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HOLOCENE VALLEY AGGRADATION AND GULLY EROSION IN HEADWATER CATCHMENTS, SOUTH-EASTERN HIGHLANDS OF AUSTRALIA

IAN P. PROSSER

School of Geography, University of New South Wales, P.O. Box 1, Kensington, NSW, 2033, Australia

JOHN CHAPPELL AND RICHARD GILLESPIE

Department of Biogeography and Geomorphology, Australian National University, P.O. Box 4, Canberra, ACT, 2601, Australia

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ABSTRACT

Late Quaternary stratigraphy of a 50 km^2 catchment on the south-eastern highlands of Australia reveals processes and history of denudation, and helps resolve a long-standing debate about factors controlling episodic valley aggradation and degradation during Holocene times. Valley sedimentation occurred when swampy vegetation fully colonized valley floors and obliterated all channels, promoting aggradation for periods of several thousand years, with most incoming sediment being trapped in swampy meadows. Much of the sediment was reworked from late Pleistocene alluvial fan and valley fill deposits, and primary hillslope erosion was minor during the Holocene. Differing sedimentation patterns between the Late Pleistocene, Holocene and Post-European settlement periods reflect regional changes in sediment supply and transport capacity as a result of major environmental change. Within the Holocene, however, valley fill stratigraphy is controlled by massive, episodic gully erosion terminating aggradation. Gully initiation appears to be controlled more by thresholds of incision into vegetated valley floors than by changes to sediment supply. Whether the thresholds are exceeded because of climatic change, autonomous change or extreme events cannot yet be determined. Overall, the Holocene history represents continuing complex response to events of the Late Pleistocene, and does not support the K-cycle concept, which has strongly influenced late Quaternary geomorphology in Australia.

KEY WORDS Holocene Valley fills Gully erosion Climatic change Thresholds

INTRODUCTION

Holocene valley fills show alternating episodes of aggradation and downcutting, suggesting fluctuating geomorphic processes, across a diverse environmental range, but there are different interpretations of these deposits in terms of relative effects of climatic, anthropogenic and intrinsic factors (Butler, 1967; Vita-Finzi, 1969; Patton and Schumm, 1981; Graf, 1983; Knox, 1983). Some workers tended to regard changes from aggradation to downcutting, or vice versa, as due to climatic change, in palaeoclimatic terms, but more recent concepts of lagged responses and of autonomous change associated with intrinsic thresholds suggest that these stratigraphic records may not simply reflect external factors (Born and Ritter, 1970; Schumm, 1977; Womack and Schumm, 1977). The geomorphic processes and controlling factors probably vary from one situation to another, but it is important to understand the conditions under which particular processes and controls dominate. Such an understanding will lead to more accurate assessment of human impact on the landscape and help determine the sensitivity of geomorphic processes to environmental change.

Butler (1959, 1967) dominated earlier work on colluvial and alluvial deposits in Australia, and introduced the influential concept of 'K-cycles' of alternating landscape instability and stability to explain the stratigraphy.

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Brief phases of instability, involving accelerated erosion of slopes and headwaters, were believed to result in regionally synchronous aggradation of valleys and footslopes, followed by a long period of stability during which soil formation predominated. Later work concentrated on defining the ages of aggradation and on interpreting their climatic significance (Walker, 1962; Coventry and Walker, 1977; Williams, 1978). As more deposits were dated, however, and independent evidence of palaeoenvironmental conditions arose from pollen analysis, lacustrine deposits and archaeology, it became clear that valley-fill stratigraphy was not a simple reflection of past climatic changes. The controls on Holocene deposits became particularly uncertain with debate centring around the importance of small climatic changes, Aboriginal burning of the landscape and autonomous change (Hughes and Sullivan, 1981; Young and Nanson, 1982; Walker, 1984; Young *et al.*, 1986). The debate remains unresolved, partly because work concentrated on the chronology of events and neglected analysis of the geomorphic processes (with the exception of Young and Nanson, 1982). Furthermore, the focus was on aggradation and little attention was given to periods of valley downcutting. It seems appropriate then to reanalyse the deposits themselves in order to construct a history of geomorphic processes before addressing the question of controlling factors.

In this paper, late Quaternary deposits of a headwater basin in the south-eastern highlands of Australia are examined and compared to published records to identify the processes of denudation and sedimentation. Sources of sediment, the nature of sediment stores, depositional environments, and the chronology of aggradation and downcutting are considered. This study concerns headwater basins which, it will be shown, are upstream of the limits of permanent channels but occasionally have been invaded by deep gully networks. Geomorphic processes and controlling factors are thus likely to be quite different from the more thoroughly studied changes to dimensions of permanent alluvial channels.

STUDY AREA

The study is based on detailed stratigraphic sequences at Wangrah Creek, a headwater drainage basin of the Murrumbidgee River, on the Southern Tablelands of New South Wales (Figure 1). Wangrah Creek has a drainage area of 50 km^2 and descends from a plateau at 1300 m elevation in the east to 500 m elevation in the west. The catchment is dominated by moderately steep slopes of up to 15° gradient and 500 m in length, developed on Ordovician slates and sandstones, and supporting open *Eucalyptus* forest. Mean annual rainfall at the head of the basin is 723 ± 207 mm, and is evenly distributed throughout the year.

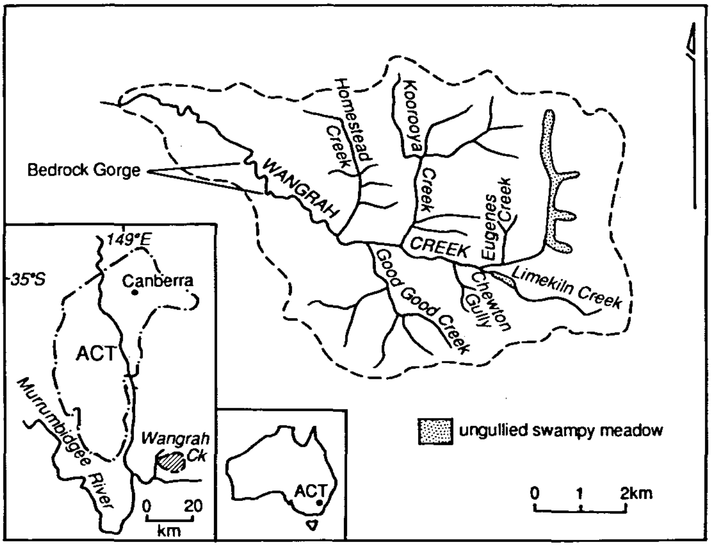

Figure 1. The drainage basin of Wangrah Creek, New South Wales. Stream channels are entrenched in gullies, except in reaches shown as ungullied swampy meadows

The basin has a continuous gully network eroded to bedrock through up to 8 m of late Quaternary alluvium. Base-level at the downstream end is defined by a small bedrock gorge. Upstream of the gorge are alluvial flats 50 to 300 m wide, mostly of the one surface but locally there are two or three terrace levels, each less than 1 m apart in elevation. The upper reaches contain narrow, discontinuous remnants of a single alluvial surface. Small alluvial fans, many of which are incised by the present gully network, are found at the confluence of most tributaries with trunk valleys.

There is evidence that Wangrah Creek and other basins in the region contained no continuous channels before European settlement. Early surveys of the Southern Tablelands paid particular attention to the availability of water and the form of channels. Frequent reference was made to chains of ponds—deep pools of clear water with little or no connecting channels (Eyles, 1977)—and an 1842 map shows that a sequence of pools preceded the present gully in the lower reaches of Wangrah Creek (NSW State Archives Map No. 47.831). The original form of the valleys is preserved locally at sites that have escaped gully erosion in historical times, including a section of Limekiln Creek and the headwaters of Wangrah Creek (Figure 1), and sections of other creeks in the region. Floors of all these valleys are covered to their full widths by swampy ground with a rough surface of tall sedge and tussock grass up to 80 cm high, and flows spread through the vegetation, often in several preferred pathways which may include shallow scour pools. These wet valleys without continuous channels are termed 'swampy meadows' in this study and are similar to the cienegas of south western United States (Melton, 1965) and the dambos of Africa (Boast, 1990).

METHODS

The Holocene and Late Pleistocene stratigraphy is based upon drill cores and extensive exposures along gully side-walls. Twelve transects were made across the valley floor upstream of the bedrock gorge, and a longitudinal section was constructed of the uppermost 2 km of entrenched main valley. Previous workers in the region described Quaternary valley-fills mainly in pedological terms (e.g. Butler, 1967; Coventry and Walker, 1977), but to determine the geomorphic history it is important to distinguish primary sedimentary characteristics from subsequent pedogenic features. Hence, the deposits are defined as lithostratigraphic units and described using the sedimentary textural classification of Folk (1954) with some additional laboratory analysis of particle size. Pedogenic overprinting of each unit is described using United States Soil Taxonomy (Soil Survey Staff, 1975).

Radiocarbon ages of deposits were initially determined radiometrically at the ANU Radiocarbon Laboratory using detrital charcoal, but problems arose in older deposits due to contamination by younger organic compounds. It was found that conventional alkali extraction of humic materials (Gillespie, 1980) did not completely remove the contaminants, and that it was necessary to use more rigorous chemical treatments based upon pollen preparation techniques. Chemical treatments included hydrofluoric acid, chlorate oxidation and alkali extraction, which produced residues of mainly pollen and charcoal particles. Ages of the residues were measured at the New Zealand Institute of Nuclear Sciences by accelerator mass spectrometry (AMS). ^{14}C ages of the residues were greater than those of both the extracted humic materials and charcoal after alkali extraction (Gillespie *et al.*, 1992). Chronology of our older units is based on AMS results, and ages of the youngest units, which show no sign of contamination, are based on radiometry.

STRATIGRAPHY

Three formal lithostratigraphic units are defined: the Bangalay, Wangrah and Limekiln Formations. Within these, several informal stratigraphic units are identified for the purpose of detailed interpretation. These are swampy meadow units 1 to 3, and various gravel fill, alluvial fan and minor slope units distinct to each location. Geomorphic and stratigraphic relationships between units are illustrated in Figure 2.

Bangalay Formation

The Bangalay Formation overlies bedrock and contains the oldest Quaternary sediments of the basin, deposited in most smaller valleys as coalesced alluvial fans which extend upslope into hillslope hollows.

Deposits are up to 10 m thick in the valleys and can be up to 2 m thick within 200 m of the drainage divide. At the base are continuous beds of cobbles and boulders within a clayey gravel matrix. Overlying this are brown, planar bedded sands and subangular gravels dipping 10 to 15° towards the valley and 2 to 4° down-valley in the valley bottoms. Gravels are non-oriented, planar bedded and are upward-fining. Deposits are strongly weathered, with most gravels easily disintegrating in the hand. Pedogenesis is strong in the upper part of the Formation, forming a Paleudult with a hard setting, sandy, bleached, A2 horizon, 20–30 cm thick, and a 20–50 cm thick B2t horizon.

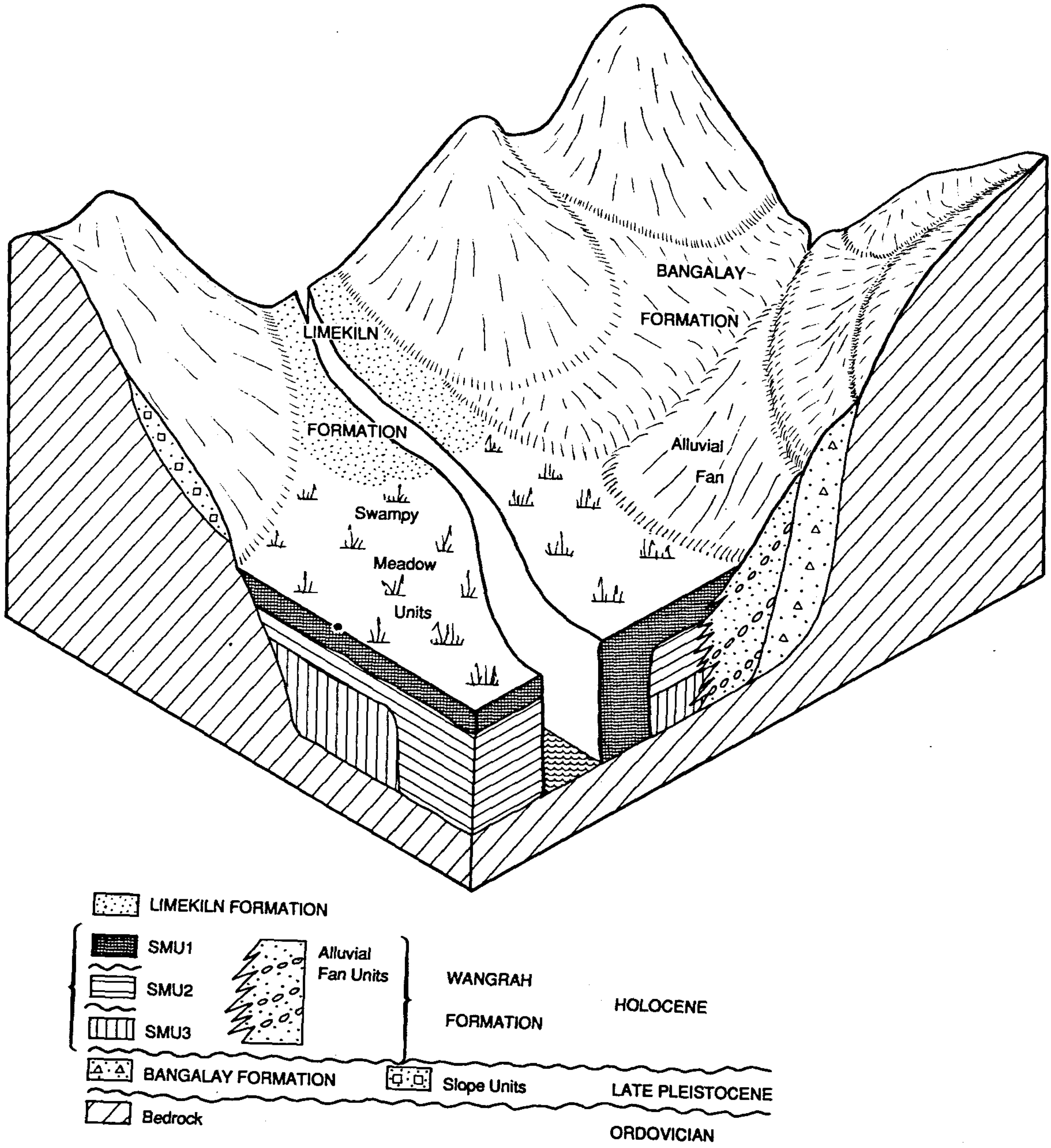

Figure 2. Schematic diagram of stratigraphic and geomorphic relationships between Late Quaternary units in Wangrah Creek basin. A wavy line denotes an erosional unconformity

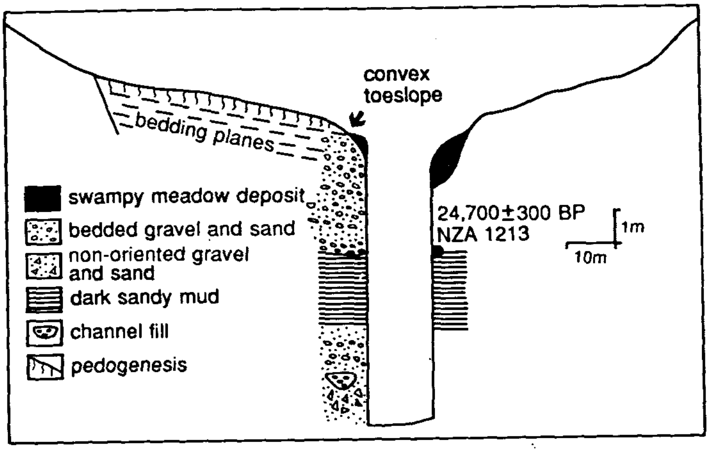

Figure 3. Stratigraphy of the Bangalay Formation in the Chewton Gully tributary of Wangrah Creek

Single units of vertically continuous fan deposits were found in Eugenes Creek, and two sequences separated by a 2 m thick, massive, dark grey sandy clay were found in Chewton Gully (Figure 3). Incision of the tributary valleys has formed convex toeslopes on the fans, truncating bedding and soil horizons, and the Wangrah Formation is inset within this surface (Figures 2 and 3). The Bangalay Formation is not found in the trunk valleys of the basin, but deposits bordering these valleys grade to a level 2–3 m above the bedrock floor, suggesting that coeval alluvial deposits existed in the trunk valley but were flushed out before deposition of the Wangrah Formation.

Units of the Wangrah Formation

The Wangrah Formation contains valley fills and coeval alluvial fan units which dominate the stratigraphy of trunk valleys. Three valley fills, each with a sharp boundary to weathered rock of the adjacent slopes, are distinguishable throughout the lower reaches, and are named swampy meadow units 1 to 3 (SMU1–3), in order of increasing age. The fills are massive, uniform deposits of grey to black, fine sandy silt and clay up to 6 m thick, although discontinuous scour troughs occur occasionally in SMU1, filled with clast-supported rounded cobbles, or gravels and sand. The sediment is mildly organic (2–8 per cent organic carbon), highly bioturbated, and contains many root channels and rhizomorphs of precipitated iron oxides. The depositional environment is identified by comparison with present-day swampy meadows where identical sediments are accumulating. The base of SMU3 is coarser than the other units and often contains planar beds of clayey matrix-supported gravels and sands.

Swampy meadow units are separated by horizontal disconformities, and by steep unconformities which represent phases of gully erosion (Figure 4). Disconformities are often hard to recognize because of the uniform lithology of each unit, but are characterized by a slightly darker colour in the top of an underlying unit, separated by a sharp boundary from lighter and sandier sediment of the overlying unit. Organic content and colour value (darkness) increase towards the top of each unit, possibly because rate of sedimentation diminishes upwards and degree of pedogenesis increases. There is little other evidence of pedogenesis except where SMU2 forms a higher terrace and, after exposure for several thousand years, shows minor leaching of organic matter and clay from the top 10 cm of deposits and illuviation immediately below to form an incipient Argiudoll.

Earlier papers refer to a fourth, older, swampy meadow unit (Prosser, 1987, 1990, 1991). Further field study of basal sections of SMU3 denies rather than confirms this older unit, and AMS radiocarbon dates indicate that deposits formerly named as SMU4 are of similar age to lower parts of SMU3. Hence, deposits previously recorded as SMU4 are now considered to be part of SMU3.

Alluvial fan units of the Wangrah Formation are found at the junction of many valleys with trunk valleys (Figures 2 and 4) and are smaller, finer-textured and have gentler gradients than those of the Bangalay

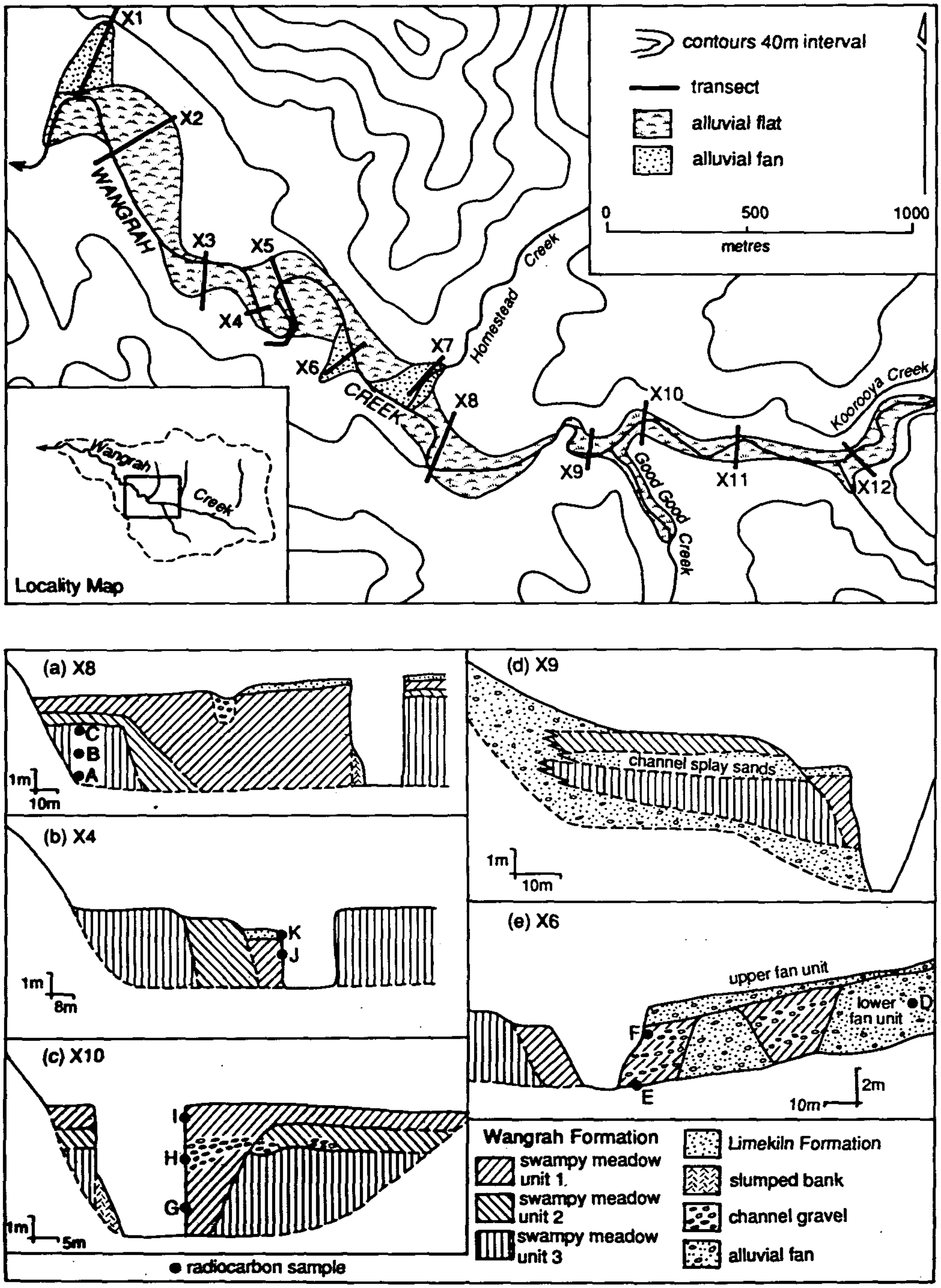

Figure 4. Selected stratigraphic transects from lower reaches of Wangrah Creek, upstream of bedrock gorge. Map shows locations of all transects studied, including those shown here. Radiocarbon ages of lettered points are: A = 12 420 ± 150; B = 11 740 ± 270; C = 8840 ± 130; D = 8610 ± 410; E = 2910 ± 130; F = 1230 ± 90; G = 2630 ± 130; H = 1370 ± 80; I = 870 ± 120; J = 1150 ± 130; K = Modern

Formation (the largest measures 200 × 300 m). All fans are found at the mouths of valleys containing incised Bangalay Formation deposits. The fan deposits are up to 6 m thick, contiguous with swampy meadow units, and are unconformably inset into the Bangalay Formation or overlie bedrock. Planar beds of sand and subrounded gravel, 20–100 cm thick, alternate with brown to greyish brown, silty, gravelly sands. Gravel clasts are flat-lying or weakly bedded, and are supported by a matrix of clayey and silty sand. Larger fans contain

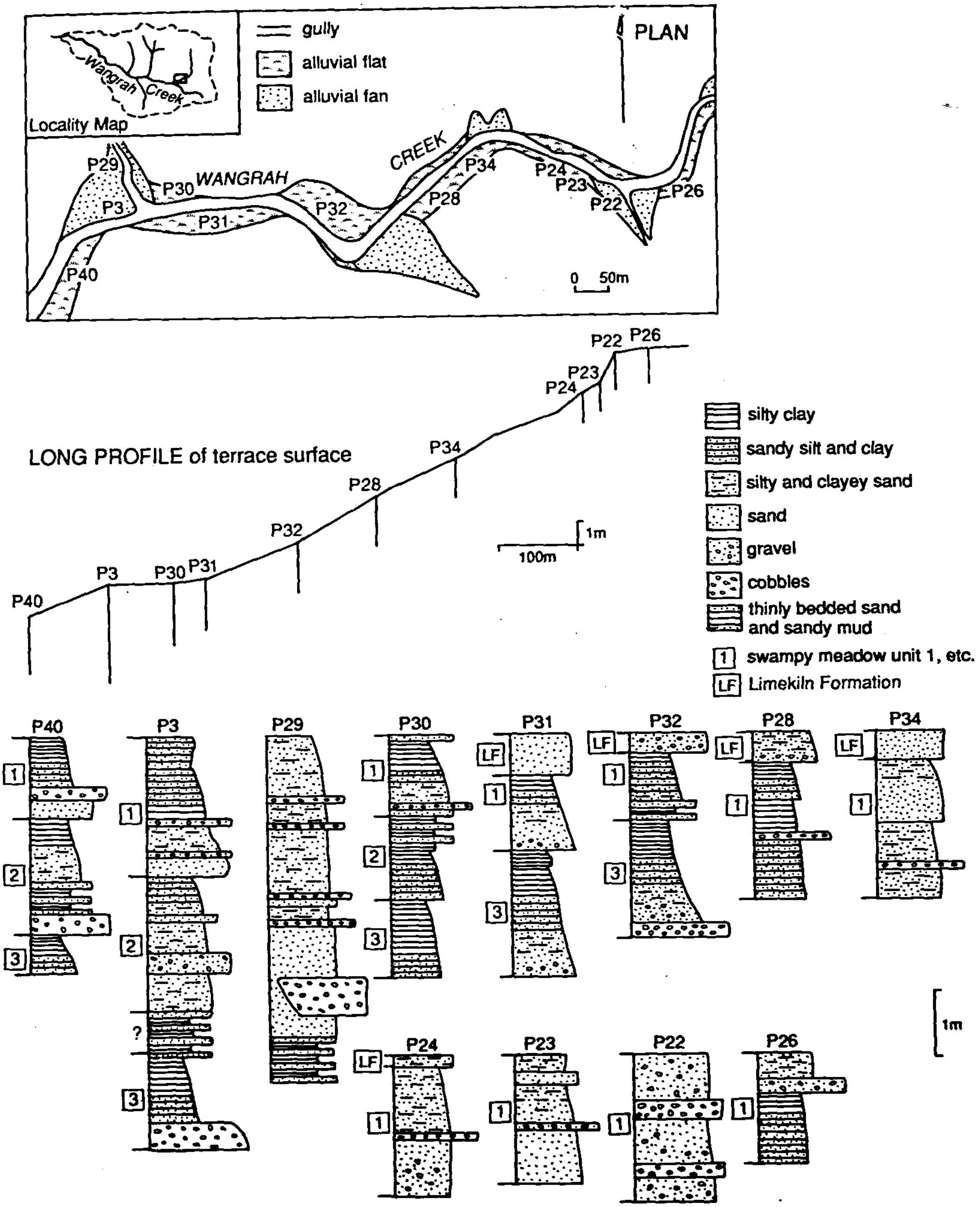

Figure 5. Stratigraphic sections and long profile of bank exposure and drill core profiles in Wangrah Creek upstream from Limekiln Creek. Map shows location of profiles and of tributary fans

occasional trough elements of course, rounded, clast-supported gravel. Some units show minor pedogenesis towards an Udipsamment with a weakly leached A2 horizon overlying a clay-enriched incipient B2t horizon.

Stratigraphic relationships within the Wangrah Formation

Stratigraphic relationships between SMUs, alluvial fans and intervening degradation of the Wangrah Formation are crucial to the interpretation in this paper. Detailed relationships between swampy meadow units and alluvial fans are best illustrated by the longitudinal section of the upper reaches where an alluvial fan has formed at the mouth of each tributary (Figure 5). Fan deposits, illustrated by profiles P22 and P29 (Figure 5), are poorly bedded sands and gravels, where silty or fine-sandy clays, typical of swampy meadow deposition, are absent. Upward-fining sequences of swampy meadow sediments overlying sands and fine gravels occur at and downstream from the fan toes. In profile P3, three upward-fining sequences are identified, each topped with swampy meadow sediment (Figure 5). Two sharp breaks in texture and colour are interpreted as disconformities between separate units of the Wangrah Formation, named SMU1 to SMU3 on the basis of their swampy meadow facies. The coarse basal sediments can be traced upstream to the nearest fan and general fining downstream from fans is illustrated by the two series P22–P23–P24, and P29–P3–P40. In the trunk valley immediately upstream of each fan, the Wangrah Formation is composed of typical fine-textured swampy meadow sediments (sections P26, P28, P30) which lens out upstream as the next fan is approached. The fluctuating slope of the terrace parallels the sedimentary features, being greatest immediately downstream of each fan and diminishing below that. The combined features indicate: (i) that each tributary supplied the bulk of at least the coarse sediment in the Formation; (ii) that swampy meadow units are downstream extensions of alluvial fans; and (iii) that fan deposition followed each episode of valley degradation.

There is clear evidence in the lower reaches that degradation of each SMU was in the form of gully erosion similar to that of the present day. Gully sidewall exposures of the Wangrah Formation are virtually continuous in the lower reaches of Wangrah Creek, and selected exposures are shown in Figure 4. Sidewalls of two palaeogullies separate SMU1 from SMU2, and SMU2 from SMU3 deposits, respectively, at section X8 (Figure 4a). The older of these is an almost vertical linear cut, and the younger a gentler slope, both having many modern analogues in the present gully walls. At section X10 a single palaeogully sidewall separates SMU1 from SMU3 and continues to bedrock. SMU2 is found sandwiched between horizontal surfaces of SMU1 and SMU3 (Figure 4c).

Away from the buried sidewalls, the tops of each unit are horizontal and the units overlie each other, but there are variations. SMU1 overtops SMU2 which overtops SMU3 at X8 and X10, for example, while the surface downsteps from SMU3 to SMU1 in small terraces, less than 1 m apart, at section X4 (Figure 4b). Drilling of the two higher terraces confirmed the presence of SMU2 and SMU3, and similar stratigraphy, with buried older units, was found in drillcores taken from alluvial flats adjacent to sites where only SMU1 is exposed in the present gully wall.

In the upper reaches, SMU1–3 have been firmly identified in profiles P40 and P3, although no comparable breaks are recognized in the tributary fan at profile P29 (Figure 5). Upstream tracing of units is complicated by discontinuous exposures and by intrusion of tributary fan deposits; we are confident that the full sequence, SMU1–3, occurs at P30, but SMU2 is missing only 40 m upstream at P31, and beyond that at P32. Yet further upstream the degree of weathering and lack of disconformities in the stratigraphy indicate that both SMU2 and SMU3 are absent. Collectively, these features imply that each phase of gully erosion proceeded beyond Eugenes Creek.

An important stratigraphic relationship between fan aggradation and gully erosion is visible in section X9, which combines exposure from the trunk valley with drillcores through a small tributary fan (Figure 4d). SMU2 overlies SMU3, separated by splay-channel sands, and both units wedge out into fan gravels. No disconformity was recognized in the fan deposits, but it is clear from sections X4, X8 and X10 that downcutting to bedrock occurred in the trunk valley, between SMU3 and SMU2. This fan appears to have remained active while the trunk stream was downcutting, and the fan is aggrading today above the nickpoint formed by the trunk gully. Many of the larger alluvial fans, however, were trenched by tributary gullies to Wangrah Creek. Section X6, for example, shows incision of a lower fan unit and backfilling by a mixture of fan and swampy meadow deposits (Figure 4e).

Limekiln Formation

This Formation is composed of bedded sands and fine gravels up to 120 cm thick conformably overlying SMU1 as discontinuous sheets extending the full width of the valley. The formation represents splay deposits from discontinuous gullies, which were the initial stages of the present continuous gully network (Prosser, 1991). This relationship is illustrated at Limekiln Creek, where a section of swampy meadow exists downstream of a discontinuous gully. The Limekiln Formation caps SMU1 downstream of the gully and resembles a low-angle fan, with a convex cross-section and an apex which meets the gully terminus. No Limekiln Formation deposits are found upstream of the point of gully initiation (identified from air photographs), confirming their origin as channel splay deposits rather than the result of slope erosion. In Wangrah Creek itself the Limekiln Formation overlies SMU1 at sections X4, X8, X9, and profiles P30 to P24 in the upper reaches, for example, but is not found at X6 and X10 (Figures 4 and 5). The deposits at X8 extend upstream into Good-Good Creek, indicating discontinuous gully erosion in this tributary before incision of the present trunk gully.

Slope units

Purely colluvial deposits are uncommon in the basin, and the only exposure is a road cutting through three slope units near the head of Wangrah Creek. The basal unit contains non-oriented fine gravels with strong pedogenesis, indicated by a bleached A2 horizon overlying clay and weathered gravel. Sharply overlying this are dark red, planar beds of fine sand, silt and clay, with thin beds of weathered, moderately sorted gravels. The top unit consists of much less weathered, non-oriented, and poorly sorted gravels in a clay matrix, which in places fill small troughs cut into the underlying deposits. Other young slope deposits are restricted to the wettest hillslope hollows and are conformable with the Wangrah Formation.

RADIOCARBON CHRONOLOGY

Radiometric (ANU samples) and AMS dates (NZA samples) are listed in Table I, which includes results from Gillespie *et al.* (1992). The Bangalay Formation was dated at 24 700 ± 300 BP (NZA 1213; Figure 3) from the top of the clay separating the two gravel fills in Chewton Gully. Colluvial deposits at the head of Wangrah Creek are probably of comparable age, as a black clay unconformably underlying the lowest gravels gave an age of 32 230 ± 500 BP (NZA 1211).

Radiometric dates from SMU3 are up to several thousand years less than AMS ages from the same stratigraphic position, reflecting the presence of soil-organic contaminants not removed by conventional pretreatment methods, and must be treated as minimum estimates. There may be discrepancies between AMS and radiometric results from SMU2 but these cannot be evaluated from the data, and all results from units SMU1 and SMU2 are taken at face value.

The first aggradation of the Wangrah Formation, represented by unit SMU3, spans the interval from 13 000 to 8000 BP or somewhat younger. Three AMS dates from near the base, middle and top of the unit in section X8 are internally consistent, and downward extrapolation gives a basal date of at least 13 000 BP (NZA 545, 544, 566 in Table I; Figure 4a). A radiometric date from the same profile (ANU 5369) gave an age approximately 2000 years younger than the equivalent AMS date. No samples were obtained from the true top of the unit, but a radiometric age of 7880 ± 380 BP (ANU 5715) was obtained from sand splay deposits immediately above SMU3 at profile P3 in the upper reach of Wangrah Creek.

The second aggradation, represented by SMU2, apparently commenced about 5000 BP and persisted for some 2000 years. No dateable material was obtained from the base of the unit, but an age of about 5000 BP is inferred at two sites. Sample ANU 5374, from 0·6 m above the bottom of the exposure at X2, gave 4690 ± 80 BP. Charcoal 0·3 m below the top of SMU2 at section X7 gave 3225 ± 85 BP (NZA 746) and humic sediment at 1·3 m gave 4250 ± 90 BP (NZA 754); downward extrapolation suggests a basal age of about 5000 BP. Radiometric dates from two bank exposures put the top of the unit at 3000 BP (ANU 5453, and 5317 in Table I).

Table I. Selected radiocarbon dates from Wangrah Creek

Sample no.	Description	Radiocarbon age (yr BP)
Slope deposits		
NZA 1211	Clay beneath base of deposits at head of basin	32 230 ± 500
Bangalay Formation		
NZA 1213	Clay between gravel fills in Chewton Gully	24 700 ± 300
Wangrah Formation		
SMU3		
NZA 545	70 cm above base of unit at section X8	12 420 ± 150
NZA 544	Middle of unit at section X8	11 740 ± 270
NZA 566	30 cm below top of unit at section X8	8840 ± 130
ANU 5369	70 cm above base of unit at section X8	9840 ± 180
ANU 5715	Splay deposit overlying SMU3 in P3, upper reaches	7880 ± 380
SMU2		
ANU 5374	60 cm above base of unit at section X2	4690 ± 80
NZA 754	70 cm above base of unit at section X7	4250 ± 90
NZA 746	30 cm below top of unit at section X7	3225 ± 85
ANU 5317	Top of unit near Limekiln Creek	3110 ± 130
ANU 5453	Top of unit at section X5	3000 ± 150
SMU1		
ANU 5365	40 cm above base of unit at section X7	2950 ± 100
ANU 5451	Base of unit at section X6	2910 ± 130
ANU 5364	50 cm above base of unit at section X12	2720 ± 120
ANU 4456	200 cm above base of unit at section X10	2630 ± 130
ANU 5394	50 cm above base of unit at section X5	2480 ± 160
ANU 4798	70 cm above base of unit in Limekiln Creek	2360 ± 230
ANU 5367	Middle of unit at section X8	2190 ± 100
ANU 4455	Middle of unit at section X10	1370 ± 80
ANU 5454	100 cm below top of unit at section X4	1150 ± 130
ANU 4453	40 cm below top of unit at section X10	870 ± 120
ANU 5393	50 cm below top of unit at section X5	810 ± 100
ANU 5512	Top of unit at section X4	Modern
Alluvial Fans		
ANU 5532	Middle of lower fan unit at section X6	8610 ± 410
ANU 5517	Base of upper fan unit at section X1	3450 ± 140
ANU 4019	Base of fan unit in Limekiln Creek	3250 ± 250
ANU 5452	Below upper fan unit at section X6	1230 ± 90
ANU 5318	Base of fan unit near Limekiln Creek	1040 ± 110
Limekiln Formation		
ANU 4452	Base of unit near Limekiln Creek	Modern

Aggradation of SMU1 commenced around 2900 BP, shown by basal ages at sections X6 and X7 (ANU 5451, 5363 in Table I), and continued until gully erosion began in historical times. A basal age of 2360 ± 230 BP (ANU 4798) from SMU1 in Limekiln Creek suggests that aggradation commenced almost simultaneously in this tributary. The overall pattern of aggradation is delineated with 20 ^{14}C dates in Figure 6, which shows that the unit accumulated rather uniformly throughout most of the valley system, but lagged somewhat in the steeper upstream reach at profiles P30 and P34. Mean sedimentation rate in the lower and middle reaches and in Limekiln Creek is about 1·2 mm a^{-1}, although dates higher in sections X5, X6 and X10 indicate that deposition towards the top of the unit slowed to 0·5–0·7 mm a^{-1} (ANU 5395, 5452, 4453 in Table I).

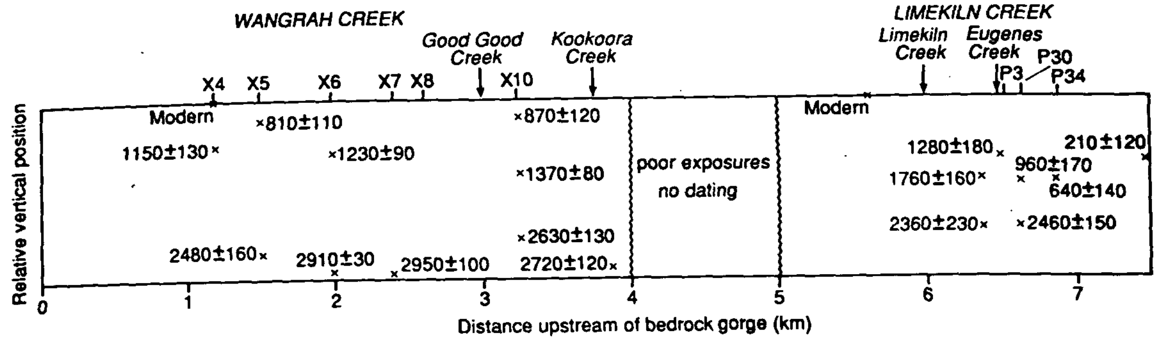

Figure 6. Schematic longitudinal section of Wangrah Creek, showing radiocarbon ages within swampy meadow unit 1 (SMU1). Positions of tributaries, and of transects and profiles with ^{14}C dates, are shown at top. True thickness of SMU1, which ranges from 1 to 6 m (generally thicker downstream), is not shown; dates are shown in relative positions within the profiles from which samples were collected

The few dates from tributary fans are consistent with their stratigraphic relationships to swampy meadow units of the Wangrah Formation. The fan unit at section X6, incised and filled with SMU1, is contemporaneous with SMU3 (ANU 5532, Table I; Figure 4e). Fan deposits at section X1 correspond to SMU2, with an age of 3430 ± 140 BP (ANU 5517), and fan sedimentation in Limekiln Creek corresponds to SMU1 (ANU 5019). A small fan near the confluence of Limekiln Creek, with a basal date of 1040 ± 110 BP (ANU 5318), lagged behind aggradation of SMU1.

SEDIMENT VOLUMES AND DENUDATION RATES

The sediment volume was calculated for SMU1 and coeval fan deposits in Limekiln Creek, where the Wangrah Formation is almost entirely composed of SMU1. From 10 transects based on sidewall exposures and 21 drillholes, the volume deposited in the last 3000 years is estimated as 28 500 m^3. This is equivalent to 1·1 mm ka^{-1} of erosion over the Limekiln Creek catchment (area = 3·8 km^2), given a rock density of 2·5 g cm^{-3} and a measured sediment density of 1·2 g cm^{-3}.

Contemporary rates of sediment yield reported from sites in southeastern Australia are shown in Table II. The figures from Strike-A-Light Creek and from farm dams are likely to be greater than natural rates over the last 3000 years, because historical forest clearance and agriculture have accelerated sheet and gully erosion (Edwards, 1988; Eyles, 1977), but the other entries are consistent with the above estimate based on the volume of SMU1 in Limekiln Creek. Hence, it appears that most of the sediment eroded from the catchment over the last 3000 years was trapped in swampy meadow and fan deposits, and present and

Table II. Modern erosion and sediment yield data from southeastern Australia

Rate (mm ka^{-1})	Location	Type of data	Source
0·7	Wangrah Creek	Erosion plot on Bangalay Formation	Prosser (1990)
1·6 ± 2·4	NSW	19 erosion plots on minimally disturbed sites	Edwards (1988)
1·0	Queanbeyan River	Suspended sediment yield	Douglas (1966)
3·0	Strike-A-Light Creek*	Suspended sediment yield	Douglas (1966)
3·8–8·6	Southern Tablelands	Farm dam sedimentation (catchment area < 1 km^2)	Neil and Galloway (1990)

* Includes the Wangrah Creek drainage basin

past denudation rates are very low. We believe that Limekiln Creek is representative of the main body of the Wangrah Formation, because sediment textures and organic fractions of the swampy meadow deposits are similar throughout the Wangrah system.

The mean rate of sediment yield from Wangrah Creek during historical gully erosion was estimated from the dimensions and age of the present gully network. Gully erosion commenced after 1842, and the present gully network was well developed by 1900. The first aerial photographs, taken in 1944, show that the length, width and depth of gullies were approximately the same as exist today (Prosser, 1991). The length of the gully network is 22 km; average depth and width are 3 m and 5 m respectively (from 19 surveyed transects), equalling a volume of $3{\cdot}3 \times 10^5$ m^3. If this had been derived from the entire catchment during the period 1842–1944, the denudation rate would be 36 mm ka^{-1}. Clearly, sediment yield from valley floors during historical gully erosion was much higher than the long-term yield from the slopes. Duration of erosion between SMU2 and SMU1, when much of SMU2 was removed from the valley, is not sufficiently well established to allow a similar calculation, but our radiocarbon results suggest that erosion lasted only a few hundred years, at most, which resembles the historical phase to a significant degree.

LATE QUATERNARY GEOMORPHIC PROCESSES

The Bangalay Formation and coeval slope deposits were deposited between 34 000 and 14 000 BP, and this period includes similar, radiocarbon-dated slope and major alluvial fan deposits elsewhere in the region (Costin and Polach, 1971; Costin, 1972; Coventry and Walker, 1977; Gillieson *et al.*, 1985). Sediment and soil characteristics indicate equivalence to K_3 deposits of Butler (1967) and van Dijk (1959). Even small hillslope hollows contain significant volumes of poorly sorted, angular gravels and the deposits represent a period of slope erosion, which included mass movement processes.

Sediments of the Wangrah Formation appear to be largely derived from the Bangalay Formation. Alluvial fans, which grade into swampy meadow deposits at all levels of the Wangrah Formation, occur ony at the mouths of tributaries where the Bangalay Formation has been incised. The sharp boundaries between the Wangrah Formation and weathered bedrock of adjacent slopes, and the lack of Holocene slope deposits, suggest that hillslopes themselves were not major sediment sources. The absence of Bangalay Formation sediment in the trunk valleys and the inset position of the Wangrah Formation indicate significant erosion of the Bangalay Formation before Wangrah sedimentation commenced. This incision propagated through larger tributaries, initiating many of the toeslopes which continue to erode today.

Swampy meadow and Holocene alluvial fan units have been described from many other valleys of the southeastern highlands (e.g. Costin, 1971; Coventry and Walker, 1977) and are equivalent to K_2 and K_1 deposits of van Dijk (1959) and Butler (1967). The number and timing of units varies between individual valleys, but most ^{14}C dates fall within the last 13 000 years (Prosser, 1991). Swampy meadow deposits have previously been described as minimal prairie soils (van Dijk, 1959; Butler, 1967; Coventry and Walker, 1977) and the lack of bedding and organic incorporation throughout attributed to homogenization following deposition (Walker and Green, 1976). Comparison with present-day swampy meadows, however, shows that bioturbation and organic accumulation proceed during aggradation because of low rates of deposition and good vegetation cover. The ^{14}C dates for SMU1, the lack of any laterally continuous stratigraphic breaks, and absence of coarse sands away from tributary fans, all indicate relatively uniform, slow deposition of each unit under low energy conditions. Similar patterns of Holocene valley fill sedimentation downstream of alluvial fans have been described for sandstone valleys north of Sydney (Erskine and Melville, 1983).

Overall sediment supply to the Wangrah Formation was relatively low, for much of the Bangalay Formation still remains in the basin. Coarse sediment, conformable with and below SMU3, suggests that rates of sediment supply were highest in the early Holocene following initial incision of the Bangalay Formation. Van Dijk (1959) observed that there were few comparable colluvial units to the K_1 valley fills, but subsequent work drew analogy from late Pleistocene denudation and attributed late Holocene valley fills to accelerated slope erosion (Coventry and Walker, 1977; Williams, 1978; Hughes and Sullivan, 1981). The stratigraphy of Wangrah Creek, however, provides no evidence for such erosion during the Holocene.

Holocene valley degradation was recognized by earlier workers, but the record from Wangrah Creek demonstrates that this took the form of massive gully erosion which terminated aggradation and removed much of the previously deposited sediment over a relatively short time. Historical records show that the present gully network of Wangrah Creek, and others in the region, were formed in less than 100 years (Eyles, 1977; Starr, 1989; Prosser, 1991). Similarly, the late Holocene erosion of Wangrah Creek is limited to a few hundred years by radiocarbon dates from the top of SMU2 and the base of SMU1. The early Holocene erosion, between SMU2 and SMU3, appears to be different, as it is bracketed by radiocarbon dates 3000 years apart; whether a gully system persisted through this interval, or an intervening unit was deposited and subsequently removed, is not known.

The Holocene history presented here contrasts with the long-held beliefs, initiated by Butler (1959), that aggradation represents climatically induced accelerated sediment supply, and that valley and slope degradation are part of the same period of instability. Holocene alluvial fans and valley fills were deposited under stable, low energy conditions, and aggradation continues today beyond the limit of present gully erosion, and probably did so beyond the limits of past gully erosion (section X9; Figure 4d). Under these conditions, episodic gully erosion is the dominant control on valley fill stratigraphy, rather than sediment supply from upstream, and is the expression of landscape instability, when much of the previously deposited sediment is delivered downstream over a relatively short period.

CONTROLS ON AGGRADATION AND GULLY EROSION

Late Pleistocene denudation, which generated the gravel fills of the Bangalay Formation, occurred when the region was significantly colder than today, and largely treeless. Glacial features and periglacial deposits in the nearby Snowy Mountains and lake-sediment pollen records indicate treeless subalpine conditions at lower elevations than Wangrah Creek, and temperatures were 6–8°C cooler than today (Galloway, 1965; Bowler, 1981; Kershaw, 1981; Singh and Geissler, 1985; Chappell and Grindrod, 1983; Colhoun and Peterson, 1986). Transition to more equable climate, open sclerophyll forest and moderate lake levels, similar to the present, occurred at the end of the Pleistocene (Kershaw, 1981; Chappell and Grindrod 1983; Dodson, 1986) accompanied by a reduction in hillslope mass movement and the development of swampy meadows throughout the trunk streams.

Previous work emphasized the onset of valley aggradation at 3000 BP, invoking accelerated hillslope erosion under slightly colder and wetter climate (Coventry and Walker, 1977; Williams, 1978) or under increased Aboriginal burning of the landscape (Hughes and Sullivan, 1981), but this is difficult to defend. Almost identical swampy meadow and alluvial fan deposits are found for much of the earlier Holocene, and analysis of radiocarbon dates from the region does not suggest accentuated aggradation in the late Holocene (Young *et al.*, 1986; Prosser, 1987). The style of aggradation appears insensitive to these smaller environmental changes, which had little effect on regional vegetation patterns (Dodson, 1986). Similarly, on the sandstone plateaux south of Sydney, patterns of valley aggradation observed today under sedge and heathland continue back to at least the end of the Pleistocene (Young, 1986).

There are many potential causes of gully erosion (Cooke and Reeves, 1976; Graf, 1983) which cannot be properly resolved from the evidence presented here, but the denudation history does impose some important constraints on the two Holocene episodes. In systems such as Wangrah Creek, with low sediment supply and dense vegetation cover on valley floors, increased peak discharge or decreased resistance to scour are likely to be more important than changes to sediment load or transporting capacity of flows as causes of gully erosion. Climatic controls or extreme events are obvious possible causes, but to be consistent with the stratigraphy they must have a recurrence interval of several thousand years. This rules out changes to rainfall patterns observed over historical times and invoked as causes elsewhere (e.g. Pickup, 1976; Leopold, 1976; Balling and Wells, 1990). Regionally synchronous erosion would be strong evidence for a climatic control, but cannot be assessed at present. There are scattered radiocarbon dates from other valleys which show no clear regional pattern of erosion (Prosser, 1991), but dating could be marred by contamination of samples by younger organic matter. A regional history of erosion awaits further radiocarbon dating using techniques outlined in Gillespie *et al.* (1992).

Both episodes of gully erosion were initiated when swampy meadows had expanded throughout the trunk valleys and overtopped the previous level of aggradation, suggesting that these conditions were in some way intrinsically unstable. Enlarged swampy meadows tend to increase discharge in the main valley, because they create additional areas of saturation overland flow and provide a direct link between slope runoff and streamflow. Simulation of hydrographs and monitoring of streamflow in Limekiln Creek indicates that in this region of low hillslope runoff, the swampy meadow contribution significantly increases the frequency of small floods (Prosser, 1991). We observed in remnant swampy meadows that tussock grass and sedges do not grow in pathways of constantly flowing water and that incipient channels develop at these sites. Expansion of swampy meadows may have increased flows sufficiently for minor channels to form, which would be prone to erosion during extreme floods. Once again, though, this hypothesis needs to be tested against the regional pattern of erosion.

Intrinsic instability, climate change and extreme events have also been proposed as causes of historical erosion (e.g. Mosley, 1972; Nanson and Erskine, 1988; Balling and Wells, 1990). In this region, however, the record of rapid, regionally synchronous erosion last century (Eyles, 1977; Starr; 1989; Prosser, 1991) points clearly to human impact, as arguments for other causes invoke events that were probably repeated several times over the last 3000 years.

CONCLUSIONS

In the south-eastern highlands of Australia, episodic aggradation during the Holocene was associated with low sediment supply from source areas, despite deposition of alluvial fans on the margins of trunk valleys. Aggradation was under densely vegetated swampy meadows, where most eroded sediment was deposited and where there were no continuous channels despite drainage areas up to $50\,km^2$. Each aggradational phase lasted for several thousand years and was terminated by gully erosion similar in scale to that of the present day. Episodic aggradation and degradation occurred regardless of overall landscape stability, attributable to equable climate, forest cover and tectonic stability. Under these conditions the stratigraphy is controlled by thresholds of incision into the vegetated valley floors, and not by climatically induced changes to sediment supply. It cannot yet be determined whether the thresholds were triggered by climatic change, autonomous change or extreme floods, but denudation since at least the mid-Holocene was insensitive to the known environmental changes. The Holocene history of gully erosion constrains possible causes and helps demonstrate that historical gully erosion was a result of the introduction of European agriculture.

A climatic explanation is appropriate, however, for changes of denudation and depositional regimes at the end of the Pleistocene. The Holocene history can be viewed as a complex response to events in the late Pleistocene: rapid denudation on treeless hillslopes during the last glacial maximum generated valley-floor and footslope deposits which were reworked during the Holocene, feeding aggrading swampy meadows which were episodically destabilized and the deposits flushed downstream. The continued adjustment to massive supply of sediment in the late Pleistocene is similar to that reported by Church and Slaymaker (1989) and Knox (1989).

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