the Sydney Basin (see, too, Stockton and Holland, 1974) but did not affect elevations below about 1200m. And as noted earlier, not all European researchers accept that climatic changes affected the development of dells in other parts of the world.

Erosional activity associated with the dells.

Schmitthener (1925) rejected both climatic change and inheritance of stream patterns from now-eroded overlying strata as causes of the form of dells in south-western Germany. He saw the characteristics of the dells as geomorphically determined and the dells as the major sites of plateau denudation. He considered that movement of debris in the dells leads to areal erosion, which contrasts with the linear erosion caused by water flowing in channels. Similarly, Penck (1924, transl. 1972) suggested three inter-related mechanisms by which the dells extend:

- corrasion, in which loosened bedrock is mechanically eroded by a mass of debris moving slowly over the bedrock/sediment contact.

- bound-down mass movement, or sheet denudation involving the migration of slope detritus, subsurface below a vegetative cover. This occurs wherever vegetation cover is continuous.
- intensification of subsurface weathering by swampy groundwater.

Penck (1924, transl. 1972) commented that many of the dells were originally eroded, at least in part, by water. Since infilling however, corrasion and bound-down mass movement have been responsible for their development, corrasion being the means of headward extension.

More recently, Mackel (1974), working in Zambia, has suggested that erosive processes operating in the dells (dambos) lead to denudation and planation of the plateau surface. He outlines 3 major processes:

- subsurface lowering, particularly below the valley axes, due to weathering by percolating acidic waters. This process, termed bedrock corrosion by Bunting (1961), prepares subsurface material which can be readily eroded by later stream action.
- extension of the dell surface by slopewash along the margins.
- paludification, as ecological conditions become unfavourable for tree growth along the lowering margins of the dambos.

In the Illawarra dells, bedrock corrosion appears to be a slow process, notwithstanding the wet, acidic and reducing environment at the base of the dell sediments (cf. Harden, 1966). Zones of rotted sandstone below the transported sediments are rarely more than a few centimetres deep. And as noted in Chapter 5, the absence of in-situ buried trees within the sediment and the stability of the dell margins in the short-term indicate that paludification during the Holocene has not extended the Illawarra dells as it has the Zambian dambos. The dells lack the prominent washbelts along the margins, such as characterise the dambos. However, as shown in Chapter 3, slopewash from the surrounding ridges is the main source for the sediment which infills the dells. Whether the sediment is derived from slopewash or from bedrock corrosion, it is, under most conditions, retained in the dells. Mass movement appears to be the cause of patterned ground in the seepage zones, but this process causes localised movement rather than transport of sediment out of the dells. And bedrock corrasion, as defined by Penck, does not seem to occur. It is in fact difficult to envisage what evidence could indicate that such mechanical subsurface erosion was occurring. However several facts suggest that it does not. First, there is no apparent mixing of the thin layer of weathered bedrock and overlying transported sediments in the dells. Second, the preservation of bedding laminations in weathered bedrock suggest that no mechanical disruption has occurred. Third, while patterned ground indicates near-surface mass movement, the existence of buried channels in the transported sediments (see Fig. 3.4) indicates that mass movement does not affect the sediments near the bedrock surface.

In summary, the erosional processes in the Illawarra dells are apparently less active than those proposed for dells in Germany (Schmitthener, 1925; Penck, 1924, transl. 1972) and Zambia (Mackel, 1974). The Illawarra dells are seen not as the sites of major denudation but primarily as storage areas for sediment moving off the ridges into the stream network.

The onset of sedimentation in the dells.

The onset of sedimentation cannot be attributed to periglacial processes or to tectonic movements, as we have seen. Nor does it coincide with the change to warm and wetter conditions at the close of the Pleistocene (about 10,000 B.P.) (Bowler et al., 1976; Dodson, 1974; Macphail, 1979). Indeed, most of the sediment accumulated well after that time (see Tables 3.1 and 7.1). It is possible that Aboriginal burning may have influenced sedimentation, although Singh et al (1981) suggest that burning may simply reinforce climatically-induced vegetational changes. However Macphail and Shepherd (1973) suggest that there was a marked expansion of button-grass moorlands in Tasmania during the late Holocene, probably as a result of Aboriginal burning. In a parallel argument, Hughes and Sullivan (1981) comment that burning may have suddenly increased sedimentation rates on the uplands of eastern N.S.W. as Aboriginals moved onto the plateau after the rising sea level drowned their former coastal territories. Like Macphail and Shepherd, they refer to changes in the late Holocene whereas many of the dell sediments are far older. Furthermore, none of the basal sediments in the dells are richer in charcoal than those higher in the profile (Table 8.1), indicating that fire was not an important trigger for the start of sedimentation.

There is, in fact, good evidence that no single cause has led to infilling of the dells. The basal ages (see Table 3.1) approximate a straight line on probability paper (Fig. 8.2), implying that the dates are normally distributed. When only the oldest date for each dell is plotted, and also when data from the Blue Mountains (Stockton and Holland, 1974) are included, again

DISTRIBUTION OF BASAL AGES IN THE DELLS

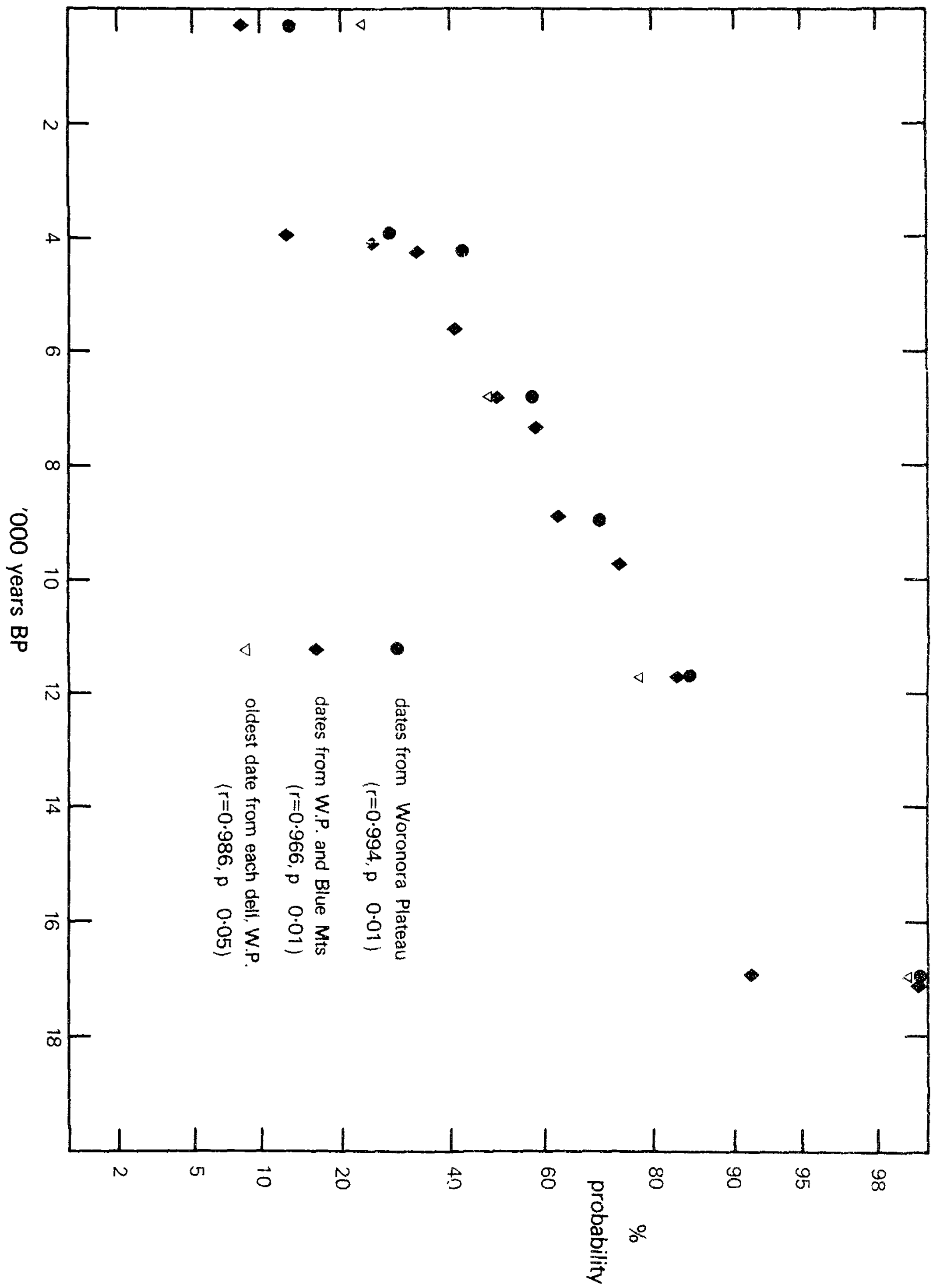


Table 8.1. PROPORTION BY WEIGHT OF CARBON FRAGMENTS (COARSER THAN 0.05mm) IN SEDIMENTS OF THE GULLY WALLS, DRILLHOLE SWAMP.

Profile position	Height above bedrock (cm)	Carbon content (%)	Sediment colour (Munsell)
CP	25	1.30	v dk gr
	50	1.30	v dk gr br
	100	0.60	dk gr
	125	0.22	v dk gr
	150	0.28	v dk gr
	240	4.16	lt gr
	310	0.46	v dk gr
	370	0.58	bl
	420	0.69	dk gr
	450	2.21	bl
C1	5	0.35	br gr
	25	1.10	br gr
	75	1.17	bl
	95	1.85	v dk gr br
20 m downstream of C1	25	0.09	gr br
	50	0.36	bl
	80	0.44	bl
7 m downstream of C5	25	0.06	br
	70	1.37	gr br
	125	0.45	gr br
	200	1.16	dk gr

the plots are straight lines and show no significant discontinuities. These results imply that the onset of sedimentation at any dell is a random event, there being no regionally-effective trigger occurring at a particular time.

Discussing the scatter of dates in the Blue Mountains, Holland (1974) suggested that valley-floor swamps have been cut and refilled at various times during the Holocene. The mechanisms by which a body of sediment within a dell could become inherently unstable have been outlined earlier (see Chapter 7); they involve accumulation of sediment on the margins and upstream sections of the dell, and concentration of flow and hence erosive energy downstream. Certainly most of the dells narrow downstream, and such channels as occur in the dells are found only near the dell exits. Indeed, wherever two basal dates are available within a dell, the downstream date is the younger (see Table 3.1). At the Drillhole Swamp gully a basal date of 8850 B.P. (near C3) lies 50m downstream of one of 11700 B.P. (CP); at Martins Swamp, the basal date near M1 transect is 4320 B.P. whereas 250m upstream at M2, the corresponding value is 6820 B.P.; at the Loddon catchment, near the pools the basal date is 290 B.P. while 3km further upstream the corresponding date is 16950 B.P. In the Blue Mountains also, at North Katoomba Ck, Stockton and Holland (1974) record basal dates of 5660±500 B.P. at 960m a.s.l. but 7350±160 B.P. at 975m a.s.l. As the sediments exposed by gullying at the Drillhole Swamp show, severe localised erosion of the dells has occurred during the Holocene. Probably the very young age of sediments beside the pools on the Loddon River also indicates previous erosion and recent redeposition at that site. Hence the present sediments appear to be the most recent suite of deposits in dells whose bedrock floors have been filled, then on occasions partly or fully flushed, and then refilled.

It is clear that dells like those of today have characterised at least some of the headwater valleys on the Woronora Plateau since the late Pleistocene. The absence of tree stumps or significant amounts of wood in the dell sediments further implies that none of the dells studied occupies a valley which has been forested during that time. These facts, allied with the evidence for occasional substantial erosion of dell sediments, suggest that the dells:

- are valleys carved originally by stream erosion and by mass movement on the valley sides
- may be choked, by sediment washing into the bedrock floor, because of the low competence of their streams and of the sandy sediment supplied.
- remain sediment-choked over long periods because of the stabilising feedback interrelationships between the mass of sediment, the retention of water in the sediment, the absence of a continuous channel and the vegetative cover.
- may then be flushed either partly or fully, when the vegetative cover is breached or burnt off and an open channel is established.
- are eroded by fluvial action during such periods of flushing, when not only stored transported sediment but also some rotted bedrock could be removed.
- may then re-commence accumulating sediment, for the reasons noted above.

No part of this sequence requires environmental conditions substantially different to those which prevail now. However, this fact does not imply that there has been no environmental variation on the plateau during the past 17,000 years. Rather it implies that there has been no single environmental change which can account for sedimentary accumulation in the dells. Furthermore, the evidence suggests that no variation over this time has been great enough to alter the long-term hydrological balance, and thence to alter the rate and processes of sedimentation or to drastically affect the vegetation. Indeed the processes described above may well have been shaping the dells for considerably longer than the maximum period (17,000 years) determined for the sites studied. The surface of the plateau was uplifted no later than the mid-Oligocene (R. Young, 1978), so that the dichotomy between the incised gorges and the upland relief must have been established at least since the mid Tertiary. However it is difficult to bridge the gap between the 17,000 years, for which data are available, and the previous 30 million years.

Conclusions.

The seemingly paradoxical circumstance of swampy terrain existing at the head of deep gorges, with which this study began, is not only explicable in terms of contemporary processes but is also common to plateaux in many parts of the world. In an area where precipitation exceeds evaporation, the swampiness results from the accumulation of sediment in valleys whose streams are unable to maintain continuous open channels. The contrast between the treeless sedgeland/heath and the surrounding forest in turn results from the poorly aerated condition of the dell sediments. And, as emphasised repeatedly in this study, there are important feedback interrelationships between hydrology, sedimentation and vegetation which reinforce the swampy conditions once they are established. Hence the geomorphic position of the valleys is the prime determinant of their environmental conditions; very similar dells can develop under a wide range of humid climates.

The dells on the Woronora Plateau have not developed under the influence of Pleistocene periglaciation, nor even under the influence of climates as cold as those usually associated with the presence of patterned ground. Indeed the sediments and such plant fossil evidence as is available suggest that there has been no significant change in the physical setting of the dells at least since the late Pleistocene. Extrapolation beyond that time is obviously highly speculative; but since the geomorphic influence is great, we may tentatively suggest that processes affecting the dells have been similar to those of today for many millenia.

The dells of the Woronora Plateau do not appear to be the sites of rapid denudation and planation on the plateau; rather, they act mainly as long-term sediment traps. They are contemporary features of the landscapes, rather than being relicts either of a past climate or of a disrupted drainage system. The dells are relict only in the sense that they exist on a formerly more extensive plateau which is very slowly being consumed by linear stream erosion.

REFERENCES

Adamson D., Selkirk P.M. and Mitchell P.B. 1982. Fire, lyrebirds and landscapes in the Sydney Region. Paper to the Australian Geomorphology Conference, University of Wollongong, August.

Allington K.R. 1961. The bogs of Central Labrador - Ungava. Geografiska Annaler 43, 3-4, 401-417.

Andrews E.C. 1911. Erosion and its significance. J. Royal Soc. N.S.W. 45, 116-136.

Armstrong W. 1978. Root aeration in the wetland condition. pp.269-297 (in) Hook D.D. and Crawford R.M.M. (eds.). Plant Life in Anaerobic Environments. Ann Arbor Science, Michigan, 564.

Baker G. 1959. A contrast in the opal phytolith assemblages of two Victorian soils. Australian J. Botany 7, 88-96.

Balek J. and Perry J.E. 1973. Hydrology of seasonally inundated African headwater swamps. J. Hydrology 19, 227-249.

Barratt B.C. 1966. Factors of mull and mor development in temperate grasslands. Proc. N.Z. Ecological Soc. 13, 24-29.

Beadle N.C.W. 1940. Soil temperatures during forest fires and their effect on the survival of vegetation. J. Ecology 28, 180-192.

Beadle N.C.W., Evans O.D. and Carolin R.C. 1972. Flora of the Sydney Region. Reed, Sydney, 724 p.

Beck K.C., Reuter J.H. and Perdue E.M. 1974. Organic and inorganic geochemistry of some coastal plain rivers of the southeastern United States. Geochim. Cosmochim. Acta 38, 3, 341-364.

Berner R.A. 1981. A new geochemical classification of sedimentary environments. J. Sedimentary Petrology 51, 2, 359-365.

Boatman D.H., Goode D.A. and Hulme P.D. 1981. The Silver Flowe III: Pattern development on Long Loch B and Craigeazle mires. J. Ecology 69, 897-918.

Bowler J.M., Hope G.S., Jennings J.N., Singh G. and Walker D. 1976. Late Quaternary climates of Australia and New Guinea. Quaternary Research 6, 359-394.

Bowman D.M.J.S. and Jackson W.D. 1981. Vegetation succession in southwest Tasmania. Search 12, 10, 358-362.

Bowman, H.N. 1974. Geology of the Wollongong, Kiama and Robertson 1:50,000 sheets. Explanatory Notes. Geological Survey N.S.W., 179.

Browne W.R. 1969. Geomorphology pp.559-580 (in) G. Packham (ed.) Geology of New South Wales, J. Geological Soc. Australia 16, pt.1.

Buchanan R.A. 1980. The Lambert peninsula, Ku-ring-gai Chase Nat. Pk. Physiography and the distribution of podzols, shrublands, and swamps, with details of swamp vegetation. Proc. Linnean Soc. N.S.W. 104, 1, 73-94.

Bunting B.T. 1961. The role of seepage moisture in soil formation, slope development and stream initiation. American J. Science, 259, 503-518.

Buol S.W., Hole F.D. and McCracken R.J. 1973. Soil Genesis and Classification. Iowa State Univ. Press, 360 p.

Burrough P.A., Brown L. and Morris E.C. 1977. Variations in vegetation and soil patterns across the Hawkesbury Sandstone from Barren Grounds to Fitzroy Falls, N.S.W. Australian J. Ecology 2, 2, 137-159.

Caine N. and Jennings J.N. 1968. Some blockstreams of the Toolong Range, Kosciusko State Park, N.S.W. J. Proc. Royal Soc. NSW 101, 93-103.

Campbell C.A. 1978. Soil organic carbon, nitrogen and fertility. pp.173-271 (in) M. Schnitzer and S.U. Khan (eds.) Soil Organic Matter, Elsevier Scientific, Amsterdam, 319p.

Campbell E.O. 1964. The Restiad peat bogs at Motumaoho and Moanatuatua. Trans. Royal Soc. N.Z. Botany 2, 219-227.

Chowdhury R.N. 1978. Slope Analysis. Elsevier, N.Y., 423 p.

Conaghan P.J. 1980. The Hawkesbury Sandstone: gross characteristics and sedimentary environment. pp.188-253 (in) C. Herbert and R. Helby (eds.). A Guide to the Sydney Basin. Geological Survey N.S.W. Bulletin No. 26, 603 p.

Costin A.B. 1954. A Study of the Ecosystems of the Monaro Region of New South Wales. Govt. Printer, Sydney, 860p.

Coventry R.J. 1976. Abandoned shorelines and the Late Quaternary history of Lake George, New South Wales. J. Geological Soc. Australia 23, 3, 249-273.

Crerar D.A., Knox G.W. and Means J.L. 1979. Biogeochemistry of bog iron in the New Jersey Pine Barrens. Chemical Geology 24, 1/2, 111-135.

Daniels R.E. 1978. Floristic analyses of British mires and mire communities. J. Ecology 66, 773-802.

Davies J.L. 1965. Atlas of Tasmania. Lands and Survey Department, Hobart.

Davis C. 1941. Plant ecology of the Bulli District. Pt ii. Plant communities of the plateau and scarp. Proc. Linnean Soc. N.S.W. 66, I-II, 1-19.

Dean W.E. Jr. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J. Sedimentary Petrology 44, 1, 242-248.

Dodson J.R. 1974. Vegetation history and water fluctuations at Lake Leake, southeastern Sth. Australia. I. 10,000 BP to Present. Australian J. Botany 22, 719-741.

Duchaufour P. 1970. Precis de Pedologie, Masson, Paris, 481 p.

Dury, G.H. 1977. Peak flows, low flows and aspects of geomorphic dominance. pp.61-74 (in) K.J. Gregory (ed.), River Channel Changes, Wiley, N.Y., 448p.

Dury G.H. 1980. Step-functional changes in precipitation at Sydney. Australian Geographical Studies 18, 2, 62-78.

Folk R.L. 1974. Petrology of Sedimentary Rocks. Hemphill, Texas, 182 p.

Forster G.R., Campbell D., Benson D. and Moore R.M. 1977. Vegetation and soils of the Western region of Sydney. CSIRO Div. Land Use Research, Tech. Memorandum 77/10, 53p.

Galloway R.W. 1965. Late Quaternary climates in Australia. J. Geology 73, 603-617.

Gambrell R.P. and Patrick W.H. 1978. Chemical and microbiological properties of anaerobic soils and sediments. pp.375-423 (in) Hook D.D. and Crawford R.M.M. (eds.) Plant Life in Anaerobic Environments, Ann Arbor Science, Michigan, 564.

Gellie N.T.H. 1980. The ecology of button-grass moorlands. Forestry Commission of Tas., Bulletin, 6, 38 p.

Glaser P.H., Wheeler G.A., Gorham E. and Wright H.E. Jr. 1981. The patterned mires of Red Lake Peatland, northern Minnesota: vegetation, water and landforms. J. Ecol. 69, 2, 575-599.

Gregory K.J. and Walling D.E. 1973. Drainage Basin Form and Process. Edward Arnold, London, 456p.

Griffiths J.C. 1967. Scientific Method in the Analysis of Sediments. McGraw Hill, N.Y., 508 p.

Haantjens H.A. 1969. Fire and wind erosion, or earthworms, as the cause of microrelief in the Lower Sepik plains, New Guinea. Australian J. Science 32, 52-54.

Hamelin L.E. 1957. Les tourbieres reticulees du Quebec-Labrador subarctique: interpretation morpho-climatique. Cahiers Geographique Quebec 2, 3, 87-106.

Harden R.W. 1966. Bedrock corrosion and drainage extension at Dahlia Swamp. Australian J. Science 29, p.225.

Harden R.W. 1967. Some aspects of the fluvial morphology of the Upper Georges River basin. M.Sc. thesis, Univ. of Sydney.

Harder H. and Flehmig W. 1970. Quartzsynthese bei teifen temperaturen. Geochim. Cosmochim. Acta 34, 295-305.

Heinselman M. 1963. Forest sites, bog processes and peatland types in the glacial Lake Agassiz region, Minnesota. Ecological Monographs 33, 4, 327-374.

Hettner A. 1928. Die Oberflachenformen des Festlandes. Teubner Verlag, Stuttgart. Transl. by P. Tilley, 1972, The Surface Features of the Land, Hafner, N.Y., 193p.

Holdgate M.W. 1961. Vegetation and soils of the south Chilean islands. J. Ecology 49, 559-580.

Holland W.N. 1974. Origin and development of hanging valleys in the Blue Mountains N.S.W. Ph.D. thesis, Univ. of Sydney.

Hughes P.J. and Sullivan M.E. 1981. Aboriginal burning and late Holocene geomorphic events in eastern N.S.W. Search 12, 8, 277-278.

Humphreys F.R. and Craig F.C. 1981. Effects of fire on soil chemical, structural and hydrological properties. pp.177-200 (in) A.M. Gill, R.H. Groves and I.R. Noble (eds.) Fire and the Australian Biota, Aust. Academy of Science, Canberra.

Humphreys G.S. 1981. The rate of ant mounding and earthworm casting near Sydney NSW. Search 12, 5, 129-131.

Ingram H.A.P. 1967. Problems of hydrology and plant distribution in mires. J. Ecology 55, 711-724.

Ingwerson F. 1976. Vegetation of the Jervis Bay Territory, 80 p. Conservation Series No. 3, Dept Capital Territory. Aust. Govt. Publ. Service.

Ivanov, K.E. 1981. Water Movement in Mirelands (transl. by A. Thomson and H.A.P. Ingram), Academic Press, London, 276 p.

Jackson K.S., Jonasson I.R. and Skippen G.B. 1978. The nature of metals-sediment-water interactions in freshwater bodies, with emphasis on the role of organic matter. Earth Science Reviews 14, 97-146.

Jackson W.D. 1965. Vegetation. pp.30-35 (in) J.L. Davies (ed.) Atlas of Tasmania. Lands and Survey Dept., Hobart.

Jackson W.D. 1968. Fire, air, water and earth - an elemental ecology of Tasmania. Proc. Ecological Soc. Australia 3, 9-16.

Jennings J.N. 1981. Periglacial small sorted net. Australian Geographer 15, 2, 114-116.

Johnson M. and Johnson W.D. 1972. Occurrence of silica in the natural waters of the Huntley-Robertson district, southern N.S.W. Australian J. Marine Freshwater Research 23, 105-119.

Jones H.E. 1971. Comparative studies of plant growth and distribution in relation to waterlogging. III. The response of Erica cinerea L. to waterlogging in peat soils of differing iron content. J. Ecology 59, 583-591.

Kapp W.A. 1980. A study of mine subsidence at two collieries in the Southern Coalfield, N.S.W. Proc. Australasian Instit. Mining Metallurgy 276, 1-11.

Kershaw A.P. 1981. Quaternary vegetation and environments. pp.81-101 (in) A. Keast (ed.) Ecological Biogeography of Australia, Dr. Junk, The Hague, 805p.

Kirkpatrick J.B. 1977. Native vegetation of the West Coast Region of Tasmania. pp.55-80 (in) M.R. Banks and J.B. Kirkpatrick (eds.), Landscape and Man, Proc. Symposium of Royal Society of Tasmania.

Klatkowa H. 1965. Vallons en berceau et vallees seches aux environs de Lodz. Acta Geogr. Lodziensis 19, 142 p.

Kononova M.M. 1966. Soil Organic Matter. 2nd English ed., (transl. by T. Nowakowski and A. Newman), Pergamon, Oxford, 544 pp.

Kovalev V.A., Zhukhovitskaya A.L. and Sokolovskaya A.A. 1974. Relation of chemical discharge of rivers to the swampy characteristics of drainage areas. Lithol. Mineral. Resourc. (Litol. Polezn. Iskop.) 9, 4, 393-398.

Kulczynski S. 1949. Peat bogs of Polesie. Memoires, Academie Polonaises Sciences et Lettres, 15, 365 p.

Lahermo P., Valovirta V.E. and Sarkioja A. 1977. The geobotanical development of spring-fed mires in Finnish Lapland. Geological Survey Finland, Bulletin 287, 44 p.

Lake P.S. and Newcombe K.J. 1975. Observations on the ecology of the crayfish Parastacoides tasmanium (Decapoda: Parastacidae) from SW Tasmania. Australian Zoologist 18, 3, 197-214.

Langmuir D. 1971. Eh-pH determination. pp.597-634 (in) R.E. Carver (ed.) Procedures in Sedimentary Petrology, Wiley-Interscience, NY, 653 p.

Lawson B. 1978. Sodium balance and observations on the ecology of the freshwater crayfish, Euastacus keirensis (Riek) and E. spinifer (Heller). B.Sc. Hons Thesis, Univ. of N.S.W.

Leopold L.B., Wolman, M.G. and Miller J.P. 1964. Fluvial Processes in Geomorphology. W.H. Freeman, San Francisco, 522 p.

Linacre E. 1969. Empirical relationships involving the global radiation intensity and ambient temperature at various latitudes and altitudes. Archiv. f. Meteor. Geofysk. Bioklima 17, 1-20.

Louis H. and Fischer K. 1979. Allgemeine Geomorphologie. W. de Gruyter, Berlin, 814 p, 2 vol.

Mackel R. 1974. Dambos: a study of morphodynamic activity on the plateau regions of Zambia. Catena 1, 327-365.

Macphail M.K. 1979. Vegetation and climates in Southern Tasmania since the last glaciation. Quaternary Research 11, 306-341.

Macphail M.K. 1980. Regeneration processes in Tasmanian forests. Search 11, 6, 184-190.

Macphail M and Shepherd R.R. 1973. Plant communities at Lake Edgar, south west Tasmania. Tas. Naturalist 34, 1-23.

Mainguet M. 1972. Le modele des gres. Problemes generaux. Institut Geographique National, Paris.

McElroy C.T. 1951. Contour trench formations in the upland plains of New South Wales. J. Proc. Royal Soc. N.S.W. 85, 53-62.

McLeod S. 1975. Studies on wet oxidation procedures for the determination of organic C in soils. pp.73-79 (in) Notes on Soil Techniques 1973. CSIRO Div. Soils.

Melville M.D. and Fitzpatrick E.A. 1982. Some hydrological characteristics of the sandstone plateau areas near Barren Grounds N.S.W. Proceedings 1st Australian Geomorphology Conference, 6 p.

Millington R.J. 1954. Sphagnum bogs of the New England plateau, N.S.W. J. Ecology 42, 328-344.

Mirlieb H. 1978. The distribution of heathland communities in relation to their nutrients and water table on the Budderoo Plateau. B.Sc. Hons Thesis, Univ. of N.S.W.

Mitchell, B.D. 1975. Oxides and hydrous oxides of silicon. Ch.11, pp.395-432 (in) J. Gieseking (ed.), Soil Components, Vol.2, Springer-Verlag, NY, 684 p.

Moore P.D. and Bellamy D.H. 1973. Peatlands. Paul Elek, London, 221 p.

Morisawa M. 1968. Streams: Their Dynamics and Morphology. McGraw Hill, N.Y., 175 p.

Moss A.J. and Walker P.H. 1978. Particle transport by continental water flows in relation to erosion, deposition, soils and human activities. Sedimentary Geology 20, 81-139.

Mount A.B. 1979. Natural regeneration processes in Tasmanian forests. Search 10, 5, 180-186.

Mullin J.G. and Riley J.P. 1955. The colorimetric determination of silicate with special reference to sea and natural waters. Analytica Chimica Acta 12, 162-176.

Nicolls K.D. 1957. A reconnaissance of the Corinna-Pieman Heads area - Soils. Papers Proc. Royal Soc. Tasmania 91, 17-21.

Nie, N.H. 1975. SPSS: statistical package for the social sciences, 2nd ed., McGraw-Hill, NY, 675 p.

Northcote K.H. 1966. Explanatory data for Sheet 3 (Sydney-Canberra-Bourke-Armidale area), Atlas of Australian Soils. CSIRO-Melb.U.P. 107 p.

Ollier C.D. 1979. Evolutionary geomorphology of Australia and Papua-New Guinea. Institute of British Geographers. Transactions (New Series) 4, 516-539.

Orioli G.A. and Curvetto N.R. 1978. The effect of fire on soil humic substances. Plant and Soil 50, 1, 91-98.

Paijmans K. (ed.) 1976. New Guinea Vegetation. CSIRO/ANUP, Canberra, 212 p.

Penck W. 1924. Die morphologische Analyse. Geographische Abhandlungen 2. Transl. by H. Czech and K. Boswell, Morphological Analysis of Landforms 1972, Hafner, N.Y., 429p.

Price L.W. 1971. Geomorphic effect of the Arctic ground squirrel in an alpine environment. Geografiska Annaler 53A, 100-106.

Proctor M.C.F. 1974. The vegetation of the Malham Tarn fens. Field Studies 4, 1, 1-38.

P'yavchenko N.I. 1976. Interrelation of forest and bog. Results of station research. U.S. Forest Service, Washington, 181 p.

Regel C. 1947. The bogs and swamps of White Russia. J. Ecology 35, 96-104.

Reynolds R.G. 1978. Coal Mining Under Stored Water. Report of Public Enquiry, N.S.W. Govt. Printer.

Rose S. 1981. Palynology and history of the Holocene at Dry Lake, Thirlmere, N.S.W. B.Sc.(Hons) thesis, Univ. of N.S.W.

Ruscoe Q.W. 1975. The distribution and properties of soils and their biota. pp.139-176 (in) G. Kuschel (ed.) Biogeography and Ecology in New Zealand. Dr Junk, The Hague, 689 p.

Schmitthener H. 1925. Die Entstehung der Dellen und ihre morphologische Bedeutung. Zeitschrift f. Geomorphologie 1, 3-28.

Schumm S.A. 1979. Geomorphic thresholds: the concept and its applications. Institute of British Geographers. Transactions (New Series) 4, 485-515.

Siever, R. 1962. Silica solubility 0-200°C and the diagenesis of siliceous sediments. J. Geology, 70. 127-150.

Singh G., Kershaw A.P. and Clark R. 1981. Quaternary vegetation and fire history in Australia. Ch. 2, pp.23-54 (in) A.M. Gill, R.H. Groves and I.R. Noble (eds.) Fire and the Australian Biota, Aust. Academy Science, Canberra.

Sjors H. 1959. Bogs and fens of the Hudson Bay Lowlands. Arctic 12, 2-19.

Sjors H. 1961. Surface patterns in Boreal peatland. Endeavour 20, 80, 217-224.

Sjors H. 1963. Bogs and fens on the Attawapsikat River, Northern Ontario. pp.45-133 (in) Contributions to Botany 1960-61: National Museum of Canada Bulletin 186.

Slack N.G., Vitt D.H. and Horton D.G. 1980. Vegetation gradients of minerotrophically rich fens in western Alberta. Canadian J. Botany 58, 3, 330-350.

Smith D.G. 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacial meltwater river. Bull. Geol. Soc. America 87, 857-860.

Soons J. 1958. Formes de vallees dans les Vosges. Revue de Geomorphologie Dynamique 5-6, 65-71.

Specht R., Roe E.M. and Boughton V.H. 1974. Conservation of major plant communities in Australia and Papua New Guinea. Australian J. Botany Supplement Series 7, 1-667.

Stace H.C.T., Hubble G.D., Brewer R., Northcote K.H., Sleeman J.R., Mulcahy M.J. and Hallsworth E.G. 1968. A Handbook of Australian Soils. Rellim Technical Publ., Glenside, S. Australia, 435 p.

Standard J.C. 1969. Hawkesbury Sandstone. pp.407-415 (in) G. Packham (ed.) Geology of New South Wales, J. Geological Soc. Australia 16, pt. I.

Stockton E.D. and Holland W.N. 1974. Cultural sites and their environment in the Blue Mountains. Archeology & Physical Anthropology in Oceania 9, 1, 36-66.

Suter P.J. and Richardson A.M.M. 1977. The biology of two species of Engaeus (Decapoda: Parastacidae) in Tasmania: III: Habitat, food, associated fauna and distribution. Australian J. Marine Freshwater Research 28, 95-103.

Taylor G. 1923. The warped littoral around Sydney. J. Royal Soc. N.S.W. 57, 58-79.

Thorn C. 1978. A preliminary assessment of the role of pocket gophers in the alpine zone of the Colorado Front Range. Geografiska Annaler 60A, 3-4, 181-187.

Tricart J. 1970. Geomorphology of Cold Environments (transl. E. Watson), Macmillan, London, 320 p.

Tricart J. and Cailleux A. 1972. Introduction to Climatic Geomorphology. (transl. by C.J.K. de Jonge), Longman, 295 p.

Troll C. 1966. Landscape Ecology. Publications of the ITC-UNESCO Centre for Integrated Surveys. 23 p.

van Breemen H. and Brinkman R. 1976. Chemical equilibria and soil formation. Ch. 8, pp.141-170 (in) G.H. Bolt and M.G.M. Bruggenwert (eds.) Soil Chemistry. A. Basic Elements. Elsevier, Amsterdam.

Vitek J.D. and Rose E.M. 1980. Preliminary observations on a patterned fen in the Sangre de Cristo Mts., Colorado, U.S.A. Zeitschrift f. Geomorphologie 24, 4, 393-404.

Wace N.M. 1961. The vegetation of Gough Island. Ecological Monographs 31, 337-367.

Walter H. 1973. Vegetation of the Earth. (transl. by J. Wieser), Springer-Verlag, N.Y. 274 p.

Walter H. 1977. The oligotrophic peatlands of Western Siberia. Vegetatio 34, 3, 167-178.

Walter H., Harnickell E. and Mueller-Dombois D. 1975. Climate-diagram Maps of the Individual Continents and Ecological Climatic Regions of the Earth. Springer-Verlag, N.Y. 36 p., 9 maps.

Wardle P. 1980. Primary succession in Westland National Park and its vicinity, New Zealand. N.Z. J. Botany 18, 2, 221-232.

Werger M.J.A. and Coetzec B.J. 1978. The Sudano-Zambian region. pp.303-462 (in) M.J.A. Werger (ed.) Biogeography and Ecology of Southern Africa. Dr Junk, The Hague.

Young A.R.M. 1976. The characteristics, origin and stability of debris-mantled slopes near Wollongong, Australia. M.Sc. thesis, Univ. of Wollongong.

Young A.R.M. 1978. The influence of debris mantles and local climatic variations on slope stability near Wollongong, Australia. Catena 5, 95-107.

Young A.R.M. 1981. Report on the sedgelands at Porters Creek, near Ulladulla, N.S.W.. Report to the National Parks and Wildlife Service, Nowra office.

Young A.R.M. 1982. Soil-vegetation relationships in the fens on the Illawarra plateau, from 12 000 years BP to the present. Paper to the Symposium on Mountain Ecology in the Australian Region, Ecological Society of Australia, Canberra, May.

Young R.W. 1977. Landscape development in the Shoalhaven River catchment in southeastern N.S.W. Zeitschrift f. Geomorphologie 21, 262-283.

Young R.W. 1978. The study of landform evolution in the Sydney region: a review. Australian Geographer 14, 71-93.

Young R.W. and Johnson A.R.M. 1977. The physical setting: environmental hazards and urban planning, pp.38-57 (in) R. Robinson (ed.) Urban Illawarra, Sorrett, Melbourne.

Young R.W. and Nanson, G.C. 1982. Terrace formation in the Illawarra region of New South Wales. Australian Geographer 15, 212-219.

APPENDIX 1. SEDIMENTOLOGICAL DATA.

Colour = damp Munsell Soil Colour.

pH = acidity in 1:2 by volume soil : water suspension, measured on a Metrohm pH meter.

M.C. = field moisture content, as a percentage of dry (105°C) weight.

L.O.I. = loss-on-ignition, at 550°C in a muffle furnace for 1 hour or longer if obvious organic material remained, as a percentage of dry (105°C) weight (Dean, 1974).

C = organic carbon content, as a percentage of dry (105°C) weight, by the modified Walkley-Black dichromate digestion method.

Fe = iron expressed as Fe O , as a percentage of dry (105°C) weight. Iron was extracted in IN HCl and determined by atomic absorption spectrophotometry.

μ = mean grain size, in phi units.

s.d. = standard deviation in phi units.

sk = skewness, in phi units.

kurt = kurtosis, in phi units.

These grain size parameters were calculated by the method of moments from combined sieve (0.5ϕ intervals from -0.5 to 4ϕ) and pipette (5.5, 7, 9, 10ϕ) data.

<1ϕ = coarser than 0.5 mm = percentage coarse sand.

1-2ϕ = 0.25 - 0.5 mm = percentage medium sand.

2-4ϕ = 0.063 - 0.25 mm = percentage fine sand.

4-9ϕ = 0.063 - 0.002 mm = percentage silt.

>9ϕ = finer than 0.002 mm = percentage clay.

All grain size data refer to fractions by weight after the removal of organic matter by hydrogen peroxide digestion, followed by dispersal with sodium hexametaphosphate using an ultrasonic bath for 10 minutes.

List of Munsell soil colours.

bl	10YR2/1, 2.5YR2.5/0, 7.5YR2/0
v dk gr	10YR3/1
dk gr	10YR4/1
gr	10YR5/1, 10YR6/1
lt gr	10YR7/1, 10YR7/2
v dk gr br	10YR3/2
dk gr br	10YR4/2
gr br	10YR5/2
lt gr br	10YR6/2
dk br	7.5YR4/4, 10YR4/3
br	10YR5/3
pale br	10YR6/3
v pale br	10YR7/3, 10YR7/4
lt ol br	2.5Y5/4
br y	10YR6/6
dk y br	10YR4/6
y br	10YR5/4, 10YR5/6
lt y br	10YR6/4
r	2.5YR4/6

Sample Number	Colour	pH	M.C.	L.O.I.	C_{org}	Fe	μ	s.d.	sk.	kurt.	<1ϕ	1-2ϕ	2-4ϕ	4-9ϕ	>9ϕ
Loddon Tributary (0.5 m depth)															
L1/1	vdkgr	4.0	34	5.1	1.63	1.7	3.1	3.0	1.5	4.3	18.2	33.7	23.3	15.7	9.2
2	vdkgrbr	4.3	25	3.6	1.08	0.7	3.2	2.9	1.6	4.7	15.1	33.6	25.3	18.0	8.0
3	ybr	3.8	18	1.6	0.75	0.7	2.9	2.8	1.7	5.1	17.0	33.6	25.5	16.4	7.5
4	ybr/dk grbr	3.7	17	1.8	0.29	1.5	3.0	3.0	1.4	4.1	23.9	28.8	19.7	20.1	7.5
5	dkgrbr	3.7	20	1.7	0.41	0.3	3.4	3.0	1.1	3.4	19.3	32.6	11.8	29.8	6.5
6	ybr/ dkgrbr	3.8	16	1.3	0.25	2.2	3.1	2.4	1.5	5.1	11.8	32.6	25.8	25.7	4.1
7	bry/r	4.1	18	1.1	0.12	1.4	3.3	2.2	1.3	5.1	8.4	23.0	35.9	30.0	2.7
8	vdkgrbr	3.9	30	1.8	0.60	0.8	3.1	2.2	1.8	6.7	7.6	24.5	41.3	22.3	4.3
9	dkybr/ grbr	4.0	26	2.5	0.20	4.5	3.4	2.8	1.5	4.7	9.8	21.1	42.0	18.7	8.3
10	bl	3.9	72	11.8	5.73	0.6	5.6	3.7	0.4	1.5	2.5	17.5	28.3	24.1	27.6
L2/1	bl	4.4	140	17.7	6.38	2.1	4.4	3.9	0.7	2.0	17.7	26.0	13.4	23.0	19.9
2	bl	4.5	85	13.2	5.11	0.8	5.1	3.9	0.4	1.6	10.8	25.3	12.3	27.3	24.3
3	bl	4.4	79	9.7	3.97	0.9	4.0	3.2	0.9	2.7	14.7	28.6	14.7	31.3	10.7
4	bl	4.2	46	8.3	3.33	0.5	4.0	3.6	1.0	2.5	16.1	29.5	17.3	21.3	15.8
5	bl	4.0	71	13.2	6.05	0.2	3.6	3.3	1.1	2.9	17.6	30.3	17.8	22.6	11.7
6	bl	4.1	37	5.1	2.32	0.1	2.7	3.1	1.8	4.9	28.9	40.2	11.6	10.3	9.0
7	bl	3.9	34	5.0	2.30	0.2	2.7	3.1	1.7	4.8	27.6	41.0	11.1	11.4	8.9
8	vdkgrbr	3.9	28	3.2	0.91	0.2	2.5	2.8	1.9	5.7	27.3	40.2	13.4	12.3	6.8
9	bl	4.0	50	8.0	2.96	0.3	2.9	3.2	1.6	4.3	22.4	42.4	13.5	10.7	11.1
10	vdkgrbr	3.9	21	2.0	0.56	0.1	2.3	2.7	2.0	6.2	32.5	37.9	12.7	10.8	6.1
11	bl	3.9	44	5.8	2.81	0.1	2.4	2.7	2.1	6.5	29.4	38.8	16.0	9.3	6.5
12	bl	4.1	71	13.4	5.96	0.1	2.7	3.2	1.6	4.3	31.0	33.1	15.9	10.9	9.1
13	vdkgrbr	4.0	30	3.4	1.10	0.2	2.0	2.8	2.2	6.9	41.7	34.8	10.0	6.8	6.6
14	dkgrbr	3.8	24	2.7	0.76	0.1	2.3	2.8	1.9	5.7	41.2	31.7	9.3	11.9	5.9
15	dkgrbr	3.6	20	1.8	0.38	0.1	2.3	2.4	2.2	7.7	24.8	41.4	19.7	10.2	3.9

Sample Number	Colour	pH	M.C.	L.O.I.	C_{org}	Fe	μ	s.d.	sk.	kurt.	<1φ	1–2φ	2–4φ	4–9φ	>9φ
Martins Swamp (0.5 m depth)															
M1/1	vdkgrbr	4.9	28	2.7		0.2	2.1	2.6	2.0	6.8	34.3	32.6	17.5	11.0	4.6
2	bl	4.9	37	5.4	1.32	0.3	2.1	2.6	1.9	6.2	33.7	32.6	20.0	6.3	7.4
3	vdkgrbr	4.9	26	1.4	0.70	0.3	1.8	2.2	1.9	6.9	36.9	31.2	21.2	8.9	1.8
4	ltybr	5.0	18	1.1		0.7	1.8	2.4	2.2	8.1	38.6	30.5	20.3	7.2	3.4
5	br	4.9	19	1.4		0.3	1.7	2.3	2.3	9.0	42.3	27.3	21.1	6.2	3.1
6	dkbr	5.1	24	1.7		0.3	1.8	2.3	2.2	8.6	36.8	51.0	8.8	3.3	0.1
7	bl	5.3	82	9.7		0.1	5.9	3.8	0.1	1.6	7.1	16.5	12.0	34.4	29.8
8	bl	5.0	79	13.1	6.06	0.3	4.2	3.7	0.8	2.2	11.4	36.3	14.4	19.5	18.4
9	vdkgr	4.8	37	5.5	2.71	0.5	2.9	3.2	1.5	3.9	28.3	35.2	12.2	15.3	9.0
10	vdkgr	4.9	26	3.4	1.31	0.3	2.4	3.1	1.8	5.2	35.2	33.6	12.4	8.9	9.9
11	grbr	4.9	21	2.5	0.45	0.2	3.1	3.1	1.3	3.6	20.3	36.7	16.4	17.5	9.1
12	vdkgr	4.9	29	2.9		0.4	2.5	2.6	2.0	6.4	22.8	44.4	13.7	14.0	5.1
M2/1	bry	4.9	10	1.4		0.6	2.4	2.6	2.0	6.6	20.7	42.9	21.0	9.8	5.6
2	dkbr	4.9	14	2.1		0.5	2.3	2.6	2.0	6.4	23.7	42.2	18.6	10.2	5.3
3	dkgrbr	4.8	21	2.2		0.7	2.3	2.4	2.1	7.6	20.2	44.0	21.7	10.0	4.1
4	dkgrbr	4.7	26	2.3		0.8	2.6	2.6	2.2	7.0	12.6	49.8	22.1	9.7	5.8
5	dkbr	4.9	25	1.7		0.6	2.3	2.3	2.4	8.9	17.0	50.6	20.3	8.1	4.0
6	vdkgrbr	4.6	24	2.3		0.2	2.3	2.5	2.3	7.7	22.2	46.9	18.4	7.0	5.5
7	bl	5.0	260	34.0		1.7	5.3	3.7	0.2	1.6	7.4	25.2	12.0	32.6	22.8
8	bl	5.0	505	55.6		1.6	8.1	2.9	-0.6	2.5	0.8	3.7	4.9	48.3	42.3
9	bl	4.9	679	55.8		1.7	7.8	2.8	-0.4	2.4	1.2	3.1	5.0	55.1	35.6
10	bl	4.9	81	12.0		2.1	2.9	3.2	1.6	4.1	24.0	42.8	11.5	11.6	10.1
11	bl	4.9	38	6.5		0.7	2.9	2.9	1.7	4.8	16.8	41.1	22.6	11.2	8.3
12	dkgrbr	4.5	26	2.5		0.1	3.0	2.8	1.8	5.2	7.8	47.1	27.1	9.6	8.4

Sample Number	Colour	pH	M.C.	L.O.I.	C_{org}	Fe	μ	s.d.	sk.	kurt.	<1ϕ	1-2ϕ	2-4ϕ	4-9ϕ	>9ϕ
Drillhole Swamp, 0.5 m depth, transect across forest/dell ecotone.															
F1	dkgr	4.4	12	3.2		0.3	2.9	2.4	2.4	8.1	4.9	36.9	46.4	6.5	5.3
F2	dkbr	4.5	28	5.1		1.7	3.2	2.8	1.7	5.0	6.8	34.6	40.5	9.8	8.3
F3	bl	4.6	49	9.9	3.20	0.9	3.5	3.2	1.4	3.7	6.9	39.0	31.1	10.4	12.6
F4	bl	4.3	103	19.1	6.43	3.8	4.7	3.6	0.7	2.0	6.7	22.9	31.4	20.0	19.0
F5	bl	4.2	62	11.9	5.04	2.5	4.3	3.4	0.9	2.3	3.1	28.5	35.0	17.2	16.2
Drillhole Swamp gully, relict sediments.															
C1/0.4m	vdkgr	3.9		11.0	3.12	0.2	2.1	2.6	2.6	8.6	31.0	45.9	12.7	3.9	6.5
/0.75m	bl	3.8		22.2	7.46	0.1	3.1	3.3	1.4	3.6	22.2	36.8	17.0	12.7	11.3
/2.40m	bl	3.8		14.3	3.96	0.2	2.6	3.1	1.9	5.4	26.5	43.1	14.8	6.0	9.6
/2.80m	bl	4.5		15.8	6.29	0.1	3.1	3.2	1.6	4.0	16.5	42.5	19.8	8.9	12.3
/3.40m	bl	4.5		16.5	5.61	0.1	3.0	2.9	1.8	5.1	9.7	47.4	24.9	8.5	9.5
/3.80m	bl	4.7		6.8		0.1	1.7	1.9	3.8	17.8	23.7	60.8	10.2	2.3	3.0
C2/0.4m	bl	3.9		11.0	5.74	0.1	3.0	2.9	1.6	4.6	16.1	38.5	23.1	14.6	7.7
/1.0m	bl	3.7		41.0	14.77	0.3	6.9	3.3	-0.4	2.1	4.4	11.0	4.3	48.7	31.5
/2.55m	vdkgr	4.2		6.6			1.7	2.1	3.6	15.6	31.2	54.3	8.8	1.8	3.9
/3.05m	vdkgr	4.2		2.1			1.4	1.7	4.4	24.4	38.1	54.4	3.7	1.5	2.3
C5/0.4m	vdkgr	4.5		13.2	5.4	0.1	3.2	3.2	1.3	3.5	20.0	35.2	19.5	14.9	10.4
/1.0m	dkbr	4.4		2.6		0.1	1.7	1.8	3.7	18.8	24.3	55.3	15.4	2.8	2.2
/1.75m	bl	4.4		12.1	5.08	0.1	3.8	3.7	0.9	2.2	23.7	31.5	7.7	23.0	14.1
/2.65m	bl	4.3		29.2		0.3	5.2	3.9	0.3	1.5	9.7	23.3	16.5	25.3	25.2
/3.0m	bl	4.7		7.2		0.1	3.2	3.1	1.5	3.9	11.6	45.1	19.8	13.8	9.7
/4.5m	ybr	4.9		1.4		0.1	2.1	2.1	2.8	11.0	19.4	52.4	18.8	6.1	3.3

Sample Number	Colour	pH	M.C.	L.O.I.	C_{org}	Fe	μ	s.d.	sk.	kurt.	<1ϕ	1-2ϕ	2-4ϕ	4-9ϕ	> 9ϕ
Martins Swamp (varying depths as indicated)															
M1/1/0.1m	bl	4.8	97	17.0	5.64	5.5									
/1/0.25m	bl	5.4	61	9.5	3.90	0.6	2.9	2.9	1.8	5.1	16.3	41.3	23.1	11.3	8.0
/1/0.95m	grbr	4.9	24	1.4		0.1									
M1/2/0.1m	bl	4.8	169	34.9	9.83	2.2									
/2/0.35m	bl	5.0	119	25.3	8.0	2.5	4.0	3.5	1.0	2.5	13.6	31.1	20.4	19.4	15.5
/2/0.95m	grbr	5.2	26	2.4		0.2									
M1/3/0.8m	ltolbr	4.9	25	1.3		0.8	2.0	2.4	1.9	6.6	32.8	33.1	21.8	7.6	4.6
M1/4/0.1m	bl	4.6	52	7.5	2.30	0.2	2.3	2.8	2.0	6.3	33.0	34.0	17.8	8.2	7.0
M1/5/0.1m	grbr	4.5	18	3.4	1.06	0.2	1.9	2.3	2.4	9.4	35.7	31.3	23.3	6.4	3.3
M1/6/0.1m	br	5.0	16	3.7	1.01	0.4	2.0	2.4	2.0	7.4	34.7	28.7	20.9	12.3	3.4
M1/7/0.1m	bl	5.2	90	19.0	6.78	0.6	5.7	3.2	0.2	2.0	5.9	11.8	13.5	47.0	21.8
/7/0.9m	bl	5.4	58	6.1		0.1									
M1/9/0.2m	bl	4.9	116	13.5	3.56	2.2									
/9/1.0m	vdkgr	5.5	26	4.9		0.6									
M1/10/0.2m	bl	5.0	60	8.9	3.59	1.7									
/10/1.0m	grbr	5.2	26	1.7		0.1									
M1/11/0.2m	bl	4.8	73	12.2	5.33	0.9									
/11/1.0m	dkgrbr	5.3	19	2.1		0.1									
M1/12/0.2m	bl	4.7	48	6.3	2.05	0.4	2.7	2.8	2.1	6.3	15.1	50.2	16.6	10.6	7.5
M2/1/1.1m	ybr	4.8	13	1.8		0.3									
M2/3/1.0m	vpalebr	4.9	20	1.3		0.1									
M2/4/0.1m	bl	4.6	42	7.1		2.9									
/4/0.7m	br	4.7	16	1.3		0.1									
M2/6/0.1m	bl	5.1	75	13.3		2.0									
/6/1.0m	grbr	4.8	19	1.2											
M2/7/0.1m	bl	4.8	665	54.9		7.8									
/7/1.0m	grbr	5.0	29	4.0		0.3									
M2/8/0.1m	bl	4.9	897	64.3		15.4									
/8/1.5m	grbr	5.1	29	2.8		0.1									
M2/9/0.1m	bl	4.9	1067	63.2		23.5									
/9/1m	bl	4.9	439	49.6		1.2									
/9/2m	bl	5.2	50	6.4		0.4									

Sample Number	Colour	pH	M.C.	L.O.I.	C_{org}	Fe	µ	s.d.	sk.	kurt.	<1ϕ	1-2ϕ	2-4ϕ	4-9ϕ	>9ϕ
Martins Swamp (varying depths as indicated, continued)															
M2/10/0.1m	bl	4.9	67	12.2		4.0									
M2/11/0.1m	bl	4.7	120	22.4		6.44									
/11/0.8m	grbr	5.1	21	1.7		0.2									
M2/12/0.1m	bl	4.3	38	5.7		0.1									
/12/0.75m	grbr	4.9	41	6.2		0.6									

Sample Number	Colour	pH	M.C.	L.O.I.	C_{org}	Fe	µ	s.d.	sk.	kurt.	<1ϕ	1-4ϕ	>4ϕ
6R Swamp, varying depths as indicated													
6R1/0.2m	bl		201	34.6									
1/0.7m	bl	4.4	47	8.6							17.8	61.3	20.9
1/1.0m	bl	4.4	43	8.5									
6R2/0.2m	bl		192	20.9									
2/0.7m	bl	4.5	48	10.1							12.0	56.0	32.0
6R3/0.2m	bl		297	34.2							22.1	42.3	35.6
6R4/0.2m	bl	4.0	67	16.8							3.3	63.3	33.4
6R5/0.2m	bl		64	14.1									
/0.7m	dkbr	4.0	18	2.4							19.2	68.0	12.8
6R6/0.2m	vdkgr		15	5.8									
/0.7m	dkbr	3.9	15	1.4							21.4	67.8	10.8
6R7/0.2m	bl		50	15.4									
/0.7m	palebr	3.9	14	1.0							41.5	51.4	7.1
6R8/0.2m	bl		55	16.0									
/0.7m	palebr	3.8	16	1.4							30.5	59.3	10.2
6R9/0.2m	bl		28	11.7									
/0.7m	ltgrbr	3.8	15	1.0							20.1	68.2	11.7

APPENDIX 2. MARTINS SWAMP - WATER LEVELS AND WATER CHEMISTRY, OCTOBER 1979 to JULY 1980.

pH = acidity, measured in the field using an Activon meter with a plastic-shielded glass electrode.

D.O. = dissolved oxygen, measured in the field as mg/l using a Delta Scientific model 1010 meter. Original readings were converted to percentage of saturation, taking temperature and elevation into account. The data here are expressed as % saturation.

C_{org} = dissolved organic carbon. Water samples taken in clean plastic bottles were filtered through No.42 Whatman paper, acidified immediately to pH 2-4 with conc. HNO_3 and later analysed using a slightly modified Dohrman DC-50 Organic Analyser. Analyses were done by Mr J. Land, Department of Chemistry, University of Wollongong. Values less than 5μg/g (=ppm) are not significantly different from one another, as they are at the extreme low range for the instrument as calibrated.

SiO = dissolved silica content, expressed as ppm. Filtered samples were analysed using a Bausch and Lomb Spectronic 20 colorimeter, after silicomolybdate reduction (Mullin and Riley, 1955).

W.L. = water level in uncased auger holes, measured in cm below groundsurface. Negative values thus refer to water standing above the surface.

nd = no data, due to instrument malfunction or hole collapse.

Date	Exit					Pool					M1/1				
	pH	D.O.	C_{org}	SiO_2	W.L.	pH	D.O.	C_{org}	SiO_2	W.L.	pH	D.O.	C_{org}	SiO_2	W.L.
18.10.79		71	nd				43	6.9		30		32	7.6		30
1.11.79		68	6.7				54	5.5		23		37	8.8		23
16.11.79	5.0	54	3.8			4.4	46	2.7		14	4.0	43	8.0		10
30.11.79	4.8	62	nd			4.7	49	6.9		15	4.0	36	nd		18
14.12.79	5.6	61	3.6			5.3	65	5.3		27	-	-	-		dry
11.1.80	4.3	78	4.7			4.6	43	7.6		12	4.2	46	2.7		17
25.1.80	4.8	63	5.3			4.9	47	5.8		nd	4.2	44	2.6		nd
8.2.80	4.7	55	6.6			4.5	37	9.3		12	4.0	37	3.8		19
22.2.80	4.8	78	3.7			4.8	55	4.8		24	nd	nd	nd		nd
7.3.80	nd	94	nd			nd	63	nd		24	nd	9	nd		38
21.3.80	4.6	66	4.7			4.5	51	4.6		13	3.9	19	2.2		19
4.4.80	4.9	74	9.7			4.5	54	7.8		23	4.0	40	3.2		36
18.4.80	5.0	79	10.4	3.1		4.6	56	10.4	2.9	22	4.0	30	5.7	3.8	37
2.5.80	4.4	72	10.7	3.6		4.4	70	8.8	4.0	-1	4.1	75?	4.0	4.0	0
16.5.80	4.2	66	4.2	1.4		4.2	49	11.2	2.4	0	3.7	37	5.7	1.4	0
30.5.80	4.3	73	6.6	1.4		4.1	70	9.1	1.0	0	4.5	36	6.5	1.0	0
13.6.80	4.3	59	3.0	2.6		4.4	54	7.6	3.2	0	3.9	35	11.5	3.0	2
27.6.80	4.7	74	4.4	4.3		4.3	62	3.3	4.1	7	3.9	35	5.9	3.0	8
11.7.80	4.8	72	2.5	2.6		4.5	56	5.7	3.0	8	4.0	39	6.8	2.4	11

Date	M1/2					M1/3					M1/4				
	pH	D.O.	C_{org}	SiO_2	W.L.	pH	D.O.	C_{org}	SiO_2	W.L.	pH	D.O.	C_{org}	SiO_2	W.L.
18.10.79		9	11.4		45		-	-		dry		-	-		dry
1.11.79		24	7.6		40		-	-		dry		-	-		dry
16.11.79	-	62	8.6		21	-	65	-		44	-	-	-		dry
30.11.79	4.5	29	5.9		35	4.2	46	-		60	-	-	-		dry
14.12.79	-	-	-		dry	-	-	-		dry	-	-	-		dry
11.1.80	4.3	37	3.3		23	4.3	48	6.8		26	4.0	50	-		42
25.1.80	4.3	7	3.1		nd	-	29	-		nd	-	-	-		dry
8.2.80	4.2	37	4.1		29	4.2	42	3.3		40	4.2	46	6.3		51
22.2.80	-	-	-		61	-	-	-		dry	-	-	-		dry
7.3.80	-	11	-		52	-	-	-		dry	-	-	-		dry
21.3.80	4.0	15	3.5		31	3.9	33	2.9		44	4.0	26	-		61
4.4.80	4.4	18	3.6		48	-	-	-		71	-	-	-		dry
18.4.80	4.5	26	8.7	3.8	60	-	-	-	-	dry	-	-	-	-	dry
2.5.80	3.9	71	6.1	2.7	13	4.0	81	5.0	4.0	22	4.3	72	4.6	3.8	57
16.5.80	3.7	27	7.3	1.7	9	3.7	35	9.1	1.9	7	3.8	39	6.4	2.4	6
30.5.80	3.9	22	5.7	1.2	9	3.8	12	7.2	2.3	9	3.9	16	10.5	0.7	12
13.6.80	4.2	24	7.3	3.2	12	3.9	12	7.7	4.1	10	4.1	33	4.8	3.0	22
27.6.80	4.0	28	6.4	4.1	20	3.8	25	4.5	3.9	27	4.1	32	5.5	4.5	43
11.7.80	3.9	27	7.5	3.2	23	4.0	39	8.9	2.1	47	4.1	51	-	-	62

APPENDIX 3. SPECIES LIST AND LOCATIONS.*

	L1	L2	M1	M2
Lycopodiaceae				
Lycopodium laterale R.Br.	4,7	11,14	4	-
Selaginellaceae				
Selaginella uliginosa (Labill.) Spring	1,2,5-10	2,3,5,6,8,9, 11-15	1-3,12	1,3,4,6,12
Gleicheniaceae				
Gleichenia dicarpa R.Br.	1	1,2,8,12	1,7-9,11	1,2
Dennstaedtiaceae				
Pteridium esculentum (Forst.f.)Cockayne	-	-	5,6	1,12,13
Lindseaceae				
Lindsaea linearis Sw	2-7	8,10,15	-	2
Droseraceae				
Drosera binata Labill.	-	2-4,12,14	-	-
D. spathulata Labill.	2-4,6-8,10	6,8,11,13-15	-	-
Haloragaceae				
Gonocarpus salsaloides				
Proteaceae				
Isopogon anemonifolius (Salisb.)	5,6,8	15	5,6,11,12	13
Banksia spinulosa Sm.	5,6	-	1,2	-
B. oblongifolia Cav.(syn. B.asplenifolia)	1-9	8,10	-	-
B. robur Cav.	2,10	1-7,9,11-14	1-4,7-12	3-7,9-12
B. ericifolia L.f.				
Hakea teretifolia (Salisb.)	2-10	1-4,6-15	7,10-12	-
Grevillea sericea (Sm R.Br.				
Baueraceae				
Bauera rubioides Andr.				
Fabaceae				
Phyllota phylicoides (Sieb. ex DC)	1	1,2,4,9,12	2-4,9-11	3-8,10-12
Pultenaea divaricata Williamson				
Dillwynia floribunda Sm.				
Viminaria juncea (Schrad.) Hoffmgg.				
Mimosaceae				
Acacia longifolia (Andrews) Willd. var. longifolia	-	-	5,6	1,2,12,13
Myrtaceae				
Leptospermum juniperinum Sm.	10,2	1-5,9	1-4,7-9,11, 12	8-12
L. lanigerum var. lanigerum (Ait.) Sm.	1,2,10	1-9,13,14	1-4,7-9,11	11-13
Callistemon citrinus (Curtis) Skeels	1,10	1,2	-	-
Melaleuca squarrosa Sm.	1,2,10	1-5,13	1,3,4,7,8	9
Baeckea linifolia Rudge.	-	2-6,9,11, 13-15	1-4,6,9-12	2-6,10-12
Eucalyptus spp (largely E.haemastoma)	-	10	4-6	1,2,12,13
Casuarinaceae				
Casuarina paludosa Sieb. ex Spreng.				
Umbelliferae				
Platysace linearifolia (Cav.)	8	-	5,6	1,2,13
Epacridaceae				
Epacris paludosa R.Br.	1,2,10	2-6,11-14	-	-
E. microphylla R.Br.	6	13,14	-	-
E. obtusifolia Sm.	3,4,7,9,10	-	-	-
Woollsia pungens (Cav.) F. Muell.	-	5	8	7-10
Sprengelia incarnata Sm.	1,7	5,12	1,7,9,10	3-5

* According to Beadle N.C.W. et al, (1976). Flora of the Sydney Region. Reed, Sydney.

	L1	L2	M1	M2
Menyanthaceae				
Villarsia exaltata (Sims) G. Don.	1-3, 10	1,5	-	-
Stylidiaceae				
Stylidium graminifolium Swartz ex Willd.				
Goodeniaceae				
Dampiera stricta (Sm.) R.Br.	2,5-7,9	8, 10, 15	4,5	1-3, 12, 13
Goodenia bellidifolia Sm.	2-5,7,8	2-6,8-11, 13, 14	1	2,3,5,12
Xyridaceae				
Xyris operculata Labill.	3,4,6-10	1-9, 11-15	1,4, 11, 12	-
X. ustulata Nilss.	1, 10	5, 11, 12	-	10
Liliaceae				
Blandfordia nobilis Sm				
Iridaceae				
Patersonia sp.	6	6,8, 10, 15	-	1, 13
Xanthorrhoeaceae				
Xanthorrhea sp.	1-10	1,2,4-15	11	4-7
Lomandra obliqua (Thunb.) MacBride	6	10	-	-
Haemodoraceae				
Haemodorum corymbosum Vahl.	2-8	8, 10, 15	4,6	1,2
Juncaceae				
Juncus planifolius R.Br.				
Restionaceae				
Lepyrodia scariosa R.Br.	2-4,6,8-10	2-4,6,8,9, 11, 15	5,6	2-6, 10-12
L. gracilis R.Br.				
L. anarthria F.Muell. ex Benth.				
Restio complanatus R.Br.	2-7	4-15	1,7, 10-12	5,6
R. dimorphus R.Br.				
R.gracilis R.Br.				
Leptocarpus tenax (Labill.) R.Br	3-9	1-11, 13-15	2-6,8-12	1-6, 10-12
Hypolaena fastigiata R.Br.				
Empodisma minus (Hook f.) Johnson & Cutler	2-5,7-9	1-6,8-15	1-4,7-12	1-12
Cyperaceae				
Chorizandra sphaerocephala R.Br.	1,2,8-10	1-9, 11-15	1,2,7-11	4-11
Schoenus brevifolius R.Br.	7-9	1-6, 10, 12	1	-
S.melanostachys R.Br.				
Gymnoschoenus sphaerocephalus R.Br.	9, 10	1-9, 11, 12, 14	1-3,7-12	4-12
Lepidosperma longitudinale Labill.	1,9, 10	1-7,9, 14	1-4,7-12	3-11
L. forsythii Hamilton	-	2-4, 11, 12	7,8, 11	-
L. limicola N. Wakefield				
L. neesii Kunth				
Baumea teretifolia (R.Br.) Palla.				
Gahnia sieberana Kunth.	1	-	-	-
Ptilanthelium deustum (R.Br.) Kukenth.	2-4,6,8	7-11, 13, 15	11, 12	3,5
Gramineae				
Hemarthria uncinata R.Br.				
Entolasia stricta (R.Br.) Hughes				
Tetrarrhena juncea R.Br.	9	2,3,4,7-9, 11, 12	1-4,7-12	2-12