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Debris flows in northeastern Victoria, Australia: occurrence and effects on the fluvial system

IAN D. RUTHERFURD
Cooperative Research Centre for Catchment Hydrology, Department of Civil Engineering, Monash University, Clayton, Victoria 3168, Australia

PAUL BISHOP
Victorian Institute of Earth and Planetary Sciences, Department of Geography and Environmental Science, Monash University, Clayton, Victoria 3168, Australia

TIM LOFFLER
Department of Civil Engineering, University of Adelaide, Adelaide, South Australia 5005, Australia

Abstract A large storm in October 1993, in northeast Victoria, produced more debris flows (about 30) than have been reported before in Australia. Such debris flows are associated with storms of at least 50 year recurrence interval. The debris flows were typically between 0.5 and 1 km in length, experienced flow velocities up to 10 m s^{-1}, and were most common on resistant granite and acid-volcanic lithologies with slopes greater than about 25°. The debris flows were of little significance to modern stream processes. Thirteen debris flows in one 35 km^2 drainage basin contributed about 10% of the total sediment mobilized during the flood. Five hundred metres of channel migration and widening in the stream contributed the same volume of sediment as the largest debris flow (about 2000 m^3). However, in the longer term the debris flows are a significant process because they deliver coarse colluvium (up to 1.5 m B-axis) directly to the modern stream and flood plain, and could produce lowering of the landscape at a rate of 5 m per million years.

INTRODUCTION

Record rainfall in northeastern Victoria, Australia (Fig. 1), on 4 October 1993 produced record floods in the larger streams. For example, over three hours the Broken River rose from a minor flood to the largest flood on record (Bureau of Meteorology data). The floods caused considerable erosion, with several of the smaller tributaries suffering dramatic widening and incision. Over $4 M (Australian) of Natural Disaster Funding has been allocated to the repair of stream erosion in the Ovens and Broken River drainage basins.

An unusual feature of the storm event was the initiation of more than thirty debris flows, which are known locally as "mud flows". Several of these flows cut roads. As we describe below, these flow events have many of the classic features of debris flows (Costa, 1984, 1988), and are clearly different from other mass-wasting phenomena reported in southeastern Australia, such as the relict periglacial scree slopes and "rock rivers" of the highlands (Talent, 1965); or the earth flows (slip-circle failures) in the Otway and Strzelecki Ranges. There are few reports of debris flows in Australia.

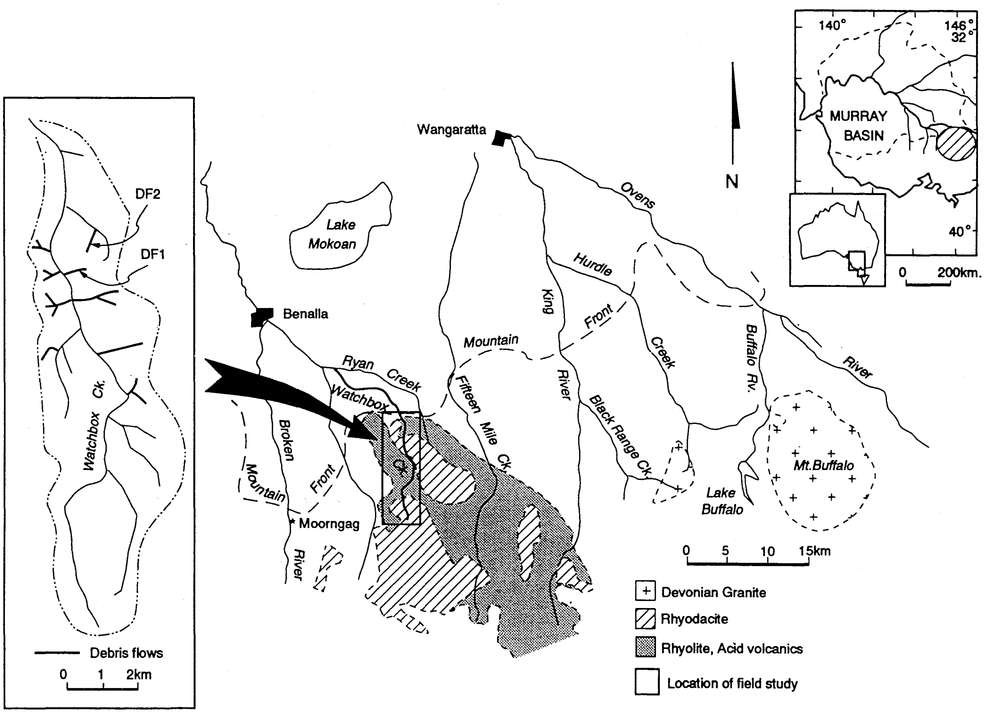

Fig. 1 Location of the study area in northeast Victoria, with detail of the Watchbox Creek basin.

Several debris flows have occurred on Mt Bellenden Kerr in wet-tropical Queensland. Wasson (1978) has described a single debris flow near Lake George in New South Wales, and another 2 km long debris flow occurred in Lilydale, Melbourne, in the 1890s (Shire of Lilydale, 1993). Thus, to our knowledge, this northeast Victorian flood event has produced an unprecedented number of debris flows in the European history of Australia.

In northeastern Victoria the debris flows are prominent effects of the floods, being visible from tens of kilometres away, and they are considered locally to have been major sources of sediment to the stream systems. This paper reports the characteristics and distribution of debris flows from the October 1993 storm event, specifically in the headwaters of the Broken River. In particular we:

(a) determine the distribution and frequency of debris flow events;
(b) describe the debris flows using two detailed case studies; and
(c) identify their importance in contributing sediment to stream systems, and their role in longer term landscape evolution.

Distribution of debris flows from the storm event

The storm event of 4 October triggered approximately 30 debris flows in the drainage basins of the Broken and Buffalo Rivers. The number of debris flows could be roughly counted from an aerial inspection after the floods. No official aerial photographs have been taken of the river headwaters since the flood. All of the debris flows occurred in forested drainage lines that have only ever been selectively logged.

Debris flows typically occurred on steep, resistant rock types with slopes above 25°. Thus, the highest density of debris flows (approximately twenty were counted) occurred on the steep and resistant acid volcanic lithologies and Middle Creeks in the drainage basins of Ryans (Fig. 1). These debris flows cut four roads, and were a major immediate impact of the storm. The highest density of debris flows (15) occurred in the Watchbox Creek basin (Fig. 1).

There were also many debris flows on Mt Buffalo (Fig. 1), a granite pluton with almost vertical cliff walls. Debris flows were restricted to the eastern and southern aspects of the mountain, particularly in Sandy, Bunyip and Boulder Creeks. Boulders from debris flows choked Sandy Creek, causing a channel avulsion. This was one of the major impacts of debris flows in the region because the new avulsed stream-channel cut through prime tobacco land.

Finally, debris flows were less common on the most common lithology in the region, Devonian greywacke and sandstone. Only 10 debris flows were counted, with two occurring in the basins of Ryans and Black Range Creeks, and smaller flows along Boggy and Fifteen Mile Creeks.

Frequency of debris flows in the region

The recurrence interval of debris flows in the region was estimated by inspecting aerial photographs from 1963, 1975, and 1993. An area of about 750 km^2, covering all of the acid volcanic lithologies (basins of Ryans and Fifteen Mile Creeks), and some of the sedimentary lithologies was selected. It was hypothesized that debris flows, even 10 years old, would be visible on the photographs, and so their recurrence interval could be estimated. The granite region of Mt Buffalo was not considered in this analysis.

No relict debris flows could be identified on the sandstone lithologies. Thus the recent debris flows on this rock-type can be considered as rare events over the last 30 years. The only relict debris flows that could be identified on the aerial photographs occurred in a small portion of the acid volcanics, with eight flows in the basin of Watchbox Creek and five in a small basin to its west. All of the debris flows could be identified on all three series of photographs. They occurred before 1963, and thus had not been covered by vegetation over 30 years.

Therefore, the last debris flows in the region occurred more than 30 years ago, and these were more spatially confined than the recent event. Engineers from the Shires of Benalla and Oxley concur that there have been no debris flows in their shires in living memory. It is also important to note that the eight debris flows in Watchbox Creek that are visible on the 1963 photographs were freshly stripped-out again in the 1993 storm, and another five new flows occurred. In short, debris flows are rare in the region affected by the 1993 flood. It probably requires a storm of at least 50 year recurrence interval to produce debris flows throughout the acid volcanic region, and to produce any debris flows in the less-steep sandstone drainage basins. Debris flow scars remain visible for at least 30 years. Further evidence for the infrequency of debris flows is provided by the stratigraphic sequences exposed where creeks have cut laterally into alluvial fans deposited below debris flow chutes. We saw no evidence in the stratigraphy of the large, sub-angular boulders carried by the recent debris flows, again suggesting that such flows are rare events.

Description of debris flows

The remainder of this paper will discuss debris flows that occurred on the acid volcanic lithology of the Watchbox Creek drainage basin (Fig. 1). Thirteen debris flows occurred in the headwaters of Watchbox Creek (35 km^2 drainage basin), a tributary of Ryans Creek, which is itself a tributary of the Broken River (Fig. 1). The closest pluviograph to Watchbox Creek is 15 km to the west at Moorngag. This station has a 12 h duration, 50 year average recurrence interval rainfall of 7.5-8 mm h^{-1} (*Australian Rainfall and Runoff*, vol. 2., map 5.8). Bureau of Meteorology records for Moorngag on the night of 4 October showed a 12 h duration of 10 mm h^{-1}, suggesting a greater than 50 year recurrence interval for the storm event. Unofficial raingauges suggest that the storm was considerably more intense than this. For example, Mr Person's 250 mm raingauge in Watchbox Creek overflowed after 5 h between 2.00 a.m. and 7.00 a.m. on 4 October. This rainfall intensity of 50 mm h^{-1} is supported by other landholders in the region.

The drainage basin of Watchbox Creek is composed of Devonian rhyodacite, rhyolite and acid volcanics. All of the debris flows occurred in fully forested drainage basins (open forest of broad and narrow-leaf peppermint (*Eucalyptus dives* and *E. radiata*)) that have only ever been selectively logged. Thus, unlike many of the debris flows described in the literature, that occur following logging (see DeRose *et al.*, 1993; and review in Gresswell *et al.*, 1979) or grazing (Lehre, 1982), these are examples of geomorphic events occurring with their natural frequency. Two debris flows were investigated in detail (described here as DF1 (grid ref. DV267383) and DF2 (DV273393)) (Fig. 1), and three others were inspected. DF1 and DF2 will be described in detail, and then compared with the other flows.

Description of debris flow 1 (DF1)

DF1 (sub-basin area of 15 ha) has left a clear, bedrock channel about 700 m long and over 5 m wide (Figs 2 and 3). The maximum measured slope in the debris flow was 33°. Sediment was deposited in a fan adjacent to Watchbox Creek. The flow had many of the classic features of a debris flow, namely: poorly sorted, coarse levee and fan deposits (both matrix and clast supported); mudlines on marginal trees; prominent super-elevation of mudlines at bends; and removal of all trees in the centre of the flow-path (Costa, 1984, 1988). The failure could be more correctly classified as a debris flow that passes downslope into a "channel confined debris torrent" (Kelsey, 1982).

Unlike other debris flows (cf. Tsukamoto *et al.*, 1982; Benda, 1990) DF1 was not initiated from a colluvial hollow, but from a straight section of the catena, with planar cross-slopes. The head of the debris flow evacuated saprolite and core-stones directly from the weathered bedrock. Hence, the heads of these debris flows represent a direct path of downslope transport of the weathered material. It was not clear whether the debris flow was initiated by failure at the top that carried the remainder of the downslope material along, or by failure at the bottom that triggered failures progressively up the slope.

The debris flow had a maximum discharge of 145 $m^3 s^{-1}$, and a maximum velocity of about 9 m s^{-1}. Flow velocity was estimated with three independent methods (Costa, 1984) (Table 1). Superelevation was measured at three bends (Fig. 2), and velocity was

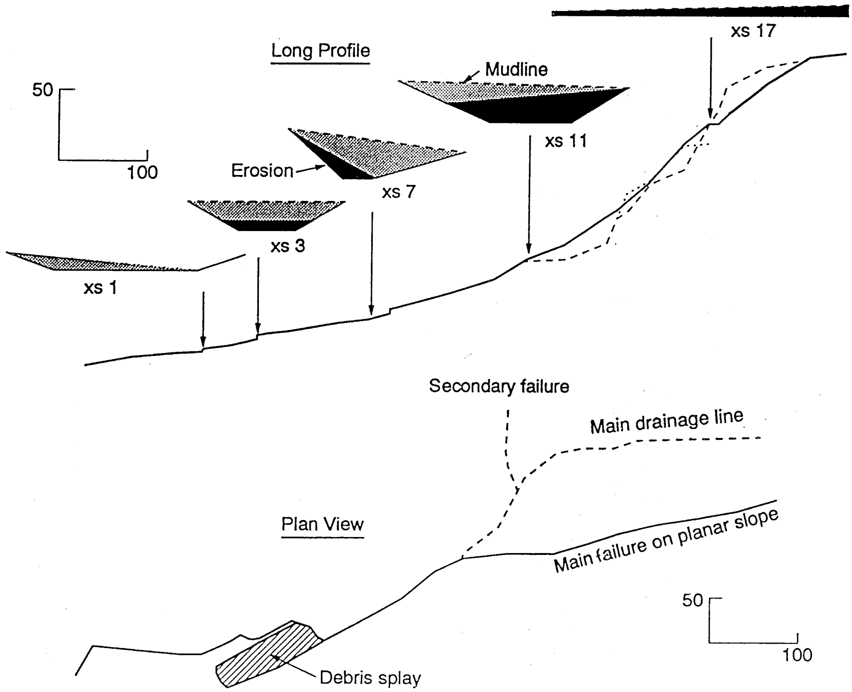

Fig. 2 Profile and plan-view of debris flow 1 (DF1). A sample of 5 of the 17 cross sections is shown.

estimated with the formula:

$$v = \sqrt{\Delta h g r_c \cos S / b} \tag{1}$$

where Δh = superelevation, $g = 9.81$, r_c = radius of curvature, S = channel slope, b = water surface width. In addition, velocity was estimated by measuring the diameter (d) of the five largest clasts ($v = 0.18d^{0.49}$), and by measuring the height of the stagnant head on the upstream and downstream side of trees

$$v = \sqrt{2gh/\alpha} \tag{2}$$

(where h = height of stagnant head, α = momentum correction factor).

There are problems using these equations, derived for normal water flows, for estimates of velocity in hyperconcentrated, non-Newtonian debris flows. Nevertheless, the results (Table 1) are very consistent at the order-of-magnitude level across the methods, indicating that the flow travelled between 4 and 9 m s^{-1}. Assuming that the erosion originated from the apex of the failure (Fig. 2), these velocity figures suggest that the front of the debris flow reached the apex of the fan about 1.5 minutes after initiation.

The instantaneous discharge carried by DF1 was probably over half of the peak discharge carried by Watchbox Creek during the flood. From the area and velocity estimated at cross section seven of DF1 (Fig. 1), discharge was estimated to be between 35 $m^3 s^{-1}$ and 95 $m^3 s^{-1}$. The lower estimate assumes that the debris flow only occupied the area evacuated by erosion, whilst the upper estimate assumes that the flow

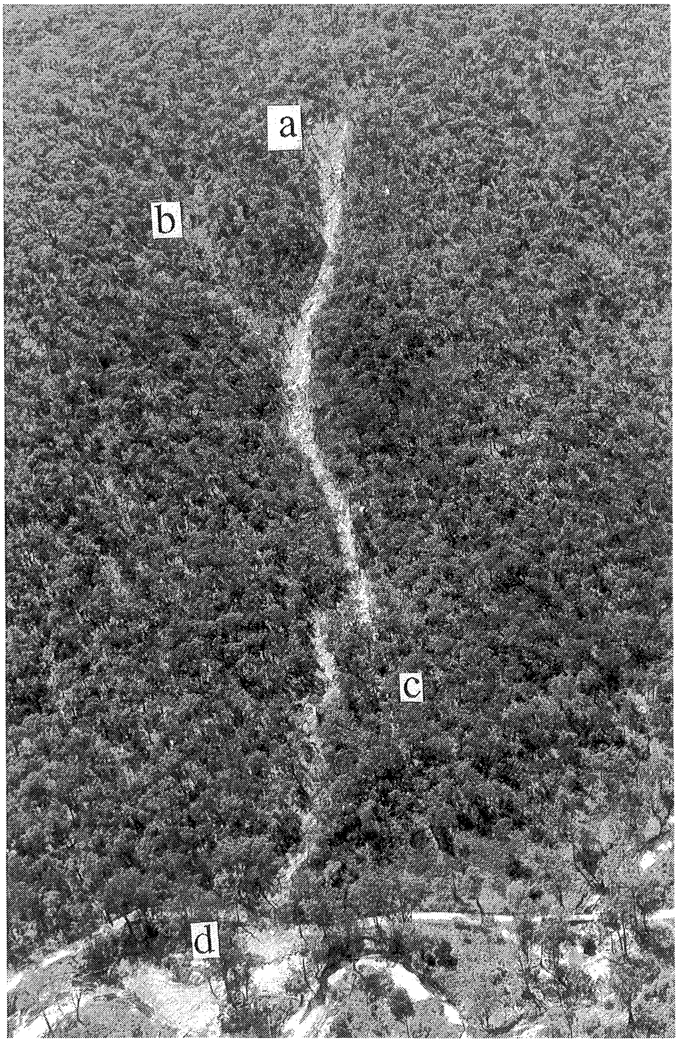

Fig. 3 Oblique aerial photograph of DF1. Note the following: the rotational slump at the head of the failure (point "a"); the main path of failure does not follow the main drainage line (point "b"); the debris splay visible through the trees below the sharp bend (point "c"); and the fan of material at the junction with Watchbox Creek (point "d").

occupied the full cross section delimited by the mudlines. For comparison, the peak discharge carried by Watchbox Creek during the flood, was estimated to be 110 $m^3 s^{-1}$ from Manning's equation. If basin area is considered to be proportional to discharge from the basin, then the discharge of Watchbox Creek can be used to estimate the water discharge that would normally be expected from the 15 ha basin of DF1 in the 1993 storm. Proportionally the basin area of DF1 should produce less than one cubic metre of water per second. Given the minimum discharge in DF1 of 35 $m^3 s^{-1}$ suggested above, it is likely that the debris flow would have contained less than 5% water, with the rest being sediment. The following approximate sediment budget suggests that less than a third of this large volume of sediment reached Watchbox Creek.

Table 1 Estimates of flow velocity in the debris flow.

Method	Position	Estimate
Superelevation	Cross section 14 (near the top) (Fig. 2)	8.9 m s^{-1}
	Cross section 7 (middle)	5.0 m s^{-1}
	Cross section 1 (apex of fan)	4.2 m s^{-1}
Five largest clasts	Bed of debris flow scar (mean diameter = 1.01 m)	5.4 m s^{-1}
	Debris splay (see below) (mean d = 1.4 m)	6.3 m s^{-1}
Stagnant head	Edge of fan (head = 2 m)	6.2 m s^{-1} (probably over-estimate)

Volume of sediment eroded and deposited

Sediment volumes were estimated from 17 cross sections surveyed across the debris flow (of which five examples are reproduced in Fig. 2). The area of material eroded at each cross section was estimated by projecting a line from the upper edge of the freshly eroded colluvium or rock, down to the edge of the old channel bed. The edge of the darker, organic-stained surface of the former channel bed could be differentiated from the freshly exposed rock surface. The proportion of silts and clays, and sand, at each cross section was estimated and compared with the grain-sizes deposited in different sediment stores in order to estimate the calibre of the material that was delivered to Watchbox Creek.

The areas of the 17 cross sections indicate that an order of magnitude more sediment was eroded from the channel margins as the debris flow passed down the drainage line, than was eroded from the alcove at the top of the debris flow (Table 2).

Sediment was deposited in four locations, in:

Table 2 Rough sediment budget for debris flows 1 and 2. Data come from field surveys as described in the text.

Zone (Defined in Fig. 2)	Erosion (m^3):		Deposition (m^3):	
	Debris Flow 1	Debris Flow 2	Debris Flow 1	Debris Flow 2
Erosion alcove at top of failure	500	750		-
"Barrel" of debris flow	7000	1500	190	500
Fan apex		1100		1500-2600
Debris splay	-		1400	-
Fan			3400	450
TOTALS	7500	3350	4990	2450-3500
Throughput to trunk stream			2510	0-900
% throughput			33%	0%-27%

(a) boulder berms within the eroded debris flow channel;
(b) coarse marginal levees;
(c) a "debris splay" (see below); and
(d) in the distal fan.

The majority of deposition (45%) was in the fan (Table 2), but a large volume (19%) was also deposited in an interesting feature which may be defined as a debris splay. Five hundred and fifty metres from the apex the debris flow met a sharp bend in the channel (Figs 2 and 3). This bend produced 2.5 m of superelevation, and as a result about 1400 m^3 of sediment was deposited over-bank on the un-failed slope beside the debris flow channel. The resultant splay was 110 m long, 20 m wide, and up to 1 m thick. It consists of a full range of particle sizes from silts and sands to 1.5 m diameter boulders (B axis).

This deposit is significant because it represents a mechanism for depositing large volumes of coarse material well above the channel. In this case the debris splay was over 6 m above the channel floor. The debris splay was deposited on a poorly sorted unit that may represent former debris splays. An initial bend in the path of a debris flow can thus produce debris splays that progressively build upward, producing a significant store of sediment in the valley.

Importantly, less than one third of the sediment eroded from DF1 reached Watchbox Creek (Table 2). The boulders deposited in Watchbox Creek from the debris flow could be differentiated from the existing bed load in the creek because they were more angular and iron stained. Although large boulders, up to 1.6 m in diameter, were deposited in the creek by the debris flow, none of the deposited particles travelled more than 100 m down the creek.

In order to compare the sediment yielded from DF1 with the sediment remobilized from the flood plain, the volume of sediment eroded by cutbank erosion in a 450 m stretch of Watchbox Creek was measured above and below the debris flow. The minimum volume of erosion was estimated from the length of tree roots exposed by the erosion. In this reach, 1800 m^3 was eroded from the flood plain by lateral erosion (58% gravel, 42% silt and clay). This was over two-thirds of the maximum 2500 m^3 of sediment delivered to the creek by DF1. Thus, about half a kilometre of bank erosion in the third-order stream mobilized as much sediment in the stream as was delivered by the largest debris flow in the valley.

This result can be extrapolated to the full length of Watchbox Creek. Of the 15 debris flows that occurred in the Watchbox Creek basin, DF1 was the only one where the deposited fan reached the trunk stream. Thus the maximum sediment yield to Watchbox Creek from debris flows would be less than twice the yield from DF1 alone, say 5000 m^3. Extrapolating the rate of flood plain erosion estimated in Watchbox Creek above, to the full 10 km length of Watchbox Creek suggests that at least 40 000 m^3 of sediment was liberated from the flood plain during the flood. This figure ignores channel incision. Therefore, it is unlikely that the debris flows introduced more than 12% of the total mobilized sediment in Watchbox Creek during the flood event, ignoring other diffuse basin sources.

Description of debris flow 2 (DF2)

DF2 occurred to the north of DF1, on the opposite side of the ridge, and flows into a small tributary of Watchbox Creek that we have named Teachers Creek. Erosion and deposition were estimated from 16 cross sections just as in DF1. DF2 is about half the length of DF1 (450 m), but shares the following features.

(a) The debris flow was initiated on a planar portion of the slope (with a slope >25°), rather than in a drainage line or colluvial hollow. Thus, DF2 removed weathered material directly from the slope. The coarsest fraction of this material came from the head of the failure (>1.5 m boulders), whilst the bulk of the sediment came from colluvium at the margins of the flow.

(b) The 3300 m^3 of sediment removed from the slope was deposited in an alluvial fan, and only a small proportion of the fine fraction was delivered to Teachers Creek (Table 2). Widening and deepening within Teachers Creek produced an order of magnitude more sediment than did erosion from DF2. Further evidence that DF2 had little impact on the stream comes from channel dimensions in Teachers Creek. A survey of 26 cross sections along the creek, upstream and downstream of the toe of the DF2 fan demonstrated that the input from DF2 had no influence on either channel size or channel width-depth ratio.

(c) DF2 delivered coarser sediment to the flood plain/fan than do other processes. Adjacent streams could transport particles of less than 0.3 m diameter, whilst DF2 delivered 1.6 m boulders.

One contrast between DF1 and DF2 is that much of the sediment eroded from DF2 came from vertical stripping of the A horizon over a large area.

DISCUSSION

The debris flows initiated by the 1993 flood in northeastern Victoria are typical of debris flows described throughout the world in terms of slopes, depth of colluvium, and flow velocities (e.g. Kelsey, 1982; Tsukamoto *et al.*, 1982; Benda, 1990). The only possible differentiating characteristic is their initiation in planar portions of the hillside, rather than in colluvial hollows.

Debris flows are rare events in Australia, with this event in northeastern Victoria being the largest debris flow event described. It should be emphasized that all of these debris flows occurred in essentially undisturbed forested basins, and probably represent a "natural" geomorphic event. Therefore, we can conclude that debris flows will only be widespread in northeastern Victoria in high intensity storms of greater than 50 year recurrence interval. They are most likely to occur in highly resistant and steep lithologies, such as granites and acid volcanics. These lithologies do not make up a large proportion of the Australian Highlands. For example, they occupy less than 10% of the Broken and Ovens River basins upstream of the mountain front.

Despite being spectacular events that leave prominent scars on the landscape, the debris flows in northeastern Victoria deliver only a small volume of sediment directly to the stream system, and they cannot be considered a management problem in terms of increased stream sediment loads. The only damage done by debris flows was to deposit boulders on roads.

Even though debris flows in this region do not deliver large volumes of sediment directly to streams, in comparison to the sediment mobilized from the flood plain storage, they are geomorphically important. This is because they transfer coarse colluvial material, derived from resistant lithologies, directly into stores of sediment that are accessible to erosion by larger streams. Thus, both DF1 and DF2 deposited coarse sediment in fans that will be eroded by lateral migration or avulsive channel change of the trunk stream. Other erosion processes move material more slowly. For example, soil creep will move coarse sediment directly onto the flood plain, whilst gradual erosion by tributary streams can move some coarse material onto fans. The largest clast that was observed to be delivered to the trunk stream by the floods, without a debris flow, was 0.3 m in diameter. By contrast, DF1 delivered 1.5 m boulders to Watchbox Creek. Of course, it is not clear whether the gradual processes of creep and stream erosion move a larger total volume of material than do the catastrophic, but rare, debris flows.

The debris splay reported here from DF1 is an interesting geomorphic feature. In this case, superelevation of the debris flow has been a process that can deposit very coarse material over 5 m above the channel floor. As the deposit grows deeper with successive debris flows it will become more effective at diverting the flow, thus producing a feedback mechanism that could lead to the deposition of several metres of sediment within a debris flow chute.

Finally, it is interesting to consider the possible role of debris flows in sculpting headwater slopes. All of the debris flows inspected in the northeast stripped the regolith to bedrock, and large areas of fresh bedrock were exposed where rocks in transit had struck the surface. In particular, the debris flow tended to smooth the floor of the channel by abrading any irregularities or protrusions. Although this form of erosion appears minor during one debris flow event, over millions of years it is significant. For example, in the upper end of DF1, about 5% of the bedrock surface was chipped to at least 10 mm depth. If it is assumed that debris flows occur every 100 years, then by extrapolation, approximately 10 mm would be removed from the floor of the flow every 2000 years. Assuming the frequency of debris flows remained the same, then over the 2 million years of the Pleistocene debris flows could have eroded the drainage line a distance of 10 m. This would translate to a lowering of the basin divide by 5 m per million years, which is consistent with long-term denudation rates throughout south eastern Australia (Bishop, 1985; Gale, 1992).

A weakness in this extrapolation is the possibility that debris flows become less frequent as the drainage line is eroded. Debris flows in the northeast did not occur in drainage lines that were deeply incised. That is, there were no debris flows where the side slopes into the drainage line were very steep. In these drainage lines the colluvial material is removed before it builds up in the stream, or on its margins. This could be in part related to the size of the basin, but it could also be related to the more efficient delivery of colluvium to the drainage line by the steeper side-slopes. This would imply that debris flows become less frequent as the drainage line is incised. This proposition has implications for the relationship between the evolution of stream channels and the evolution of the catena into the stream. Unfortunately the sample size of debris flows in this region is probably insufficient to test the proposition quantitatively.

CONCLUSIONS

A large storm in October 1993, in northeast Victoria, produced more debris flows (about 30) than have been reported before in Australia. Such debris flows are associated with storms of at least 50 year recurrence interval. The debris flows were typically between 0.5 and 1 km in length, experienced flow velocities up to 10 m s^{-1}, and were most common on resistant granite and acid-volcanic lithologies with slopes greater than about 25°. These characteristics are typical of debris flows that are common elsewhere. The only possible differentiating characteristic of the debris flows investigated on the acid-volcanic lithologies is their initiation in planar portions of the hillside, rather than in colluvial hollows.

The debris flows were of little significance to modern stream processes. Thirteen debris flows in one 35 km^2 drainage basin contributed approximately 10% of the total sediment mobilized during the flood. Five hundred metres of channel migration and widening in the stream contributed the same volume of sediment as the largest debris flow (approximately 2000 m^3). However, in the longer term the debris flows are a significant process because they deliver coarse colluvium (up to 1.5 m B-axis) directly from the hillside to the modern stream and flood plain, making it available for later transport. In addition, erosion of bedrock by the high velocity debris flows could produce lowering of the landscape at a rate of 5 m per million years. It is probable, however, that the frequency of debris flows declines as drainage lines incise.

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