Sediment remobilization and storage by discontinuous gullying in humid southeastern Australia.

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ABSTRACT Historical records show that a phase of discontinuous gullying began between 1838 and 1867 in Fernances Creek, a tributary of Wollombi Brook in humid southeastern Australia. The cause of this phase of gullying involved the interaction of several factors including a steep valley floor segment where human disturbance preceded a period of frequent large floods. Field measurements of valley and gully cross sections and the longitudinal profile have been made for Fernances Creek. These data and the lithostratigraphy allowed the computation of an approximate sediment budget that showed most of the sediment remobilized by gullying had been retained in the gully system, despite the magnitude of flood discharges and the competence for sediment transport in the channel. Much of the flood discharge, however, occurs outside the channel and depositional zones occur on valley floor segments of increased width, decreased slope and well vegetated surfaces.

INTRODUCTION

Discontinuous gullies (Leopold and Miller, 1956) cut into late Quaternary valley fills are common throughout humid southeastern Australia. Those in the upper Wollombi Brook basin (340 km^2; 32° 57'S, 151° 08'E) near Sydney have developed since European settlement in 1827 and have been investigated in detail here.

Valley floors in the Wollombi Brook basin are characterized by four reaches of varying length, which, in downstream sequence, are:

(a) an upper stable section above the area affected by modern discontinuous gullying;
(b) a middle incised section eroded over the last 150 years;
(c) a lower depositional zone where the gully-derived sand splays over the entire valley floor; and
(d) a downstream stable section of suspended load channels below the influence of upstream gullying. This section has remained unchanged since European occupation and only occurs in the longer valleys unaffected by major tributaries.

The fact that sand remobilized by modern gullying has failed to reach the downstream stable section is shown by the extremely small capacity of the channels, large percentage of silt plus clay in the bed and banks, well vegetated perimeters, and wide grass-covered and fine-grained flood plains. These characteristics suggest that most of the sand remobilized by gullying must be stored in the valley upstream. This view conflicts with that of Leopold and Miller (1956:32) who state that only a small proportion of the total excavated material is deposited in the widened, incised sections of a discontinuous gully, and in the fan below. The remainder of this paper addresses the causes and processes of sediment

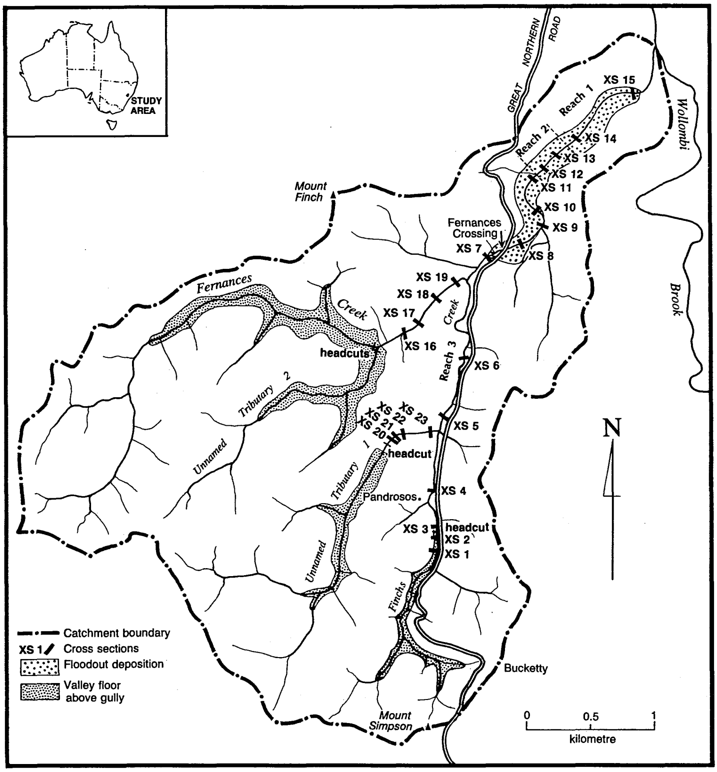

FIG. 1 Location of Fernances Creek drainage basin showing the valley network, gully reaches and surveyed cross sections.

remobilization and storage by the modern phase of gullying in Fernances Creek basin (Fig. 1), a representative tributary of Wollombi Brook.

Fernances Creek has a basin area of 13.8 km^2, a mean annual rainfall of 900 mm and a mean annual evaporation of 1160 mm. The drainage basin is cut into intercalated sandstones and shales. Further descriptive details are contained in Erskine and Melville (1983).

GULLY MORPHOLOGY AND PROCESSES

Before the modern phase of gullying there was no channel cut into the valley floor, as still occurs upstream of cross section 2 (see cross section 1, Fig. 2). The initiation of a number of knickpoints over the last 130 years has led to the development of three discontinuous gullies. Those in reaches 1 and 2 have formed in the depositional zone of the large compound gully of reach 3 (Fig. 1). A field-surveyed longitudinal profile of the gully bed and valley-fill surface clearly defines these reaches and shows marked variations in bed and valley-floor slope over relatively short distances (Fig. 3). A steep valley-floor segment is usually present on the lower section of each gully, a trend previously recognised by Schumm and Hadley (1957) for small arroyos in semi-arid USA. However, the pre-gully valley-floor has been buried by variable depths of sandy overbank deposits on the lower 2900 m of the long profile but has been trenched to form a terrace upstream of this point (Fig. 3). Consequently, the profile of the pre-gully valley floor

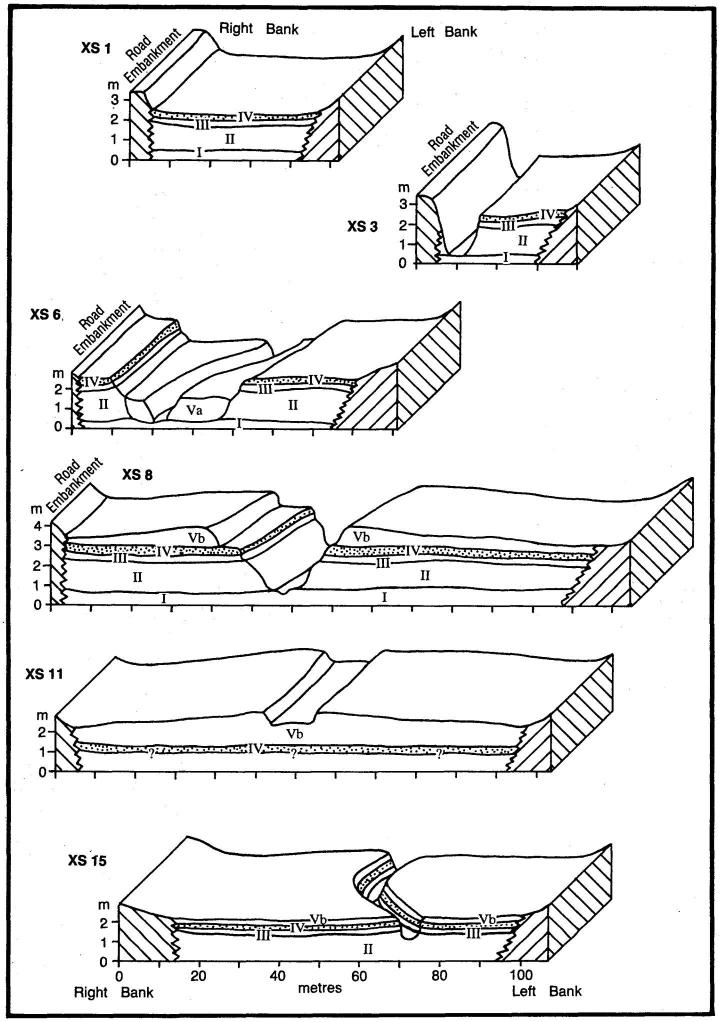

FIG. 2 Downstream changes in valley cross section and valley-fill lithostratigraphy. For location of cross sections see Fig. 1 and definition of lithostratigraphic units see Table 1.

in the lower half of the network can only be reconstructed from heights of isolated bank exposures. Nevertheless, a number of such points immediately downstream of Fernances Crossing do indicate a local steepening there of the pre-gully valley floor (Fig. 3). Gullying is commonly initiated on the steepest sections of valley fills (Schumm and Hadley, 1957; Patton and Schumm, 1975) and during a minor flood on 7 February 1981 secondary knickpoints up to 1 m high were observed to originate on steep bed slopes at points A and B on the long profile (Fig. 3). These initiation points corresponded to a slope discontinuity at the downstream end of the steep segment.

Once initiated, knickpoints have maintained their form and migrated upstream, eroding the valley fill and rejuvenating tributaries. The present limits of incision of the drainage network are shown in Fig. 1.

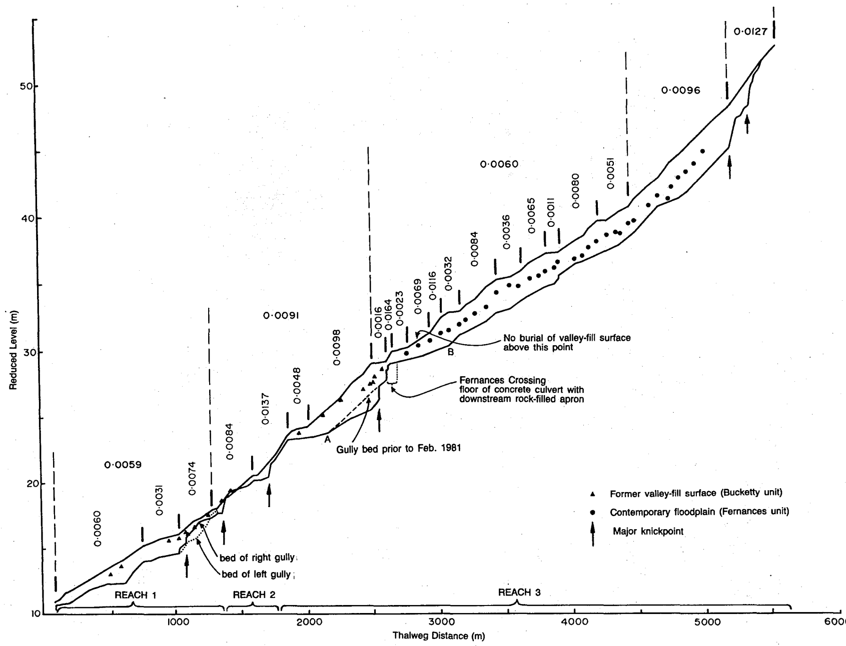

FIG. 3 Field-surveyed longitudinal profile of lower Fernances and Finchs Creeks. Slopes (m/m) shown as numbers above present valley floor.

A vertical knickpoint will be maintained if the fill being eroded is stratified and has a caprock and if the eroded sediment is removed from the base of the headcut (Leopold et al., 1964; Gardner, 1983). The stratified nature of the valley fill is outlined in a subsequent section. Sand layers act as the knickpoint-forming horizon with the overlying coherent, fine-grained sediment acting as the caprock . Plunge pools are present at the base of all knickpoints and plunge-pool action appears to effectively remove the excavated sediment downstream. The knickpoints at the upstream limits of the gully have incised to 2 m below the valley floor (e.g. cross section 3, Fig. 2). The depth of incision remains relatively constant until the region immediately upstream of Fernances Crossing where gully depth decreases rapidly to less than 1 m (Fig. 3) and the floodout deposits commence (Fig. 1). Little sediment storage occurs in the upstream portions of the gully. In the main part of the gully, along Finchs Creek below cross section 4, significant gully widening and sediment storage occur (cross section 6, Fig. 2). This gully widening involves undercutting of the sands of the valley fill and the deposition of these materials in the floodplain flanking a somewhat sinuous channel within the gully. The gully below Fernances Crossing narrows and initially deepens due to recent incision but then rapidly shallows as the intersection point is approached. Immediately above the intersection point the channel is perched on top of a sandy ramp in the centre of the valley (cross section 11, Fig. 2).

Sediment storage also occurs in an extensive floodout downstream of cross section 7. A floodout is a form of channel failure where the bed load is not transported by all flows and so is deposited in a fan (Sullivan, 1976). Although massive overbank and channel deposition have occurred in this zone, channel extinction only occurs downstream of the intersection point at 1850 m on the long profile. The reasons for the substantial reduction in competence as the channel approaches the intersection point are outlined below.

Sullivan (1976) believed that flow velocities in the floodout zone reach a critical point at which they are no longer competent to transport the bed load. Although she derived a formula to express the discharge at which bed load transport should cease, we have found that this formula is incorrect. To determine if stream competence is reduced to such an extent that the threshold of motion condition is not exceeded by within-channel flows, downstream variations in stream power were investigated. Unit stream power (ω) at bankfull stage was calculated for cross sections 2 to 15 by the formula:

$$\omega = \rho QS/W \qquad (1)$$

where ρ is the specific weight of water, Q is discharge, S is energy slope and W is channel width. Threshold unit stream power (ω_0) for sediment transport was calcuated by Bagnold's (1980) equation:

$$\omega_0 = 290\ d^{1.5} \log\ (12D/d) \qquad (2)$$

where d is modal particle size and D is channel depth. The results are shown in Fig. 4. Unit stream power decreases progressively downstream for the gully in reach 3, with the exception of the recently trenched cross section 8. This downstream reduction is caused by a decrease in hydraulic radius, slope, and mean velocity. Stream power increases further downstream within the gullies of reaches 2 and 3. However, bankfull flows are competent to transport the bed material at all cross sections for which there are particle size data, i.e. $\omega > \omega_0$. It is therefore concluded that bankfull discharge is competent to transport the bed load throughout the gully network. These results, however, do not explain the formation of the floodout.

There is no continuous channel downstream of cross section 11. Where a channel is present it is very narrow and has only a small capacity. With the exception of cross section 8, channel capacity (determined by Manning's equation) in the floodout zone corresponds to a flood with a return period of less than 1.49 years on the annual series (determined by Boyd's (1978) regional flood frequency method). Six of the 9 cross sections have bankfull return periods of less than 1.19 years on the annual series. During most floods the discharge passing over the flood plain far exceeds that retained in the channel. As a result, large amounts of sand are deposited in the overbank area, in some cases producing a channel perched on top of a sediment wedge in the centre of the valley i.e. cross section 11, Fig. 2.

HISTORY AND CAUSES OF GULLY DEVELOPMENT

The Great North Road was constructed through the study area between 1830 and 1831 (Parkes, 1979) and crossed Fernances Creek at Fernances Crossing (Fig. 1). Surveys undertaken for road design included information on drainage and allow the reconstruction of valley-floor conditions before the road was completed. Maps compiled from surveys between July 1828 and April 1831 show no channel on Fernances and Finchs Creeks, although Wollombi Brook is depicted as a small sinuous stream with occasional large pools. A further four surveys for land subdivision were carried out by the same surveyor between 1837 and 1838. The only channel shown on these plans is a series of interconnected small pools downstream of cross section 15 at the basin outlet (Fig. 1). Therefore, at the time of first European settlement the valley floor was unchannelled. Annotations

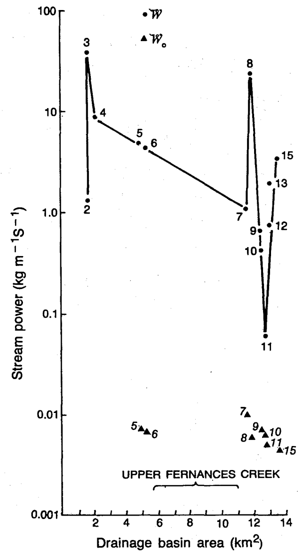

FIG. 4 Computed values of unit stream power (ω) and threshold unit stream power (ω_0) for sediment transport as a function of basin area in Finchs and Fernances Creek at each of the numbered cross sections.

on some early survey plans also refer to "plentiful water" and indicate that swampy conditions existed in some areas. This is supported by stratigraphic evidence (see next section) which shows that the valley floor before gullying was composed of organic, fine -grained sediments similar to cienega deposits.

Discontinuous gullying was well advanced by September 1867. Extensive sand deposits are mapped on a subdivision plan of that date between the Crossing and cross section 11 in the floodout zone. Futher sand deposits and a channel are noted on another plan of the same date by the same surveyor for the area immediately upstream of the Crossing at the head of the floodout. Valley trenching must have occurred by 1867 to account for these sandy deposits and channel of the floodout. Therefore, the gully was initiated some time between 1838 and 1867.

Three factors suggest that the Crossing was the approximate initiation point. Firstly, the first reference to a channel in the basin is on the 1867 plan for the area just upstream of the Crossing. Secondly, the Crossing is located immediately upstream of a pronounced local steepening in the pre-gully valley floor (Fig. 3) where the valley is constricted by a structural bench. Thirdly, road works for the Crossing would have decreased surface roughness by clearing valley-floor vegetation, also have confined flood flows between embankments and involved trenches for drainage. These factors would have increased local flow velocities and sediment erodibility, predisposing the area to erosion. Although the timing of gully initiation is only broadly known it does cover a period when large floods were recorded. Grady (1963) noted that a a series of large floods on Wollombi Brook in 1856 and 1857 resulted in much destruction, especially on the floodplain. Moriarty (1870) also referred to large floods on Wollombi Brook in 1857 and 1864. Therefore, the cause of the present phase of gullying in reach 3 was the interaction of three factors: (a) a valley floor segment of steeper slope and restricted width; (b) local human disturbance of the valley-floor surface by road construction; and, (c) a number of large floods in rapid succession. However, it is believed that human disturbance was, at best, only a trigger-pull mechanism which may have hastened a change that would have occurred naturally, but perhaps later, at this critical point of the valley floor. Knickpoints form preferentially on steep valley-floor segments as part of a repetitive cycle of cut and fill (Schumm and Hadley, 1957; Schumm, 1961; Patton and Schumm, 1957; 1981).

The gullies in reaches 1 and 2 are younger than that in reach 3 and have different causes. Trenching in reach 1 was caused by baselevel lowering when Wollombi Brook was gullied in 1949. The gully in reach 2 was initiated on the steep valley floor segment at 1500 m on the long profile during a large flood in 1977.

VALLEY-FILL LITHOSTRATIGRAPHY AND HOLOCENE GEOMORPHIC HISTORY

Five lithostratigraphic units have been identified and mapped throughout the basin (Table 1 and Fig. 2). All radiocarbon dates reported in Table 1 have been obtained on charcoal larger than 30 mm b-axis diameter to reduce the possibility of contamination by material reworked from older deposits (see Blong and Gillespie, 1978). Unfortunately, charcoal is the only dateable material incorporated within these sediments.

The oldest sediments sampled to date are the clays of the Finchs unit which were deposited in a swamp environment. The duration of swamp sedimentation is unknown but terminated soon after 5920 years BP (Table 1). Finchs unit acted as base level for a subsequent major phase of gullying which reworked the entire overlying valley-fill sequence. This prehistoric gullying deposited a thick sheet of sandy sediment (Pandrosos unit) across the entire valley floor of each tributary. Although infilled palaeochannels have been found within the Pandrosos unit, they appear to have been discontinuous. These gullies were completely infilled before the valley floor was blanketed by fine-grained material (Simpson and Bucketty units). Clay sedimentation commenced in 4070 years BP and was initially discontinuous (Simpson unit). Subsequently, a continuous sheet of fine-grained sediment (Bucketty unit) was deposited throughout the alluvial reaches of the basin. By 1867 the modern phase of gullying had been initiated and resulted in the trenching of the Bucketty, Simpson and Pandrosos units upstream of cross section 7. This trench is still being extended headwards and widened and is being partially infilled with sandy material (flood plain facies of Fernances unit). Sediment eroded from the gully in reach 3 and not stored in the flood plain is largely deposited as a sandy sheet over the Bucketty unit in the floodout (floodout facies of Fernances unit).

APPROXIMATE SEDIMENT BUDGET

An approximate sediment budget was derived for the modern phase of gullying in Fernances Creek using computed volumes of sediment excavated by gullying, and sediment stored in the channel, flood plain and flood-out zones. These volume computations used areas digitized for the gully and the Fernances lithostratigraphic units at each cross section (Fig. 1) and field and map-measured distances along the valleys and gullies.

The results of these computations show that approximately 190 000m^3 of sediment was excavated by gullying in the basin. Of this volume, approximately 70 000m^3 was retained in the flood plain facies of the Fernances unit and a further 100 000m^3 was retained in the floodout facies of the same unit.

TABLE 1 Description of valley-fill lithostratigraphic units of Fernances Creek. For location of cross sections referred to in the description, see Fig. 1.

STRATIGRAPHIC UNIT	SUMMARY CHARACTERISTICS	DISTRIBUTION	AGE
Finchs unit (I)	Dark grey (10YR4/1*) massive plastic clays of unknown thickness containing abundant charcoal	Outcrops discontinuously in gully bed upstream of cross section 9	5920± 120 years BP (SUA 1852). From top of unit
Pandrosos unit (II)	Interbedded sands, clayey sands and sandy loams up to 2m thick containing some channel-fill structures	Exposed in side walls throughout gully network	
Simpson unit (III)	Lenticular dark yellowish brown (10YR4/6) clays with well-developed blocky or prismatic peds; up to 0.8m thick	Exposed in side walls throughout most of the gully network.	4070±180 years BP (ANU 5117) From base of unit
Bucketty unit (IV)	Sheet deposit of very dark grey (10YR3/1) self-mulching, organic loams and clay loams with well-developed polyhedral peds; up to 0.3m thick	Trenched by present gully upstream of cross section 7 and buried by floodout sediments downstream	220±110 years BP (SUA 1843). From top of unit
Fernances unit a) flood plain facies (Va)	Interstratified sands, loamy sands and sandy loams up to 2m thick which partially infill a trench cut into Bucketty, Simpson and Pandrosos units	Throughout most of the gully network upstream of cross section 7	
Fernances unit b) floodout facies (Vb)	Sheet deposit of interstratified sands, loamy sands, sandy loams and sandy clay loams ranging from 0.3 to 1.5m thick	Fernances Creek downstream of cross section 7	Older than 1867 A.D. (see text)

* Munsell soil colour of moist sample

Several qualifications of these values must be made. Firstly, sediment input from sources external to the gully have been assumed negligible for the modern period of gullying. This assumption is justified because little evidence of recent sandy sediment deposited from side-tributary fans or valley sources upstream of the knickpoints can be seen in the sediment stratigraphy (Erskine & Melville, 1983). The thick vegetation sward of the valley surface above the gully perimeter would trap any such sediment and its presence would be obvious above the organic fine-grained sediment of the Bucketty unit. A small mass movement, immediately upstream of cross section 9 has contributed approximately 10m^3 of sediment but this has also been ignored.

The second cautionary note concerns an assumed equality in bulk density of the excavated and stored sediments. This assumption seems justified because of the predominance of sandy material.

A final reservation concerns the values of cross-sectional areas and valley and gully lengths used in the volume calculations. Much detailed field measurement and knowledge has been used in these computations but more cross sections, better valley and gully distance measurements, and more lithostratigraphic data would improve the accuracy of the calculations. Nevertheless, we feel confident that such improvement would not alter the obvious conclusions from these data that, in Fernances Creek drainage basin, most of the sediment excavated by the modern phase of discontinuous gullying is retained in the basin. Only some of the material, particularly some of the colloidal fraction, has been exported from the basin up to this time.

DISCUSSION AND CONCLUSIONS

Patton & Schumm (1981) have observed that a large proportion of the sediment excavated by discontinuous gullying in a semi-arid environment is stored in the gully system. Our study has also established the discontinuity of sediment transport for the humid environment of Wollombi Brook. The approximate sediment budget computed for Fernances Creek shows that about 90% of the material excavated by modern gullying is stored in the system and of this material, approximately 40% is held within the channel and flood plain of the main gully while 60% is stored in the overbank and floodout zones.

Also as Schumm (1961) has proposed, the deposition of sediment in the floodout has caused an increase in the width/depth ratio of the channel and a decrease in the channel energy slope and bed material particle size (Erskine & Melville, 1983). As sediment is dumped in the floodout its downstream segment steepens and the potential develops for initation of secondary knickpoints. The knickpoints commence excavation of the floodout and, by lowering base level in the pre-existing gully, lead to further erosion in the main gully reach. In some instances of discontinuous gullying these secondary processes can lead to coalescence of the gullies to form a continuous channel but this does not seem to be a common outcome in Wollombi Brook.

The downstream alternation of erosional and depositional zones has been observed for the main channel of Wollombi Brook and for those of its tributaries affected by modern gullying. Schumm (1961) proposed that aggradation occurs in main channel segments with small tributary contributions where the increase in discharge is much less per unit channel length. This situation is observed on Wollombi Brook but in some other instances, either deposition or erosion is observed downstream of the tributary confluences depending upon the nature and characteristics of the discharge and sediment load from the tributary, relative to that of the main channel.

An issue of great interest in this study concerns the duration of gullying and intervening stable phases. Radiocarbon dates obtained so far in Wollombi Brook basin suggest that most alluvial sediment is of Holocene age. The dates from Finchs and Bucketty units of Fernances Creek suggest the stable phases extend over many hundreds of years. These quiescent periods are interrupted by phases of gullying and sediment remobilization that are of great magnitude but relatively short duration. The result of this study that must be stressed, however is the short distance of transport for most of this remobilized sediment.

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