A rare occurrence of landslides initiated by an extreme event in March 2007 in the Alligator Rivers Region, Australia

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Abstract The wettest water year on record at Jabiru Airport (2600 mm) in northern Australia occurred in 2006/07. A total of 1940 mm of rain fell in February and March 2007, with 737 mm occurring over 72 h between 28 February and 2 March. This rainfall and the associated flood event had return periods of at least 1:100 years on the annual maximum series. At least 49 landslides occurred on well vegetated, exhumed olivine dolerite surfaces surrounded by quartzose sandstone in the East Alligator River drainage basin. The number, extent, morphometry and soil properties of the landslides were determined using remote sensing imagery, combined with field and laboratory measurements. No evidence of previous mass movements on dolerite was found. The frequency of these mass movements is certainly much rarer than 1:100 years. Mass movements have not previously been considered a significant sediment source in this area because of their truly rare occurrence.

Key words mudslides; debris slides; landslide frequency; olivine dolerite; clay soils; extreme events

INTRODUCTION

For the last 15 years rainfall has been consistently above average in the "Top End" of Australia (Erskine *et al.*, 2011). Annual rainfall alternates between sub-decadal to multi-decadal runs of below average and above average rainfall in this area (Erskine *et al.*, 2011). In the Alligator Rivers Region (ARR) of the Top End (Fig. 1), a 28 000 km^2 area that includes the drainage basins of the East, South and West Alligator Rivers and the Wildman River, these rainfall trends are particularly well developed (Carter, 1990; Erskine *et al.*, 2012a). Elsewhere in Australia, Erskine & Warner (1988, 1999) found that catastrophic floods occur preferentially during runs of wet years. This also seems to be the case in the Top End because the two largest floods on Magela and Gulungul creeks in the ARR (Fig. 2) occurred in March 2007 and in February 1980 (Moliere, 2005; Erskine *et al.*, 2012b) during the last two wet periods of Erskine *et al.* (2011, 2012a), i.e. 1973–1984 and 1994–2007.

The most intense rain storm on record in the ARR occurred in March 2007 (Erskine *et al.*, 2012b; Erskine & Saynor, 2012) and initiated a series of landslides where olivine dolerite was exposed. No landslides had been previously recorded in the ARR on olivine dolerite, similar to the situation reported by Rutherfurd *et al.* (1994) for northeastern Victoria during the October 1993 record storm. The purpose of this paper is to present results on the classification, number, extent, morphometry and soil properties of the landslides and the mass of sediment eroded by landslides. The data were collected by a combination of remote sensing, field measurements and laboratory determination. More detail on the March 2007 storm and flood, and the effects of the landslides on suspended sediment transport in Magela Creek are contained in the companion paper by Erskine & Saynor (2012).

METHODS

Rainfall and flood data are analysed in Erskine & Saynor (2012). Pre- and post-landslide Landsat and ALOS AVNIR-2 images were obtained and used to identify and map landslides. Field measurements, including aspect, slope angle and distance and landslide depth were collected at nine landslide sites.

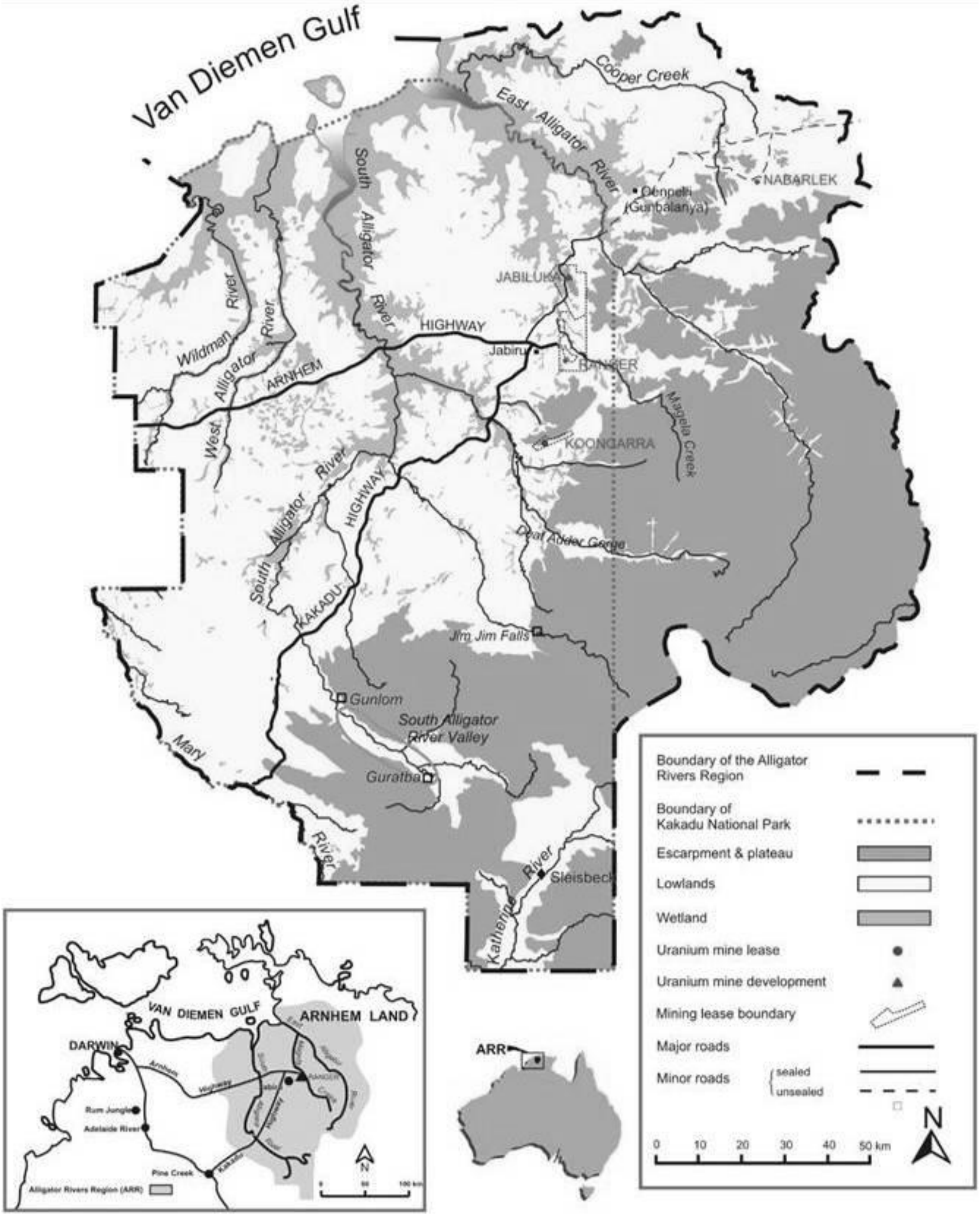

Fig. 1 Alligator Rivers Region (ARR) in the "Top End" of northern Australia. Long-term rainfall stations are located at Oenpelli and Jabiru Airport. Koongarra Mining Lease has been rescinded.

Sediment samples were collected from many landslides and subjected to grain size analysis, x-ray fluorescence and the Emerson (1967, 2002) aggregate stability test. Cores were used to collect landslide samples for bulk density determination. Grain size analysis was conducted by the combined sieve and hydrometer method of Gee & Bauder (1986). Grain size statistics and sediment textural groups follow Folk (1974).

2007 STORM AND FLOOD

Erskine & Saynor (2012) discuss this storm in detail. The raingauges closest to the landslides are 21–22 km away at Ranger Tailings Storage Facility and Jabiru Airport (Fig. 1). For the 72 h period between 17:00 h on 27 February and 17:00 h on 2 March 2007, 784 mm were recorded at Jabiru

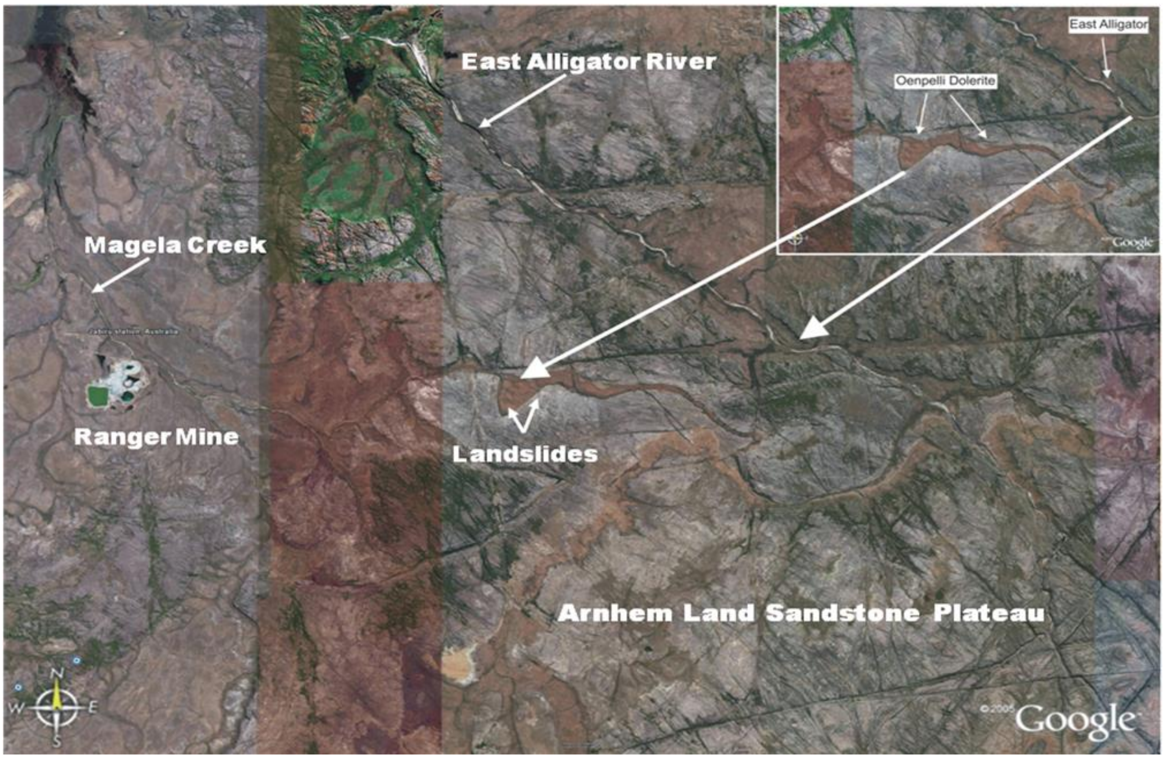

Fig. 2 Location of the landslides and Ranger Mine in the East Alligator River catchment, northern Australia.

Airport. However, Probable Maximum Precipitation (PMP) for 72 h duration here is 2200 mm (Bureau of Meteorology, 2011). Three distinct rain bursts occurred with the last, the most intense. Return periods for durations between 48 and 72 hours exceeded 1:1000 year. Furthermore, the 24-hour total of 398 mm is the largest recorded in the region, although PMP for 24 h duration is 1380 mm (Bureau of Meteorology, 2011).

The highest flood since gauging commenced in 1971 was generated by this storm on both the Magela and Gulungul creeks. However, on both creeks, the flood ratio (peak discharge/mean annual flood) was less than the threshold of 10 proposed by Erskine & Saynor (1996) as the minimum for a catastrophic flood. Nevertheless, it was an extreme event with return periods at both gauging stations of at least 1:100 year.

RAINFALL-GENERATED LANDSLIDES

A helicopter pilot first reported a series of landslides in western Arnhem Land east of Jabiru (Fig. 1) to the senior author in late March 2007. An aerial inspection of the landslides was completed on 11 April 2007. The area in which landslides occurred was largely confined to small surface outcrops of Oenpelli Dolerite (mainly olivine dolerite) which is surrounded and unconformably overlain by Palaeoproterozoic Mamadawerre Sandstone (Needham *et al.*, 1974; Stuart-Smith & Ferguson, 1978; Needham, 1984; Carson *et al.*, 1999). While an occasional rockfall occurred along sandstone escarpments, other types of landslides were usually restricted to Oenpelli Dolerite during the March 2007 storm. A Rb-Sr total-rock and mineral age of 1718 ± 65 my was obtained on the dolerite which consists of at least four lopoliths up to 250 m thick (Stuart-Smith & Ferguson, 1978).

Seventeen landslides have been identified in the Magela Creek basin and at least 32 in the rest of the East Alligator River basin further to the east. The number of landslides for Magela Creek is more accurate because it was determined by combined field work, aerial reconnaissance and remote sensing whereas the 32 landslides in the East Alligator basin were identified purely from ALOS AVNIR-2 images. Using the classification of Cruden & Varnes (1996), the landslides were mudslides, multiple mudslides, debris slides and multiple debris slides. Field observations indicated that the failure plane was usually associated with the contact of the soil with weathered dolerite. The failure plane was always highly irregular.

LANDSLIDE MORPHOMETRY

Table 1 contains the results of the field measurements of the dimensions of selected landslides and the volume and mass of sediment eroded. This work was completed on 15 and 16 August 2007 before the beginning of the wet season following the occurrence of the landslides. It expands what was previously reported by Saynor *et al.* (2009). The convention for numbering the landslides is that each landslide has been allocated a number based on the remote sensing. Where there are multiple landslides in the sense of Cruden & Varnes (1996), each component is denoted by a lower case letter starting at "a" and progressing through the alphabet. Where the landslide determined by remote sensing has combined individual landslides, the original numbering has been retained and each separate landslide is denoted by an upper case letter. The estimated eroded sediment mass by landslides in the Magela Creek basin by the March 2007 storm was 13 4931 t. This is much larger than the 78 102 t estimated by Saynor *et al.* (2009) because we have used a larger and hence we believe more reliable data set. Furthermore, our mean landslide depth is larger and we have subsequently found three additional landslides. For the whole East Alligator River catchment, the estimated eroded mass was 389 000 t. The former mass is only equivalent to 11 years of total terrigenous sediment yield for Magela Creek at the gauging station near Ranger Mine (G8210009) using the highest value cited by Erskine & Saynor (2000). Total terrigenous yield refers to the combined suspended load and solute load (Erskine & Saynor, 2000). This result is compatible with the results of Erskine & Saynor (1996) for catastrophic floods in southeastern Australia on rivers with low flood variability comparable to that at G8210009.

Table 1 Classification, morphometry and volume of eroded sediment for each landslide selected for field measurements. Mass of eroded sediment was obtained by multiplying volume by the mean landslide bulk density of 1.17 t m^{-3}.

Landslide number	Landslide type[1]	Mean width (m)	Mean depth (m)	Length (m)	Volume (m^3)	Mass (t)
1	Debris slide	37.9	2.5	147.5	13 959	16 332
2	Debris slide	10.7	3.0	22.0	706	826
3	Mudslide	16.4	1.5	10.0	246	288
4	Mudslide	20.9	2.5	74.0	3 873	4 532
5a	Multiple mudslide	10.6	1.8	28.5	546	639
5b	Multiple mudslide	7.4	3.0	34.5	770	901
8Aa	Multiple mudslide	60.0	2.0	21.3	2 560	2 995
8Ab	Multiple mudslide	27	2.0	6.4	347	406
8B	Mudslide	70.2	2.0	70.0	9 825	11 495
9a	Multiple Mudslide	48.8	2.0	100.0	9 769	11 430
9b	Multiple Mudslide	52.3	2.0	126.0	13 168	15 407
9c	Multiple Mudslide	15.7	1.5	47.0	1 107	1 295
10a	Multiple Mudslide	20.3	1.5	59.0	1 792	2 097
10b	Multiple Mudslide	10.8	2.0	101.0	2 188	2 560
10c	Multiple Mudslide	4.3	2.0	23.0	198	231

[1]After Cruden & Varnes (1996).

Table 2 lists additional landslide features for those selected for field measurements. Landslides were usually long and narrow with length/mean width ratios always less than 9.3. There was a preferred aspect for the landslides with 71% aligned on a compass bearing of 45–90°

and 225–270°. We believe that this was a function of the orientation of steep dolerite ridges at right angles to this preferred orientation. No landslides occurred on slopes less that 17° and the smallest headscarp height was 1.0 m. This suggests that the last episode of landsliding in the ARR was a relatively long time ago, permitting the weathering of steep dolerite slopes (>17°) to depths of greater than 1 m. All of the field measured landslides had well developed run-out features because of the steep slopes (Fig. 3). However, only two produced temporary landslide dams on the channels into which the landslides ran-out.

Table 2 Additional landslide features for those selected for field measurements.

Landslide number	Length–width ratio	Aspect (°)	Slope angle (°)	Headscarp height (m)	Run-out feature	Landslide dam
1	3.9	240	24	2.1	Yes	Yes
2	2.1	215	19	3.5	Yes	No
3	0.6	0	20	3.0	Yes	No
4	3.5	130	27	2.5	Yes	No
5a	2.7	260	17	3.0	Yes	No
5b	4.6	250	20	1.0	Yes	No
8Aa	2.8	70	18	2.1	Yes	Yes
8Ab	4.2	70	19	2.9	Yes	Yes
8B	1.0	45	19	2.0	Yes	No
9a	2.0	230	21	1.0	Yes	No
9b	2.4	230	21	3.3	Yes	No
9c	3.0	230	28	2.0	Yes	No
10a	2.9	240	23	1.5	Yes	No
10b	9.3	240	24	2.0	Yes	No
10c	5.3	240	23	2.8	Yes	No
Mean ± SE	3.4 ± 0.6	N/A	21 ± 0.8	2.3 ± 0.2	N/A	N/A

N/A – Not Applicable

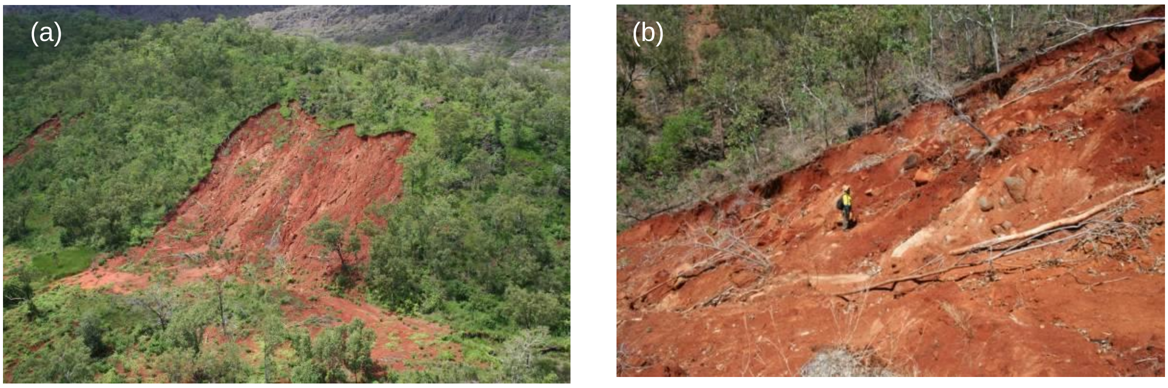

Fig. 3 (a) Oblique aerial view of landslide 8B which is a multiple mudslide. (b) Sidewall and irregular basal failure plane of landslide 8Aa over olivine dolerite. This is a multiple debris slide.

Landslide 1 dammed Magela Creek with a debris dam which was approximately 8 m high and which did not survive the flood that initiated the debris slide. Remnants of this dam were found on the opposite bank of Magela Creek and overlying quartzose sandstone further upslope. Landslides 8Aa and 8Ab dammed a small channel and the landslide debris was up to 0.3 m high. Such temporary landslide dams have also been reported during extreme events by Erskine (2005) on Middle Miocene basalt, alkali rhyolite and trachyte at Mt Canobolas near Orange, NSW, and by Currey (1952) on Jurassic mudstone on the East Barwon River, Victoria.

LANDSLIDE SEDIMENTS

The results of 12 grain size analyses showed that the landslide sediments were either slightly granular medium sandy mud (42%) or granular mud (58%), according to Folk's (1974) textural classification. Using the graphic grain size statistics based on the cumulative frequency curves, the landslide samples were extremely poorly sorted, coarse to strongly coarse skewed, mesokurtic to platykurtic, silts and clays (Folk, 1974). The landslide sediments are diamictons which are nonsorted sediments consisting of sand and/or larger particles dispersed through a muddy matrix (Flint *et al.*, 1960). As noted by Erskine (2005), these sediments usually consist of a matrix-supported fabric, angular and subangular gravel clasts, a matrix texture of mud or sandy mud, and crude, highly irregular bedding.

The same samples used for grain size analysis were also subjected to Emerson's (1967, 2002) aggregate stability test. All samples slaked but did not disperse when placed in deionized water. When remoulded at field capacity and 5 mm balls were placed again in deionized water, the soil balls exhibited minor slaking but no dispersion. Finally, a 1:5 soil:water suspension was made and shaken for 10 minutes. Following standing for 5 minutes, the suspended clay was flocculated (Class 6). The lack of dispersion suggests that that these highly slakeable soils are sensitive to disruption by internal forces during landsliding and to high energy tropical rain, to entrain and suspend the fine grained sediment. We expected these soils to be highly dispersible because of the red pulses reported by Erskine & Saynor (2012) in Magela Creek, but this was not the case.

The results for major elements for three landslide samples subjected to X-ray fluorescence are summarised in Table 3. As expected for tropical soils, the dominant major elements are SiO_2, Al_2O_3 and Fe_2O_3. The high Fe_2O_3 content is most likely due to the presence of haematite and is the reason for the red soils discussed by Erskine & Saynor (2012). Therefore, soil colour and, in particular, "red" landslide soils mixed with yellow soils from elsewhere were used successfully to determine the landslides as the main sediment source for a series of red flood pulses on Magela Creek in 2008 (Erskine & Saynor, 2012).

Results for trace elements for the same three landslide samples determined by x-ray fluorescence are summarised in Table 4. Major trace elements are Mn, Ba, V and Cu. Most importantly, U was not present at concentrations above the lower limit of detection. Other trace elements present at concentrations below lower limit of detection were Cd, Cs, Hg, I, Pb and Se.

Table 3 Summary results for major elements for the three landslide samples determined by x-ray fluorescence.

Sample	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	TiO_2 (%)	MgO (%)	Cl (ppm)
Landslide 9b	36.457	29.262	18.600	0.862	0.744	402
Landslide 8B	38.192	30.840	17.272	0.861	0.503	99
Landslide 1	37.747	30.197	16.460	0.668	0.603	238

Table 4 Summary results for trace elements for the three landslide samples determined by x-ray fluorescence.

Sample	Ba (ppm)	Co (ppm)	Cu (ppm)	Mn (ppm)	V (ppm)	Zn (ppm)	Zr (ppm)
Landslide 9b	243	58	292	995	373	76	96
Landslide 8B	120	48	128	909	229	43	99
Landslide 1	309	58	135	1144	223	80	104

OLDER LANDSLIDES

Field and aerial inspections plus stereoscopic vertical air photograph and ALOS image interpretation have so far failed to find any evidence of older landslides, except for occasional rockfalls along sandstone escarpments in the ARR. Stereoscopic interpretation of 1:50 000, 1982, vertical, colour air photographs established that none of the landslides identified here existed at that time. The diameter at breast height over bark (DBH) was determined for 23 trees which were located on landslides and which were moved by the 2007 landslides. The maximum diameter was 0.55 m and the mean, 0.21 ± 0.02 m (SE). While we cannot convert these diameters to tree ages, none are particularly large, which would indicate a long period of landform stability. Landslides, other than rockfalls, are truly rare occurrences in the ARR, but we currently do not know how rare. Williams & Guy (1973) reported that Hurricane Camille in 1969 approached the PMP in the Appalachian Mountains, USA, and caused wholesale landsliding, which they called debris avalanches, and eroded all sediment above competent bedrock in hill slope hollows. We predict that a similar process will occur on areas of Oenpelli Dolerite during intense storms approaching PMP in the ARR. Therefore, the area potentially subject to landslides could be as large as 2.5 km^2. Mudslides and debris slides were initiated by extreme rainfall of long duration which would have caused prolonged soil saturation and positive pore water pressure. The restriction of the 2007 landslides to surface outcrops of Oenpelli Dolerite with slopes greater than 17° and soil depths >1 m indicates that soil cohesion is an important factor in landslide initiation.

DISCUSSION AND CONCLUSIONS

An extreme event in March 2007, during a 15-year run of wet years, delivered 737 mm of rainfall over 72 h between 28 February and 2 March. This rainfall and the associated flood event had return periods of between 1:100 years and 1:1000 years on the annual maximum series. It is the largest event recorded since 1971 but was only about one-third of the PMP for a range of durations. At least 49 landslides were triggered on well vegetated, exhumed olivine dolerite surfaces surrounded by quartzose sandstone in the East Alligator River drainage basin. The landslides were mudslides, multiple mudslides, debris slides and multiple debris slides, according to the classification of Cruden & Varnes (1996). The landslides were relatively long and narrow features, restricted to slopes greater than 17° and were aligned perpendicular to the orientation of the main dolerite ridge. The landslide headscarps were at least 1 m high, indicating that these slopes had been stable for a considerable period of time. The landslide sediments were either slightly granular medium sandy muds or granular muds and hence had high clay contents. The soils readily slaked but did not disperse, as has been found for landslides on other volcanic rocks (Erskine, 2005). X-ray fluorescence indicated that the landslides were dominated by SiO_2, Al_2O_3 and Fe_2O_3, and contained the major trace elements of Mn, Ba, V and Cu. No evidence of previous mass movements on dolerite was found although the maximum diameter of trees which withstood the 2007 landslides in the Magela Creek basin was only 0.55 m. Rutherfurd *et al.* (1994) reported a similar finding for northeastern Victoria following the record storm of October 1993. The frequency of mass movements in the ARR is certainly much rarer than 1:100 years. Mass movements have not previously been considered a significant sediment source in this area because of their truly rare occurrence and the small area of dolerite. The mass of landslide sediment indicates that landslides will only be sediment sources of short-term significance (Erskine & Saynor, 2012). Nevertheless, localised storms located over landslides can generate “red” flood pulses which are of different colour to the remaining soils on lowlands, flood plains and sandstone in the ARR (Erskine & Saynor, 2012).

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