Mass Movements of Warrumbungle National Park, New South Wales, Australia

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The Warrumbungle Range is the mountainous eroded remnant of an Early Miocene shield volcanic complex located in the central west of New South Wales. A high-severity wildfire in Warrumbungle National Park in January 2013 was followed by intense rain, causing a number of debris flows. Several flows impacted on infrastructure such as roads and culverts and posed a severe risk to public safety, prompting a broader assessment of mass movement hazard within the park. High resolution LiDAR DEM revealed 542 locations with evidence of mass movement processes that pre-date the fire. The most common types of mass movement visible in the DEM are rotational slumps (353, 65%). The distribution of these indicated stratigraphic control, with 50% of slumps within 440 m of the volcanics-sandstone geologic contact, and typically occurring within unconsolidated volcanic colluvium and/or in situ deeply weathered volcanics. Debris flows are the next most common mass movement type after rotational slumps. Debris flow scour channels generally occurred on colluvial slopes in more elevated sites, within the volcanic rocks. DEM-extracted morphometric data was used to identify areas of debris flow hazard in WNP. Several large mass movements are morphometrically different, with some evidence for formation under different hydro-climatic conditions. A simple conceptual model of how mass movements contribute to the evolution of the Warrumbungle Range is proposed involving groundwater, deep weathering, slope retreat by mass failure, colluvial deposition and periodic incision by debris flows.

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KEYWORDS: debris flows, fire impacts, mass movements, slumps.

INTRODUCTION

In January 2013, a wildfire in the Warrumbungle Range of NSW affected 56,290 ha, including 95% of the 23,312 ha Warrumbungle National Park (WNP). Seventy-two percent of the fire burnt with high or extreme fire severity. On 1 February 2013, an intense storm from the southwest delivered between 60 and 90 mm of rain within 30 minutes and was ranked the 19th most intense on record in WNP (Yu 2015). Further, this storm occurred over a fire ground with little groundcover, and caused flash flooding and massive erosion, including debris flows. In many locations, first- to second-order drainage lines were scoured, often to bedrock, and the eroded material deposited in drainage lines downstream. Several such flows impacted on infrastructure such as roads and culverts and posed a severe risk to public safety. This prompted a broader assessment of the incidence of debris flows and the hazard posed by mass movements more generally in WNP.

This is the first study on mass movements in this region. We therefore lack knowledge on fundamental processes that govern landscape evolution in the Warrumbungles and hazards to infrastructure and human life. The study set out to determine the dominant mass movement processes in WNP (excepting rock fall and topple) and whether these may be controlled by geological factors. Furthermore, the study uses radiocarbon dates from levees and colluvial hollows to evaluate the frequency of debris flow events in the region. Finally, we use the findings to propose a simple conceptual model of how mass movement processes contribute to the evolution of landscapes in WNP.

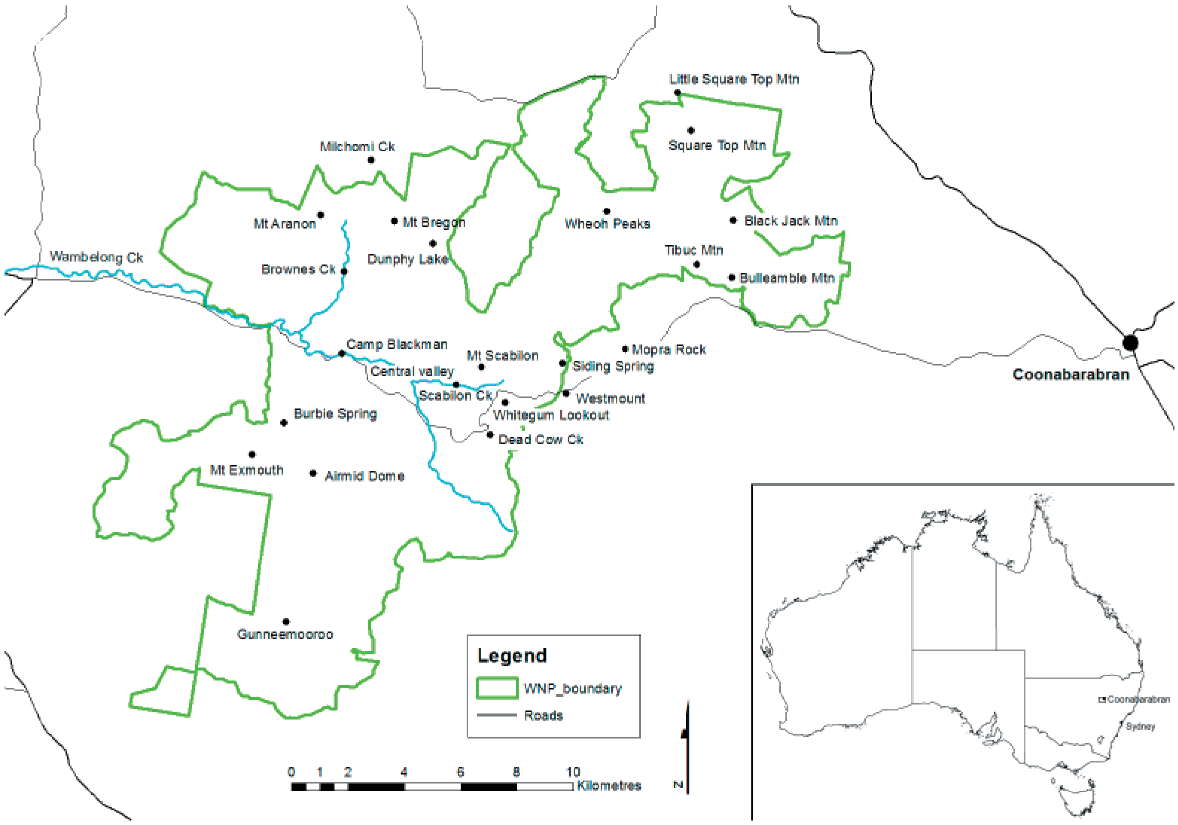

Figure 1. Study area.

Study Area

The study area (Fig. 1) is set in the WNP (23,312 ha) in the Warrumbungle Range in the central west of New South Wales (NSW). The study area is approximately 360 km northwest of Sydney and centred on the area approximately 25 km west of Coonabarabran.

The Warrumbungle Range is the eroded remnant of an Early Miocene shield volcanic complex. The range comprises rolling to steep hills and mountains, rising to 1,206m at Mount Exmouth and formed mainly of lava flow and volcaniclastic deposits punctuated by lava domes, plugs and dykes of the Warrumbungle Volcanics (Troedson and Bull 2018). A range of coherent volcanic rock types occur from mafic, through intermediate to felsic, with trachyte, trachyandesite and trachybasalt all common, and minor rhyolite also occurring. In the central part of the park, Wambelong Creek occupies a central valley, where Jurassic sandstones are exposed. Generally, the Warrumbungle Volcanics overlie relatively flat-lying Pilliga Sandstone; in parts of the northern section of the park the volcanics overlie Keelindi beds, comprising sandstones and conglomerates.

The climate in WNP is characterized by hot, humid summers and mild to cool winters. The mean maximum temperature at Coonabarabran Airport Automatic Weather Station (Bureau of Meteorology [BoM] station 064017) in January is 31°C, the mean minimum in July is 5°C. The mean annual rainfall at Westmount (BoM station 064046), on the eastern boundary of the park, is 1,034 mm.

The vegetation in WNP is generally open *Eucalyptus-Callitris* forest or Dry Sclerophyll Woodlands and Forests (Hunter 2008; Keith 2004), with a variable understory of shrubs and grasses.

The soils on trachytes are, in terms of the Australian Soil Classification (Isbell and NCST 2016), generally Brown to Red Dermosols. Soils on more felsic Warrumbungle Volcanics are generally Yellow and Brown Kandosols to Leptic Tenosols. Soils on Pilliga Sandstone are generally sandy Red to Yellow Kandosols and Chromosols. Approximately 16% of WNP is bare rock, being cliff lines in sandstone landscapes and as volcanic plugs.

Visitors are attracted to the Warrumbungles by the spectacular volcanic peaks, and WNP was established in several stages from 1953, attaining its present dimensions in 2010. The park has an annual visitation of ~35,000 (NPWS 2012).

Figure 2. Debris flow, February 2013, Dead Cow Creek.

Previous work

The Warrumbungle region has attracted the attention of geologists since the 19th and early 20th century (Edgeworth David 1896; Jensen 1907), and a great deal of work has been done in relation to petrogenesis (Faulks 1969; Hockley 1972; Duggan 1989; Duggan and Knutson 1991, 1993; Ghorbani 1999) and dating of the volcanic rocks (Dulhunty and McDougall 1966; McDougall and Wilkinson 1967; Dury et al. 1969; Dulhunty 1972; Wellman and McDougall 1974; Cohen et al. 2008). Troedson and Bull (2018) compiled, corrected and extended previous geology mapping (Offenburg 1968; Barnes et al. 2002), based on data within Honours theses and PhD theses (Hockley 1972, 1975; Timmers 1998), and interpretation of new field, petrographic, geochemical, and remotely-sensed data including aerial photography, Digital Elevation Model (DEM), and airborne geophysical data.

A number of workers have discussed the geomorphic evolution of the volcanic complex (Jensen 1907; Timmers 1998), but without recognising the ubiquity and significance of mass movements. Duggan and Knutson (1991) and Whitehead (2010) noted landslips, and the Burnt Area Assessment Team (BAAT) that reported on the 2013 fire noted debris flows in the Dead Cow and Scabilon Creeks (NPWS 2013) (Fig. 2). Troedson and Bull (2018) identified Neogene sedimentary deposits in the central valley that they regarded as mass movements. There have been no other mentions in literature of land instability in the Warrumbungle Range.

Similarly, there appears to be few studies of mass movements in nearby Cenozoic volcanic areas, although Melville (1976) addressed landslides on the north coast of NSW, Macgregor et al. (1990) noted landslips in the Border Ranges-Mt Warning area, and Erskine (2005) carried out a risk assessment for forestry in slip-prone areas near Mount Canobolas. Other studies in the region have been undertaken in areas of relatively flat-lying sedimentary (Sydney Basin) rocks. Blong and Dunkerley (1976) and Cunningham (1988) examined rockfalls in the Blue Mountains region, and Walker (1963), Bowman (1972) and Young (1978) assessed slope stability in the Wollongong escarpment.

A large body of research literature, particularly from the western USA, has been dedicated to evaluating the hazard posed by post-fire debris flows and their role in landscape processes (Riley et al. 2013). In Australia, research is more limited: Leitch et al. (1984) described a 'mud torrent' from a storm following the 1983 'Ash Wednesday' fires in Warburton (Victoria); Rutherfurd et al. (1994) studied sediment delivery from debris flows in northeastern Victoria; and Ferguson et al. (2004) and Lyon and O'Connor (2008) examined the link between post-wildfire debris flows and poor water quality in northeast and central Victoria. Large debris flows also occurred in the Cotter River catchments near Canberra after the severe 2003 wildfire (Worthy 2006), and Nyman et al. (2011) documented the occurrence of post-fire runoff generated debris flows in dry sclerophyll forests in south-eastern Australia. More recently Nyman et al. (2019) demonstrated how mass movements in south-eastern Australia are linked to regional hydroclimatic conditions and the El Niño Southern Oscillation. However, debris flows have not previously been noted in the Warrumbungle Range.

The number of publications discussing the use of Light Detection and Ranging (LiDAR) in 'landslide' studies has grown considerably during the last decade (Jaboyedoff et al. 2012). High resolution DEMs have been used to map mass movements in many locations around the world (McKean and Roering 2004; Glenn et al. 2006 Ardizzone et al. 2007; Schulz 2007; Van Den Eeckhaut et al. 2007) and to provide insight into the material type, and to infer landslide behavior and activity.

MATERIALS AND METHODS

Mapping and field investigations

As part of the Warrumbungle Post-fire Recovery Project, LiDAR was acquired over WNP and a 1 m DEM prepared. The LiDAR data is available at https://elevation.fsdf.org.au/. This provided the base layer for terrain interpretation and analyses based on morphometric factors (Staley et al. 2006; Cavalli and Marchi 2008). Mass movements were identified and mapped using ArcMap 10.4 and classified according to Varnes (1978) and Cruden and Varnes (1996). Slumps were mapped where there was an identifiable headscarp on the DEM >5 m in breadth, and from the headscarp to the depositional lobe. Debris flows were mapped from the uppermost point of the erosion channel to proximal end of the fan at the base of the debris flow channel. For each mass movement, site and elevation data was extracted from the DEM for the uppermost point or headscarp, and the lowest point of the toe (slumps) or the lowest point of the erosion channel (debris flows). Slope data were extracted from a resampled 5 m DEM to negate data noise. Slow earthflows were mapped on the basis of large areas of hummocky ground and/or other evidence of movement such as burial of dykes.

Mass movement sites were inspected in the field, where accessible, although these comprised only a small proportion (~4%) of the total detectable on LiDAR. More detailed field investigations were undertaken at several debris flows and at other mass movement sites just above the Warrumbungle Volcanics - Pilliga Sandstone boundary to determine the depth of transported material and the degree of bedrock weathering. Sites inspected are discussed below and noted on Fig. 1.

Determining the age range and frequency of mass movements in WNP

The mass movements identified in WNP appear to span a wide age range, based on a range of morphometric, regolithic and other site variables, including: the clarity of mesotopographic features such as sharpness of a headscarp; any superimposition of movements; and any other evidence for post-depositional geomorphic processes within the transported material, such as formation of drainage lines.

The frequency and nature of movements under current hydroclimatic conditions was established by examination of the DEM and aerial photos. Aerial photos dating back to 1955 were examined to identify recent movements. Where accessible, recent movements may be confirmed by the degree of revegetation of disturbed or depositional areas. Information of recent landscape instability in the vicinity of WNP was also obtained from NPWS staff and other sources. As a result, the dates of certain historic mass movements are known.

Radiocarbon dates of charcoal from debris flow levees and colluvial hollows can provide data to help determine the erosion regime in headwaters. We sampled charcoal from three levees and two colluvial hollows in the Dead Cow Creek catchment in order to obtain an indication on how the post-fire event in 2013 sits within the longer-term geomorphic processes that have shaped the landscape (Fig. 3). Charcoal in colluvial hollows can be used to estimate the rate of colluvial deposition (Reneau et al. 1989; Hales et al. 2012). Radiocarbon dates of charcoal in levees (Fig. 4) can provide an indication of when debris flows occurred in the past (Lancaster and Casebeer 2007; Smith et al. 2012).

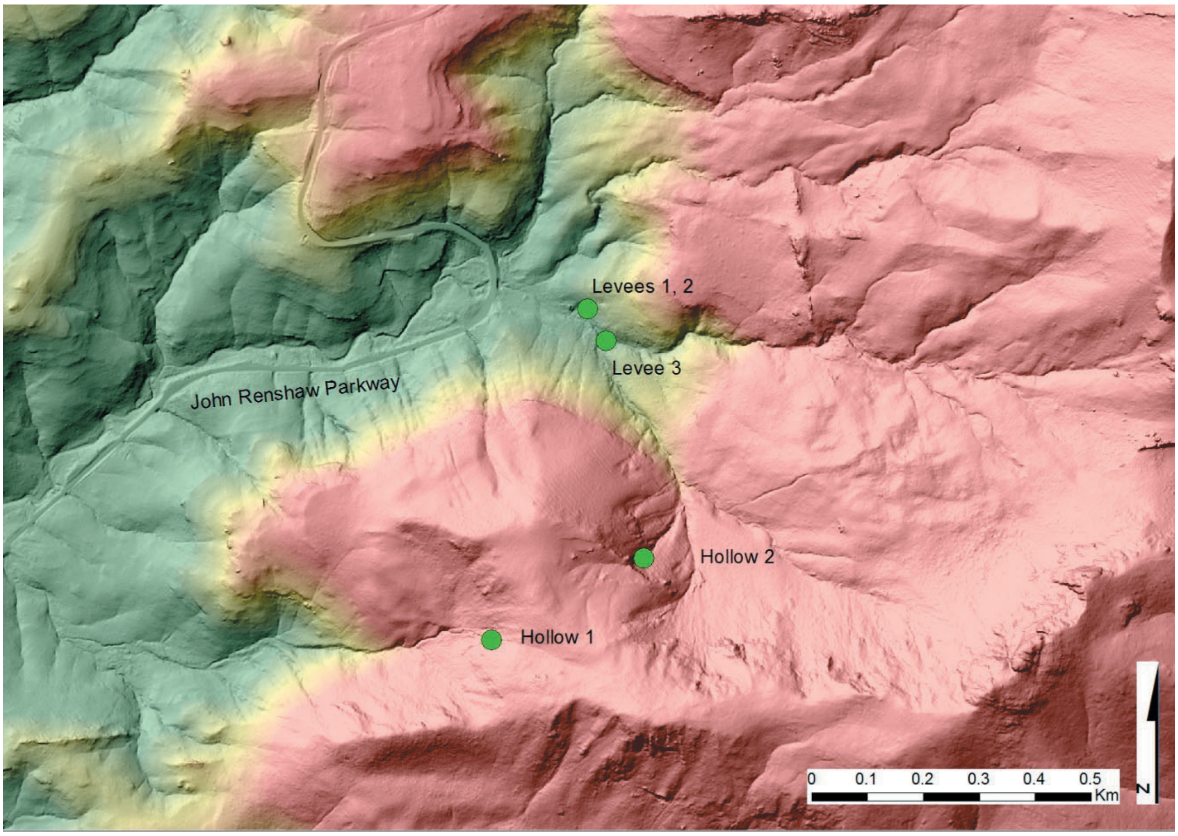

Figure 3. Sites in the Dead Cow Creek catchment where charcoal was sampled for radiocarbon dating. Figure prepared from 1 m DEM with hillshade.

Figure 4. Debris flow levee material at levee 3 site.

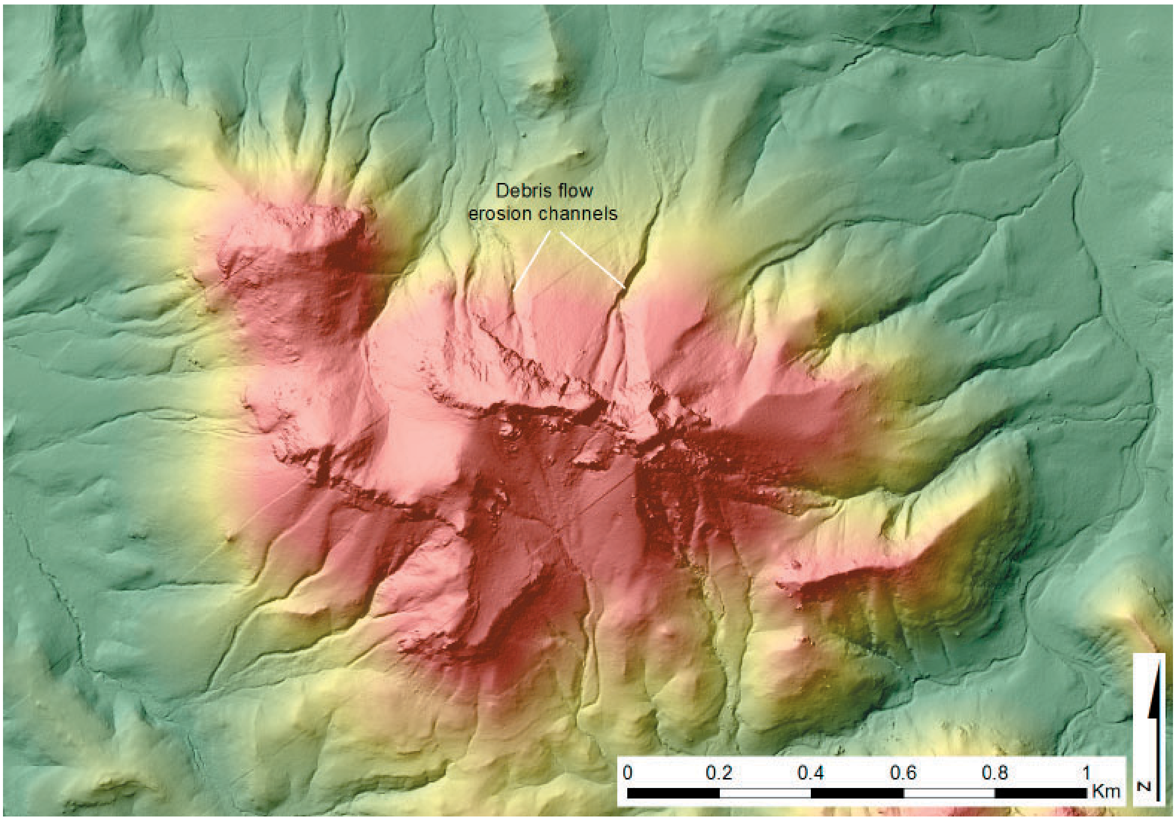

Figure 5. Debris flow scour channels, Wheoh Peaks.

RESULTS

Mapping

Five hundred and forty-two (542) individual mass movement locations totalling 408 ha were identified and mapped by examination of the high-resolution DEM. These data are available at https://www.environment.nsw.gov.au/eSpade2Webapp. Ninety-four per cent (94%) of the mass movements were located within areas mapped as Warrumbungle Volcanic Complex rocks, and <6% were on Pilliga Sandstone (17 ha, or 4.1% of the area of mass movements generally), based on geology data from Troedson & Bull (2018).

Debris flows

Seventy-seven (77) locations of mass movement processes were classified as debris flows. These were generally linear to sub-linear scour channels up to 700 m in length and 30 m in breadth, and found on steep (>92% average, 41% minimum) rectilinear colluvial slopes. The DEM revealed dozens of such channels associated with volcanic peaks, particularly in the north-west of WNP around Wheoh Peaks, Black Jack Mountain and the Tibuc-Bulleamble Mountain area (Fig. 5).

Historic aerial photographs and other remote imagery showed that the vast majority of such flows pre-dated the 2013 fire and storm. The only debris flows known to have been activated within the last 60 years were flows on Wheoh Peaks, Square Top Mountain, Little Square Top Mountain, Black Jack Mountain, and Airmid Dome (Fig. 6). The latter flow was dated to one of three intense rainfall events between December 2009 and February 2010, and therefore unrelated to fire or associated loss of groundcover. On 1 February 2013, several flows activated in the Dead Cow Creek area (Fig. 1) and one in Scabilon Creek.

Initiation and deposition slope angles for the 77 mapped debris flow scour channels are shown in Fig. 7. Debris flows were not observed to release on slopes <41% in WNP. Deposition may occur on slopes <27% on average, and the run-out, generally comprising a downstream fining sequence of boulders and logs to gravels and sands, can occur over several kilometres where the flow is valley-confined.

Radiocarbon dates of charcoal samples (shown in Table 1) from levees range from modern (calibrated radiocarbon age of 58 - 8 years BP) at 30 cm below the contemporary channel to much older for charcoal samples from levees deeper in the channel profile at

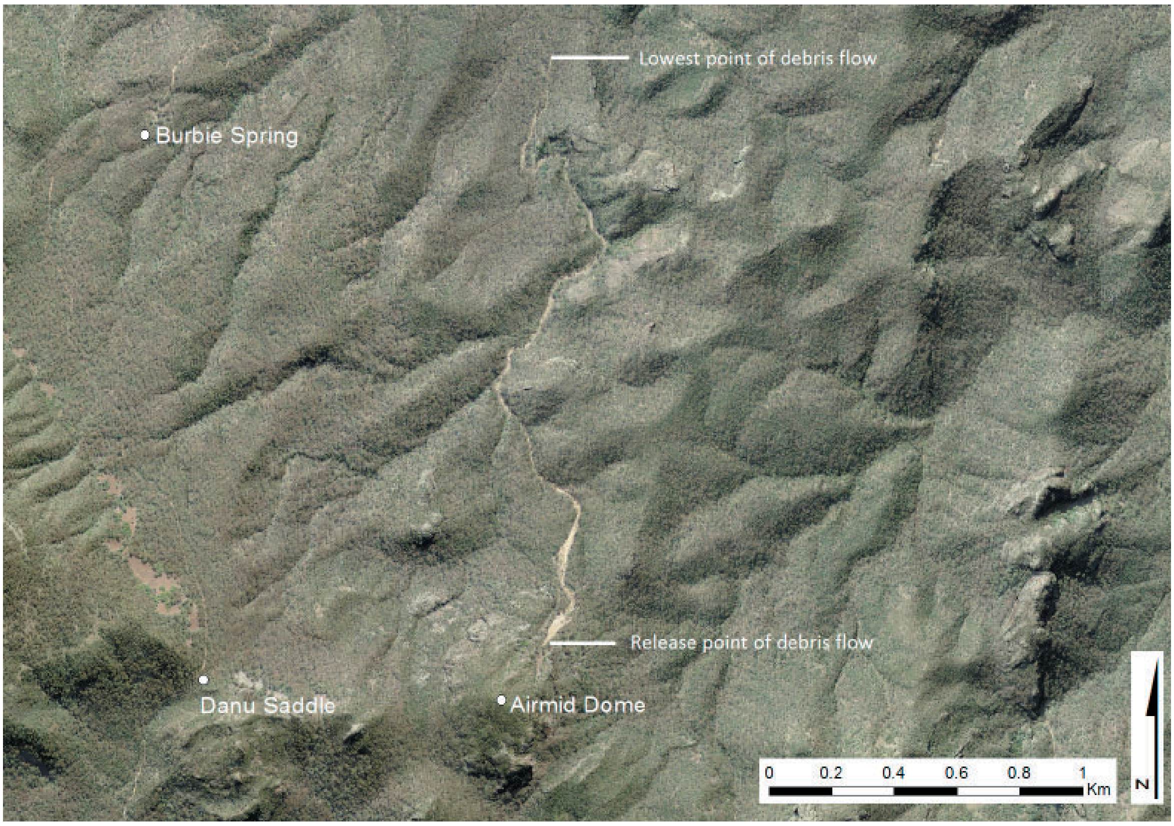

Figure 6. Airmid Dome debris flow.

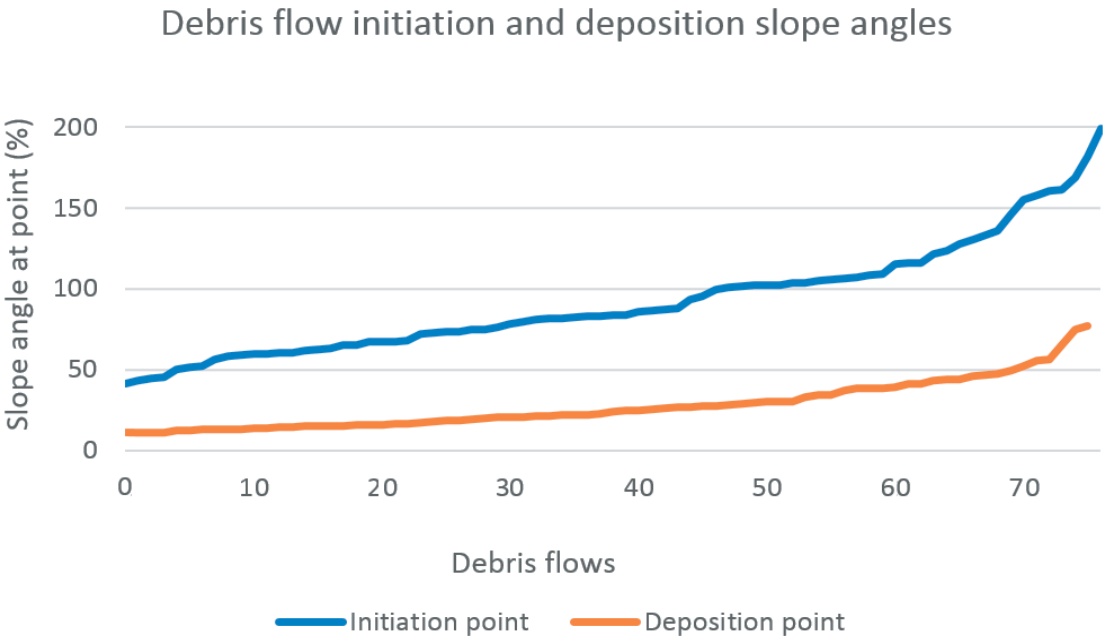

Figure 7. Frequency distribution plot of slope of debris flow release and deposition points.

Table 1. Radiocarbon dates from charcoal samples from old levees and colluvial hollows, reported as per standard convention (Millard, 2014). Dates were analysed at the Beta Analytic radiocarbon dating lab using Accelerator Mass Spectrometry (AMS). Charcoal was pre-treated using standard acid-alkali-acid method.

Sample code	Beta Analytics laboratory code	Sample location	Easting[1]	Northing[1]	Conventional radiocarbon age (BP) or Percent Modern Carbon (pMC)	δ13C from isotope-ratio mass spectrometry (o/oo)	Calibrated age (years BP) [2]
Levee 1 30 cm	522304	Old levee at 30 cm below bank of contemporary channel	694020	6535232	107.09 ± 0.40 pMC	-25.7	58 - 8
Levee 2 95 cm	522309	Old levee at 95 cm below bank of contemporary channel	694020	6535232	540 ± 30 BP	-24.8	525 - 500
Levee 3 125 cm	522308	Old levee at 125 cm below bank of contemporary channel	694054	6535175	1650 +/- 30 BP	-26.3	1492 - 1416
Hollow 1 140 cm	522307	Colluvium at channel head at 140 cm below contemporary hillslope surface	693846	6534638	880 +/- 30 BP	-26.3	738 - 683
Hollow 2 80 cm	522305	Colluvium at channel head at 80 cm below contemporary hillslope surface	694122	6534786	940 +/- 30 BP	-24.3	906 - 736
Hollow 2 110 cm	522306	Colluvium at channel head at 110 cm below contemporary hillslope surface	694122	6534786	4630 +/- 30 BP	-26.8	5254 - 5057

[1] Coordinates in MGA GDA94 zone 55.

[2] Dates calibrated by Beta Analytics (BetaCal3.21: HPD method: SHCAL13 (Hogg, et.al.,2013) using MatCal in Matlab (Lougheed et al, 2016). The date range is the 95.4% probability interval.

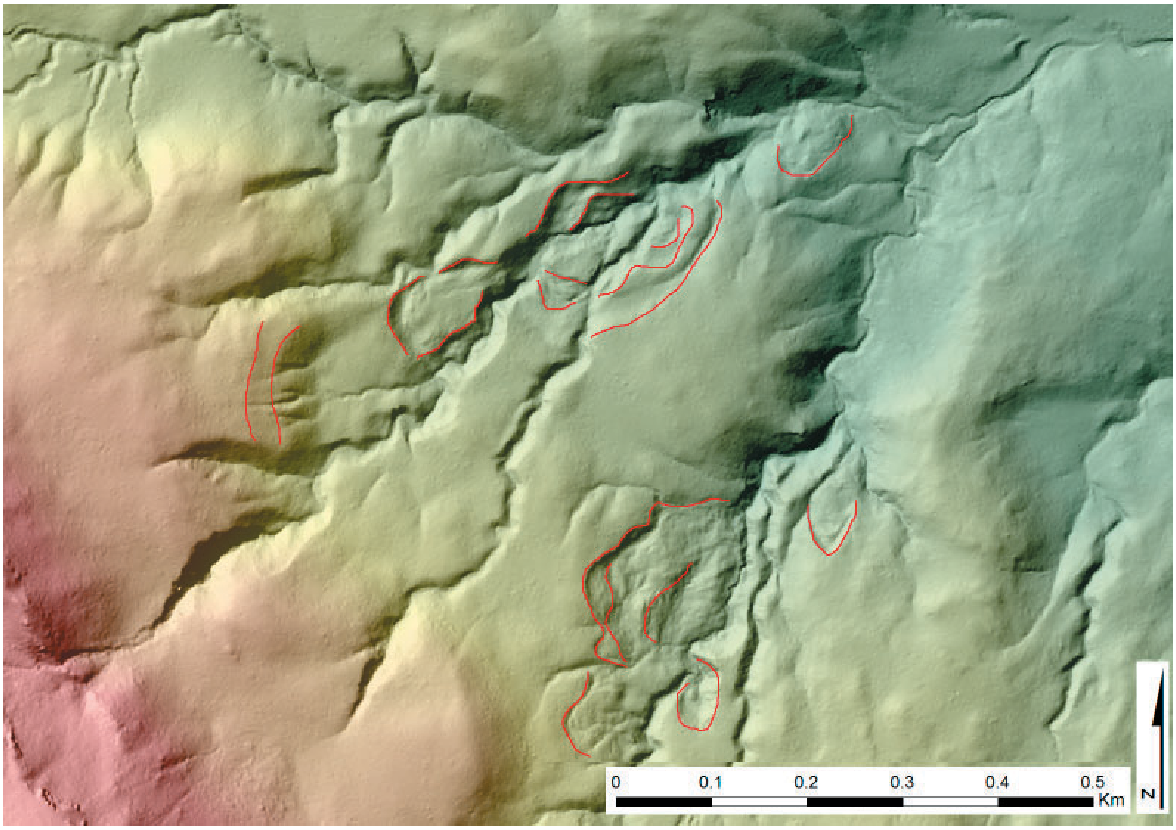

Figure 8. DEM image of rotational slumps, Milchomi Creek catchment. Figure prepared from 1 m DEM with hillshade.

125 cm (calibrated radiocarbon age of 1492 - 1416 years BP). The time interval between the radiocarbon dates in levee 1 and levee 2 (95 cm below contemporary channel bank) is ~500 years. There is an interval of ~1000 years between levee 2 and levee 3.

Calibrated radiocarbon dates from the base of exposed colluvial profiles indicate when the material was last eroded by debris flows or landslides. In hollow 1, which was located on a scree slope at the base of volcanic escarpments (the west oriented headwater in Fig. 3) the age of charcoal samples near the base of the eroded channel (at 140 cm below the surface) was 738 - 683 years BP. In hollow 2, which sits at the sandstone-volcanic boundary, the charcoal sample at the base of the profile (110 cm below the current hillslope surface), was dated to be 5254 - 5057 years BP. The radiocarbon date of charcoal from 80 cm below the surface was 906 - 736 years BP. With these dates, the rate of sediment accumulation in the hollows is in the order of 0.015 - 0.12 cm yr^{-1}. With hillslope lengths of 120 - 150 m, these infilling rates correspond to denudation of 2.5 - 20 mm kyr^{-1} which are within the range of values reported for hillslopes in southeast Australia (Smith et al. 2012).

Many debris flow channels, including most in the Wheoh Peaks, Black Jack Mountain and the Tibuc-Bulleamble Mountain areas, incised into colluvial and/or prior debris flow materials. The periodicity of debris flows may be set in part by the formation of indurated layers within the regolith of previous flows or colluvial deposits. Once permeability and transmissivity of the regolith is so limited, intense runoff is more likely to result in overlying unconsolidated surficial materials becoming hydraulically loaded to the point where slope stability is exceeded.

Slumps

The most common mass movement type in WNP evident in the DEM is the slump, of which 353 were identified. The smallest slump mapped was 19 m^2. Larger examples were up to 8.7 ha. The majority of slumps were identified as rotational, with a hummocky toe. Several revealed multiple headscarps and possibly, phases of activity (Fig. 8).

Fifty per cent (50%) of slump headscarps were initiated within the volcanic sequence within 440 m of the Warrumbungle Volcanics-Jurassic sandstones geologic boundary as determined by Troedson and

Bull (2018) (Fig. 9), with the inflection in Fig. 10 suggesting a causal relationship up to 1700 m from the boundary.

Field investigations were undertaken at several sites including Burbie Spring, Brownes Creek, Siding Spring, and Gunneemooroo to understand the processes involved at the volcanics-sandstone boundary. These revealed that the material immediately above the volcanic-sandstone boundary at these sites is typically unconsolidated volcanic colluvium and/or in situ deeply weathered volcanics (Fig. 11). In all cases mass failure was initiated in this material.

The elevations of the initiation points of slumps and that of the nearest sandstone contact were determined from the DEM and the difference calculated (Fig. 12); the inflection and sparse data on the right indicates that the elevation difference averages 81 m, but may be up to ~200 m.

Information regarding slump frequency is scarce, as slumps are generally difficult to detect beneath the vegetation on aerial photographs. A slump on Mopra Rock, just outside the park is known to have occurred in 1955 (P. Thompson, Coonabarabran Landcare, pers. comm), and a small slump in the upper Wambelong Creek valley occurred in 2018. A large rotational slump in the upper Wambelong Creek valley with a vertical headscarp with exposed soil is not known to have moved in several decades (A. Dow, NPWS, pers. comm.), suggesting a high degree of preservation on a decadal time scale. A presumed megaslump caused the formation of Dunphy Lake, a small intermittent wetland in a remote northern section of the park. This movement can be proxy dated from the palustrine sediments; Lobb (2015) retrieved two cores from the intermittent wetland, and dated the sediments using OSL and radiocarbon providing an age of 18.2 ka for initiation of wetland sediment accumulation at that site.

Slow Earthflows

Some areas exhibited hummocky, unstable terrain without a headscarp. The largest such area was 26 ha, near Gunneemooroo (Fig. 13). It is likely that further areas of undetected unstable surficial materials are present, older areas of instability being generally less detectable.

Other Movements

A Pleistocene age can be inferred for a 1.2 km long slow earthflow filling a former valley of the Dead Cow Creek catchment (Fig. 14), with an estimated volume of 2 x 10^6 m^3 of material. This material is indurated and has erosive drainage features developed within it, suggesting a Pleistocene age, and may relate to a climatic period with higher soil moisture regimes. A small intermittent 'lake' basin not unlike Dunphy Lake has developed towards the proximal end of the flow.

DISCUSSION AND CONCLUSIONS

Analysis of a high-resolution LiDAR DEM has revealed the large number, locations and types of hitherto largely unknown pre-historic to historic mass movements in WNP, features that were previously undetectable by aerial photographs or other remote imagery. Five hundred and forty-two (542) individual mass movements were mapped and classified: 353 were slumps; 58 were slips on hillslopes; 40 were slips in drainage lines; 81 were debris flows; and 9 were slow earthflows. Mass movements, especially slumps, are concentrated immediately above the volcanics-sandstone geological boundary and may occur on gentle slopes, as low as 4% with an average of 47%. In contrast, debris flow release points are located on steeper slopes, a minimum of 41% and an average of 102%. The large number of slumps that may be identified and which are therefore presumably younger than the 18.2 ka Lake Dunphy presumed megaslump gives an indication of the frequency of such events. In the Dead Cow Creek catchment, recurring debris flows can occur every few hundred years.

Mass movements appear to be a key process in long-term landscape evolution in the Warrumbungles, and probably have been since shortly after the eruption of volcanic materials. A model of landscape evolution is proposed, focusing on processes at the boundary (Fig. 15). In areas where unconsolidated volcanic colluvium and/or in situ deeply weathered volcanics directly overlies the sandstones, such as the Wheoh Peaks, Black Jack Mountain and Tibuc-Bulleamble Mountain areas, relatively rapid recession of colluvial slopes occurs from immediately above the boundary predominantly by land slippage and debris flows, leaving isolated caps of coherent volcanic rocks (Fig. 5).

In other areas with a deeper pile of coherent volcanics, rainfall enters groundwater via volcanic jointing, and appears to be impeded and directed laterally above the sandstone contact, resulting in greater weathering of the volcanics immediately above the contact, and the expression of artesian springs. A number of named springs or waterholes are located within a few hundred metres of the geological boundary (Jensen 1907; Hockley 1972; Troedson and Bull 2018). Weathered and unconsolidated volcanic

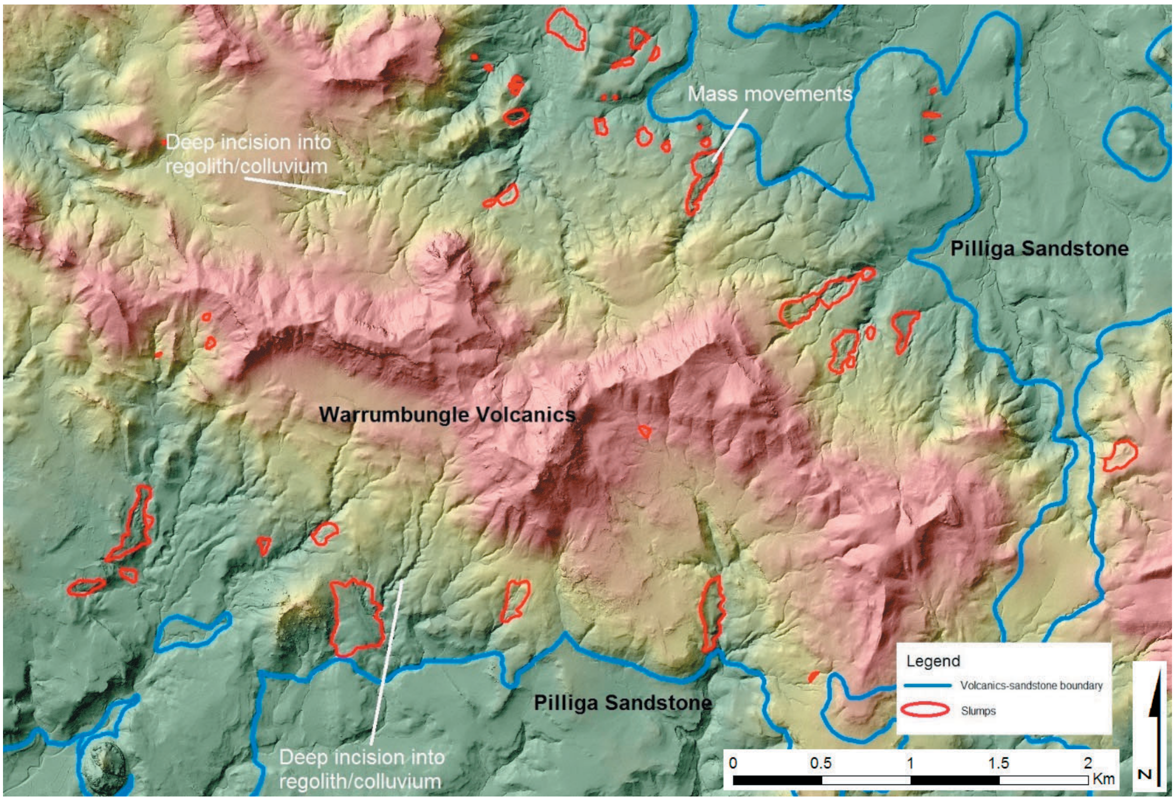

Figure 9. DEM image of slump distribution in the Mt Aranon-Bregon range, northwestern WNP, showing proximities to the mapped volcanics-sandstone geologic boundary. Figure prepared from 1 m DEM with hillshade.

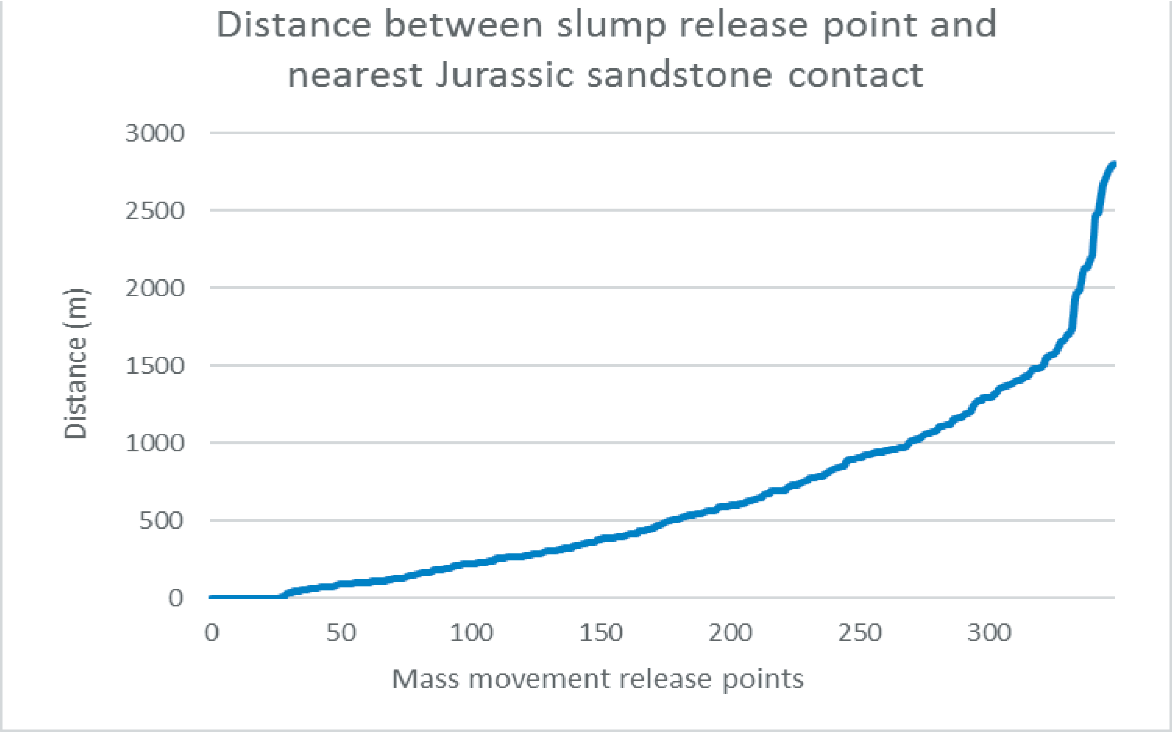

Figure 10. Frequency distribution plot of distances from slump release point to the volcanics –sandstones geologic boundary.

Figure 11. Deeply weathered in situ volcanics at Burbie Spring.

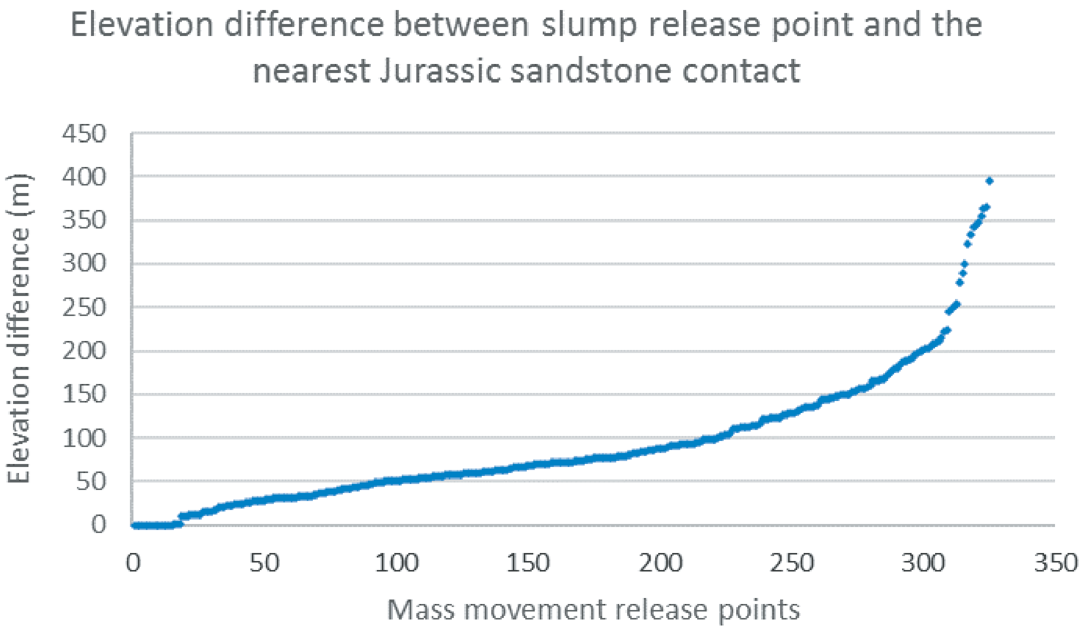

Figure 12. Frequency distribution plot of elevation difference between slump release points and the volcanics-sandstones geologic boundary.

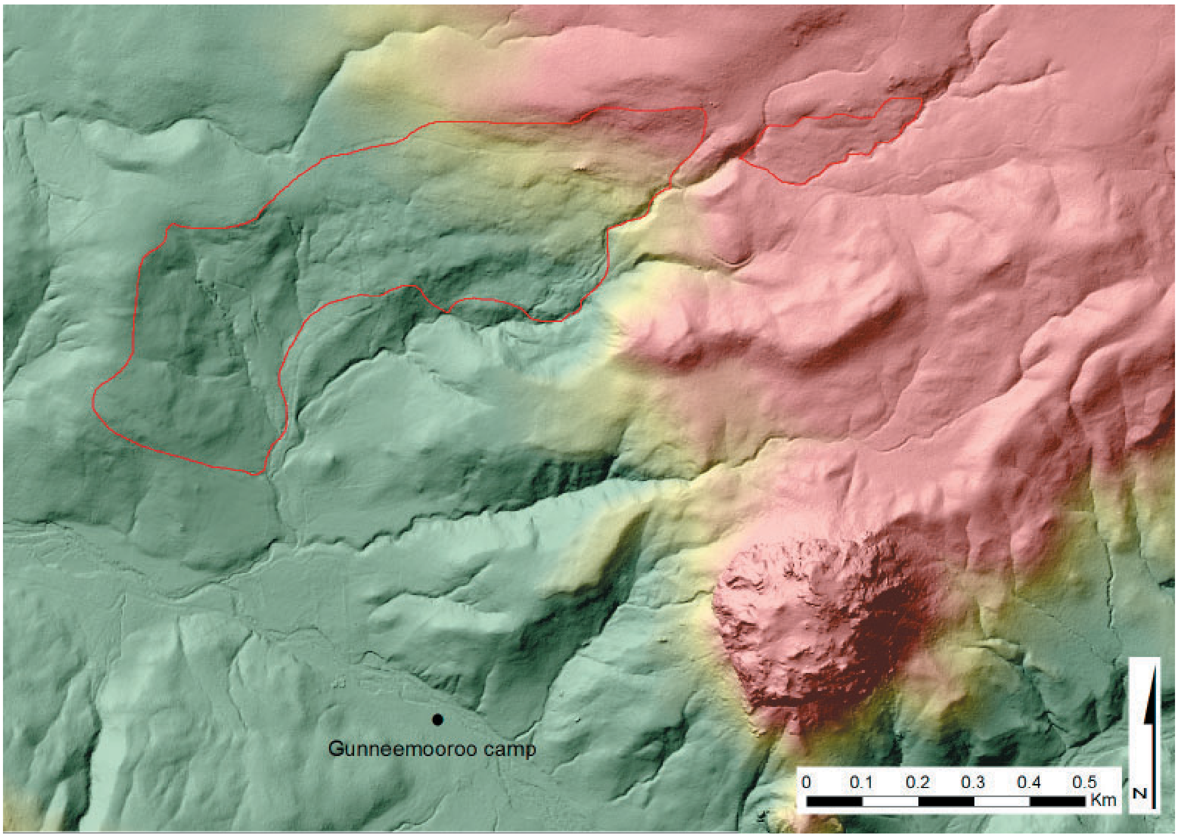

Figure 13. DEM image of hummocky, unstable terrain, Gunneemooroo area.

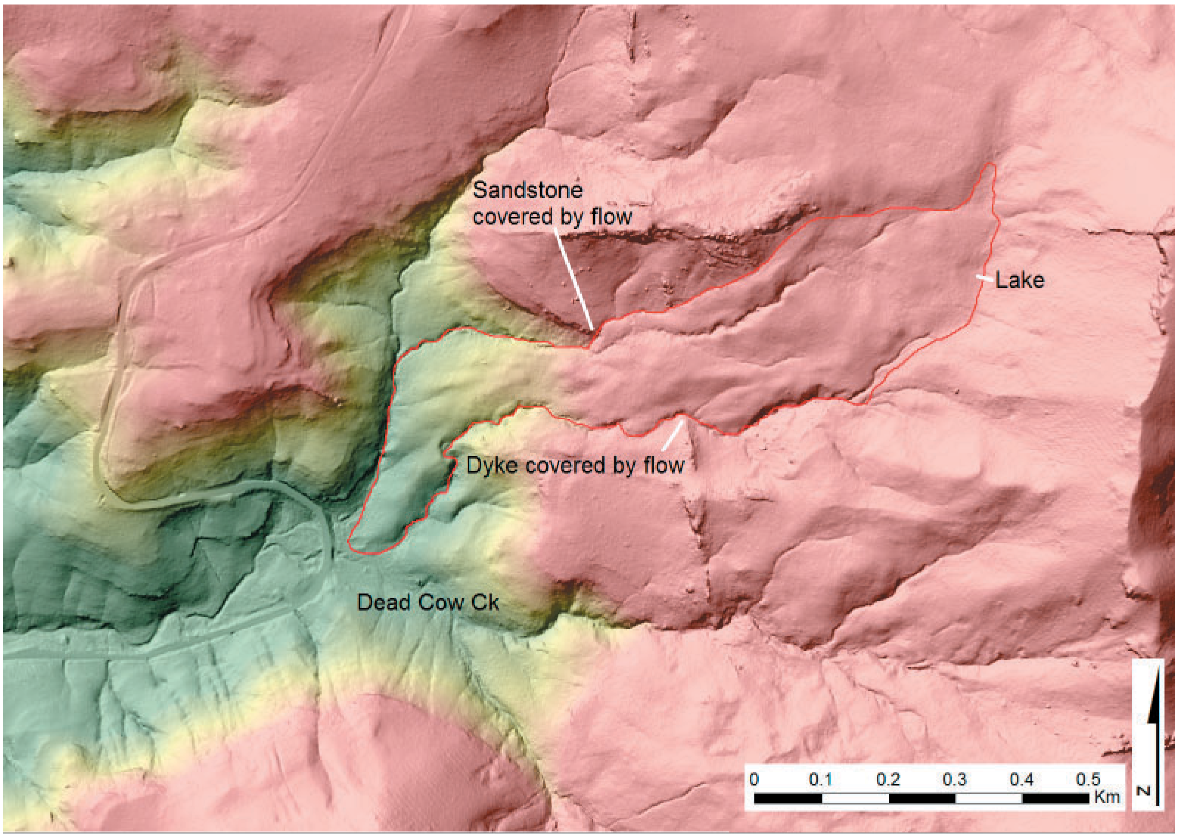

Figure 14. Dead Cow Creek catchment slow earthflow.

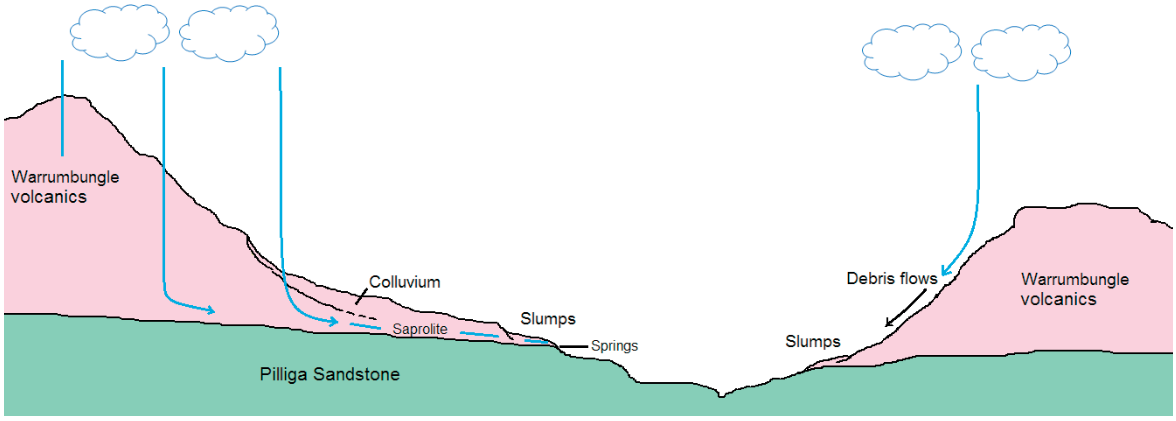

Figure 15. Conceptual model of processes at the sandstone-volcanic boundary.

regolith directly above the contact becomes deeply incised by stream action (Fig. 9) and periodically fails by slumping (Fig. 8). Stratigraphic undermining may also occur from higher within the volcanic sequence, leaving a larger 'apron' of volcanic colluvium and deeply weathered volcanic regolith (Fig. 9).

This study relied on the geological mapping of Troedson and Bull (2018). However both this work and the present study were constrained by lack of access to many areas of WNP. In these areas, much of the geological mapping was carried out by interpretation of aerial photography and other remotely sensed data. Similarly, more detailed inspection of more sites near the volcanics-sandstones contact, particularly in relation to groundwater hydrodynamics and weathering patterns would inform a more robust model of landscape evolution. Further, work on debris flows could be extended beyond the limited number of sites in this study to examine timing and possible synchronicities with other sites, such as the north-eastern part of WNP.

Mass movements appear to have been a significant process of landscape evolution in the Warrumbungles since at least the late Pleistocene, with one movement (Dunphy Lake) dated to the Last Glacial Maximum. Certain features, such as the Dead Cow Creek deposit, and the central valley Neogene sedimentary deposit, have few modern identified analogues. The processes responsible for their formation do not appear to operate under current hydro-climatic conditions.

This work has direct relevance to park planning and hazard management. It has highlighted the hazards posed by mass movements to the public and to infrastructure, identified slopes and areas at risk of debris flows and slumps, and outlined the processes and conditions under which mass movements may be active. Furthermore, the dating of debris flow deposits and colluvial sediments provide an early indication on the frequency with which these types of events can be expected to occur. The results may also have wider implications beyond WNP, to post-volcanic landscape evolution in other Cenozoic volcanic areas in NSW.

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