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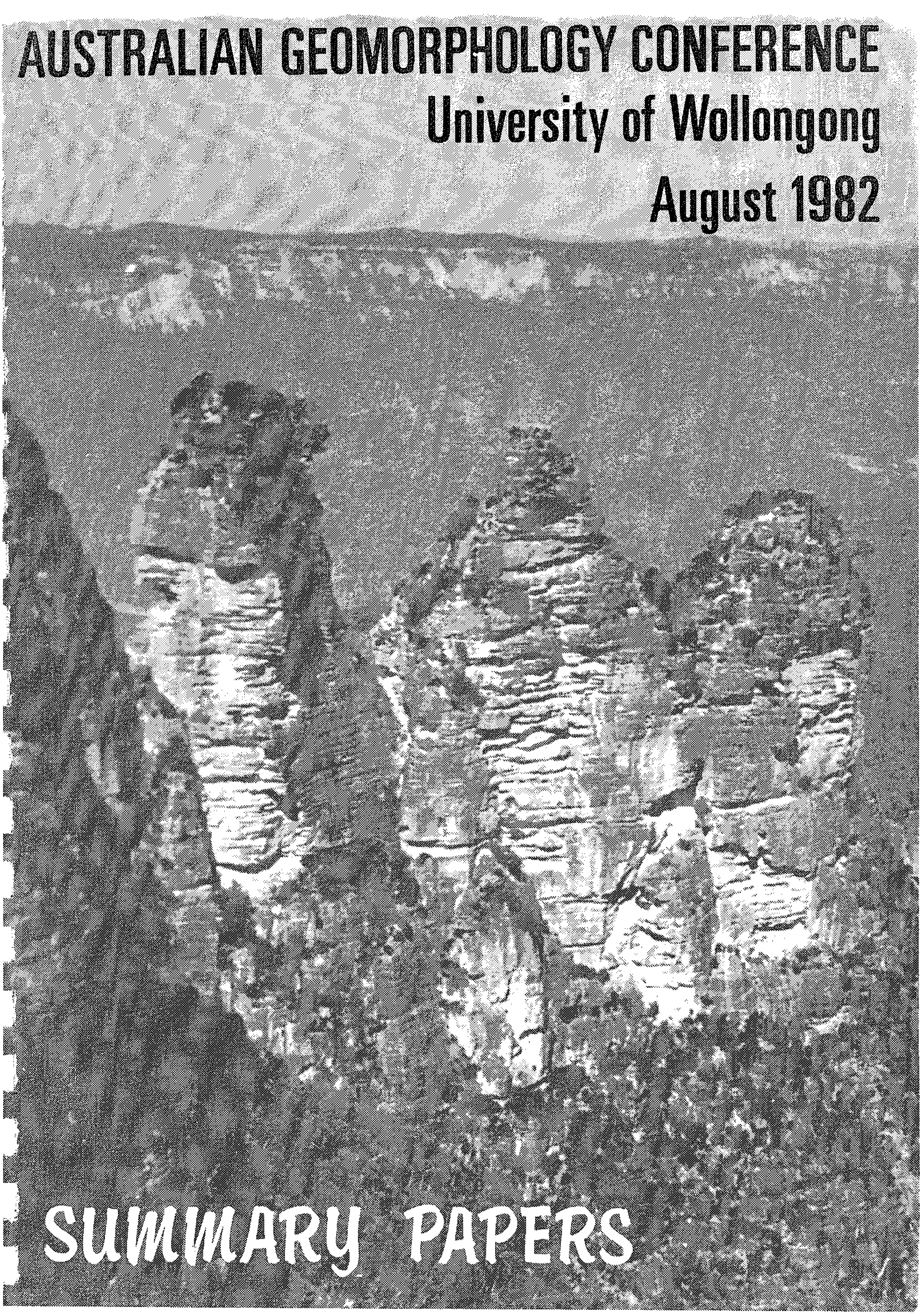

SUMMARY PAPERS

NOTICE TO READERS

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SANDSTONE SESSION

THE AGE OF FOLDING OF HAWKESBURY SANDSTONE ON THE LAPSTONE MONOCLINE, N.S.W. - A PALAEOMAGNETIC STUDY

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ABSTRACT

Palaeomagnetic data from haematite-rich beds within the Hawkesbury Sandstone on and about the monocline indicate that it formed before the oldest haematite was introduced to these beds. The age of this oldest haematite is 15±7 Ma. On the basis of these data, it can be concluded that the monocline is older than mid-Miocene.

INTRODUCTION

The Lapstone Monocline,a prominent fold in Hawkesbury Sandstone forming the eastern boundary of the Blue Mountains, was traditionally considered to have formed in the late Pliocene - early Pleistocene Koscuisko Uplift, and this interperetation is still occasionally quoted. Recently, there has been an increasing number of suggestions that the fold may be considerably older (Branagan 1975, Langford-Smith 1976, Smith 1979), such arguments being based on inferred links between the monocline (or the highlands which it borders) and other more or less "datable" features in the highlands. We present palaeomagnetic data from the fold itself in order to place constraints on the age of folding.

PRINCIPLES

The technique of palaeomagnetism relies on the capacity of certain types of iron-bearing minerals,such as haematite, to preserve ancient magnetic field directions, and affords a method of establishing the time of formation of such iron-bearing minerals. Haematite, a common iron mineral in surface outcrop of Hawkesbury Sandstone (Standard 1969), acquires a permanent chemical remanent magnetisation (CRM) consistent with the direction of the Earth's field, when a critical or minimum 'blocking' volume is reached (Haigh 1958). The age of the haematite is determined by comparison of the measured direction of magnetisation with the Australian Apparent Polar Wander Path (APWP).

This age can then be used to constrain the age of folding because if the haematite was introduced into the Hawkesbury Sandstone on the monocline after the folding, the preserved directions of magnetisation would be independent of the amount and direction of dip. In this case the age of the haematite would set a minimum age for the folding. However, if the introduction of the haematite preceded folding the preserved directions of magnetisation would be displaced (by an amount consistent with the dip and strike of the fold) from the directions preserved in horizontal rocks, and this would set an upper age limit to the time of folding.

SAMPLING AND LABORATORY METHODS: A portable drill was used to collect cores from the variously dipping haematite-rich sandstones at a number of sites on and near the monocline. At least 6 samples (cores) were drilled from each site, and 157 samples (cores) were drilled from 17 sites. Cores were 6 to 15cm long and were oriented using both sun and magnetic compasses. At least one specimen (2.2cm long) per core was thermally demagnetised through 8 to 14 steps from 200°C to 600°C.

ANALYSIS: Of the 17 sites sampled, four were eliminated from the subsequent statistical analysis because of very low intensities of magnetisation and/or very scattered directions of magnetisation. The remaining data were analysed using the procedures described by Kirschvink (1980) which are based on principle component analysis (PCA) and fit linear segments to the successive demagnetisation steps of each specimen. A linear or near-linear segment of the demagnetisation curve indicates that only one component of magnetisation has been removed during those demagnetisation steps which fall on the linear segment.

In virtually all specimens, the analysis yielded more than one linear segment, and in most cases the direction from the highest-temperature segment was selected for subsequent analysis. The high temperature, and most stable, directions were chosen because they probably most closely resemble the original CRM direction. As a result of the PCA, 16 specimens were eliminated from further analysis, either because they yielded scattered directions or because the PCA did not identify any linear segment. The remaining specimen directions and pole positions (118 specimens from 13 sites) were averaged by site (Fig. 1a). Figure 1b shows directions of magnetisation at each site after unfolding to the horizontal.

DISCUSSION AND CONCLUSION: The site mean field directions from the 13 sites have a clustered, elongate distribution (Fig. 1a) which becomes progressively more dispersed as the monocline is unfolded to the horizontal (Fig. 1b). This shows that the introduction of haematite into the sandstone post-dated the monocline formation and, therefore, the age of the haematite gives a minimum age for the monocline.

Normally, the mean directions of magnetisation from each site would be averaged to provide an overall mean direction of magnetisation of haematite on the monocline and the corresponding pole position would be compared with the Australian APWP to obtain an average age of formation of this haematite. Several aspects of the data indicate, however, that this procedure would probably result in a loss of information.

Five of the 13 sites contain both normal and reversed directions of magnetisation, both between and within specimens. The remaining 8 sites are each of single polarity, but 7 are normal and one reversed. The presence of reversals between sites, within sites and within specimens is strong evidence that deposition of haematite has continued for sufficient time to average secular variation in the earth's magnetic field and that the difference in mean directions of magnetisation at each site result from Australia's northward drift during haematite deposition in the Hawkesbury Sandstone. This interpretation is supported by several other lines of evidence.

i. All site pole positions (Fig. 2) are located between Australia and the present South Pole which would not be expected if secular variation had not been averaged; in fact, fewer than 10% of the specimen poles lie beyond the South Pole in the opposite hemisphere to Sydney.

ii. Using Watson and Irving's (1957) test, neither the specimen directions of magnetisation nor their corresponding poles are distributed according to Fisher's (1953) distribution ($p < 0.001$) as they would be expected to be if they were simply recording secular variation in the Earth's field.

iii. According to the F-test of McFadden and Lowes (1981), the pole positions of the various sites, which would be expected to be statistically identical if they resulted from secular variation associated with one relatively short period of haematite deposition, are not statistically identical ($0.01 < p < 0.025$).

iv. A second version of this F-test demonstrates that the poles lying at either end of the spread of site poles along the Australian APWP (Fig. 2) are significantly different ($p = 0.03$ and $p = 0.07$), as would be expected if they related to different events of haematite deposition.

We argue therefore, that the spread of site pole positions is the result of Australia's northward drift during deposition of the haematite. This age of the oldest haematite (rather than an average age) will therefore given a minimum age of the monocline.

The data from HS 46 (the "oldest" site with the greatest precision) indicate that haematite was crystallising in Hawkesbury Sandstone on the Lapstone Monocline about 15±7 million years ago (Fig. 2). We conclude that the age of the oldest haematite sampled on the monocline is Miocene (with the uncertainty of 7 million years) and that the monocline had formed by the mid-Miocene. The age of formation could, of course, be much older given the unknown time gap between monocline formation and the introduction of the haematite into the sandstone beds.

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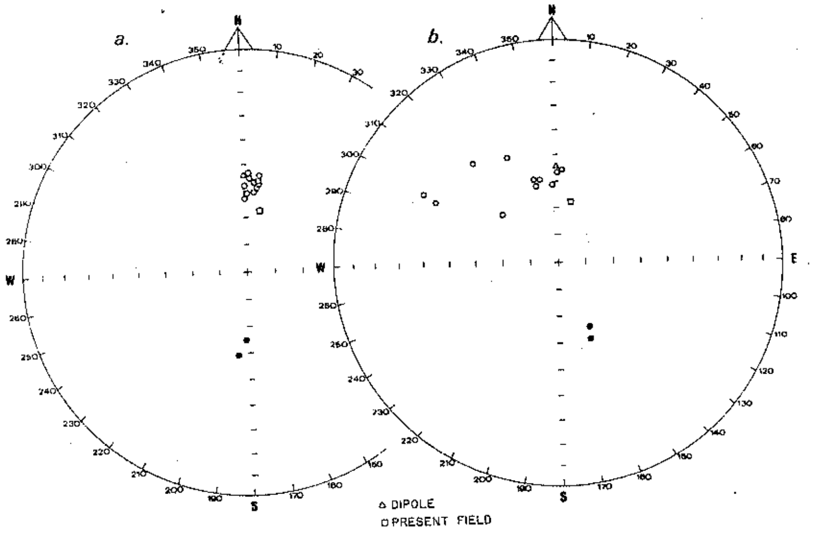
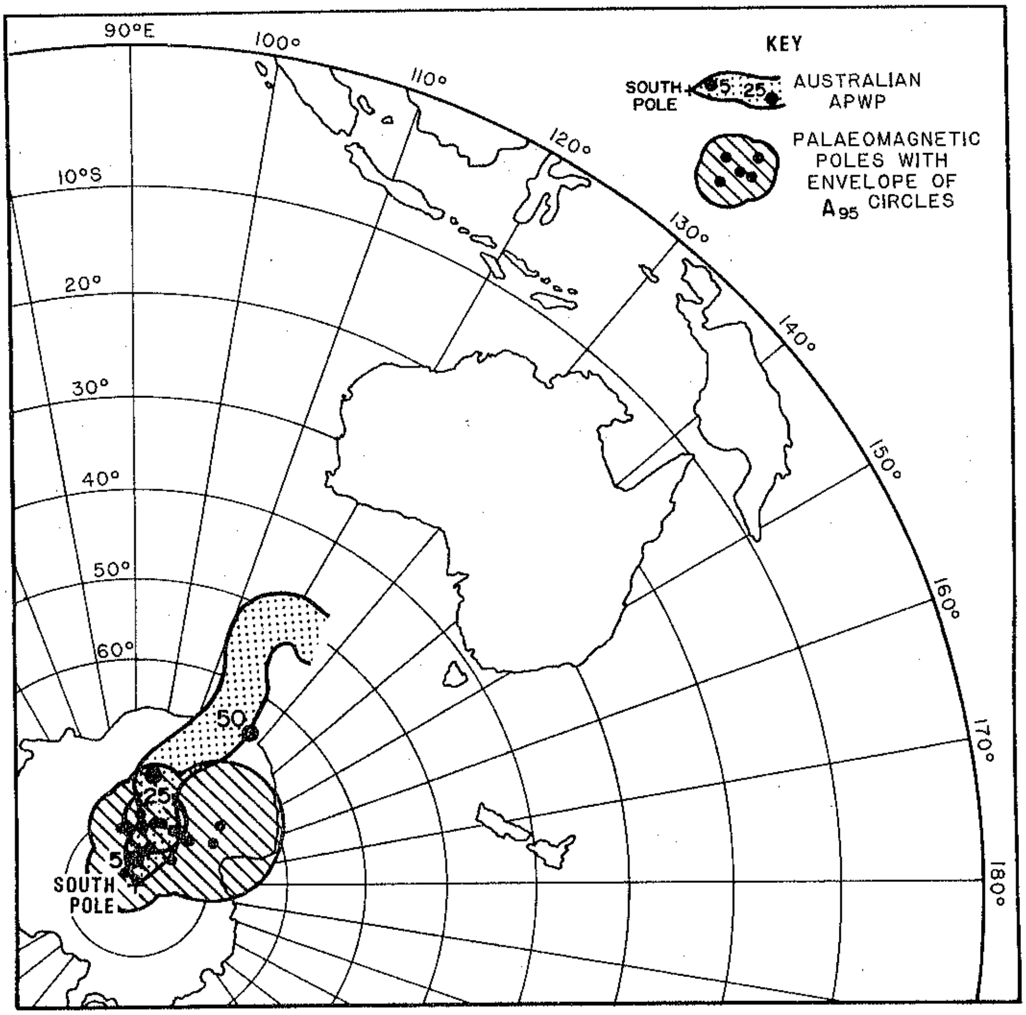
FIGURE CAPTIONS

Figure 1 Site mean cleaned directions of magnetisation from the Lapstone Monocline: (a) with folded beds in present attitude; (b) with beds unfolded to horizontal. Solid (open) symbols plot on lower (upper) hemisphere (equal area net). The dominant polarity is shown for sites with mixed polarity.

Figure 2 Apparent polar wander path for Australia from the late Mesozoic to the present, and site pole positions and envelopes of A_{95} circles from Hawkesbury Sandstone on the Lapstone Monocline. A_{95} circle for HS 46 is also shown.


a.
b.
N
S
W
E
△ DIPOLE
□ PRESENT FIELD


KEY
SOUTH POLE
5
25
AUSTRALIAN APWP
PALAEOMAGNETIC POLES WITH ENVELOPE OF A_{95} CIRCLES
90°E
100°
110°
120°
130°
140°
150°
160°
170°
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10°S
20°
30°
40°
50°
60°
50
25
5
SOUTH POLE

THE ORIGIN OF THIRLMERE LAKES, N.S.W.

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ABSTRACT

The origin of Thirlmere Lakes is related to warping of Sydney Basin sediments near Picton, N.S.W., which resulted in disruption of a formerly south-westerly flowing stream having its headwaters in what is now the Razorback Range. Knickpoint retreat along streams now flowing down the warped surface to the northeast is removing alluvium which accumulated as a result of the warping.

INTRODUCTION

Thirlmere Lakes are located in an incised sandstone valley 9.6 km southwest of Picton, N.S.W. (Fig.1). They comprise a string of freshwater lakes with swampy margins which intermittently drain to the west through Blue Gum Creek. To the north, alluvium along the valley of Cedar Creek suggests that the lakes may have been more extensive in the past. Previous work (Vorst, 1974) has shown that at least 50 metres of unconsolidated sediment underlies the lakes, its alternating organic and inorganic nature probably reflecting fluctuations between closed and open lacustrine conditions. The age of these sediments is unknown. An investigation of the origin of the lakes was undertaken, firstly, to provide some indication of the age of the sediments, and, secondly, to determine the significance of such an "anomalous" feature of the landscape to the geomorphic evolution of the Sydney area.

GEOLOGIC AND GEOMORPHIC SETTING

The geologic boundaries in Fig. 1 have been determined from extensive field mapping. The cross-section derived from them (Fig.2) indicates that the massive, quartz-rich Hawkesbury Sandstone outcrops in the south and southwest of the study area, and forms a ramp-like surface dipping below the predominantly shaly Wianamatta Group which forms the Razorback Range to the north and northeast. The ramp has a slope of 1 in 30 (approx. 2^0), and can be clearly seen when travelling north along the Thirlmere - Buxton Road.

Landforms and drainage patterns in the area reflect, in part, this geologic control. Streams to the west of Thirlmere Lakes are steeply incised and the terrain is rugged. On the ramp surface, however, slopes are long and smooth, and deep incision by streams such as Matthews Creek and Cedar Creek is confined to their lower reaches, where their profiles reflect the dip of the resistant sandstone strata (Fig.3). On the Wianamatta Group, a relatively smooth plateau surface is separated by a short but steep escarpment from the dissected terrain beyond (Fig.4). In the east, the plateau surface is confined to the summit of the Razorback Range, but it is more extensive in the west, around the upper reaches of Monkey Creek. In both cases, it is probably coincident with a more resistant bed in the Wianamatta Group, perhaps the Razorback Sandstone Member. Active scarp retreat is evidenced by extensive mass movement features which are found only on

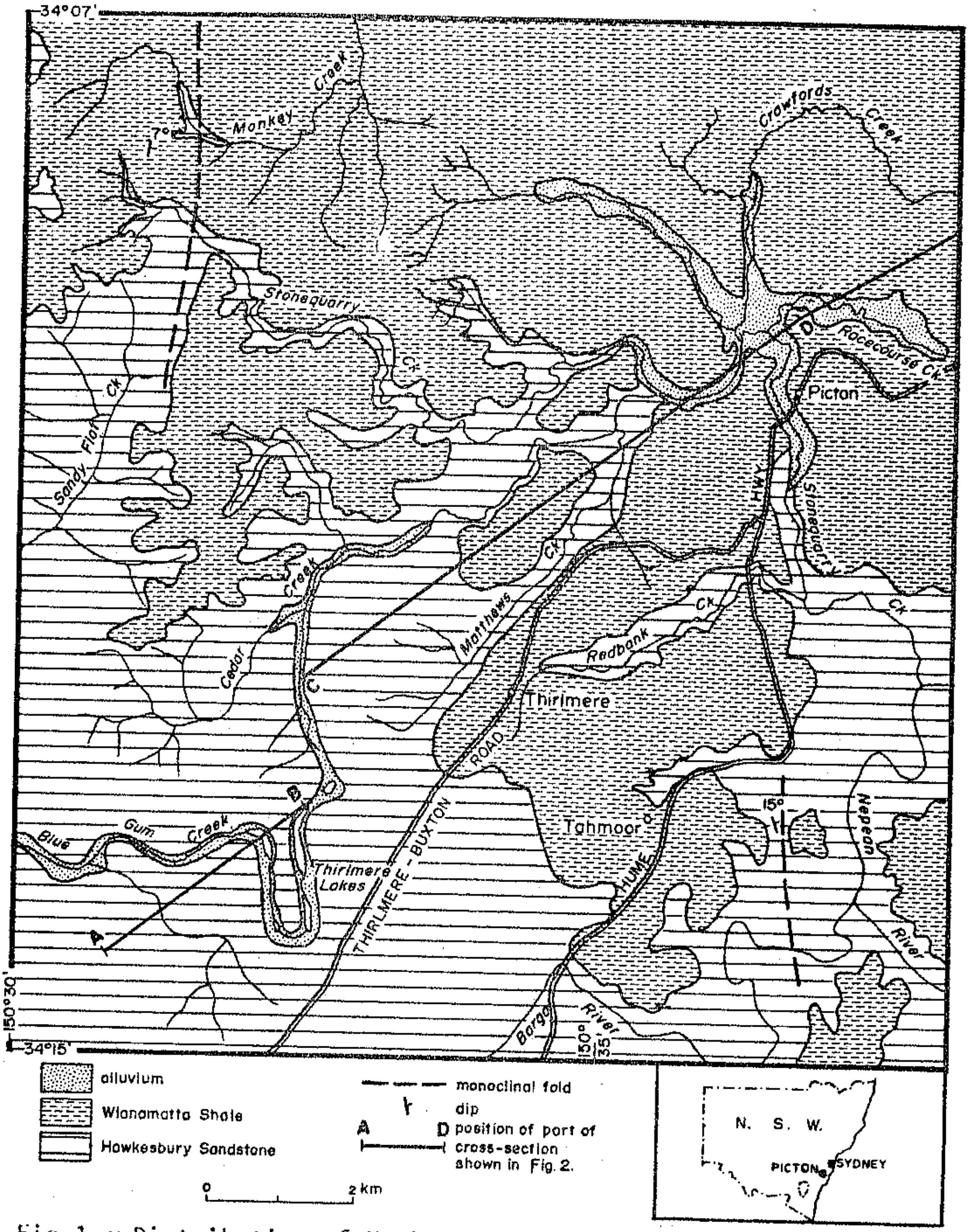

Fig.1 : Distribution of Hawkesbury Sandstone, Wianamatta Group and alluvium in the study area.

the shale slopes below the escarpment. Most of the streams in the area drain to the north, except for the tributaries of Stonequarry Creek, which drain south. This area of centripetal drainage is clearly seen in Fig. 4.

Two areas of alluvium occur in the study area (Fig.1). The Stonequarry Creek/Racecourse Creek alluvium is 12 metres deep in places and overlies weathered Wianamatta Shale (R.J.Blong, pers. comm.). The Thirlmere Lakes alluvium may be at least 50 metres deep and probably overlies Hawkesbury Sandstone (Vorst, 1974).

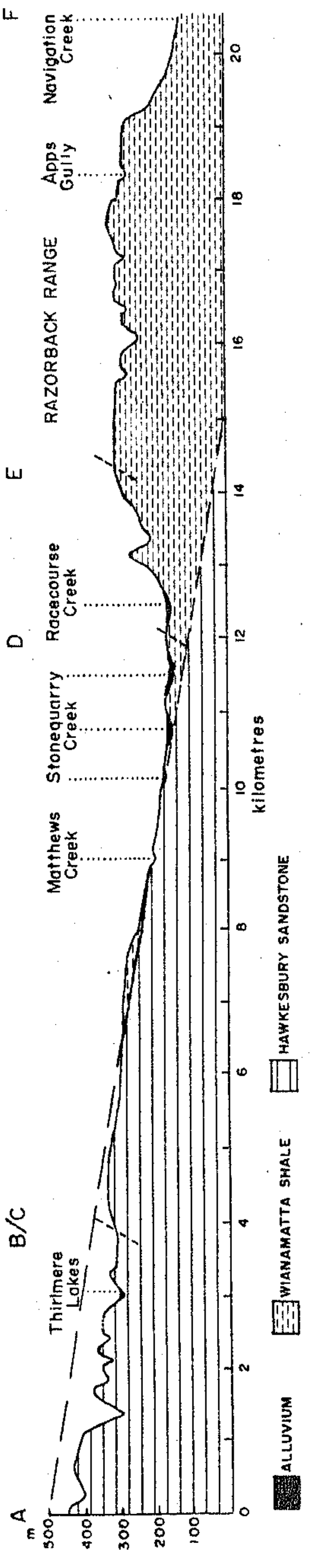

Fig.2 : Geological cross-section through study area (location shown on Figs. 1 and 4).

SIGNIFICANCE FOR THE ORIGIN OF THIRLMERE LAKES

The north-easterly dip of the Hawkesbury Sandstone in the study area may be caused by one of two factors. On the one hand, it may reflect the paleocurrent direction of the depositing streams. Alternatively, it may result from post-depositional warping, for which there is substantial evidence both within and outside the study area. It is this warping which is likely to have lead to the formation of Thirlmere Lakes.

Herbert (1976) notes that just prior to the onset of the Hawkesbury Depositional Episode in the Sydney Basin, tectonic tilting established a paleogradient to the northeast, confirmed by current directions measured by Standard (1964, in Herbert, 1976). Herbert (1976) later implies that the meandering streams which deposited the Wianamatta Group sediments had a different paleodrainage direction, originating in the northwest of the basin and flowing southeast. At the present time, however, beds within the Wianamatta Group also dip to the north and northeast, indicating that post-depositional alteration of the dip direction has taken place, most likely through warping which has affected both the Wianamatta Group and the Hawkesbury Sandstone beneath.

Tectonic alteration of the margin of the Sydney Basin is reflected in the presence of the Lapstone Monocline and associated faults forming the eastern margin of the Blue Mountains Plateau. Maps in both Packham (1969, p.371) and Herbert (1976, p.46) indicate that monoclinal folds also occur in the vicinity of Picton, curving around from northwest to southeast and forming the margin of the Illawarra Plateau extending southwards to the Shoalhaven River. The approximate location of one of these (the "Thirlmere Monocline" - Packham, 1969) is indicated in Fig. 4. Minor folds have also been observed in the field, to the southeast of Oakdale and to the east of Tahmoor (Fig.1). Thus it seems possible that tectonic downwarping of the sediments has taken place resulting in the subsidence of the Razorback Range area relative to the Thirlmere Lakes area.

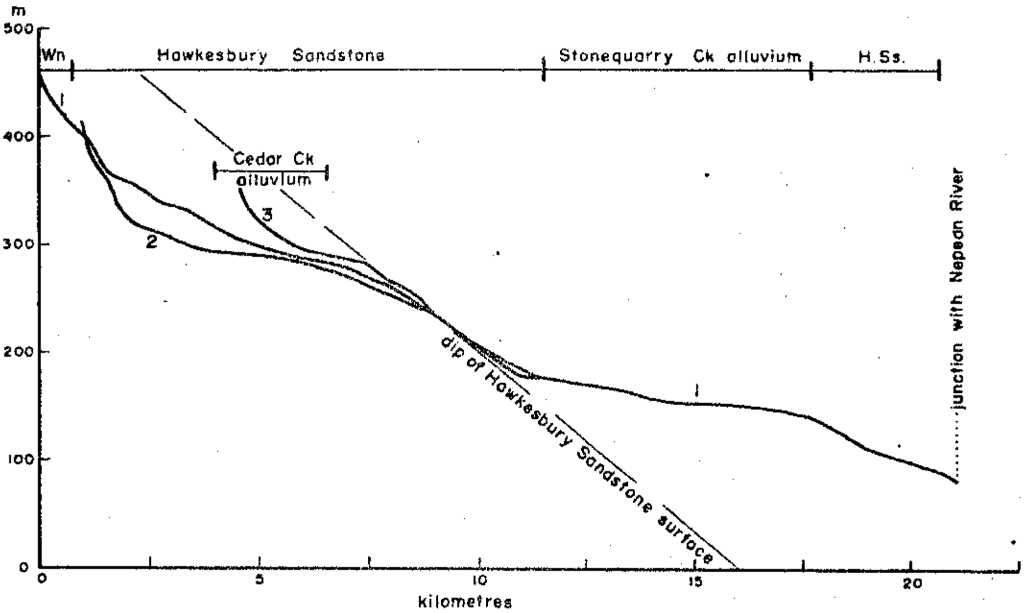

Fig.3 : Longitudinal profiles of streams draining sandstone ramp.
1 = Stonequarry Ck; 2 = Cedar Ck; 3 = Matthews Ck.

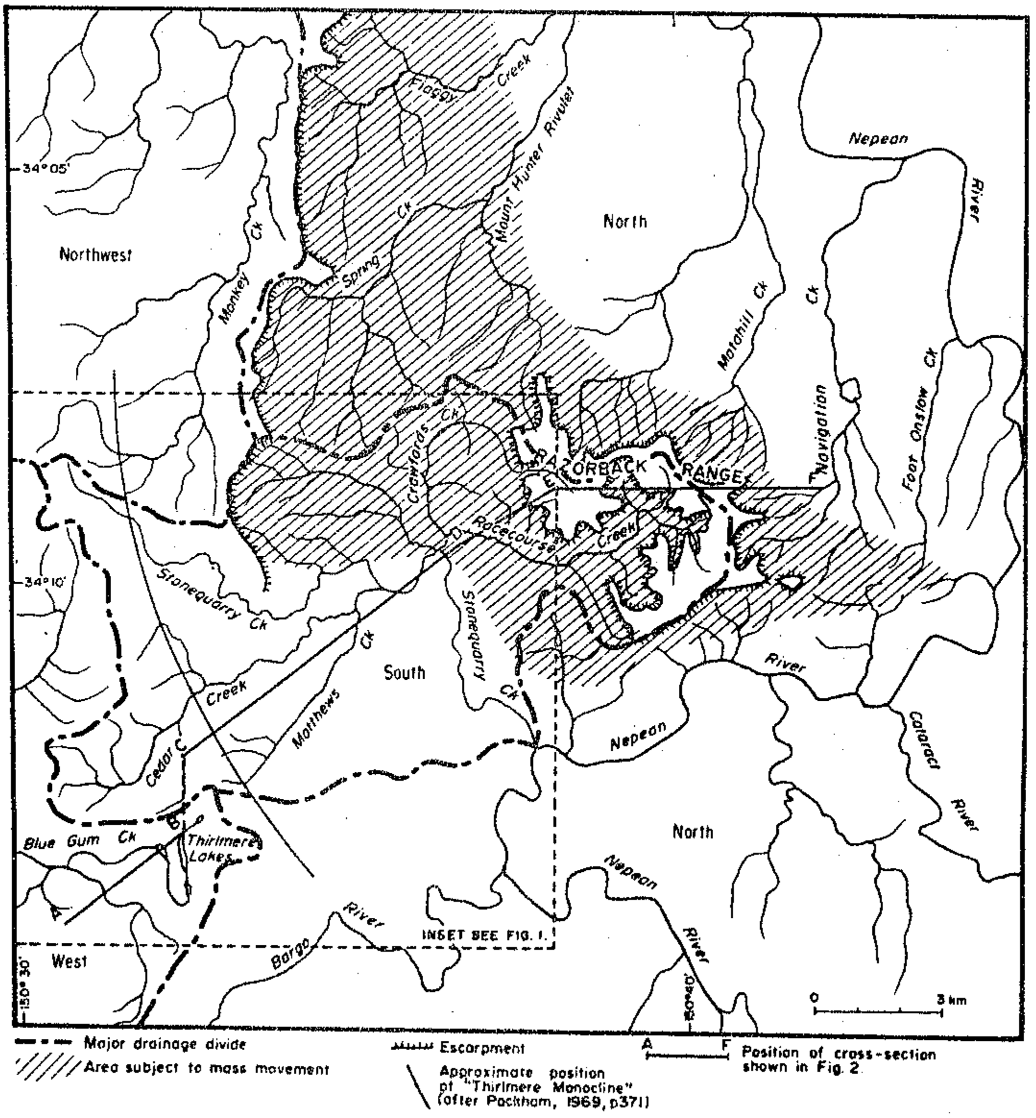

Fig.4 : Drainage patterns and landform features in the study area.

The effect of this warping was to truncate the drainage originally flowing southwest, through the valley now occupied by Thirlmere Lakes. This is reflected in both the anomalous drainage direction of the northern tributaries of Stonequarry Creek, i.e. Racecourse and Crawfords Creeks, and in the accumulation of alluvium at the point where the Hawkesbury Sandstone surface dips down below the shale (Fig.2). Thus the Racecourse Creek alluvium occupies a position in the landscape similar to that of a fault angle lake, although no faulting is involved here. The streams have merely aggraded their valleys as their headwaters slowly subsided.

Thirlmere Lakes, and the alluviated valley to the north and west of them, occupy a position on the axis of the warp (Ollier, 1978), with the accumulation of sediments and formation of the lakes occurring as the former stream course gradually became elevated above its original catchment. Evidence for the former westerly flow direction is given by the elevation of the bedrock valley beneath the sediments. Hawkesbury Sandstone outcrops at 285 m a.s.l. at Chiddy's Bridge in Cedar Creek to the north, and at less than 266 m a.s.l. in Blue Gum Creek to the west of Thirlmere Lakes (Vorst, 1974), therefore giving the bedrock base a slope to the west. Subsequent incision and knickpoint retreat has eliminated any evidence of the former valley floor to the north beyond Chiddy's Bridge, and new drainage has been established on the sloping ramp. Incision into the Racecourse Creek alluvium probably occurred as a result of scarp retreat initiated to the east of the present Razorback Range with subsequent lowering of base level and the retreat of a knickpoint along Stonequarry Creek (Fig.3). Now that streams like the Nepean River are cutting down into the resistant sandstone, knickpoint retreat may proceed more slowly than in the past, when they flowed through shale.

AGE OF THE SEDIMENTS

If, as is hypothesised above, sediments began accumulating in the Thirlmere Lakes valley as a result of downwarping to the northeast, then the age of the sediments may be given by the approximate time at which warping commenced. There is no reason to assume that such warping did not occur at the same time as that leading to the formation of the Lapstone Monocline. Recent work by Bishop, Hunt and Schmidt (1982) on the paleomagnetism of iron within the Hawkesbury Sandstone on and around the monocline suggests that it may be at least 15 million years old. Therefore, the oldest sediments in the Thirlmere Lakes valley may be of similar age.

ACKNOWLEDGEMENTS

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TESSELATED SANDSTONE PAVEMENTS OF THE FOURTH KIND: A SPECIAL CASE OF A GENERAL PHENOMENON

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Tesselated sandstone pavements formed as a result of the presence of several well-developed joint sets are relatively common and easily explained.

In such cases the surface usually remains relatively flat, although iron-enrichment or leaching may occur along the joints, causing them to be either locally raised above the surface, or to be planes of erosion.

The surface is usually divided into squares or rectangles, less commonly into triangles and other shapes depending on the number and orientation of the joint sets. As the rock is planed off the surface still shows the pattern.

A second type, which is less common, but also understandable, is the result of drying during exposure at the time of formation of shallow-water fine-grained deposits. The surface forms a characteristic mud-crack pattern, often polygonal, and the individual "plates" tend to be concave upwards. Such patterns are essentially episodic in their formation, and although they may be repeated during the erosion of a rock mass there will not be continuous exposure.

A third type which may be developed is a series of uniform polygons. On examination such a surface is found to be an erosional plane cutting through a series of essentially vertical polygonal columns. These columns are formed as a result of contact metamorphism.

A fourth type, which I have briefly described earlier (Branagan 1969, 1973), is also occasionally developed but its mode of formation is somewhat more problematical.

It consists dominantly of polygonal plates each of which is essentially convex upwards. The plate size varies, apparently relative to grainsize, but there is occasionally also some control of the overall pattern by master joints, and the surfaces (as distinct from individual plates) may be flat, convex or concave upwards.

When well-developed these pavements have an appearance of continuity with depth and individual surfaces could be confused with the third type mentioned above. However examination in detail of a large variety of these surfaces shows that they are essentially limited in depth.

In the Sydney region these surfaces are particularly well-developed on the sandstone plateaux to the north, south and west of the metropolis, both in Hawkesbury Sandstone and some of the finer-grained Permian sandstones.

They are also present in Permian Sandstones near Hobart, are beautifully displayed in the Ronchard Gorge area near Fontainbleau, France, and have been described by Netoff (1971) from near Boulder, Colorado.

From the apparent sporadic nature of the occurrences and the few papers highlighting their appearance it might be concluded that the phenomenon is relatively rare. This is probably true in one sense - that perfectly developed examples occur infrequently. My observations suggest that such examples are but special cases of an extremely common phenomenon.

Cracking is very common on both natural and man-made surfaces and is developed on surfaces with virtually any orientations. Such cracking is a result of differential movement between the near surface portion of the material and the main mass beneath the surface. The movements are periodically expansive and contractive, and, depending on the consistency of the material, and any natural weakness already present, will tend to fail about equally spaced centres, failure planes will be established normal to lines joining the spaced centres, and a polygonal pattern will be developed.

The regularity of the pattern in rocks will be a function of the uniformity of the material, grainsize and history of weathering of the rock surface. The last matter may be most significant, particularly for the pavements found in the Sydney area. There is some evidence that the relatively long period of cool conditions in the Pleistocene may have been most influential.

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SANDSTONE PSEUDOKARST OR KARST

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ABSTRACT

Similarities to karst are found in siliceous cemented quartz sandstone and related rocks, especially in tropical parts of Gondwana continents. Overseas and Australian evidence for this is outlined and the conclusion reached that silica solution at normal temperatures and pH is the critical process, making karst the appropriate designation rather than pseudokarst.

INTRODUCTION

Discussion of the pseudokarst or karst aspect of sandstone landscapes is appropriate at this first Australian symposium on these terrains since it is in the Gondwanaland continents that this has been found most explicitly. Uncertainty as to whether it is a matter of pseudokarst or karst is only partly a terminological matter : it arises also because of our present uncertainty about the operative processes.

Some authorities have delimited karst lithologically, in fact to carbonate rocks because it is best developed in limestone and dolomite. Others, myself included, have regarded this as arbitrary and define karst in terms of the process, solution, which is thought to be crucial in the development of the landforms and drainage characteristic of karst. Pseudokarst then comes to mean country with resemblances to karst, which are due to other processes.

Even this may be inadequate because the word 'solution' when applied to carbonate rocks truly means carbonation as a general rule though not always. Therefore it has been argued by some that it is legitimate to extend it to include also hydrolysis and hydration thought responsible for such features as runnels in granite (Silikatkarren). There is an important geomorphological difference, however, in that carbonation of carbonate rocks leaves little residue behind whereas the chemical attack of water on silicate rocks produces large volumes of residue which can inhibit the development of underground circulation and caves. Nevertheless it is process which should govern our application of these terms.

What provoked my own interest in this aspect of sandstone geomorphologyis in itself revealing. In 1963 E.S. Hills published in his Principles of Structural Geology a striking oblique air photo of what he described as limestone towerkarst in Northern Territory. Eventually I identified its location as the Ruined City of South-eastern Arnhem Land, which Dunn (1963) had more recently found to consist, not of limestone, but of siliceous cemented quartz sandstone. In 1965 a brief first visit to northern Arnhem Land unveiled to me unexpected likenesses between its sandstone plateaus, in parts chopped up by meshes of corridors and canyons, in parts reduced to towers jumping out of plains, and the Limestone Ranges of West Kimberley. There were thus plenty of grounds for Hills' misapprehension whilst on a wartime RAAF intelligence flight.

OVERSEAS EVIDENCE

Mainguet (1972) presented magnificent illustrations of similar relief in African quartz sandstones where caves were described early this century (e.g. Hubert 1920) and later by well known French karst scientists such as Gèze, Paloc and Renault. Mainguet describes field of towers, closed depressions, and arrangements of springs and streamsinks in successive storeys in the landscape. She argues for substantial underground conduits as part of the drainage and for some gorges to be due to cave collapse.

Even more startling have been recent accounts from Gondwana parts of S. America. Earlier White et al. (1966) had discussed minor solution sculpture of quartzite in Venezuela but the Venezuelans themselves (e.g. Sczerban et al. 1977) have dealt with much larger karstlike features in quartzites and metamorphosed siltstones in the Lower Proterozoic Roraima Group. Access is difficult and ground information still limited. A few examples will make the point nevertheless:

(1) The Cueva del Cerro Autana is an inactive cave labyrinth 650 m up the 800 m cliffs of a large mesa. 400 m of passage include tubes 20 m in diameter.

(2) The Sausarinami Simas are three collapse dolines in a 700 km^2 mesa 1500 m high. They are vertically walled holes, 150 to 400 m wide and deep. There are also internal drainage basins up to 10 km^2 on the mesa.

(3) The caves and dolines of the Meseta de Guaiquinima relate to an active underground river which links stream sinks, caves in collapse dolines and big springs, with a straightline distance from sinking to rising of nearly 2 km.

Similar features have been found over the border in the contiguous Guyana plateau and also across the Amazon lowland in Gondwana Brazil. It is possible that the 'furnas' of Parana State, collapse dolines with deep lakes in them, that have previously been regarded as due to solution in limestone underlying the sandstone in which they are found, may also be due to cave formation and roof collapse entirely within the sandstone.

AUSTRALIAN EVIDENCE

Despite that suggestion, I am not inclined to revise my own interpretation of the Braidwood Big Hole in the upper Shoalhaven valley, 114 m deep in Devonian quartz sandstone and conglomerate, as other than due to collapse into a cave in underlying Silurian limestone. There is evidence from this country, however, to set beside that from overseas for intrinsic karstlike forms in quartz sandstone. Thus the minor solution forms in quartzite from Venezuela are matched in the well known Wonderland in the Grampians of western Victoria.

In various parts of Northern Territory and adjacent Queensland there is to be found Mainguet's 'ruiniform' relief in Upper Proterozoic quartz sandstone, nowhere better displayed than in the Ruined City (Jennings 1979a), despite a local relief no more than 50 m. The lower part of the Bessie Creek Formation is thick bedded and cut up by corridors and platea (Brook & Ford 1978) aligned with ESE and SE joints. The floors are flat and the walls vertical, but with basal weathering caves. These lower beds also break up into a few, bulky towers. The upper part of the formation is thin bedded, with much cross-bedding, and is also affected by additional NE and N joint sets. So it is cut up into innumerable aretes, turrets and spires. There are also many weathering caves, especially in the middle of this part, breaching aretes and towers. The weathering caves show the usual signs of the combination of case hardening and interior leaching of cement. Surface hardening occurs on cave interiors as well as the exterior surfaces, with repetition of hardening, breaching, evacuation and resealing. However, these weathering caves are simply exaggerated tafoni and so not distinctively karstic.

Although aboriginal guides talked of deeply penetrating large caves here, we were shown none nor allowed to search ourselves. Also only small springs were still running in the dry, issuing from but slightly opened joints and bedding planes. However, there were many small tubes of elliptical or circular cross-section, with stained or eroded tracks of wet season outflow. One closed depression, about 50 m long, 20 m across and 10 m deep, was encountered, which implies underground drainage. More probably are present. Wet season drainage can be inferred therefore to have a significant underground component, not of Darcy Law flow, but of conduit type of secondary permeability.

Yulirienji Cave south of the Roper River is the kind of cave which I was unable to search for in the Ruined City (Jennings 1979b). It is a rounded tunnel through Hodgson Sandstone, another Upper Proterozoic quartz sandstone, the remnant of a former river cave. Also White (1967) describes two active stream caves in similar lithology in northern Arnhem Land, one with a perennial stream, the other with a wet season one only.

Grey (1841) described river caves, streamsinks and corresponding risings in his exploration of north Kimberley, which have never been sought out since. How worthwhile that could be has been shown by the location recently by R. Munster of what he has named Whale Mouth Cave near the head of Turkey Creek in East Kimberley. In May of this year our party failed to complete either exploration or survey but we know it to be about 140 m in depth and about 300 m in length. A river, big in the wet if small in the dry, runs through it in a series of falls, rapids and plunge pools. The exit gapes to the tune of about 50 m height and 30 m width in the sandstone cliff. The inflow doline, about 50 m across and 15 m deep on its lowest side, interrupts a surface valley, which now hangs high and dry above the trunk stream that breaches the sandstone cliff in a gorge with falls in it.

It would be misleading not to mention similar features in extratropical Australia. The Natural Tunnel at Hilltop, N.S.W., is an active, 85 m long stream through cave and there is a similar one along Cowan Creek in Kuring-gai Chase closer to Sydney about 60 m long (Pavey 1974). Endless Cave, Kincumber near Gosford, N.S.W., is 35 m long and an intermittently active outflow cave fed from small solution tubes. All these are in Triassic Hawkesbury Sandstone. Archaeologically famous Kenniff Cave in Jurassic sandstone in the Carnarvon Range in Queensland is more than a weathering cave according to Joyce (Mulvaney and Joyce 1965), who considers it has been eroded headwards by water coming from pipes in joint planes.

DISCUSSION

The difficulty with these karstlike features in quartz sandstone is that at normal temperatures and pH quartz reaches saturation equilibrium at about 5 ppm, a low figure.

With minor solution features on the surface, the answers appear ready to hand. In solution pans, in the tropics and subtropics especially, the pH of stagnant water can exceed 9.0 fairly frequently and the saturation equilibrium rises markedly. However, this does not help with open features with free water flow such as the flutes and runnels found in Permian sandstone in the northern Budawangs, N.S.W., and the grikes of the Wonderland of the Victorian Grampians. White et al. (1966) provided an explanation for their Venezuelan occurrences; they found the surface quartz had been partially converted to amorphous silica by atmospheric weathering and this has a solubility a magnitude greater than that of quartz.

However, caves, and so the larger closed depressions dependent on them for evacuation, cannot be explained thus. It is true that once a throughway for turbulent water has been created mechanical fluvial actions so evident in Whale Mouth Cave, for example, can readily enlarge it. But how is that throughway to be provided? The Venezuelans have offered two explanations, one of which does not seem to be of general applicability. This latter depends on hydrothermal alteration at a prior stage removing the siliceous cement and leaving rotten rock which is later removed by meteoric waters. It is relevant that M. Muir (pers. comm.) reports a Northern Territory drillhole penetrating Lower Proterozoic quartz sandstone some 400 m without encountering solid rock. This would however be attributed to ancient deep weathering rather than to hydrothermal waters. However Whale Mouth Cave is carved through quartz sandstone which gives every field sign of being strong rock (thin section study should be completed before the conference).

The initial stages of the development of underground circulation in quartz sandstone are preferably explained by solution at normal temperature and pH. This would appear to require much time (Mainguet 1972) and the Venezuelans initially explained their large caves in this rock type in terms of high temperatures, high rainfall, dense rainforest and prolonged tectonic stability. Douglas (1969) showed how the silica load of rivers depends on runoff and so on rainfall in part. His figures can be analysed further to indicate that there is also a temperature control in that average loads of tropical and extratropical rivers differ significantly. However the loads of tropical rivers are still low. Does time then provide the answer? The denudation chronologies of the areas concerned in Africa, S. America and Australia are so poorly known as yet that a positive answer seems premature.

However, if solution without leaving much residue or residue which is difficult to move in developing cavities (Jennings 1979a) is the critical process in originating underground drainage in sandstone, one must conclude with White et al. (1966) that it is sandstone karst, not pseudokarst, that is under scrutiny.

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ROTATIONAL AND BLOCK GLIDE FAILURES IN SANDSTONES OF THE SOUTHERN PART OF THE SYDNEY BASIN

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Abstract

There is much field evidence in the southern Sydney Basin of mass failure triggered by processes other than undercutting along claystone beds. Two types of failure are discussed here:

a) rotational movement caused by the foot of sandstone slabs moving forward over weathered silty beds;

b) sliding of vertical columns of sandstone over failure planes within, or cut across, siltstones.

Field evidence from this area is compared to analyses of similar failures in open-cut mines, but the mechanics of the block glides remain obscure.

Introduction

The occurrence in areas of coal mining of the major contemporary mass failures in Sydney Basin sandstones emphasises the need for an understanding of the processes operating on, and the stability characteristics of, the main clifflines in the region. Yet, while the influence of sandstones on sub-surface mine failures has received considerable attention, little has been written on cliffline failures of the region. And what has been written emphasises the role of slab and toppling failure triggered by undercutting along claystone beds, and, in a few instances, by stress release caused by unloading. However, at least in the southern part of the Basin, rotational and block glide failures also are important. Evidence from several field sites is briefly outlined here.

Stratigraphy and Rock Properties

The geology and geomorphology of the region has been described in detail elsewhere (e.g. Herbert and Helby, 1980; Young, 1977). In short, the landscape is dominated by two major plateau surfaces bounded by prominent clifflines; the upper one lies on the Hawkesbury Sandstone, and the lower one on the Nowra Sandstone. Regional dips on these sandstones are only a few degrees. Although extensive engineering works have been carried out in the region, little geotechnical information is available for these sandstones or the siltstones interbedded with, or occurring under them. Geotechnical data from further north in the Basin are summarised in Figure 1.

Characteristics of Failures

1. Nowra Animal Park.

This site is on the north side of the Shoalhaven River west of Nowra, where the 20 m Nowra Sandstone cliffline comes almost to the river bank. Only a thin layer of Wandrawandian Siltstone lies above river level and it is almost completely mantled by sandstone blocks. At times of lower sea level, however, extensive outcrops of siltstone would have been exposed on the walls of the valley. Sandstone blocks of up to 6000 m^3 have moved from the cliffline here. A count of 20 blocks with a minimum size of 30 m^3 showed that only half dip away from the cliff and could be attributed to undercutting or toppling failure. The remainder dip backwards into the cliff, and clearly have failed in a rotational movement caused by a forward movement of the toe of the blocks. The rotational movement is superbly illustrated at the "Cathedral Cave", where the base of a block about 20 m high has moved some 15 m outwards; the upper portion of this block leans against the cliff, forming a triangular "cave" 30 m long, 8 m high and with a maximum width of 6.5 m. The primary mode of failure seems to be rotational, and this in turn seems to trigger secondary toppling of smaller blocks.

2. Chimney Stack Pinnacle.

This very extensive area of block debris extends for some 500 m below Nowra Sandstone cliffs near Yalwal (Yalwal 31680 sheet: 425 874). Much of the valley wall below the cliff is cut in Wandrawandian Siltstone. In a count of 25 blocks with a minimum size comparable to those at Nowra, only 5 dipped outwards away from the cliffs, though many smaller blocks have toppled down steep slopes beyond the main blockfield. Two facts are noteworthy. Firstly, the largest blocks form a discontinuous outer rampart of sandstone towers which, in places, is almost 100 m from the main cliffline. Secondly, the dips on the main blocks of the rampart range only from 2° to 0°. The crest of the rampart lies some 4°, or 4 to 6 m, below the top of the cliffline. The main blocks have travelled outwards in a gliding motion without any appreciable tilting. However smaller blocks have toppled backwards from the towers and others have toppled from them down the steep slopes of the valley.

3. Flat Rock - Long Reach

Sequential stages in block gliding can be seen along cliffs on the southern side of the Shoalhaven River. At Long Reach (Berry 25000 sheet: 745 395) crevasses from a few centimetres to 2 m wide, and up to 12.5 m deep, zig-zag from joint set to another. The initial movement is virtually horizontal, for projecting plates on the outer block lie at the same height as recesses from which they came on the inner side. On cliffs west of Flat Rock Creek (Nowra 25000sheet: 776 375) crevasses 6 to 8 m wide and up to 10 m deep have opened. While some blocks here have been displaced about 2 m vertically, others are at the same elevation as the cliffs from which they have moved. Again, dips on many blocks are only a few degrees, though horizontal rotation has opened secondary crevasses normal to the cliff face.

4. 12 Apostles Spur

Blocks along the cliffs near Nowra can glide only a few tens of metres before toppling down steep slopes. But at 12 Apostles Spur on the western side of Bundundah Creek (Yalwal: 305 846) vertical towers comparable in size to those near Chimney Stack lie up to 180 m from the adjacent cliffline. These Nowra Sandstone towers have moved across a gently sloping surface which has maximum inclinations of between 7° and 10°, though the top of one tower half way across the slope seems to be at the same elevation as the top of the cliffs. The origin of the gentle slope is not clear, but it is not the product of retrogressive retreat of the cliffs from a previous position marked by the outer towers, for there is no apparent mechanism by which the debris from such a retreat could be moved from behind the Towers.

5. Other Sites

These are only a few examples of a widespread phenomenon. Similar failures in the Hawkesbury Sandstone can be seen on the eastern side of the Fitzroy Falls and near Manning's Lookout in the headwater tracts of the Kangaroo River drainage system.

Failure Mechanisms

Two types of failures involving forward movement of the toe of sandstone blocks, rather than undercutting and toppling of them, are widespread in the southern parts of the Sydney Basin.

1. Blocks may fail with a backwards rotation as the toe ploughs forward over siltstones; these movements appear to trigger secondary toppling of smaller blocks.
2. Failure may also take place as a series of vertical columns glide away from clifflines. These movements are sometimes accompanied by the toppling or collapsing of blocks.

The simple geometry of most of the block fields indicates that failure has occurred as simple linear sliding, though in some cases bi-linear sliding on a secondary failure plane may have occurred (cf. Richards et al., 1981).

The great size of the sliding blocks, together with the low angles of slopes down which they have moved, pose difficulties in deciphering the mechanisms of failure.

Movement occurs when

$$\gamma = \mu \sigma$$

(γ is shear stress; μ is a friction factor; σ is stress normal to the sliding plane).

(a) As $\sigma = W \cos \alpha$

with $\alpha = 4°$, for a 2280 m^3 tower at Chimney Stack

$\sigma =$ 5230 tonnes (approximately) on 130 m^2.

Because the failure lies within a few hundred metres of the divide, and as the site seems well-drained, it is unlikely that σ could be reduced sufficiently by porewater pressure.

(b) It is also unlikely that μ could be reduced to a critical value by simple weathering of the siltstone. For weathered shales and siltstones in the Sydney Basin typically Plastic Index is <10. Comparison with failures in the Goonyella open cut (Richards *et al.*, 1981) and bedding plane properties in the Pelton Colliery (Jaggar, 1978) suggests that sufficiently low frictional resistance would only occur in thin clay bands. I have as yet seen no evidence of such bands at the sites reported here.

(c) A substantial increase in γ triggered, say, by earthquake shock cannot be ruled out. However earthquakes with intensities of at least 10 on the Modified Mercalli Scale would presumably be required, and that would presume a level of seismic activity far greater than that of the present-day. Yet, as A. Young (1977) has demonstrated, Late Tertiary - Early Pleistocene mass failure on the Illawarra Escarpment was of far greater magnitude than the largest present-day failures.

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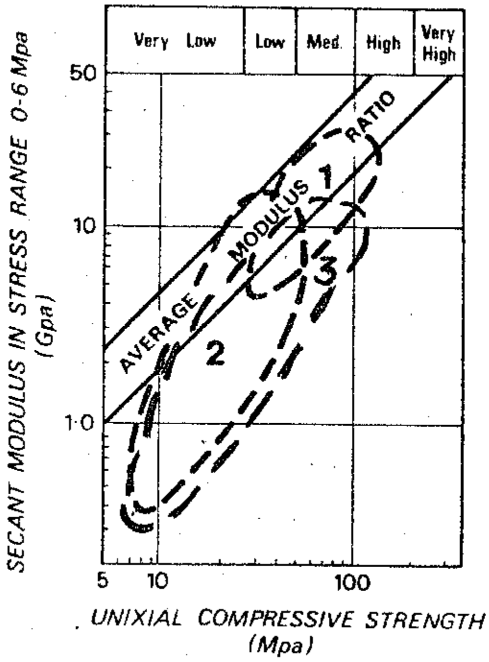

Fig. 1 Selected strength characteristics

1. Coal Measure Sandstones
2. Hawkesbury Sandstone
3. Claystones and shales (Coal Measure)

Some Processes on hillslopes in the Sydney Basin

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Abstract

Field experiments on sandstone hillslopes in the Sydney Basin have supported the hypotheses that bioturbation in the form of surface mounding by various fauna types are together with rainsplash and slopewash very important soil movement processes. The partly complimentary processes of rock burial and rock exposure are also significant whereas the status of soil creep remains uncertain. Additional data from outside the Sydney Basin support these contentions.

From within and outside the Sydney Basin on soils derived from sandstones and granites the rates of surface mounding by fauna vary from about 10^2 to 10^4 g/m²/yr, combined rainsplash and slopewash 10^0 to 10^3g/m²/yr, rock burial, rock exposure and rock creep 10^2 to 10^5mm/1000yrs and soil creep mostly $<10^1$cm³/cm/yr.

Introduction

In a previous paper (Bishop et al 1980, p156; and partly summarised by Mitchell et. al., this conference) it was stated that any acceptance of the hypothesis proposed to explain the genesis of Duplex soils on hillslopes raises two important questions. What are the surface movement processes involved? and does this model of genesis have a wider application than just the Sydney Basin?"

This paper will consider the former question.

Processes observed in the field

Field examination of numerous sandstone hillslope sites have revealed that processes such as rainsplash, slopewash and bioturbation are extremely active. Field evidence for these processes can be seen in sand grains adhering to bark and leaves commonly up to 25cm above ground level but frequently exceeding 50cm, pillars or pedestals of soil capped by gravel, twigs and leaves, lobate micro-topography giving rise to small terraces, ant mounds and earthworm casts etc. Many of these processes and resulting features (micro-landforms) can be observed forming during rainstorm events especially on surfaces with little protective vegetation cover such as in areas recently burnt, whilst active bioturbation can be observed daily.

Whilst the above are perhaps the most commonly observed soil movement processes operating there are others involving surface material which are less obvious either because they are uncommon or because their effects are not readily apparent. Such processes include for example rockfall, gullying of talus slopes (Wasson & Blong unpublished), the flaking and pitting of sandstone during fire (Selkirk & Adamson, 1981) treefall, direct burrowing of sandstone by fauna, wind erosion and the alteration of sandstone to yield sands, silts and clays. In some cases combinations of many of these processes can produce distinct micro land form features such as small caverns in cliff faces (Johnson, 1974). Yet again other processes may occur. For example, even though no field evidence for soil creep has been found it is possible that this and or other mass movement events may occur. The existence, for example, of apparent concentrations of quartz pebbles and bands of sandstone cobbles in large, deep; quartz sand sheets in "Depositional Sites" which when mapped out have the appearance of alluvial fans may be the result of former mass movement such as erosion by gullying in the source area (sandstone hillslopes) and deposition below nick points via debris flows.

Comparison of some processes

The next stage of this study has been an attempt to more closely identify and quantify some of these processes and their role in soil formation.

As rainsplash, slopewash and bioturbation are visually the more important processes our efforts have focussed on demonstrating their efficacy. Other processes have also been examined and of these soil creep deserves additional comment. Soil creep as it is currently understood (or misunderstood) has retained a special attraction to many slope process and landform studies in the geomorphic literature and yet the overwhelming implication of such studies eg Young (1960) & Williams (1973) is that the slowness of this process, if indeed it exists, is such that the techniques used to measure it are not sufficiently accurate to elucidate it. Nevertheless because of this historical emphasis and the increasing uncertainty of its importance some measurements on creep have been included.

One additional point needs to be made. Our experience both within and outside the Sydney Basin suggests that at many sites more than one 'significant' process is operating and as a consequence it was considered necessary to examine more than one process at any site some of which may play complimentary and/or opposing roles.

Basic results are presented here (Table 1a) along with other studies for comparison, in particular those of Williams (1968, 1972, 1973 and 1974).

Because of the complexities of these processes and the difficulties in obtaining meaningful results it is necessary to make an assessment of their reliability. Firstly rainsplash and slopewash are considered together primarily because they are difficult, in a practical sense to separate. Secondly the rainsplash and slopewash data from Cattai, Cordeaux, Brocks Ck. and Shoalhaven are from open trays with uncontrolled catchments and thus for these sites the results presented are most probably considerable underestimates. Furthermore, important factors such as slope length, slope angle and vegetation cover very considerably both inter- and intra- site whilst additional factors such as rainfall erosivity and soil erodibility are probably important inter-site variables (Table 1b). This data is of low to moderate reliability.

Soil creep measurements were all made from young-pits (Young, 1960). Again there are important site variables (Table 1b) which add to the difficulty in interpretation; the data is of unknown reliability. Rock burial, rock creep and rock exposure are fairly straight forward measures. The former is an estimate of burial by soil material and the later the opposite, both of which used tiles set out in transects whereas rock creep ie downslope movement of surface clasts was measured from painted stones (Williams 1974); during the periods of measurement they are probably fairly reliable results. The measurements of bioturbation used here refer to the amount of material brought to and/or accumulated at the surface and as such is referred to as the 'rate of surface mounding by fauna'. These were estimated by various methods (see for example Williams, 1968a and Humphreys, 1981) and the reliability varies. On the whole however they are probably as good as or better than the reliability of the rainsplash and slopewash data.

Despite all of these problems the information tabled here is the best available. Nevertheless, because of the variations in the reliability of the results it is considered that meaningful discussion can only be made at an order-of-magnitude level.

By converting rates of rainsplash and slopewash to units used in creep Williams (1973) showed that the combined rainsplash and slopewash was between five and seven times more important as an erosion process than soil creep for soils on both sandstone and granite in two very different environments. In contrast the average rates of soil creep at both Cattai and Cordeaux are negative ie movement is uplsope. Some, but not all, of these results can be explained in terms of experimental design problems whilst others may record actual upslope movement for example disturbance due to root growth and other biological activity. The data could probably be best regarded as indicating zero creep as the process is currently understood. All that can be claimed at present is that soil creep mostly amounting to $<10^1 cm^3/cm/yr$ is a difficult process to measure whereas in comparison rainsplash and slopewash amounting 10^0 to $10^3 g/m^2/yr$ are readily observable and measureable.

Of the other processes measured the rates of surface mounding of 10^2 to $10^4 g/m^2/yr$ by various fauna types (ants, earthworms, termites, echidnas and lyrebirds) are of the same or a higher order of magnitude than the combined rainsplash and slopewash. The quantities of material brought to and/or accumulated at the surface are impressive. Likewise the rates of rock creep, rock burial and rock exposure amounting to 10^2 to $10^5 mm/1000$ yrs.

Discussion

The field observations which led to the hypothesis that rainsplash, slopewash and bioturbation are some of the most important processes operating in topsoils on hillslopes in the Sydney Basin have been supported by field experiments. Because of problems in measurement the role of soil creep remains uncertain except that it appears much less important than bioturbation and/or combined rainsplash and slopewash.

The processes of rock burial, rock exposure partly complementing both rainsplash, slopewash and surface mounding, are important also. The apparently greater importance of rainsplash and slopewash to soil creep was shown for sites outside the Sydney Basin by Williams (eg 1973) and our current investigation both within and outside the Sydney Basin lend support to this with the additional rider that bioturbation in the form of surface mounding is just as important.

To continue this approach future work will need to assess the importance of these processes to (i) both transportation and the concentration of coarse textured materials, and (ii) the rates of supply of material from altered sandstone to the mobile topsoil.

Preliminary results in the Sydney Basin so far show that many processes are involved in the liberation of quartz sand from both exposed and buried sandstones including for example biological activity, whilst the main agents for downslope transport would seem to be rainsplash and slopewash with bioturbation performing a role in preparing material for downslope movement.

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TABLE 1a RATES OF VARIOUS PROCESSES OPERATING ON HILLSLOPES WITHIN AND OUTSIDE THE SYDNEY BASIN ON SANDSTONE AND GRANITE

Lithology		Location	Soils (sub-division of Northcote)	Rainsplash and slope wash (g/m²/yr)	Soil Creep (cm³/cm/yr)	Rock burial or creep exposure (mm/yr)	Surface mounding by fauna (g/m²/yr)	Reference
Sydney Basin	Narrabeen Group	Blackheath	Uc	71 maximum	-	-	Lyrebirds 4470	this paper
		Cattai	Dy	3.6 (1.62 to 7.83)	- 1.14 (-10.76 to + 13.04)	0.24 (rock burial)	Ants 545	this paper
			Uc	25.2				
	Hawkesbury Sandstone	Cordeaux	Uc	32.03 (4.4 to 68.0)	- 5.18 - 8.50 to - 1.66)	0.34 (rock burial)	Ants 841 Earthworms 133	Humphreys (1981) and this paper
		Deep Ck.	Dy	520 (250 to 820)	-	-	-	Blong et al. (1982)
		Oxford Falls	Dy	-	-	0.57 maximum (rock exposure)	-	this paper
Other Sandstone		Brocks Ck. N.T.	D	approx. 67 [55.8cm³/m²/yr (19 to 101)]	4.39 (0.49 to 14.25)	10 to 30 (rock creep)	-	Williams (1973, 1974)
		Shoalhaven N.S.W.	Uc and Gn	approx. 123 [102.8cm³/m²/yr (12.4 to 308.4)]	3.25 (0 to 8.57)	-	-	Williams (1972, 1973)
GRANITE		Brocks Ck. N.T.	Gn Dr	approx. 106 [53.6cm³/m²/yr (12 to 169)]	7.33 (1.18 to 16.15)	-	Termites 115 to 470	Williams (1968, 1973) Lee & Woods, 1971 (for additional termite data)
		Killonbutta N.S.W.	Dy Uc	41.6	-	-	Echidnas 117 Ants 35.5 Earthworms 7.1	this paper
		Shoalhaven N.S.W.	Gn to Dy	approx. 71 [53.7cm³/m²/yr (1.6 to 290.6)]	1.90 (0 to 7.92)	-	-	Williams 1972, 1973

TABLE 1b ADDITIONAL DATA ON METHODS AND SITE CHARACTERISTICS

LOCATION	METHODS AND SITE CHARACTERISTICS	REFERENCE
CORDEAUX	Slope wash measured from 4 plots of various size, slope length 62 to 100m, Slope up to 5°, period of measurement 2.7 yrs., Creep measured from 2 pits with 2 sets of experiments in each Rock burial measured from 2 rows of tiles over 2.7 yrs. Ant mounding from 20, 5 x $1m^2$ plots & earthworms from 20, 1 x $0.25m^2$ plots over 1 yr.	Humphreys (1981) and this paper
CATTAI	Slope wash measured from 6 plots of various size, slope length 10 to 38m, Slopes 2.5 to 9°, period of measurement 2.7 yrs., Creep measured from 3 pits with 2-3 sets of experiment in each Rock burial measured from 4 rows of tiles over 2.7 yrs. Ant mounding from limited small plot & large survey data.	this paper
DEEP CK.	Slope wash measured from 3 plots, $8m^2$ each, slope length 4m, slope 12°, Period of measurement 1 yr immediately following bushfire, ground cover increased 20-55%.	Blong et al (1982)
OXFORD FALLS	Monitoring of micro topography over 2.2 yrs after fire. Rock burial from 8 rows of tiles. Slopes 4 to 8°.	this paper
BLACKHEATH	Slope wash from 8 plots of various sizes, Lyrebird activity by observation & direct measurement over 2 yrs. Slopes 0 to 30°	this paper
SHOALHAVEN (sandstone)	Slope wash measured from 20 plots of various size, slope length 18 to 290m, Slope 2°45' to 25°, period of measurement 2 yrs, vegetation cover 5 to 90%. Creep measured from 13 pits on slopes from 3°30' to 12°40', over 2 yr period	Williams (1972, 1973)
BROCKS CK. (sandstone)	Slope wash measured from 9 plots of various size, slope length 27 to 121m. Slopes 0 to 15°05', period of measurement 2.4 yrs, vegetation cover sparse to moderate. Creep measured from 12 pits on slopes from 0°25' to 14°20', over 2.4 yr period. Rock Creep measured from 24 rows of clasts, hillslopes 5 to 20°; over 2 yrs.	Williams (1973, 1973)
KILLONBUTTA (granite)	Slope wash from 6 plots of various size. Faunal activity from 12, 5 x 2m plots, slopes 1 to 6° measured over 2.3 years.	this paper
SHOALHAVEN (granite)	Slope wash measured from 15 plots of various size, slope length 25 to 226m. Slopes 2° to 14°20', period of measurement 2 yrs, vegetation cover 5 to 99%. Creep measured from 15 pits on slopes 2°30' to 21°05', over 2 yr period	Williams (1972, 1973)
BROCKS CK. (Granite)	Slope wash measured from 13 plots of various plot, slope length 60 to 291m, Slopes 1 to 3° period of measurement 2.4 yrs, vegetation cover sparse to moderate. Creep measured from 15 pits on slopes 1 to 3°, over 2.4 yr period. Termites.	Williams (1968, 1973) Lee & Woods (1971)

SOME HYDROLOGICAL CHARACTERISTICS OF THE SANDSTONE PLATEAU AREAS NEAR BARREN GROUNDS, N.S.W.

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INTRODUCTION

Sedge/heathlands are a distinct vegetation feature on the Hawkesbury Sandstone plateau surface above the Illawarra escarpment. Young (1980) has described the controls, characteristics and distribution of such features in the Cordeaux and Cataract catchments and used the term 'dells' for their description. In general they are treeless and developed in unchannelised, organic sand, valley-fill sediment that is waterlogged for prolonged periods.

Young (1980) found that the proportion of the catchments occupied by dells is relatively small (Cateract 10.3%, Cordeaux 2.9%). We have observed over several years that these types of landscapes supply a sustained flow of high quality water. Thus, although the sedge/heathlands only occupy relatively small proportions of the catchments, their dense vegetation and location in plateau drainage lines of low gredient ensures an almost perfect sediment trap efficiency, at least in their undisturbed state.

The distribution of vegetation communities within these sandstone plateau surfaces appears to be predominantly controlled by site specific hydrological regimes and we are therefore attempting to establish the determinants and characteristics of these regimes.

Physical features of the study area.

Two contiguous but contrasting catchments (each approximately 1 km^2) located above the northern escarpment of Brogers Creek in the Kangaroo Valley have been the subject of an hydrological study since January, 1979 (for location see Fig.1). The distribution of three distinct natural vegetation communities has been established from air-photo interpretation and field mapping (see Fig.1). The two catchments were chosen originally in anticipation of marked differences in their hydrological characteristics, particularly due to differences in their topography and vegetation.

Community I is a closed heathland of shrubs and ferns located along permanently waterlogged drainage lines. The soils are relatively deep, highly organic, silty loams or silty clays. Although the valley surface is generally unchannelised, a chain of deep, elongated pools created by bedrock controls tends to occur in the lowermost sections of the valley.

Community II is a closed to open heath/sedgeland of low shrubs and sedges that experiences spatially and temporally variable waterlogging. Soil depth is spatially variable depending upon weathering in the underlying sandstone beds but a general stepping of the bedrock occurs and this is sometimes reflected in the ground surface microrelief and occasional bedrock outcrop. A general downslope decrease in particle size and increase in organic matter is reflected in field textures varying from loamy sands to organic silty loams. Impermeable bedrock control on the elevation of the watertable in this community causes the watertable to remain near to the ground surface in areas of shallow soils.

Community III is a woodland/open forest that on hilltops has a low sand heath understorey developed on generally shallow, bleached sandy lithosols with occasional iron-indurated, weathered sandstone outcrop or heavier textured (possibly duplex) soils with iron-indurated platy gravel in stone lines. In valley bottom sites (particularly in Waterfall Catchment) community III is more commonly on open forest with tall understorey developed on generally deep, well-drained sandy soils but with occasional benches of sandstone outcrop. A small area of a fourth community (Community IV) has been mapped at the western end of Stockyard Catchment where the forest on the kraznozemic soils of the Budderoo Lamprophyre has been cleared and improved pastures established.

The areas and proportions of each of these communities in the two catchments are shown in Table 1.

TABLE 1. AREAS AND PROPORTIONS OF VEGETATION COMMUNITIES IN STOCKYARD AND WATERFALL CATCHMENTS

Vegetation Community and Type	Stockyard Catchment		Waterfall Catchment	
	Area (m^2)	Proportion (%)	Area (m^2)	Proportion (%)
I - Closed heathland	131,506	13	39,666	6
II - Open-closed heath/sedgeland	329,472	33	211,980	30
III - Woodland/ open forest	501,601	51	456,971	64
IV - Improved pasture	25,842	3	-	-
TOTAL	988,421	100	708,617	100

From Table 1, a relatively larger proportion of Waterfall Catchment is occupied by Community III and as can be seen in Fig.1, a significant proportion of this is in valley bottom sites. Only one small valley bottom site is occupied by Community III in Stockyard Catchment and there is a correspondingly larger proportion of Communities I and II, particularly along the valley axis.

Experimental

A continuous record of discharge from each of Waterfall and Stockyard Catchments has been obtained since January, 1979 using F-type Leupold-Stevens stage height recorders on 1:5 USDA broad-crest weirs. The measured stage height/discharge rating relationship of these weirs has so far been established as within 5% of the theoretical rating.

A central climate base station has been established where meteorological elements of wind (run and direction), temperature (wet and dry bulb at screen height) and rainfall are continuously monitored. Fortnightly measurements of maximum and minimum temperature (at screen height) and of total rainfall across the catchments are also obtained (for rain gauge locations see Fig.1). Evaporation is obtained fortnightly from class A pans located at the base station and at Waterfall weir. The base station pan is fitted with an overflow storage so that a continuous estimate of evaporation can be obtained, even through protracted rainfall periods. Any missing values of evaporation in either pan over the fortnightly periods have been estimated by correlation between the pans and by correlation between the base station pan and that read daily at Cataract Dam.

A small (approx. 5 ha) catchment has recently been established near the base climate station with the installation of a USDA HS Flume and Leupold-Stevens F-type stage height recorder to estimate discharge. Detailed topography, soils and vegetation of the catchment are being mapped and measurement of evapotranspiration using a series of weighing microlysimeter and of fluctuations in the water-table elevation is now in progress.

Experimental results

The network of fortnightly-read storage rain gauges have shown no long-term systematic regional trend in rainfall across the catchments. Any differences in any period of measurement appears to depend upon the particular characteristics of any rainfall event. Therefore, the amount of rainfall in each catchment has been computed by a simple mean of the raingauges in each catchment but using the central base station in the computation for both catchments. For the period 29/9/79 to 11/6/82 the rainfall thus computed for Waterfall Catchment was 4452 mm and for Stockyard Catchment, 4410 mm.

For the same period (29/9/79 to 11/6/82) the total runoff estimated from catchment discharge and area measurements was 2827 mm and 2360 mm for Waterfall and Stockyard Catchments, respectively. Thus 64% of rainfall is discharged as runoff from Waterfall Catchment while 54% is discharged from Stockyard Catchment. Waterfall Catchment has a tendency to a more peaked discharge but even in complex runoff events there is a close time coincidence in the peaks of discharge in both Catchments.

Pan evaporation for the period 29/9/79 to 11/6/82 was markedly different between the two sites being 3418 mm and 2311 mm for the base climate station and Waterfall weir sites respectively. We believe that the degree of exposure at the base climate station site tends to overestimate potential evaporation for the catchments as a whole while the protection afforded by the weir site in the valley underestimates potential evaporation. In the absence of more precise estimates we assume that a mean of the two pan values is reasonable for estimating potential evaporation.

A model for the prediction of water yield in Stockyard Catchment

We tentatively propose a simple generalized model for the prediction of water yield in this type of soil/vegetation landscape and will apply it to Stockyard Catchment. We realise that our model lacks the sophistication of others, such as that used by Aston and Dunin (1980), but believe it is appropriate for the particular catchment, the fortnightly rainfall and pan evaporation data available and the purpose concerned.

We believe that the vegetation communities we have mapped represent a range of distinct hydrological regimes and therefore any model should explicitly depict the expansion/contraction of saturated areas that we have observed. It has been observed that after a protracted dry period, fortnightly rainfall in excess of 100 mm is sufficient to saturate all areas of Stockyard Catchment except in the woodland/open forest areas occupied by Community III.

Thus the catchment is seen to consist of three basic parts: (1) a permanent lowland wet area, where water is freely available at all times to satisfy evapotranspiration at the potential rate, i.e. potential evapotranspiration, (2) a permanent upland dry area, where saturated conditions at the surface are intermittant and generally short lived after heavy rainfall, and where evapotranspiration can be expected to fall below the potential rates with the depletion of water held in the root zone, (3) an intermediate area, which has essentially the characteristics of (1) following heavy rainfall, and of (2) during drier periods.

To accommodate the concept of an expanding and contracting saturated area, a system for variable weighting of the measured rainfall and pan evaporation is incorporated into the model. The value of the weighting factor assigned to the wet area when fully contracted is taken to be 0.13, this being the relative area of Community I. This weighting is increased to a maximum of 0.46 with very wet conditions, the value then being based upon the combined relative areas of Communities I and II. Therefore the basal weighting given to the dry area (Community III and II) varies between a maximum of 0.87 and a minimum of 0.54.

Various indicators might be used to specify the weightings to be applied over any given fortnightly period, but we consider that such an index necessarily must make reference to both the prior wetness and current rainfall conditions. A wetness index (W.I.) tentatively adopted for setting the magnitude of the weighting factors is defined as the ratio of the sum of estimated water held in storage at the end of the prior period and one-half of the current period's rainfall, divided by the specified maximum storage, which we take as 100 mm. Zero storage capacity is specified for the wet area because potential runoff is assumed to be generated there at any time when current rainfall exceeds the potential evapotranspiration, which we take to be 0.8 times the measured pan evaporation for the fortnightly period.

From general observation, it is taken that a set wetness index maximum value of 2.5 corresponds to maximal expansion of the wet area. The general relationship for quantifying this weighting factor between limits of 0.13 and 0.46 is thus taken to be $F_1 = (0.4 \times W.I.) + 0.13$. The weighting factor for the dry area (F_2) is then given as $F_2 = 1.0 - F_1$.

Actual evapotranspiration for the wet area is assumed to be at the potential rate at all times. For the dry area, actual evapotranspiration is taken to be equal to the potential rate if estimated water held in storage at the end of the prior period exceeds one-half of the specified storage capacity (i.e. 0.5 x 100 = 50 mm), and is considered to decline linearly with reduction in water held in storage below that level, becoming zero if all water in storage is depleted.

For the wet area, a weighted potential runoff is generated within any fortnightly period with weighted rainfall in excess of the weighted potential evapotranspiration (F_1 x 0.8 x pan evap.). For the dry area, a weighted potential runoff occurs only after water held in storage reaches the specified capacity of 100 mm. In any fortnightly period when the weighted potential evapotranspiration for the wet area is not satisfied by its weighted rainfall, a transfer of water from the storage of the dry area is assumed to make good the current evapotranspiration requirements of the wet area.

The weighted potential runoffs of the two areas are combined to give an estimate of total potential runoff for the catchment. This estimate is taken to represent water that becomes available for discharge to streamflow in the current and subsequent periods. The actual temporal distribution of this quantity is assumed to be expressed as the product of an assigned recession coefficient and the sum of the current period's potential runoff together with any carry-over from previous periods. Although doubtlessly an over-simplification of the recessional behaviour of streamflow in this catchment, this is considered an adequate basis for temporally distributing the generated potential runoff from this model which uses fortnightly data inputs.

Although conceptually simple, the model has been found to give generally good estimates of water yield from Stockyard Catchment over fortnightly periods. Over the long period between 29/9/79 and 11/6/82 the model gives an estimated total runoff of 2420 mm compared with 2360 mm of measured runoff at the stream gauging station for Stockyard Catchment. Good agreement between estimated and observed runoff for larger fortnightly amounts (>100 mm) is especially encouraging. For measured runoff amounts of less than 60 mm, there is an apparent tendency for overestimation, and the reasons for this are being investigated.

As previously noted, the model is considered tentative and is obviously particularly deficient in its temporal resolution. No attempt to improve the model will be made until more detailed and more relevant data are available to assess the characteristic expansion/contraction of the saturated area within such hydrologic systems.

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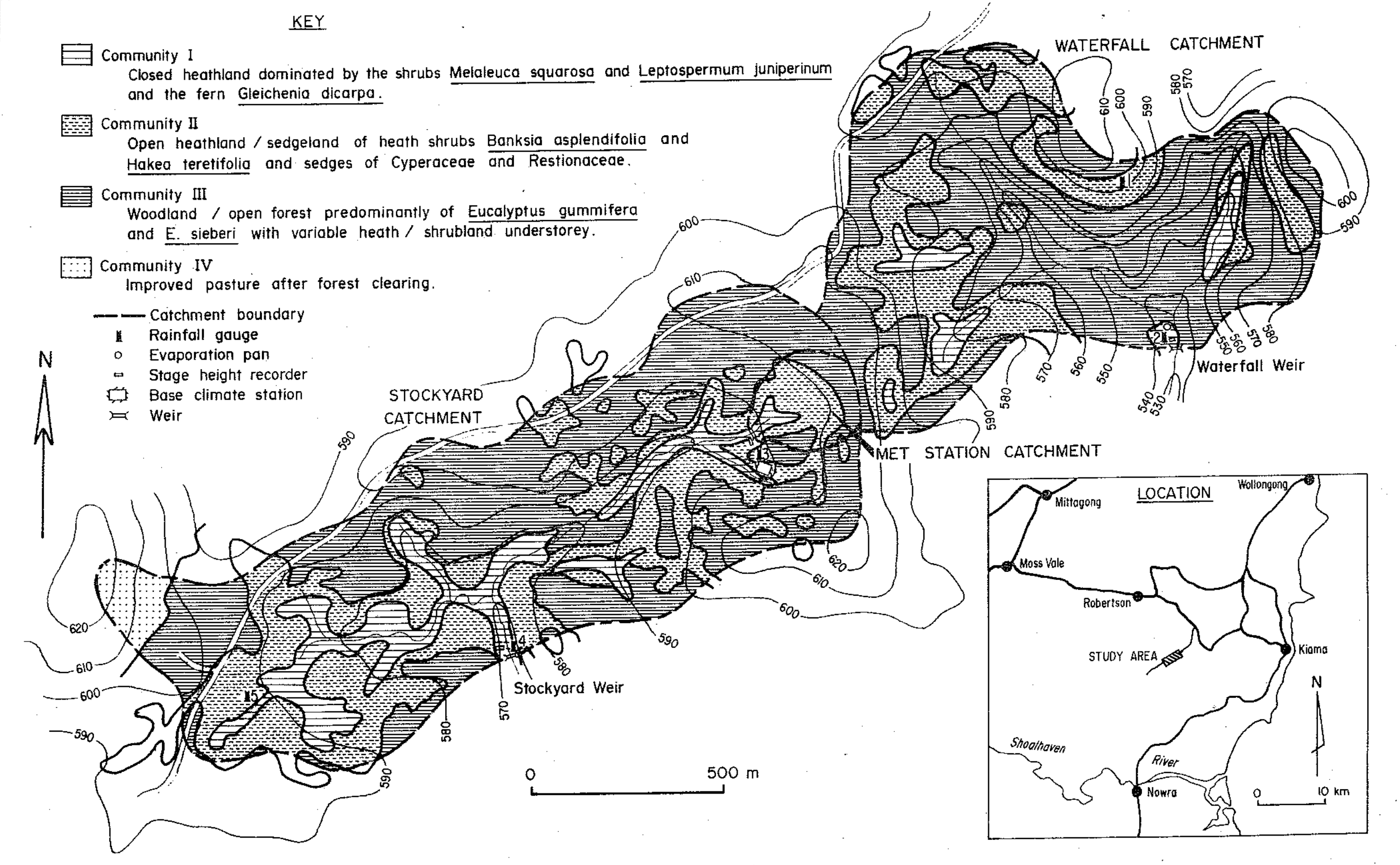

Fig. I Vegetation Communities in the Budderoo Catchments Study Area.

PATTERNED GROUND ON THE UPLAND SWAMPS IN THE ILLAWARRA.

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> It is known that in the huge expanses of mire in the forest zone of Europe, Siberia, the Far East and North America, there are vast territories occupied by mire microtopes with a strip-ridge type of plant cover ... The wide expanse of such complexes over the earth's surface and within every large mire system entitles one to think that it is probably the most stable form of plant cover under mire conditions, and ensures the best conditions for the adaptation of plants to changes in hydrological conditions.
>
> Ivanov, 1981, p.199.

A strip-ridge microtope similar to that described by Ivanov characterises the upland swamps on the sandstone plateaux south of Sydney. These upland swamps do not spread over vast expanses, as do the mires of the Boreal zone, but lie within broad shallow small valleys on the plateau surfaces. They occupy less than 10% of the catchment areas of the Cataract, Cordeaux and Avon Rivers, and very rarely overlap even low watersheds between low-order tributaries. Nevertheless they form a distinct ecosystem (or Biogeocenose) within the more widespread and familiar sclerophyll forest that characterises the plateau. Their vegetation is sedgeland-wet heath, closely akin to the button-grass moorlands of Tasmania, and their soils are typically peaty podzols (Stace et al., 1968).

The Form of the Patterned Ground.

The pattern is composed of ridges and furrows which approximately parallel the slope contours. Its amplitude is usually 10-30 cm, rarely more than 50 cm. Both ridges and furrows are 30-250 cm wide, with the furrows often being a little wider than the intervening ridges. The ridges extend across the slope for up to 10 m before fusing to create elongated lenticular furrows. On the ridges, vegetation grows densely. Graminoid species such as *Gymnoschoenus sphaerocephalus*, *Lepidosperma longitudinale* and *Xanthorrea* spp. dominate, but some shrubs such as *Banksia robur* and *Hakea teretifolia* are scattered along the ridges. The furrows, in contrast, are sparsely vegetated. More than 50% of the furrow floor may be bare. The sedge, *Chorizandra sphaerocephala*, and aquatic plants such as *Villarsia exaltata* are often the only occupants.

The microtope is found not only in the Illawarra area but also on the Nowra Sandstone plateau behind Ulladulla, on the Dorrigo plateau in northern N.S.W. and on the Monaro plateau near Kiandra (Costin, 1954; McElroy, 1951). The patterning of the microtopography and the vegetation is like that found in the patterned fens of Canada (Sjors, 1963; Slack *et al*., 1980), Minnesota (Heinselman, 1963) and alpine Colorado (Vitek and Rose, 1980). In the Illawarra, the microtope is best-developed in the least-dissected part of the Woronora Plateau, the Sublime Point - Maddens Plains area in the north-eastern corner of Cataract catchment. Within this area it is associated with tributary seepage zones in the swamps, where water movement is concentrated but insufficient to carve a well-defined continuous open channel. Again, this accords with observations of other patterned fens.

Indeed Ivanov (1981) considers that flow equilibria in mires require that a strip-ridge pattern of vegetation communities develop. He argues that constancy of water level for a given community is achieved by changes in the proportion of furrows (where hydraulic conductivity is high) and ridges, these changes being determined by the necessity of maintaining a constant average rate of seepage through the various parts of the mire. This interpretation clearly begs the question of the origin of microtopography which provides the disparate environments on which the different vegetation communities have become established.

The Initiation of the Ridge-furrow Microtopography.

McElroy (1951) considered ten possible causes for the initiation of the ridge-furrow systems:

i) human activity. Clearly this cannot apply in the sparsely-inhabited Boreal zone. It may also be rejected here. Maddens Plains were never cultivated and in fact were avoided by the early graziers, because the stock developed a rickets-like disease if grazed there (Mrs Bessie George, nee Madden, pers. comm.).

ii) animal activity. Crayfish (Euastacus kierensis) burrowing within the microtope excavate sediment from below the furrows and pile it onto the ridges. At Maddens Plains ejecta cones may weigh up to 1.5 kg and average 700 g, there may be up to 9 burrow entrances per square metre in the furrows, and the debris in the cones represents at least 350-450g/m^2 of material moved. Collapse of the furrow floors into the burrow systems and the apparent net transfer of debris onto the ridges accentuates the existing microtopography but the crayfishes' activities do not explain the origin of the patterns. Where burrows are found on smooth slopes (rather than in their usual place amidst the strip-ridge microtope), the burrows are often oriented downslope and not across the slope as the furrows are.

iii) water erosion. Strings of debris are deposited on some slopes in the swamps by sheetwash following baring of the surface by fires. These are found on relatively dry slopes where burning of the heath vegetation cover yields many twigs, seeds, woody fruit and charred leaf fragments. In the wetter seepage zones, where sedges and rushes dominate, little debris remains. Furthermore the debris strings are an order of magnitude smaller than the strip-ridge system.

iv) fires.

v) jointing. This may be rejected, as the sediments are not consolidated.

vi) gilgai formation. There is no evidence for displacement or doming of the subsoil. The gradients and the soil profiles of furrowed and adjacent smooth slopes were similar, and there was no profile change between individual ridges and the furrows beside them.

vii) suncracks. Hardly a possibility in the wettest micro-environments within swamps.

viii) salt pan formation. This is not compatible with the wet, acidic conditions.

ix) seed deposition in snow beds. Not applicable here as the area does not receive snow.

x) solifluction. McElroy, largely by eliminating the other possibilities, accepted this mechanism as the prime cause of patterning.

Boatman et al., (1981) however reject even gravity as a cause, suggesting that elongate pools on some Scottish mires form as the result of extensive flooding of the mire surface or the enlargement of small, presumably random irregularities. Sjors (1961) proposes similar mechanisms. This concept is hard to reconcile with the rhythmic regularity of the microtope.

If mass movement is the cause, then flow rather than shear failure must be involved. A sample of organic sand yielded residual shear strength parameters of $c'_r = 3.24 N/cm^2$ and $\Phi'_r =$ 21°, giving the furrowed 4° slope a factor of safety of 2.55. Slopes unstable with respect to shear failure have factors of safety of about 1. Deformation of the surface by flow would account for the fact that the furrows are most widely-spaced on the gentlest slopes and close together on slighly steeper slopes. The absence of patterning from steep slopes may be due to the more rapid drainage on such slopes reducing pore-water pressures in the sediments below a critical value.

Are the Features Relicts of Former Climates?

The preceding discussion of contemporary mechanisms would have little relevance if the patterned ground had formed under past, different conditions. Both Heinselman (1963) and Vitek and Rose (1980) suggest that frost action at least is important in pattern formation. Similar patterns are often associated with gelifluction, i.e., solifluction over frozen subsoil. However the ridge-furrow systems of Maddens Plains have formed under climatic conditions not grossly different from those of the present. The sediments in these particular swamps have accumulated within the last 17000 years. As I have argued elsewhere (Young, 1982), even during the last glacial maximum periglacial conditions did not affect the Woronora Plateau. Indeed the close interrelationships between topography, vegetation and hydrology in the patterned ground indicate that the patterning is a contemporary feature.

The Ecological Significance of the Patterning.

The strip-ridge microtope in the swamps of the Woronora Pleateau is of considerable ecological significance. It protects the seepage zones of the swamps from erosion by braking overland flow during times of rapid runoff; it provides the habitat of the small crayfish *Euastacus kierensis* and perhaps other animals; it stores surface water for long periods during dry weather and may be an important source of water for small mammals in such times; it is closely integrated with the hydrological balance of the swamps. Yet it is a poorly-understood and rarely-recognised phenomenon. As development encroaches to an increasing extent on the sandstone plateaux of the Sydney Basin, the patterned ground and the upland swamps within which it is found are environments which deserve careful preservation.

Acknowledgements

Dr Russell Blong kindly analysed the shear strength parameters of the organic sand from the patterned ground.

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A model of soil development for the Sydney Basin

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Abstract

A model for soil formation developed primarily in the Sydney Basin recognises three nodal landscape settings of Residual, Transportational and Depositional sites to which the distribution of soils can be closely related. Elaboration of this model has depended on testing the role of lateral surface movement in the genesis of Duplex soils on hillslopes (Transportation sites) and comparing this with traditional interpretations. Evidence drawn from numerous field observations and supported by mineralogy, particle size analyses and fabric studies support the interpretation that Duplex soils on hillslopes on the Hawkesbury Sandstone are best explained by the differential resistance to alteration of bedrock combined with downslope movement of the coarser textured surface layers.

Introduction

Over the last decade the model of soil formation proposed by Paton (1978) has been developed from field observations in Eastern Australia and particularly the Sydney Basin. Central to this model has been the recognition of Duplex or texture contrast soils (Northcote, 1974) and an understanding of their genesis.

Early soils mapping by Paton and Thompson (1968) in southern Queensland showed that Duplex soils typically occupied a particular landscape position, viz. hillslopes and upper terraces whereas elsewhere gradational and uniform soils (Northcote, 1974) dominated. If these texture contrast soils are controlled by landscape it follows that their genesis is related to landscape factors, the most obvious parameter being the relative opportunity for lateral surface movement of soil material. As a result of this mapping a model was developed of soil formation for which three nodal landscape settings were identified; Residual, Transportational and Depositional. To date these settings or site types have not been rigorously defined but they represent geomorphic environments where the relative potential for sediment movement is:

(a) Minimal - low gradient, small catchment areas and neglegible runoff, e.g. plateau surfaces or hilltops.

(b) Very high - steeper gradients with active slopewash eg. hillslopes.

(c) Low - depositional areas of low gradients below active transportational slopes.

Elaboration of the model has depended on testing the role of lateral movement in the genesis of Duplex soils on hillslopes and comparing this explanation with the traditional interpretations.

By way of background Duplex soils are those showing a much coarser A horizon (eg sands, to sandy loams abruptly overlying much finer material in the B horizon (eg clays). To date the dominant idea concerning the formation of texture contrast has been the translocation of clay from the A to the B horizon and the presence of clay Skins is the usual evidence cited. In many situations in Australia this evidence has been found lacking and the hypothesis of clay destruction in the A horizon has been postulated. Because direct evidence of this process is wanting a combination of both hypotheses are frequently used eg Handbook of Australian Soils (Stace, et. al. 1968). Sometimes, even this expediency is considered insufficient and the texture contrast is explained in terms of original sedimentary layering. The problems concerning the origin of texture contrast soils in Australia is further complicated by the grouping of these soils into many different great soil groups in this 'Handbook', in which a number of additional processes are alleged eg the translocation of sesquioxides in the podzolics, the degree of leaching of salts and exchangeable Na and Mg in the solonetz, solodized solonetz and soloths.

Soils on the Sydney Sandstone

The sandstone environment of the Sydney Basin has provided an ideal setting to develop this model. General observation on the Hawkesbury Sandstone in the Hornsby Plateau region has shown that there is a basic relationship between soil and landscape.

The typical soil toposequence on the sandstone plateau has: laterites, yellow earths and other siliceous sands (Uc's and Gn's) on 'Residual' sites; yellow podzolics (Dy's) and siliceous sands (Uc's) on 'Transportational' sites; podzols, earthy sands and alluvial soils in 'Depositional Sites'. (Fig.1).

Of the soils of the 'Residual' sites only laterites have been examined in any detail (Hunt et. al. 1977). Here, evidence was presented to support the hypothesis that laterites are iron-rich sandstone units modified by surface and/or near surface mobilization and reorganization of iron minerals ie in situ alteration of bedrock. On 'Depositional' sites where field evidence suggests that the soil parent materials are accumulations of sediment (mostly sand) derived from upslope, only podzols have been studied closely.

Here podzols are found on deep (>1-2m) siliceous, and well drained sand bodies on which a characteristic vegetation occurs (Buchanan & Humphreys, 1979). The genesis of this soil in terms of its geomorphic setting appears to be largely controlled by the stripping of sesquioxides and organic matter from individual quartz grains in the A horizons, to produce a bleached horizon (A_2), and the deposition of iron at 30-70cm depth to produce pans (B horizon).

Texture contrast soils on Sandstone Hillslopes

On sandstone hillslopes the common soil sequence consists of pockets of shallow stoney sands (U'cs) directly overlying sandstone adjacent to texture contrast soils in which the 'A' horizons are morphologically (colour, grain size, composition, fabric, etc) very similar to the Uc soils, thus suggesting that these topsoils are closely related in origin.

To farther examine this hypothesis, initial sites with marked contrasts in lithology were sought. In the Sydney Basin such sites exist where diatremes of volcanic breccia and dykes of similar basic composition penetrate the sandstone. Because of the less resistant nature of these igneous materials the diatremes normally occupy depression areas in the sandstone plateau. A diatreme at Peat's Crater, 40km NW of Sydney provide a dramatic illustration of this (Bishop et al 1980). In cross-section (Fig.1.) a continuous layer of sandy to loamy material mantles the lower footslopes of the sandstone and the weathered volcanic breccia. Upon closer examination topsoil clearly thickens and coarsens slightly downslope from the sandstone over the breccia contact to the break in slope which coincides with the limit of sandstone gravels. The topsoil mantle then thins out and the texture becomes finer over a spur in the valley floor. The continuity of this layer together with the close similarities in many of its characteristics is again suggestive that the topsoil overlying the breccia is derived from the sandstone upslope. Confidence in this interpretation is enhanced by an analysis of the heavy minerals and other grain characteristics of the various materials. (Table 1) The similarity of the topsoil and sandstone and the dissimilarity with the subsoil and breccia is plainly evident.

The next phase of this project has been to test the validity of the role of slope movement in the more general sandstone situation where texture contrast soils are developed over (i) shale lenses (mudstone facies of Conaghan & Jones, 1975) and other argillaceous sandstones or (ii) relatively homogeneous sandstones. In the first situation the *in situ* nature of the clay rich subsoil is demonstrated, in many cases, by the continuity of joint patterns in the bedrock to the planar void pattern in the subsoil and/or the continuity in bedding planes frequently containing layers of ironstone clasts up to the junction of the A/B horizons along which a stone line may develop downslope (eg West Head Road, Hunt et. al. 1977) Fig.2. or when numerous bands of ironstone occur a complete disruption of them so that the A horizon contains an appreciable gravel content scattered throughout.

The A horizons of these texture contrast soils contain, bipyramidal quartz overgrowths on the sandgrains which are characteristic of the sandstone but which are generally absent on any quartz grains in the clay rich subsoils.

The other situation involves texture contrast soils developed on Hawkesbury sandstone material that is very uniform in grain size and mineralogy. One such sequence has been examined at Patonga, 40 km north of Sydney (Bishop et al 1980) where a sandy A horizon overlies both hard bedrock and bedrock that has been subjected to in situ alteration to yield clayey materials. (Fig. **3**). From the point where sandstone outcrops at the surface a basic proximal and distal facies relationship is observed. The equant clasts of the gravel fraction decrease in size and volume downslope whereas the loamy sand A horizon increases in thickness and the differentiation of the stone line from the overlying A horizon increases. These trends are enhanced by an examination of the other clast type. Platy clasts at a point where the stone line is well differentiated from the overlying A horizon, show a basic imbricate fabric with downslope dips mostly ranging between 8-30° and sometimes to 60° and more, all being considerably steeper than the 2° slope of the base of the surface layer but with a dip azimuth distributed about the slope azimuth.

Discussion

In all the examples given here there is strong evidence for the acceptance of the model for texture contrast soils on hillslopes on the Hawkesbury Sandstone ie differential resistance to alteration of bedrock combined with downslope movement of the coarser textured surface layers. In all cases this can be seen from basic field stratigraphic relationships and has been supported by mineralogy, particle size analysis and fabric studies. There is little need to invoke hypotheses such as clay illuviation, clay destruction or original sedimentary layer.

Two important questions arise from the study on Texture Contrasts soils: What are the surface processes involved? and does this model have applicability outside the Sydney Basin?

Surface processes have been under study both within and outside the Sydney Basin and will be examined briefly in the following paper .

Outside the Sydney Basin, some of the original work from Queensland has been published (Thompson & Paton, 1980) and work on both granite and Palaeozoic sediments in eastern NSW is currently in progress as well as additional studies on the Hawkesbury Sandstone. This research is being conducted not only on texture contrast soils but other soils from both 'Residual' & 'Depositional' sites.

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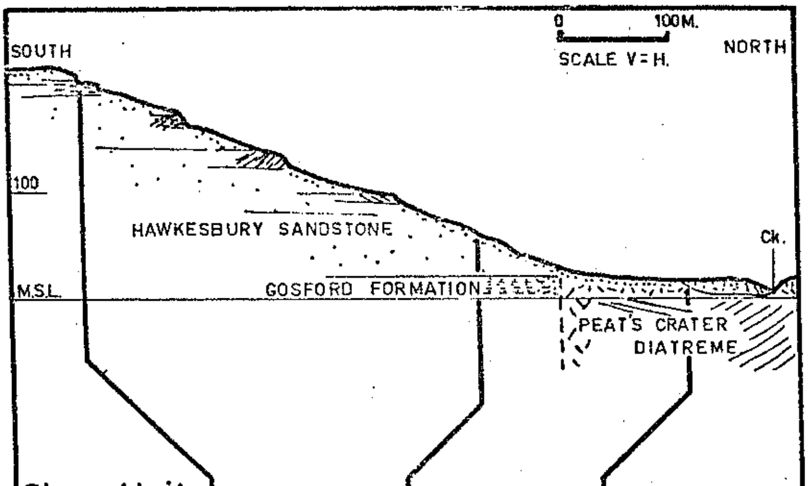

	Plateau Top	Regolith Covered Benches	Colluvial Debris Slope	Alluvial Terraces
Slope Unit.	PLATEAU TOP	REGOLITH COVERED BENCHES	COLLUVIAL DEBRIS SLOPE	ALLUVIAL TERRACES
Soil.	YELLOW EARTHS ON SANDSTONE.	PODZOLICS ON SANDSTONE AND SHALE SOME LITHOSOLS.	LITHOSOLS ON SANDSTONE. RED PODZOLICS ON VOLCANIC BRECCIA.	ALLUVIAL SANDS. PODZOLS MAY OCCUR IN OLDER SANDS UNDER 'PODZOL TYPE' VEGETATION.
	Gn.2.21 & Gn.2.24	Dr. & Dy. & Uc.5.23	Uc.5.23 & Dr.5.11	Uc.1 & Uc 2.35
Process.	IN SITU WEATHERING, LEACHING, AND NEW MINERAL FORMATION.	SURFACE MOVEMENT OF MATERIALS OVER IN SITU WEATHERED ROCK.		DEPOSITION OF COARSE GRAINED WEATHERING PRODUCTS FROM UPSLOPE, LEACHING UNDER 'PODZOL TYPE' VEGETATION.
Site Type	RESIDUAL	TRANSPORTATIONAL	TRANSPORTATIONAL	DEPOSITIONAL

Soil / Slope Relationships Peat's Crater.
FIGURE.1

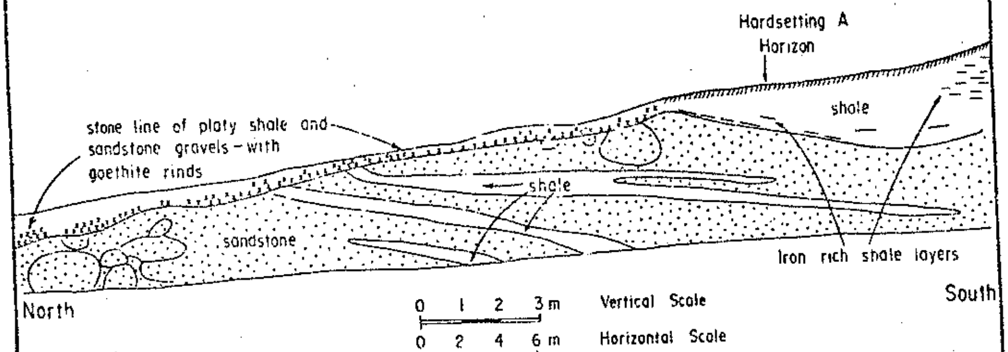

FIG. 2.

Section along road cutting West Head Road Ku-ring-gai Chase.

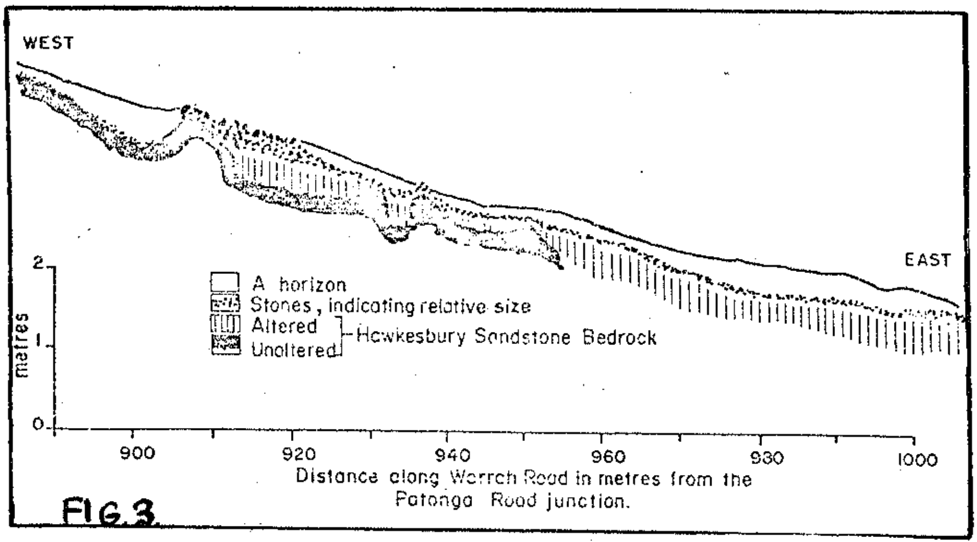

FIG.3

Downslope pattern of stone line, Warrah Road.

Table 1 Summary mineralogy of Duplex soil and rock types at Peat's Crater*

Property	Duplex soil		Sand-stone	Weathered breccia	Fresh breccia
	A horizon	B horizon			
Field texture:	Sandy loam	Light clay	Rock	Rock	Rock
Mean size (0):	2.68	approx.8.0	1.77	-	-
Quartz crystal overgrowths:	Abundant	Absent	Abundant	Absent	Absent
Heavy minerals:					
% Rutile	20	1	21	0	0
% Ilmenite, zircon tourmaline & leucoxene	46	0	65	0	0
% Limonite	44	99	12	82	5
% Microxenoliths & xenocrysts	0	0	0	18	95
% Others	0	0	2	0	0

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* Mean values quoted only. Full details are given in Bishop et. al. (1980).

Vegetation Patterns on the Sassafras Plateau

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ABSTRACT

Quasi-concentric vegetation patterns in a humid temperate area on the Sassafras Plateau (35°05'S 150°15'E) are described and correlated with habitat factors using Greig-Smith pattern analysis. Bands of *Eucalyptus obtusiflora* Tall Closed Scrub, *Casuarina distyla* Tall Shrubland, *Calytrix tetragona* Dwarf Shrubland, *Lepyrodia scariosa* Open Sedgeland and sandstone outcrops form the pattern. The patterns are a microcosm of more extensive communities elsewhere on the Sassafras Plateau. The patterned area is developed on horizontally bedded sandstones with alternating harder and softer beds. Differential erosion forms a series of terraces and a moisture gradient across each terrace causes a repeated series of habitats down the slopes. Effect of waterlogging on small-seeded (*Casuarina distyla* and *Leptospermum scoparium* var. *rotundifolium*) and large-seeded (*Banksia ericifolia* and *Hakea teretifolia*) shrub was investigated in a glass house trial. Smaller-seeded species performed best in freely-drained treatment, and larger-seeded species in medium-high water table conditions. This with their distribution and reproductive behaviour. Small-seeded species are more common on drier and paradoxically, less fire-prone, sites. Vegetative reproduction is more common on wetter, more fire-prone sites. The vegetation patterns are caused by the interaction of species' responses to soil drainage and fire and to the fire-proneness of the site.

Distribution of Scribbly Gums and Angophoras in Relation to Soils

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ABSTRACT

The soils on which angophoras and scribbly gums grow were sampled extensively and a particle size analysis, total phosphorus analysis and loss-on-ignition were carried out. The different angophora species grew on soils with significantly different percentages of coarse sand and levels of phosphorus while the scribblies were, as a group, restricted to infertile soils, with a few minor exceptions. *E. signata* on the North Coast of N.S.W. occupied soils of even lower fertility than the other four scribbly species.

1. INTRODUCTION

Two groups of trees are frequently strongly represented in the vegetation communities that occur on the Hawkesbury and Narrabeen sandstones of the Sydney Basin: angophoras (*Angophora* spp.) and scribbly gums (*Eucalyptus* superspecies Haemastoma (Pryor and Johnson 1971)).

As groups of species, the scribbly gums and the angophoras show two contrasting patterns of ecological distribution particularly with regard to soils. The scribbly group appears to be restricted to physically highly demanding habitats characterised by very infertile soils (Rotherham *et al.* 1975). Individuals suffer a chronic lack of nutrients and frequent and severe shortages of water.

There are five scribbly species: *E. signata* from the sand dunes of the North Coast of N.S.W. and southern Queensland; *E. rossii* on the sandstones and granites of the Tablelands and western slopes with an outlying population on the Pilliga sandstone around Coonabarabran; *E. racemosa* extending southwards from the Hunter Valley from Quaternary sand and gravel deposits onto the Hawkesbury sandstone; *E. sclerophylla* centred on the Hawkesbury sandstone of the Blue Mountains and the surrounding conglomerates and granites and *E. haemastoma* which occurs on the Hawkesbury and Narrabeen sandstones and Quaternary alluviium between Sydney and Newcastle. South of Sydney an undifferentiated population of scribblies occurs on Hawkesbury sandstones and Quaternary alluvia south to King's Point.

In comparison, with the exception of rainforests and swamps, the genus *Angophora* spans the whole spectrum of fertility and moisture regimes on the east coast of Australia. It occurs in the range of habitats which support vegetation communities from coastal heath (*A. hispida*, *A. costata*), through Dry Sclerophyll Woodland (*A. bakeri*, *A. costata*), and Dry Sclerophyll Forests (*A. costata*, *A. floribunda*) to Wet Sclerophyll Forests (*A. costata*, *A. subvelutina*). All these communities can occur on the sandstones of the Sydney Basin, their distribution being controlled largely by topography and drainage.

It was decided to analyse the soils on which these 10 species occurred in order to investigate edaphic factors which were possibly limiting their distribution and to establish the range of soils over which each scribbly and angophora species is capable of growing under natural conditions.

2. METHODS

Details of methods are available in Mowatt 1981.

2.1. Collection of Soils

Soils were collected so as to represent as thoroughly as possible the range of soils on which the angophoras and scribblies are able to establish populations. More soil samples were collected for those species which grew on a greater range of soil types, or extended over a wider geographical range e.g. *A. costata* and *E. rossii.*

It was not intended to describe the soils fully since it was felt that the amount of time required to analyse the complete soil profile over a wide range of chemical and physical properties would not be justified by the results. Only those factors which have been shown by other workers to be important in controlling the distribution of eucalypt species were examined.

At each site a soil sample was taken from the top 15 cm of the profile. The Ao horizon of undecomposed litter was not included and each site chosen was as close as practicable to an adult tree of one of the species under consideration.

Not only does the A1 contain most of the nutrients (Stace *et al.* 1968, Scott-Kemmis 1972) but it can be an indication of the nutrient levels in the rest of the profile. It is also the most important to seedling establishment, which is generally accepted to be the most critical phase, in terms of mortality, in the life-history of perennial plants (Harper & White 1974). Purdie (1977) recorded mortality rates ranging from 86 to 93 per cent in the first year of life for eucalypt seedlings in a *E. rossii* - *E. mannifera* - *E. macrorhyncha* forest.

2.2. Analysis of Soils

There are two aspects of the soil environment which are commonly limiting to the survival of eucalypt seedlings; water availability and nutrient levels. Young eucalypt seedlings are exceedingly vulnerable to desiccation, principally due to their small size and Specht (1963) showed that even small quantities of phosphorus fertilizer, beneficial to adults, increased the death rate of seedlings in heath plants.

The three soil characteristics chosen for the analysis, % organic matter, particle size distribution and phosphorus concentration, are those which are most likely to give the most information about these two critical aspects of the scribbly and angophora seedlings' environments.

2.2.1. Organic Matter

The amount of organic matter in the A1 horizon of a soil is closely related to the soil's ability to resist the leaching of nutrients and drainage of water down the profile. It can therefore be considered to indicate soil fertility, particularly in very sandy free-draining soils e.g. those derived from Hawkesbury sandstone and sand dunes. The relationship is, of course, complicated by the presence of clay and by the varying concentrations of nutrients in the litter fall.

Since none of the soils to be examined was calcareous, loss on ignition was used as an approximation for the amount of organic matter present.

2.2.2. Mechanical Analysis (Particle Fractionation)

A very high percentage of sand results in soils draining rapidly with the severity of the concomitant leaching mainly dependent on the rainfall pattern and the depth of the water table. Since both clay and organic matter increase the water and nutrient retention capacity of a soil, the two proportions should be considered in relation to each other and not in isolation.

2.2.3. Phosphate Analysis

It is known that phosphorus levels can be correlated with the distribution of some dry sclerophyll species (Beadle 1954, 1962) because phosphorus levels limit the distribution of the faster growing, more competitive wet sclerophyll species. Ashton (1976) showed that phosphorus was a severely limiting factor when the wet sclerophyll species E. regnans was grown on Dry Sclerophyll Forest soil which normally supported E. sieberi, whereas E. sieberi grew very well on the Wet Sclerophyll Forest soil.

It is also known that some of the soils supporting scribbly-dominated forests have extremely low levels of total phosphorus, in some cases approaching zero (Scott-Kemmis 1972, Mowatt 1975). Other soils supporting scribblies have higher levels, although the concentrations are still low compared to those in soils which support most other eucalypts (Stace et al. 1968).

This raises the possibility that the different levels of soil phosphorus are correlated with the distribution of the different scribbly "species" i.e. some scribbly species are restricted to soils with lower phosphorus levels than others.

Total phosphorus was therefore chosen as the chemical factor for investigation. "Total" rather than "available" phosphorus was chosen for two reasons. Firstly, all measures of "available phosphorus" include some insoluble phosphates due to the action of the extractants releasing previously fixed phosphorus. Secondly, there is evidence that Eucalyptus species are able to use "insoluble phosphates" (Mullette et al. 1974), and this has been corroborated for the scribbly gums (Mowatt 1981). The concept of "availability" of phosphorus becomes so vague under these conditions as to be meaningless.

3. RESULTS

Results of analyses are shown in Table 1. Percentage total sand and percentage coarse sand were chosen as representative of the trends present in the particle size distribution.

Table 1. Average Values for Soils Supporting Each Species. Loss on ignition (L.O.I.), % sand and Phosphorus concentration (Total P ppm) based on means of two analyses of each soil.

Species (No. of sites)	% Total sand	% Coarse sand	% L.O.I.	Total P ppm
E. signata (6)	87.7	69.4	4.4 (4)	14.3
E. rossii (9)	81.8	44.0	6.2 (7)	59.3
E. sclerophylla (6)	79.3	34.3	5.3 (4)	46.3
E. haemastoma (6)	85.3	56.0	4.1	36.2 (5)
E. racemosa (8)	85.6	52.6	3.8	51.6
Sth.Coast Scribbly (3)	79.3	41.3	7.4	37.7
A. subvelutina (6)	71.0	27.1	6.8	233.8
A. floribunda (7)	79.3	42.4	8.4	209.0
A. hispida (6)	88.0	56.7	5.2	53.2
A. costata (12)	83.6	60.3	6.9	42.2
A. bakeri (2)	78.0	31.5	4.8	34.0

To find out whether the different scribbly taxa were associated with differences between soils, the soils were grouped according to the scribbly growing on them and analysed separately from the soils which had angophoras and not scribblies associated with them.

The soils with angophoras growing on them were similarly treated and three significant F ratios based on homogenous variances were obtained:

1. P ppm ($\sqrt{x + 3/8}$) for the scribbly soils
2. P ppm ($\ln (x + 1)$) for the angophora soils
3. % coarse sand (untransformed for the angophora soils)

Student-Newman-Keuls Tests were performed on these measures. The only significant differences between species occurred between *A. subvelutina* and *Angophoras bakeri* and *hispida* in the soil P concentration (233.8, 34.0 & 53.2 P ppm respectively).

4. DISCUSSION

4.1. Distribution of Scribbly Gums and the Level of Total Phosphorus

The values obtained for total phosphate concentrations for scribbly soils varied from 0 to 115 ppm. High values were found under three species: *E. rossii* at Coonabarabran (115 ppm P), *E. racemosa* at Bucketty (100 ppm P) and *E. sclerophylla* (110 ppm P) at Morton National Park. They were thus not associated with any particular species. The values below 10 ppm P were obtained from the deep coastal dune sands of the North Coast where *E. signata* occurs. The levels obtained agree with previous work on these systems (Stace *et al.* 1968, Mowatt 1975).

The values obtained for soils derived from Hawkesbury sandstone which support populations of *E. haemastoma*, *E. sclerophylla* and *E. racemosa*, agree with those obtained by Beadle (1962) and Walker (1972) who found a range of concentrations from 23-53 ppm and 45 ppm P respectively.

The rather high phosphate concentration found in Morton National Park under *E. sclerophylla* is probably the result of the swampy conditions prevailing at this site. Areas which are subject to occasional flooding can be expected to have higher levels of nutrients than areas which are subjected to leaching during periods of heavy rainfall. Beadle (1954, 1962) points out a similar difference between ridges and valleys on Hawkesbury sandstone. The valleys, which can accumulate soils and nutrients and are generally moister, have an average soil phosphorus content of 98 ppm and can range up to 163 ppm, compared to an average of 37 ppm for the ridges.

The soils supporting the scribbly species were very similar to each other, showing much less variation than those supporting the angophora species. The only variable which did give significant differentiation between the scribbly soils was total phosphorus and even then no two scribbly soils were significantly different from each other. It seems reasonable to suggest that this is based more on a chance correlation between the predominance of a certain very infertile soil type, coastal sand podsols, and the geographical range of *E. signata* rather than any restriction of *E. signata* to soils less fertile than those supporting the other scribbly taxa.

4.2. Distribution of Angophoras

4.2.1. Total Soil Phosphorus

The angophora species show much greater differentiation in the phosphorus values of their soils, as had been expected. The highest value recorded was for A. floribunda at Pindari Dam, with 865 ppm; the lowest, 0 ppm, for A. costata at Bombah Point on the coastal sands.

Unfortunately, most of these more fertile soils collected from areas where Angophora subvelutina and A. floribunda grow, have been affected by agricultural practices. The removal of those phosphorus values which are artificially high is complicated by the naturally higher levels of phosphorus found in the soils affected, which makes it impossible to separate the soils which have been artificially fertilized from those that have not.

Despite these reservations, the soil analysis has shown a gradation in phosphorus values from A. subvelutina on the most fertile soils down to A. bakeri, A. costata and A. hispida on the infertile soils. A. costata and A. floribunda occurred on a very wide range of soil phosphorus levels while A. hispida occurred on a much narrower range, possibly due to its restriction to the single rock type (Hawkesbury sandstone).

4.2.2. % Coarse Sand

Soils supporting A. subvelutina have the lowest proportion of coarse sand, followed by those supporting A. bakeri and A. floribunda with soils supporting A. hispida and A. costata having the highest values. This sequence is very similar to the ordering of the species for phosphorus concentrations with the exception of A. bakeri which occurs on soils with both very low levels of phosphorus and low proportions of coarse sand (Table 1).

As has been already pointed out, a large proportion of coarse sand means that a soil has a very poor capacity for retaining water and nutrients. However, a high proportion of finer particles does not guarantee that the soil will be fertile and those soils which support A. bakeri appear to be both infertile (34 ppm P) and with a low percentage of coarse sand (31%).

5. CONCLUSIONS

The scribbly species all appear to be restricted to soils of very low fertility, although probably quite capable of growing in higher levels of phosphorus e.g. at the Morton National Park site.

The angophora soils showed more and greater differences between species than the scribbly soils. The results from the analysis of the angophora soils, as expressed by the variables phosphorus concentration and % coarse sand, support the order in which the angophora species were placed on the basis of their probable soil fertility. The position of A. bakeri in this ranking, which was initially unclear, now seems to be that it is found on the infertile soils which have a low coarse sand content. This is based on a very low number of samples (two) of A. bakeri soils and a more extensive sampling would be required before a definite conclusion could be drawn.

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THE GEOARCHAEOLOGY OF THE SYDNEY BASIN SANDSTONES

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ABSTRACT

Sydney Basin sandstone terrains are known to be rich in Aboriginal archaeological sites. Geoarchaeological studies carried out at a number of different types of site have drawn attention to the impact that the people of prehistoric and contemporary societies have had, and are having, on archaeological sites and their surrounds and to the consequent implications of this impact on the management of sites.

INTRODUCTION

As archaeologists with formal academic training in geomorphology we have been active in the development of geoarchaeology in Australia. Geoarchaeology is that branch of the discipline of archaeology in which the theories and methods of the earth sciences are used centrally to answer archaeological questions (Hughes and Sullivan in press). Most such studies in Australia have concentrated on site-specific problems, although others have been concerned with wider issues which overlap the related disciplines of environmental, spatial and landscape archaeology. Much of the research which has given impetus to this geoarchaeological approach has been carried out in Sydney Basin landscapes. These studies have wide implications not only for research archaeology but also for archaeological site management strategies. Additionally there are conclusions to be drawn from such studies on the nature and rates of landscape evolution in the Sydney Basin.

The following studies have been especially useful in contributing to our understanding of the geoarchaeology of the Sydney Basin:

* geomorphological studies of rock shelter archaeological deposits on the NSW south coast (Hughes 1977, 1978), the Goulburn River Valley (Haglund 1981), the Hawkesbury area (Vinnicombe 1982) and the Blue Mountains (Johnson 1979, Stockton and Holland 1974).

* archaeological surveys of the Tianjara and Budawang areas south of the Shoalhaven River (Hughes and Attenbrow 1981, Hughes _et al_ 1982).

* Landscape archaeological studies in coastal New South Wales (Sullivan 1976, 1982).

ARCHAEOLOGICAL SITES IN SANDSTONE AREAS

Sandstone areas within the Sydney Basin are rich in archaeological sites. These include grinding grooves, pecked or abraded engravings, stone arrangements, open sites comprising surface scatters of artefacts or stratified archaeological deposits, and rock shelters with archaeological deposits, engravings, drawings or paintings.

Little contribution has been made to the study of either archaeological or geomorphic processes by the direct investigation of grinding grooves or rock engravings, and stone arrangements remain enigmatic. Studies of the locations of archaeological occupation sites within the landscape however, have contributed to an understanding of people-land relationships (Sullivan 1976, 1982, Vinnicombe 1982). Both open and rock shelter sites in the Sydney Basin sandstones have been taken into account in these studies.

Obvious factors such as proximity to drinking water, food resources and comfortable camping sites affected site locations. Less obvious factors such as the selective use of rock platforms which maintain deep cracks or irregular eroded surfaces for gathering shellfish, also influenced the locations of archaeological sites. In many areas within the Sydney Basin there is now a recognised pattern of relationships between the types and nature of archaeological sites and their landscape settings.

Systematic surveys in the Mangrove Creek catchment (Attenbrow 1981), the Gosford-Wyong area (Vinnicombe 1982), the Goulburn River valley (Haglund 1981) and the Tianjara area (Hughes and Attenbrow 1981, Hughes et al. 1982) have revealed that such sandstone areas have large numbers of archaeological sites, predominantly rock shelters with archaeological deposits. The number, variety and potential for scientific research of such sites on the sandstone is very great compared with other rock types such as shale.

ARCHAEOLOGY AND LANDSCAPE EVOLUTION

One of the most intriguing features of archaeological deposits in Sydney Basin sandstone shelters is the frequency with which archaeological materials in the form of stone artefacts occur throughout the deposit down to, or to within, a few centimetres of bedrock. This feature pertains widely regardless of the source of the sediment which is generally roof-fall or colluvium. This in turn suggests causal relationships between occupation and sedimentation.

In the case of shelters where the major if not sole source of sediment is roof-fall, Hughes (1977, 1978) has demonstrated a direct relationship between the rate of accumulation of roof-fall and the intensity of site usage, and has postulated that the occupants of the shelters had influenced roof-fall and weathering in the following ways:

1. by knocking down any pre-existing layer of weathered rock;
2. by maintaining the roof and walls in a clean state through physical contact and hence exposing the rock to further weathering;

3. by influencing the shelter environments through changes in temperature and humidity, particularly by the lighting of fires.

It was nevertheless argued that these accelerated rates of weathering were still low (0.3-7.0mm/100y), and that natural rates of cavernous weathering are even lower, as were those immediately before occupation (less than 2.0mm and on average 0.1-0.5mm/100y). At these low rates of weathering and roof-fall shelters such as those investigated must have taken hundreds of thousands of years to form. This implies that the cliff-faces in which the shelters have formed have remained essentially unchanged over these long periods and that rates of hillslope retreat have accordingly been very low. We would speculate from this that the physical appearance of the sandstone hillslopes has remained virtually unchanged since the Sydney Basin was first peopled more than 25,000 years ago, and that the landscape has changed little since the beginning of the Pleistocene or perhaps even late Tertiary times.

In contrast we have argued for shelters where the major source of sediment has been colluvium that mid to late Holocene Aboriginal utilisation of the landscapes in which these sites are set, involving the use of fire, resulted in hillslope instability (Hughes and Sullivan 1981). This assertion does not contradict our claim for long-term very low rates of landscape evolution as we see the impact of Aboriginal burning as having merely led to the accelerated movement of already available sediment in the landscape from the valley slopes to the valley floor and then out to sea. The impact of this accelerated movement of sediment (and that under different climatic and base level regimes in the Pleistocene) may not yet have been reflected in increased weathering and erosion of the sandstone.

If Aboriginal people had an impact on their environment along the lines that we have suggested then explanations of Holocene geomorphic change in terms of climatic and base level change must be treated with caution. This is an opportune time to consider ways in which the influences of people, climatic change and base level change might be disentangled.

MANAGEMENT IMPLICATIONS

The effect of occupation on sandstone shelters and the identification of weathering processes has obvious management implications for the conservation of rock art (Hughes 1978). Management of art sites currently involves discouraging visitors from entering decorated shelters, as well as the investigation of bio-physical agents affecting rock surfaces. Although it is possible to control some of the processes causing the deterioration of art sites, it is important also to identify the complex of processes operating. For instance, although water wash may have a damaging effect on a painted surface, rock surface or pigment flaking which results from the expansion of salts could be accelerated if these salts were not being removed by surface wash.

Management of open engraving sites or grinding grooves generally involves the removal of roots or coarse vegetation which affect the rock surface. There is no evidence currently available that the growth of lichen or algae have such a damaging effect. Normal case hardening will tend to protect such sites, providing abrasion, e.g. from heavy footwear, is prevented.

In terms of their value for both archaeological and geomorphic research, the most important sites in the Sydney Basin are sandstone rock shelters archaeological deposits, including shell middens. These sites present fewer management problems than art sites, except where threatened by human activities ranging from trail bike riding to open cut coal mining or subsidence following underground mining. Management generally involves acquisition of the land by the National Parks and Wildlife Service, the use of covenants such as 'Protected Archaeological Area', or liaison with landowners over the use of the site.

Many of the studies which have contributed to our knowledge of the number and range of archaeological sites within the Sydney Basin sandstones have derived from environmental impact assessment or other contract work. The recommendations for site management which derive from such studies are area-specific, and do not necessarily result in a comprehensive strategy for archaeological site management being implemented.

National Parks and Wildlife Service policy is to regard all archaeological sites within National Parks, Nature Reserves and other Service estate as a permanent protected sample of the State's archaeological resources. One aim of the Service's acquisition policy is to ensure that a representative sample of all types of archaeological sites fall within such land, and within geomorphologically stable situations. To effectively carry out this policy, it is necessary to know the relationships which exist between sites and landscapes, and to know how representative the land so far acquired by the Service is. Michael Williams' paper (this volume) may present more details on this, but it appears likely that at this stage it is only within the Sydney Basin sandstone country that the National Parks and Wildlife Service can have any confidence that such a representative sample has been acquired to date.

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Fire, Lyrebirds and Landscape in the Sydney Region

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During study of the vegetation of the Greaves Creek drainage basin in the sandstones of the western Blue Mountains near Blackheath we observed the important role of two agents whose role in landscape development in the Sydney region has been neglected; fire and lyrebirds.

The role of fire in breaking down Sydney basin sandstone to ultimate mineral particles, in calcining the surface soil, and in concentrating ironstone cobbles on the surface was first described by Selkirk and Adamson (1981) in the Blue Mountains and near Sydney, and will be discussed briefly. Subsequent to fire, other important processes occur which have also been neglected. For example, surface wash buries seed (released after fire) in micro-terraces which form behind minor obstructions on burnt slopes, thereby protecting seed from predation and placing it in positions favourable for germination and establishment. This effect should be added to other advantageous effects of fire on the establishment of new generations of plants from seed - effects such as the ash bed effect, litter removal, and the reduction of competition from adults for water and light. This process of implanting seed in micro-terraces by surface wash after fire is probably generally important in the demography of plants in fire-prone environments, but it is particularly well demonstrated in the Sydney sandstone landscape.

Lyrebirds have been ignored as agents of landscape development. Our studies in the Greaves Creek valley show their dramatic role in the turnover and down-slope movement of soil and litter. During excavations for invertebrate food, lyrebirds turn over between 1 and >10 kg of mineral soil and organic litter per m^2 per annum in favoured feeding areas. These are impressive rates of bioturbation by any standard of comparison.

Lyrebirds show a range of activities which promote instability of the soil, litter and rocks on hill slopes. Their activities generate extensive heaps of intermixed litter and mineral soil in which litter decay is greatly speeded up, fungal growth is promoted, and conditions are created suitable for invertebrate fauna. The digging by lyrebirds therefore creates conditions favourable for the renewal of their food resources. The birds exert a selective effect on erosion because their activities are not random. In general they work over steep slopes rather than gentle ones, and they appear to prefer south and east-facing slopes. On their preferred hill slopes, they excavate preferentially around the base of rocks, rock ledges, and roots of trees and shrubs, probably because of the extra litter and moisture which accumulate at such sites. By their scratching, they turn over rocks up to 2 kg. Turned-over rocks, soil and litter are moved downslope - they kick debris down, not up. Soil can be thrown 2 m down slope with ease. Large rocks which are not moved directly by the birds can be sufficiently undermined to slide downhill. Persistent excavation creates areas of hillslope rather bare of plants and litter with the soil exposed to rain and slope wash. Such areas are enlarged by the birds working around the perimeter and a cliffed interface 5 to 15 cm in height is often created.

We have used 3 methods to measure the quantities of material moved:

(1) direct observation of feeding birds (timing and measuring their excavations)
(2) transects on slopes within their territory, and
(3) establishing litter and soil traps.

Further reference to the role of lyrebirds is presented by Humphreys and Mitchell (1982).

The two agents considered in this report are quantitatively important and should take their place with other better known agents such as water and chemical breakdown. Both fire and lyrebird excavation have probably operated for long times.

In addition, both agents can vary in the intensity of their effects depending upon aspect. Fire and lyrebirds can be added to other agents like frost (Holland 1974) that could contribute to valley asymmetry in the western Blue Mountains. Finally, because of the neglect of these two agents there is a need to quantify their role in the landscape wherever they operate.

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FLUVIAL SESSION

SEDIMENTARY PROCESSES IN A SANDSTONE VALLEY: FERNANCES CREEK, HUNTER VALLEY, N.S.W.

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ABSTRACT

Soil stratigraphy and textural characteristics of sediment storages have been used to infer contemporary geomorphic processes and sediment pathways in a Triassic sandstone catchment of the Hunter Valley. These studies have shown that the main contemporary supply of sediment to the valley floor from hillslopes is via tributary fans where both sedimentalogical sorting and storage occurs. Recent discontinuous gullying has caused massive reworking of the valley-fill sediment with downstream transport and storage in the channel and floodout zones. It would appear that little sand is currently being supplied from this catchment to Wollombi Brook.

INTRODUCTION

Sediment moves sequentially but episodically from its original source to its final sink through repeated cycles of entrainment, transport and deposition. Each cycle finishes when sediment is deposited in a temporary or relatively permanent storage, such as an alluvial fan, river channel, floodplain, etc. The residence time of material in these storages is highly variable, ranging from hours to more than 10^4 years.

Sediment sources (i.e. the immediate point of origin of fluviatile sediment) are usually classified as upland sources, such as channeled (gullies) and unchanneled overland flow, subsurface flow and mass movement, and bottomland sources, such as river bank erosion, bed degradation, valley trenching and floodplain scour (Brune, 1950). Valley trenching refers to continuous and discontinuous trenching of valley-fill sediments in contradistinction to the incision of colluvial deposits. Wolman (1977) noted that the precise identification of sediment sources as well as the path and timing of sediment transport and storage are major, unresolved problems in the sediment field. The present paper addresses these problems by tracing the linkage between erosion and deposition on hillslopes and channels in a catchment of the Hunter Valley. The approach adopted for this continuing study is the inference of contemporary geomorphic processes and sediment pathways from the sedimentologic properties and the soil stratigraphic relations within and between major sediment storages.

Fernances Creek is a left bank tributary of Wollombi Brook (Fig. 1) and has a catchment area of 13.82 km². Triassic Hawkesbury Sandstone caps the ridges of the main drainage divide and sandstones, shaley sandstones and shales of the Triassic Gosford Formation outcrop over the remainder of the catchment. Further details of the physical characteristics of the study area are included in the conference papers of Erskine and Melville (1981) and Melville and Erskine (1982).

HILLSLOPE PROCESSES

The original source of sediment is fine to very coarse quartz sandstone units and thin shale lenses of the Hawkesbury Sandstone and fine to coarse quartz sandstone, lithic and felspathic sandstone and shale of the Gosford Formation. Weathering of these Triassic sediments supplies material in the full size from boulders to clays. Where massive quartz sandstone beds of the Gosford Formation outcrop, structural benches are present, resulting in a terraced hillslope morphology. Downslope of the lowest structural bench, slopes are mainly rectilinear with slight basal concavities (hillslope profiles 1 to 5, Fig. 1). Preliminary work suggests that deep (> 1m) hydraulic mantles, composed of loamy sand, sandy loam, loam and clay, with varying proportions of gravel, extend from the lowest bench to the valley floor. At the base of the lowest bench ground cover is incomplete, topsoils are water-repellant and algal crusts are common. Below this, the absence of surface wash deposits and an abrupt contact between alluvial and valley-fill sediments suggests that minimal sediment transport is occurring over vegetated lower slopes. The stratigraphy of the hydraulic mantles is variable and exhibits at least two K cycles (Butler, 1959), indicating that alternate phases of hillslope stability and instability have occurred in the past. The supply of variable-size sediment from hillslopes to low-order channels is generally restricted to areas upstream of alluvial fans.

FAN PROCESSES

Alluvial fans are common, contemporary landforms on most tributaries of Fernances Creek. They function both as a sediment store and as a pathway for sediment movement from hillslopes to the main drainage network. Carbon incorporated within fan sediments is currently being dated to determine the time span over which fans have been active. Three fans have been investigated in detail (Fig. 1), one is under dry sclerophyll forest (fan 1; catchment area of 0.16 km^2) and the others are mainly under unimproved pasture with small areas of forest (fan 2 and 3; catchment areas of 0.14 and 0.51 km^2, respectively).

The morphology, stratigraphy and sedimentology of fan 1 has been discussed at length in another conference paper (Melville and Erskine, 1982). The longitudinal profile, field sample sites and stratigraphy of fan 3 are shown in Fig. 2. Each fan exhibits little correlation between layers at different sample sites. Vertical textural variations are generally marked and are attributed to time series changes in sedimentary processes and sediment supply. Surface samples show a progressive downslope fining in particle size from gravels and sands upstream of the intersection point to fine-textured sediments ranging from organic loams to organic light clays on the fan toe (Fig. 2). There is also an accumulation of organic matter on the lower segments. Melville and Erskine (1982) found that both mean size and the degree of sorting of the surface sediments of fan 1 progressively decrease in the downslope direction. Sediment sorting occurs with downslope transport on the fan as a result of reduced competence of overland flow due to declining slope and increased surface roughness.

CHANNEL PROCESSES

A sequence of knickpoints (i.e. sediment transport discontinuities) on Fernances Creek have formed a discontinuously incised channel (Fig. 1). The most upstream gully (i.e. reach 3) was present in 1867 when the first land survey of the area was completed. Carbon contained within the valley-fill sedimentsis currently being dated to determine the time of initial trenching.

Loams, clay loams and clays were deposited on an unincised valley floor prior to trenching; this is still occurring upstream of the knickpoint on Finchs Creek. These fine textures closely correspond to the sediment being transported through alluvial fans at the present time. In reach 3 the knickpoint has incised through up to 0.5 m of loam and clay into 1.5 m of sand and clayey sand. Subsequent to the initial incision the channel continues degrading to the surface of a plastic, medium clay and then widens by basal undercutting of the banks. These erosional processes result in the episodic input of large quantities of sediment to the channel which becomes temporarily overloaded with sand. As a result localised aggradation and steepening of the bed occur. The sediment stored in the channel bed is then intermittently flushed out by recurring secondary knickpoints about 0.5 m high. There are at least three secondary knickpoints in reach 3 at the present time. Sediment finer than 40 never comprises more than 1 percent by weight of the bed material because of this continuous reworking.

The main longer term sediment stores within the channel system are depositional benches and floodouts (Erskine and Melville 1981). A paired bench inset below the former valley floor is present between cross sections 4 and 7 (Fig. 1). It is generally about 40 m wide and is composed of about 1 m of interstratified sands, loamy sands and sandy loams. The principal valley sediment storage is a floodout extending from cross section 10 to downstream of cross section 14 (Fig. 1). The gully in reach 2 is developed within this depositional zone. The floodout has a surface form of a low-angle fan with an ill-defined, distributary channel pattern. It is composed of at least 1 m of interbedded sand, loamy sand, sandy loam and sandy clay loam. The floodout has a very high trap efficiency for sands. In reach 1 the channel is relatively sinuous, narrow, deep and of small capacity with a partly vegetated bed. These characteristics suggest that only minor amounts of sand are being transported through the floodout to Wollombi Brook.

DISCUSSION AND CONCLUSIONS

In low-order channels above the apex of alluvial fans sediment finer than 40 behaves as wash load and is not deposited in significant quantities. Cobbles, pebbles and sand comprise the bed-material load, with boulders forming a lag deposit. Sediment sorting with transport down the fan has produced a series of discrete depositional environments characterised by a textural sequence similar to Moss and Walker's (1978) bed stage hierachy. At the fanhead the framework (A) and contact (C) populations dominate (coarse bare bed stage with clogged contact population); on the middle part of the fan, the interstitial (B) population first appears in small quantities between the A population (fine ripple bed stage); on the toe, the A and B populations are present in approximately equal quantities (suspended load bed stage). The development of the suspended load stage demonstrates that fans are contemporary sediment stores, supplying fine material to the main channel network.

Although knickpoint migration and bank erosion in reach 3 have removed at least 86,000 m^3 of valley-fill sediment from a 2.9 km length of the valley floor, a significant, but as yet undetermined proportion has been retained in the channel bed, bench or floodout. The sand fraction, however, has only been reworked short distances from one store to another.

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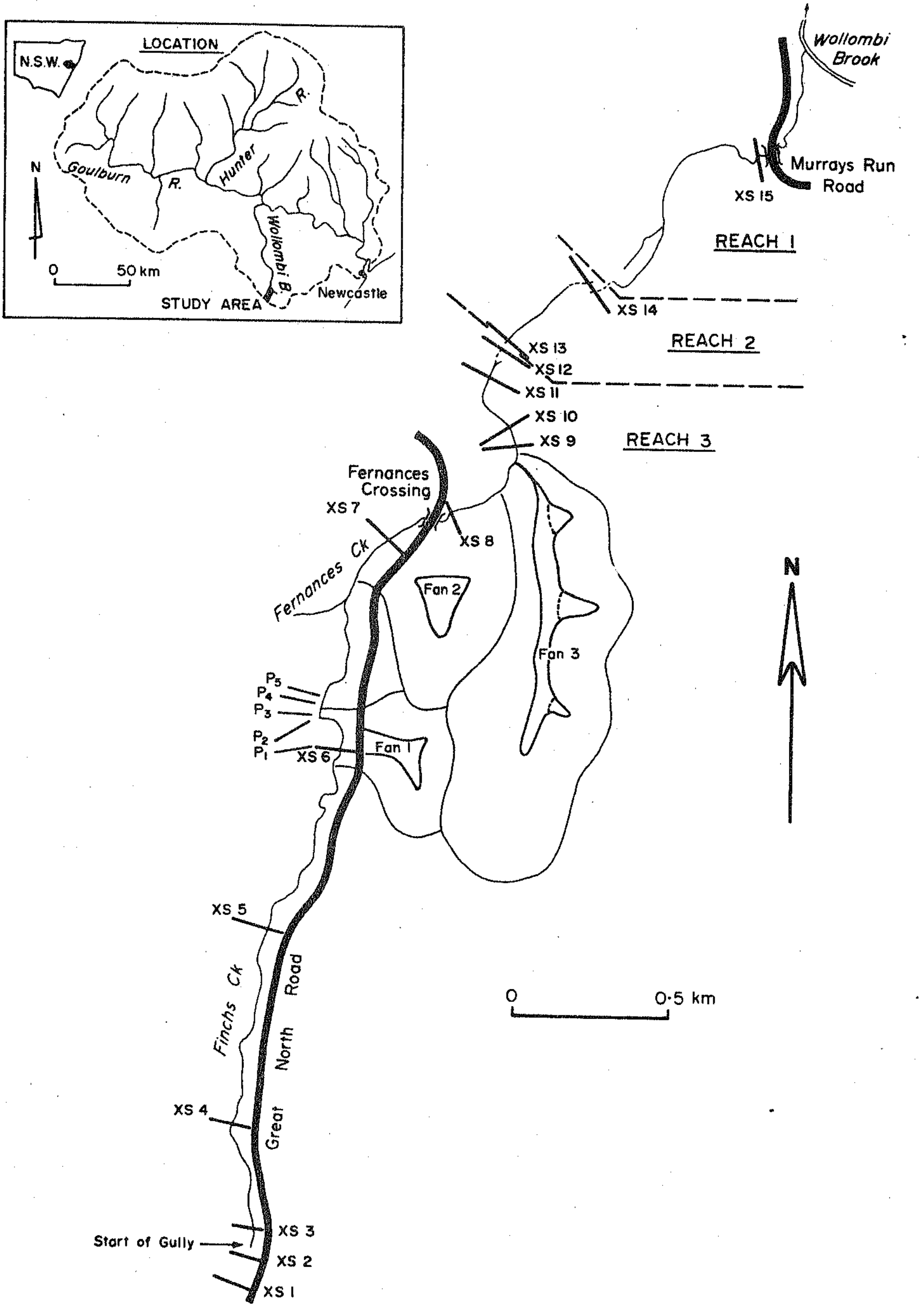

Fig. 1 Location map of study area in Fernances Creek catchment.

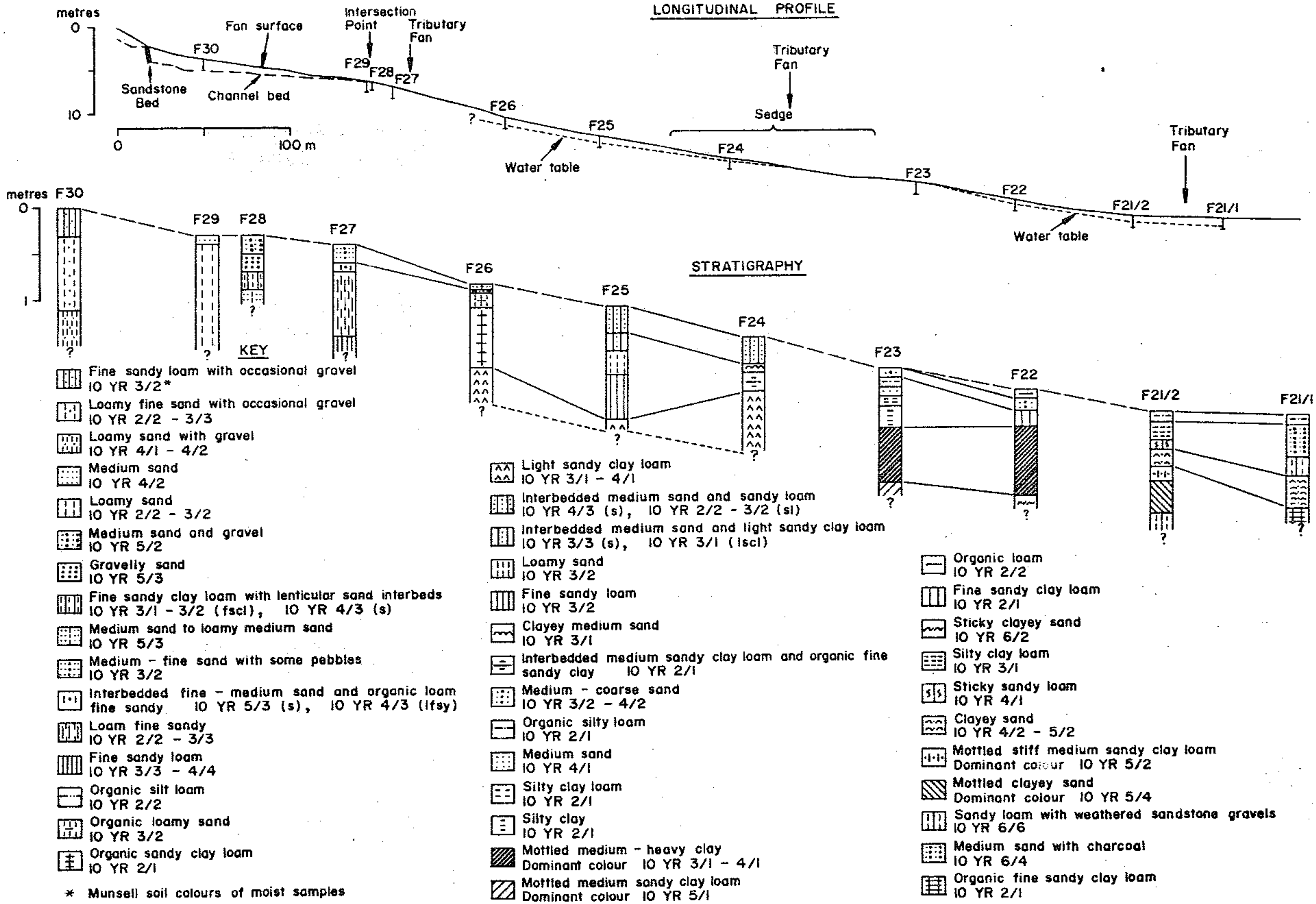

Fig. 2 Longitudinal profile and stratigraphy of Fan 3.

CHANNEL CHANGES IN THE SANDSTONE AND SHALE REACHES OF THE NEPEAN RIVER NEW SOUTH WALES

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ABSTRACT

Between Douglas Park and the Grose Junction (100km), the Nepean alternates between sandstone gorges and alluvially-flanked shale reaches. These have responded differently to water and sediment discharge changes imposed by regulatory structures and natural regime variation. Sand and gravel operations have also affected alluvial reaches. Expected below-dam adjustments involving scour have been confirmed by surveys. However, these have been exaggerated by higher discharges since 1949, associated with a changed natural regime.

INTRODUCTION

Channel changes can be natural or induced through catchment and channel modifications. Prior conditions need to be known to carry out comparative studies.

In the 100km Douglas Park to the Grose Junction (Fig 1), the Nepean channel occupies three gorge and three alluvial tracts. Bed elevations fall from 61 to 1m with highly variable gradients (Fig. 2). While there has been no real change in location, depth and width variations indicate that this is an unstable channel. In addition to catchment changes, the channel has been altered by 10 riparian weirs, five dams, sand and gravel operations and in increase in precipitation from about 1949.

This paper summarizes results of surveys carried out in three parts of this system. Depth changes have been obtained by comparing modern surveys with a 1911 surveyed long profile. Width changes have been derived from maps, airphotographs and bridge surveys. Results are discussed in light of impacts of dams, weirs and extraction industries, as well as the changed regime.

CHANNEL CHANGES

Several recent studies have reviewed channel changes (Schumm, 1977, Gregory 1977a, Rhodes and Williams 1979, Hollis 1978, Petts 1980, Park 1981). While change is natural, accelerated modification may be attributed to climatic variation (Pickup 1976), to catchment man-induced change (Walling 1979), to regulatory structures (Petts 1980, Park 1981) and to sand and gravel operations (Warner and Pickup 1978).

Local examples also include: Bell and Erskine (1981, climatic change), Bird (1980, flood mitigation structures), Gregory and Scholer (1977b and 1974, respectively, on dams) and Warner and Pickup (1974 and 1977 with McLean, on sand dredging).

In a system where there are large dams, weirs and now many farm dams, there should be a reduction in total runoff (Q^-), attenuation of flood peaks (Q_p^-) and a great reduction in sediment discharge (Q_s^-). According to Schumm's channel metamorphosis (1977), these should induce a modification like:

$$Q^- \, Q_s^- \approx b^- \, d^\pm \, \lambda^- \, S^\pm \, P^+ \, F^-$$

In a system free to adjust, width (b), meander wavelength (λ) and width-depth ratio (F) should be reduced. With an increase in sinuosity (P), slope (S) should be reduced and depth (d) may increase.

In these alternating gorges and alluvia, adjustments are constrained. Slope changes are restricted by weirs and bedrock outcrops. In the gorges, changes might be:

$$Q^- \, Q_s^- \approx b^- \, d^+ \, \lambda^0 \, S^0 \, P^0 \, F^-$$

and in alluvial sections

$$Q^- \, Q_s^- \approx b^- \, d^+ \, \lambda^- \, S^0 \, P^+ \, (\text{if } \lambda^-) \, F^-$$

Since 1949 in fact, discharge has increased inspite of the dams:

$$Q^+ \, Q_s^- \approx b^+ \, d^+ \, \lambda^0 \, S^0 \, P^0 \, F^-$$

The b^+ is less and the d^+ is greater in the sandstones than in the alluvial sections.

THE CHANNEL AND EXTERNAL STIMULII

The gorges are cut in Hawkesbury Sandstone and the alluvial sections in Wianamatta Shales. The gorges are old features, the lower two being antecedent, and channel mobility in the shales is limited because meanders are entrenched in bedrock and Pleistocene terraces. Table 1 and Figure 2 summarise details of the long profile for the six sections.

The channel has been adjusting to changes over the last 200 years: some would argue longer (Hughes and Sullivan 1981). Indirect impacts include: land clearance, grazing, cropping, urbanization, soil conservation and farm dams. These are confined to the shales (about 10% of the total catchment) in intensive use and to metasediment and igneous areas (25%) in extensive land use.

Direct impacts include: the five large dams (1907-1960), the 10 weirs and sand and gravel operations. The four Nepean dams (Fig. 1) only affect 37% of the catchment above Wallacia or 6% above Penrith. The Warragamba shuts off water and sediment from 83% of the catchment above Penrith. However, runoff after closure (1960-1971) was still 27% higher than for the earlier "dry period" (1892-1948). The weirs act like sediment traps, causing aggradation, then trees stabilize shoals, channel capacity is diminished, and bank erosion and flooding are increased.

The extractive industry has removed: 844,000m^3 of sand from the bed and bank above Wallacia; and 6,284,000m^3 of sand and 6,796,000 of gravel (derived from the Warragamba catchment) from between Penrith and North Richmond in the period 1968/69 to 1979/80 (Warner 1981). In the period 1952 to 1968, the figures for the latter section were 4 and 9 mill m^3 respectively (Scholar 1974), making a total of 26 mill m^3 of aggregate.

RESULTS

Four sources of change have been examined: width changes from air photographs, comparison of maps, bridge surveys and depth changes from 1911 and 1980-82 long-profile surveys.

Six sets of air photographs (1947-1978) were used to assess water-surface width changes at 10 locations in the lower Gorge I and 6 in the upper part of Alluvium I (Table 2). Water width is controlled by weir ponding and was used in preference to bank tops, which were irrelevant in the gorge, mutilated in dredged alluvial sections and hidden by dense vegetation elsewhere.

Values in Table 2 are related to flooding at Windsor (Riley, 1981) and show some tendency to decrease in "dry" periods and increase in wetter times.

Modern maps do not show bankfull channel width, whereas old county and parish maps probably showed something like full channel width, beyond the margins of alienated land. However, comparison of the same 16 widths referred to above, for a 1925 county map and an earlier parish map showed little consistency within the data.

Bridge sections reveal deepening between 1870 and 1980 for the Menangle railway bridge and, just downstream, silting up of the road bridge since 1928. This is limited information and scour around bridge piers might be expected.

Long-profile depth comparisons have been possible for three sections: (a) Black Hole to Bergins Weir - 9.66 km (Fig. 3); (b) Bents Basin to Penrith Weir - 24.27km (Fig. 4); and (c) Penrith Weir to the Grose Junction - 15km (Fig.5).

The upper reach has been deepened by 2.1m on the centreline, 2.7m mean in the gorge, 2.2 m in dredged sections and 1m elsewhere. In the second section, the upper alluvial channel has gone from 2.7 to 4m depth (dredging mainly); the main sandstone gorge from 9 to 13m - with one hole -11 O.D. and downstream of the gorge, from 2.7 to 3.3m. 14 cross sections from the Penrith Lakes Development Corporation allowed some comparison downsteam of the lowest weir. In the first 5km, the depth has increased by less than 1m, while downstream the mean increase is about 3 m.

DISCUSSION

Depth adjustments are greater in the gorges than in alluvial sections. Gorge width changes are limited to growth and decay of bars, whereas elsewhere there are fewer constraints from alluvial banks. Gorge scour has been facilitated by: (a) prior bed deposits, (b) proximity to dams, (c) competence of over-dam, sediment-deficient water, (d) increased volume of such water since 1949, and (e) confined highly turbulent flows.

Alluvial reaches have generally sanded up behind weirs and channel improvement works have been required upstream of Wallacia Weir. Downstream of Penrith bed and bank degradation are related to extensive sand and gravel extraction.

Increases in runoff associated with higher precipitation have tended the emphasise the role of sediment-starved waters with any additional sediment load trapped above the dams.

CONCLUSIONS

Initially weirs modified water and sediment discharges through the alternating sections. Then the Nepean dams reduced both in a dry period. However, flow competence was sufficent to evacuate sand from gorges to weired alluvial reaches. This caused bank-erosion and loss of capacity, eventually requiring channel improvement works. Higher flows after 1949 further increased flow competence. These extended into the post-Warragamba period, where high discharges have caused considerable scour in the bed of the Nepean gorge. Sand and gravel removals have further enlarged the lower alluvial section and bed degradation has been pronounced. How much more adjustment remains in the system is unknown.

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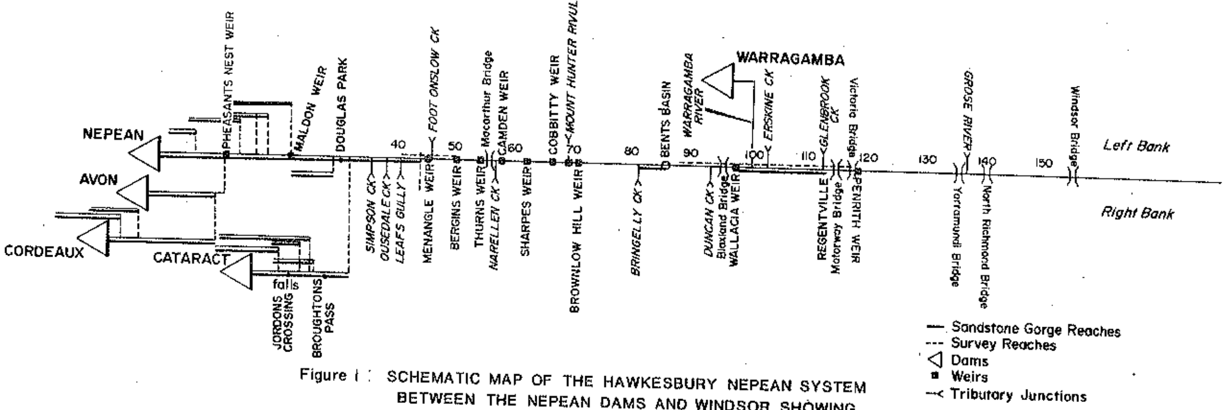

Figure 1: SCHEMATIC MAP OF THE HAWKESBURY NEPEAN SYSTEM BETWEEN THE NEPEAN DAMS AND WINDSOR SHOWING THE LOCATIONS OF DAMS, WEIRS, TRIBUTARIES, SANDSTONE GORGES AND STUDY REACHES.

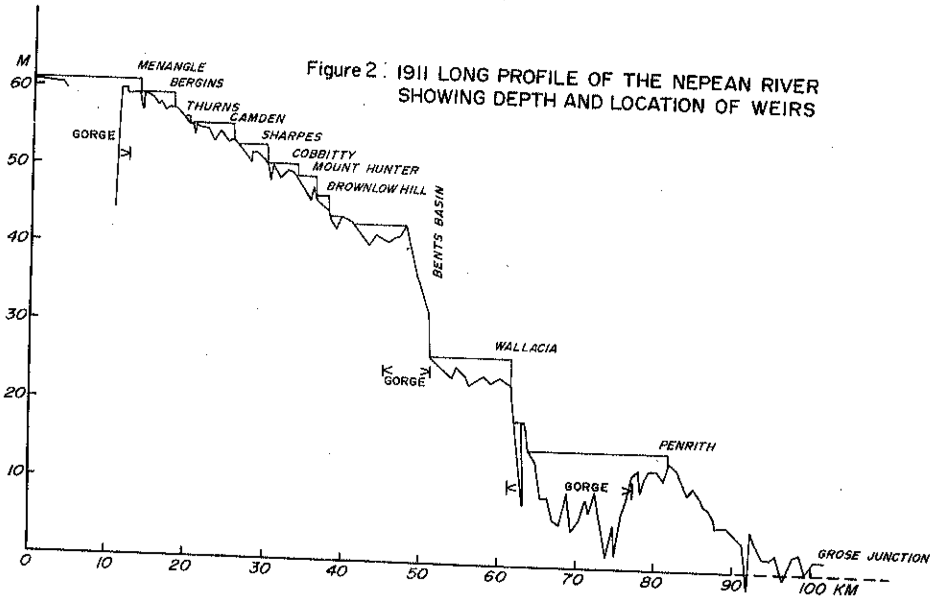

Figure 2: 1911 LONG PROFILE OF THE NEPEAN RIVER SHOWING DEPTH AND LOCATION OF WEIRS

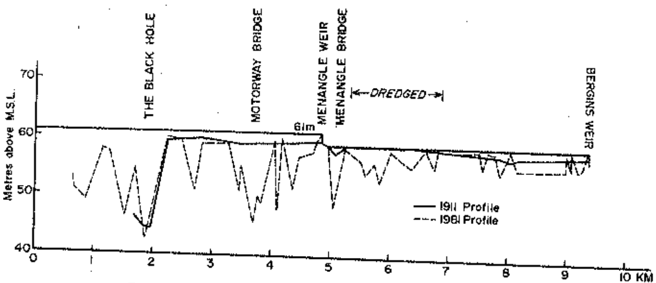

Figure 3: 1911 AND 1980 LONG PROFILES FROM THE BLACK HOLE TO BERGINS WEIR

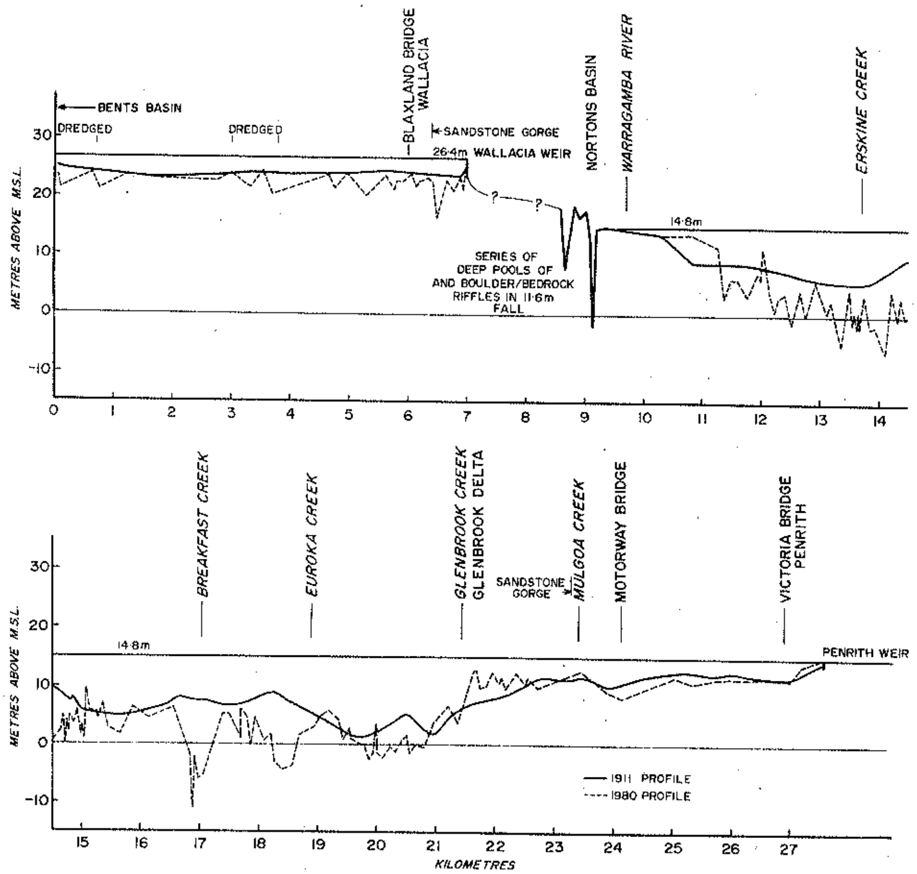

Figure 4: 1911 AND 1980 LONG PROFILES FROM NEAR BENTS BASIN TO PENRITH WEIR

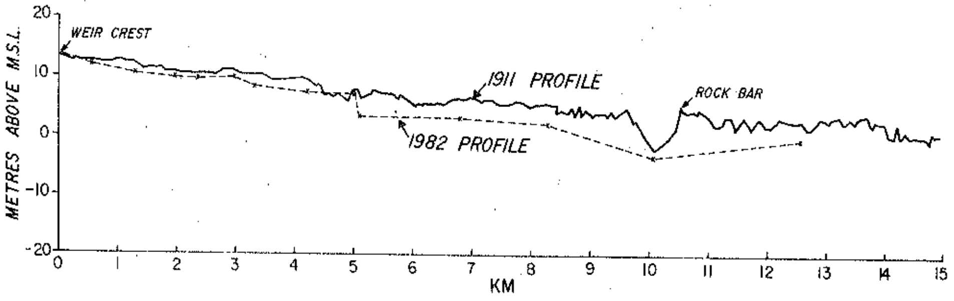

Figure 5: NEPEAN LONG PROFILE BETWEEN PENRITH WEIR AND THE GROSS JUNCTION

TABLE 1

Morphological characteristics of the Nepean between Douglas Park and the Grose Junction

Section	L(km)	Initial Gradient (S_1)	Subdivided * With Weirs (S_2)	Sinuosity P	Remarks
Gorge I	13.4	.0001	0031**upper .0000 lower	1.29	Douglas Park to Menangle
Alluvium I	33.0	.0005	.0005	1.61	Menangle to B.B. Gorge
Gorge II	4.3	.0025	.0005 upper 0040 lower	1 43	Bents Basin Gorge
Alluvium II	10.1	.0003	.0003	1.19	B.B. to Wallacia
Gorge III	16.0	.0007	.0033 upper .0000 lower	1.14	Nepean Gorge
Alluvium III	24.0	.0004	.0000 above weir .0005 below	1.25	Gorge to Grose
Total	100.8	.0006		1.33	

* split where two distinctive gradients prevail
** for 20km above Douglas Park

TABLE 2

Width changes in 10 sandstone and 6 alluvial/shale sections from 1947 to 1978 on the Nepean River near Menangle.

		1947/49	1949/56	1956/61	1961/65	1965/70	1970/78
Sandstone							
	W^+	4	5	1	7	4	7
	W^-	5	4	6	2	6	3
	W^0	1	1	0	0	0	0
	W?	0	0	3	1	0	0
Shale/ Alluvium							
	W^+	0	4	4	3	2	5
	W^-	5	1	2	0	4	1
	W^0	0	1	0	1	0	0
	W?	1	1	0	2	0	0
Total							
	W^+	4	9	5	10	6	12
	W^-	10	5	8	2	10	4
	W^0	0	2	0	1	0	0
	W?	2	0	3	3	0	0
No of floods		0	21	0	8	3	13
No of "big floods" (>10m)		0	3	0	2	1	3

CHANGES IN STREAM CHANNEL MORPHOLOGY AT TRIBUTARY JUNCTIONS LOWER HUNTER VALLEY

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ABSTRACT

Some Lower Hunter Valley stream channels were surveyed upstream and downstream of tributary junctions. The channels did not adjust downstream of junctions according to established regional rates of change in morphologic variables as functions of discharge or other independent basin variables. It is suggested that other independent factors, in particular, sediment load and calibre, could be important in determining the nature of channel change at tributary junctions. In addition, interrelated changes in cross-sectional, profile and planform variables may be expected below junctions. The resultant channel morphology, in terms of these variables, might not be wholly determinate. It is concluded that whilst simple power function hydraulic geometry relationships may adequately describe regional rates of channel morphological change, the downstream changes which occur at tributary junctions are not defined by such a model.

INTRODUCTION

Geomorphologists concerned with channel form have shown little interest in the changes which occur in channel morphology at tributary junctions. This is surprising, considering that at tributary junctions quantum inputs of discharge or increments in drainage basin area occur, and in response, similarly abrupt changes in channel morphology should be expected.

Miller (1958) developed an empirical model relating downstream channel dimensions to the dimensions of the two joining channels, such that:

$$A_a = k\ (A_b + A_c)$$

where, A = a channel variable

b and c = subscripts denoting joining streams

a = subscript denoting the resultant stream.

The problem with this model (also used by Park (1975)) is that the relationship does not allow 'k' to vary according to the relative size of joining tributaries (Richards, 1980).

Richards (1980) found the width of stream links on the River Fowey, Cornwall, to vary stochastically about a mean value, implying that discharge inputs through stream links are insignificant insofar as they affect channel geometry. Richards (1980) thus proposed a model of channel change at tributary junction based on the independant variable Shreve magnitude (M) which increments only by discrete units at stream junctions. The model is of the form,

$$A_R = c\;M_R^{\,b} \qquad (1)$$

where $A_R = \dfrac{A_D}{A_U}$, $M_R = \dfrac{M_D}{M_U}$

and A = a channel variable.

D,U = subscripts denoting downstream & upstream.

c = a constant close to unity.

The above model recalls the power function 'downstream' hydraulic geometry relations first introduced by Leopold and Maddock (1953). If it is assumed that channels conform to these relationships then a general model of channel change at tributary junctions can be hypothesised. Consider a general equation of regional ('downstream') hydraulic geometry:

$$A = a\;B^{b} \qquad (2)$$

where A = a dependent channel variable

B = a discharge index or surrogate basin measure (i.e. basin area or sum of stream length)

a = a regionally characteristic coefficient

b = a regionally characteristic exponent.

Now if channels are measured directly upstream (U) and downstream (D) of tributary junctions then it is hypothesised that:

$$A_R = c\;B_R^{\,b} \qquad (3)$$

where $A_R = \dfrac{A_D}{A_U}$; $B_R = \dfrac{B_D}{B_U}$

and c = a constant near unity.

This model differs from that proposed by Richards (1980) in that it assumes the morphological changes downstream through links (however small) to accord with the regional rate of downstream change.

Both models (equations (1) and (3)) were tested using data collected from channel junctions sampled from the Lower Hunter Valley, N.S.W., and also using Miller's (1958) tributary junction data from the Sangre de Cristo Ranges, New Mexico.

METHOD

Testing of the models requires the establishment and comparison of two sets of relationships:

(i) regionally characteristic channel morphology relationships of the form of equation (2).

(ii) channel morphology change at tributary junctions relationships of the form of equations (1) and (3).

Eighteen tributary junctions were selected for survey. Upstream and downstream measurements (on main or trunk channel) provided data for (i) and (ii) above. It was convenient to also measure the joining tributary channel, thereby providing additional data for (i).

Measurement of Channel Variables

In addition to the variables normally considered important in studies of 'downstream' hydraulic geometry : width (W), mean depth (D), slope (S) and roughness (n); channel capacity (C) and width - depth ratio (F) were also measured.

To provide a comparison, measurements were taken at both pool and riffle sections and treated as two separate samples. The second pool and fourth riffle were arbitrarily selected for survey. Where a pool and riffle sequence could not be identified, cross-sections were surveyed at five times and ten times the channel width from the junction, the former being grouped with 'pool' data, the latter with 'riffle' data.

Most of the channels investigated were incised, but to a degree which varied from site to site. The valley flat was therefore unsuitable as a channel boundary upon which to base a regional comparison. However the channels did have a fairly distinct lower bench (or benches) present. Definition of the active floodplain (or bankfull bench level) was based primarily on morphological criteria (similar to the method of Park (1975)).

A comparison of various channel slope measuring techniques revealed the best measure to be that of the bedslope between the extreme riffles of a surveyed long profile (refer Gippel (1982)).

Channel roughness was estimated using the method of Cowan (1956).

Measurement of Independent Variables

Bankfull discharge was calculated for each channel by averaging the values estimated by the Manning Equation at the pool and riffle cross-sections.

Basin area, sum of stream lengths and Shreve magnitude were measured from 1 : 25,000 CMA Topographic Maps using the blue line network.

RESULTS

1. Regional relationships, channel variables versus Shreve magnitude (M), basin area (A), sum of stream lengths (L), and estimated bankfull discharge Q_{bf}).

All channel variables (at both pool and riffle sites) were closely correlated ($p > 0.01$) with the four independent variables.

Regression equations of the form of equation (2) were calculated for each pair of variables. The exponents were within the range of those found in other studies from different regions. The four independent variables displayed similar relationships with the channel variables, although there was a statistical difference between the exponents calculated for the pool and the riffle data sets.

2. Change at tributary junctions relationships.

Channel cross-sectional dimensions did not always increase, and slope and roughness did not always decrease at junctions, as expected from the established regional hydraulic geometry relationships.

The changes in channel variables (W_R, D_R, C_R, F_R) at junctions showed no degree of correlation with changes in the independent variables (M_R, A_R, L_R, Q_{bfR}), when measured at pools. Slope and roughness change also showed no correlation with the changes in the independent variables.

When measured at riffles W_R was significantly correlated with L_R and Q_{bfR}. F_R (measured at riffles) showed significant correlation with all four independent variables. Regression equations were calculated for the above pairs of significantly correlated change ratios:

$$W^r_R = 0.78\ L_R^{0.582};\quad W^r_R = 0.86\ Q_{bfR}^{0.754}$$
$$F^r_R = 0.73\ A_R^{0.703};\quad F^r_R = 0.69\ L_R^{0.830};\quad F^r_R = 0.71\ M_R^{0.815}$$
$$F^r_R = 0.84\ Q_{bfR}^{0.545}$$

(r is a subscript denoting riffle data)

The hypothesis requires that for the above relationships to be acceptable they should have a coefficient near unity and exponents close to those of the established regional relationships. The relevant regional relationships are:

$$W^r = 1.87\ L^{0.500};\quad W^r = 2.94\ Q_{bf}^{0.510}$$
$$F^r = 9.64\ A^{0.160},\quad F^r = 8.34L^{0.151};\quad FR = 7.53M^{0.154}$$
$$F^r = 9.77Q_{bf}^{0.147}$$

Using arbitrary limits, such that for coefficients, c = 1 if

$$0.90 \leq c \leq 1.10$$

and for exponents, b (eq . (2)) = b (eq. (3)), if

$$b\ (eq\ (2)) - b\ (eq.\ (3)) \leq 0.05,$$

none of the above equations satisfy the requirements of the hypothesis.

Statistical analysis has demonstrated that both Richards' (1980) model based on Shreve magnitude, and the hypothesised model, based on hydraulic geometry relationships, do not adequately describe changes in channel morphology measured at Lower Hunter Valley tributary junctions. Identical analysis of Miller's (1958) data from the Sangre de Cristo Ranges confirmed this result by also failing to establish an adequate model of morphologic change at tributary junctions.

DISCUSSION

Regarding the model of Richards (1980), it is relevant to note that Richards (1980) found it suitable to describe width changes at tributary junctions on the River Fowey, Cornwall only using Shreve magnitude data generated from a contour crenulated network. Data generated from a blue-line network (as in this study) was found to be inadequate. Apart from this measurement problem there are three main points of discussion which help to explain (in a geomorphic sense) the results of this study.

1. Inadequacy of bankfull discharge (or surrogate measures) as an independent variable.

The concept of regional hydraulic geometry assumes that bankfull discharge is the channel forming discharge and has a constant frequency of occurrence throughout the area being investigated. However, the flow characteristics of a drainage basin may change with increasing drainage area, and this change is not necessarily linear (Klein, 1981).

Hydrograph characteristics of joining channels may be important in determining the magnitude of downstream change in channel morphology. Miller (1958) and Park (1975) described the confluence of bankfull flows by the continuity equation. However, when tributaries join, their flows are added, but the peaks of their respective hydrographs do not necessarily coincide. This is important since most morphological activity is thought to occur within a short time span of the hydrograph peak (Klein, 1981).

2. Influence of changes in bed material and sediment load characteristics at tributary junctions.

Whilst it is accepted that it is discharge which primarily determines the absolute size of a channel, it is thought that relative measures which express channel shape are influenced by other independent and semi-independent variables, of which the most important is sediment load characteristics.

Evidence in the literature indicates that when a stream is joined by a tributary which is transporting sediment of a contrasting nature, abrupt changes in channel width, slope and sinuosity may result.

3. Complex changes in channel morphology at tributary junctions.

Cross-section, profile, and planform channel variables have been shown, by other workers, to be inter-correlated. Pair-wise and partial correlation coefficients indicated that changes in cross-sectional channel variables at measured Lower Hunter Valley tributary junctions were interrelated with observed changes in slope and roughness.

A model of channel change at tributary junctions should thus include both discharge and sediment load as independent variables determining the change in planform, profile and cross-sectional channel variables. In terms of these interrelated channel variables there may be many combinations possible of resultant channel changes, since a relative over or under adjustment by one or more of them, at any particular junction site, will presumably influence the magnitude, and perhaps direction, of adjustment of the other variables.

Conceptual difficulties involving matters of indeterminacy and equifinality could obstruct the development of a quantitative model of complex adjustments in channel morphology at tributary junctions.

CONCLUSION

The general conclusion drawn from the results of this study is that whilst variations in channel morphology can be suitably described in the regional sense by the simple power function hydraulic geometry model, these macro-scale correlations may not be relevant to changes at channel junctions because here the processes operate at a comparatively micro-scale level. Thus, changes in channel morphology at tributary junctions require an explanatory model of much greater complexity.

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AN EMPIRICAL MODEL OF LATERAL MIGRATION FOR MEANDERING RIVERS

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ABSTRACT

An empirical model is developed for predicting channel migration rates of meander bends using measurements of stream power, the medium grain-size of the sediment at the base of the stream banks, the height of the cut-bank, and the curvature of the bend. The model requires further testing and refinement, but it is hoped that it will be of considerable practical application for predicting bank erosion rates and channel re-alignment.

INTRODUCTION

In general terms the rate of channel migration (M) is dependent on stream power (Ω), bank strength and height (τ_b, h), bend curvature expressed as the ratio radius of channel curvature to channel width (r/w), and probably the sediment transport rate (Q_s).

$$M = f\ (\Omega,\ \tau_b,\ h,\ r/w,\ Q_s) \text{-------------} 1$$

There will be a direct positive relationship between migration rate and stream power, but an inverse relationship with bank strength and height. Bend curvature and sediment discharge are less obvious; the effect of curvature has been thoroughly researched and is complex (Hickin and Nanson, 1975; Nanson and Hickin, in press), and the effect of sediment discharge is unknown at this stage.

In general, the first type of control is the magnitude of the inertial or centrifugal force exerted by the bench flow on the supporting outer (concave) bank. From elementary mechanics the opposing centripetal force (F) is specified by

$$F = \frac{m\ v^2}{r} \text{----------} 2$$

where m, v and r are respectively mass, velocity and radius of bend curvature.

For a given discharge in a developing bend, m is constant and v and width (w) are conservative variables over a wide range of bend curvatures (r/w). If we assume a direct relationship between F and the rate of lateral migration (M) as a first approximation, it follows that

$$F = CM = \frac{k}{(r/w)} \text{------------} 3$$

The limited data previously available for only one river (Nanson and Hickin, 1 in press) appear to validate equation 3 (Figure 1). A simple inverse relationship between migration rate and bend curvature seems to apply for $r/w > 2.5$. No attempt is made in this paper to model the complex interactive flow effects which lead to the positive relationship for $r/w < 2.5$, although discussions of the possible physical controls are given by Bagnold (1960), Hickin and Nanson (1975), Hickin (1977) and Begin (1981).

The role of sediment transport in equation 1 is also poorly understood. In the long run it must be sufficient to set the rate of lateral accretion equal to that of lateral erosion, but the rates must differ considerably in the short run. Indeed, our observations on Western Canadian rivers suggest that this divergence of accretion and erosion rates can lead to a cycle of lateral migration characterized by relatively short periods of rapid lateral erosion and longer periods of channel stability and point-bar construction (Nanson and Hickin, in press). The result is a concertina-like pattern of cut-bank retreat followed by point-bar catchup.

THE STUDY RIVERS AND DATA SELECTION

The 21 meandering river channels selected for study are located in British Columbia and Alberta (Figure 2). Basically, they are limited to two types: those with gravel dominant in the basal sections of the cut-banks, and those with sand there.

Channel migration was measured for between 4 and 35 bends on each river using time lapsed aerial photographs shown between 20 and 35 years apart. This provided migration data for 194 bends from the 21 rivers. Channel widths were averaged from several measurements in each bend, and radius of curvature was measured for each bend using the method described by Nanson and Hickin (in press). Cut-bank heights were measured in the field. Our field experience in Western Canada suggested that the 5 year flood on the annual series is approximately morphological bankfull flow, so this value was obtained from Water Survey of Canada records for all but 5 of the 21 rivers. For the remaining ungauged reaches estimates of bankfull flow were obtained from ground surveys and applications of the Manning formula. Slopes were surveyed in the field with the exception of 4 rivers where 1:25,000 map slopes were used.

The strength of bank material (its resistance to lateral erosion) was not directly measured because of the unresolved problem of quantitatively specifying and integrating the various strength components (such as material size, cohesiveness, stratigraphic relations, vegetative protection and binding, extent of ground ice, etc.). Instead, the mean diameter of the outer-bank sediments were simply noted in terms of ten Wentworth textural classes from silt to boulders, as well as an estimate of the dominant range of sediment size.

DATA ANALYSIS AND INTERPRETATION

The relation between bend migration rate (expressed in units of channel width ($M^* = M/w$) and channel curvature is shown in Figure 3A for all the bends studied. The data are enveloped by curves displaying the same basic characteristics as those describing the corresponding Beatton River data (Figure 1B). Maximum migration rates occur at $2.0 < r/w < 3.0$. In the domain $r/w < 2.0$, as the bend curvature tightens, M^* declines very rapidly to zero at $r/w \approx 1.0$. In the domain $r/w > 3.0$ maximum M^* increases with decreasing bend curvature in a manner consistent with the theoretical notion expressed by equation 3, that $M^* \propto \frac{1}{r/w}$ Figure 3A also reveals that many bends were not migratory ($M^* = 0$) during the 20-30 year photographic record. Although some of these cases might be explained by unusually resistant outer bank materials,most of them probably reflect a sampling problem related to the intermittent nature of channel migration, a phenomenon discussed previously. If the record were longer, most of these values probably would more closely conform to the long-term non-zero migration means, such as those obtained from tree-ring data on the Beatton River (Figure 1). By the same reasoning, of course, some of the migration rates plotted in Figure 3A are undoubtedly too high.

Simple averages of all bend migration rates by reach are not the best migration statistics for comparison because bend curvature distributions and the frequency of zero migration values vary between reaches. The most useful basis for comparison is the maximum migration rate exhibited by each reach, despite the possibility that some maximum values may reflect anomalous conditions such as unusually weak boundary materials. The distinct advantage of using the maximum migration rate is that such values mostly occur on bends where $2.0 < r/w < 3.0$, thereby minimizing the effect of bend-curvature variation. Similarly, the problem of non-migrating bends due to out-of-phase intermittent migration is overcome. Figure 3B shows the maximum migration data for the twenty-one test reaches, together with the envelope curves of Figure 3A. Nearly all the maximum migration rates plot within or very near the critical curvature zone $2.0 < r/w < 3.0$, with the exception of points 2 and 15 (these have been adjusted for,using a method that can be explained in verbal discussion).

Ignoring variations in sediment discharge (Q_s) between reaches, it should now be possible to express migration rate data directly in terms of stream power, strength of boundary materials, and bank height (from equation 1). Stream power can be expressed as -

$$\Omega = \gamma QS \text{ -----------------------} 4$$

where Q = is the five year flood discharge, S is channel slope, and γ is specific weight of water.

The relationship $M_{max} h$ verses Ω is graphed by bank material type in Figure 4. Clearly there is an orderly separation of channels with outer banks of gravel (solid circles) from those with sandy banks (open circles). The line of separation through the transitional cases of sandy gravel (half solid circles) has a 45° slope indicating that -

$$\frac{\Omega}{M_{max} h} = C = \tau_b \text{ ---------------------} 5$$

for a given calibre of outer-bank material. The corresponding family of linear graphs relating $M_{max} h$, stream power (Ω) and bank strength (τ_b) are assumed to meet at the origin, and are shown in Figure 5.

The results of Figure 5 are quite consistent, of course, with the intuitive notion that migration rate should increase as stream power increases, and decrease as bank strength becomes greater, other things remaining constant. The relation of bank strength (τ_b) to the textural character of basal material in the outer banks of the channel is shown in Figure 6. The bar lengths are proportional to sediment sorting, and the circle identifies the approximate median diameter (D_{50}). Clearly there is a positive, but rather surprisingly conservative, relationship between the coefficient of resistance to lateral migration and sediment texture ($\tau_b \approx D_{50}$). It is important to note, however, that this simple power relationship probably does not hold below the fine sediment range shown in Figure 6, because of fine sediment cohesion.

A MODEL FOR PREDICTING MAXIMUM CHANNEL MIGRATION RATES

The relations shown in Figures 5 and 6 represent a means for predicting the maximum rate of channel-bend migration. Estimates of τ_b can be obtained by measuring D_{50} in the field and determining the coefficient of resistance from Figure 6. The mathematical equivalent of this procedure can be followed by solving the following equations -

$$M_{max} = \frac{\Omega}{\tau_b h} \quad (\text{for } 2.0 < r/w < 3.0)\text{-------------}6$$

where the relation between τ_b and D_{50} is very conservatively approximated from Figure 6 by -

$$\tau_b = 125\ D_{50}^{0.36}\ (\pm 50\%)\ (\text{for } 0.05\text{mm} < D_{50} < 50\text{m})\text{--------}7$$

Equation 6 only applies to bends for which $r/w \simeq 2.5$, but it can be generalized to any bend curvature greater than 2.5 by introducing equation 3 where $k = 2.5$:

$$M_{max} = \frac{2.5\Omega}{\tau_b h\ r/w} \quad (\text{for } r/w > 2.5)\text{---------------}8$$

Combining equations 7 and 8 yields -

$$M_{max} = \frac{\Omega}{50D_{50}^{0.36}\ h\ r/w} \ (\text{for } r/w > 2.5)(0.01\text{mm} < D_{50} < 50\text{m})\text{--------}9$$

Equation 9 is offered as an essentially empirical device for predicting the maximum rate of channel migration for bends of varying curvature ($r/w > 2.5$). Like all empirical relationships, however, their predictive capability is obviously limited by the character of the data base. We have tested the model on three bends on the Mississippi River where we predicted maximum migration rates of 14-35m/year. The actual measured rates from maps of the Mississippi were 19, 20 and 22m/year. Testing of the model using British migration data is still proceeding.

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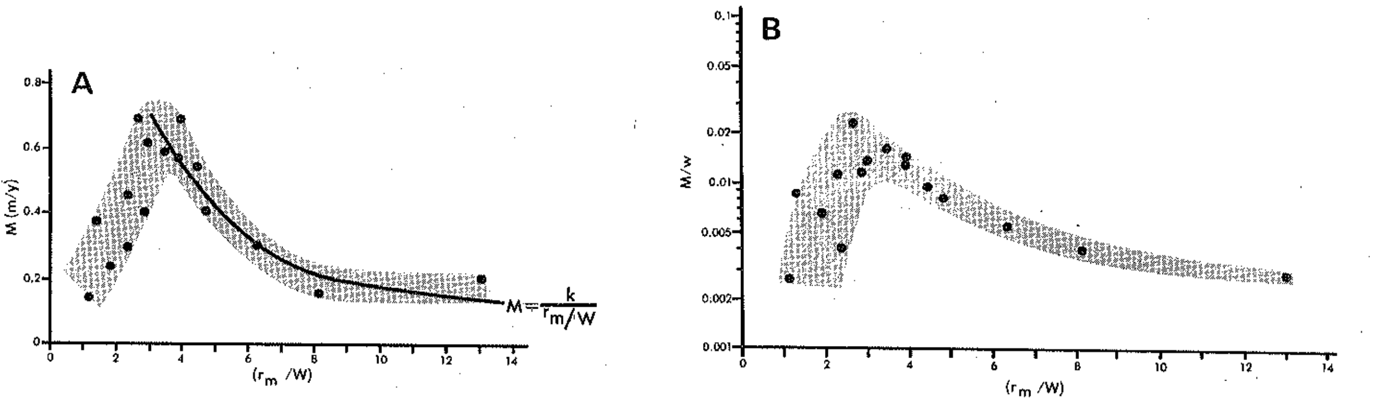

FIG. 1 Channel migration rate (in meters per year and in channel widths) versus channel curvature (radius of curvature/width)

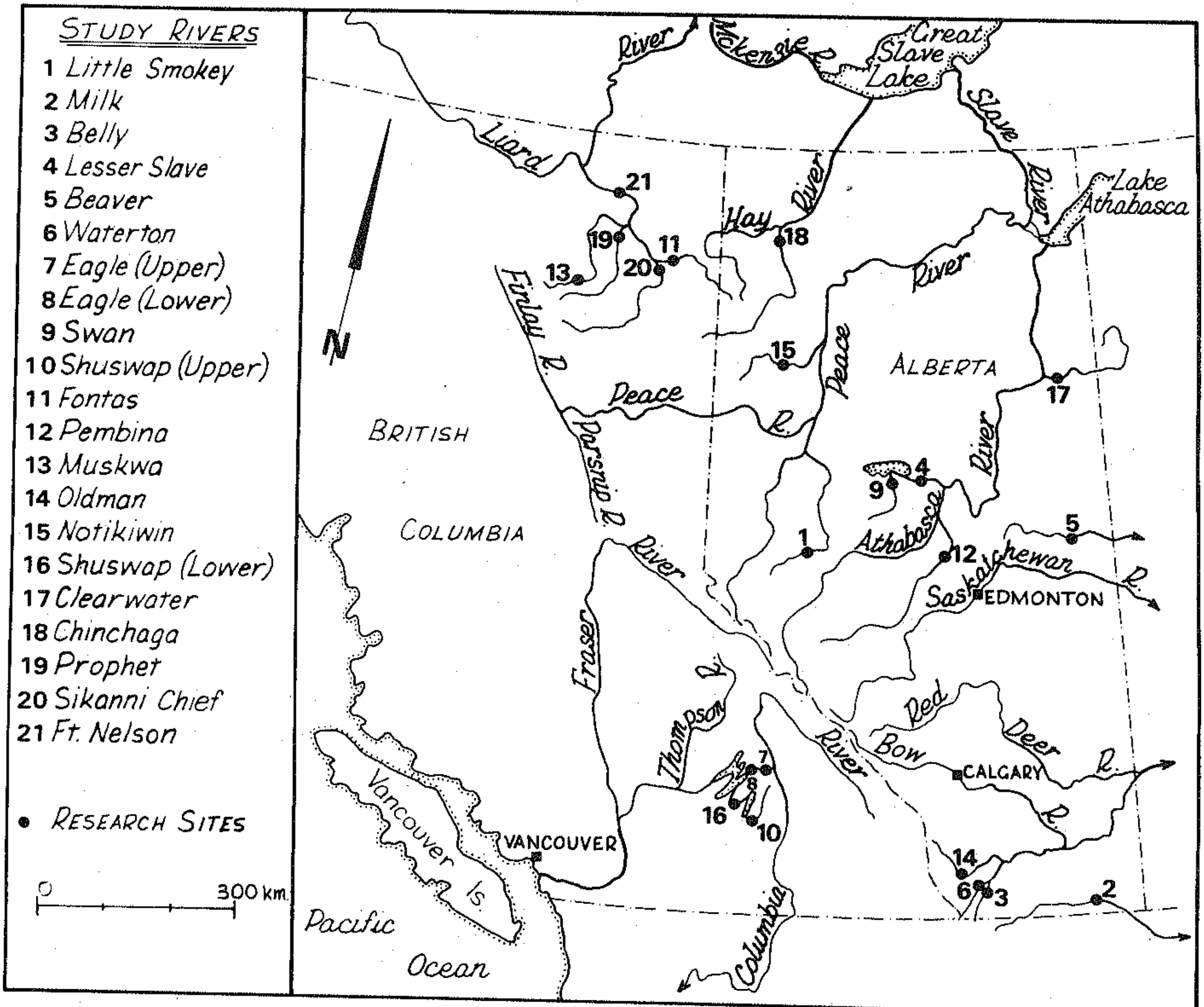

FIG. 2 The study rivers.

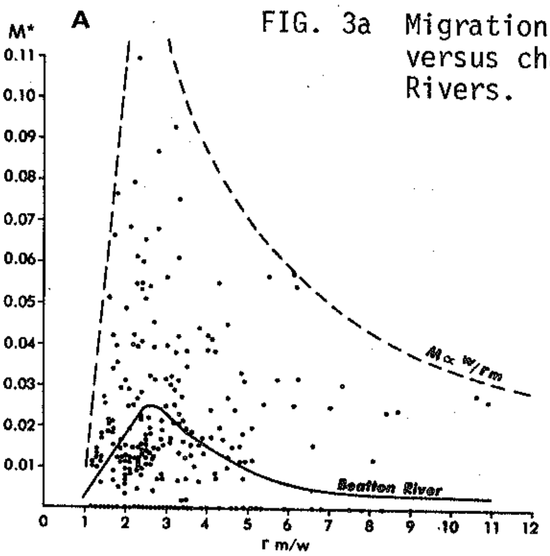

FIG. 3a Migration rate (expressed in channel widths per year) versus channel curvature for 194 bends on 21 Canadian Rivers.

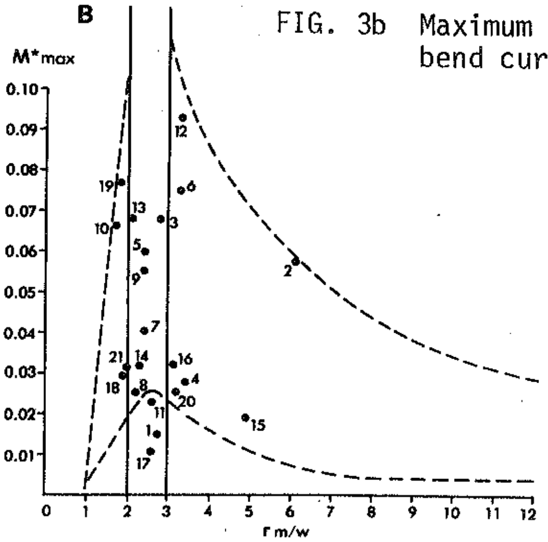

FIG. 3b Maximum migration rates (in channel widths) versus bend curvature for the most rapid bend on each river.

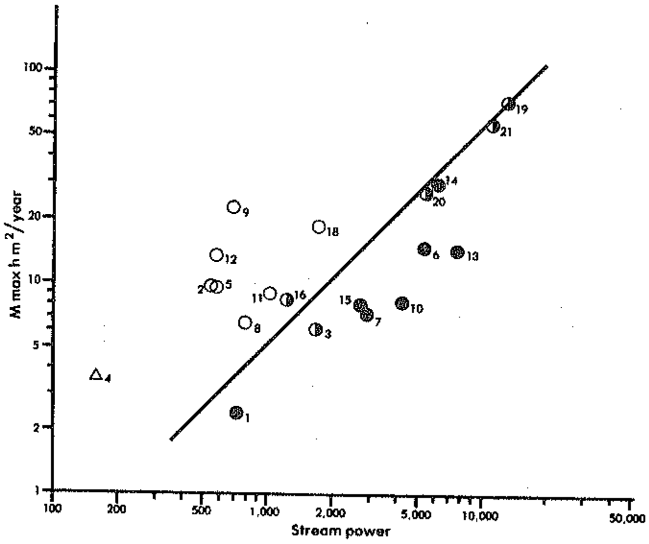

FIG. 4 Maximum migration rate versus stream power.

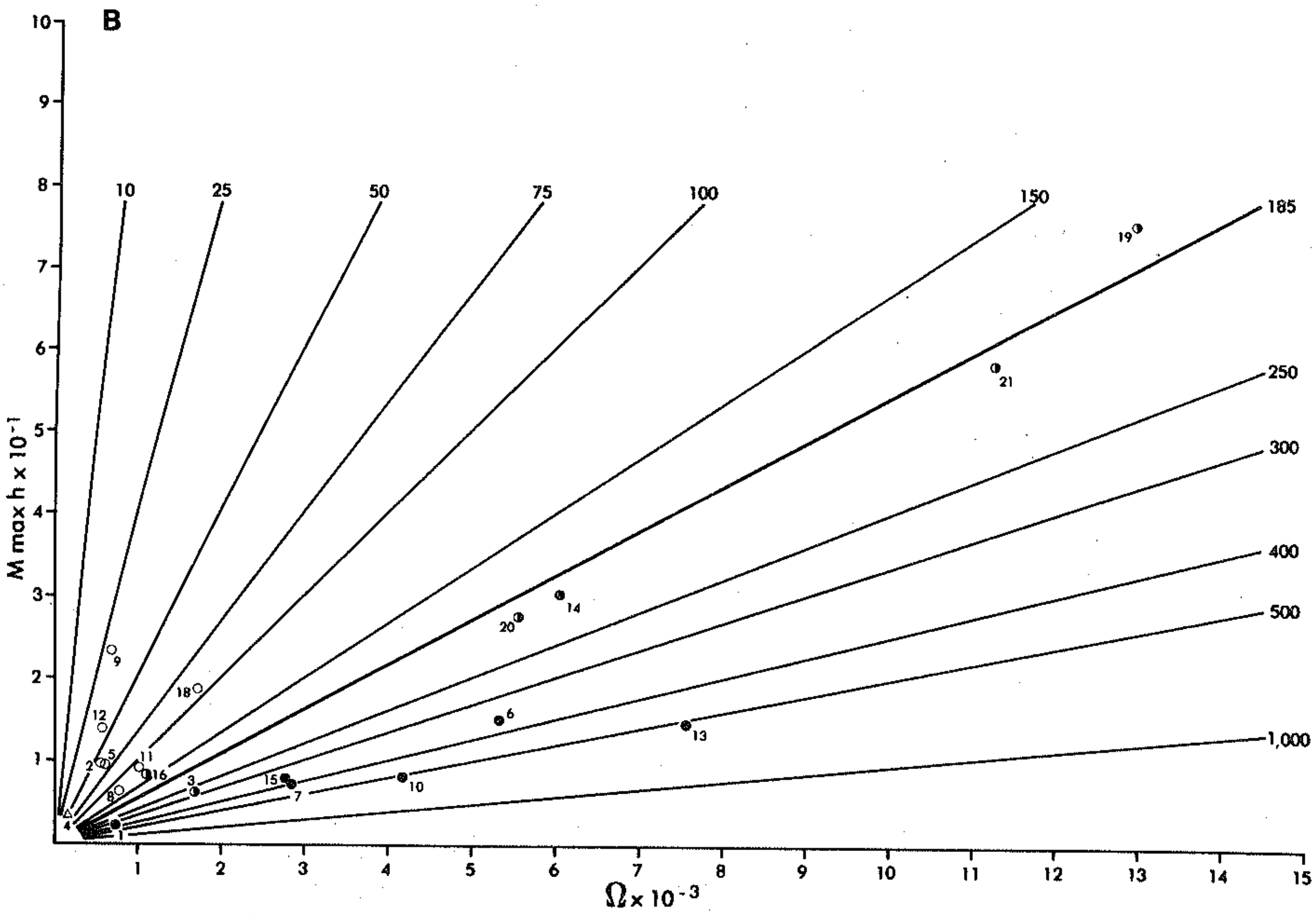

FIG. 5 Maximum migration rates X bank heights versus stream power for given bank resistances (τ_b)

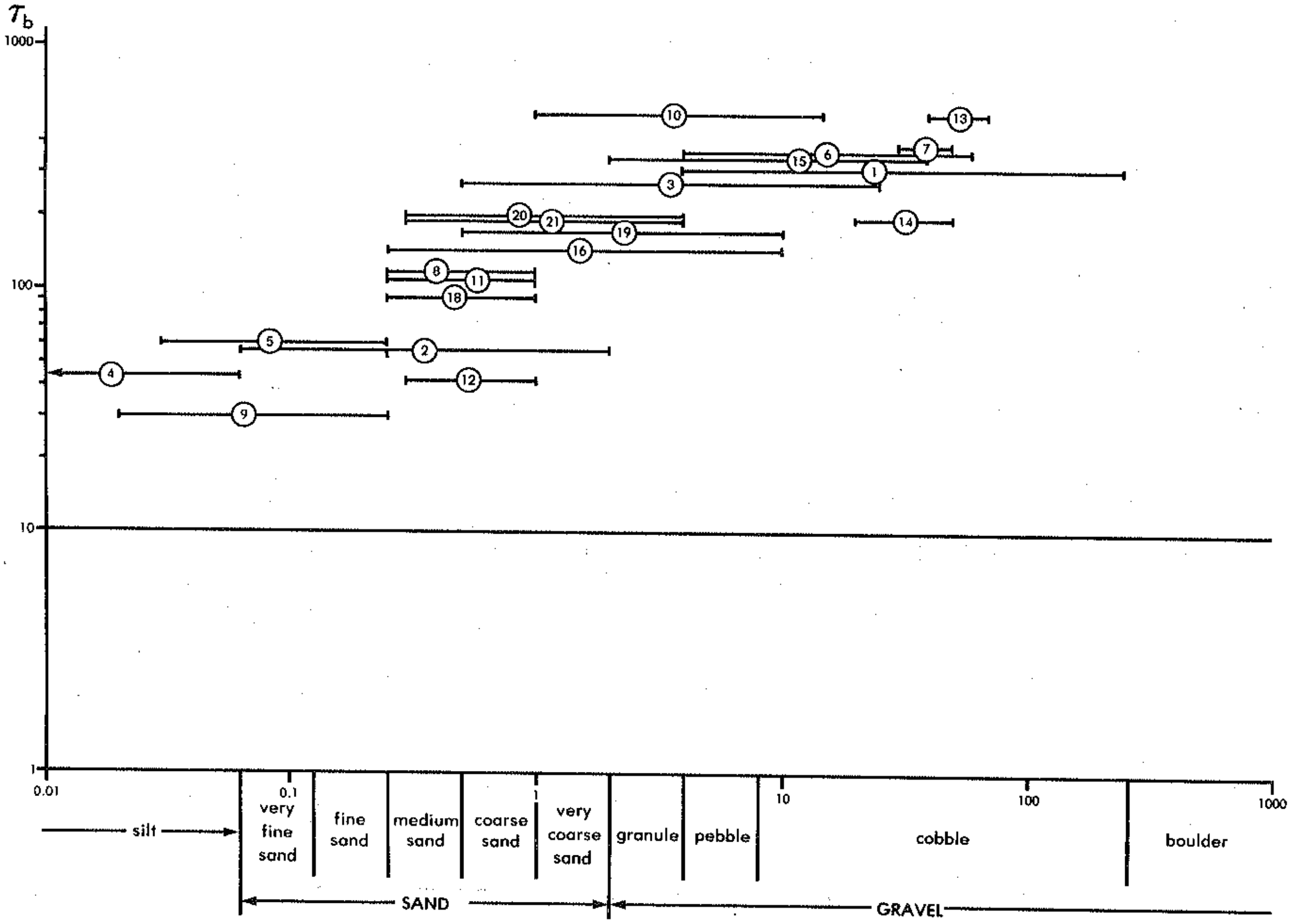

FIG. 6 Bank resistance (τ_b) versus sediment size.

LEFT & RIGHT HANDEDNESS AND MEANDER MIGRATION

David Dunkerly

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MEANDER CUTOFF SEDIMENTATION

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ABSTRACT

A survey of a meander cutoff on the Murrumbidgee River near Wagga Wagga revealed a slightly dish-shaped fine grained infill bounded at its lower margin by coarse sands and gravels of the pre-cutoff channel. Textural analysis of the infill sediments revealed tendencies for median grain size to decrease both vertically above the former channel bed and laterally away from the entrance and exit regions towards the central part of the cutoff. Some truncation of entrance and exit sediments appears to be indicated by the pattern of sedimentary units exposed at these locations.

INTRODUCTION

Meander cutoffs occur on the floodplains of most meandering rivers. They are typically produced by the short circuiting of meander loops during periods of overbank flow. Because they do not occur in flume channels formed in uniform materials (Friedkin, 1945) it is suspected that cutoffs are often produced by meander train distortions which in turn arise from inhomogeneities in the resistance of floodplain sediments.

Cutoffs perform two important geomorphic roles. During floods cutoff lakes are surcharged and contribute to water storage on the floodplain. On the Murrumbidgee River such storage is capable of effecting considerable hydrograph attenuation between Wagga Wagga and Narrandera (Murrumbidgee River Flood Mitigation Study, 1977). In addition cutoffs trap five grained sediments from suspension. Although textural data are not readily available in the literature it has been claimed (Carey, 1969) that cutoff infills contain the finest sediments likely to be encountered on the floodplain. In turn it is assumed that cutoff clay plugs form resistant bodies which retard channel migration and encourage renewed episodes of cutoff formation.

This study examines the morphology and sedimentary character of a meander cutoff in an advanced stage of sedimentation on the floodplain of the Murrumbidgee River near Wagga Wagga, New South Wales.

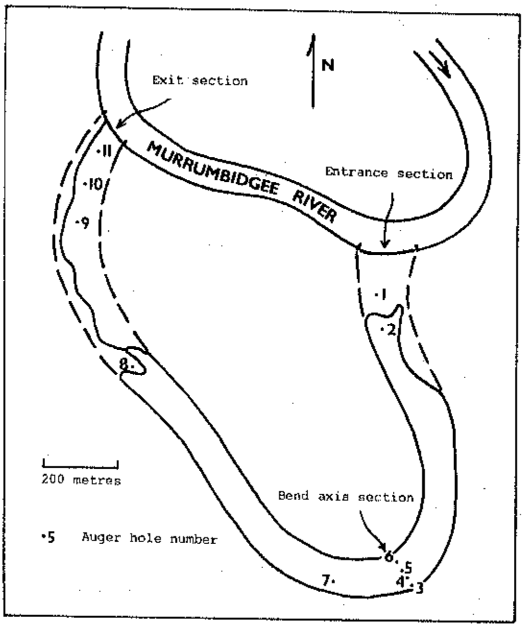

Figure 1. Location map of Flowerdale Lagoon showing survey sites.

TABLE 1

MEDIAN GRAIN SIZE OF FLOWERDALE SEDIMENTS

Sample site	Depth (m)	Median (ϕ)	Sample site	Depth (m)	Median (ϕ)	Sample site	Depth (m)	Median (ϕ)
Entrance site	0	3.5	Hole 4	4	7.0	Hole 9	5	7.2
	1	6.9		5	7.6	Hole 10	2	7.1
	2	6.9		5.5	7.9		3	7.5
	3	6.4	Hole 8	0	8.0	Hole 11	3	7.1
	4	6.2		1	8.2	Exit Section	0	5.4
Hole 1	1	6.2		2	8.2		1	6.1
	3	6.7		3	8.2		2	6.3
Hole 2	3	7.8		4	8.5		3	7.0
Hole 4	0	8.6		5	6.6		4	7.8
	1	9.3		5.5	6.5		5	4.6
	2	8.5	Hole 9	3	6.7		6	4.7
	3	8.4						

FIELD AREA

The Murrumbidgee near Wagga Wagga is a suspended load and sand and gravel bedload river with an average discharge of 120 m^3s^{-1}. At bankfull stage the channel is about 80 metres wide, 6 metres deep and has a slope and sinuosity of .0003 and 2.3 respectively. The upper half of the floodplain thickness is dominated by cohesive fine sand, silt and clay whereas the lower half is predominantly medium and coarse sand with basal gravel.

Near Wagga Wagga cutoffs are common with 20 examples occurring in a 50 kilometre length of valley up and downstream of the town. Most are single loops in an advanced stage of sedimentation and all are surcharged at levels below that of the two year flood on the partial-duration series. Flowerdale Lagoon (Figure 1) is a single loop cutoff located near to the western boundary of Wagga Wagga's residential area. It has a mean axial infill thickness of between 5 and 6 metres.

Transverse sections of the entrance and exit regions of the Flowerdale infill are exposed in cutbanks of the Murrumbidgee River. During May 1980 the lagoon floor was exposed after a lengthy dry spell and hand augering of the infill sediments was possible. Levels were determined by conventional instrument survey and reduced to local river gauge datum. Sediment samples collected at cutbank sections and auger holes (Figure 1) were subjected to textural analysis in a Sedigraph 5000D continuous grain size sampler housed in the Geography Department at the University of Wollongong.

CROSS SECTIONS OF FLOWERDALE INFILL

Three cross sections of the cutoff infill were surveyed (Figure 1). The dimensions of the pre-cutoff channel are defined by the top of the basal coarse sand and gravel layer present at each section. Similar sediments are found on the bed of the present Murrumbidgee channel.

Bend axis section (Figure 2)

Infill character at the bend axis was determined at four auger holes sunk into the lagoon floor. Although the water table was encountered in the first metre of three holes extraction of sediments to the basal sands and gravels was permitted by the highly cohesive nature of the grey lagoon muds. The 90 metre wide asymmetric channel surveyed corresponds closely to many modern bend sections on the Murrumbidgee River and does not suggest a significant post-cutoff change in river regime.

The boundary between the infill muds and the basal sands and gravels was abrupt in each hole. A short transition period from pre-cutoff channel flow to low energy lacustrine sedimentation is therefore suggested in this part of the cutoff. Similar sharp sediment boundaries were observed in holes 7 and 8. Although the lagoon muds are of essentially uniform character a weak upward fining trend is suggested by the median grain size data for auger hole 4 (Table 1). This trend is repeated at auger hole 8.

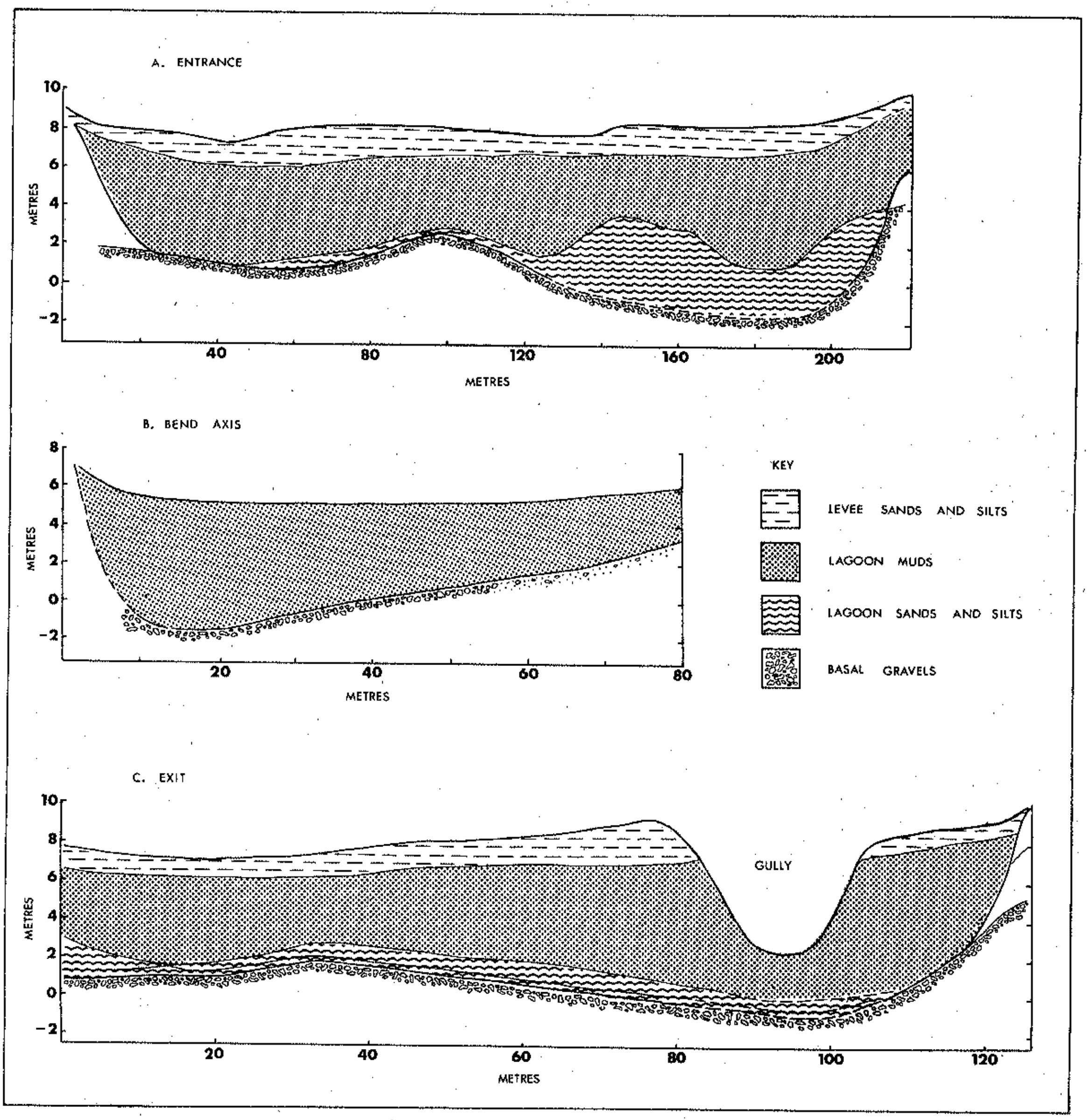

Figure 2. Cross sections of the Flowerdale Infill.

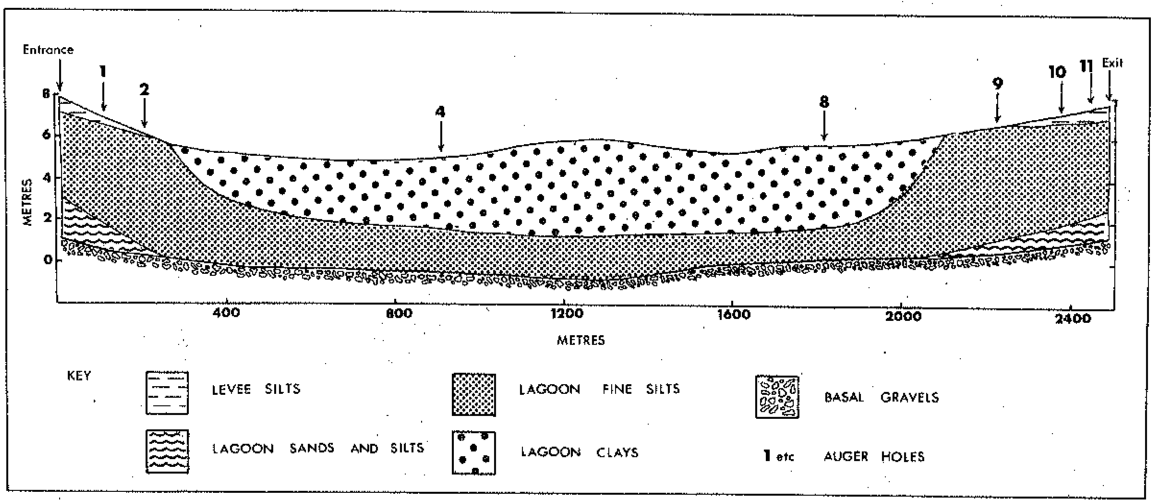

Figure 3. Longitudinal section of Flowerdale Infill.

Entrance section (Figure 2)

Cutbank erosion has exposed a wide infilled channel at the cutoff entrance. The gravel ridge centrally sited in the channel probably indicates the location of a former longitudinal braid island similar to those found on wide bends on the present river. The infill sediments at the entrance section are more complex than those exposed at the bend axis and include a stratum up to 3 metres thick of medium sands with occasional silt lenses directly over the basal gravels. The sands display cross laminations directed into the cutoff and appear to have been deposited by flow into the cutoff soon after its formation. These sands presumably helped to quickly isolate the central region of the cutoff from the high energy depositional environment close to the active channel.

Directly above the sand unit is a thick layer of uniform and strongly structured lagoon muds which passes abruptly into surficial sandy silts. This uppermost unit is between one and two metres thick, is structureless and retains rudimentary sedimentary stratification. It is interpreted as a recent levee deposit.

Exit section (Figure 2)

The exit section revealed a 120 metre wide channel with a particularly well defined cut-bank boundary. The sedimentary units present are similar to those at the entrance section and include basal gravels, thick lagoon muds and recent surficial levee silts. Above the basal gravels, however, is a unit consisting of 25 cm of coarse to medium sand and an overlying 75 cm of sandy silts which pass by a diffuse boundary into the lagoon muds above. The exit section is presently being trenched by a gully which discharges water into Flowerdale Lagoon after flood surcharge or local heavy rain.

LONGITUDINAL SECTION OF FLOWERDALE INFILL

The dimensions and textural characteristics of a longitudinal section of Flowerdale Cutoff are shown in Figure 3. The infill is dish-shaped with elevated areas near to the present Murrumbidgee channel and a depressed central area which is usually occupied by a shallow lake. The hump at the central part of the infill surface is the product of recent runoff from a nearby housing subdivision.

Because of inadequate definition of the fine tail of many of the 34 sediment distributions plotted by the Sedigraph 5000D it was decided to present data for median grain size only. For the purpose of illustration the infill samples were then classified by median size as clay (finer than 8ϕ), fine silt (6ϕ to 8ϕ), coarse silt (4ϕ to 6ϕ) and fine sand (2ϕ to 4ϕ).

Grain size data (Table 1 and Figure 3) indicate a tendency for sediments to become finer both with distance above the basal gravels and with increasing distance from entrance and exit regions towards the cutoff axis. These trends are consistent with decreasing energy of the environment in which the sedimentation occurred. Less clear, perhaps, is the presence of levee sands and silts directly above the lagoon muds at the entrance and exit regions.

DISCUSSION

Perhaps the most striking feature of the infill sediments is their fineness and their uniformity. The median grain sizes of the lagoon muds, which comprise over 95 per cent of the infill deposits cluster strongly around the silt/clay boundary of 8ϕ units. This value contrasts with values of approximately 0ϕ and 4ϕ for nearby point bars and concave-bank benches respectively (Page and Mowbray, 1982).

Basal gravels define the pre-cutoff channel perimeter at all sections. The sands and silty sands immediately above the gravels taper sharply away from the entrance and exit sections and are assumed to constitute the remains of sedimentary wedges which plugged the initial cutoff and isolated the cutoff lake from subsequent high energy channel flow.

The presence of sandy levee silts above the lagoon muds at both entrance and exit sections suggests a shift in the depositional enviornment and is consistent with lateral truncation of infill sediments by cut-bank erosion on river bends which presently intersect the lagoon infill (Figure 1). Modern levee sedimentation has simply deposited silts over the lagoon muds exposed by cut-bank retreat.

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MAN'S IMPACTS ON THE DRAINAGE SYSTEMS IN THE LOS ANGELES BASIN

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ABSTRACT

Urbanization of the Los Angeles lowlands caused additional runoff which soon overtaxed the natural, unstable channels. In order to prevent urban flooding, channels were enlarged, straightened and lined with concrete, and to maintain inproved capacities, it then became necessary to retain bedload sediments from mountains and foothills in a variety of structures. Such measures have resulted in a very costly and highly modified drainage system.

INTRODUCTION

The Los Angeles Basin is drained by four rivers: Los Angeles, San Gabriel, Rio Hondo and Ballona Creek. Their total catchment area of 4450km^2 includes, block mountains and canyons, interior valleys and alluvial fans, foothills, lower alluvial fans and coastal plains. The 1970 population was about 7 million or nearly three times the 1935 figure.

Two hundred years ago this area was virtually unpopulated. Winter floods and their sediment loads passed down the channels unchecked. In the course of massive, sprawling urbanization, these natural processes have become environmental hazards, threatening life and property, and very costly to manage. Other hazards such as earthquakes, bushfires and landslides also add to the problems of managing water and sediments.

This paper seeks to present details of some of man's impacts on the hydrology and geomorphology, largely in terms of catchment, channel and sediment-movement modifications.

THE AREA AND ITS MODIFICATION

Only 200 years ago the Los Angeles Basin was sparsely populated by Indians and Spaniards, who were inconvenienced by occasional floods, droughts and channel changes. The distinctive mountain, fan, valley, foothill and plain environments were drained by rivers which flooded mainly after winter rains. Ground water recharge of fans provided rising waters to maintain flow in the Los Angeles River near the original pueblo (Mann 1976). Elsewhere, underground water sources were good.

Figure 1 shows the four major drainage basins and landform types. Initially, this landscape was able to absorb a large part of rainfall inputs and runoff from the mountain canyons. Even the San Gabriel Mountains, with very steep slopes and only a chaparral vegetation cover, were capable of retaining moisture in deep weathered mantles (Troxell 1942). Obviously the coarse fan heads allowed infiltration of much mountain runoff. Areas of higher runoff were restricted to the finer sediments, mainly in the Santa Monica Mountains and the western part of the San Fernando Valley.

The main changes imposed by urbanization have been to seal these pervious surfaces, to restrict water entry to aquifers and to cause much higher proportions of precipitation to runoff more rapidly and in higher peaks. These processes have been aided by the development of storm drains. Urbanization on a large scale soon taxed local channel capacities and, since many of these were unstable fan washes, there were problems with shifting water courses. The only permanent channel locations were in canyons and in the gaps between interior and coastal valleys. Bushfires in the mountains and foothills destroyed protective vegetation (Rantz 1970) and allowed more runoff and greater sediment yields.

The physical impacts of urbanization therefore modified the hydrology of the catchment, which in turn required channel improvements. These in turn, served to emphasise the sediment problem. Each of these impacts is considered in the next three sections.

CATCHMENT AND MODIFICATION

There has been a progressive change to the natural surface during the process of urbanization so that about 44% of the total Los Angeles and San Gabriel catchments was affected in 1979 (Hoag 1982). In 1947 the figure was only 19.3%. The only major areas not urbanized are the San Gabriel Mountains, together with parts of the lower flanking foothill blocks.

Thus large surface tracts have been sealed and runoff is much higher than previously. Generally urbanization has affected lower rainfall areas (250-500mm per yr) and the highest rainfall (>1000mm) remains in the mountains. The impacts of such changes are summarized in Table 1.

CHANNELIZATION

Floods have been recorded and written about since first Spanish settlement (Lynch 1931) and in more recent times larger individual floods have been reviewed (McGlashan and Ebert 1918, Burke 1938 and 1952, Troxell and Peterson 1937, Troxell et. al. 1942, L.A. County Flood Control District 1943, Rantz 1970).

It was the growing inconvenience of flooding and channel migration with increasing urbanization which lead to the formation of the Los Angeles Flood Control District in 1915 (Rantz 1970). This was set up to control the waters of the four rivers and their tributaries. Federal help followed with flood control acts in 1936 and subsequently, which gave the Corps of Engineers authority and funds for: flood control basins, debris basins and channel improvements (Rantz 1970). Together the Corps and LACFCD have built 20 flood control reservoirs, 61 of 106 debris basins, and improved 560km of channel. Another 440 km are to be improved: 1520km of storm drains have been built at $700mill, with $1bill for the further 1000km required (Rantz 1970).

The efficient concrete channels of today are a far cry from the shallow (often < 1m deep), shifting channels of the past. The natural channels ranged from steep mountain canyons to sluggish conditions on the coastal plains (Tujunga Wash (1897) s = 0.018 - 0.0058, interior valley 0.0038, the narrows and L.A. 0.0039, lower valley .0032, coastal plain 0.0016).

There has been some tendency to increase channel slope in often near-straight concrete-lined channels, but earlier channels and washes had low sinuosities. In stabilising channels, their depths and capacities have been greatly increased, while roughness has been considerably reduced. They have a design capacity, based on a 4 day rainstorm to carry about the 100 year flood (War Dept. 1939).

Studies of hydraulic geometry reveal that velocity exponents are greater than those for width and depth (range 0.35 to 0.55). Water is exvacuated at high velocities which approach 10m/sec at capacity for some channels.

SEDIMENT CONTROL

This was necessary following the improvement of channels and it involves three methods:

1 check dams in steep, small catchment canyons. These are essentially sediment traps; 292 were built 1955-1975 (Brothers 1982).

2 debris basins, often in urban areas at or below canyon mouths. These can be cleaned out and 97 were constructed between 1928 and 1980 (Brothers 1982).

3 water storage dams in interior valleys and flood mitigation dams at the large canyon throats or on the plains. In the larger valleys water storages trapped sediments and volumes indicate a denudational range of 0.71 - 12.31 m/1000yr. Flood mitigation and sediment control from the large canyons are catered for by large control dams.

DISCUSSION

High urban investment in development of flood-prone landforms and slide-affected slopes attracts a high cost protection. The physical changes imposed by the large urban sprawl modified the catchment hydrology to the point where natural channels could no longer cope. It was then necessary to improve the channels. To maintain their capacity and efficiency, bedload sediment supplied had to be restricted. The impacts are on going and ever increasing in magnitude to points where consequent modifications of channels and sediment control will become necessary.

Development within the system is now enhanced by detailed studies of land categories and a complex response model (L.A.C.F.C.D. 1971), but these do not mean that main structural designs can be relied upon to cope with all future runoff.

CONCLUSIONS

This brief summary has attempted to show something of man's impacts in urbanizing the fans, foothills and plains of the Los Angeles Basin. The consequences of urbanization have also created the demand for a totally artificial drainage system to evacuate increased runoff, and which retains bedload contributions from mountains and foothills in various mitigation structures.

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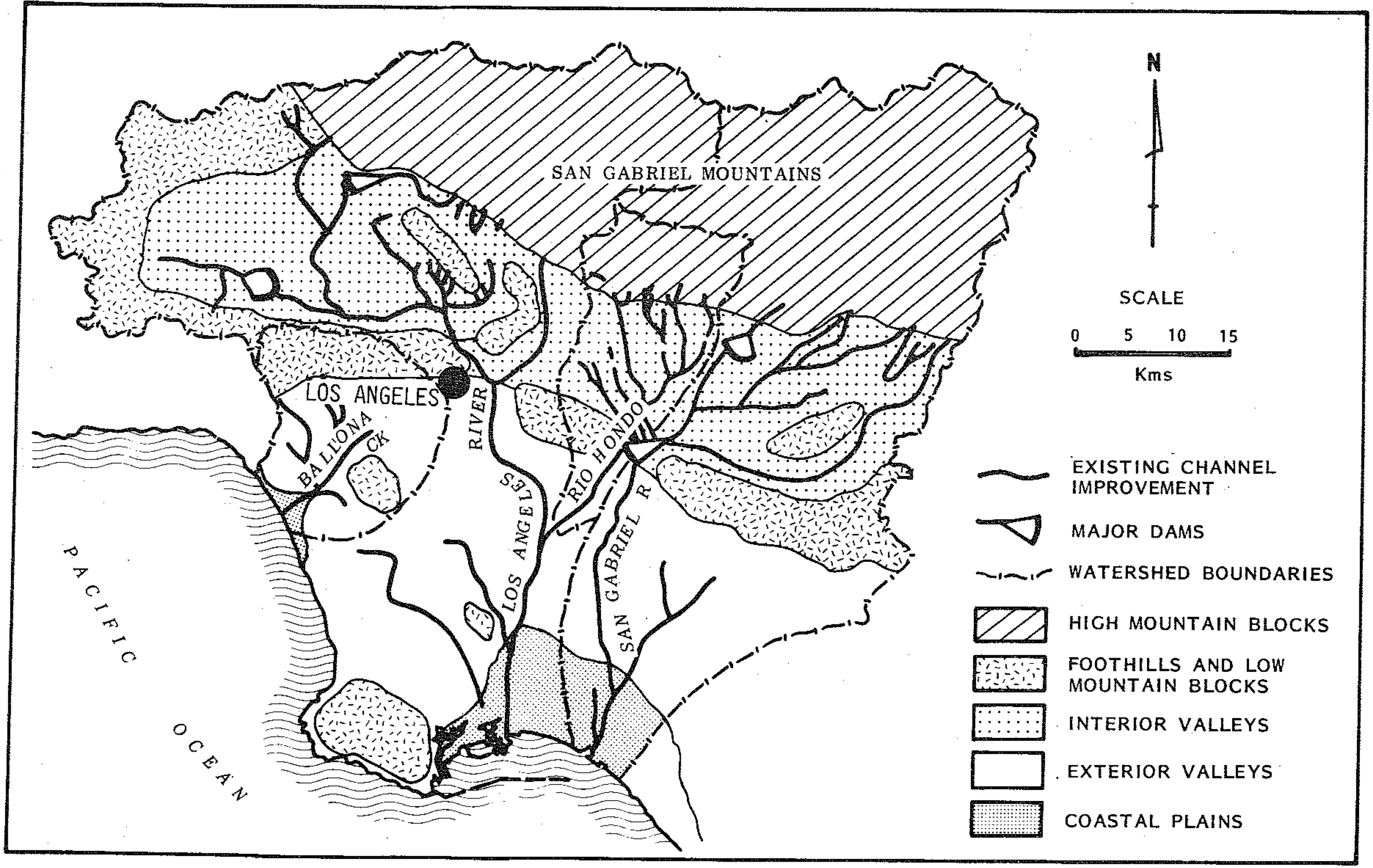
TABLE 1 HYDROLOGIC CHANGES BY LANDFORM TYPE:

LANDFORM	CHANGES	HYDROLOGICAL CHANGES
High Mountains	Few: Roads, Brushfires Check Dams: Debris Basins	Q^+ Q_s^+ Infil$^-$ Landslides$^+$ Q_p^+
Mountain Canyons	Few: Dams, Roads	Q, Q_s stored: valley floor aggradation, Q_p^+
Upper Fans	Orchards, then Urbanization	Q^+ Q_s^- (dams) Infil$^-$ W.T.$^-$ S.M.$^-$ Q_p^+
Interior Valleys (away from fans)	Farming, then Urbanization	Q^+ Q_s^- Infil$^-$ S.M.$^-$ Q_p^+
Foothills	Dams, Urbanisation, Roads Check dams: Debris Basins Brushfires	Q^+ Q_s^+ Infil$^-$ R.O.$^-$ Landslides$^+$
Outer Fans	Farming, then Urbanization Industrialization	Q^+ Q_s^- Infil$^-$ S.M.$^-$ W.T.$^-$ Q_p^+
Coastal Plains	Land fill, Drainage, Urbanization, Industralization	Q^+ Q_p^+ Q_s^- Infil$^-$

Q: discharge, Q_s: sediment discharge, Infil: infiltration, Q_p: peak discharge, W.T.: water table S.M.: soil moisture, R.O.: runoff

TABLE 2 CATCHMENT DATA FOR THE LOS ANGELES BASIN

CATCHMENT	AREA (km^2)	PERCENTAGE	CHANNEL LENGTH (km)	TRIBUTARY LENGTH (km)
Los Angeles	1950	44	80	360
San Gabriel	1808	41	93	121
Rio Hondo	355	8	32	96
Ballona Creek	334	7	14	30


SAN GABRIEL MOUNTAINS
LOS ANGELES
BALLONA CK
RIVER
LOS ANGELES
RIO HONDO
SAN GABRIEL R
PACIFIC OCEAN
N
SCALE
0 5 10 15
Kms
EXISTING CHANNEL IMPROVEMENT
MAJOR DAMS
WATERSHED BOUNDARIES
HIGH MOUNTAIN BLOCKS
FOOTHILLS AND LOW MOUNTAIN BLOCKS
INTERIOR VALLEYS
EXTERIOR VALLEYS
COASTAL PLAINS

A COMPARISON OF BANK EROSION IN SMALL URBAN AND RURAL CATCHMENTS

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Observations of reduced stability of stream channels in urban environments have frequently been reported (e.g. Wolman, 1967; Bonham, 1975). However, most of these observations are qualitative and provide little information to the engineer or planner charged with the task of designing an urban stormwater drainage network. As there is an increasing demand for urban watercourses that can serve as recreation and wildlife reserves and not just avenues for stormwater removal (Bonham, 1975; Brotchie, 1977; Keller and Hoffman, 1977; Talbot, 1979) details of the stability of channels in urban areas are becoming increasingly necessary. With this in mind an 18 month programme of channel monitoring was undertaken in small urban and rural tributaries of Dumaresq Creek, Armidale, in northeastern N.S.W.

THE STUDY AREA

Three small catchments on the northern valley slopes of Dumaresq Creek were chosen for monitoring. Catchment A (0.74 km^2) was 20.6% impervious as a result of urban development, while Catchments B (0.57 km^2) and C (0.43 km^2) were rural with predominantly unimproved and lightly grazed pastures. In other respects, such as soils and slopes, these catchments were similar.

Three distinct types of rural channel could be identified. These included broad shallow depressions in the headwaters, gullies on the steeper slopes, and stream channels. In both rural catchments the channel morphology altered frequently from one form to another. The urban tributary channels were consistently larger than the adjacent rural channels (except rural gullies) and the variability in channel form was much less. Along all channels, whether they be rural or urban, gullies or depressions, knickpoints were observed in the channel profile. These were spaced between 10 and 220 m apart, but more frequently between 25 and 37.5 m. The knickpoint faces were usually inclined at or near 90^0 and were commonly 0.5 to 0.7 m in height. Because of disturbances due to infilling, realignment and so on, the knickpoints in the urban channels were not as frequent or well developed.

METHODS

Along the channel boundaries 15 cm nails were used as erosion pins, and were measured on average every 10 days over an 18 month period. To supplement these observations, cross-sectional surveys of the channels at fixed sites were repeated every four months, using a tape and rule on the smaller channels, and a level and staff on the larger.

Small broad-crested compound rectangular weirs (U.S.D.A., 1964) with pressure bulb water level recorders and rising-stage suspended sediment samplers were installed to collect streamflow and sediment yield data over the same period.

CATCHMENT HYDROLOGIES

Complete streamflow and sediment yield data are only available for Catchments A and B. Between these two catchments there was a six fold difference in runoff over the eighteen month study period (312.7 mm depth from Catchment A compared to 52.4 mm depth for Catchment B). On a storm-period basis this difference varied considerably, but was most pronounced for the smaller flows. Significant differences in peak discharge, lag time, time of rise and base time of the hydrographs were also observed. The suspended sediment yield from Catchment A was six times that of Catchment B (15.25 $m^3km^{-2}yr^{-1}$ compared to 2.5 $m^3km^{-2}yr^{-1}$), while bedload movement in both catchments was restricted by the supply of material and occurred predominantly after some form of disturbance.

RATES OF CHANNEL CHANGE

In both catchments, collapse (mainly slumping) at knickpoint sites was the predominant mode of channel erosion. Detailed surveys of selected knickpoint scarps further revealed that most headwall retreat occurred as a result of collapse after and not during streamflow. Between runoff events channel erosion continued at a slow pace. This was the result of moisture content changes (swelling and contracting of the banks), raindrop impact, frost action, and trampling by humans and animals.

No significant change in channel size occurred during the 18 months in either Catchments B or C (Figure 1). In contrast, at two sites within Catchment A (sites A1 and A6) there was considerable change. Site A1 was adjacent to a roadway. Here the pattern of channel erosion and deposition reflects periods of deliberate infilling, high sediment inputs, and an altered drainage network, all of which were associated with the reshaping and bitupaving of this street. These effects, combined with additional sediment inputs from a housing construction site, were also transferred via the stormwater drainage network to site A6 further downstream. Apart from these two sites the remaining urban channel reaches were unaffected by these disturbances.

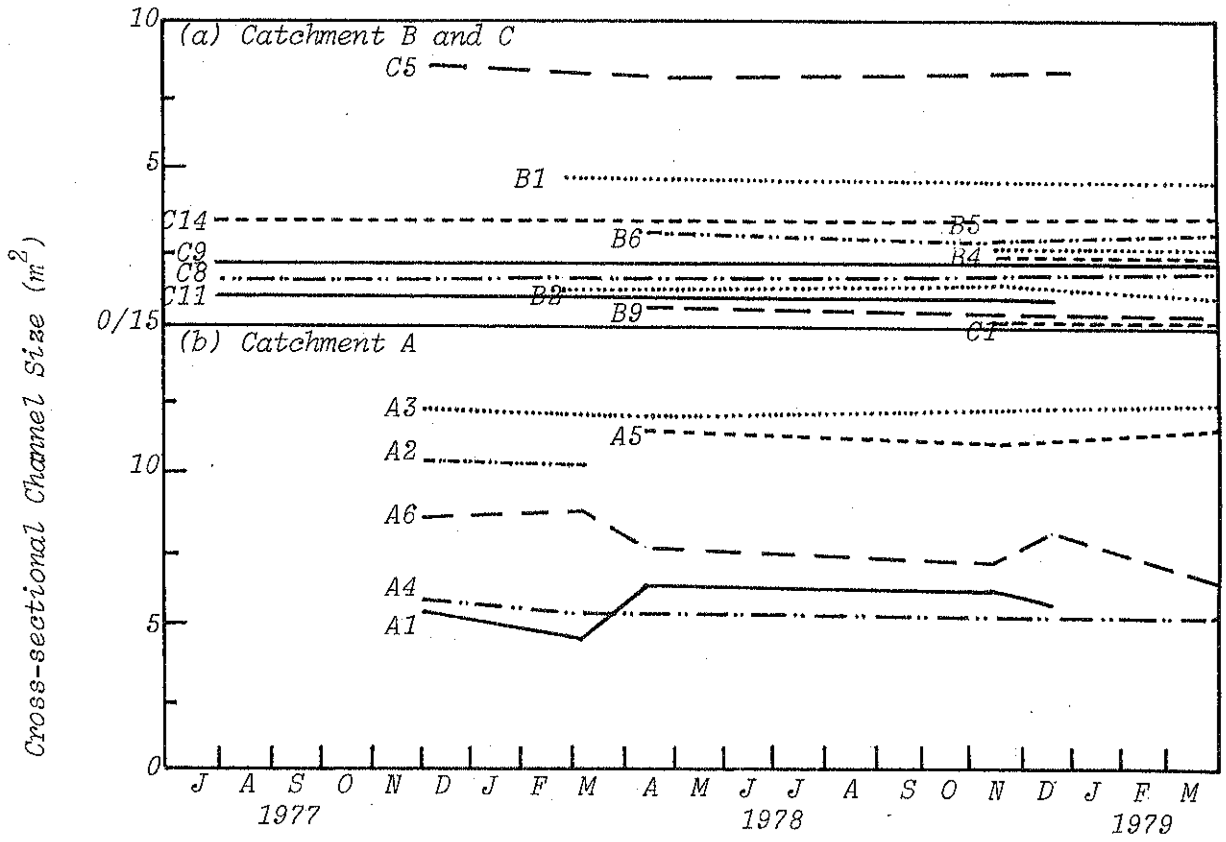

FIGURE 1: Changes in cross-sectional channel size, Catchments A, B and C.

More detailed observations of channel stability are available from the erosion pin data. For the 18 month study period the average channel erosion in Catchment A was 112 mm compared to 44 mm in Catchment B (Figure 2). The most significant difference in erosion rates occurred in late January - early February, 1978, when an average of 24.6 mm was eroded in Catchment A but only an average of 1 mm in Catchment B. On this occasion runoff was minimal in Catchment B (Figure 2). Erosion in early May 1979 in Catchment B, was unaccompanied by erosion in Catchment A. However, in this case erosion in Catchment B did not result from surface runoff. A dry period preceding this event had led to extensive drying and cracking of the channel boundary, so that moisture absorbed during rainfall in early May led to numerous collapses. This phenomenon did not occur in Catchment A because minor flows during this relatively dry spell kept the channel from drying out to the extent of that observed in Catchment B.

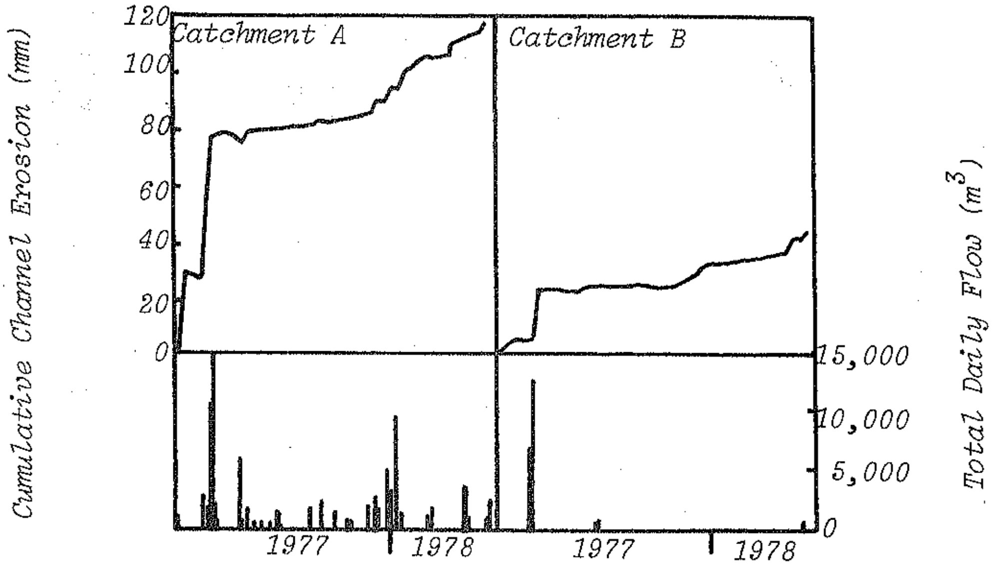

FIGURE 2: Channel Erosion and Runoff over time for Catchments A and B.

Despite the obvious differences in the rate of channel erosion between these catchments, the two cumulative erosion graphs (Figure 2) are remarkably similar in form. That is, periods of erosion in Catchment A usually coincide with periods of erosion in Catchment B. Thus the increased incidence of flow events in the urban catchment (3.7 times as many as that in the rural), is having little impact on channel erosion. This is not entirely unexpected since the additional flows in the urban catchment were predominantly minor.

ANALYSIS OF CATCHMENT DIFFERENCES

For Catchments A and B the variation in channel erosion over time was correlated against various hydrologic characteristics. The results of these analyses are provided in Table 1.

Table 1: Correlation of Channel Erosion (r) against Selected Hydrologic Parameters

	Catchment A	Catchment B
Peak 15min. rainfall intensity (mm)	0.49**b	0.55**bc
Total discharge (m^3)	0.85**a	0.95**a
Peak discharge ($l.s^{-1}$)	0.44**b	0.96**a
No. of peak flows	N.S.	0.69**b
Duration of surface runoff (hrs)	N.S.	0.75**b
Total runoff in preceding week (m^3)	N.S.	N.S.
Average sediment concentration ($mg.l^{-1}$)	N.S.	0.31*c

** Significant at 0.01
* Significant at 0.05

Letters indicate r values not significantly different. Interpret catchments independently.

The strongest relationships are between total discharge and channel erosion in both catchments and also between peak discharge and erosion in Catchment B. However, the independent variables were themselves highly intercorrelated and it may be that total discharge is only a good indicator of channel erosion in these catchments because it provides information on other aspects of streamflow. To use an example from Catchment B, the correlation coefficient between total discharge and erosion was 0.95 and between the duration of surface runoff and erosion it was 0.75. But the correlation between total discharge and duration of surface runoff was 0.80. To what extent does the relationship between total runoff and erosion reflect the relationships of these two variables with the duration of surface runoff? To test this, the correlation between erosion and each independent variable was recalculated with the remaining independent variables held constant. This technique is commonly known as partial correlation. It

"...is an index of the linear relationship that would still exist between these variables if all linear influences of one or more other variables could be removed." (Hays, 1981).

The results of these analyses are presented in Table 2.

Table 2: Partial Correlation (rp) of Erosion with Selected Hydrologic Parameters

	Catchment A		Catchment B	
	rp	rp^2	rp	rp^2
Peak 15min. rainfall intensity (mm)	0.38	0.14	0.43	0.18
Total discharge (m^3)	0.87	0.76	0.53	0.28
Peak discharge ($l.s^{-1}$)	-0.01	0.00	0.48	0.23
No. of peak flows	-0.26	0.07	-0.37	0.14
Duration of surface runoff (hrs)	-0.60	0.36	-0.16	0.03
Total runoff in preceding week (m^3)	0.22	0.05	0.00	0.00
Average sediment concentration ($mg.l^{-1}$)	-0.22	0.05	0.47	0.22

In both catchments total discharge remains as the most important independent variable. In Catchment B, total discharge accounts for 28% of the variance of erosion not accounted for by the other factors, and the bulk of the correlation between each variable and erosion is indirect. In Catchment A, total discharge accounts for 76% of the variation unaccounted for by the other factors.

To characterise the relationships between total discharge and channel erosion, regression analysis was employed. In an attempt to provide a better fit than that provided by linear regression alone, exponential and polynomial regressions with the data were also undertaken. The line of best fit in Catchment A, is a second order (quadratic) polynomial regression of the form:

$$E = 0.721 - 0.22.10^{-4}QT + 0.318.10^{-6}QT^2$$

$N = 45$, $r = 0.98$, $r^2 = 0.96$, $p < 0.001$

where E is channel erosion (mm), and
QT is total runoff (m^3).

For Catchment B a simple linear regression suffices:

$$E = 0.402 + 0.85.10^{-2}QT$$

$N = 49$, $r = 0.95$, $r^2 = 0.90$, $p < 0.001$

At first sight it seems that landuse has had an impact on the relationship between total discharge and erosion. In the rural catchment this relationship is linear while in the urban catchment it is curvilinear. However, in both catchments, and particularly in the rural environment, the data available for analysis have been severely restricted by the low number of runoff events. In Catchment B there were no periods with a total discharge between 2,000 and 24,000 m^3 and only one event above 24,000 m^3. In Catchment A there were seventeen periods with total discharge between 2,000 and 24,000 m^3. To illustrate the effect of these insufficient records on the data analysis, the seventeen periods in Catchment A just mentioned were deleted from the data file and the regression analyses undertaken once again. The line of best fit for Catchment A is now a simple linear regression of the form:

$$E = 0.351 + 0.82.10^{-2}QT$$

$N = 28$, $r = 0.98$, $r^2 = 0.97$, $p < 0.0000$

Since this regression function is similar to that for Catchment B it is possible that one unique relationship may characterise the entire data set, regardless of the catchment that these data were obtained from. If this were the case, then the impact of urbanisation would not be to modify the relationship between streamflow and erosion from that observed in the rural environment, but rather to promote a shift in scale. Analysis of covariance confirms that these two sets of data come from a population with a common regression line. This is not evidence that if additional data were available for Catchment B that the relationship between total discharge and erosion would also be curvilinear. Rather it casts doubt on the interpretation of these data because of the small sample sizes. If further study were to confirm that the relationship between erosion and runoff in both catchments were similar, then we would have an important tool for predicting channel stabilities under various levels of urban development.

A knowledge of the channel erosion processes does not entirely resolve this dilemma because of the interaction of channel form and process. In both catchments collapse at knickpoints as a result of slumping was the dominant mode of channel change. The relative importance of this process in Catchment B as opposed to Catchment A was higher, but this is because there were fewer knickpoints in Catchment A. In addition there was no evidence that the incidence of bank collapse per knickpoint differed between the catchments. If one could assume that the relative dominance in processes was a function of channel form alone, then there is some support for the idea that the relationship between erosion and streamflow is similar for both urban and rural environments. This is a particularly important problem, but one that cannot be resolved with the available data.

CONCLUSIONS

Channel change in Catchments A and B occurs predominantly as bank collapse. Channel erosion in Catchment A, however, was two and a half times that of Catchment B, and seems to reflect the increase in runoff for the less frequent flow events. Even during periods of frequent low flows in Catchment A channel erosion was minimal. It is possible that a similar relationship between the volume of runoff and channel erosion could apply to both catchments, and that total discharge during a storm provides a good indicator of the average channel erosion in a catchment. Further research on this aspect of urban stream channels is necessary, for the ability to predict the nature and the rates of channel change in urban areas could markedly improve the design and management of urban waterways.

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RELATION BETWEEN LAKE GEORGE LEVEL AND WINDSOR FLOODS

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Abstract

Auto-correlation and lag cross-correlation analyses suggest that the relation between Lake George water levels and Windsor flood frequency has remained constant since 1857 but that it was different from the present in the period 1818-1856.

Introduction

Two of the longest records of hydrologic regime in Australia are available from Lake George and Windsor. Estimates and measurements of Lake George levels extend back to 1818 while records of Windsor floods commenced at circa 1799. An important fact about the two records is that they may be used to define the hydrologic regime at the extremities of the one catchment, namely the Hawkesbury (Fig 1). Thus, a comparison of the two records over the period 1818 to the present may indicate spatial and temporal variations in the hydrology of the Hawkesbury.

It is the aim of the present paper to compare the two records in order to define the nature of the relation between them.

Nature of the records

Lake George levels have been compiled by Jacobson and Schuett (1979) from records collected by Russell (1886), Bureau of Mineral Resources (including C. Burton's 1967 compilation), N.S.W. Department of Public Works and Water Resources Commission. Apparently no records were collected between 1930 and 1946 (Fig 2). The lake was probably dry for most of this period although there is evidence of water in the lake on occassions (Jacobson, 1979, pers comm.). The early period of the record, compiled by Russell (1886), must be considered with some caution since Lake George was not discovered until 1818 (Woolley, 1974) and Russell used many aproximations to get his hydrograph. For this study the December level of the lake is assumed to represent lake level for the calender year. The data do not warrant an attempt at estimating annual mean lake level.

The Windsor flood record is a stage record. The gauging station is not rated because of tidal and backwater influences. The record is well documented. The most recent compilation, that by the N.S.W. Department of Public Works, relies on data gathered by Josephson (1885), Tebbutt, reports in the Windsor-Richmond Gazette and State Emergency Service, Windsor Council and other government organizations. For the purpose of this study only floods that fill the channel and begin to inundate the floodplain, that is floods of at least 6 metres height, are considered herein (Riley, 1981, Table 2). Six metres is the level identified as minor flooding and is probably close to perception level (Gerard and Karpuk, 1979). Thus the probability of omissions is low.

Subdivision of record

Six periods are considered herein in order to assess the temporal association between lake level and flood frequency. These periods are:

1) 1818-1978 2) 1818-1930 3) 1946-1978 4) 1818-1856 5) 1857-1893 6) 1894-1930

The first period is the entire length of common record although the 1799-1978 Windsor record is examined for autocorrelation. Periods 2 and 3 are selected in order to avoid the 1930-1946 period of missing data. Period 3 is also chosen in order that the most recent period can be compared with earlier periods, there being evidence that period 3 is hydrologically different from the earlier periods (Cornish, 1977; Riley, 1980; Pickup, 1976; Abrahams and Cull, 1979). The 1818-1930 period is split into 3 near equal period (periods 4,5 and 6) in order to test for homogeneity in the second period.

Comparison

The method of comparison used herein is correlation analysis of the time series in the time domain. Comparison of auto and lag cross correlograms of the two records for the six periods will enable the temporal trends in the relations within the records and between the records to be identified. The techniques of auto and lag cross correlation are described by Yevjevich (1972), Kisiel, (1969), Kendall (1973), and Charles (1975). The program suite developed by Akaike and Nakagawa (1972) was run on a UNIVAC 1106.

Autocorrelation

Persistence is common in hydrologic data and its nature partly characterizes the hydrologic system (Chow, 1966, 8-12; Raudkivi, 1979; Ribeny, 1970). Autocorrelation analysis enables persistence to be identified.

Correlograms of autocorrelation of the number of floods per year at Windsor gauge show no significant correlations for the short period records (Fig 3) except for 2 points in the 1818-1856 correlogram and 2 in the 1857-1893 correlogram. The exceptions may be explained in terms of the number of expected spurious significant correlations at the 5 % level. For the longer periods correlations are significant up to a lag of 13 years.

Whilst the lag correlations for the short periods are generally not significant at the 5% level there are certain similarities among them and with the correlogram of the longer time period. There is a high correlation for lags 0 to 5 years and a low correlation for lags 5 to 10 years for the periods 1818-1856 and 1894-1930. A peak positive correlation is also present in three of the correlograms for lags of approximately 12 and 25 years. The correlograms of the 1857-1893 and 1946-1978 periods differ from the other 4 correlograms although the difference is not statistically significant.

The 1818-1930 and the 1799-1978 correlograms differ in form. The latter is more typical of the correlograms for the short periods. However, the differences are not statistically significant.

Lake George levels show significant autocorrelations up to 8 years for the short records (Fig 4). The autocorrelations are significant up to 13 years for the long records. The correlograms are similar although the 1818-1856 correlogram more closely resembles the 1818-1978 and 1818-1930 correlograms than the correlograms of the other short periods.

The differences between the autocorrelation correlograms of Lake George and Windsor may be attributed to differences between the hydrology of flood events and lake storage. Variations in lake levels are more damped than are variations in the number of floods per annum. Matalas (1967,p.823) notes that autocorrelation coefficients of annual flood discharges are low. Flood frequency autocorrelations should be even less significant. Neverthless, for the long periods there is a significant 10 to 15 year persistence in both lake levels and flood frequency. For the shorter periods the persistence is significant only to lags of approximately 5 years in lake levels.

Lag cross correlation

Neither lake levels nor flood frequency are ideal indicies of hydrologic regime. Ideally the comparison of the hydrologic regime of areas should be in terms of water volumes, i.e. lake volume and annual discharge. However, whereas lake levels may be related to volume of water in storage the data are not available to enable flood frequency to be related to annual discharge. Hence, the correlation of Lake George levels with Windsor flood frequency should not be good.

The lag cross correlogram of the 1818-1930 period shows significant positive correlation for lags of 0 to 15 years and significant negative correlations for -20 to -35 and 26 to 40 years (Fig 5). The implication of the significant lags is that high lake levels suggest high flood frequencies for the next 10 to 15 years. High flood frequencies suggest low lake levels in 20 to 30 years time. There appears to be symmetry about a lag of 5 years.

The correlograms for the shorter periods differ from that of the long period. They also differ from each other. The 1818-1856 correlogram shows a significant positive correlation for lags 3 to -12 years and 0 to 4 years. The other 3 short period correlograms show at least one significant negative correlation for lags of between -5 and -10 years and all except the 1857-1893 show no significant correlation for lags 0 to 10 years.

Discussion

From the autoregression correlograms it may be concluded that runoff and water storage events persist for 10 to 15 years in the Hawkesbury catchment. The persistence has been statistically constant since 1818.

Autocorrelogram patterns of annual rainfall in the catchment are similar to correlograms of the Windsor flood frequency in that there are significant correlations for lags 0 to 2, 13 and and 22 years and low correlations for other lags (e.g. Mt Victoria , for 1872 to 1976 , Fig 6). However, at this stage of the investigation insufficient rainfall records have been examined.

The unlagged correlation between Lake George levels and flood frequency is significant for all the periods except 1857-1893 and 1894-1930. The correlograms are essentially the same except for the 1818-1856 period. In the latter case there are significant peaks that do not occur in the correlograms of the other periods.

The apparent symmetry in the 1818-1930 correlogram about the 5 year lag may be a result of the time it takes the flood runoff regime to adjust to changes in the hydrologic regime of the upland areas of the Hawkesbury.

The differences in the cross correlation correlograms suggest spatial changes in the hydrologic regime of the catchment. The lag cross correlograms suggest that the period 1818-1856 is different from the remainder. The auto correlograms suggest a slight difference in the period 1857-1893. Previous studies of the Windsor record (Riley, 1980) suggest that the 1799-1879 period differs significantly in terms of flood magnitude from the period 1880-1979. The lag cross correlograms suggest a significant change in the hydrologic cycle in the Hawkesbury catchment and support the hypothesis that prior to c1856 the hydrological connection between southwestern and eastern extremities of the Hawkesbury was different from what it is presently. Whether these changes are climatic or a response to land use is a matter for further investigation. However, it is worth noting that the Lake George area and the lower

Hawkesbury catchment occupy different zones in the mapped relation between rainfall and latitude of the surface high pressure belt (Pittock, 1975, 1978).

Conclusion

Correlograms of autocorrelation and cross correlation of Lake George levels and Windsor flood frequency show significantly consistent patterns over time in the Hawkesbury catchment for all except the 1818-1856 period.

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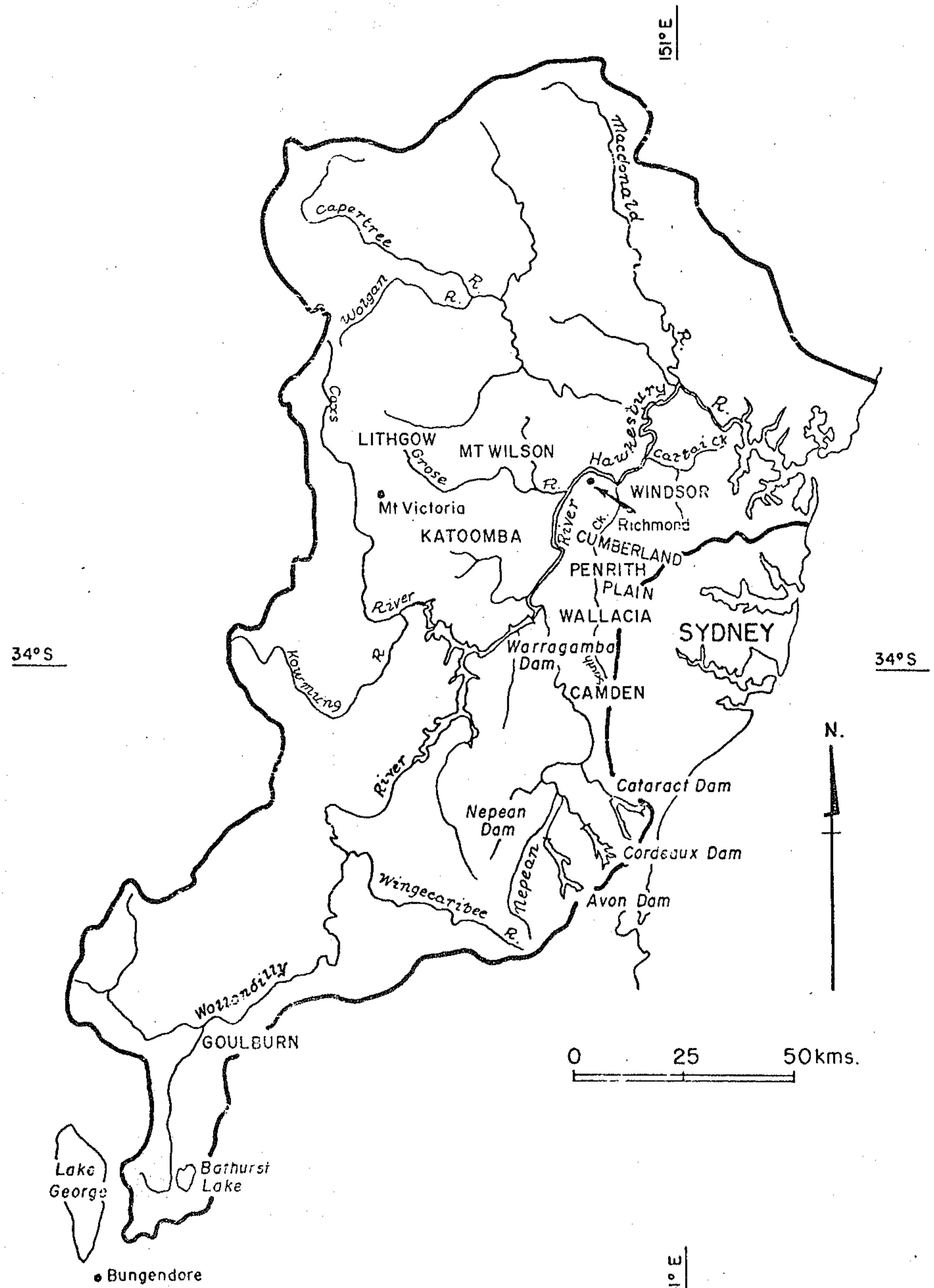

Figure 1. Hawkesbury catchment

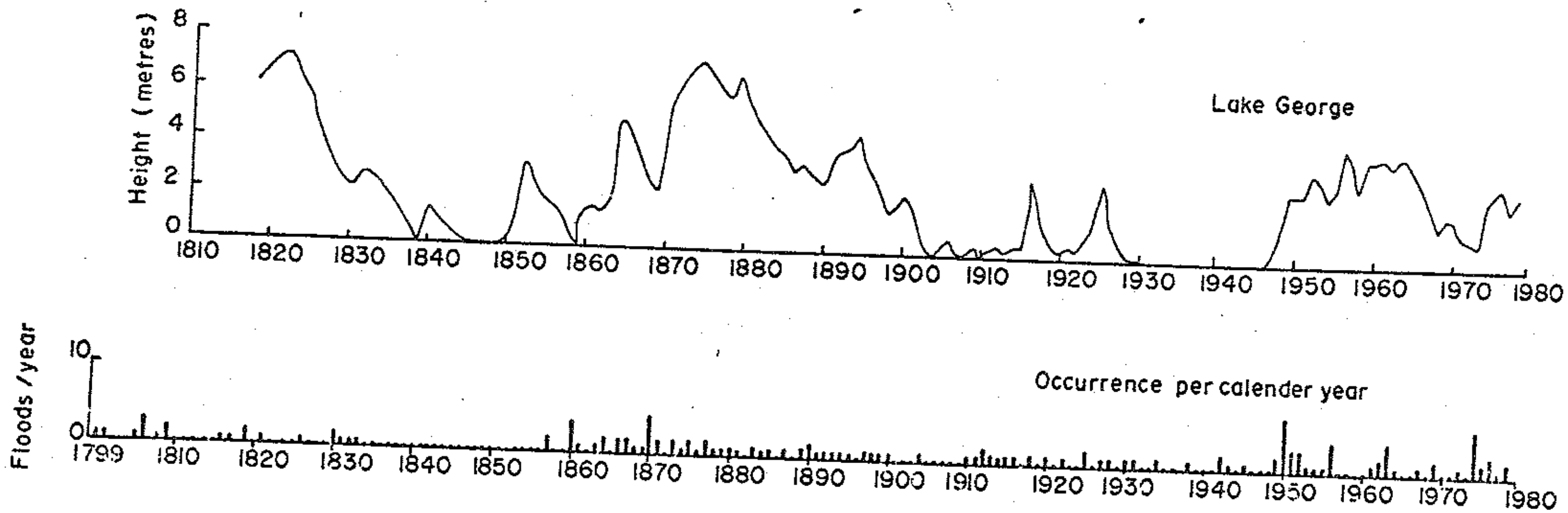

Figure 2. Lake George water levels and Windsor flood frequency

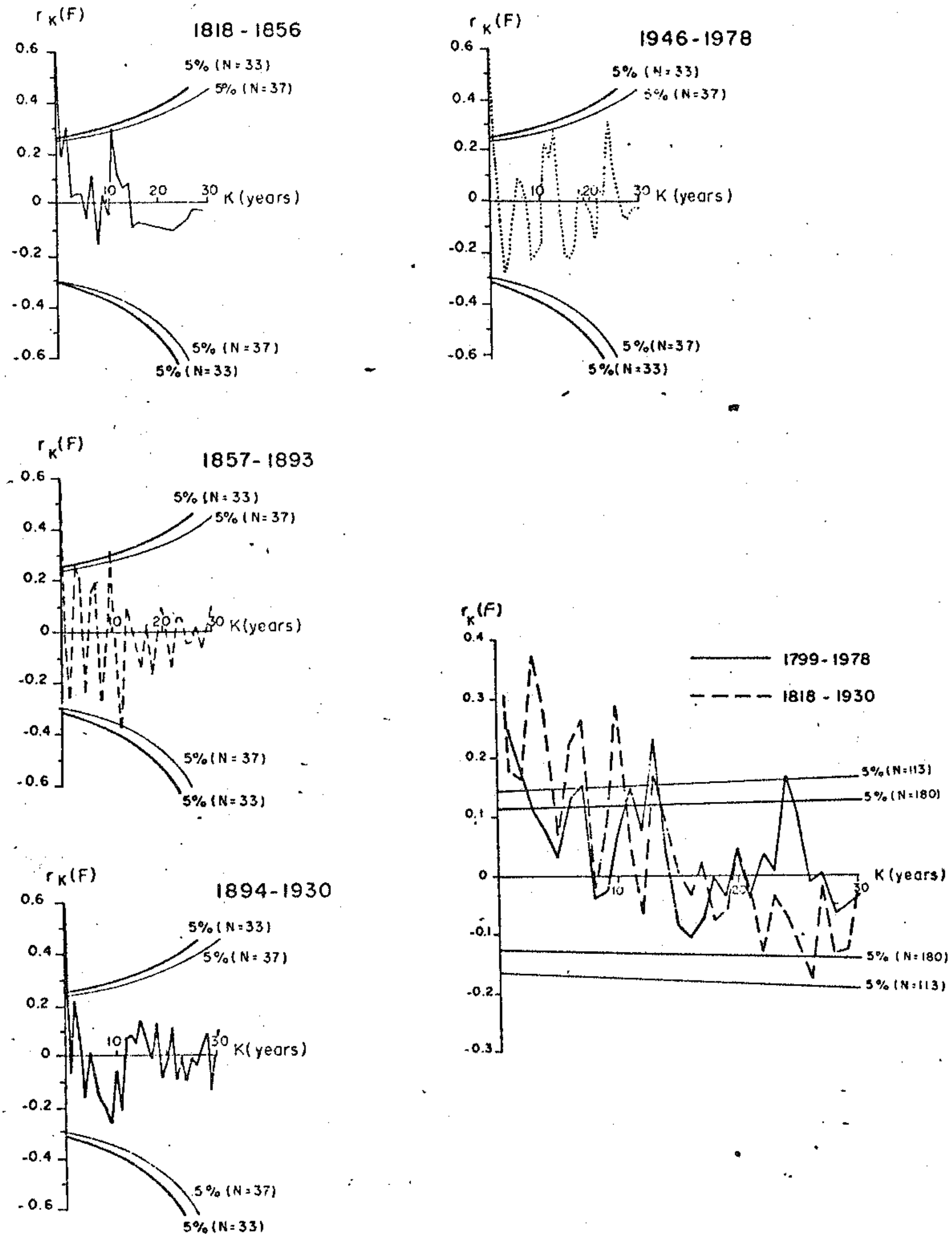

Figure 3. Autocorrelation of Windsor flood frequency

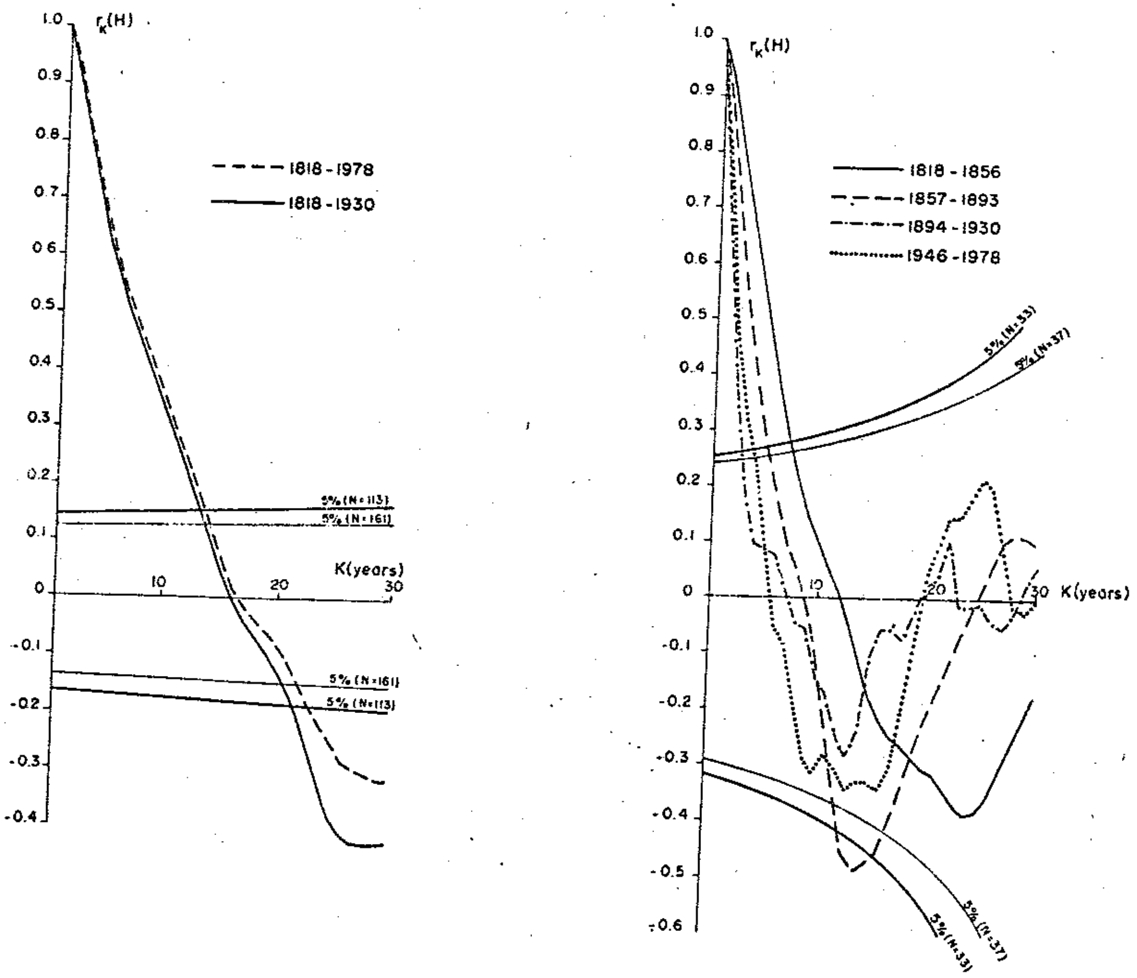

Figure 4. Autocorrelation of lake George levels

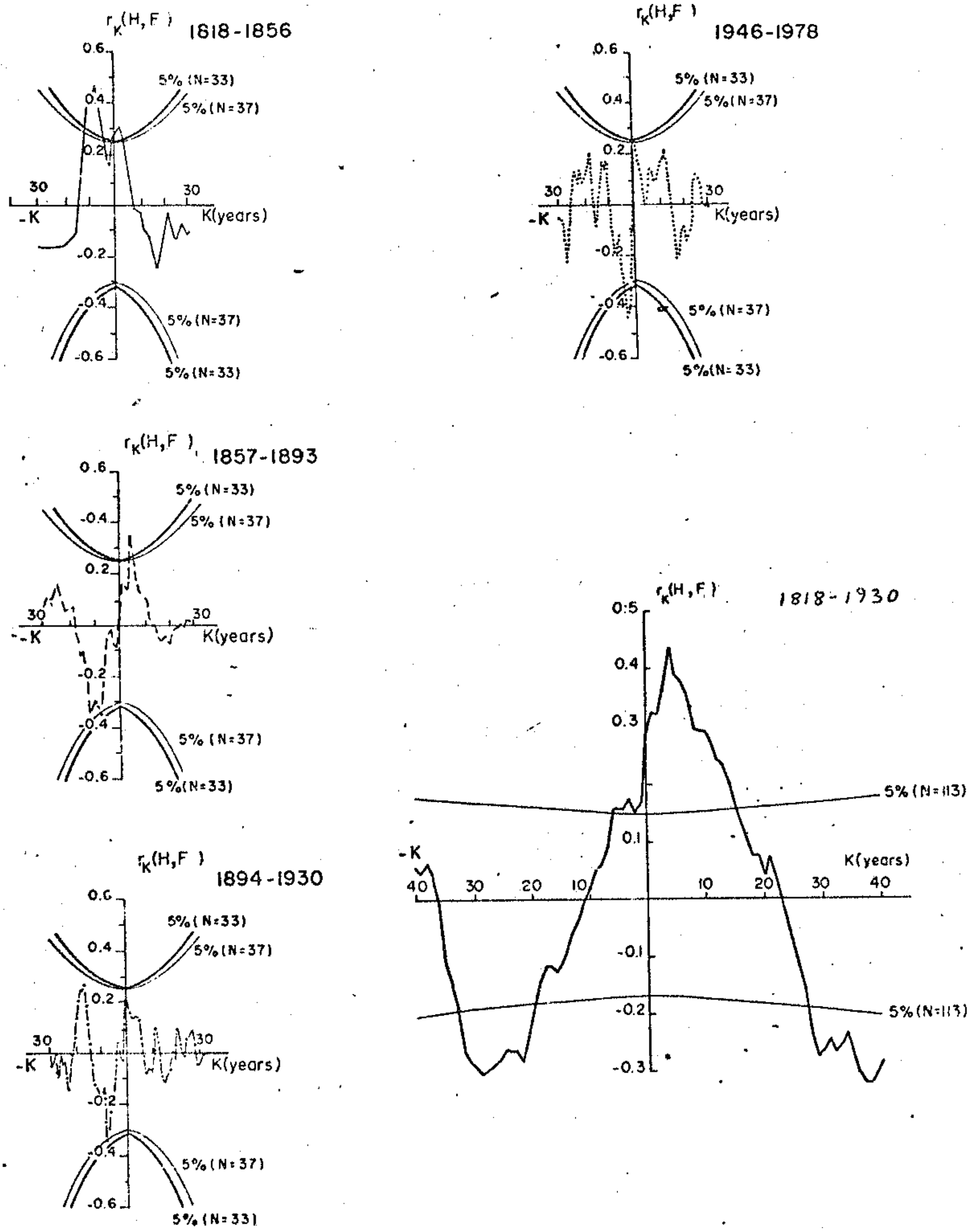

Figure 5. Lag cross correlograms of Windsor flood frequency (F) and Lake George levels (H)

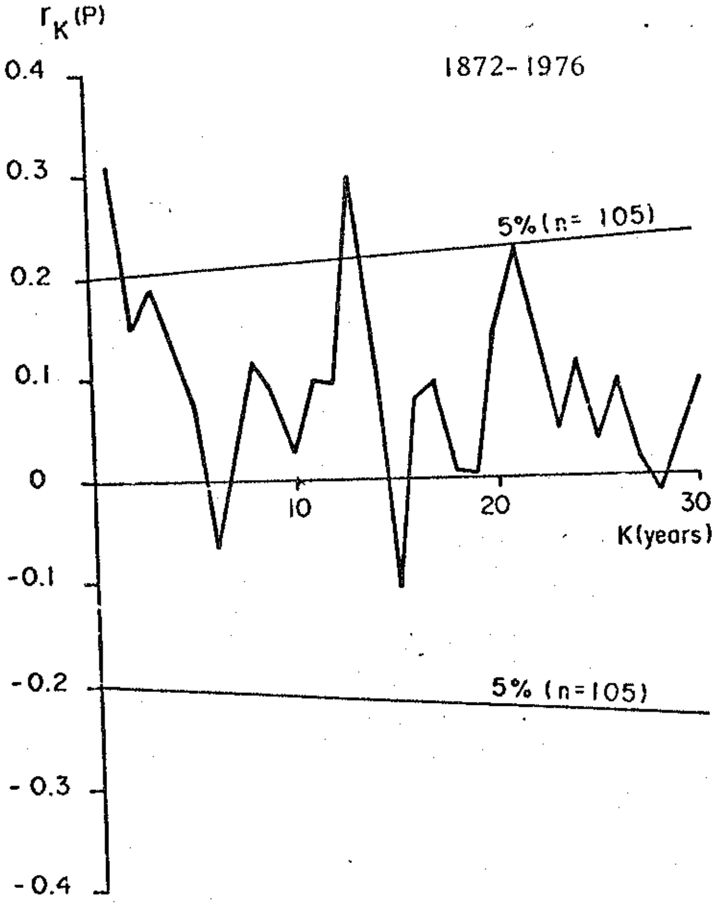

Figure 6. Autocorrelation of annual rainfall depths, Mt Victoria

LANDSCAPE EVOLUTION IN CONSOLIDATED DUNESANDS ON A HUMID TEMPERATE COAST

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ABSTRACT

The dunefields of the Aupouri and Karikari peninsulas, at the northern tip of New Zealand, illustrate water's role in dissection of consolidated dunesands on a humid temperate coast. The resultant landforms are in some respects analogous to those produced by water erosion in semi-arid sandstone landscapes of low relief.

INTRODUCTION

The landscape of the Aupouri and Karikari peninsulas owes its form as much to erosion of consolidated dunesand by water, as to transport of unconsolidated sand by wind.

Five periods of dune advance have been separated by stable intervals, when scrub, rainforest and swamp vegetation have colonised the dunes. Intense podsolisation has weathered and indurated the dunesands; carbonaceous sandstone pans from 0.5 to 5 metres thick are widespread. Annual rainfall ranges from 1000 to 2200 mm, and strong groundwater discharges move towards the coast at depth. Seasonal swamps or lakes form in inter-dune hollows, and sap away the enclosing ridges, to form gently inclined, extensive flats. Short streams recede headwards from the coast, breaching dune ridges, and gully sandstone pans beneath the flats. Their lower reaches, where impeded by coastal foredunes, become swampy and expand sideways by undermining sandstone pans at the water table.

The morphology of the dunes is now outlined, with emphasis not on their primary aeolian form, so much as on the morphological changes which vegetation, soils and drainage have exerted during long periods of stability. The sequence from youngest to oldest illustrates the complete landscape evolution of a coastal dunefield under humid temperate conditions.

TRANSVERSE DUNES

The dune ridges are unweathered, unvegetated and unstable in their natural state. (Most have been arrested by Forest Service plantings of marram grass, lupin and pines since 1963). Prior to stabilisation, they are huge barchans, shaped and driven inland by the prevailing south-west winds.

The inter-dune hollows are close to the regional water-table. Apart from a thin (c. 0.5m) veneer of fresh wind-blown sand, they are composed of weathered, consolidated dunesand, a remnant of the older dunefields across which the barchans advance. Upstanding 'mesas' and 'buttes' c. 2-3 metres high, capped by ironpans and sandstone pans, are common. Sparse sedge, toitoi grass and flax may establish.

TYPE 3 PARABOLIC DUNES

The dune ridges are anchored by a natural scrubland of spinifex, pohuehue and manuka. The dunesand is slightly weathered, but unconsolidated and extremely prone to wind erosion. The dune ridges are undissected, other than by frequent blow-outs.

The dune hollows are moist and well-vegetated by swampland plants, principally sedge, toitoi grass and flax. The water table rarely rises above the surface, and there is little or no peat accumulation. Weathered, unconsolidated sand, derived from the dune ridges, forms a layer of variable depth over buried remnants of older, consolidated dunesand.

TYPE 2 PARABOLIC DUNES

Dune ridges formerly supported a rainforest, dominated by kauri and podocarp species. This was destroyed by fires (either natural or Polynesian), prior to European settlement, and replaced by scrubland similar to that on the Type 3 dunes. The dunesands are consolidated by weathering to a depth of several metres. 'Eggcup' podsols, which have indurated the sand beneath individual kauri trees, are common. The dunes are subject to moderate wind erosion if vegetation is breached, but owing to consolidation of the sands by weathering, deep blow-outs are rare. Surface drainage is absent, and the dunes are undissected.

The moist hollows have developed podsolic soils beneath former rainforest. Severity of podsolisation ranges from thin ironpans, 1-2 cm thick, to indurated sandstone hardpans up to 1 metre thick, overlain by up to 10 cm of bleached silica sand, and 0.5-2 metres of sandy peat filled with logs and branches. The water-table commonly rises above the peat surface in winter. Permanent lakes, their beds formed by the sandstone hardpan and their shores ringed by water-sorted silica sand, are widespread.

TYPE 1 PARABOLIC DUNES

The dune ridges formerly supported a rainforest similar to that on the Type 2 dunes. The dunesands are consolidated by weathering to a depth of several metres, and have developed podsolic soils, ranging from thin ironpans 1-2 cm thick to indurated sandstone hardpans up to 0.5 metres thick, overlain by up to 10 cm of bleached silica sand. The dunes are subject to severe surface soil loss, by wind or sheet wash, down to the hardpan. The dune ridges are breached by surface stream networks, and truncated by sapping at the edge of swamps.

Dune hollows have grown outwards by sapping the enclosing ridges, to form gently inclined flats. Isolated remnant ridges often protrude from the middle of an otherwise flat surface. Sandstone pans, from 1 to 3 metres thick, are overlain by up to 10 cm of bleached silica sand, and 0.5-2 metres of sandy peat, filled with logs and branches. (In many places, peat has been destroyed by drainage and repeated burning). The flats are trenched by stream gullies, incised to a depth of 2-3 metres in the underlying weathered, consolidated sand. Gullies recede headwards by sapping the hardpan, and their lower reaches, where impeded by coastal foredunes, fill with peat and expand sideways by undermining the hardpans at the water table. Lakes are absent, but many rings of water-sorted silica sand, surrounding peat deposits several metres deep, testify to their former locations.

PRE-PARABOLIC SURFACE

This surface unconformably underlies the Type 1 dunes, and is separated from them by discontinuous, thin lignite seams. Beyond the eastern limits of the Type 1 advance, it still forms the peninsulas' contemporary surface till it accretes on solid rock.

Dune ridges are unrecognisable, though low rounded hummocks may represent their remnants. The surface is composed of extensive, gently inclined flats, separated by low scarps. Everywhere, the soil is podsolised, to an intensity rarely seen on Type 1 dunes. Carbonaceous sandstone pans up to 5 metres thick are overlain by 10-50 cm of bleached silica sand, and a few centimetres of sandy, organic topsoil. Peat is generally absent, but this may be a consequence of repeated burning. Where uncleared for farming, the surface is clad by sparse, stunted manuka scrub and sedge; although modified by fire, this scrubland may well represent the surface's natural vegetation before the advent of man (Kauri gum and timber is embedded in the soil, but has been carbon-dated to ages in excess of 30,000 years).

The surface is deeply incised by well-developed gully networks, which are sometimes flanked by erosional terraces, and occupied by broad peat swamps in their lower reaches, where drainage is impeded by the foredunes of the eastern coast. In places, the gullies and coastal cliffs expose 10-30 m of indurated aeolian or waterlaid sandstones, with seams and lenses of lignite. The sequence probably represents several periods of dune advance interspersed with intervals of stability, early in the Upper Pleistocene.

CONCLUSION

Given sufficient time, consolidated coastal dunesands in a humid temperature climate develop landforms which are surprisingly analogous to those of semi-arid sandstone landscapes. 'Pans' formed by seasonal lakes and swamps; incised gully networks; and gently sloping planation surfaces separated by low scarps, are common to both. In humid temperate climates, weathering, induration and even cementation of the top few metres of dunesand, by intense podsolisation beneath rainforest and swampland, is sufficient to initiate processes of dissection by water.

REFERENCE

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GLACIAL AND RIVER EROSION OF THE SUB-ICE ROCK,

McROBERTSON AND ENDERBY LANDS,

ANTARCTICA

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ABSTRACT

During the summers of 1976/77 and 1979/80 the Australian National Antarctic Research Expedition measured ice thickness and ice surface altitude between Mawson and Molodezhnaya bases, over a 200 km by 600 km coastal strip of the East Antarctic ice sheet. The observations were made from light aircraft using ice radar equipment. The present-day altitudes of the rock surface have been corrected for the isostatic-loading effect of the present ice to give rock surface altitude on deglaciation. The flight line spacing averages 30 km so the rock height cannot be contoured to give a detailed map of deglacial topography. However, maps have been prepared of profiles, smoothed altitude, local relief, and also maps showing envelopes of the highest and lowest altitudes.

The topography can be divided into three zones: 1) a coastal zone of low relief with most valley bases near sealevel; 2) a slope zone, 70 to 160 km inland, with a high relief of 600 to 1400 m, and 3) a highland zone with 400 to 600 m of relief with valley bases at 600 to 1000 m altitude.

Glacial troughs are generally oriented at right angles to the coastline; they are restricted to the coastal zone. The troughs average 70 km apart, are 5 to 15 km wide, and the deglacial altitude of their base is generally well below sea level. The coastal zone between the troughs has a subdued subglacial and subaerial topography that is consistent with past glacial erosion of rock by 'areal scouring'. Evidence for more extensive ice sheets in the past includes coastal outcrops of glacially eroded rock, and glacially eroded troughs in the sea bed both below the floating tongues of present-day glaciers and seaward on the continental shelf.

Valleys in the slope zone are interpreted as being partly glacially and partly subaerially eroded, and valleys in the highland zone as being wholly subaerially eroded. In both areas the valley bases on deglaciation would be above sea level, and they are narrower than the known definite glacial troughs and more closely spaced. In one area a planar erosion surface, 50 km in extent, is defined by flat concordant mountain tops below the present ice level.

The highland crest parallels the coastline just north of the southern margin of the mapped area (69°S). The direction of flow of the present Antarctic ice cap is north to the coast, across the highland. The complete absence of glacial troughs cutting the highland is interpreted as evidence that there is little past or present glacial erosion in the highland zone.

The inferred geomorphic history is as follows. The oldest features are the highlands and the planar erosion surface. Shallow subaerial dissection of the highland zone and the planar erosion surface was complete before the area was covered by the Antarctic ice cap in the Oligocene-Miocene. This highland area was not subsequently glacially eroded, probably because basal ice temperatures have remained below freezing point. In the coastal zone the major valleys were widened by 'selective linear erosion', the base of the glacier being near pressure melting point. Between the glaciers the basal temperatures were also high and there was widespread 'areal scouring'. In the slope and coastal zones where deep erosion was adjacent to existing mountains, the unloading of the crust by erosion caused isostatic uplift of the mountain, so now there are areas where the mountain tops are well above the present ice level. These mountain tops were subsequently sculpted by local mountain valley glaciation. There is no evidence for surging of glaciers in this area such as that inferred in the Lambert Glacier basin to the east. However, the extent of the ice cap has been greater at least once in the past.

THE EFFECT OF ANTECEDENT SOIL WATER CONDITIONS AND RAINFALL VARIATIONS ON RUNOFF GENERATION IN A SMALL EUCALYPT CATCHMENT

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ABSTRACT Runoff generation mechanisms were investigated in a 1.8 ha eucalypt catchment in the headwaters of the Yass River, NSW (Topalidis and Curtis, 1982). A network of tensiometers and piezometers was installed within the central depression and along several transects on the sideslopes to evaluate the soil water status of the hydrophobic lithosol soils of the catchment. This information and physical observations were used to interpret current and historic rainfall-runoff data. The most common runoff mechanism was the return flow component of exfiltration (saturation) overland flow from saturated areas in the central depression of the catchment. The contribution of rainfall on the saturated areas, which was 2% of the catchment's area was negligible. Post-ponding (Hortonian) overland flow was found to be of significance, and in conjunction with return flow produced the largest runoff responses. Antecedent soil water conditions were of critical importance, the runoff response depending largely on whether the catchment was wet, with the perched water table at depth, or saturated, with the water table at the surface and stream outflow occurring. A dry catchment produced negligible runoff, with most of the rainfall infiltrating via macropores.

REFERENCE : TOPALIDIS, S. and CURTIS, A.A. (1982) The Effect of Antecedent Soil Water Conditions and Rainfall Variations on Runoff Generation in a Small Eucalypt Catchment. The First National Symposium on Forest Hydrology, 1982, Melbourne, 11-13 May. The Institution of Engineers, Australia. Preprints of Papers. pp. 43-49. (The Institution of Engineers, Australia, National Conference Publication No. 82/6).

KARST & COASTAL SESSION

SPELEOTHEM DATES, COASTAL TERRACES AND UPLIFT RATES IN THE SOUTH ISLAND, NEW ZEALAND

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ABSTRACT

Previous isotopic research on New Zealand speleothems has focussed on paleotemperature reconstruction (Hendy & Wilson 1968; Hendy 1971). This paper reports the use of $^{230}Th/^{234}U$ and ^{14}C age data from speleothems to investigate the relationships between cave levels, emerged coastal terraces and uplift rates on the west coast of the South Island. Data are presented from two localities, Westport and Paturau, which suggest differential emergence rates of $0.27\pm^{0.28}_{0.09}$ m/1000 years and $0.14\pm^{0.05}_{0.03}$ m/1000 years. The former uplift rate, which is for the Westport area, adds general support to the ages assigned by Suggate (1965) to the well developed flight of terraces in the area, the last interglacial terrace being expected at about 39 m , assuming that sea level stood at +4 to 6 m some 125 ka ago. Suggate had assigned terraces at 34-36 m and 40-45 m to the early and late phases of the last (Oturi) interglacial.

Further north at Paturau, a terrace at 60 m was found to be at least 275±70 ka old and possibly more than twice that age. A cave associated with the terrace was invaded by the 60 m sea, which injected beach cobbles and marine shells (including *Mactra* sp. or *Dosinia* sp.). From the same site a speleothem was dated $450\pm^{\infty}_{100}$ ka, but its age relationship to the marine deposits is uncertain.

Speleothems in a cave at 4-5m above present sea level have been found to date to at least 52±6 ka, and there is no evidence to suggest that they have been affected by marine inundation. A neighbouring 4 m marine platform at Paturau is therefore likely to be of at least that age.

Since a number of speleothems encountered have ages near or beyond the dating limits of the Th/U method, investigations are proceeding using paleomagnetism. It is expected that many caves around the northwest coast of the South Island at elevations exceeding 60 m above sea level will contain material older than 500 ka.

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CAVE DEVELOPMENT IN THE HIGHLANDS OF PAPUA NEW GUINEA

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ABSTRACT:

The histories of two long limestone caves in the Hindenburg and Muller Ranges of Papua New Guinea show markedly similar phases of development. Under a continuously wet climate, caves pass from an initial, non-integrated nothephreatic regime, through dynamic phreatic to vadose phases. Interbedding of impermeable lithologies may act to perch cave levels, while impounding of karst drainage by impermeable rock structures exerts base level control. Periodic blocking of cave conduits by sediments may force development of anastomoses or conduits at other levels. The relation between dated cave levels and surface karst features indicates rapid rates of landscape development.

INTRODUCTION:

Models of limestone cave development have largely been developed in temperate karsts, and have been reviewed by Jennings (1971), Sweeting (1972), and Waltham (1981). Ford and Ewers (1978) have developed a model of cave formation which breaks away from earlier models postulating one hydrologic state during development. They suggest that the three common cases are vadose, phreatic, and water-table caves, with non-integrated caves and artesian phreatic caves being special cases. Any cave system may be a combination of the three cases through time, and they cite examples from North American and European caves. Although this model explains much of the observed variation, it neglects the effects of slowly moving groundwater, the nothephreatic case of Jennings (1977).

Published studies of tropical montane karsts are few. Waltham and Brook (1980) have discussed cave development in the Gunung Mulu karst of Sarawak, relating cave levels to former resurgences.

In recent years the efforts of speleologists have resulted in the documentation of cave systems in the P.N.G. Highlands (Brook, 1976; James & Dyson, 1980). These caves are in similar structural situations to those in the Canadian Rockies, from which many of the examples of Ford & Ewers (1978) are drawn. In this paper I therefore examine cave development under a different, perennially wet tropical climate, and suggest some modifications to their model.

THE REGIONAL SETTING:

The caves which are the subject of this paper lie in the Muller and Hindenburg Ranges. These high limestone massifs form the southern flank of the Southern Fold Mountain (Löffler, 1977) of P.N.G. (Figure 1). The area experiences a continuously heavy rainfall regime, with each week receiving more than 50mm of rain. Average annual rainfall ranges from 7919mm at Tabubil in the west to 4272mm at Nomad River in the east. There is a steep rainfall gradient across the Hindenburg Range from Tabubil to Telefomin (3531mm). The average annual rainfall for the Hindenburg Ranges is between 4-6000mm, while for the Muller Range the likely annual rainfall is about 4000mm. There is a marked lack of seasonality in rainfall, and thus large quantities of water for solution of limestone and maintenance of streamflow are always present. The diurnal pattern of rainfall for Tabubil is typical of the ranges. Rain usually commences as light drizzle around 1400 hrs, with intense rain from 15-2000 hrs. Early mornings are generally clear. The intense late afternoon rain produces rapid rises in streamflow, and much solutional and corrasional attack must occur during this period.

Diurnal temperature range is from 10 to 20°C, while cave temperatures are fairly constant within the range 12-14°C.

The combination of continuously heavy rainfall and thick, uplifted limestone sequences might be expected to produce exceptionally long and deep caves. Unfortunately complications of lithology and structure combine to limit development.

The Hindenburg and Muller Ranges are formed in the resistant Darai Limestone, a late Oligocene to middle Miocene foraminiferal biomicrite which is between 1000-1500m thick (Arnold, Griffin & Hodge, 1979). The limestone is underlain by recessive Jurassic siltstones, sandstones and shales, and there are remnants of Pliocene calcareous siltstones and mudstones which conformably overlie the limestone. Sections of the Durai Limestones are exposed in the massive cliffs which bound the southern flank of the ranges, in dolines, and in caves. Francis (1980) has pointed out the presence of clastic interbeds in the limestone in the Muller Range, typical sections having 30-50m thick limestones separated by 5-20m thick beds of relatively impermeable siltstones and mudstones. To the west, in the Hindenburg Ranges and the Star Mountains, these clastic interbeds are fewer in number and thinner, resulting in pure limestone sequences up to 300m thick.

Uplift took place in the early Pliocene along east-southeast plunging anticlinal arches, giving rise to detachment tectonics in which rupturing and overriding of limestone sheets produced packages of multiple overthrusts (Jenkins, 1974:546). Uplift was complete by the early Pleistocene, and subsequent movements are probably the result of gravity sliding on the less competent Jurassic rocks. Anticlinal structures in these rocks are exposed below the massive scarps which bound the Muller and Hindenburg Ranges on the south. The traces of thrust faults, and of dense conjugate joint sets, are visible in aerial photography of the limestone areas, and much of the drainage and karst forms are directed. The retreat of the major scarps is aided by wedge failure along conjugate joints, and extensive aprons of avalanche debris below these scarps suggest long-term dominance of mass movement in scarp retreat.

CAVE DEVELOPMENT:

Two major cave systems will be considered in this paper. Selminum Tem has a total of 20.5km of passages developed on five levels within the Hindenburg Plateau, while Atea Kananda has four levels totalling 30.5km underlying the Muller Plateau. The dating of events in the cave histories has been by U/Th series dating of calcite speleothems, while correlation between passages has rested on morphology and on sedimentary sequences within them.

The initial formation of cavities in the limestone probably followed partial stripping of the Pliocene caprock, in the early

Pleistocene. In both caves, the uppermost levels have well preserved phreatic tubes with spongework and solutional rock pendants, indicative of sluggish flow which Jennings (1977) has termed "nothephreatic". At this time, secondary permeability in the rock mass would be low, and the cavities appear to have formed at joint and fault intersections where flow was enhanced. In Selminum Tem, the fragments of this network lie on a gradient to the crest of the resistant Jurassic sandstone in the Alice Anticline (Figure 2), and include the Upper Bitip Cave, Trinity Cave, Upper Selminum Tem, and the Hole in the Wall. In Atea Kananda, similar passages extend for 6-8km on a gradient to the crest of an anticline in the Jurassic Ieru Formation below the Nalirege Escarpment (Francis, James, Gillieson & Montgomery 1980:113). Cave development would therefore have occurred in an impounded karst (Jennings, 1971:5).

Further stripping of the caprock permitted development of integrated dynamic phreatic systems. At Selminum Tem, the streams Ok Bitip and Feram sank near the Finim Thrust. Large quantities of water aided in the erosion of a phreatic tube 30m in diameter which extends aslant the dip and along the strike to minimise resistance to the former outflow point, whose altitude related to a lowered anticlinal crest. The flow was sufficient to transport clasts of cobble size up reverse gradients of phreatic loops with an amplitude of 50m. In the Atea Kananda, the Yu Dina stream sank at successively higher points up a now dry valley, forming long, joint guided passages draining the northern limb of the Mamo syncline and emerging at levels well above the present springs.

In both systems, periodic influxes of sediment blocked the phreatic conduit, forcing development of anastomoses and lower conduits. The structures of deep, stratified sediments indicate deposition into standing water, analogous to turbidites, mixed with mudflow and stream bedload deposits. The phreatic conduits were abandoned 20-22000 yrs. b.p. at Selminum Tem, and 14000 yr. b.p. in the Atea Kananda.

Lowering of the structurally controlled base level at both caves resulted in vadose incision. In the Atea Kananda, perching of cave levels on mudstone interbeds occurred, resulting in three levels of vadose canyons (Figure 3) - Ugwapugwa, the Ooze Cruise, and the Ship Canal. The latter today carries 4 m^3s^{-1} as base flow. Following recession of the Yu Dina sink up its valley, the Yu Atea invaded its passages and enlarged them.

This phase of development resulted in the formation of the large vadose trench, 30-50m wide by 30m high, in Selminum Tem. The Ok Kaakil invaded former sinks and developed flood bypass channels to other sinks for the system. At some time before 14-16000 yr. b.p., a diamicton entered the system and penetrated the passage for 2km, probably as a "sliding bed facies" (Saunderson, 1977). Porphyry clasts in the diamicton suggest a provenance on the southern flank of the Star Mountains.

A further diamicton was deposited in the vadose canyon between 10000 and 14-16000 yr. b.p. This penetrated the passage for 3km, attaining a depth of 8m at the downflow end. After this, the canyon was abandoned in favour of a maze network of lower phreatic passages. This abandonment was related to further base level lowering, and to an increase in fissure frequency through solutional enlargement. Percolation streams invaded the canyon and drained to the lower phreatic passages. By this phase, the large Kaakil Springs at the base of the Hindenburg Wall had become active, emerging at the contact between the Darai Limestone and the Ieru Formation. Lowering of this contact resulted in progressive lowering of the spring, and of passage levels in Selminum Tem. There is good correspondence between spring and cave levels, the intervals being 30, 25, and 20m in each case. The lowest level in Selminum Tem is a series of water filled shafts.

In the Atea Kananda, breaching of the clastic interbeds underlying each level resulted in new, lower levels, the lowermost being a series of shafts and collapsed chambers. The hydraulic gradient in the northern limb of the Mamo syncline permitted phreatic tubes rising up the southern limb for 45m. At present the cave streams drain to the Nali Springs at the base of the scarp.

Similarly the phreatic passages behind the Kaakil Spring rise along the dip for 30-35m, and act as flood overflow conduits after heavy rainfall on the Hindenburg Plateau.

On both the Muller and Hindenburg Plateaux, large cliffed dolines are present and intersect formerly active cave conduits. These dolines are between 100-400m in diameter, and up to 160m deep. The Selminum Doline breaches the Upper Cave 30m above its base. Its development must therefore postdate the last phase of activity of that conduit, some 20-22000 yrs. b.p. Rapid development of such features is indicated, and is probably facilitated by stoping of blind shafts, a process visible in the caves. Similarly the presence of breached cave passages of the same developmental phase in the Hindenburg Wall suggests rapid rates of scarp retreat.

CONCLUSIONS:

A number of factors control cave development in the montane karsts of P.N.G.

(1) Under the prevailing climate, large quantities of potentially aggressive water are available for limestone corrosion and corrasion.
(2) Clastic interbeds in limestone sequences may have important control over cave levels, even in conditions of steep hydraulic gradients, and may permit perching of cave levels with different flow regimes e.g. a phreatic level perched over a vadose level.
(3) Structures in impervious rocks may act to impound the karst, producing "artesian phreatic" development, and cave levels may relate to progressive erosion of the impermeable rocks.
(4) Intrinsic changes due to periodic sediment blockage may force development of new conduits under phreatic flow regimes, including localised up - dip flow.
(5) The developmental sequence nothephreatic - dynamic phreatic - vadose may be temporarly reversed, and is the complex result of interactions between climate, lithology, structure and fissure frequency through time. Adherence to explanation by a single factor neglects the real complexity of karst development.

The early nothephreatic phase of cave development, neglected in Ford & Ewer's (1978) model, is an important precursor of other flow regimes, as it is during this phase that preparation of the rock mass for integrated conduits occurs. To neglect it is to deny the long and complex histories of most cave systems.

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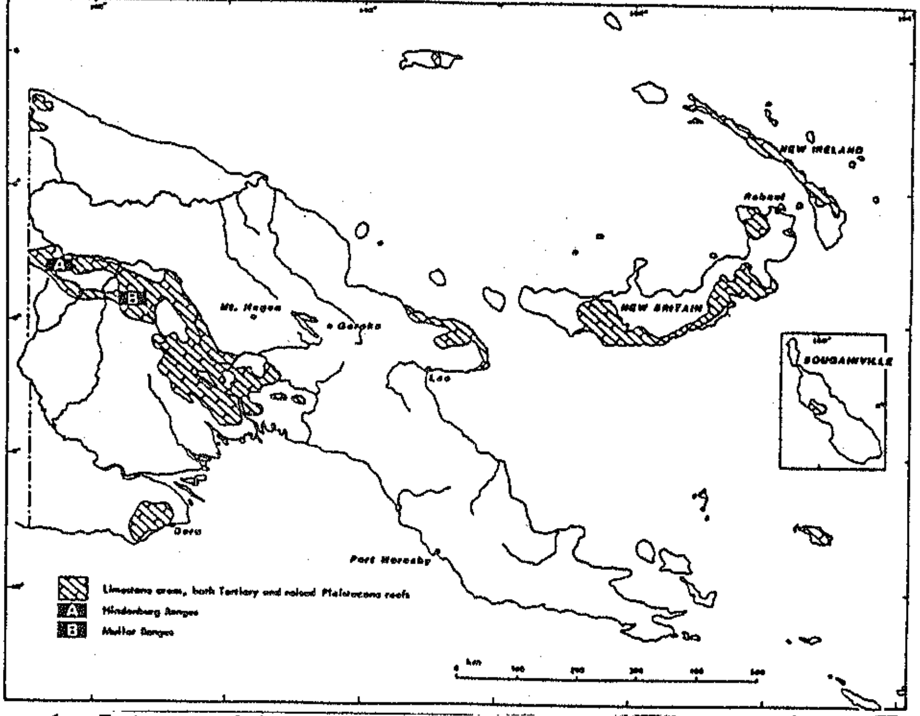

Figure 1: Extent of karst landforms and location of study areas in Papua New Guinea.

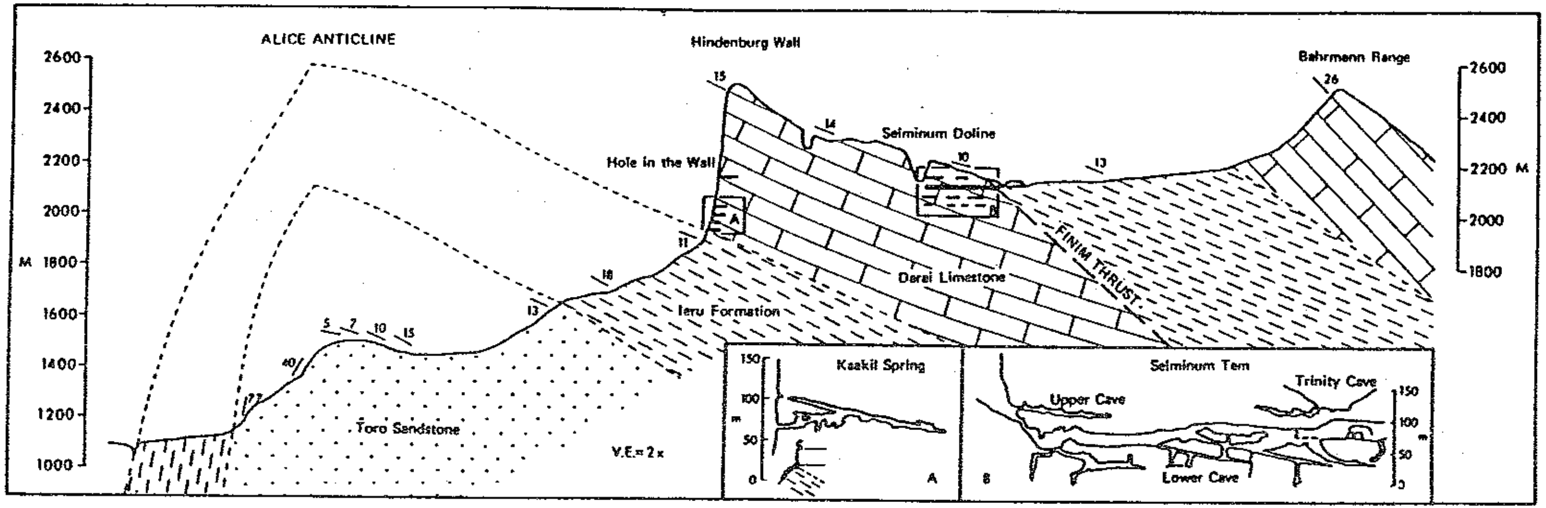

Figure 2: Geological section of the Hindenburg Plateau with levels of passages in Selminum Tem system.

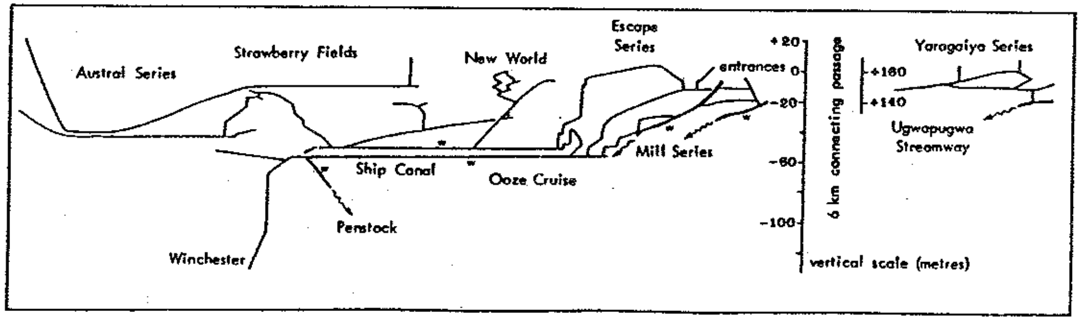

Figure 3: Levels of passage development in the Atea Kananda.

HISTORICAL CHANGES IN MORPHOLOGY OF STANWELL PARK BEACH, N.S.W., 1890-1980

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SLOPES & SOILS
SESSION

MONITORING UNSTABLE SLOPES WITH SPECIFIC REFERENCE TO SEASONAL EARTHFLOWS

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Abstract

The clear understanding of any process involves investigation based on accurate replicable data. The explanation of the earthflow process, in particular, depends on accurately answering questions concerning the clay-water interaction and how this varies in space and through time.

Analogue laboratory experiments have proved an inherently inaccurate approach in this respect and their results have caused severe problems when attempting to relate them to the field situation. A promising solution to the problem lies in the establishment of an automated, solid-state data recording system to measure continuously clay-water parameters within unstable slopes. In order for the monitoring system to yield appropriate data, equipment had to be designed to function below the "shear" plane as well as within the mobile mass. Probes have been developed to sense changes in soil moisture, temperature, pore pressures, dilatancy and rainfall, all of which are important to understanding the earthflow process. These factors had to be measured initially on a continuous or near-continuous basis in order to detect the degree of change in each of the recorded variables over time.

Introduction

During a period of seven weeks from the end of July 1977, much of southern Hawke's Bay and Wairarapa, New Zealand, experienced mass movement and flooding of sufficient severity for the region to be declared a disaster area. The mass movement occurred in at least five discrete episodes involving various types of flow failure and by the reactivation of numerous seasonal earthflows. As part of a larger project, to study the distribution and causes of slope failure, a catchment was chosen to represent the mudstone/siltstone earthflow prone hill country found in eastern Wairarapa.

The area in general has undergone significant tectonic deformation resulting in folding and unlift. The basin dissects the scarp face of a large cuesta-like landform (Maungaraki cuesta) to expose northwest dipping Waitotaran and Opoitian mudstones and siltstones of Pliocene age. Limestone residuals of Nukumaruan age, derived from the crest of the retreating scarp, crop out at lower levels. The intensely jointed nature of the mudstone in the lower basin is probably a result of movement along a NE-SW trending fault. The 1.2 km^2 basin rises steeply from the road at 180 m a.s.l. to the Eringa Trig (575 m a.s.l.), the highest point on the escarpment. The geology together with tectonic uplift and subsequent erosion have produced compound slopes ranging from 21-35 degrees. The normal yearly rainfall from 1948-70 is 1188mm with the highest annual total received being 1688mm. Over half the rain falls during the months May to July inclusive, the period when erosion problems become most pronounced.

High rainfall and steep slopes produced by stream degradation have resulted in the mudstone regolith within the catchment being characterised by shallow soil slip erosion of moderate severity. A large deep-seated seasonal earthflow in the jointed mudstone is kept active through stream erosion of its toe. This earthflow is an 'old' feature, being well formed by the time the first air photographs of the region were taken in 1941. The lower slopes of the flow have subsequently been reactivated (Fig 1). The research programme within this basin has been primarily designed to study the critical clay-water interactions resulting in the initiation and maintenance of this deepseated seasonal earthflow. Probes were developed to sense changes in soil moisture, temperature, pore pressures, dilatancy and rainfall, all of which are important to understanding the earthflow process.

A system of solid state data loggers provided an excellent method for recording the data from these probes, however their use required the conversion of each relevant parameter into an electrical signal based on either voltage or resistance. The limitation of initially having only four channels per logger was overcome by developing a multiplexer unit to cascade four probes, measuring slow changing variables, into one channel (Figs 2, 3).

SOIL MOISTURE

A. Gypsum Block Data Logging

Although the measurement of soil moisture tension through the change in resistance of gypsum blocks has been an accepted method since the 1930s, its application to data loggers presented several problems which had to be solved.

a) Gypsum blocks tend to polarize if measured with DC resistance measuring devices such as the data logger - AC techniques are therefore used.

b) The relationship between soil moisture and block resistance has a tendency to be logarithmic whilst the logger has a capacity more appropriate to linear scales (Fig 4).

c) The logger scans for less than 10msec therefore a steady state must be reached in the circuiting within 6msec.

d) As the soil moisture block is in electrical contact with the soil, it is desirable that it be electrically isolated from the data logger to prevent interference.

e) As soil moisture is a slow changing variable, it was decided that multiplexing three probes, at various depths, would increase the coverage without any loss in precision of the data record. This led to problems of 'series' resistance within the multiplexers having to be considered.

f) The heterogeneous nature of the soil meant that calibration in terms of percentage moisture was not possible and so pF values had to be used. This approach however, makes the technique used more widely applicable.

g) The resistance measured by the probes is also affected by temperature. The temperature on each site therefore had to be measured at the same time as the resistance to allow all data to be reduced to pF values at standard temperature.

During the study period, 'sensors' with concentric electrodes were used, as these gave better resolution at the wet end of the soil moisture spectrum than sensors with parallel electrodes (Fig 4). The blocks used were remarkably consistent in response having a standard error of only 0.035 pF over the 14 sensors tested. Consequently it was possible to use one calibration for all probes and to use them interchangeably, if the internal resistance of the multiplexer was known.

B. Neutron Probe Data

The data loggers provided an excellent means of recording soil moisture changes through time, however cost restricted their use to only four locations. An indication of the spatial fluctuations in soil moisture was obtained through a network of 16 access tubes for a neutron probe. Readings from two of these tubes had to be abandoned during winter months as they acted as virtual peizometers containing 1.5 metres of free water.

Typical monthly moisture variations within the data (Figs 5, 6, 7) show:

a) consistency of readings at both the dry and wet ends of the soil moisture spectrum,

b) very rapid (<3 weeks) recharge of soil moisture with the onset of winter,

c) slow reduction of "stored" soil moisture over the summer months,

d) characteristic hysteresis usually associated with a soil moisture regime,

e) greater seasonal variations in soil moisture within the flow due to intense cracking of the surface layers compared to the surrounding area,

f) that depth to constant soil moisture is reached closer to the surface of sites on the flow than on surrounding areas,

g) that depth to constant soil moisture increases towards the crown of the earthflow. At the toe of the flow variations cease below a depth of 1m.

h) Discontinuity in soil moisture fluctuations at approximately 0.7m which coincides with the average depth to failure of the shallow surficial slips which occur extensively throughout the basin, and

i) that movement of soil moisture is transmitted as a detectable pulse through the regolith.

TEMPERATURE RECORDING

As temperature sensing probes were used to measure soil temperature and ambient air temperature they had to be waterproof, accurate and yet maintain a precision of at least 0.5°C. It was also necessary that a steady state be reached in the circuiting within 6msec so the logger could sense a stable signal and that the probe was compatible with the multiplexing system to achieve economies in data collection.

Miniature glass encapsulated thermistors proved most satisfactory as they produce a linear response. However, to provide weatherproofing they were enclosed in silicon tubing which was subsequently packed with RTV sealant.

Input modules were designed to adjust the resistance range sensed by the logger to that produced by the particular thermistor used.

Calibration was undertaken with the probes arranged within the same circuit as the one to be used in the field. The linear correlation coefficients of the 14 probes used were all better than 0.99 and the probes provided a resolution of greater than 0.2°C.

PORE WATER PRESSURE

Electric Piezometers

Electric piezometers were specifically designed to operate below the "shear" plane and to produce an electrical signal compatible with the data logger monitoring system (Figs 8, 9, 10). Design criteria which had to be met were;

a) isolation of probes from the environment - this was achieved by milling a protective housing from stainless steel rod,

b) maximum precision in the measurement scale - this was obtained by using a semi-conductor transducer of the smallest possible range and scaling the input module,

c) capability of taking pressure readings relative to ambient air pressure, thus requiring a backward gauge transducer,

d) a steady state within 6msec,

e) a 12v supply providing a regulated stable source and yet economy of battery life (Fig 3),

f) calibration of the probes in situ and by manipulation of the input modules to obtain a resolution of 3cm.

Standpipe Piezometers: Initial Results

Standpipe piezometers were installed throughout the earthflow and within the stable regolith to determine the flow paths and to provide data supplementary to that collected on the data loggers. Holes were drilled vertically into the stable bedrock at 20 locations and standpipes were installed in sand filters at 2m intervals; the holes were backfilled with a bentonite-sand-cement slurry.

An initial appraisal of the data gathered (Fig 11) reveals the following trends:

a) ground-water recharge begins once soil moisture capacity is satisfied, and occurs within two months,

b) draw down from ground-water continues until late May,

c) the range of pressure variation is greatest on stable ground but the piezometric surface does not get closer to the ground surface than 2m,

d) on the earthflow the range of pressures experienced increases downslope,

e) the piezometric surface within the lower zones of the flow is seldom more than 1m below ground surface,

f) positive pore pressures develop during the winter months to such an extent that from July-October artesian pressures exist in the lower zones of the flow,

g) the water budget approach appears to offer a simple means of determining the clay-water status over time.

CLIMATE MONITORING

The measurement of climatic data is a conventional procedure and the adaptation of accepted methods to data logging posed no problems. A tipping bucket raingauge, with a 0.5mm resolution, and thermistors were used, with only slight modification of the logger input modules, to provide an automated climate recording system.

EARTHFLOW MOVEMENT

Four inclinometer access tubes were installed through the mobile mass into the underlying stable mudstone in the winter of 1978. Resurvey of these tubes has provided information on the location of the "shear" plane and mode of movement. Problems were encountered owing to the length of the probe which limited its use to distortions with a radius of greater than 3 metres. The type of probe used is designed for hard rock engineering and is not suitable for studies in the rapidly deforming soft rocks of Tertiary age in New Zealand. Preliminary survey of the raw data indicates several trends (Fig 12):

a) the inclinometers have provided a good insight into the rheological characteristics of the material,

b) the centre of the surface of the flow moves fastest,

c) the flow movement resembles that predicted by the Rankine active state in soil mechanics,

d) the end of the winter season is characterised by an apparent rebound up slope of the tubes, caused presumably by contraction of the clays. This rebound is least in the toe region,

e) movement is sporadic and once initiated continues at a decreasing rate until stability is regained. This is probably linked to the dissipation of pore pressures after failure,

f) the "shear" plane is a discrete 10cm layer at depths varying from 6 to 12.5 metres depending on the location with respect to the morphology of the flow (Fig 13),

g) the theory of plasticity as applied to glaciers appears to offer much to the study of earthflows.

The monitoring of hydrological, climatic and movement parameters within the large creeping earthflow has now ceased and an initial data scan suggests that the instrumentation developed worked satisfactorily and produced consistent results.

Acknowledgements

This work is part of a study funded by the Soil Conservation and Rivers Control Council of the Ministry of Works and Development whose assistance is gratefully acknowledged.

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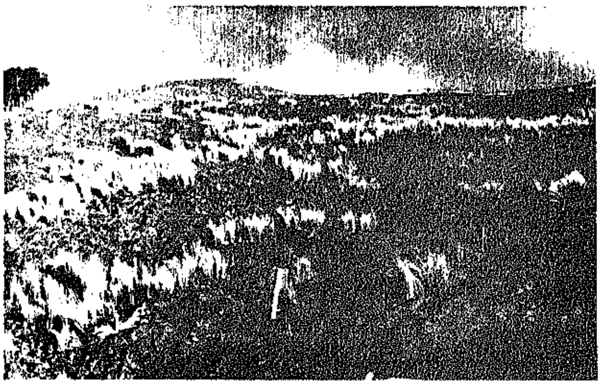

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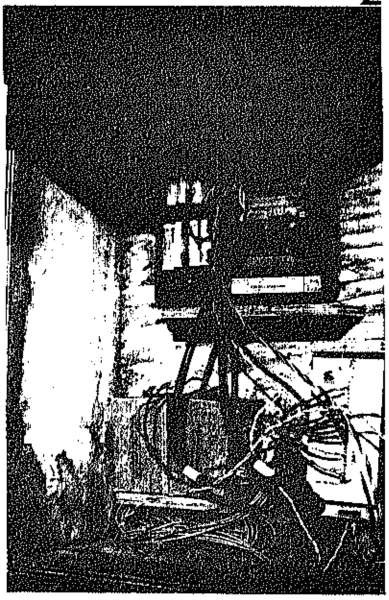
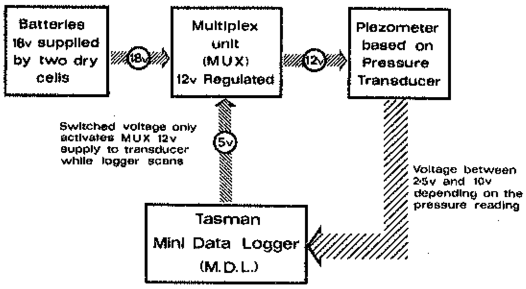


3

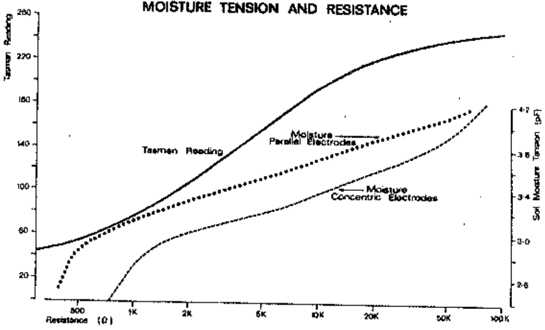
SCHEMATIC DIAGRAM OF CIRCUIT LINKAGES



RBM/JA McC

4

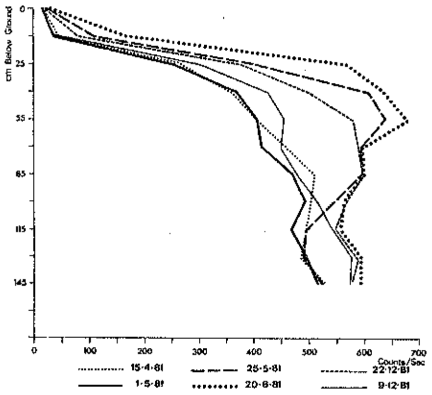
RELATIONSHIPS BETWEEN TASMAN READINGS AND RESISTANCE, AND SOIL MOISTURE TENSION AND RESISTANCE



After R & Jordan 1979

5

SOIL MOISTURE TUBE
STABLE GROUND
B4



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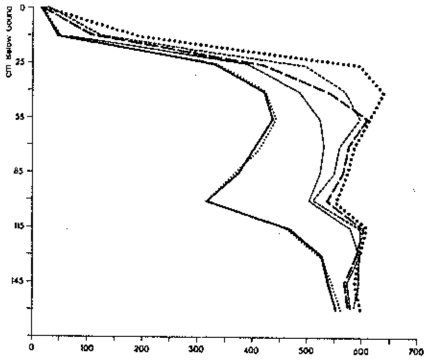
SOIL MOISTURE TUBE
TOP SLOPE FLOW
B3



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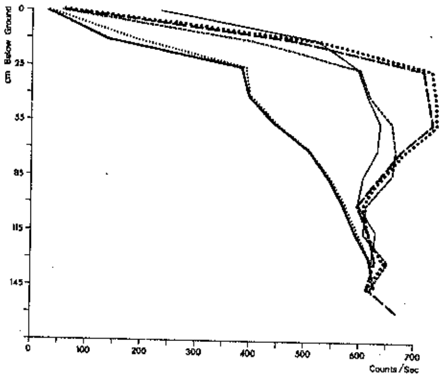
SOIL MOISTURE TUBE
BOTTOM SLOPE FLOW
D3



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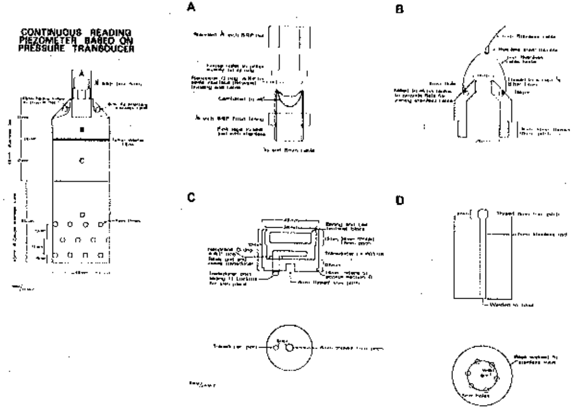
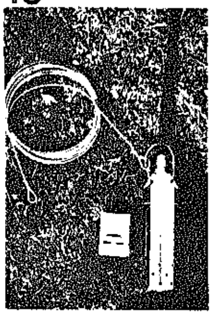

CONTINUOUS READING PIEZOMETER BASED ON PRESSURE TRANSDUCER

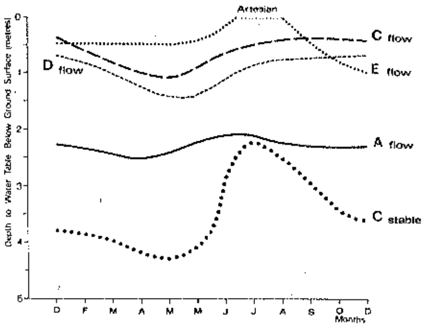
9

10



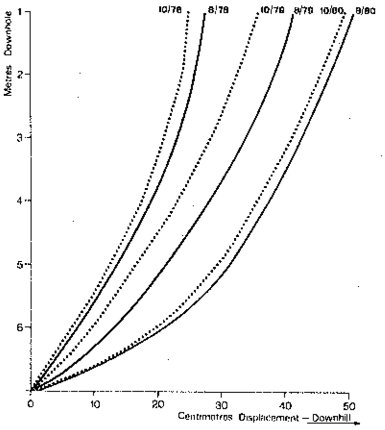
11

GENERALIZED STANDPIPE RECORD



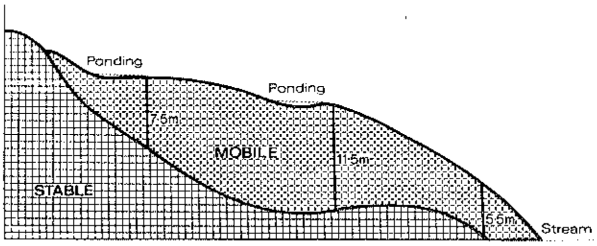
12

GENERALISED INCLINOMETER PLOTS FROM TOE



13

CROSS-SECTION THROUGH MOETAPU EARTHFLOW



WIDTH 120m LENGTH 425m

WEATHERING AND SOIL FORMATION, NEW ENGLAND, N.S.W. - A CASE STUDY

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ABSTRACT

An understanding of the evolution of surface materials is fundamental in the Australian context. Geomorphologists are best equipped to analyse information on surficial deposits and to interpret process and other factors relating to formation especially bedrock geology. A case study of weathering and soil formation on the Mt. Duval adamellite near Armidale, NSW provides an example of how an understanding of process leads to a model which can in turn be reversed to provide information about bedrock geology from a knowledge of surficial materials. The model presented includes mineralogical and geochemical transformations and an estimate of transfers of material.

INTRODUCTION

Since so much of the Australian continent is mantled by a thick layer of regolith (including geologically recent sediments, deeply weathered profiles and ancient and modern soils) there is an ever-increasing need for earth scientists to analyse the relationship between this material and the underlying geology. In the past mapping of Australia has left large areas marked merely as Cainozoic, Tertiary or Quaternary materials with little further analysis. There is a need to understand this material and to be able to "see through it" to the hard rock beneath.

One role of the geomorphologist is that of interpreter; to apply his/her specialised knowledge to translating the characteristics of the regolith into usable descriptions of the underlying geology. This requires that the process of formation be understood. This paper attempts to describe the process of rock weathering and soil formation on the Mt. Duval adamellite situated some 10km northeast of Armidale, NSW.

There are a number of obvious problems in discussing the evolution of regolith. Some of the characteristics of regolith bear no relationship to underlying geology because it is not in situ. Also the relationships between bedrock and regolith are extremely complex and further complicated by the fact that uniformatarianism does not necessarily apply (the geologically ancient ages ofprogressively more Australian landscapes are being demonstrated). The complexity of relationships can be demonstrated by attempting to define the chemical and mineralogical starting point of subaerial weathering as distinct from hydrothermal of diagenetic alteration.

The Mt. Duval adamellite is a coarse grained sometimes porphyritic grey granite. The modal mineralogy includes phenocrysts of K-feldspar and plagioclase in an evengrained groundmass of quartz, K-feldspar, plagioclase, biotite and amphibole. Normative calculations substantiate the modal mineralogy and allow closer analysis of plagioclase and K-feldspar yielding bytownite (An 0.76, Ab 0.24) and orthoclase respectively, and hornblende as the dominant amphibole (Table 1).

THE MINERALOGICAL CHANGES

Since biotite remains relatively unaltered until both feldspars are practically destroyed, chlorite alteration in the freshest granites is the result of deuteric or hydrothermal processes. Likewise tiny spots of kaolin formed in crystalline orthoclase in these same rocks must have a similar origin. Thus the freshest granite samples can justifiably be taken as the starting point for the weathering process.

Table 1 (a) Modal mineralogical analyses of the Mt. Duval adamellite

	Quartz	Plagioclase	K-feldspar	Biotite	Amphibole (Hornblende)	Opaques
Median	29.2	34.0	27.3	12.8	1.0	0.1
Mean	29.7	31.4	26.3	11.1	1.4	0.1
Range	25.8	25.1	22.8	7.1	0.0	0.0
	34.3	35.2	28.7	13.3	4.1	0.1

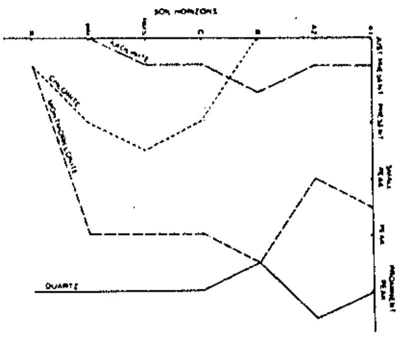
Table 1 (b) Normative mineralogy

	Quartz	Orthoclase	Albite	Anorthite	Biotite	Hornblende	Magnetite	Corundum	Total
Mean	24.99	19.11	29.33	9.40	11.12	3.67	0.43	0.77	98.72
Median	24.90	20.29	30.63	10.21	11.41	4.53	0.42	0.0	102.39
Range	11.48	15.31	17.84	4.82	4.41	0.0	0.31	0.0	98.80
	39.69	28.69	32.15	11.56	15.39	10.89	0.53	6.01	101.65

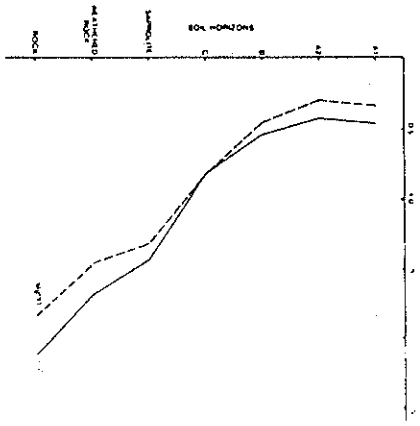
Table 2 Mineral weathering susceptibility and weathering products (based on thin section evidence)

Mineral		Weathering products and processes
Orthoclase	Increasing resistance Decreasing susceptibility to weathering ↓	Very early weathers to what appears to be kaolin. First spots then general envelopment of crystal.
Plagioclase		Weathers first along twin lines and in the Ca rich centres and then along fractures to kaolin and smectite materials but not to sericitic materials.
Hornblende		Weathers from the outside of grains towards the centre to chlorite and opaques with the release of iron oxide stains.
Biotite and (Deuteric Chlorite)		The grains intergrown with hornblende weather first, along lamellae and retain the cleavage. Products appear to be chlorite, illite, vermiculite and finally smectite or kaolin materials. Changes to a deep red colouration.
Quartz		Shows little weathering even at the stage of physical breakdown of the rock but has marked iron staining on boundaries of almost all grains.

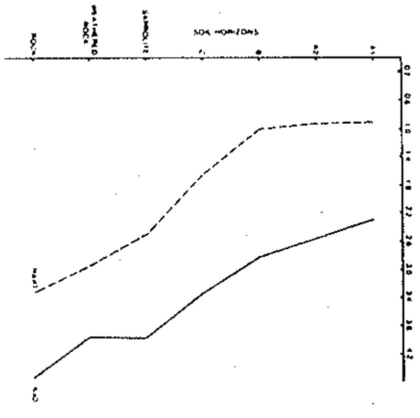
Figure 1. Changes down the profile in adamellite soils



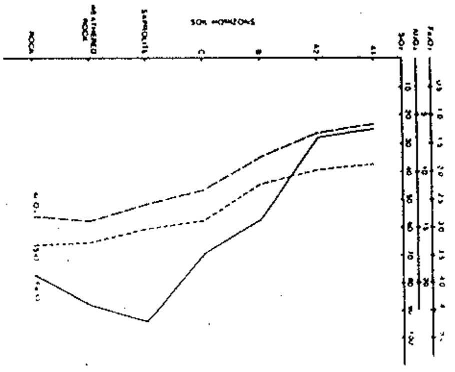
(a) A typical composite picture of clay contents (based on XRD)



(b) Corrected CaO and MgO content of the profile



(c) Corrected K_2O and Na_2O content of the profile



(d) Corrected SiO_2, Al_2O_3, and Fe_2O_3 content of the profile

The initial mineralogical transformations appear to be in the order orthoclase, plagioclase, hornblende and biotite with quartz showing no sign of weathering before the physical breakdown of the rock (see Table 2). The first indication of weathering is the release of iron oxides from mild leaching of the mafic minerals. The red staining moves down the veins, then along the cracks between minerals and finally spreads across the grains. This is paralleled by the breakdown of orthoclase then the clouding and disruption of the twinning in plagioclase and finally the breakdown of hornblende and biotite. Quartz shows no signs of weathering.

The feldspar minerals predominantly alter to kaolinitic clays initially. However, the smectite clays are dominant throughout the profiles on qualitive XRD evidence. A review of the literature shows general disagreement with this conclusion although sericite is frequently mentioned, as is the reaction: plagioclase to montmorillonite (Tardy et.al., 1973). A typical composite picture of the clay content of the average profile is shown in Figure 1.(a). The resulting combined soil primary and secondary mineralogy is tabulated as Table 3, and shows the relative breakdown of primaries and build up of stable secondaries.

A selection of typical mineralogical reactions is given in Table 4, based on an assumption: oxidative weathering and hydration by carbonic acid and dis-associated water in enriched drainage solutions is the predominant process (Verstraten, 1977). This is well supported by an acid soil pH, the free draining nature of the soil and by a good correlation between the theoretical reaction products and those shown to be present.

There is considerable mineralogical evidence that most weathering breakdowns pass through several intermediate stages before reaching stable end points. Minerals which would be considered unstable (or at best metastable) under the environmental conditions in the study catchment such as chlorite, illite, vermiculite and montmorillonite are present (some) throughout the profiles but particularly in the clay horizons. Chlorite, illite and vermiculite can be seen as transition minerals, but the presence of montmorillonite right through into the highly leached and sandy A horizons suggests it is at least a metastable end product in this environment. Table 3 demonstrates the dominance of smectite clays over kaolin which is supposedly the stable product (Keller, 1954), while the more complex (higher cation and less hydrated) clays are broken down by the gradually more intense weathering of the shallower horizons (particularly the A_1 and A_2).

THE GEOCHEMICAL CHANGES

The geochemical changes can be quantitatively determined from horizon elemental oxide content. The most consistent and effective approach is to average the data from the 23 profiles sampled for each elemental oxide in each horizon to correct it and then to tabulate this for an average profile.

Correction involves converting the relative concentrations to the actual mass of mineral that has been released during weathering. The corrected amount of oxide present in each horizon (in grams) can be estimated from the relative concentrations of zircon. The number of units of an index mineral present in the bedrock is a reference point, from which ratio between the reference point and the concentration in any other horizon can be calculated. The corrected oxide concentrations (Figure 1) can be converted to the amount lost during the weathering reaction as calculated for each unit volume of horizon in the profile by subtracting the amount present from the amount initially in the bedrock. The data is further converted so that it represents all the rock weathered to form the present thicknesses of each horizon present. There has been only a very small net loss of iron from the catchment and since iron is expected to be virtually immobile under acid leaching environs such a conclusion, in a practical way, supports and vindicates the use of zircon as an index mineral. Downward movement of iron into lower horizons can be explained in terms of fluctuating water levels, oxidation and reduction environments and consequent formation of insoluble iron oxides and hydroxides in mottled soil horizons. (Table 5)

The Weathering Process

The total quantities of material lost are extremely large but removal has occurred over a long time. Rock weathering begins as groundwater passes slowly through the rocks gradually altering both biotite and orthoclase at very slow rates and at depths up to 6 metres. As the rock is moved closer to the surface (by erosion of overlying material), orthoclase begins to alter to a kaolinitic clay by hydration with consequent release into solution of K^+ ions and soluble silica; the uptake of H^+ ions and the relative concentration of Al^{3+} ions result in percolating waters becoming high in cations and dissolved silica. The elemental oxide losses from weathered rock show that both silica and potassium are markedly removed at this stage but they also demonstrate that leaching of calcium, magnesium and sodium from bytownite is beginning long before it is evident mineralogically. The feldspar weathers firstly from the calcium rich centres of the strongly zoned crystals, releasing more calcium than sodium and forming kaolinitic clays rather than smectites probably due to low levels of magnesium. While still at the weathered rock stage hornblende begins to weather releasing magnesium, iron and aluminium. Plagioclase is still weathering at this stage but now, in the presence of magnesium, forms a higher proportion of montmorillonite. The iron and aluminium that are leached form less soluble oxides and hydroxides. Iron is not leached from the horizons, but remains as ubiquitous goethite and limonite (red stain). Once hornblende has begun to weather to chlorite greater access by solutions to biotite leads to a similar series of reactions. Biotite breaks down by hydration as lamellae are gradually expanded, potassium and magnesium are released and replaced by water and protons. Iron and aluminium continue to be absorbed into the same products possibly also forming small amounts of haematite and corundum respectively.

The breakdown of the last of the primary minerals, which is allied to the expansion of many of the secondaries leads to volume changes and physical breakdown of the rock to saprolite which retains much of the rock fabric while minerals continue to alter. Chlorite passes to illite with continued loss of potassium to solution. The saprolite also demonstrates a continuing loss of the cations calcium, magnesium, sodium and potassium as the feldspars, hornblende any remaining biotite and chlorite weather; and the increased relative enrichment of iron continues. Depletion of both silica and aluminium continues at a relatively rapid rate. As the saprolite becomes more intensely leached by greater volumes of more acidic solutions (lower concentrations of metal ions, passing through less dense material), firstly, all the biotite and chlorite and broken down while plagioclase continues to undergo leaching. Enrichment of iron in the saprolite is also occurring as Fe^{2+} and Fe^{3+} bearing minerals are weathered from horizons immediately above them. Silica being released, from primary silicates exists as the soluble H_4SiO_4 comple, while silica as quartz seems to remain stable and increases in relative proportion up the profile. Further into the C horizon K^+ continues to be leached at a steady rate (as vermiculite and illite are weathered) but calcium, magnesium and sodium drop away rapidly. The low concentrations of magnesium are not consistent with the dominance of smectite clays.

In the B horizon only traces of orthoclase and hornblende remain, while chlorite, vermiculite and illite continue to be depleted; a result which can be related to the steadily decreasing potassium and again, the marked reduction in calcium, magnesium, and sodium. The dominant clays are now smectites and kaolins, which

Table 3 Mineralogy of granite soils (based on XRD analysis)

Horizon	Primary Minerals	Secondary Minerals
A_1	Quartz*** Plagioclase* Hornblende? Magnetite?	Montmorillonite** Kaolin* Corundum * Illite?
A_2	Quartz*** Plagioclase* K-feldspar? Hornblende? Magnetite?	Montmorillonite** Kaolin** Corundum * Chlorite? Illite? Vermiculite?
B	Quartz*** Plagioclase* K-feldspar? Hornblende? Magnetite?	Montmorillonite** Kaolin* Corundum * Chlorite? Illite? Vermiculite? Halloysite?
C	Quartz*** Plagioclase** K-feldspar* Hornblende* Magnetite?	Montmorillonite** Kaolin? Corundum * Chlorite** Illite* Vermiculite* Halloysite?
Saprolite	Quartz** Plagioclase** K-feldspar* Hornblende* Magnetite* Biotite* Apatite?	Montmorillonite** Kaolin* Corundum ? Chlorite* Illite? Vermiculite* Halloysite*
Weathered Rock	Quartz** Plagioclase** K-feldspar* Hornblende* Magnetite* Biotite** Apatite?	Montmorillonite** Kaolin** Corundum ? Chlorite** Illite* Vermiculite* Halloysite*
Rock	Quartz** Plagioclase** K-feldspar** Hornblende** Magnetite* Biotite** Apatite*	Montmorillonite* Kaolin? Chlorite* Illite? Vermiculite? Halloysite*

*** Very strong peak
** Strong peak
* Peak present and identifiable (all major identification peaks present)
? Probable peak (ie. a majority of identification peaks present)

Table 4 Probable chemical reactions in granite weathering

1. Orthoclase + water + carbonic acid → Illite + soluble ions + soluble silica + bicarbonate
   Orthoclase + water + carbonic acid → Kaolinite + soluble ions + soluble silica
   Orthoclase + water + carbonic acid → Montmorillonite + soluble ions + soluble silica + bicarbonate
2. Plagioclase (bytownite) + water + carbonic acid → Montmorillonite + soluble ions + corundum + protons
   Plagioclase (bytownite) + water + carbonic acid → Kaolinite + soluble ions + bicarbonate
3. Hornblende + water + carbonic acid → Chlorite + montmorillonite + soluble ions + soluble silica + bicarbonate
4. Biotite + water + carbonic acid + Al ions → Chlorite + cations + soluble silica + bicarbonate
5. Quartz + water → Soluble silica (if at all)
6. Magnetite + water → Goethite + haematite + protons
7. Apatite + carbonic acid → Soluble ions + water + bicarbonate
8. Chlorite + carbonic acid → Vermiculite + soluble ions + water + bicarbonate
   Vermiculite + carbonic acid → Montmorillonite + insoluble corundum + soluble ions + water + bicarbonate
   Illite + carbonic acid → Montmorillonite + corundum + soluble ions + water + bicarbonate
   Montmorillonite → Kaolinite + soluble silica
9. Haematite + water → Limonite

Table 5 Total losses from rock weathering on granite soils

Horizon	Mass (kgx10^7)	Oxides (kgx10^6)						
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
A_1	10.4774	30.24	8.79	2.76	1.74	1.57	2.32	2.21
A_2	24.8508	66.63	19.09	6.19	4.20	3.80	5.44	4.82
A	6.6215	18.43	4.32	1.70	1.11	1.01	1.46	1.34
B	42.8107	94.23	23.76	4.32	6.76	5.91	8.90	7.66
C	73.3802	67.36	19.08	3.01	9.54	7.41	10.71	8.51
Saprolite	188.0811	107.21	25.01	-15.05	12.79	9.40	15.80	9.97
Weathered Rock	18.1031	18.83	-0.36	-0.92	0.78	0.67	0.69	1.09
Total		402.68	100.69	2.01	36.92	29.97	45.32	35.60
Grand Total	=653.99kg x 10^6 or 653,990 tonnes							

in themselves contain very little of these elements, so the ions are either in solution or adsorbed. Near the top of the clay rich B horizon, leaching is greatly accelerated because of the rapid throughflow of water in the sandy and porous A horizons. Because of the duplex profile, water movement is more likely to be lateral and downslope following infiltration, rather than down the profile. As a result plagioclase is rapidly broken down (Trudgill, 1976) and no other primaries survive except quartz. Quartz and plagioclase exist as resistates in the A horizons alongside a clay assemblage in which kaolin has reached parity with smectites. The A horizons retain cations at a level only slightly below that of the B horizon, an effect probably due to nutrient cycling by vegetation. Cations are present despite lower pH values, lower clay content, and increased water movement in the presence of lower cation exchange capacity clays. Such a situation could only be sustained if the cations are continually added by litter decomposition processes and adsorbed to both clays and humic colloids.

CONCLUSION

In general the foregoing discussion follows accepted weathering processes (Bruce-Smith 1972), except that the usual division between geochemical and pedochemical weathering (Flach et.al., 1968) cannot be made in such a continuous process. An understanding such as this can lead, by a reversal of the argument, back to predictions about bedrock geology from known parameters of soil and saprolite. The depth and period of weathering, the age of the catchment and the extent of lowering of the landscape are readily deduced from the same model.

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WAGGA WAGGA BRICKPIT REVISITED: A PRELIMINARY REPORT

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ABSTRACT

The Wagga Wagga brickpit is a type section for the soil stratigraphic units of the region. Initial work by Beattie is extended, establishing the great thickness of the oldest unit, the Marinna, and identifying a complex pattern of cut and fill sequences. The pit walls illustrate the variablility of the soil stratigraphic units and highlight the problems of correlation.

INTRODUCTION

The Wagga Wagga brickpit (Fig. 1) is a large quarry site, (160 m long by 130 m wide, with an average depth of 10 m), which is located on the southern flanks of Willan's Hill, in the heart of the city. The pit is excavated in unconsolidated alluvial, colluvial and eolian Quaternary materials that form a 21m-22m thick cover to the weathered bedrock below. Over the last forty years approximately 170 000 m^3 of clay has been removed for brick manufacture, but now the site has reached is maximum size being restricted laterally by surrounding industrial development, and vertically by the watertable. It is currently being progressively infilled, with the northern and western faces now masked by industrial and urban waste. Eventually, the pit will be lost as a Quaternary type site in south eastern Australia.

Late Quaternary sediments in this region of the south west slopes of the Eastern Highlands have been subdivided into five discrete soil stratigraphic units (Beattie, 1972). These units (from youngest to oldest: Kyeamba, Yarabee, Brucedale, Willis and Marinna are regionally extensive with the three younger units occurring as surface, relict soils in localities around the area. However, the Willis and Marinna soil stratigraphic units are exposed only in excavations and bore holes, and occur exclusively as truncated and buried soils. The Wagga Wagga brickpit, of W.R. Willis and Son is the type site for the Willis stratigraphic unit.

EASTERN FACE - BEATTIE'S ORGINAL SECTION

The eastern face is 130 m long and ranges in height from 10 m in the south to over 14 m high at the northern end (Fig. 2). The sediments are derived either from alluvial and colluvial materials flushed off Willan's Hill or from wind blown clays. Some stratigraphic units, for example the Yarabee and Brucedale, are clearly a mixture of both these materials while one, the Willis parna unit, is composed completely of windblown clay, Deposition

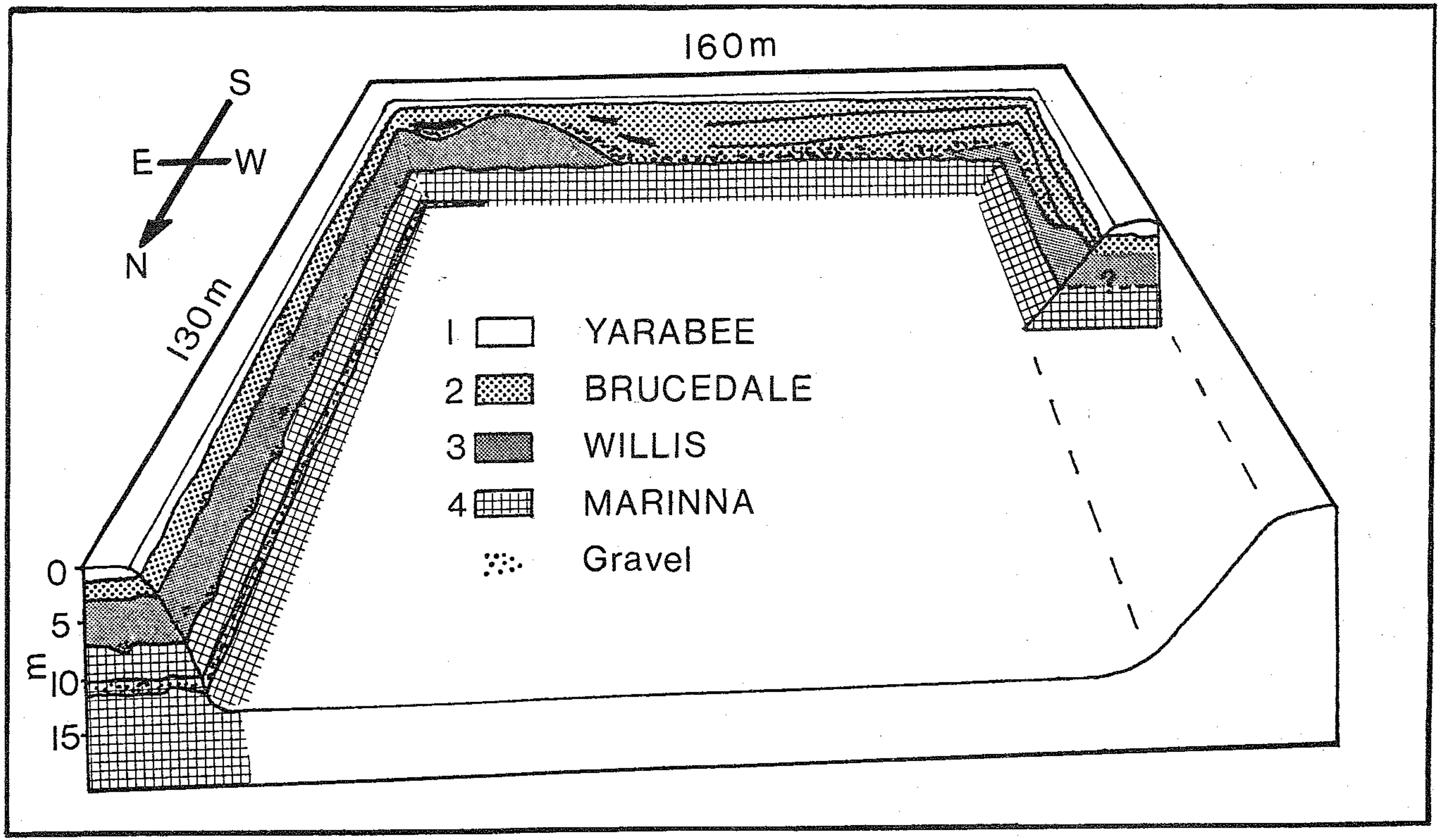

Figure 1, WAGGA WAGGA BRICKPIT

at this site was episodic, and the breaks in sedimentation are marked by pedogenic phases. It is these pulses of soil development that allow the sediments to be subdivided into discrete soil stratigraphic units. The periods of soil development always close with a pulse of erosion prior to renewed deposition. All the buried soils are truncated, and their upper boundaries are characterized by erosional contacts, some of which may have thin gravel lenses at the junction.

The main features of the soil stratigraphic units are as follows:

Kyemba: Not present at this site.

Yarabee: Here, the Yarabee is only 1.0 m to 1.4 m thick and soil development extends through the sediment to overprint the underlying, older unit, the Brucedale. The soil type corresponds with a Red Brown Earth: 10-15 cm of sandy clay loam A horizon, over clayey B and Bca horizons. The secondary carbonate extends 50-60 cm into the older sediments and is characterised by 1 cm soft friable carbonate glaebules.

Brucedale: On the eastern wall the Brucedale is usually only 1 m to 2 m thick and appears to be the basal remants of a mature soil; truncation has removed the upper horizons prior to the burial by Yarabee sediments.

The soil development is characterised by a yellow brown/brownish red medium clay with good structure, well-organised clay (frequent argillans and mangans) and indurated vertical columns of secondary carbonate. The carbonate columns extend down into the underlying Willis unit.

Willis: The Willis is composed of two main sedimentary layers: a windblown clay layer and a thicker, colluvium/alluvium layer. They are included in one soil stratigraphic unit because soil development extends through the two sedimentary layers with no separate soil on the upper surface of the underlying alluvium Willis layer.

Willis Parna: This is a 1.50 - 2.00 m thick unit on the eastern face with a grey colour, a well-developed structure (prismatic with angular blocky secondary peds), abundant void cutans (argillans, mangans and palygorskans) and a clayey texture with no sand. Soil development extends through the clay unit with 1 m long secondary carbonate columns overprinting the Willis Colluvium below.

Willis Colluvium: Colluvial materials mixed with eolian clay form a 2-3 m thick unit resting on the basal Marinna. Frequent gravel layers occur within the deposit and appear to be shallow (20-50 cm) cut and fill sequences accompanying the predominant colluvial character of the deposit.

Soil development extends from the Willis parna unit above, with the formation of pedality, mottling, frequent pedotubules, and complex patterns of cutan development.

Marinna: The Marinna is a thick (12 m +) complex stratigraphic unit. It is composed of several sedimentary layers all of which are overprinted with evidence of soil development. Immediately below the Willis colluvium boundary the deposit is a dark red

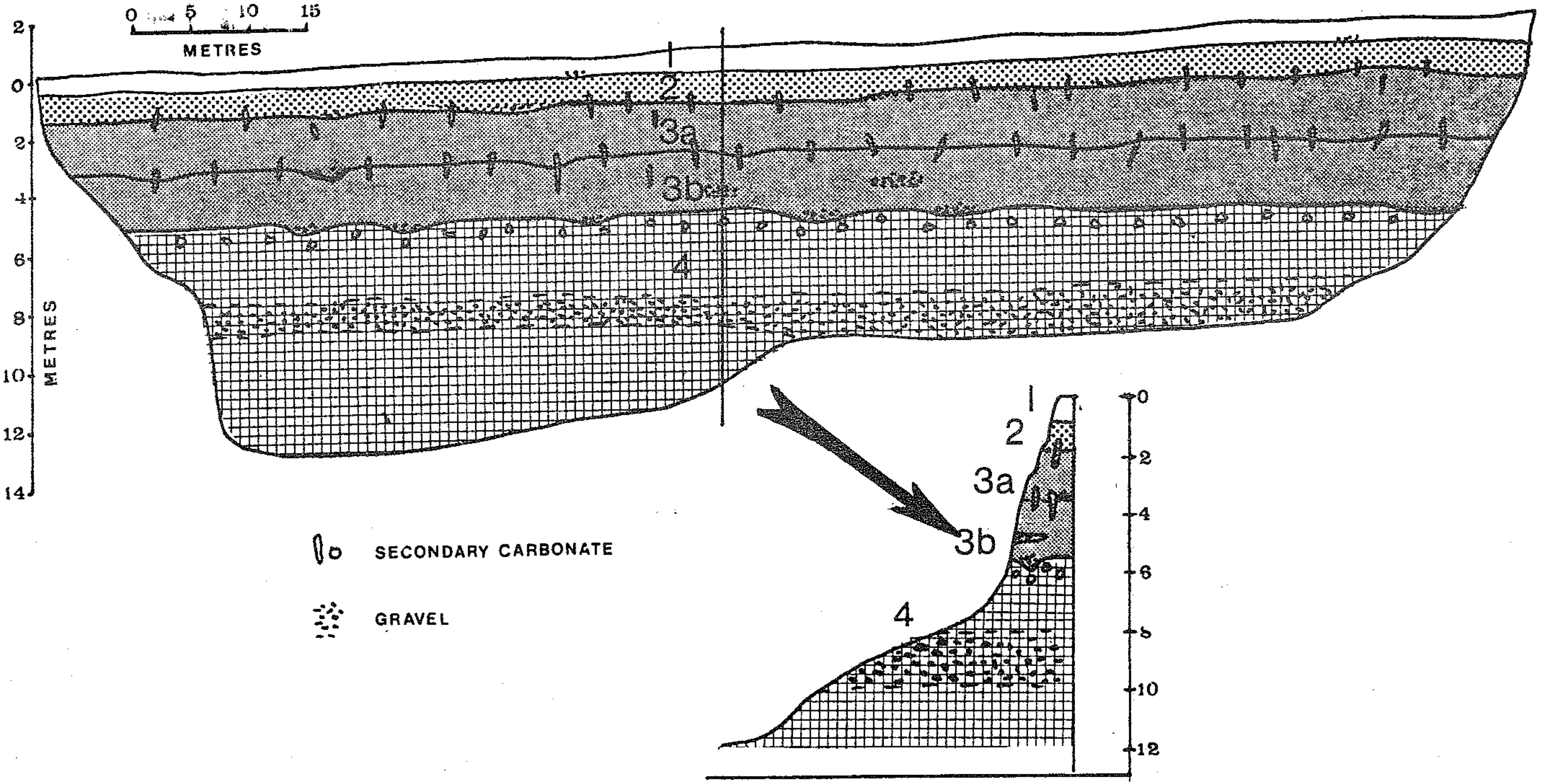

Figure II, EASTERN FACE

(10 R 3/6 D) sandy clay with frequent (20% +) grey mottles (10 YR 5/1 D). Here soil development is evident from the pedality, abundant cutans, and the indurated secondary carbonate glaebules. Below this layer occurs a 1.5 to 2 m thick gravel rich horizon which can be traced the length of the eastern faces. The gravel is all local in orgin, having a lithology (phyllite and quartzite) comparable to that of Willan's Hill; no exotic gravel size material has been identified. Deeper in the eastern face the Marinna's sandy clays are strongly mottled yellow brown and grey, forming a distinctive feature to the base of the eastern wall, and to the floor of the whole brickpit.

Auger holes sunk in the floor of the brickpit established the presence of these mottled sandy clays to over 21 m below the modern surface. At this depth fragments of weathered, phyllite were recovered which were interpreted as evidence of in situ weathering, of the deeply buried bedrock.

The complex pattern, the great thickness and the depth of soil development indicate that this basal unit, presently believed to be one soil stratigraphic unit, may well be a composite of several such units.

SOUTHERN AND WESTERN FACES

The stratigraphic units established on the eastern face can be traced around the brickpit onto the southern face. However, slumping of sediments down from the orginally vertical, 160 m long, southern face makes interpretation difficult in some sites. Similarly, dumping of industrial waste over the western wall has completely blanketed all but the first 30 m of the western exposure. The Marinna, with its characteristic grey mottle forms a useful marker horizon around the walls. Above this unit, some of the younger stratigraphic units show considerable variation compared with the eastern face: the Willis is eroded by fluvial action, and the truncated sediments are infilled by a greatly thickened Brucedale sedimentary sequence with at least two soil forming phases. A continuous Yarabee soil stratigraphic unit can be followed from the eastern face and with the Marinna below form convenient stratigraphic horizons.

In the south eastern corner of the southern face, the Willis parna is truncated by a 20 m wide and 3 m deep gully (Fig. 3). Basal sediments infilling the gully are gravel rich sandy clays which grade upwards into finer textured, light and medium clays free of the coarse (2-4 cm) gravel, but containing buckshot gravel lenses. Soil development of Brucedale age overprints the sediments producing pedogenic features (e.g. pedality, argillans, pedotublues and mangans).

A second, larger cut and fill sequence takes up much of the southern wall and all the exposed western wall (Fig. 3). The channel sequence is over 100 m wide and 6 m deep at its centre. Slumping of the face has obscured the eastern boundary of the channel with the Willis unit, but the western contact is clearly exposed on the western wall. There, the Willis parna unit is truncated by a sandy clay sediment associated with frequent gravel lenses. This erosional contact of the basal unit of the

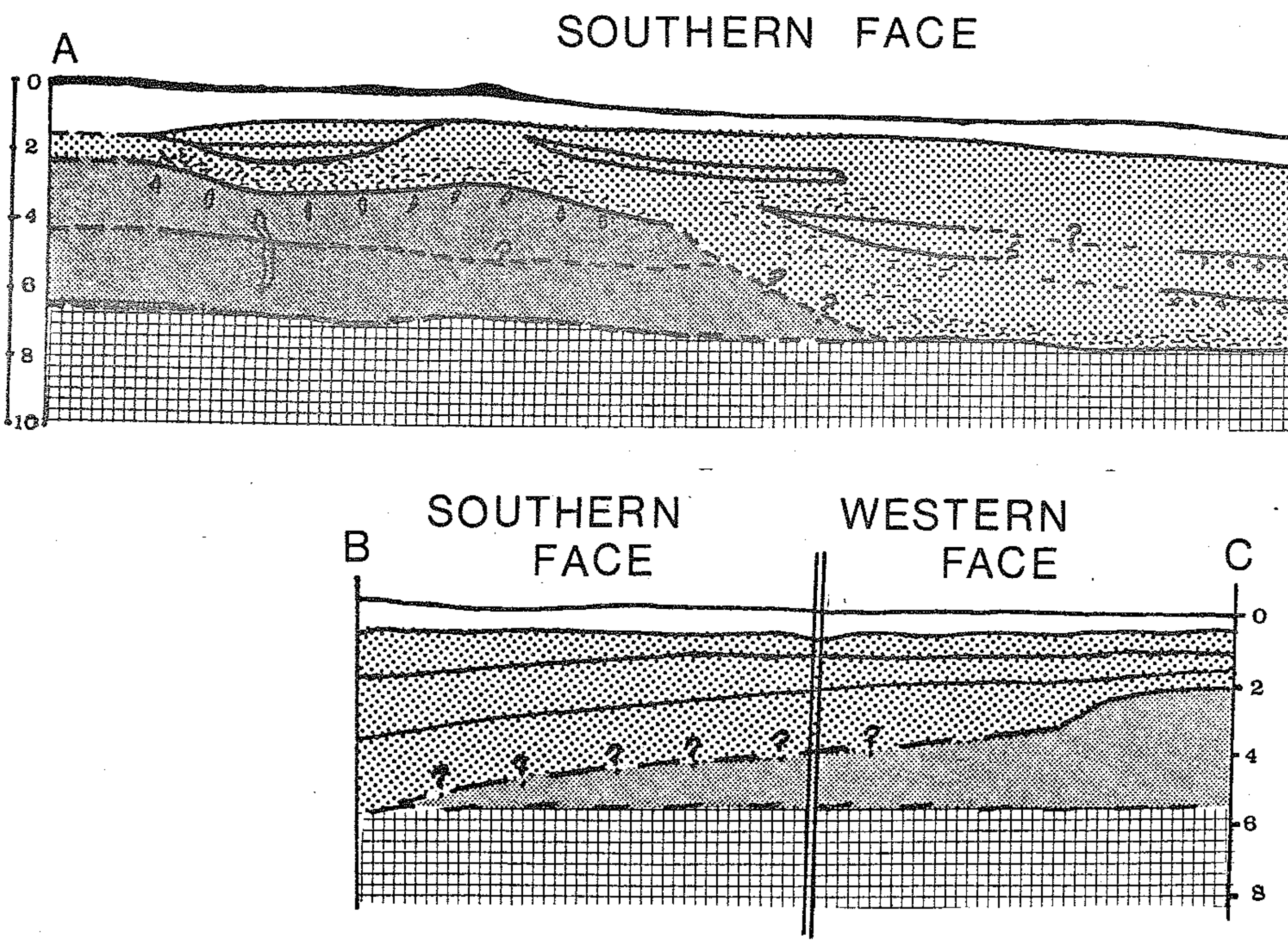
SOUTHERN FACE
A
B
0
2
4
6
8
10
B
SOUTHERN FACE
WESTERN FACE
C
0
2
4
6
8

Figure 3,

channel infill is also exposed on the southern face where a 2 m thick sandy clay unit rests with a sharp boundary on the truncated Marinna stratigraphic unit. Here, in the channel centre, the gravel at the contact is sub rounded, and can be over 6 cm in diameter. Sediments infilling the channel section, pass upwards from this basal, gravel rich, sandy clay, to light and medium clays associated with 1-2 cm thick lenses of buckshot gravel. The upper units are complex, with several sedimentary units being identified, and some having marked dips either eastwards or westwards into the channel centre (Fig. 3). Soil development has extended down into these infill sediments, in at least two soil formation phases. The stratigraphic relationship of the channel sediments, and the degree of soil development allow correlation with the Brucedale stratigraphic unit.

CONCLUSIONS

The plot of the soil stratigraphic units on the three faces of the brickpit indicates the variability of soil and sedimentary units across a buried landscape. The Brucedale unit is usually regarded as a 1-2 m thick sedimentary layer composed of a mixture of parna and alluvium/colluvium, on which a mature, calcareous soil has developed. However, the rapid change to an alluvial infill situation in which two phases of soil development are distinguishable illustrates the complications to be expected on a regional scale. Correlation on sedimentary and soil morphological evidence is always problematic.

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GENESIS OF LATERITES IN SOUTH AUSTRALIA

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