THE UNIVERSITY OF QUEENSLAND

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# The distribution and paleoclimate implications of periglacial landforms in eastern Australia

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## Abstract

It is widely recognised that during the Late Quaternary, glaciation was limited in Australia, especially away from Tasmania. This contrasts with the widely recognised occurrence of periglacial landforms in SE Australia, particularly in Australian Alps and Tasmania. However, very little research has been undertaken into these landforms. The aim of this thesis is to investigate the extent and timing of Late Quaternary periglacial conditions in south-eastern Australia and to understand the geomorphic processes and environments associated with these landforms. This thesis presents an updated understanding of the distribution, morphology and climatic significance of periglacial landforms in eastern Australia. The thesis is divided into two sections. The first section is focused on modern 'active' periglacial landforms found primarily in the mountainous areas of Tasmania and focuses on two studies of modern freeze-thaw processes in western Tasmania. At higher elevations (1000 m) notable freeze-thaw features are active at the present time including stone banked lobes on Mt Rufus. Freeze-thaw features were identified to only 150 m above sea-level near Queenstown. However, these low elevation freeze-thaw landforms are small scale features associated with short periods where shallow ground ice forms. The second section of the thesis focuses on relict periglacial landforms that display no evidence of modern activity and most likely relate to late Quaternary cold climate conditions. It primarily focuses on the block deposits of eastern Australia, their morphology, distribution and climatic significance. Block deposits and associated landslide deposits from northern New South Wales to Tasmania were mapped. Four sites were studied in more detail and dated using surface exposure dating (SED). They yielded ages ranging from early Holocene to OIS 5 which are internally consistent within sites but vary widely between sites. These data provide evidence for repeated phases of periglacial activity during the last glacial cycle. At Guyra, several phases of mass movement were recognised with large scale landslides associated with a much earlier warm and humid climate dominating the landscape. Freeze-thaw landforms of the late Quaternary are superimposed on these older forms. The scale of last glaciation cooling is indicated by evidence for a possible nivation hollow bounded by a pronival rampart located near the town of Guyra (29°30'S). From this site a cooling range of 8-11°C is inferred, but additionally, relatively moist conditions are required for the nivation feature to form.

The concept of a relatively humid glaciation also emerges from the mapping of the freeze-thaw landforms on a regional basis. In particular the occurrence of block deposits and screes in northern New England in patterns matching the modern precipitation gradient

indicates that freeze-thaw was preferentially concentrated in a zone parallel to the coast. It is inferred that this zone represented an area of intermediate moisture landward of the divide separating a region that was too wet (along the divide) from areas further west that were too arid for the maximum development of periglacial landscapes. This zone falls between the modern 850 and 1000 mm isohyets but it was not possible to specify the LGM rainfall. The fact that the zone parallels modern rainfall boundaries indicates that modern (easterly dominated) circulation was dominant at that time also. Further south, periglacial landforms are more widely distributed.

**Declaration by author**

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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**Publications during candidature**

**Slee, A.,** Kiernan, K., Shulmeister, J. and Jenkinson, A., Stone banked lobes as a product of mild freeze-thaw action: An example from western Tasmania, Australia. Accepted *Geografiska Annaler: Series A, Physical Geography*, 22/12/2015

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| Contributor | Statement of contribution |
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| Adrian Slee (Candidate) | Fieldwork (50%) |

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| Kevin Kiernan | Fieldwork (50%)<br><br>Wrote and edited paper (5%) |

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periglacial, freeze-thaw, quaternary, block stream, solifluction, frost-window, surface exposure dating, landslides

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# List of Abbreviations

- ASL Altitude above Sea Level
- BP Before Present
- Cal Calibrated
- $C^{14}$ Radiocarbon Dating technique
- CFc Temperate Cool Wet (maritime)
- cm Centimetre
- DEM Digital Elevation Model
- ELA Equilibrium Line Altitude
- GPR Ground Penetrating Radar
- GPS Global Positioning System
- Ha Hectare
- Ka Kilo-years (thousand years BP)
- Km Kilometres
- LGM Last Glacial Maximum
- LIDAR Light and Radar or Laser Illuminated Detection and Ranging
- LIST Land Information System Tasmania
- m Metres
- MAAT Mean annual air temperature
- MHz Megahertz
- OSL Optically Stimulated Luminescence dating technique
- PSA Pacific South America mode
- SAM Southern Annular Mode
- SED Surface Exposure Dating

# Chapter 1. Introduction

Mid-latitude periglacial landscapes are those in which frost shatter and ground ice processes induced by frequent freeze-thaw cycles play a significant role in landscape evolution (Augustinus 2002, Slaymaker 2009). Within a periglacial landscape the presence of seasonal and /or diurnal ground ice may produce a broad suite of landforms. These include but are not limited to rock glaciers, block streams, solifluction lobes and patterned ground formed by processes including frost induced soil creep, frost cracking and frost heaving (Karte 1983). This suite of landforms are therefore associated with cool to cold climatic conditions where mean annual precipitation values are too low for glaciers to form or where mean annual temperatures are too mild for the development of permafrost and glaciers but permit the development of seasonal ground ice (French 2013). In Australia, glaciation during the last glacial cycle was restricted to the higher regions of Tasmania (Colhoun *et al.* 2010) and the Main Range in the New South Wales Southern Alps, where glaciation may have only covered approximately 15 $km^2$ (Barrows *et al.* 2001). Relict periglacial landforms, particularly block deposits, have been recognised to have a far greater extent in the Australian Alps (Caine and Jennings 1968, Webster 1974, Barrows *et al.* 2004) and therefore their distribution and the comparative lack of glaciated terrain has been suggested to indicate cold dry conditions during the last glacial cycle (Galloway 1963). The greater extent of relict periglacial landforms in Australia in comparison to the minimal extent of glacial landforms (Barrows *et al.* 2002) highlights the comparative significance of periglacial landforms for paleoclimate reconstructions in eastern Australia. While the works of Webster (1974) and Caine (1983) document block deposits from the Victorian Alps and Northeast Tasmania respectively, until this project, no detailed documentation of the distribution and climatic significance of periglacial block deposits has been undertaken in Australia.

## 1.1. Main research questions

The lack of knowledge of the distribution, morphologic characteristics and climatic implications of periglacial landforms in Australia represents a significant gap in Australian paleoclimate reconstruction and geomorphology. Therefore this study has five main research goals.

1) To document and map the distribution of relict periglacial landforms in south-eastern Australia with the aim of defining the limits of a ‘periglacial’ zone of strong frost action.

2) To investigate the periglacial landforms in south-eastern Australia that are active under the prevailing modern climate

3) To aim for a better understanding of the temporal distribution of periglacial activity in south-eastern Australia.

4) To explore the climatic controls on the formation of periglacial landforms in Australia

5) To utilise the morphologic, temporal and distribution of periglacial deposits to constrain paleoclimate reconstructions.

This thesis contains two major sections. The first part of the thesis considers modern processes and environments in Australia to try to help define the modern limits of periglacial processes. Most of this work was undertaken in Tasmania (as detailed in Chapter 2) which has the majority of active periglacial landforms. The second part of the thesis (Chapters 3 to 8) concentrates on relict periglacial landforms, most notably block deposits and screes, at the northern (warm) limits of past periglacial activity. The focus is to determine the extent of frost action during past Glaciations and if feasible to determine the extent of cooling required for the expanded periglacial activity.

Before addressing these components of the thesis, it is necessary to define periglacial processes, in the context of this thesis (Chapter 1.2) and to review prior work of freeze-thaw processes and landforms in Tasmania. For convenience, reviews are divided into a Tasmanian (Chapter 3) and the SE Australian mainland (Chapter 4).

## 1.2. Introduction to landforms of periglacial origin

Within the study of geomorphology there is no clear definition of what landforms and environmental conditions define ‘periglacial’ environments. Some authors describe periglacial landscapes as only those that are a result of permafrost conditions or at least seasonal soil freezing (e.g. Brodzikowski and Van Loon 1987, Slaymaker 2009). Others have strict definitions of periglaciation defined by geographic locations such as that suggested by Warburton (1992) “A geographic zone immediately adjacent to existing or former glaciers / ice sheets”. However these definitions are far too specific to adequately describe all periglacial environments. In contrast, other definitions for periglacial environments focus on cold environmental conditions as being the major driver for periglacial processes, whereby permafrost does not have to be present for an environment to be periglacial. Soons and Price (1990) propose that periglacial environments are those that have “Severe environmental conditions in which frost processes are of major importance in developing landforms” but French (2000) more broadly defines such environments as “cold non-glacial conditions, that is, environments in which frost related processes dominate”.

Due to the relatively low altitudes and latitudes of the Australian mountains, permafrost is unlikely to have had a major role in landscape development during Quaternary cold periods. The only locations in Australia likely to have had potential for permafrost during glacial maximums would have been un-glaciated parts of the central plateau of Tasmania and the highest parts of the Main Range of the Australian Alps in the vicinity of Mt Kosciusko (Galloway 1965).

What Australian mountains do have is significant evidence of landforms developed in diurnal and seasonal freeze-thaw environments under cold climatic conditions. These environments fit in the definitions of ‘periglacial’ as proposed by Soons and Price (1990), French (2000), and Matsuoka (2001a); however frost processes can be active in relatively mild environments if significant cold air drainage effects are present on the local scale. McIntosh *et al.* (2012) argue that the term ‘periglacial’ is too narrow for describing active and relict ground ice and freeze-thaw associated landforms and processes, and they suggest the general title ‘Cold climate deposits’ or more precisely ‘extraglacial cold climate deposits’ is more suitable than ‘periglacial landforms’ for describing a broader range of landforms and processes in Australia.

Non-glacial cold climate landforms in Australia can be divided into six groups:

1) Block (boulder) deposits: rock glaciers, pronival ramparts, block fields, block streams

2) Patterned ground: Ice wedges, sorted polygons / stone circles, sorted stripes

3) Solifluction and gelifluction deposits: turf and boulder lobes, non-sorted steps

4) Angular rubble deposits: scree, stratified scree

5) Nivation landforms: nivation hollows and pronival ramparts

6) Tors

### 1.2.1. Block deposits

The term block deposit has been used by some authors (e.g. Boelhouwers 1999a, Barrows *et al.* 2004) to describe undifferentiated block streams, block slopes and other boulder deposits linked to ground ice conditions in periglacial environments. This term is used within this thesis as a collective description for the entire range of clast supported periglacial boulder deposits. While block deposits are generally considered to be indicators of past periglacial conditions, there has been significant literature (Van Steijn *et al.* 2002, Andrè 2003, Andrè *et al.* 2008) that have suggested that they are of polygenetic origin and may have developed at least in part under deep chemical weathering during Tertiary and interstadial warm periods of the Quaternary (Rea *et al.* 1997, Andrè *et al*. 2008). The widespread evidence for clay weathering products and rounded nature of boulders associated with some block deposits, do suggest that block deposits in part owe their formation to chemical weathering (Caine 1983, Rea *et al.* 1997). The principle driver of formation of block deposits has been debated particularly in the Falkland Islands (Andrè *et al.* 2008, Hansom *et al.* 2008, Wilson *et al.* 2008), however studies of the deposits in the Falklands and similar studies from Scandinavia which present evidence for chemical weathering still acknowledge the role Late Quaternary periglacial conditions have played on block deposit development (Rea *et al.* 1997, Whalley 1997, Van Steijn *et al.* 2002, Andrè *et al.* 2008, Goodfellow *et al.* 2009). Block deposits with obvious headwall sources are clearly products of mechanical weathering with chemical weathering playing a secondary role in formation. All of Australia's documented block deposits are located in cool temperate mountain environments and many are found below headwalls (see Jennings 1969, Webster 1974, Caine 1983, Barrows *et al*. 2004). They also exhibit evidence for past slow downslope movement and contain little or no core stones.

Therefore the location suggestive of strong climatic zonality (Harris1994) and morphology of the deposits suggest ground ice and freeze-thaw processes operating under past periglacial conditions are likely to have played the primary role in block deposit formation.

*Blockfields and block slopes*

Blockfields, boulder fields and block mantles are terms used to describe extensive angular to sub rounded (Alonso and Liaudat 2009) openwork boulder deposits containing no surface fine grained matrix found on mountain slopes; however their use in literature is inconsistent. In Australia, various authors have described extensive low angle boulder deposits found on or near mountain summits as block fields or block slopes (Webster 1974, Colhoun 2002, Barrows *et al.* 2004) and in some cases have alternated between block fields and block streams (Caine 1968a) with little or no distinction. Other authors both in Australia and Internationally (Hattëstrand and Stroeven 2002, Park Nelson *et al.* 2007) use the terms ‘blockfield’ or ‘boulder field’’ to describe all boulder slope deposits that occur on slopes of up to 35° ignoring the other boulder slope classifications of block slopes or block streams. The definition of these deposits is further clouded by the term ‘felsenmeer’ that is utilised heavily in the northern hemisphere to describe block deposits on low angle slopes (Anderson 2002, Marquette *et al.* 2004, Alonso and Liaudat 2009). Yet other terms such as ‘ploughed fields’ and ‘potato fields’ have been used in Tasmania (Jennings and Mabbutt 1967). It is clear that there is a need to develop a more rigorous nomenclature for openwork boulder deposits and for this study the term block slopes is preferred. Block slopes describe extensive areas of angular to sub rounded boulder deposits that mantle low to moderate angle mountain slopes. Block slopes are typically unconfined in that they mantle slopes regularly along contour and do not show distinct preferential boulder flow directions.

*Block streams*

These deposits, also known as boulder streams or stone runs (Wilson *et al.* 2008) form by the same process as block slopes, however they can be distinguished by their formation on a range of slopes from shallow valley floors with slope angles close to 0° to hill-slopes greater than >25°, with common valley floor confinement (Eaton *et al*. 2003) and downslope elongation of the deposits (Jennings 1969, White 1976, Boelhouwers *et al.* 2002). Many block streams display evidence of slow movement in the form of irregular topography, perched boulders, lobes and depressions in the surface of the deposits (Wilson 2013). They generally form in sheltered gullies where limited seasonal ground ice processes are most active in promoting boulder movement (Boelhouwers *et al.* 2002).

*Rock Glaciers*

Rock glaciers form where ice builds up beneath or within a debris deposit, the interstitial ice in the deposit moves downslope like a glacier transporting the surface boulders. Rock glaciers are common in marginal glacial zones (Clark *et al.* 1998) where debris cover insulates the ice core; this insulation effect effectively lowers the regional Equilibrium line altitude (ELA) (Clarke *et al.* 1994). There has been significant debate over whether rock glaciers are periglacial or glacial landforms (Berthling 2011). Presently active rock glaciers appear to show a continuum from ice cored glacial landforms; to ice supported periglacial landforms promoted by permafrost (Hamilton and Whalley 1995, Clark *et al.* 1998, Aoyama 2005). Clarke *et al.* (1994) has shown that rock glaciers may extend to altitudes several hundred meters lower than the regional ELA of clean glacial ice. Similar distribution patterns have been established for rock glaciers in marginal glacial settings; notably the Ben Ohau Range in New Zealand (Brazier *et al.* 1998, Augustinus 2002). Rock glaciers can be hard to distinguish from landforms such as pro-talus lobes (Hamilton and Whalley 1995) but they have some distinguishing characteristics including, lobate or tongue shaped landforms that have a length greater than their width that may include well developed longitudinal ridge and furrow topography and toes that form bulging convex shaped boulder piles (Clarke 1994, Aoyama 2005, Ikeda and Matsuoka 2006, Johnson *et al.* 2007, Alonso and Liaudat 2009).

### 1.2.2. Patterned ground landforms

These landforms occur where exposed ground surfaces consisting of a range of clasts sizes are affected by significant diurnal freeze-thaw cycles (Washburn 1979, Feuillet *et al.* 2012, Hallet 2013). Patterned ground can be either a) sorted whereby surface sediments are sorted into bimodal accumulations of sediment or b) non-sorted patterned ground where vegetation cover and or soil colour can be important indications of development (Krantz 1990). The most widely recognised process of patterned ground formation is by ground ice preferentially sorting clasts on and immediately below the ground surface into circular or striped patterns based on grainsize (Boelhouwers *et al.* 2003, Hallet 2013). This process is promoted by saturated soils susceptible to greater swelling upon freezing (Grab 1997). In comparison coarse material does not swell much during freezing due to its low moisture content. The outcome is differential frost heave and frost creep upon freezing (Vliet Lanoë 1991, Grab 1997). Surface needle ice helps to promote this process by growing under larger grains and effectively lifting up and displacing these clasts. Patterned ground may form in the majority of ground surfaces where soils are present but is generally best developed where there is a marked bimodal grainsize distribution of clasts within sediment with sparse vegetation cover (Viera *et al.* 2003, Kade and Walker 2008). Studies of extensive patterned ground processes on Macquarie Island and other Sub-Antarctic islands suggest that patterned ground is best developed on windward slopes in contrast to solifluction that formes on leeward slopes as a result the drying effect of strong winds decreasing soil moisture content on the windward slopes (Boelhouwers *et al.* 2003).

*Sorted stone circles, rings, polygons, nets*

These terms all refer to coarse material surrounding patches of finer grained material that commonly forms evenly spaced circular of polygonal structures on the ground surface (Ray *et al.* 1983). The variance in terminology for the same landform process is unnecessary and in the literature sorted stone polygons and circles (Feuillet *et al.* 2012, Hallet 2013) are the most widely used term for these features.

*Sorted stone stripes*

Ground surface sorting by preferential freezing and thawing of fine grained material promotes elongate stripes on slopes that are too steep for circular patterns to form (Kiernan 2008, Hallet 2013). Where vegetation is present on the slopes the variation of surface exposure and soil moisture content promoted by vegetation can facilitate a variant of stone stripes known as vegetation stripes.

*Needle ice raked ground*

Small parallel ridges of loose fine grained soil which look like they have been produced by a garden rake, form by needle ice development in the upper layers of the ground surface (Jennings 1983). Needle ice forms where elongate segregated ice crystals grow at the elevation of or beneath a surface soil layer in areas where saturated soils experience shallow diurnal freezing (Tufnell 1971, Lawler 1988, Lawler 1993). Individual ice crystals may lift up and displace soil grains that get preferentially sorted into ridges by differential thaw resulting from sun shade effects (Jennings 1983). While needle ice formation may be a microscale process, it can be a significant factor in erosion of fine grained loose material as evidenced by Lawler (1993) who documented significant stream bank erosion promoted by needle ice processes on the River Ilston in the United Kingdom.

### 1.2.3. Solifluction deposits

Solifluction processes can be described as slow moving mass movement of dominantly fine grained sediments induced by freeze-thaw processes (Bertran and Texier 1999, Matsuoka 1999, 2001a). They form as a result of frost heave of the surface sediments by ice lenses and needle ice (Lawler 1988, Viera *et al.* 2003) accompanied by the loss of soil strength as a result of high pore pressures during freeze-thaw events in wetter environments (Bertran and Texier 1999, Matsuoka 2001a). These two main driving processes vary according to the moisture content of the sediments and are commonly divided into dominantly frost heave (solifluction) in drier environments and dominantly pore water pressure processes (gelifluction) in wetter environments where there is seasonally frozen ground (Bertran and Texier 1999, Ridefelt and Boelhouwers 2006). Solifluction deposits generally move gradually and as a single mass with no strong plane of movement (Bertran and Texier 1999). In general, they produce massive poorly stratified diamicton, however their diagnostic characteristics include the preferred downslope orientation of the long axes of clasts (Boelhouwers 1999a) and deformation features including rollover overturning structures in the surface and subsurface (Hansen-Bristow and Price 1985, Bertran and Texier 1999). Solifluction processes are most active in wet environments where the soils are saturated (Ridefelt and Boelhouwers 2006, Butler *et al.* 2004) and there are strong diurnal and or seasonal freeze-thaw oscillations. High mountains in low latitudes are particularly susceptible environments to rapid solifluction (Matsuoka 2001a) which is particularly active during snow melt (Matsuoka 2001a, Oliva *et al.* 2009). Relict solifluction deposits may be useful in paleoclimate interpolations where landforms are found in low rainfall regions such as the solifluction lobes observed by Oliva *et al.* (2009) in the Spanish Sierra Nevada that suggest a relatively wetter climate in the past promoted solifluction activity. Solifluction deposits generally form lobate or steep sided terrace risers and ripples on low angle hill slopes. There are several forms of solifluction deposit that have been classified on their morphology and presence of vegetation (Matsuoka 2001a). Work by Ridefelt and Boelhouwers (2006) in Sweden has shown that different forms of solifluction will preferentially develop at different sites on a mountain slopes in relation to soil moisture content, elevation, slope gradient, vegetation cover, snow cover and lithological variation.

*Turf-banked terraces and lobes*

These landforms are a series of well-defined terraces that have a contour width much greater than their downslope length formed in dominantly fine grained material that are generally found at the change in gradient from steep slopes to flat valley floors (Oliva *et al*. 2009). Large clasts within the terraces are generally orientated with their long axes downslope in the direction of movement and vegetation cover is thickest at or near the terrace riser (Hansen-Bristow and Price 1985).

*Stone-banked terraces and lobes*

These landforms are a series of well-defined lobes or terraces that generally have a contour width much greater than their downslope length formed in course pebble to boulder material that are generally found demarking the break in slope from steep slopes to flat valley floors (Oliva *et al.* 2009). These deposits show a significant degree of sorting producing a coarse stone or boulder terrace riser grading to finer grained material in the tread (Holness 2003).

*Non-sorted stone banked terraces, lobes and crest-line steps*

These landforms have been described from locations in Australia (Costin *et al.* 1967, Kirkpatrick and Harwood 1980) and appear to be the same landform as turf banked lobes and terraces. These deposits are generally described from a botanic viewpoint as they are closely associated with alpine fjaeldmark vegetation (Kirkpatrick and Harwood 1980), they should not be deemed diagnostic of periglacial terrain and have not been further studied in this thesis.

### 1.2.4. Angular gravel deposits

This describes a range of forms associated with angular gravel to cobble sized deposits formed on mid-slope environments.

*Scree,* also known as talus deposits (Hales and Roering 2005, Scapozza *et al.* 2011*)* that form sheets or cones immediately below source bedrock outcrops (Hales and Roering 2005) are common landforms in a wide range of environments. They are most common in alpine environments as a result of the dislodgement of angular clasts generally by frost shatter processes from steep bedrock slopes and subsequent gravity induced downslope mass movement (Hales and Roering 2005). Scree deposits differ from boulder deposits in that they have a range of grain sizes dominated by angular gravels. Scree deposits produce cones or sheets (Åkerman 1984, Hales and Roering 2005) with marked rectilinear upper slopes near the angle of repose with some deposits displaying basal concavities (Caine 1969, Hinchliffe and Ballantyne 2009). They also differ to boulder deposits in that they are gravity driven and therefore are sorted with fine grained material found at the top of the deposit grading to courser material near the base (Kirkby and Statham 1975, Scapozza *et al.* 2011).

*Stratified scree,* also known as grèzes litées (Karte 1983, Clark and Ciolkosz 1988, Van Steijn 2011) or rhythmically bedded scree (Eaton *et al.* 2003) are formed by seasonal climatic oscillations influencing scree development (Scapozza *et al.* 2011) generally on concave hill slopes (Eaton *et al.* 2003). During winter frost shatter of the source rock promotes well sorted talus slopes with the coarse material moving the furthest and collecting down slope of finer material (Scapozza *et al.* 2011). During summer rainfall events or summer snowmelt the fine material on the upper slopes of the deposit is reactivated by moisture induced debris flows that bury the coarser material on the lower slopes (Van Steijn *et al.* 2002, Van Steijn 2011 and McIntosh *et al.* 2012). This activity promotes thick accumulations of stratified bedded screes with relict landforms suggested (Karte 1983, Eaton *et al.* 2003, Van Steijn 2011 and McIntosh *et al.* 2012) to indicate prevailing sparse vegetation cover of the hill slope during scree formation.

### 1.2.5. Tors

Tors are residual bedrock outcrops with strongly weathered joints that rise above the surrounding land surface (Hattëstrand and Stroeven 2002) and can vary in scale from less than a meter tall to masses of rock tens of meters tall (Linton 1955, Small *et al.* 1997). Tors are commonly located on mountain summits or ridge crests (Small *et al.* 1997, Eaton *et al.* 2003). Tors can form in most rock types, but observations during this study indicate tors are most conspicuous in granite and to a lesser extent quartzite terrain in Australia. Tors and tor like boulder deposits are widespread throughout the world and their formation and paleoclimatic significance has been debated since Linton (1955) linked tor development on Dartmoor with periglacial environments (Figure 1.1). Linton (1955) proposed two models of tor development. The first model suggested that tors developed from an erosion resistant rock outcrop that promotes tor formation as surficial erosion strips away the surrounding country rock. Linton's (1955) second model of tor formation requires deep chemical weathering of granite producing a saprolite surrounding remnant core stones. In cold climates the fine grained matrix can be removed by periglacial processes including solifluction. This promotes the exhumation of core stones that persist on the land surface that are then promoted by the subaerial weathering process outlined in the first model. Linton (1955) supported by Eden and Green (1971) suggested that both processes may have formed the tors of Dartmoor, UK. It is noteworthy that Linton (1955) was dealing with tors that were indisputably located within a periglacial setting that has recently been proposed to be a glacial environment (Evans *et al*. 2012) and much debate has centred on whether his process of tor development is valid for tor like outcrops formed in tropical or other clearly non-periglacial environments.

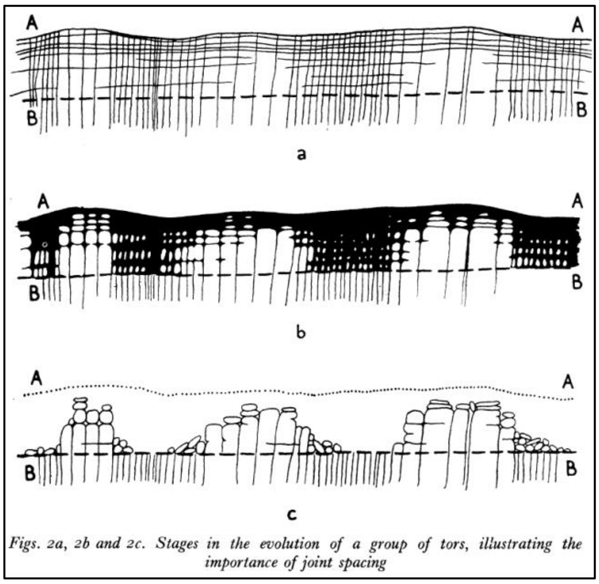



Figure 1.1) Granite weathering from Linton 1955.

Tors suggestive of periglacial development have been described in numerous areas worldwide including Central Otago in New Zealand (Wood 1969, Fahey 1986, Augustinus 2002), the Cairngorms in Scotland (Ballantyne 1994, Phillips *et al.* 2006) and the Wind River Range of Wyoming (Anderson 2002). The distribution of periglacial tors has been used to indicate non – glaciated areas of mountain ranges including the Cairngorms (Ballantyne 1994). In Australia the presence of tors on much of the granite terrain of the Australian Alps has been used to argue against widespread glaciation (Galloway 1963). Evidence that the presence of tors mitigates against glaciation has been challenged by work on tors in Scandinavia (Stroeven *et al.* 2002, André 2004) and Dartmoor (Evans *et al.* 2012). In these locations tors and other periglacial landforms have been shown to have survived under glacial ice where the ice was cold based and had little or no erosive power.

### 1.2.6. Nivation landforms

Nivation landforms form by erosion and deposition processes promoted by seasonal snow accumulation (Derbyshire and Peterson 1977, Hall and Meiklejohn 1997). While nivation processes are not necessarily related to 'periglacial' conditions, landforms such as pronival ramparts are derived from clasts formed by frost processes in adjacent bedrock.

*Nivation hollows,* Also known as snow patch hollows or nivation niches (Palacios *et al.* 2003, Margold *et al.* 2011) are generally broad depressions formed on sheltered mountain slopes that promote seasonal snow accumulation. Where the hollows have steep back walls they are sometimes called nivation cirques. In many cases snow accumulation and landform processes within nivation hollows are either the precursor to, or final stages of, cirque glacier development and represent climatic conditions that are not quite suitable for the formation of glaciers. The accumulation of deep snow pack in nivation hollows promotes the formation of pro talus ramparts (see below) and movement by periodic sliding of the snow pack can maintain steep back-walls, erode bedrock and move objects across the floor of nivation hollows and deep snow patches (Derbyshire and Peterson 1977, Jennings and Costin 1978, Jennings 1978).

*Pronival ramparts,* also described as protalus ramparts (Hedding *et al.* 2007, Margold *et al.* 2011) are ridges located on the outer edge of nivation hollows. They are generally composed of angular clast supported boulder deposit lacking fine matrix material, originated from a local source upslope (Derbyshire and Peterson 1977, Ballantyne and Kirkbride 1986, Matthews *et al.* 2011) and commonly display steep distal slopes (Matthews *et al.* 2011). Pronival ramparts form when a snow patch is present within a nivation hollow. Gravity induced rock fall and snow avalanche material (Matthews *et al.* 2011) from a source upslope of the nivation hollow rolls across the snow patch. The coarse sediment settles at the outer edge of the hollow building up an outer ridge. Finer grained material may remain in the nivation hollow where it may be reworked by snow push (Shakesby *et al.* 1999) and or other periglacial and fluvial processes. Pronival ramparts are formed by boulders dislodged from bedrock bluffs slide across ice or snow patches; nivation hollows bounded by pronival ramparts have a maximum size limit based on the slope angle and depth of the snow patch within the hollow (Hedding and Sumner 2013). If the hollow is too wide the angle of the snow patch may be too shallow for gravity driven movement of boulders across the snow surface. A model proposed by Ballantyne and Benn (1994) suggests that the maximum width of a snow patch within a nivation hollow can be no more than 70 meters for a the formation of pronival ramparts as snow accumulation within nivation hollows wider than 70 m will lead to the thickening of basal firn ice and the promotion of a small glacier. This theory was supported by an independent study by Hall and Meiklejohn (1997).

# Chapter 2. Contemporary periglacial landforms

## 2.1. Introduction

One of the problems arising from the documentation of relict landforms is that there is no obvious method of ascertaining the exact climate conditions which were operative at the time of the landform's formation. While no active block deposits have been categorically identified in Australia, other cold climate landforms including patterned ground and solifluction deposits representative of diurnal to seasonal freeze-thaw cycles have been reported from many Tasmanian mountains (Derbyshire 1973, Caine 1983, Kirkpatrick and Brown 1987), the higher regions of the Australian Alps and from one site near the summit of Point Lookout on the eastern edge of the New England Tableland where small scale patterned ground has been documented by Whittow (1968). While the landforms identified as being active freeze-thaw features, including patterned ground and small solifluction lobes and terraces, could be defined as 'periglacial' in nature, very few studies have focused on the mode of development and specific climatic conditions associated with these landforms.

This chapter focusses on active periglacial processes in Tasmania. The investigation was initially aimed at determining the (warm) climatic limit of periglacial activity but as will be noted, this proved to be infeasible. The chapter consists of two papers that examine 1) a large well developed sorted-stone terrace on the upper western slopes of Mt Rufus in Cradle Mountain National Park (1380 m, 42°7'30.576'S: 146°5'55.68'E) and 2) sites near Queenstown where the development of low altitude patterned ground forms appears to be associated with anthropogenic land disturbance. Both studies utilise field observations and temperature monitoring to investigate the development of these landforms. These studies indicate that in the western parts of Tasmania diurnal frost conditions can be efficient at facilitating the development of periglacial landforms where vegetation cover is weak or absent.

## 2.2. Active periglacial landforms of Australia

The erosion of bedrock and the transportation of sediments and soils by active periglacial and nivation processes have been largely ignored by geomorphologists in Australia as an significant landscape process under present climatic conditions. In contrast, a significant number of locations displaying active freeze-thaw and nival processes have been identified and described by ecologists studying alpine vegetation communities (Costin *et al.* 1967, Costin 1972, Kirkpatrick and Harwood 1980, Kirkpatrick 1984, Lynch and Kirkpatrick 1995 and Kirkpatrick *et al.* 2002). As a result of the lack of geomorphic investigations into active frost processes in Australia the influence of periglacial and mass movement processes on modern mountain slopes in south-eastern Australia is poorly understood.

A brief literature review of the limited knowledge of active solifluction, patterned ground and nivation processes in Australia is presented as part of this chapter and sites discussed are mapped in Figure 2.1. This is designed to set up the following two chapters which examine modern periglacial processes in Tasmania.

### 2.2.1. Solifluction

The largest active landforms of freezing and thawing origin appear to be stepped terraces and small solifluction lobes formed on thinly bedded mudstone and slate units in the highest regions of the Australian Alps above 1800 m and on exposed mountaintops above 1000 m in western Tasmania. Non-sorted stone terraces are present on the highest parts of the main range in the vicinity of Mts. Ramshead and Kosciuszko. On neighbouring Mt Twynam, Costin *et al.* (1967) and Costin (1972) described multiple small terraces that are readily identifiable on google earth imagery. Radiocarbon dating of material buried by the advancing terraces revealed late Holocene ages for the lower larger deposits indicating activity between 1500 and 3000 years BP. Dated wood fragments buried by solifluction lobes on the upper slopes of Mt Northcote revealed maximum ages of around 270 years BP (Costin 1972). This latter date suggests that small

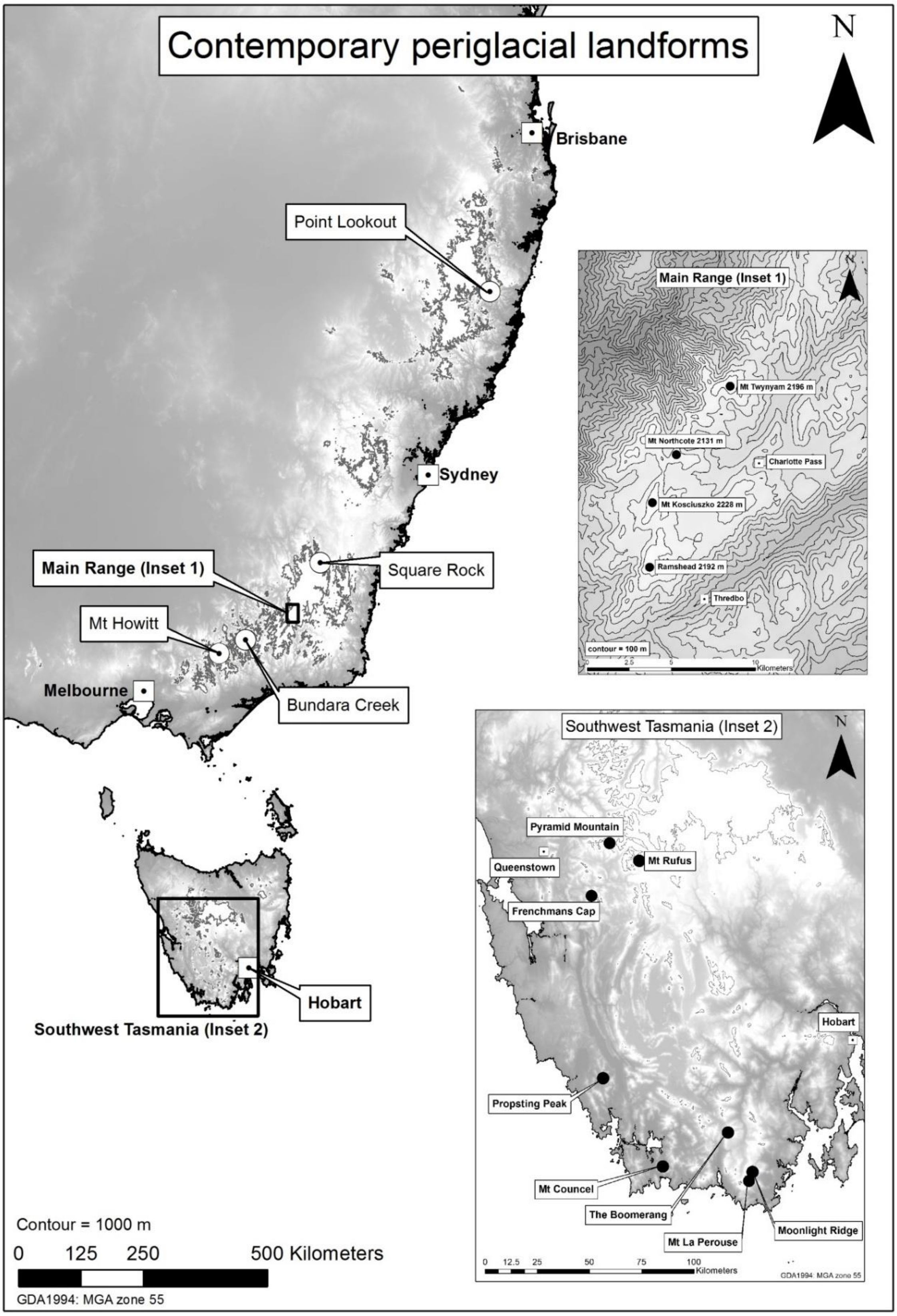



Figure 2.1) Location of sites discussed in Chapter 2.

scale solifluction is active on the highest Australian summits under climatic conditions present during recent historical times..

Active solifluction steps have been described by Kirkpatrick and Harwood (1980) forming on the flat summit plateau of The Boomerang in southwest Tasmania. Here the non-sorted steps are formed by angular mudstone clasts and evidence of minor vegetation burial and root disturbance indicate active downslope movement of the deposits. Similar non-sorted solifluction deposits have been identified on nearby Moonlight Ridge by (Lynch and Kirkpatrick 1995). At this location climate parameters where recorded over a year (1989) and in a subsequent paper (Kirkpatrick *et al.* 2002) recorded active movement of the terrace treads and risers over a 13 years period. Other locations where similar terraces have been documented include in the vicinity of Pyramid Mountain (Kirkpatrick 1984) and at a number of locations in southwest Tasmania including Mt Counsel and Propsting Peak (Kirkpatrick and Brown 1987). Sorted stone lobes with risers composed of dolerite pebbles and cobbles and finer grained treads have been documented on the western face of Mt Rufus by Kiernan (1985) who inferred that the lobes were active. This site is examined in Chapter 2 to determine whether the lobes are active and, if active, how movement occurs.

### 2.2.2. Patterned ground

Patterned ground consisting of sorted stripes, nets, polygons and stone circles have been recorded from a number of sites in Tasmania these are discussed in Chapter 3. On the Australian mainland Jennings (1981) noted patterned ground at Mt Twynam and Bundara Creek ~1300 m on the Bogong High Plains. Needle Ice up to 5 cm long forms on bare un-vegetated soil promoting granular soil creep. This granular heave and creep can produce thin patterned ground development that was noted by Jennings (1983) as being a common and widespread process over much of the south-eastern Australian highlands. Needle ice and thin ground ice promoted patterned ground was documented forming within fine sediments in a carpark near the summit of Point Lookout (1576 m, 30°29’20”S: 152°24’30”E) on the eastern escarpment of the New England Tablelands in northern NSW (Whittow 1968). Given the northerly latitude this may appear a surprisingly low elevation for active freeze-thaw processes at the present time but the area is subject to cold winter temperatures. During this thesis the author witnessed 3 cm long needle ice forming on a track in the Australian Capital Territory (Figure 2.2). This process was active at 2pm in the afternoon on a sunny day and indicates that needle ice can persist for at least several hours and potentially days after initial development. Observations of similar persistence of needle ice have been documented in the high Drakensburg by Grab (2002).

Figure 2.2) Needle ice up to 3 cm long heaving sand grains on the Square Rock Track (ACT), observed in June 2012.

### 2.2.3. Nivation

While strictly not a freeze-thaw process, nivation landforms are associated with slope processes supplying clasts to the snow patch. They also indicate environments where the snowpack can persist without the development of permafrost or glacial ice. In an Australian context these active landforms are obvious cold clime indicators and therefore warrant a brief discussion.

Active nivation hollows have been documented from several locations in south-eastern Australia. Studies of the Frenchmans Cap (Derbyshire and Peterson 1977) Mt Twynam, Mt Howitt and Mt La Perouse (Lewis 1925, Davidson 1971) nivation hollows all indicate that in the basal areas of the hollows, snow patch ice approaches the density of firn. This produces localised movement capable of transporting clasts (Lewis 1925, Davidson 1971). This movement of the basal 'firn' zone can produce fresh grooves on bedrock that have been interpreted as being 'striations' formed by active movement of the firn zone dragging larger clasts across the bedrock floor of the hollows. These were described by Jennings (1978) as “snow creep”. The best studied nivation features occur at the Mt Twynam snow patch described by Costin *et al.* (1973) Jennings and Costin (1978) and Jennings (1978). Observations over many years detailed nival processes transporting boulders across the base of the snow patch by snow creep. Lewis (1925) and Davidson (1971) observed striae in the Mt La Perouse nivation hollow and these are still visible (see Figure 2.3). At Frenchmans Cap, Derbyshire and Peterson (1977) describe the small but pronounced nivation hollow where they have recorded active nivation processes destroying rock cairns over one winter season. Derbyshire and Peterson suggest that without active rejuvenation and excavation of the bedrock basin by snow patch processes the steep rock back-wall would be rapidly broken down by frost shatter processes and the nivation hollow would be buried by the abundant debris that otherwise mantles the summit and upper slopes of Frenchmans Cap.

Figure 2.3) A 1.4 m long striations on polished bedrock, at the Mt La Perouse Nivation hollow (43°30’17”S: 146°44’41”E) one of a number observed on bedrock at this site in March 2014. These striations are formed by rocks being dragged across the bedrock by the winter snow pack, nival action.

## 2.3. Characteristics and development of a stone-banked lobe in a temperate maritime climate, Mt Rufus (42°S), Tasmania, Australia.

**This section forms the basis of the paper:**

**Slee, A.,** Kiernan, K., Shulmeister, J. and Jenkinson, A., Stone banked lobes as a product of mild freeze-thaw action: An example from western Tasmania, Australia. Accepted in *Geografiska Annaler: Series A, Physical Geography*, 22/12/2015.

### 2.3.1. Abstract

This paper describes and interprets a stone–banked lobe on the upper western face of Mt Rufus a 1417 m mountain in western Tasmania, Australia. The morphology of the lobe resembles that of a solifluction lobe. Visual observations show strong evidence for vertical and downslope movement of dolerite pebbles, cobbles and small boulders. Observations and temperature measurements for the 2013 winter season indicate that the movement appears to be associated with frost pull / heave and shallow freeze-thaw processes promoting the accumulation of coarse clasts at the lobe riser. The limited duration and depth of penetration of frozen ground at this site during the 2013 winter suggests that solifluction is the most significant geomorphic process at this site, despite the relatively mild climatic conditions, yet substantial vertical (10-15 cm) and downslope (up to 50 cm) movements were observed.

The possibility that the lobe is relict was considered, however, temperatures have been <1°C cooler on average at the coolest periods in the late Holocene. This scale of change would have a marginal effect on processes at this site. For the LGM mean annual temperatures may have cooled by up to ~4°C (Fletcher and Thomas 2010) but this would still be insufficient to promote sufficiently deep and persistent ground ice conditions suitable for solifluction processes to form the lobe. We also note that an adjacent lobe has buried organic material of a modern age. In summary, these features are cryogenic flows but with only shallow freeze-thaw processes operating in the upper 20-30 cm.

### 2.3.2. Introduction

Most work on freeze-thaw landforms and processes focuses on polar, sub-polar and continental environments where deep freeze processes including solifluction are dominant. In Australia, periglacial conditions linked to permafrost or deep seasonal ground ice are absent under the current climate and were likely to have been limited to altitudes above 1000-1200 m in Tasmania and the Australian Alps during the Last Glacial Maximum (Colhoun 2002, Barrows *et al.* 2004). Permafrost and even deep ground ice conditions appear to be absent from modern Australian environment, yet solifluction lobes and terraces on the mountains of Western Tasmania (Derbyshire 1973, Colhoun 2002, Kirkpatrick *et al.* 2002) and on the highest summits of the Australian Alps are implied to develop by episodic activity under modern climatic conditions based on field observations and radiocarbon dates of buried organic material (Costin *et al.* 1967, Caine 1968b, Costin 1972). Solifluction is the encompassing term for slow downslope mass movement by frost induced heaving and downslope creep (Harris 2007). Solifluction is associated with shallow seasonal ground ice conditions promoted by diurnal freeze-thaw operating usually in the top 30 cm of a regolith profile. In marginal periglacial settings this layer may be limited to the top 5-10 cm of the regolith (Matsuoka 2001a). Surface ice in the form of needle ice (pipkrakes) can also play a role in heaving and displacing surface grains and loosening the ground surface (Jennings 1983, Smith 1987). Solifluction is sometimes described as gelifluction, if the movement of the surface being soliflucted is promoted by the presence of saturated soils and associated high pore stresses in the upper surface layers of solifluction deposits during thaw events (Benedict 1976, Washburn 1979, Matsumoto and Ishikawa 2002, Ballantyne 2013). Solifluction deposits have a range of morphologic characteristics including lobate and terraced forms (Benedict 1970, Oliva *et al.* 2009) however the most diagnostic solifluction deposits are turf banked and stone banked solifluction lobes. These landforms feature a downslope oriented lobe of soil and rock material that shows signs of movement over pre-existing surfaces resulting in the burial of organic soils or vegetation (Kinnard and Lewkowicz 2006). Solifluction lobes can be divided into the tread zone that has an gradient usually significantly less than the hill slope on which it lies; and the riser zone that has a steep gradient at the at the front of the deposit (Hugenholtz and Lewkowicz 2002, Matsuoka *et al.* 2005). Turf banked lobes feature toe risers that are composed of dominantly fine grained soils and are generally vegetated. Stone banked solifluction lobes feature openwork pebble to boulder toe risers with a finer grained tread (Benedict 1970, Grab 2000). Clasts forming the risers of stone banked lobes commonly have strong downslope imbrication (Grab 2000, Holness 2003).

Solifluction landforms are currently located on summits in cool temperate climates with annual precipitation in excess of 2200 mm (Costin *et al.* 1967). While the turf-banked solifluction lobes in the vicinity of Mt Twynam (2196 m) in the Main Range of New South Wales have had their morphology and modern activity documented (Costin *et al.* 1967, Costin 1972). The solifluction lobes on Tasmanian mountains have received little study notable exceptions being studies by Kirkpatrick and Harwood (1980), Lynch and Kirkpatrick (1995) and Kirkpatrick *et al.* (2002) who primarily focused on small scale terraces associated with fjaeldmark vegetation. The stone-banked lobes on the upper western face of Mt Rufus (Kiernan 1985), are notable due to their relatively large size with lobe risers over 1 m tall and their occurrence on a very exposed westerly face in a maritime climate. In all respects they are morphologically similar to stone banked lobes described in the literature mostly from sub-Antarctic Islands (e.g. Holness 2003, Kiernan and McConnell 2008). These stone banked lobes occur under a variety of climate settings (e.g. Boelhouwers 1994) and this study aimed to determine the processes operating on the lobes. Are these fully cryogenic features or do they reflect a variety of geomorphic environments and processes? This paper focuses on a stone-banked lobe on the western side of Mt Rufus near the summit plateau.

### 2.3.3. Study site

Mt Rufus has a summit elevation of 1417 m and is located to the west of the Lake St Clair (Figure 2.4). The mountain is composed of sandstone, siltstone and mudstone sequences of the Permo-Triassic Parmeener Supergroup (Mineral Resources Tasmania 2014) to an altitude of approximately 1350-1400 m. These are overlain by a thin cap of Jurassic dolerite on the summit ridge. Evidence for Quaternary Glaciation including cirque basins, ice smoothed bedrock and moraine ridges are abundant on the northern, eastern and south eastern slopes of the mountain in the lee of the prevailing westerly winds (Figure 2.4). In contrast, the upper western slopes of the mountain appear to have not been impacted by late Quaternary Glaciation. To the east the Lake St Clair glacial trough hosted an extensive valley glacier during the last glaciation (Kiernan 1991, 1992) and there was also extensive glaciation in the Upper Franklin Valley to elevations of ~1000 m. As such, Mt Rufus and other high peaks formed nunataks during the last glaciation maximum.

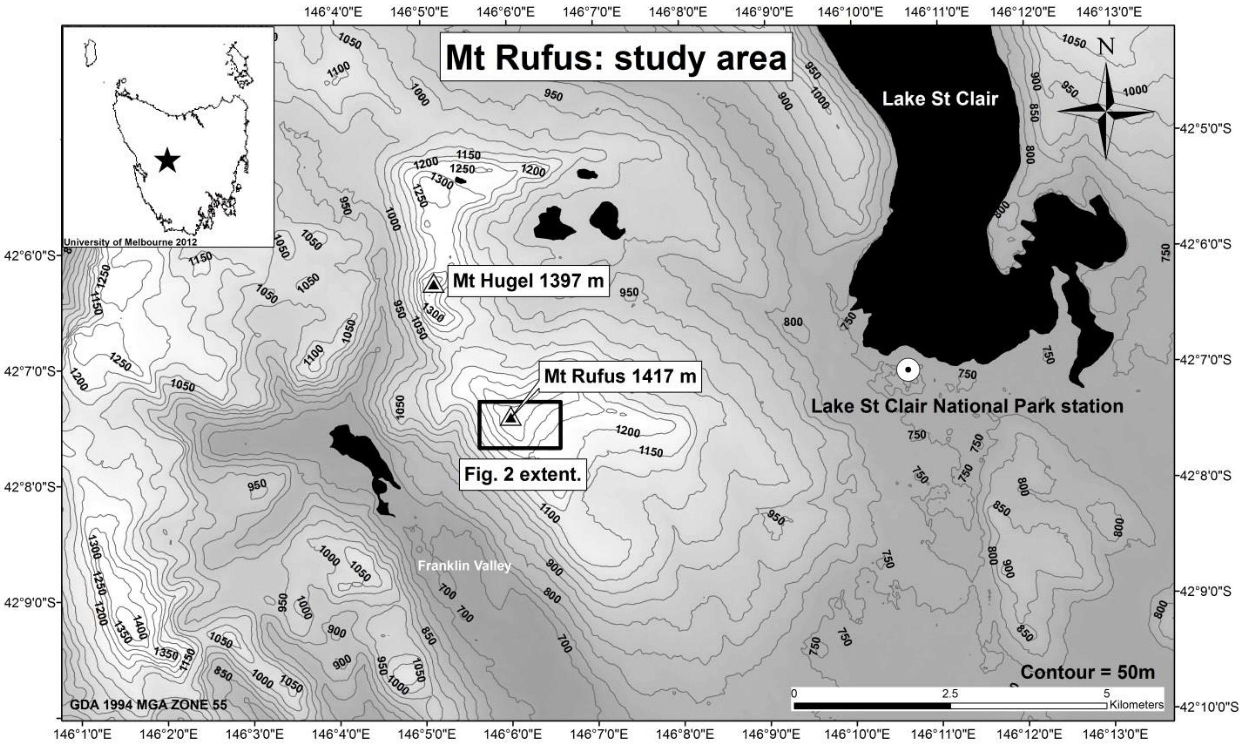



Figure 2.4) Map of Mt Rufus: showing the study site (1380 m) on the upper western slopes and the St Clair weather station (BOM 2014a) at the Lake St Clair parks office approximately 6.4 kilometres to the east and 638 m lower in elevation than the study site. Contours are 20 m.

In the vicinity of the Mt Rufus summit are a wide range of active and most likely, relict periglacial landforms. Of the active landforms associated with periglacial environments, small terracettes are documented on the eastern ridge of the mountain; rudimentary patterned ground is present on flatter areas of the summit and a series of larger scale stone-banked lobes up to 15 m long occur on the upper western slopes. Apparently inactive landforms include stone banked terraces at 1220 m to the south of the Mt Rufus summit (Derbyshire 1973), and block slopes on the upper slopes of Mt Rufus and nearby Mt Hugel (Derbyshire 1973). In addition, prominent sandstone tors are developed on the col between Mt Rufus and Mt Hugel and incipient rock glaciers have been identified on the flanks of nearby Mt Olympus (Derbyshire 1973, Colhoun 2002).

The focus of this study is on a well sorted stone-banked solifluction lobe (Figure 2.5) located on the upper western slope of Mt Rufus (-42°7’30.576’S: 146°5’55.68’E). The lobe lies on a 20° slope at an altitude of 1380 m. It is adjacent to or immediately below the contact between the summit dolerite cap (mapped as undifferentiated Quaternary Talus) and the underlying Triassic Sandstone (Mineral Resources Tasmania 2014) which is not visible at the site.

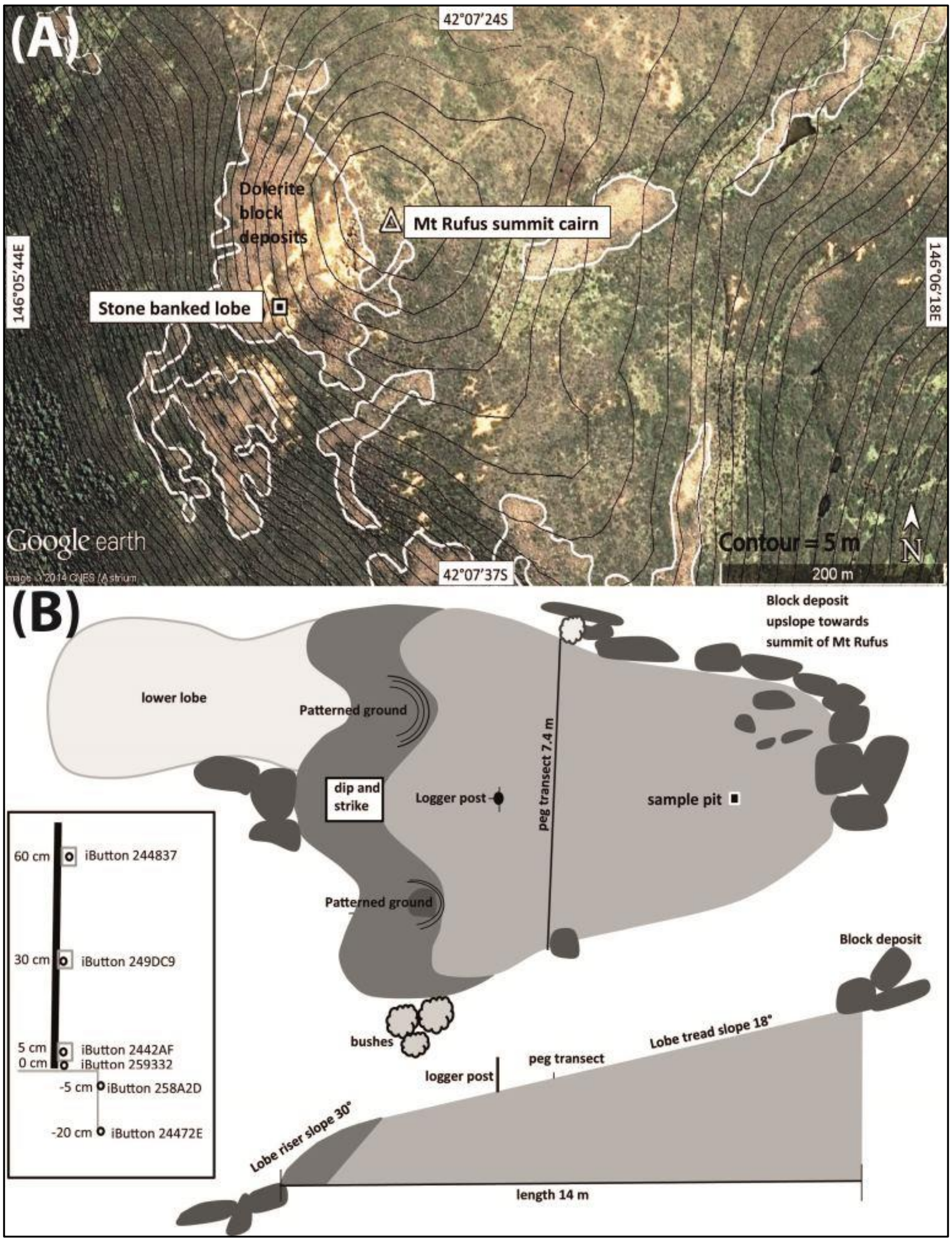



Figure 2.5) Mt Rufus lobe*:* (A) Location image of lobe on the western slopes of Mt Rufus, contour intervals are 5 m, the white polygons highlight areas of block slopes, (B) Plan map of the study site, and data logger assemblage. The inset shows the layout of the iButton logger assemblage attached to the logger post, the dark grey represents the terrace riser

composed of course clasts. The lighter grey represents the matrix dominated tread of the terrace.

### 2.3.4. Climate of Mt Rufus

Tasmanian climate is dominated by Southern Ocean westerlies. These westerlies operate all year round with a weak winter maximum. The strong westerly flow combined with the topography of the island results in a strong west-east precipitation divide with maxima in excess of 3000 mm in the west and as low as 400 mm in the east (Nunez *et al.* 1996). This overall pattern is modified by at least three major oscillatory systems, the Southern Annular Mode (SAM), the Pacific South America mode (PSA) and the El Nino Southern Oscillation. Of these, the SAM has the most significant impact on inter-annual climate and especially rainfall (e.g. Meneghini *et al.* 2007) in varying the overall westerly pattern, with positive SAM phases associated with reduced westerly flow over Tasmania resulting in diminished rainfall in the south-west of the island that includes Mt Rufus.

There is no climate station on Mt Rufus but the overall climate is temperate cool wet (maritime) (Cfc) (Peel *et al.* 2007) with frequent westerly cold fronts that can bring snow even in summer. Precipitation is estimated at between 2000 – 2400 mm annually (SoE, 2009) with a considerable amount of the precipitation falling as snow. There is no documentation of annual snow days and the length of snow cover. However, regular snowfalls can be expected for the winter months and heavy snowfall can occur at any time of the year as evidenced by the heavy snowfall observed during the site visit on the 10$^{th}$ December 2013. The nearest climate station is at the Lake St Clair National Park headquarters where mean annual temperatures are 13.1°C, mean minimum temperatures are 2.8°C, mean precipitation is 1868.3 mm, the mean number of rainfall days ≥1mm is 180.2 and the number of frost days with minima ≤0°C is 95 (BOM 2014a).

### 2.3.5. Fieldwork and methods

*Baseline work by Kiernan (1985)*

Initial work on the Mount Rufus summit was undertaken as part of a PhD study by Kiernan (1985). While his focus was not on the periglacial landforms he marked three lines across the upper, middle and lower toe and riser of a presumed solifluction lobe on the western flank of Mt Rufus to determine whether the lobe was actively moving downslope under the prevailing (modern) conditions. An inspection after 2 years revealed movement of stones on the feature. There was, however, no indication as to whether the entire lobe was moving or simply the clasts on the surface. Some wood buried by a stone-banked lobe was extracted (in 2011) from further south along the upper western slopes of Mt Rufus and dated using radiocarbon dating to determine a maximum age for the latest phase of activity on the lobes. The age indicated that the feature was active.

*Fieldwork and methods from 2013 campaign*

An overview map of the Mt Rufus – southern Lake St Clair area was created using Arc GIS and field observations coupled with Google Earth and aerial photograph interpretations (Figure 2.4). Sketch maps and descriptions of the lobe were produced in the field utilising compass, tape measurements and visual observations. These maps were later redrawn and digitised (Figure 2.5). The lobe was also photographed in both April and December. The dip and strike of 50 clasts and A-axis lengths on the lobe riser were recorded and plotted using Stereo net and a rose diagram of the dip direction of clasts was constructed (Allmendinger *et al.* 2013, Cardozo and Allmendinger 2013).

Soil and surface temperature records were collected to determine the amount and minimum depth of soil freezing and the impact of changing climatological conditions on the behaviour of the lobe during the spring and winter of 2013. Thermochron (iButton) miniature temperature loggers are widely used for the study of soil temperatures (Johnson *et al.* 2005, Gehrig-Fasel *et al.* 2008) and have been used in previous studies of freeze-thaw processes (Kade *et al.* 2006; Lewkowicz 2008; Vespremeanu-Stroe *et al.* 2012). Six iButton thermochrons (Maxim model DS1922) were established in the centre of the lobe, approximately 5.3 m from the downslope riser. Three iButton loggers were attached to a wooden stake at heights of 5 cm, 30 cm and 60 cm and were oriented to the South; plastic pots were attached to the stakes to provide shading and protection. The stake was inserted 30 cm into the ground and guy ropes were tied to boulders to stabilise it. Logger 4 was established on the ground surface (depth 0 cm) while loggers 5 and 6 were buried at a depth of 5 cm and 20 cm respectively, below the ground surface. All loggers where attached to plastic fobs that enabled them to be strung on wire for retrieval (see Figure 2.5). The ibuttons were covered in thin sandwich bags to improve water resistance. The iButton loggers were set up to record temperatures on an hourly rate, which permitted a single deployment for the whole winter season. The loggers have an accuracy of +/- 0.5°C. A line of 8 steel tent pegs pushed into the ground 16 cm and spaced at 1 m intervals perpendicular to the slope were established across the deposit approximately 1 m upslope of the logger assemblage. Clasts at the top of the lobe riser were painted to record movement.

### 2.3.6. Results

The lobe is orientated to 201° (SSW). It has a tread slope of 18° and is 14 m long and 9 m wide at its widest point. The frontal riser has a slope of 30° and is 1.2 m tall. The riser is composed entirely of sub-angular dolerite cobbles with typical A-axis lengths of 9 cm to 18 cm with an average long axis strike of 245°SW (Figure 2.6) and 12° dip. The largest clast has an A-axis of 54 cm. The gravels of the lobe surface are well sorted with the clast supported riser contrasting with the finer tread that is composed of a yellow – brown (10YR4/6) silty clays (62%) with ancillary components of fine pebbles 10.6% and occasional cobbles to boulders (up to 0.54 m) in a silt to silt to clay matrix (27.4%) These larger boulders appear to have been transported across the tread slope from their source boulder blockfield that constrains the top of the lobe.

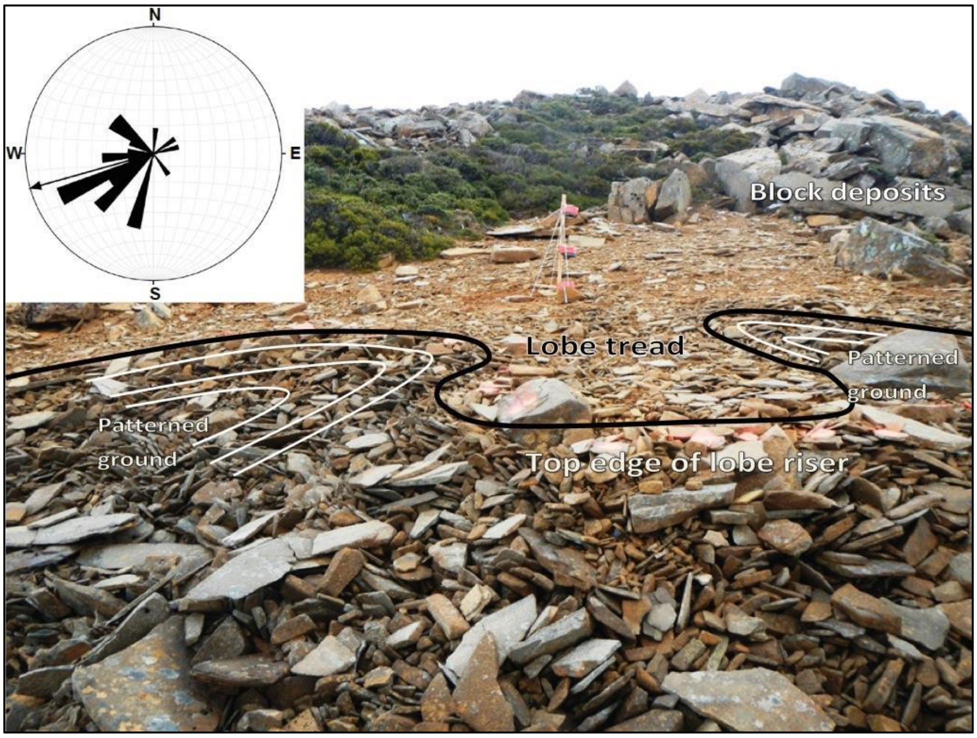



Figure 2.6) View upslope from the base of the lobe riser towards the data loggers, note the well sorted nature of the course clasts in the riser and the strongly developed patterned ground. Rose diagram displays the strike of angular clasts taken from the front of the riser to the WSW (n = 25).

*Temperature data*

The iButton temperature loggers where collected from the site on the 9th December 2013. Full datasets were collected from all 6 loggers, the number of frost cycles, oscillations above and below 0°C and -2°C where calculated with mean temperatures for the recording period with an average air temperature of 2.78°C. These observations are summarised in Table 2.2 and indicate the reduction of diurnal temperature oscillations within the ground temperature data in favour of long periods of temperatures around 0°C (see Figure 2.11) and a marginally colder mean temperature in the upper soil horizon (-5 cm).

Table 2.1) Frost cycles and mean temperature, Mt Rufus.

| **Logger** | **Frost cycles (number over period)** | **Frost cycles below -2°C** | **Mean temperature over period of record** |
|---|---|---|---|
| 244837: Air 60 cm | 77 | 31 | 2.56°C |
| 249DC9: Air 30 cm | 84 | 33 | 3.03°C |
| 2442AF: Air 5 cm | 85 | 30 | 2.75°C |
| 259332: Surface | 84 | 25 | 2.86°C |
| 258A2D: Ground -5 cm | 48 | 1 | 2.54°C |
| 24472E: Ground -20 cm | 2 | 0 | 2.81°C |

The hourly temperatures from the loggers (Figure 2.7) are compared against the daily precipitation record for the nearest Bureau of Meteorology station (Lake St Clair BOM 2014a, Figure 2.8) were compared. This showed that there was only one extended period of ground freezing recorded during the 2013 winter, in early June, where temperatures over the period of a week dropped to -3.5°C at 5 cm below the surface (logger 5) and dipped below zero at 20 cm below the surface for a period of 10 days (logger 6). This climate condition is visible from the diurnal oscillations above and below freezing recorded from the surface temperature loggers. The cooler temperatures were linked to a precipitation free period and associated high pressure system over Tasmania. It is noteworthy that the strongest diurnal temperature oscillations occurred in November (see Figure 2.7) rather than the height of winter. This reflects the dominance of westerly fronts during winter that promote warmer moisture laden air masses and snow ground cover, both of which act to reduce daily diurnal oscillation and minimum temperatures.

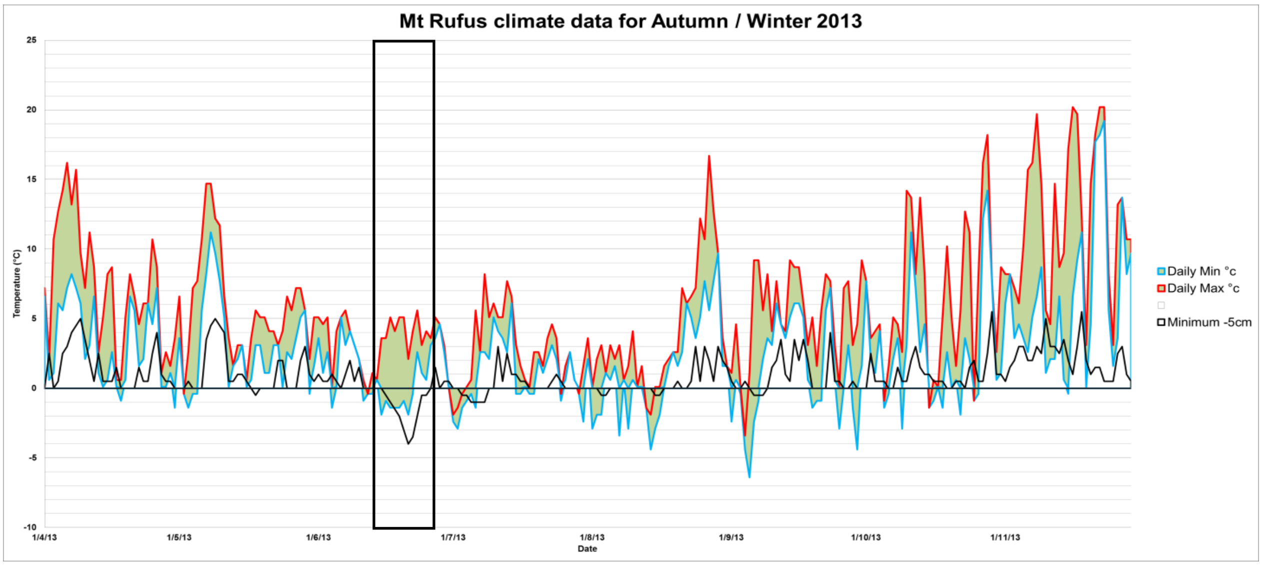



Figure 2.7) Temperature data recorded at the Mt Rufus study site for the period April 1st to December 9th 2013. The green shaded area indicates daily diurnal oscillation of air temperature at 60 cm. The section of graph highlighted by the box represents the only time during the temperature record when the ground was significantly below freezing and ice penetrated to depths of at least 20 cm in the fine matrix (see Figure 2.11).

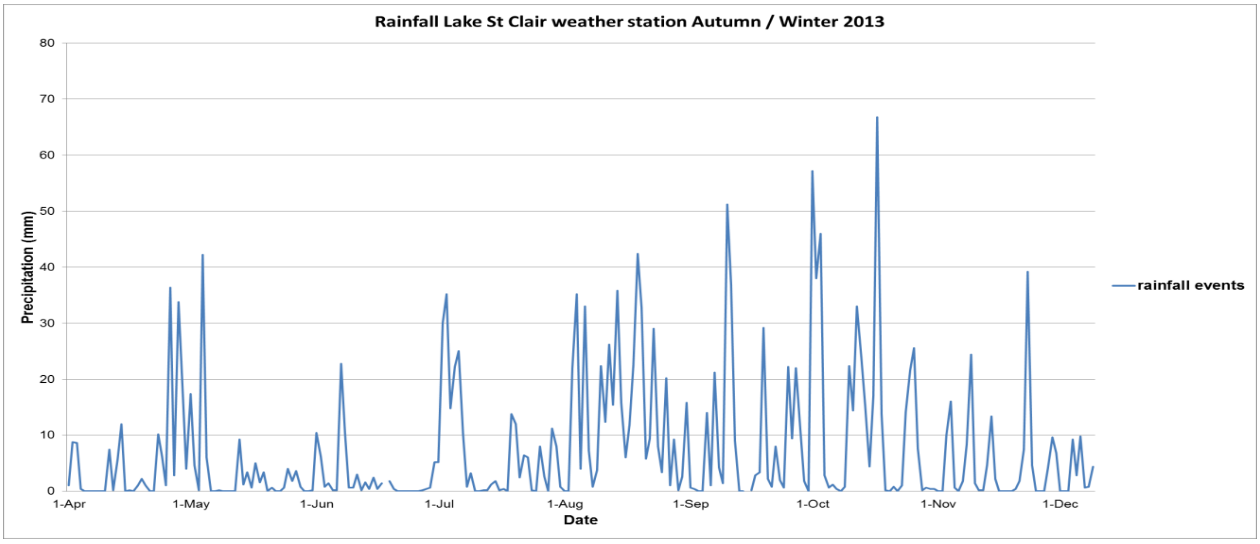



Figure. 2.8) Rainfall records at Lake St Clair weather station for the period April 1$^{st}$ to 9$^{th}$ December 2013 (source BOM 2014a).

Three other weather patterns have impacts on sub-surface temperatures.

1) Late summer warm dry periods likely to be associated with northerly weather patterns advecting warm air from the Australian Mainland. No ground ice can form under these conditions.

2) Comparatively warm wet early winter periods of precipitation bring mild absolute temperatures and resultant warm (above zero) ground conditions.

3) Winter cold fronts that promote heavy precipitation events in the form of snow. These are indicated in the temperature records by ground temperatures stabilising at around 0°C. These temperatures indicate the relatively warm moisture bearing westerlies do not promote strong frost penetration and the insulating effect of surface snows exaggerates this effect. A comparatively warm absolute minimum air temperature of -6.5°C at 60 cm above the ground during the winter confirms the relatively maritime nature of the site. This contrast with the Central Plateau to the east of Lake St Clair, where temperatures below -10°C are relatively common during winter (BOM 2014a).

*Field observations*

Field observations and photos from 30th March 2013 and 9th December 2013, where compared. Visual evidence of footprints associated with disturbance of the lobe tread during the initial installation of the logger assemblage had disappeared by December (Figure 2.9). The stake holding the temperature loggers was found tilted at an angle of 30° into the wind indicative of 20-30 cm of downslope movement at the surface of the deposit.

This was confirmed by the movement of up to 30 cm of all three boulders tied to the guy ropes attached to the stake. Five of the eight pegs in the transect upslope of the logger assemblage had been thrust out of the ground and were lying on top of the deposit. In two instances angular platy clasts up to 40 cm A-axis had moved on top of the pegs, the other three pegs showed signs of vertical movement (Figure 2.9). The measured displacement of the pegs was up to ~40 cm in a downslope (westerly) direction. There was a significant recruitment of pebble sized clasts to the surface of the deposit and no evidence of the trampling observed on the site after the initial site visit, particularly within the area of the black circle in Figure 2.9(D). Observations of the painted clasts on the top edge of the lobe riser were not as conclusive because approximately half the stones could not be relocated.

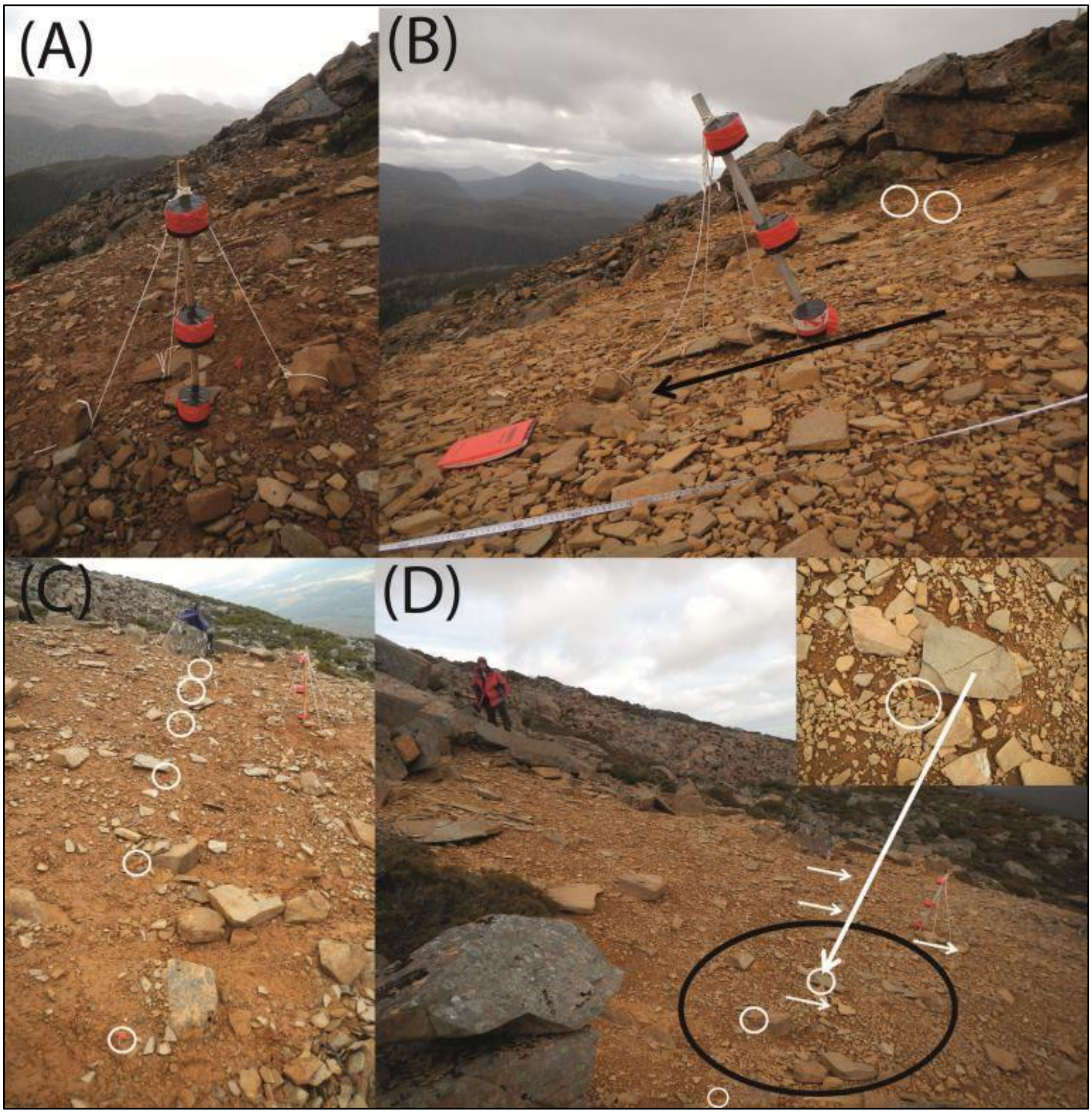



Figure 2.9) Stone movement Mt Rufus: Before and after photos pegs are circled arrows indicate the direction of surface displacement. (A) Data loggers attached to pole on 30th March 2013. (B) Post assemblage on 9th December 2013, (C) View south across the deposit of the transect of tent pegs (white circles) and logger post 30th March 2013. (D) View across the transect 9th December 2013, some pegs where located under boulders that had visibly moved downslope (inset).

While this clearly shows that they have moved from the upper edge of the riser these observations gives only a limited indication of the magnitude of the horizontal displacement of the missing clasts on the riser as the remaining stones showed little displacement. The blockfield above the lobe is composed of large dolerite boulders (up to 4 m A-axis) and extends upslope to the summit of Mt Rufus. Numerous angular dolerite clasts provide evidence for active spallation of the boulders in the blockfield (Figure 2.10). These clasts visibly accumulate at the top of the lobe where it abuts dolerite boulders.

Figure 2.10) Dolerite boulder deposits located upslope of the terrace: note the angular and vertical nature of many of the smaller boulders and signs of modern spallation in the form of angular cobbles at the spade head and an area of corresponding unweathered boulder surface to the left of the spade handle (outlined).

*Dates*

The buried wood sampled from the base of a similar lobe to the south yielded modern radiocarbon ages (Table 2.1). Though these ages come from a different lobe on the slope, the lobes are morphologically similar and this suggests that all these lobes are active.

Table 2.2) Radiocarbon results

Table 1

| ANSTO code | Sample Type | Submitter ID | $\delta(^{13}C)$ per mil | Percent Modern Carbon pMC 1σ error | Conventional Radiocarbon age yrs BP 1σ error |
|---|---|---|---|---|---|
| OZM745 | Wood | KK-MR-01 | -27.1 +/- 0.1 | 112.11 +/- 0.50 | Modern |
| OZM746 | Wood | KK-MR-02 | -25.5 +/- 0.1 | 109.33 +/- 0.38 | Modern |

### 2.3.7. Discussion

The lack of extended periods of ground ice development at the site indicates the marginal nature of periglacial processes at this site whereby mass movement induced by solifluction processes is probably absent or else limited to intermittent activity under rare cold dry conditions in winter. Morphologically the lobe has strong similarities with the lobe described by Holness (2003) on Marion Island in the southern Indian Ocean. Marion Island has a humid sub-Antarctic climate where temperatures rarely drop significantly below freezing. Though both temperature lows and highs are more extreme on Mt Rufus, both sites share cool maritime climates with generally weak freezing conditions and processes are likely to be similar. During the winter of 2013 the extent of penetration of freezing was very limited in terms of both absolute depth of penetration and duration. Nevertheless, very substantial movements were observed on the lobe tread. These processes can be divided into vertical movement and down slope movement. The observation of the rejuvenation of the tread surface, as marked by the appearance of angular pebbles on the surface, the movement of surface clasts and the displacement of the pegs all indicate that freeze-thaw processes in the top 20-30 cm are promoting the sorting of the deposit by differential frost heave processes. The thermal conductivity characteristics of a soil mass has been shown (Anderson 1988, Reid and Nesje 1988, Matsuoka and Ijiri 2003) to promote the vertical sorting and lateral movement of coarse conductive clasts though the less thermally conductive matrix (Harris and Mathews 1984). This is in part due to ice lenses descending from the surface to above thermally conductive clasts within a fine grained matrix which remains largely unfrozen (Anderson 1988). The expansion of the ice lens lifts the clasts upwards compared to the surrounding unfrozen soils promoting a space beneath the clast, which may be subsequently filled by the lateral movement of fine grained sediment thus dragging coarse clasts up the soil profile (Harris and Matthews 1984, Anderson 1988, Matsuoka and Ijiri 2003). Angular dolerite clasts are being generated in the blockfield at the top of the lobe at the present day and this is the major source of coarse clasts within the deposit. The dolerite clasts are dark coloured and dense which makes them more thermally conductive than the surrounding clay and silt matrix. This frost pull process likely accounts for the heaving of the thermally conductive steel pegs out of the ground and the lack of vertical motion of the thermally less conductive wooden fence post that was used to secure the logger assemblage. In addition to frost pull, needle ice formation can also heave clasts upward, though this process is probably confined to smaller clasts in the top few centimetres of the soil.

Coarse clasts on the tread of the lobe have been displaced downslope at variable rates with observations ranging from 10 cm to 40 cm during the 2013 winter/spring season. Clast movement on the tread was most rapid towards the centre and less rapid on the margin of the tread. This variation in movement of clasts indicates the likely presence of a saturated zone towards the centre of the deposit (Benedict 1976). The rapid movement of clasts on the tread contrasts with the apparent minimal movement of the riser. Similar contrasts in the rates of movement have been observed from stone banked lobes in the Andes by Francou and Bertran (1997) and the Antarctic Peninsula (Mori *et al.* 2006). The low or absent movement of the stone risers in these studies was associated with the washing out of the fine component from the deposit (Francou and Bertran 1997). This is obviously not feasible in Antarctica where the coarse material reaches the riser without fines in train (Mori *et al*. 2006). Observations in this study support both hypotheses with the rapid movement of coarse clasts on the tread being a result of frost heave and needle ice promoting movement of the coarse material over the fine material of the tread (Benedict 1976). In contrast, the openwork clast supported riser acts as an accumulation zone for coarse material due to the greatly reduced downslope movement, probably associated with ice promoted clast topple. While surface frost heave may be playing a role in the transport of clasts downslope the observations of a general 30-40 cm downslope movement over much of the deposit and the strong lean on the logger post, indicates movement on the entire surface of the deposit. No evidence of surface channelization, indicative of fluvial processes, was found on the deposit.

While the surface loggers where set up in an effort to document the volume of snow at the site, the lack of strong contrasts in the data between loggers 1, 2 and 3 indicates that while snow was likely to have fallen regularly on the site, it does not appear to have persisted for any length of time. There is no suggestion that deep snow occurred, whereby the top (+60 cm) logger would have been buried. Had this occurred, the temperature data would have shown a strong suppression of diurnal oscillations as the loggers would have been insulated by the snow. Therefore it appears unlikely that snowbanks of any longevity were present at this site. Gale force westerly winds are common on this mountain top. They support the likelihood of wind deflation of snow on the exposed western face of the hill. This inference of persistent snow drifting is supported by the strong asymmetry of glacial landforms on Mt Rufus that demonstrate long lived snow patches and glaciers on the leeward eastern slopes of the range under glacial climates and none on the western faces.

Despite the absence of persistent snow cover in the winter of 2013, deep freezing is not persistent, which implies that ambient air temperatures are not particularly cold. In fact the air temperatures recorded from the study site over the 2013 winter indicate very mild conditions with minima that rarely drop below -1°C. As already noted, there was only one period of 10 days in the winter of 2013 when conditions were favourable for ground ice formation. During this period (June 14th-24th) a blocking high moved across and then centred over Tasmania (Figure 2.11) promoting dry cold nights with sub-zero temperatures. Figure 2.10 shows the temperatures of the +60 cm, -5 cm and -20 cm temperature loggers for this period and clearly indicates the thermal lag and attenuation of freezing experienced at -20 cm. At least 7 nights of sub-zero temperatures were required for ground ice to penetrate to a depth of >20 cm. This contrasts with the relatively fast thermal changes experienced within the upper 5 cm of the soil. This shows the need for extended periods of dry sub-zero conditions for the development of significant ground ice on Mt Rufus.

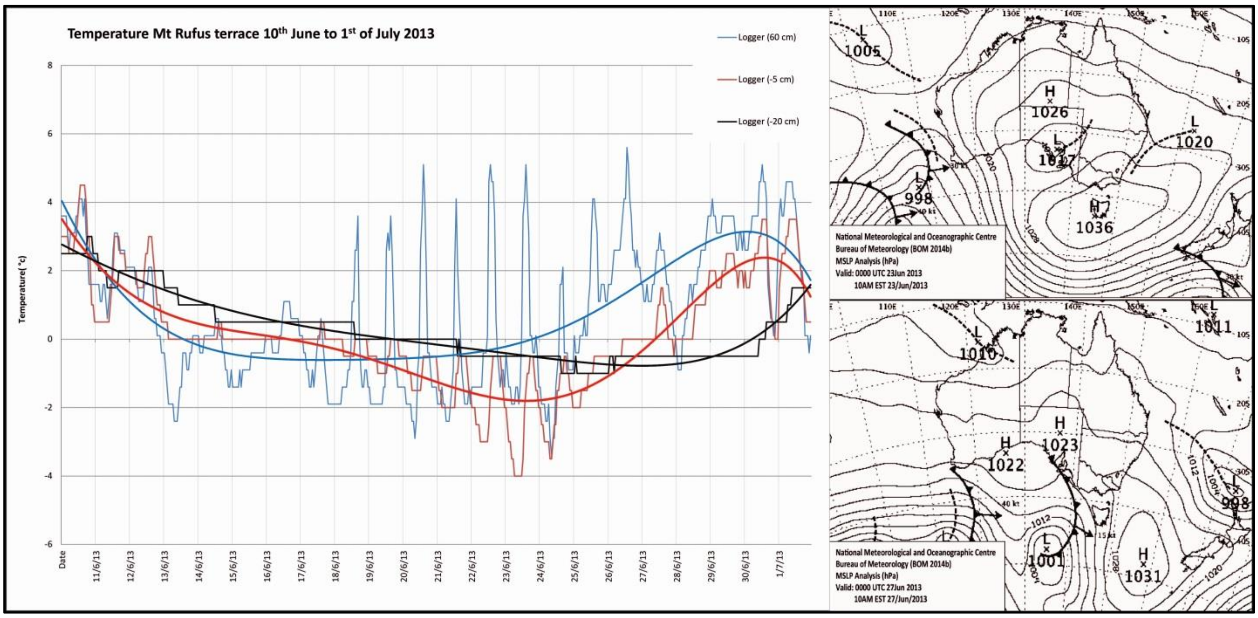



Figure 2.11) Temperature record for the period 10th June to 1st July 2013: the blue lines represent the air temperature at the lobe taken from the 60 cm logger, the red line represents the ground temperature at -5 cm and the black line is the ground temperature at -20 cm, all trend curves are 6th order polynominal. The two weather maps (BOM 2014b) show the location of the high pressure cell during the coldest day (23rd June) and immediately prior to the passing of a westerly front on the 27th June that is marked by a significant rise in the air and -5cm temperature loggers. Note that the temperatures at -20

cm are disconnected from daily temperature variations and the soil at -20 cm takes a significantly longer time to adjust to the prevailing thermal conditions than at -5 cm.

A salient observation from the climate data for the winter of 2013 is that westerly weather systems are not conducive to ground ice formation. Westerly fronts are associated with precipitation and heavy cloud cover. Most fronts coincide with temperatures above freezing. Even when westerlies were associated with colder temperatures and significant snowfall events, local conditions do not favour deep freezing. For the rare events where snow settled for extended periods, the subsurface and +5 cm level temperature loggers are isothermal at zero degrees which show the local effects of snow insulation.

The question remains as to whether the 2013 winter was representative of the climate of the Mt Rufus summit over a longer time period. There are two components to this question. Firstly, what is the inter-annual variability in climate and secondly is there a longer-term trend in the climate data?

As noted earlier, the most significant control on inter-annual climate variability is the SAM. The SAM is a climate oscillation between accelerated westerly flow at higher latitudes when the polar high intensifies (+ve phase) and a broader but weaker westerly flow when the polar high weakens (-ve phase). Because Tasmania is on the northern limits of westerly flow, the negative phase results in enhanced westerlies in Tasmania, while during the positive phase, the main westerly flow passes to the south. This means that during positive SAM years, there should be less westerly flow at Mt Rufus, especially in winter and this might be expected to result in more still air conditions that favour deep frosts. Positive SAM phases occurred in 1993, 1997/98, 2004 and 2008/2009. The PSA mode is also reflected in changes in westerly precipitation and also shows a bias to affecting western regions of Tasmania (Hill *et al.* 2009). The PSA is most effective in reducing rainfall during years with anomalously high pressure over Tasmania. The last of these and only statistically valid representative in the period from 1990 to 2005 occurred in 1999. Hence these two sets of years might be predicted to be the optimal years for freeze-thaw processes on Mt Rufus.

The closest climate station to Mt Rufus is the Lake St Clair National Park Office located 6.5 kilometres east of the summit of Mt Rufus at an altitude of 742 m asl (BOM 2014a). This station has records for the period from 1990-2013. It was assessed for the number of days below freezing and the presence / absence of un-interrupted cold periods of below 0°C minimums for at least 7 days; that allow ground ice formation to depths of more than

20 cm. Figure 2.12 shows annual minimum temperature data for the period 1990 – 2013 excluding the years 1997 and 1998 when the St Clair weather station was only partially operative. The 2013 winter received 75 days below 0°C which is somewhat below the average of 95 days for the recording period. In contrast 141 days of below zero minimum temperatures was recorded in 1995. For Lake St Clair the coldest winters in the record are 1995, 2006 and 2007, with 2007 particularly notable because mean lows remained below zero for the whole of June and July. Regrettably the Lake St Clair record is incomplete for the years 1997/1998 which were the peak +ve SAM years in the record but it is apparent that there is no simple relationship between inter-annual climate variability as reflected through modern oscillatory climate systems and the occurrence of favourable freezing weather at Lake St Clair.

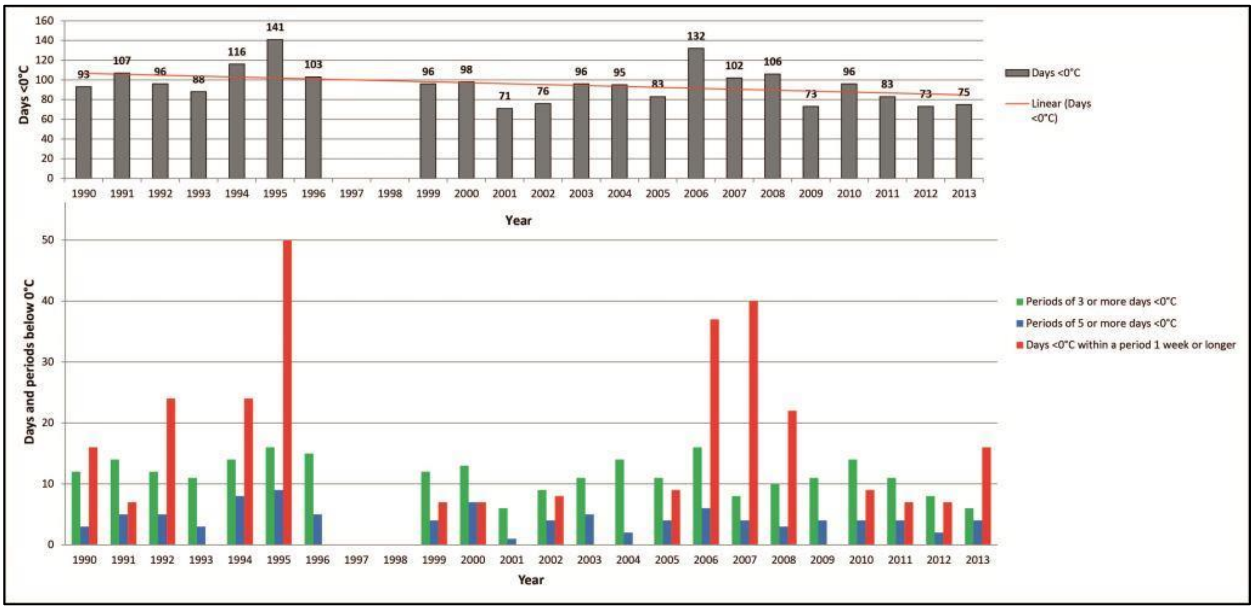



Figure 2.12) Temperature records Lake St Clair: (TOP) The number of minimums recorded with temperatures lower than 0°C at the Lake St Clair National Park centre Bureau of Meteorology weather station (BOM 2014a) for the period from 1990 to 2013 excluding the years of 1997 and 1998 due to data quality; 1995 saw a peak in cold minimums of 141. (bottom) Number of periods of sustained minimums below 0°C graphed as 3 day's (blue), 5 day periods (red) and periods of a week or longer (green). The purple columns indicate the number of minimums below 0°C during a year (x-axis) that lie within periods of sustained cold minimum temperatures. The years of 1995, 2006 and 2007 all experienced sustained periods of cold minimum temperatures. The 2013 winter saw two periods of sustained temperature minimums below 0°C, however, overall the number of minimums below 0°C was below the average of 95 for the recording period.

What is also apparent is that more intense freeze-thaw processes are only likely in two or three years during the last twenty.  This suggests that while the lobe could be promoted by intermittent solifluction during rare sustained cold winters; it does not account for the activity witnessed on the lobe during the 2013 season and therefore solifluction is likely to be associated with typical winters and is not a process associated only with extreme winters.

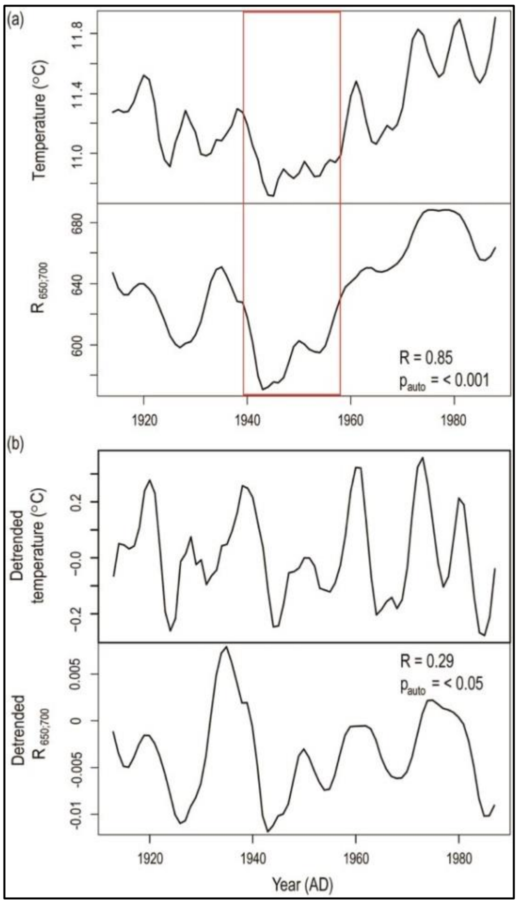



Figure 2.13) Revision of Saunders *et al.* (2013) 20th century temperature data from Duckhole Lake southern Tasmania, the box highlights the middle 20th century temperature depression of ~0.8°C below modern prevailing temperatures. The 0.8°C temperature depression while likely to have caused more freeze-thaw processes was unlikely to have promoted significantly enhanced solifluction.

Another possibility is that recent warming has reduced the impact of freeze-thaw processes on the lobe. Here there is evidence of warming over recent decades and there is the possibility of significantly cooler temperatures during the ‘Little Ice Age’. A recent record from southern Tasmania (Saunders *et al.* 2013) indicates that the coolest climate conditions in the last 800 years occurred in the first half of the 20th century with minima’s achieved in the 1940s (Figure 2.13). Since then mean temperatures have increased by over 0.8°C. A cool period also occurred in the 18th century but this was not as low as the early 20th century minimum. Though 0.8°C is a notable reduction in temperature, it is unlikely to significantly increase the impact of freeze-thaw processes at the site. What is apparent is that even though climate conditions appear marginal for solifluction, there is enough periglacial action to maintain a 20 cm thick layer susceptible to ground ice processes. These observations are similar to those observed in much stronger freeze-thaw environments such as the Bolivian Andes (Francou and Bertran 1997) and the Antarctic Peninsula (Mori *et al*. 2006) but also comparable to other marginal sites including Marion Island (Holness 2003) and the Drakensberg (Boelhouwers 1994, Grab 2000).

### 2.3.8. Summary

Well sorted stone-banked lobes are present on the upper slopes of Mt Rufus and are among the largest active periglacial landforms in Australia. These active landforms are most likely related to intermittent ground ice conditions, but winter ground ice is limited to only the top c. 20 cm of the deposits and the lobes appear to reflect surface reworking by freeze-thaw action and down slope movement of large clasts. Key processes involve the physical weathering of dolerite clasts, frost heave due to ice segregation and frost heave due to needle ice formation. The burial of woody organics at the base of the lobes demonstrates the gradual downslope movement of the riser under grain-by-grain toppling processes.

The modern temperature data indicate that the top of Mt Rufus appears marginal for periglacial action but nevertheless the landforms are as well developed as those produced under more severe climatic conditions such as the Peruvian Andes and Antarctica. It is evident that this form of solifluction operates effectively at temperatures close to 0°C and with relatively small diurnal variations. As evidenced by active solifluction under similar climatic conditions to Mt Rufus on maritime subantarctic islands such as Marion Island (Holness 2003) and Macquarie Island (Colhoun and Goede 1974).

# 2.4. Contemporary sorted patterned ground in low altitude areas of Tasmania.


### 2.4.1. Abstract

This paper summarises the distribution of patterned ground phenomena in Tasmania. It presents observations of low altitude sorted stone circles forming on glacial and alluvial deposits in the vicinity of Queenstown, Western Tasmania. Evidence suggests that freeze-thaw derived patterned ground could develop in most inland valleys in Tasmania where cold air drainage causes sub-zero ground temperatures in winter and permits the formation of ground ice to low elevations. Field observations suggest that patterned ground can only develop where freeze-thaw processes are not inhibited by vegetation. The occurrence of patterned ground below altitudes of 900 m asl in Tasmania is largely a result of anthropogenic disturbance promoting favourable ground conditions for the development of patterned ground.


### 2.4.2. Introduction

The purpose of this paper is to describe active freeze-thaw processes that are operating at low altitudes in Tasmania and to determine their level of activity and geomorphic significance. Active freeze-thaw processes at higher elevations (mostly >1000 m asl) have been described (Caine 1983, Derbyshire 1973, Colhoun 2002) but the extension of these processes to lower elevations, is little known and has not been described in the scientific literature. The study focuses on sorted ground phenomena which can form with relatively shallow freezing, rather than solifluction and other non-sorted phenomena which are well described from more alpine areas (Kirkpatrick and Harwood 1980, Kirkpatrick 1984, Lynch and Kirkpatrick 1995).

### 2.4.3. Processes and development of patterned ground

Patterned ground is a common phenomenon in periglacial environments in polar, sub-polar and high mountain regions (Washburn 1956, Noguchi *et al.* 1987, Boelhouwers *et al.* 2003, Feuillet *et al.* 2012) and has been commonly associated with freeze-thaw processes in permafrost regions (Haugland 2006) recently deglaciated areas (Haugland 2004, 2006) and continental mountain environments (Butler and Malanson 1999).

Patterned ground is also widely observed in cool to cold temperate oceanic climates such as Iceland (Feuillet *et al.* 2012).

Patterned ground can occur as number of forms including sorted stripes, stone polygons, and stone circles with the morphologic variation of the deposits attributable to the angle of the slope on which the deposits have formed and the nature of the substrate (Kessler and Werner 2003, Hallet 2013). Patterned ground is generally considered to form as a result of freeze-thaw cycles in shallow layers of a deposit and the segregation of the deposit into zones of coarse and fine material (Grab 2002, Hallet 2013). The patterns form by a number of processes. These include the frost pull of coarse material (clasts) to the surface of a deposit and subsequent expansion of saturated fine material by up-freezing and vertical heaving of the ground as a result of thermal expansion of ice lenses (Peterson *et al.* 2003, Matsuoka and Ijiri 2003). Coarse clasts are pushed out by the doming of the fines to create the stripes, polygons or circles (Peterson and Krantz 2003, Boelhouwers *et al.* 2003, Kessler and Werner 2003, Li *et al*. 2013). Differential melting and settlement based on density differences can enhance the process (e.g. Gleason *et al.* 1986). The scale of the sorted ground features have been shown to relate to the size of the coarsest size fraction available (Washburn 1956, Noguchi *et al.*1987).

In very shallow settings the formation of needle ice, promoted by low intensity frost cycles, can further promote sorting by mechanically moving fine grained sediment (Meentemeyer and Zippin 1981) and is a process that loosens the surface sediments and promotes water infiltration and deeper ground ice penetration (Jennings 1983, Noguchi *et al.* 1987). Patterned ground can form over time periods of centuries (e.g. Mann 2003), whereas Hallet (2013) on Spitzbergen suggests that it may form over a couple of decades, while in ideal conditions patterns can develop very rapidly, potentially on an annual basis (Grab 1997). Patterned ground including stone circles known as gilgai can form in arid environments where clay expansion and contraction is promoted by seasonal wetting and drying events (Paton 1974, Dixon 2009). However the landforms discussed in this paper are located in areas that are not drought prone and the main sites presented in this paper occur on quartzite and conglomerate derived glacial moraine and alluvial terrace deposits that lack a significant clay component.

### 2.4.4. Patterned ground in Tasmania

To date there has been limited documentation of patterned ground in Tasmania (Figure 2.14). Sorted stone circles have been documented from the Ben Lomond Plateau at elevations above 1350 m asl by Caine (1983). Here the patterned ground has formed in dolerite rubble. Derbyshire (1973) reports similar forms on Mt Wellington. Small sorted stone circles forming on flat slopes on both the western and north eastern slopes of Mt Rufus (42°07'64S: 146°06'10E, 1364 m asl) located during the present study supports the previous observations of Derbyshire (1963) from this site. Sorted stone nets formed in dolerite debris have been documented at Lake Nameless (~1200 m asl) on the Central Plateau (Colhoun 2002). Patterned ground forming on Mt Campbell near Cradle Mountain in the form of nets of coarse angular quartzite clasts was first reported by Derbyshire (1973). Derbyshire (1973) also reported patterned ground forming in sediment derived from conglomerate at 1005 m asl on the Murchison/ Forth River interfluve south of Cradle Mountain.

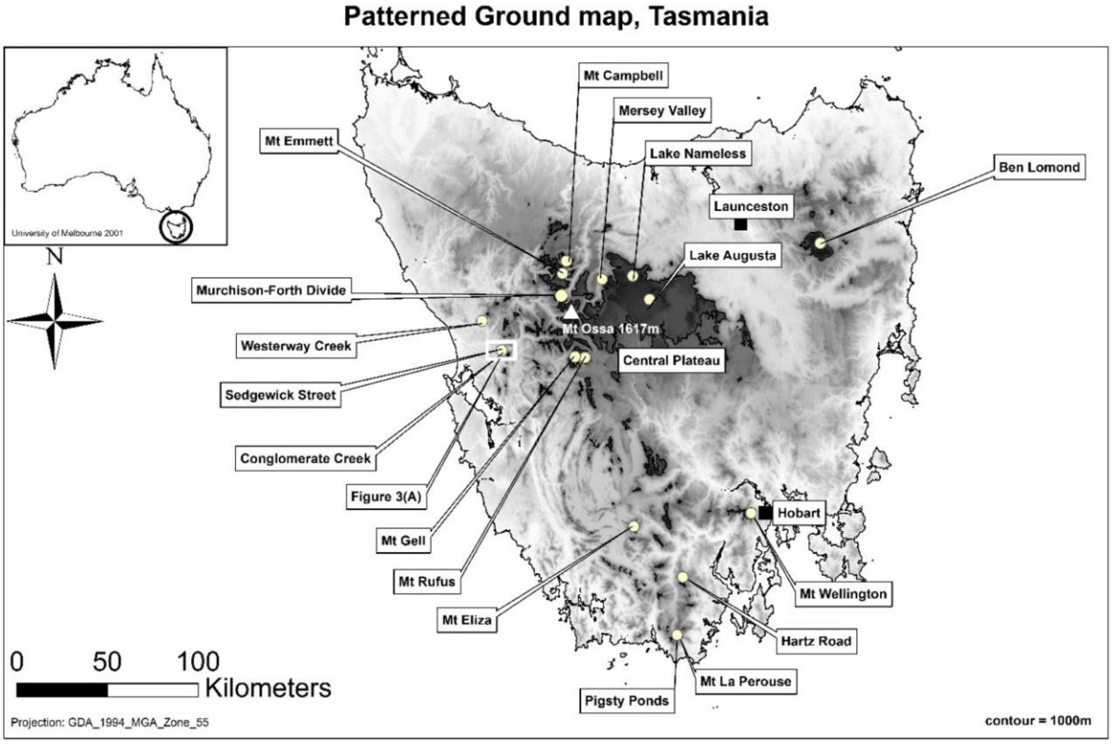



Figure 2.14) Map of locations of patterned ground in Tasmania

In addition to these published observations, patterned ground was located during this thesis on the summit plateau of Mt La Perouse (1147 m asl) in the Southern Ranges (43°30'19S: 146°44'54E) where small sorted stone nets have formed in angular mudstone rubble (Figure 2.15). These nets take the form of raised outer ridges composed of angular clasts that show signs of vertical rotation and frost heave. At the nearby Pigsty Ponds (43°29'42S: 146°43'65E, 830 m asl) sorted stone circles of up to 50 cm diameter have formed in ephemeral lake beds, these stone circles could be associated with groundwater temperature driven free convection processes rather than shallow frost induced ground ice processes as detailed by Krantz (1990).

**Contemporary patterned ground on cleared sites in highland Tasmania**

Sorted stone polygons and circles have been observed forming at the Lake Augusta Reservoir at 1150 m asl (Household 2009); a natural lake that was raised and enlarged by Hydro Tasmania in 1953 (Storey and Comfort 2007). In addition, second author, Kiernan observed patterned ground forming under power lines at lower elevations down to 900 m asl on the Central Plateau. Colhoun (2002) described stone circles forming in a quarry in the Mersey Valley at an altitude of 600 m asl. Patterned ground has also been observed by Kiernan forming on a road cutting on the Hartz Mountains road in southern Tasmania at an altitude of about 900 m asl. In summary, there is widespread evidence for patterned ground in highland Tasmania and where bare surfaces are available freeze-thaw action is likely to be still operative at the present day. This chapter presents evidence for contemporary patterned ground development at altitudes as low as c. 200 m asl.


Figure 2.15) Natural patterned ground in the sub-alpine Southern Ranges near Mt La Perouse 800 - 1150 m asl.

**2.4.5. Study sites**

*Conglomerate Creek Moraines*

The main study site (42°04'90S: 145°34'91E) is located on a moraine complex located at an altitude of 300 m asl in the upper Conglomerate Creek Valley approximately 2.5 kilometres upstream of the confluence of Conglomerate Creek and the Queen River (Figure 2.16A). Conglomerate Creek has its headwaters on the western slopes of Mt

Owen (1147 m asl) a mountain that forms part of the West Coast Range. The moraines form a complex ridge approximately 1.5 kilometres long that divides Conglomerate Creek from its major southern tributary (Kiernan 1980). The upper slopes of Mt Owen are dominantly composed of Ordovician Owen Conglomerate with minor outcrops of Cambrian Mt Read Volcanics and associated sedimentary rocks (Mineral Resources Tasmania 2010). The subdued moraines may date to the early Henty (penultimate) Glaciation (Kiernan 1980, Colhoun 1985) and contrast with the sharply defined cirques and moraines of last glacial origin on the eastern slopes of Mt Owen that extend down to elevations of 360 m asl (Colhoun 1985). The moraines rise approximately 10-20 m from the valley floor and are composed of large conglomerate boulders with a coarse sand and pebble matrix. The crest of the moraine is capped by a finer, generally sand to pebble surface layer with occasional deeply weathered larger boulders. Patterned ground was observed throughout the lower 600 m of the moraine on surfaces slopes of 4-6° and little or no vegetation cover. The patterned ground takes the form of roughly circular stone circles up to 50 cm in diameter (Figure 2.16B). The stone circles show strong size sorting with the inner circles composed largely of clasts less than 2 cm in diameter with a minor component (5-20%) of clasts of up to 4 cm; while the outer circles are composed of 90% pebbles/cobbles of 3-8 cm A-axis and 10% of large cobles up to 20 cm A-axis length. The sediment within the circles is also noticeably more angular that that of the coarser outer sediment (Figure 2.16C).

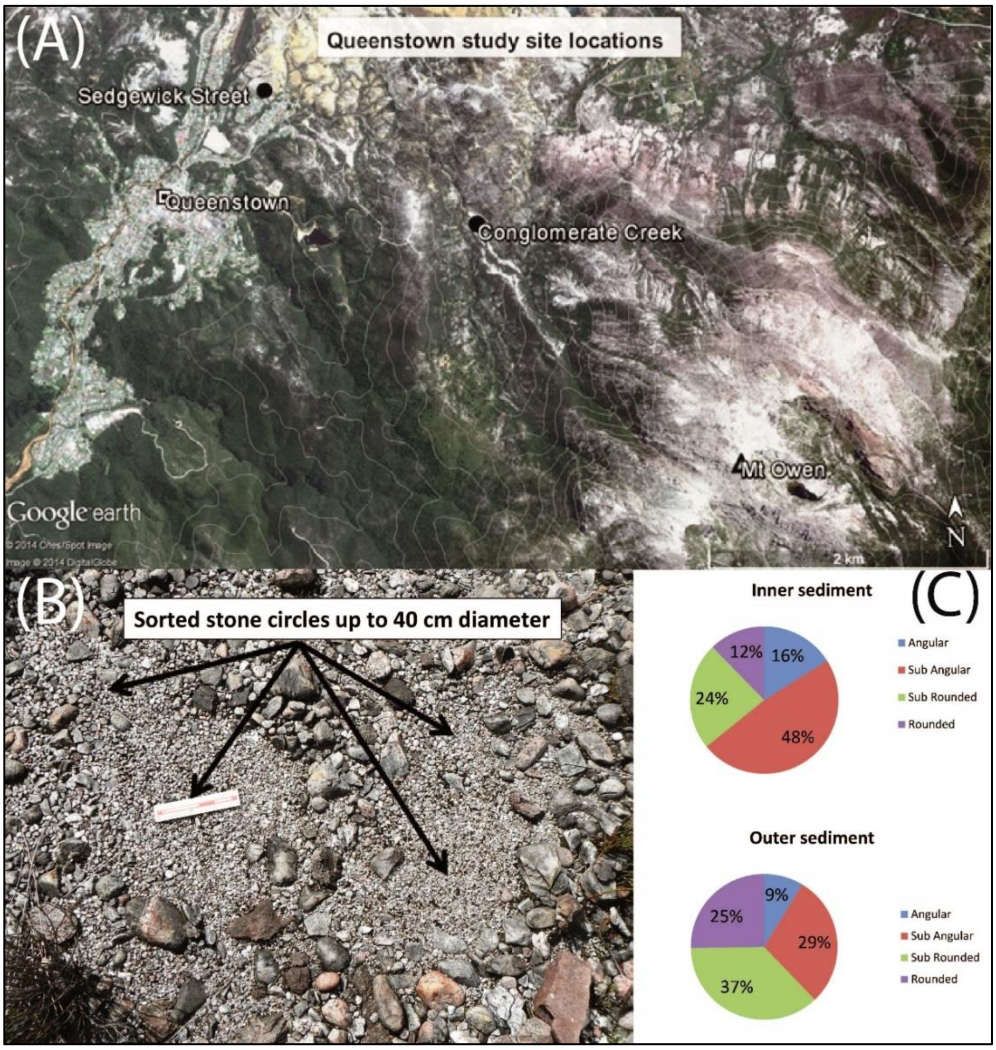



Figure 2.16) Study sites near Queenstown and patterned ground description Conglomerate Creek (n = 50).

*Site 2: Queenstown Sedgewick Street*

Small stone circles have formed on undifferentiated Quaternary glacial deposits (Mineral Resources Tasmania 2010) that form the upper hill slope to the north of Sedgwick Street in Queenstown (42°04'34S: 145°33'82E, Figure 2.17A). The site is located at an elevation of 204 m asl and the small polygons that measure up to 50 cm diameter (generally 20-30 cm) are scattered over the hilltop where benches of flat terrain enables patterned ground formation. There is ongoing disturbance around this site and this means that there is a limited area and time for sorted stone circles to form at this location.

*Site 3: Westerway Creek*

Several large stone circles up to 80 cm in diameter where observed at a road clearing on the southern approach to the Westerway Creek bridge on the Lyell Highway (41°55'84S:

145°26’22E). The stone circles lie at an altitude of 194 m asl and have formed on the top of alluvial deposits derived from Cambrian sedimentary Wurawina supergroup (Mineral Resources Tasmania 2010) associated with the nearby Westerway Creek (Figure 2.17B) that have been cleared of vegetation and exposed as a result of road and bridge works at this site.

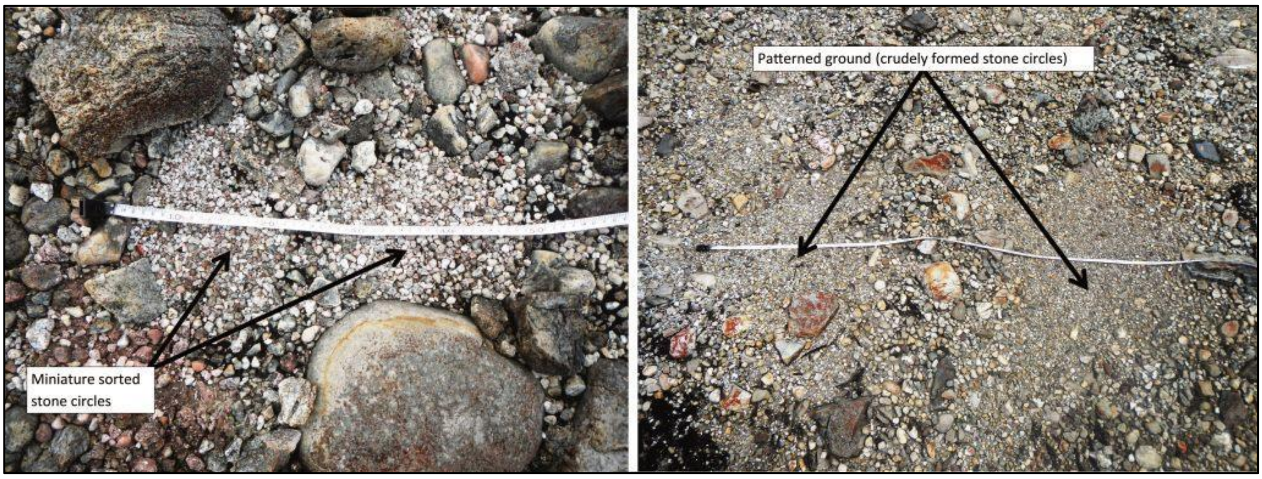



Figure 2.17) Photographs of patterned ground forms Sedgewick Street (L) and Westerway Creek (R).

### 2.4.6. Methods

Two sets of Maxim ibutton temperature loggers model 1922G were attached to small wooden stakes; these temperature loggers have an accuracy of ± 0.5°C and have been extensively used in remote field environments (Gubler *et al*. 2011, Vespremeanu-Stoe *et al.* 2012). One logger was attached at a height of 5 cm above the ground surface to measure surface air temperature and these were protected from the elements by hoods made of plastic pots. The second logger of each pair was attached to the stake by wire and buried adjacent to the stake to a depth of 5 cm. All loggers where attached to ibutton fobs for ease of identification and where protected by two layers of thin sandwich bags. The logger assemblages were placed within pre-existing stone circles at two sites on the moraine ridge approximately 35 m apart site 1 was located at (42°04’97S: 145°34’94E) and site 2 at (42°04’96S: 145°34’92E). The ibuttons logged continuous temperature data at hourly intervals during the period between the 30th March and 11th of December 2013. Logger data was downloaded to a computer using the Thermodata Viewer program developed by Thermodata Pty Ltd.

**2.4.7. Results**

The data logger at site 1 was disturbed and the results were not usable apart from supporting the surface air temperatures of site 2. Logger assemblage 2 provided both 5 cm air temperatures and -5 cm ground temperatures. These temperatures are shown in Figure 2.18. The data (Figure 2.18) demonstrate surprisingly high maximum air temperatures particularly in October and November from the 5 cm air temperature logger (supported by logger assemblage 1 data) however this may be a reflection of the strong thermal effects of reflected solar radiation on the light coloured surface clasts of quartz conglomerate that constitute the moraine. The data indicate air temperatures near the ground surface rarely dropped below freezing and only on one instance did the air temperature drop to -1.5°C. The ground temperature logger suggests at no time during the study period did the temperature of the upper layer of the soil drop below about 1.6°C and therefore at no time during the winter of 2013 was ground ice present at the study site.

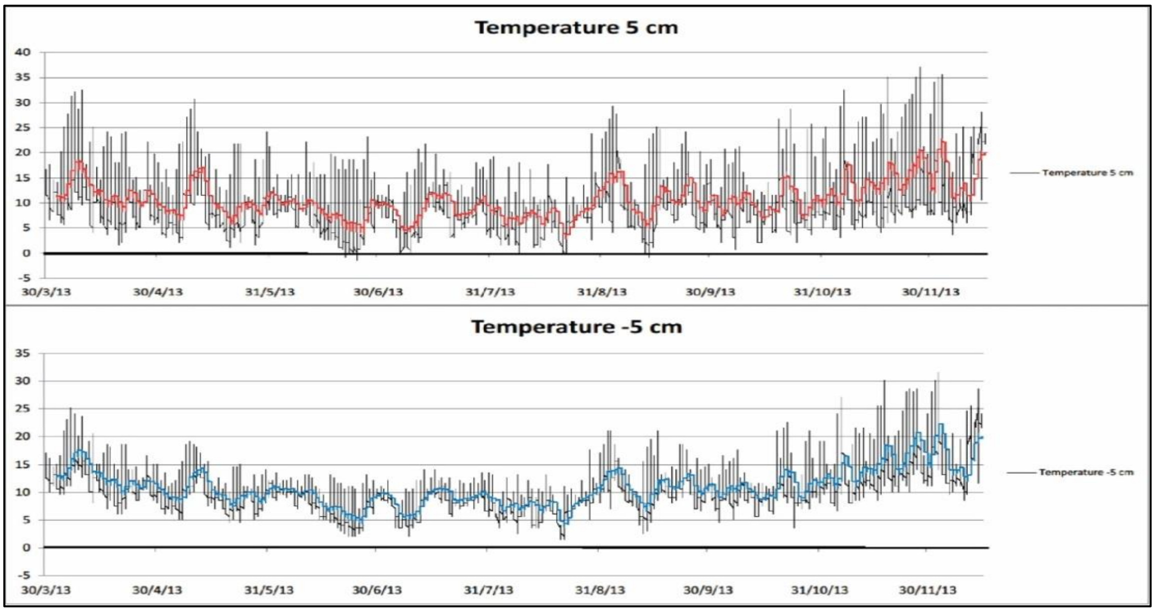



Figure 2.18) Temperature records for the winter of 2013 at Conglomerate Creek.

**2.4.8. Discussion**

The very rare days when air temperatures dropped to below freezing, indicate that the freezing was very marginal and unlikely to support the development of significant needle and ground ice growth in the uppermost surface layer of the moraine. In addition, on the second site visit to retrieve the data loggers, the partially disturbed stone circles showed no evidence of soil movement and rejuvenation over the winter.

We acknowledge that the duration of the temperature observations at this site limits our capacity to make definitive statements about temperature control of the features. Based on the temperature data recorded over the winter of 2013 the evidence points to an extremely marginal freeze-thaw environment where the landforms may be active during very occasional cold spells. In fact, they may now be largely relict features that may be active only during the occasional colder winter seasons. In the last few decades winters significantly colder than 2013 occurred in 1994, 2006 and 2007 as recorded at the nearest inland weather station at Lake St Clair National Park (42°12'S: 146°18'E, 742 m asl) (BOM, 2014b). Remarkably, there is no weather station currently operating in Queenstown. A weather station data (7XS - 42.0967°S: 145.5447°E, 129 m asl) operated between 1964-1995 (BOM 2014b). Data from this period indicates that the average annual number of days with minima below 0°C was 25, while the lowest recorded winter temperature was -6.7°C. While no temperature records exist for the area after 1995 the trend observed in the monitoring period of 1964-1995 shows a clear decline in the number of frost days from over 50 days per year in the mid-1960s to less than 40 days by the early 1990s.

The declining trend in the number of frost days recorded from the Queenstown corresponds with the Tasmania wide analysis of temperature trends by White *et al.* (2013) who note a decreasing trend in the number of below freezing nights (frost days) since 1969 at a rate of approximately 1.3 days a decade. Temperature depressions of close to 1°C below the present day are also recorded as recently as the 1940s and 50s are recorded in a lake core record taken from southeast Tasmania (Saunders *et al.* 2013). In summary, climates were cooler only a few decades ago. Since we know that the surfaces where these patterned ground features occur are young, it is reasonable to suggest that the features are now only intermittently active but were more active only a few decades ago.

Vegetation plays a role in inhibiting ground ice and therefore the development of patterned ground by protecting the ground surface, reducing wind chill effects and by disturbing patterned ground development through root penetration of the surface soil horizons (Davies 1969, Peterson *et al.* 2003, Kade and Walker 2008). This study clearly indicates that ongoing land disturbance and the maintenance of vegetation clear areas is important for patterned ground development at low altitudes. It is also noted that the freeze-thaw activity associated with patterned ground development can inhibit vegetation succession

(Davies 1969; Haugland and Beatty 2005). The age of the land clearance at the study sites is unknown, however, the development of the Mt Lyell mines and initial construction of Queenstown occurred in the 1890's and the lower Conglomerate Creek valley was still forested in 1898 (Blainey 1993) which provides a maximum age for the clearance of the moraine surfaces and hence for the patterned ground at sites 1 and 2. The Queenstown to Zeehan Road was completed in 1941 (Blainey 1993) and essentially dates the maximum age of the patterned ground at Westerway Creek (site 3) to ~70 years. Given the probability of ongoing disturbance by road maintenance they may be significantly younger features. It is also notable that patterned ground forming on the Central Plateau at an altitude of 915 m was recorded by Jennings (1956) and that he suspected that it formed over a relatively short time period when the ground surface was exposed as a result of forest fires. We conclude that sorted circles can and do form in a few decades under modern, or more accurately, near modern climate conditions.

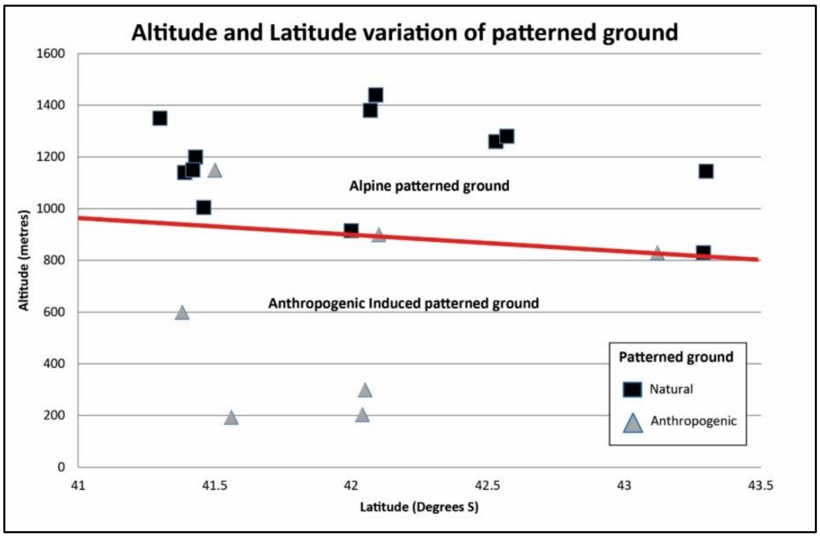



Figure 2.19) Altitude and Latitude variation of patterned ground in Tasmania.

The currently documented elevations of patterned ground in non-anthropogenic settings including the landforms located by Caine (1983) on Ben Lomond, and those located by the authors on Mt La Perouse and Mt Rufus suggest that patterned ground forms only on the most exposed summits with suitably thick sediment accumulations and little vegetation. Figure 2.19 plots the modern altitude distributions of patterned ground and suggests that the natural altitude limits for frost induced patterned ground development associated with sub-alpine periglacial conditions in Tasmania is likely to lie around 1000 m asl. What is notable is that while patterned ground can form on sites of anthropogenic disturbance at altitudes below 200 m asl, the exclusion of patterned ground from undisturbed sites below 1000 m asl is largely an effect of vegetation cover.

### 2.4.9. Conclusions

The documentation of patterned ground forming at ~190 m asl in western Tasmania since European arrival is of interest in defining the lowermost limits of frost processes on unvegetated ground surfaces. The presence of these landforms is a result of anthropogenic land clearance and the maintenance of a bare ground surface. Under natural settings, even when vegetation is reduced by impacts such as forest fires, bare ground is rarely exposed for long enough for sorted features to form. While the presence of weak patterned ground at elevations of ~190 m asl may indicate a minimum altitude of frost activity in Tasmania, the natural lower limits of the modern Tasmanian 'periglacial' zone is at c. 1000 m asl, but this represents an elevation above which bare ground is widespread rather than a true limit of frost activity.

## 2.5. Conclusions of chapter

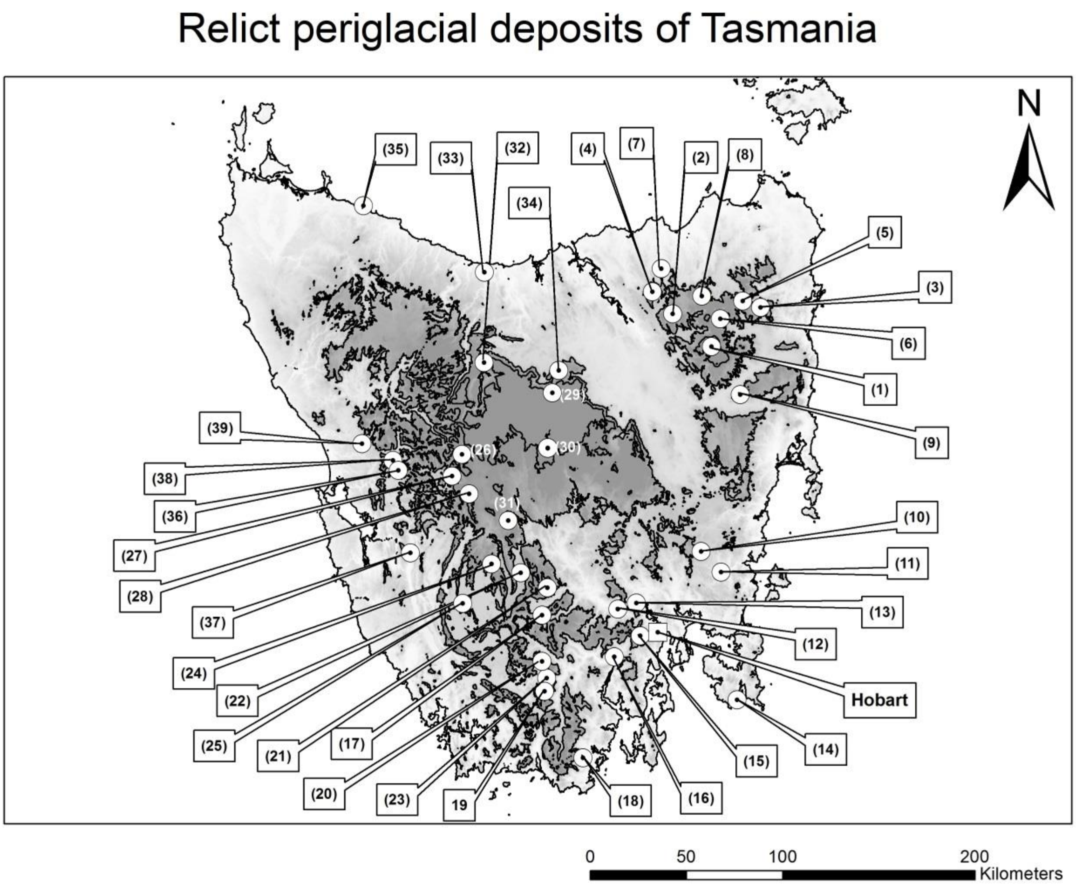
The two studies indicate that on at least the highest summits of western Tasmania periglacial processes are active under the modern climate however they are associated with the occasional period of ground ice conditions and the promotion of solifluction. Seasonal variations in the number of sub-zero daily minimums probably play a role in the level of activity on the stone-banked terraces of Mt Rufus and presumably other similar landforms elsewhere. The patterned ground paper indicates that vegetation clearance plays a major role in the development of small scale patterned ground that is likely to be associated with intermittent frost and shallow ground ice conditions at elevations below the 'natural' limits of freeze-thaw impacted landscapes in Tasmania.

# Chapter 3. Relict periglacial landforms of Tasmania

## 3.1. Introduction

Evidence for widespread Quaternary periglacial conditions in Tasmania can be identified from a wide range of landforms indicative of cold climate processes, including widespread block deposits (block streams, block fields, see Figure 3.1), putative rock glaciers in alpine and sub-alpine environments. While various stratified screes, non-stratified screes and solifluction deposits have been located at lower elevations close to the present sea level. This chapter covers a literature review of significant landforms and studies into Quaternary periglacial evidence from Tasmania and presents a description of recently documented low altitude block deposits located on Maria Island. The review covers the literature on relict landforms associated with freeze-thaw processes in Tasmania. It starts by describing periglacial landforms in north-eastern Tasmania and proceeds with descriptions around the state.

Figure 3.1) Block deposit, Mt Wellington




| | | |
|---|---|---|
| (1) Ben Lomond | (15) Mt Wellington | (29) Pine Lake |
| (2) Mt Barrow | (16) Grove landslide | (30) Monpeelyata Canal |
| (3) Mt Young | (17) Styx Road | (31) Councel River |
| (4) Mt Arthur | (18) Ida Bay karst (Exit cave) | (32) Mersey Valley |
| (5) Mt Victoria | (19) Mt Picton | (33) Forth Valley |
| (6) Upper South Esk Valley | (20) Mt Weld | (34) Quamby Bluff |
| (7) St Patricks River Valley | (21) Mt Field (Lake Fenton) | (35) Rocky Cape |
| (8) Mt Maurice | (22) Florentine Valley | (36) Nelson River Valley |
| (9) St Patricks Dome | (23) Blakes Opening | (37) Franklin River Valley |
| (10) Mt Hobbs | (24) Denison Range | (38) King River Valley |
| (11) Buckland River Valley | (25) Gordon River Road | (39) Henty Bridge |
| (12) Lower Derwent Valley | (26) Mt Oympus | |
| (13) Bridgewater | (27) Mt Gell | |
| (14) Remarkable Cave | (28) King William Range | |

Figure 3.2) Map of documented periglacial landforms in Tasmania, periglacial deposits that are described in the text are numbered on the map.

**3.2. Relict periglacial deposits of north-east Tasmania**

In north-east Tasmania glacial and periglacial landforms on the high summit plateaus of Ben Lomond (Figure 3.2, site 1) and Mt Barrow (site 2) have been described by Caine (1967, 1968a,b, 1982 and 1983) and Barrows *et al.* (2004). The Ben Lomond plateau appears to have been glaciated twice during the late Quaternary (Caine 1983). There is an extensive older plateau glaciation dating to at least Oxygen isotope stage 8 (OIS 8) and a glaciation comprising small cirque glaciers that formed in several locations at the base of easterly facing cliffs during the Last Glacial Maximum (LGM) (Barrows *et al.* 2004). While evidence for the two glaciations of Ben Lomond is present in the form of cirques, u-shaped valleys, roche moutonnée and glacial horns on and adjacent to the summit plateau (Caine 1983), suggests that intense frost shatter and solifluction has been the dominant process on Ben Lomond since the retreat of the ice that formed the older ice cap. A detailed study of the extensive block streams and possible rock glaciers was undertaken by Caine (1983). Cain's work described one of the most visually impressive extensive periglacial landscapes in south-eastern Australia. He includes detailed descriptions of the morphology and fabrics of extensive block streams some of which may have been ice cored or reworked remnants of old glacial moraines. Caine (1983) also described other periglacial phenomena including block topple landforms and tors.

Elsewhere in northeast Tasmania, Caine (1983) mapped and described relict block fields and solifluction deposits mantling the slopes surrounding the summits of the majority of the dolerite capped mountains in the northeast. These deposits descend the mountain slopes to elevations as low as 850 m on the slopes of Mt Young (3). He described a gradual rise in elevation of the periglacial zone from west to east from around 600 m on the slopes of Ben Lomond and Mt Arthur (4) to 850 m on the slopes of Mt Young. Extensive boulder deposits surround the elongate summit ridge of Mt Victoria (5). Solifluction processes here appear to have transported toppled dolerite columns, up to 15 m long, several hundred meters downslope of the summit cliff line and freeze – thaw processes may have produced an enigmatic boulder cave at this location (Slee 2011). The cave appears to have formed by either the complete removal of a column or joint widening by freeze – thaw processes (Slee 2011). Angular stratified scree deposits have been identified by Sharples (1994) and McIntosh *et al*. (2009, 2012) from several low elevation sites in north-eastern Tasmania including near Mathinna in the upper South Esk Valley (6) (Sharples 1994) and near Golconda (7) (McIntosh *et al.* 2012). The fabric and morphology of the stratified scree deposits resemble similar deposits often described as gréze litées from other locations around the globe (e.g. Steijn *et al*. 1984, Hanvey and Lewis 1991, Gardner *et al*. 1991, Bertran and Texier 1999, Eaton *et al.* 2003).

Summit tors are common landforms on the higher dolerite summits of northeast and central Tasmania where they represent both one cycle and two-cycle development as a response to periglacial conditions (Caine 1983). The summit plateau of Mt Maurice (8, 1123 m) is the only summit over 1000 m in northeast Tasmania that is composed of sandstone. On Mt Maurice small tors have formed that are likely to have developed by periglacial processes (Caine 1983, Sharples 1994). Tors formed near the summit of granite hills of 450 to 900 m altitude in northeast Tasmania have also been associated with periglacial processes (Colhoun 2002)

### 3.3. Relict periglacial landforms of East and south-east Tasmania

Sharples (1995) documents summit tors and benched scree slopes on St Pauls Dome (9, 1023 m) and rudimentary cliff and tor landforms on Mt Hobbs (10, 823 m) NE of Hobart where he attributes the pronounced asymmetry of the mountain profile exhibiting a steep south-eastern face to preferential freeze – thaw on the shaded side of the mountain. However considering elsewhere in Tasmania periglacial landforms form slope mantles on most aspects it appears likely that the asymmetry of the mountain is linked to the geology of the dolerite dyke or mass movement processes on the eastern face of the mountain, the lack of detailed description of the landforms makes it difficult to justify ‘freeze-thaw’ as the only geomorphic agent to summit asymmetry at Mt Hobbs. Derbyshire (1973) suggested that periglacial slope deposits in central eastern Tasmania are common above altitudes of 460 m and may be found below 400 m in favourable locations. Observations by Goede (1965, 1972) in the Buckland Valley (11) of south-eastern Tasmania suggested that periglacial landforms may have developed at much lower elevations. Goede (1965) reported enclosed depressions that he suggested were likely to have formed by periglacial freeze-thaw processes mantling hills as low as 60 m altitude. These observations are supported by Wasson (1977) during his study of alluvial fans in the Lower Derwent Valley (12). He described periglacial solifluction mantles descending to altitudes of 450 m and what he described as sorted nivation deposits as low as 140 m above present sea level. More recent geologic mapping of the Buckland Geology sheet indicates doleritic solifluction deposits only on the highest summits in the area between elevations of 400-

650 m (Spanswick and Kidd 2000). This discrepancy in observation highlights the difficulty faced by workers in assessing the origin of angular dolerite slope colluvium in the Tasmanian environment. Soils derived from angular doleritic colluvium have been described by Grant *et al.* (1995), Laffan *et al.* (2002) and Laffan and McIntosh (2005) and while a periglacial origin for the slope deposits on which the soils develop is generally accepted, the mode and age of formation is not well established. The majority of these deposits and soils are deeply weathered with older deposits commonly distinguished by rich red colouration, iron pans and incorporate clasts with thick weathering rinds, suggesting they have formed over a significant time and are likely to represent deposits emplaced over multiple glacial cycles (McIntosh 2002). Dolerite colluvium produced from bedrock exposures during the last glacial appears to be generally less weathered, however, McIntosh *et al.* (2005) suggest that periglacial conditions during the last glacial may have re-sorted older deposits. The explanation suggested by McIntosh *et al.* (2005) supports descriptions by Sigleo and Colhoun (1982) of low altitude angular dolerite colluvium lying beneath late last glacial aged aeolian dunes near Bridgewater (13) in the Middle Derwent Valley. Landforms of unquestionable periglacial origin are rare in eastern Tasmania. On the Tasman Peninsula angular rubble deposits associated with sedimentary beds overlying dolerite, form a significant component of a 17 m thick valley fill deposit that partially buries a last interglacial aged geo adjacent Remarkable Cave (14) (Colhoun 1977a) suggesting active freeze-thaw processes to present day sea level at this location (Colhoun 1977b) the presence of these deposits marginally above sea level in a distinctly coastal marine setting is anomalous in regards to the mapped distribution of most other 'periglacial' landforms in Tasmania. Davies (1958) was amongst the first to describe landforms as periglacial in Tasmania when he described the boulder and tor landscape on the summit plateau of Mt Wellington (15, 1271 m). He suggested that distinctive boulder steps on the summit may be low angle cryoplanation surfaces. These were formed by cryonival processes during the LGM and earlier glacial periods, given that the summit plateau of Mt Wellington must have been marginally below the Last Glacial Maximum glacial ELA of ~1300 m asl (Barrows *et al.* 2002) and that the mountain currently lies at an altitude conducive of small scale periglacial processes, it is difficult to envisage other processes that could produce such widespread block deposits. Boulders dated from low angle blockfields on the Mt Wellington Plateau using cosmogenic nuclide $^{36}$Cl have produced dates up to half a million years (Barrows *et al.* 2004) indicating that the summit plateau is unlikely to have been glaciated since at least this time but has been a site of

intense periglacial processes. At Home Hill Vineyard near Grove (16) a thick deposit of fine screes exposed in a landslide back-wall has been dated to the beginning of the LGM (McIntosh *et al.* 2009, McIntosh *et al.* 2012). This deposit of stratified screes draping a hill slope 30 m above the present sea level implies hillslope mass movement under cold climatic conditions that has been thermoluminescence dated to 28 kya, the location of this site in an inland location at the base of the Wellington Range suggests that cold air pooling may have promoted the active periglacial freeze-thaw processes on a sparsely vegetated slope. Similar stratified screes, several meters thick, has been recently exposed in the Styx Valley (17) at an altitude of 500 m asl (Figure 3.3). The deposit is undated, however a nearby paleosol that appears to lie stratigraphically beneath the scree deposits was radiocarbon dated by McIntosh *et al.* (2012) to 34.9 cal kya suggesting that the overlying scree deposits formed immediately prior to or during the LGM. The deposit is locally faulted demonstrating brittle deformation and may have been frozen. The morphology of the deposit indicates deep freezing of the subsurface to a depth of several meters may have been occurring at this site sometime during the late last glacial.

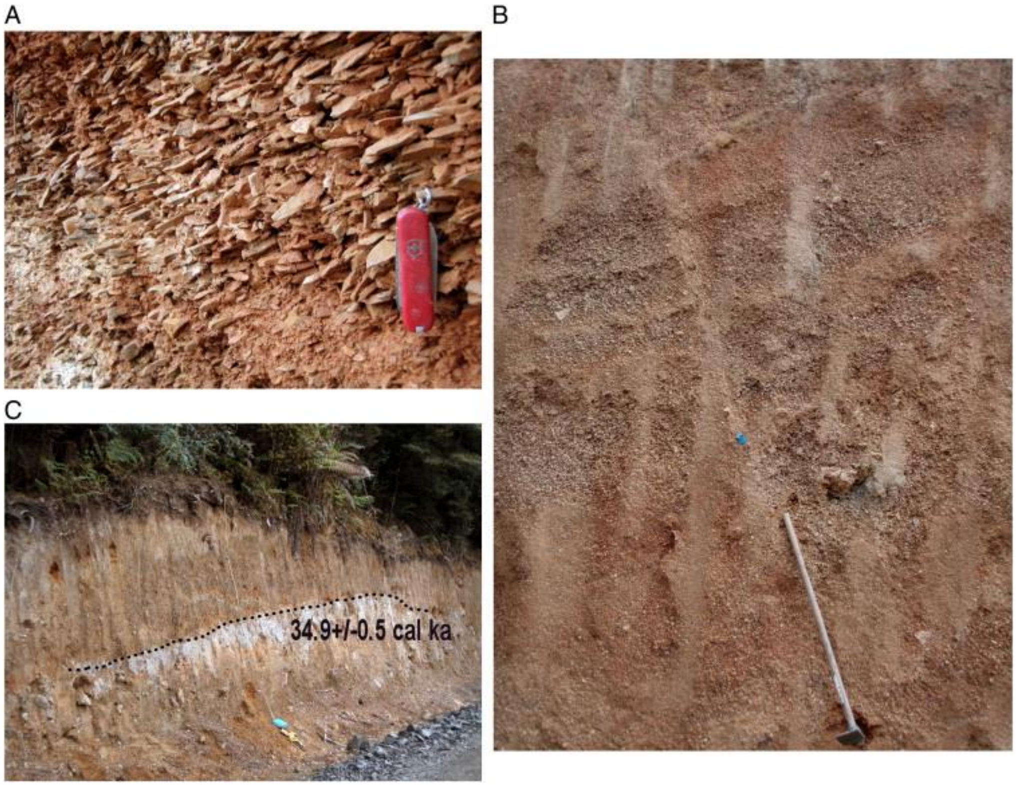



Figure 3.3) Stratified Scree (grèzes litées) exposed in a road cuttings, (A) Golconda, northeast Tasmania (B, C) Styx Valley. (Image extracted from McIntosh *et al.* 2012)

Extensive undated angular rubble cones found at the base of deep shafts in the Exit Cave system near Ida Bay (18) have been suggested by Geode (1969) to be evidence that mechanical weathering during cold climate periods have played a significant role in cave development. A talus cone of angular scree and poorly sorted gravels of likely periglacial origin was dated by Goede and Harmon (1983) by uranium-series ($^{230}Th/^{234}U$) dating a stalagmite forming on top of the deposit at 112,000± 3 kya suggesting a pre-last glacial age for the periglacial process that formed this deposit. Similar angular breccia deposits have been described and dated to the late LGM (12,600 yr BP) at Beginners Luck Cave in the Florentine Valley (22) by Goede and Murray. It appears likely that periglacial processes may have been active at these locations. However, these angular cave screes have not been studied for definitive evidence of a periglacial (frost shatter) origin.

### 3.4. Relict periglacial landforms of south west Tasmania

Blockfields are common on the slopes of the dolerite mountains to the west of the central plateau and in southern Tasmania. Extensive block fields mantling the upper unglaciated slopes of the Picton Range (19) and Mt Weld (20) have been considered to be of late last glacial age (Colhoun and Goede 1979) however they have not been dated and the significant ages of block fields on Mt Wellington and Ben Lomond (Barrows *et al.* 2004) suggest they could be older than the last glaciation. Large block field deposits and solifluction lobes have been described on the Mount Field plateau (21) including the Lake Fenton blockstream (Lewis 1921, 1922, Colhoun and Peterson 1986, McIntosh *et al.* 2012). Below the western ramparts of the Mt Field Plateau glacial and periglacial processes have directly interacted with karst processes in the sub-alpine parts of the Junee Karst (Kiernan *et al.* 2001) with glacial and periglacial deposits infilling cave entrances and deranging karst development, however Kiernan *et al.* (2001) do not detail the morphology of the periglacial landforms that are retarding the karst drainage in the area.

Angular alluvial fans and slope colluvium mantle the button grass plains at Blakes Opening (23) in the middle Huon Valley (Colhoun and Goede 1979) and large sinkholes within dolomite appear to have been infilled by angular colluvium of likely but unproven periglacial origin (Slee 2006). Well-developed periglacial deposits are comparatively rare in Tasmania's west and southwest as a result of the bedrock geology of the area being dominated by resistant crystalline rocks and the remote thickly vegetated terrain. Blockfields are located on the western slopes of the Denison Range (24) (Webster 1974) and extensive deposits of angular scree are exposed in road cuttings along the Gordon River road (25) (Colhoun 2002, McIntosh *et al*.2012).

Further north Derbyshire (1973) describes relict rock glaciers on the western slopes of Mt Olympus (26) and Mt Gell (28) descending below the summit plateaus to altitudes of 1100 m. On Mt Olympus rock glaciers have youthful appearance with prominent frontal lobes, nivation hollows and ridge topography. Observations of the lobate rock glaciers from the summit of Mt Olympus during this project reveal that they have formed at altitudes on the western face of the mountain that correlate to the LGM cirque glaciers on the eastern face. Nivation hollows and pro-talus ramparts are present on the King William Range (28) near Lake St Clair (Derbyshire 1973, Kiernan 1995).

**3.5. Relict landforms of northern and central Tasmania.**

Periglacial scree, solifluction deposits and low angle block fields are common in the un-glaciated parts of the northern central plateau above an altitude of 1000 m asl. Here extensive block fields on slopes of <7° near Pine Lake (29) were described by Colhoun and Peterson (1986). At Monpeelyata Canal (30) a paleosol within solifluction deposits was radiocarbon dated to 30,400± 2300 yr BP (Colhoun 1978). Layered angular dolerite colluvium dated by radiocarbon to greater than > 50 cal ka have been exposed in the back wall of a landslide and road cuttings on a forestry coupe in the Counsel River region on the southern edge of the central plateau (31) (McIntosh *et al*. 2009) while the dates lie beyond the reliable age for radiocarbon dating. These thick deposits are most likely associated with widespread solifluction activity in a sparsely vegetated environment during the mid-late stages of the Last Glacial Cycle.

Relict stratified and unstratified angular scree deposits thought to have been formed by periglacial processes during the LGM are found at low altitudes in the Mersey (32) and Forth (33) Valleys (Derbyshire 1973, Colhoun 2002). Deposits in the Mersey valley exposed in the back wall of a quarry have been observed by the author as stratified screes or grèzes litées. In the Lower Forth a deposit on the slopes of Sayers Hill consisting of angular slope deposits was radiocarbon dated to >30600 yr BP (Colhoun 1976). While this date gives a minimum age for the emplacement of this deposit, coarse angular basalt slope deposits, suggested by Colhoun (1976) to have formed by gelifluction processes, display very little surface weathering indicative of a youthful age of the deposit. Similar screes have been exposed by road cuttings on the middle slopes of Quamby Bluff (34) an isolated dolerite summit north of the main mass of the Great Western Tiers, near Deloraine

(Derbyshire 1973). Quartzitic stratified slope deposits and fan gravels outcrop at quarry faces near Rocky Cape (35) in the northwest. These deposits are located about 28 m above sea level and have been interpreted by Colhoun (1977b) as being of periglacial origin. They form two stratified layers separated by a paleosol. The lower deposit was dated by radiocarbon to 32-22,000 yr BP and an upper less compact surface that dates from the latter part of the LGM. Colhoun noted that anomalous wedge shaped features in the upper deposit may be relict ice wedges (Colhoun 1977b).

In western Tasmania cave sediments that date to OIS stages 2 and 3 and are of probable freeze-thaw origin have been described by authors working on cave sites in the Nelson and Franklin River Valleys. In the Nelson River Valley (36) scree deposits up to 8 meters thick have been located with a basal age of 42,140± 1610 yr BP at one site (Kiernan 2008) indicating the deposits date from MIS3. Similar angular deposits were identified in caves in the Franklin Valley (37) where charcoal dates within angular rubble deposits in Kutikina Cave returned dates of between 18,000 and 15,000 yr BP (Kiernan *et al.* 1983). In the nearby Deena Reena Cave, organic rich layers buried by angular rubble were dated to the late OIS 2 and Holocene based on 5 stratigraphic samples returning ages between 20,250±1500 and 10950±520 yr BP. These dates indicate a very late last glacial to early Holocene age for the most recent large scale production of angular scree material. The map of Deena Reena cave suggests that limited mechanical weathering may be producing small angular rubble piles under present climatic conditions at this site (Kiernan 2008).

Thick deposits of angular colluvium found in some tributary valleys of the Franklin and King River Valleys (38) are likely to be of periglacial origin (Kiernan 2008). An angular scree deposit burying wood fragments at Henty Bridge (39) has been attributed to solifluction during the last glacial (Colhoun 1985). The extensive nature of the block deposits in Tasmania is further summarised in Appendix 15.

The literature on Tasmanian periglacial deposits reveals that while the well-developed blockfields, block streams and probable relict rock glaciers that are characteristic landforms of much of the dolerite mountains of central and Eastern Tasmania have received some study by the likes of Davies (1958), Peterson (1973), Caine (1983) and Barrows *et al.* (2004). There is still significant potential for further studies into the development of these features. At lower elevations various deposits and landforms have been described as being of likely 'periglacial' origin by authors (i.e. Colhoun 1977a, Sharples 1994 and McIntosh *et al.* 2012). While some of these deposits such as the well stratified screes documented by Colhoun in the upper Mersey Valley and McIntosh *et al.* 2012 on the Styx Road have characteristics that imply formation under cold climate conditions with strong frost shattering and slope movements triggered by saturated slopes and potential seasonal ground ice. Many of the other deposits such as those at Remarkable Cave or Exit Cave are more speculative in nature and should be considered as potential indicators of periglacial conditions whereby ground ice or another non periglacial process could have produced the deposits, rather than proof of ice promoted slope processes under periglacial climates.

## 3.6. Research Note: A reconnaissance of low elevation block deposits on Maria Island, Tasmania.

This paper describes the documentation of low altitude block and scree deposits on Maria Island off eastern Tasmania. The Mt Maria W1 block deposit is of likely periglacial origin and therefore represents the lowest described well developed and extensive block deposit in Australia. This paper was published in *Quaternary Australasia* 2014, 31(2):40-44 (see Appendix 2 for published version)

### 3.6.1. Abstract

This paper provides a description of the morphology of low elevation dolerite block deposits of periglacial and cliff topple origin. These relict deposits mantle the upper slopes of the main central mountain ridge of Maria Island; an offshore continental island that lies of south-eastern Tasmania. Observations suggest that one extensive deposit on the upper western slopes of Mt Maria displays landform characteristics indicative of periglacial processes playing a significant role in its formation. The maritime setting and moderate elevation of these deposits are of interest for paleoclimate interpretations. The deposits indicate the potential for significant freeze-thaw activity during cold Quaternary glacial stages at elevated locations on the east coast of Tasmania.

### 3.6.2. Introduction

On the upper slopes above elevations of 500 m on Mt Maria and Bishop and Clark lie a series of nine un-vegetated slopes of up to 14 hectares in extent dominated by openwork dolerite boulders up to 4 m long that can be described under the loose term as ‘block deposits’. Block deposits in the form of block streams (elongate downslope ‘rivers’ of openwork boulders), block fields (openwork boulder fields on low angle slopes) and ambiguous slope deposits colloquially described in Tasmania as ‘scree’ are common landforms on the upper slopes of Tasmanian Mountains (Derbyshire 1973, Caine 1983, Colhoun 2002, McIntosh *et al.* 2012). Apart from occasional rock falls all of these landforms appear to be inactive under the present climate. They are therefore likely indicators of past periglacial climates during the last glacial (OIS stages 2-5) and earlier Quaternary glacial cycles (Derbyshire 1973). The Maria island block deposits are unusual in two respects first, because while dolerite boulder slopes (colluvium) are common at mid to low elevations in south eastern Tasmania (Colhoun 2002, McIntosh *et al.* 2012) most are largely vegetated and of moderate clast size with clasts generally less than 0.5 m long (A-axis). The block deposits on Maria Island are aerially extensive; occur at a moderate altitude; and are largely un-vegetated. They are composed of coarse clasts up to 3-4 m long. They are located on an isolated mountain massif that would have been connected to the eastern margin of Tasmania during the last glaciation.

### 3.6.3. Study area

Maria Island is a 20 kilometre long island that lies off the south eastern coast of Tasmania from which it is separated by the 5 kilometre wide Mercury Passage. The Island is composed of two mountainous landmasses connected by a 3 kilometre sand isthmus. The study focused on the larger northern section of the island where a 9 kilometre long mountain range forms the eastern backbone of the island. The range is composed of a Jurassic dolerite sill approximately 250 m thick overlying Permian siltstone, sandstone and limestone units that crop out up to an altitude of approximately 430 m (Mineral Resources Tasmania 2013). The range rises to two prominent peaks Mt Maria (711 m) in the centre and Bishop and Clarke / Mt Pedder (652 m) near the northern tip of the island. Surrounding these summits is a series of nine un-vegetated dolerite block deposits that are clearly discernible on aerial photographs and Google Earth images. The mapped extent of the block deposits is presented in Figure 3.4. Bushwalking tracks to the summits of both Mt Maria and Bishop and Clarke give access to the west facing block deposits three of which were inspected in the field.

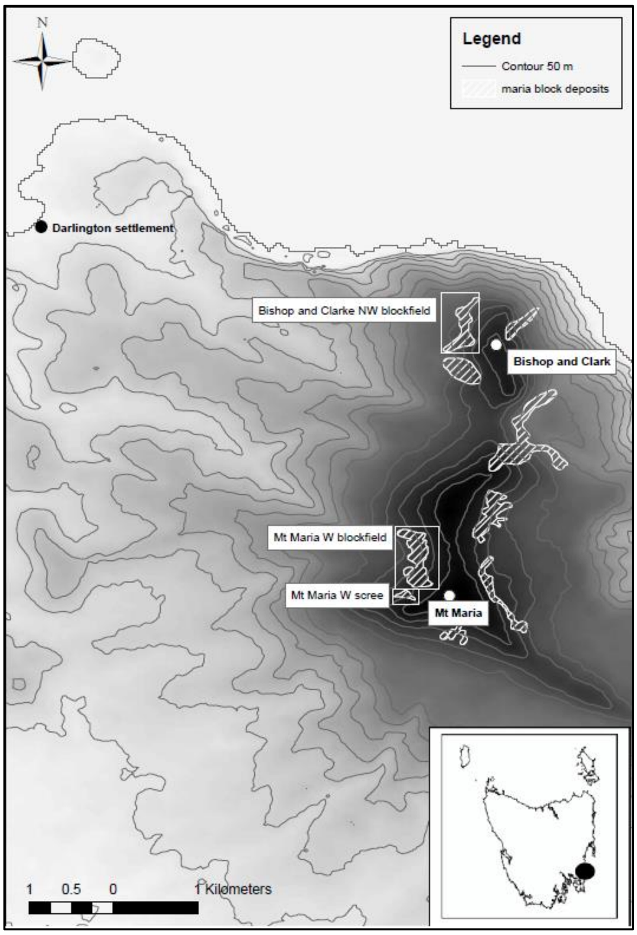



Figure 3.4) Map of study area on Maria Island showing the location of block deposits.

### 3.6.4. Observations

The three inspected and named block fields were the Bishop and Clarke NW block field, Mt Maria W scree and Mt Maria W block field. While the Google Earth images led to an initial assumption that all three block deposits were likely to have formed by the same process, field inspection revealed that the morphology of the Bishop and Clarke NW block field and Mt Maria W scree deposits differed to that of the Mt Maria W block field. The summits of both Mt Maria and Bishop and Clarke show evidence of ongoing gravitational column topple and collapse processes on the cliff edges. At other localities notably the northern accessible summit of Bishop and Clarke deposits of angular clasts measuring 20 – 40 cm long scattered on the summit indicate that while freeze-thaw frost shatter processes are unlikely to be active under current climatic conditions frost shatter may have been an active process in the past. However given the coastal location of Bishop and Clarke salt weathering could also contribute to bedrock denudation and the production of small angular clasts.

### 3.6.5. Description of the deposits

*Bishop and Clarke NW block field*

The Bishop and Clarke track crosses the length of this 7 hectares block deposit on the upper NW slopes of Bishop and Clarke below the summit cliffs at an altitude of 550 – 420 m altitude. Angular to sub angular dolerite clasts up to 50 cm long comprise around 60% of the deposit with a further 30% of smaller fragments and 10% larger boulders up to 2 m long. The deposit is in the form of a cone sloping at around 20°. Relatively smooth upper slopes give way to some minor contour aligned ridging on the lower slopes. Large boulders are present throughout the deposit but no strong downslope sorting is evident. On the mid to upper slopes of the deposit lateral grainsize variations are evident with ridges formed of large boulders surrounded by zones of finer material (Figure 3.5).

*Mt Maria W scree*

This small block deposit covering 1 ha has a similar form to the Bishop and Clarke NW blockfield with a conical form and slopes of 20 - 22°. About 20% of the clasts are <30 cm, 70% are 30 cm – 1 m and 10% large boulders up to 3 m long the majority of clasts are angular to sub-angular.

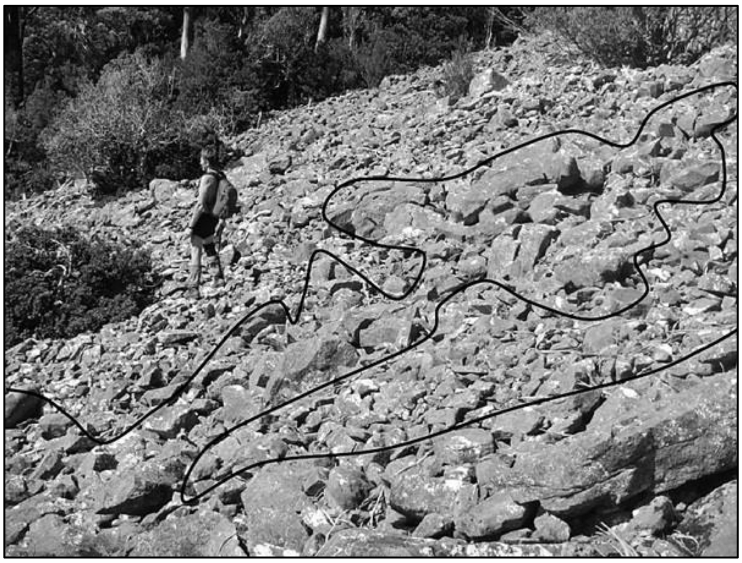


Figure 3.5) Bishop and Clarke NW block field. Patches of larger boulders alternating with finer scree on 20° slope (boundary between deposits outlined), probably related to individual column topple.

*Mt Maria W blockfield*

This large block deposit covers an area of approximately 11 ha on the western slopes of Mt Maria at an altitude of 530 – 630 m. The morphology of this blockfield differs substantially to the other two sites investigated. The angle of slope varies but is generally in the range of 12 - 16°. The block deposit is dominated by large to very large angular to sub angular boulders with A-axis of 1 – 4 m long with an estimated average length of 2 m that constitute 85% of the deposit. Clasts with lengths of 20 cm – 1m comprise 13% of the deposit and there is a minimal surface exposure of any finer grained material. There is no well-defined source area in the form of a cliff immediately upslope of the deposit, but instead a low col on the summit ridge. Elongate ridges up to 2 m in height extend downslope, with vague lobate forms and boulders projecting vertically on their a-axes. These characteristics suggest slow mass movement of the deposit in the past. However allochthonous block stream development appears to have been a marginal process due to the limited elongation of the block deposit down slope, as commonly observed in many other Tasmanian deposits (Caine 1983, Barrows *et al.* 2004). At a couple of locations small boulders appear to have been sorted into well-defined patches surrounded by the much larger boulders that comprise the majority of the deposit. These patches take the form of circles several meters in diameter and vaguely defined stripes (Figure 3.6). The size of the features would suggest they are not related to frost produced patterned ground. Tree fall might conceivably account for the patterning however this seems unlikely due to the volume of rock displaced, the degree of sorting, the lack of characteristic root-ball depressions in the surface and the lack of any evidence for very large trees growing on the blockfield under current climatic conditions.

Figure 3.6) Mt Maria W block field. One of the anomalous patches of smaller size clasts surrounded by larger boulders at Mt. Maria W blockfield (backpack approximately 50 cm long circled). The northern section of the block deposit is visible in the background.

### 3.6.6. Discussion

The morphology and location of both the Bishop and Clarke NW block field and Mt Maria W scree indicates that these deposits have formed largely by gravitationally induced column topple during cliff retreat. Given a lack of evidence for recent frost action, formation of this deposit was probably most active during the Last Glacial cycle, when cliff topple was probably enhanced by freeze-thaw processes and limited vegetation cover under the colder climate. In several locations ridges of large boulders are readily explained by the breakup of individual large topples during their rapid downslope movement. In contrast the Mt Maria W block field cannot be easily explained by gravitationally induced column topple as there is no major cliff upslope of the deposit and the very large size and chaotic distribution of the boulders (Figure 3.6), the latter contrasting with the finer mixed clast size of the neighbouring talus deposits. While there is evidence of past frost shattering of dolerite clasts on the summits of Mt Maria and Bishop and Clarke, neither the Bishop and Clarke NW blockfield nor Mt Maria W scree require periglacial conditions for their formation. In the case of the Mt Maria W2 blockfield the ridging and low slope angle and the large size of the boulders suggests that periglacial mass movement by solifluction or interstitial ice is likely to have been a factor in the vertical and downslope displacement of parts of the deposit. This process may also offer an explanation for the patches of fine material which may have risen to the surface where internal pressure forced finer material upwards. A second possibility is that this block field is largely autochthonous and formed in situ by very slow freeze-thaw processes coupled with subsidiary chemical weathering. The prominent ridges and sorted patches of finer grained material evident in the deposit may be related to the pre-existing bedrock structure and its behaviour upon sub aerial weathering. A problem with the latter theory is that if in-situ weathering of the bedrock by freeze thaw processes was the major formative process why would this process be limited to specific slopes on Maria Island given that other presumed periglacial block streams elsewhere in Tasmania exhibit signs of slow downslope movement such as large pressure ridges at the confluence of block streams on Ben Lomond (Caine 1982). This may be partially explained by the observations of Caine (1968a) at Mt Barrow who noted that the upper parts of elongate blockfields there are autochthonous source areas dominated by randomly oriented boulder fabrics that give way to allochthonous block stream development downslope where the clasts are strongly aligned downslope. In the case of the Mt Maria W block field the high width to length ratio of the deposit is determined by a stratigraphic bench formed by underlying sandstone.

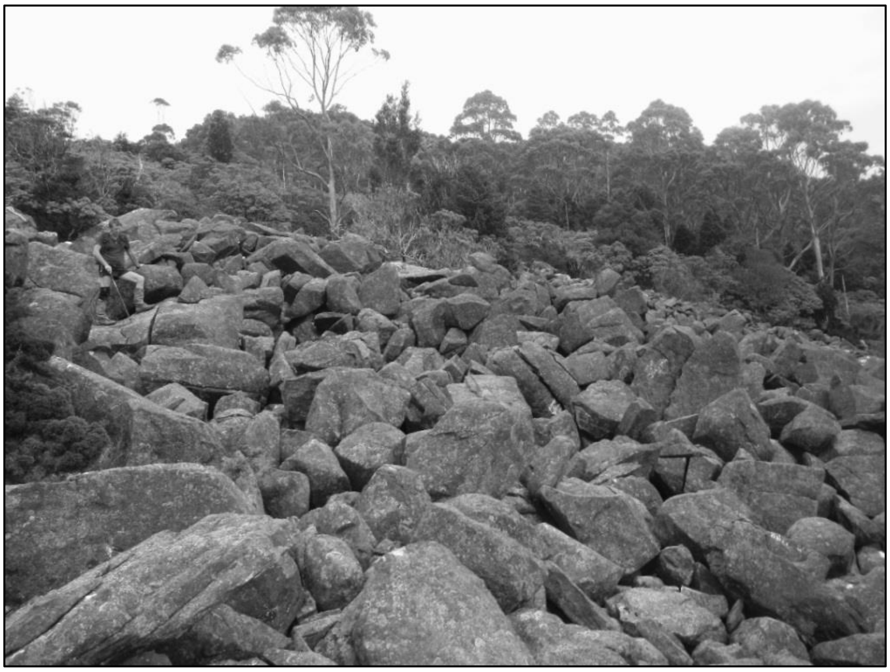


Figure 3.7) Mt Maria W block field, elongated ridges.

Although the sorting of fine clasts and morphologic forms of sections of the deposit suggests minor internal movement possibly associated with spring lines was likely. The sub surface sedimentology of the deposit might shed further light on the origins of this deposit however the sheer size of the surface boulders inhibits excavation and morphologic classification of this feature.

To date the only study to assess the age of Tasmanian block deposits was undertaken by Barrows *et al.* (2004) on the blockfields of Ben Lomond and Mt Wellington. The limited number of dates they obtained by cosmogenic methods revealed a wide spread of Quaternary ages spanning several glacial climatic stages with ages ranging from the late Last Glacial 22.1 ± 1.3 kya to 498 ±43.5 kya. This spread of dates suggests that many Tasmanian block fields have long and complex histories whereby they have undergone multiple periods of activity and have been subject to a broad range of climatic conditions.

### 3.6.7. Conclusions

The block fields present on the upper slopes of Mt Maria and Bishop and Clark represent a suite of relict landforms that are likely to have developed under periglacial conditions. The deposits are likely to have last been active during the late Last Glacial time when transgressive scree deposits at the base of the high dolerite cliffs where reactivated and minor block stream activity may have occurred. The Mt Maria W block field is composed of very large boulders on moderate to low angle slopes and does not appear to have formed by cliff collapse. It is likely to be of autochthonous origin that has been affected by secondary allochthonous block stream development under a periglacial climate. The significance of this is that it the Mt Maria W block field is the lowest elevation well developed block field of likely periglacial origin in Australia, being significantly (200 – 300 m) lower than similar block fields elsewhere in Tasmania such as the block fields and block streams of Mt Wellington. Given Maria Island lies of the south eastern Tasmanian coast and formed an isolated mountain range during the last glacial sea level low stand. The presence of landforms likely to have developed in a periglacial environment implies freeze-thaw and possibly intermittent ground ice conditions were present in a currently maritime setting during colder Quaternary climates.

### 3.7. Summary of Tasmanian periglacial landforms

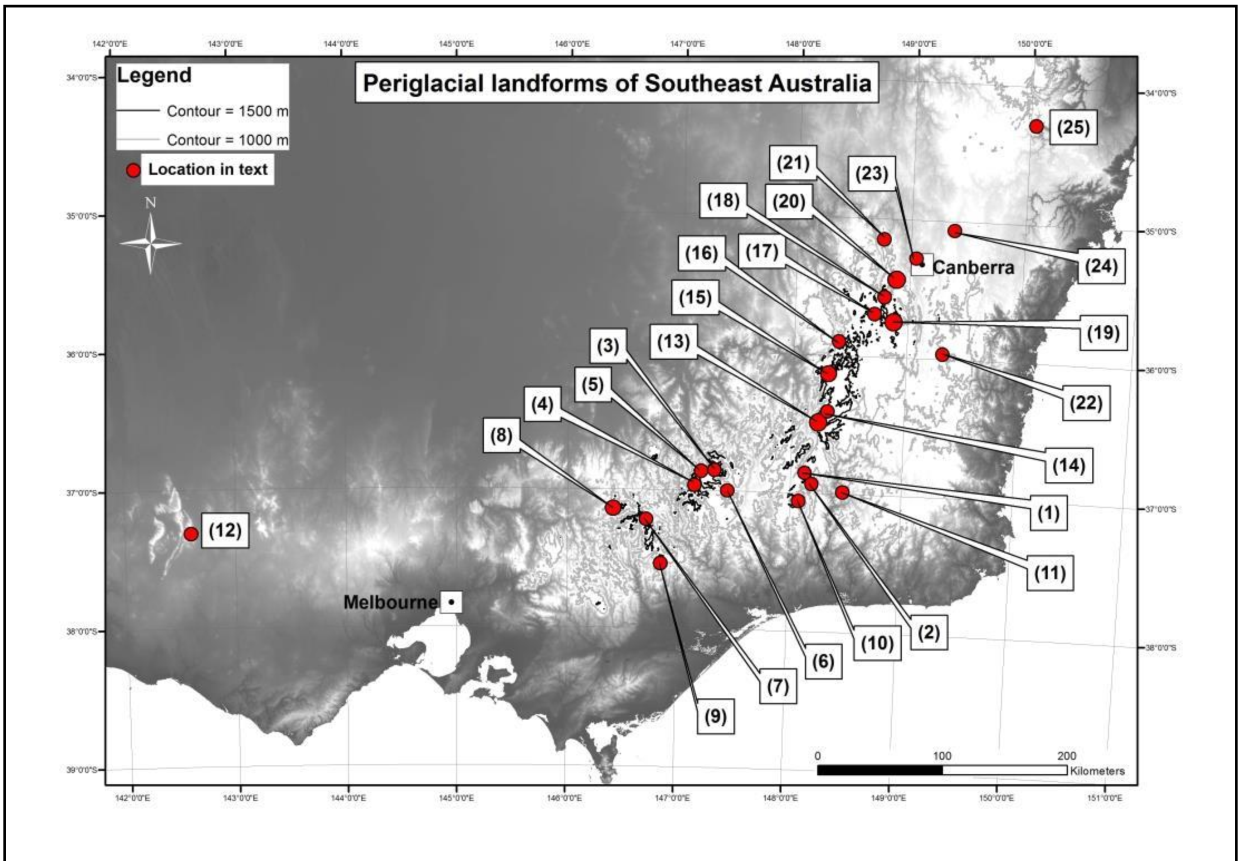
This review reveals the widespread evidence for the development of landforms under periglacial climates prevalent through the late Quaternary in Tasmania. There are regional trends with apparent elevations of features rising from south to north and east to west. In the west, the extent of freeze-thaw landforms is limited by former glacial activity. Overall, strong freeze-thaw action appears to have extended to within a few hundred metres of sea-level at most, during cold phases. The greatly depressed freeze thaw elevations suggest that elevation changes in freeze-thaw can be calculated by examining modern lower limits of this process and comparing to Pleistocene lower limits.

## Chapter 4. Relict periglacial landforms of the Australian Mainland a review

The purpose of this chapter is to provide detail on the known extent of periglacial landforms in SE Australia. For convenience sake the review is split into the two states (Victoria and New South Wales) because much of the grey literature is sourced from state government departments.

## 4.1. Introduction: Periglacial deposits of Victoria

The documentation of periglacial landforms in the Victorian Alps and other highland areas of Victoria has been sporadic and largely focused on the more extensive or accessible high altitude block deposit landforms (e.g. Talent 1965, Webster 1974, Rosengren *et al.* 1981 (Fig 4.1). Periglacial landforms are widespread in the Victorian Alps; however, with the exception of some block deposits they have been inadequately described. This lack of documentation is particularly evident below the sub-alpine zone.




| | | |
|---|---|---|
| (1) Mt Cobberas | (10) Reedy Creek Chasm | (19) Mt Kelly |
| (2) Mt Wombargo | (11) Gattamurgh Creek | (20) Tidbinbilla Range |
| (3) Bogong High Plains | (12) Mt William | (21) Mt Coree |
| (4) Mt Hotham | (13) Main Range | (22) Bredbo River Valley |
| (5) Mt Jaithmathang | (14) Mt Tate | (23) Black Mountain |
| (6) Mt Battery | (15) Toolong Range | (24) Lake George |
| (7) Howitt Plains | (16) Ravine | (25) Wombeyan Karst |
| (8) Mt Buller | (17) Cooleman Plains Karst | |
| (9) Wellington Plains | (18) Brindabella Range | |

Figure 4.1) Documented periglacial landforms in south-eastern Australia.

### 4.1.1. North-east Victoria

The work of Talent (1965) documents a number of block deposits in the Victorian Alps, generally above altitudes of 1300 m asl. These landforms have been further investigated by Rosengen *et al.* (1981). The most notable and well documented block deposits in the state lie in the vicinity of Mounts Cobberas (1838 m asl, Figure 4.1 (1)) and Mt Wombargo 1634 m (2)) in far northern Gippsland and on the Bogong High Plains ((3) ~1750 – 1900 m asl). At Mounts Cobberas and Wombargo extensive block streams, some in excess of 1 km long extend downslope from the summit areas (Talent 1965, Ashton and Moore 1978, Rosengren *et al.* 1981). Their distribution is dominantly on the western slopes of the mountains and the deposits display smooth profiles on moderate angle slopes of up to approximately 30° (Ashton and Moore 1978).

Ashton and Moore (1978) noted that the extent of block deposits in this area are greater than that indicated on state topographic maps. The elevations of the block deposits range from near the summit of Mt Cobberas at 1838 m asl to Rocky Plain at 1150 m asl. None of these landforms have been dated. Block fields and block streams are common landforms on the Bogong High Plains with the lowest extensive block stream located at approximately 1300 m asl in the upper catchment of the Cobungra River (Rosengren *et al.* 1981). Block streams are particularly abundant in the highlands around Mt Hotham ((4) 1876 m asl), Mt Jaithmathang ((5)1852 m asl) and Mt Loch where several large block streams have been assessed to be of national or state conservation significance (Webster 1974, Rosengren *et al*. 1981). A number of block streams are located on Mt Higginbotham (1820 m asl) a minor peak of Mt Hotham, where they extend downslope from the summit and were classified by Barrows *et al.* (2004) into two forms based on their location on the hill slope. They described proximal block deposits from the upper hill slope immediately below the summit bedrock source areas and distal block deposits for isolated vegetation free deposits that lay some distance downslope from any obvious source area. Boulders sampled from two proximal block deposits yielded ages of 20.8±1.1 kya and 16.3±.09 kya based on Surface Exposure Ages (SED) using $^{36}Cl$. A date of 58.9±2.8 kya from a boulder within the lower extent of a distal block deposit suggests that periglacial processes have been active on the Mt Higginbotham slopes early during the last glaciation. However Barrows *et al.* (2004) recognise that the age of the distal block deposits may reflect inherited exposure. Webster (1974) documented a large block field on Mt Battery ((6) ~1250 m) a site that is significantly lower than most block deposits documented in Victoria. Small solifluction lobes are relatively common features on the summit areas of the Bogong

High plains and have been observed on Mt Nelse, Basalt Hill and at Middle creek by Rosengren *et al.* (1981) however none of these features have been described in detail. Based on the altitude of these features at >1700 m asl, modern activity would not be unexpected and at Middle Creek the lack of lichen on boulder surfaces incorporated in the frontal lobes of the solifluction deposits may indicate recent activity (Rosengren *et al.* 1981). Extensive block deposits are also located on the western slopes of the Howitt Plains (7) (Rosengren *et al.* 1981) and small block streams are present on the upper slopes of Mt Buller (8) (Webster 1974). Talus slopes of likely periglacial origin considering their altitude, size, lack of vegetation and location adjacent small cliff faces have been noted in the Wellington Plains / Gable End region (9) towards the southern end of the Victorian Alps (Rosengren *et al.* 1981). Further to the east in Gippsland, small block streams and anomalous large scale vegetation stipes are suggestive of periglacial activity near Reedy Creek Chasm (10) at altitudes of approximately 1200 m asl. (McRae-Williams *et al.* 1981). However, these features have not been described in detail and a photograph of the vegetation stripes provided by McRae-Williams *et al.* (1981) does not show any detail that could not be equally explained as stripes promoted by the interaction of sheet wash and vegetation. Further east, surprisingly low elevation block deposits (most likely what this project defines as mountain scree, see chapter 7) have been briefly described by McRae-Williams *et al.* (1981) at Gattamurgh Creek (11) in the Middle Snowy River Valley at approximately 700 m asl. However, McRae-Williams *et al.* (1981) admit to having not visited the site and as far as the author is aware these landforms have not received any further study. Considering this the true morphology and significance of these deposits are unknown their description as block streams can be considered highly speculative.

#### 4.1.2. Western Victoria

An undated block deposit composed of angular sandstone boulders up to 2 m diameter was described by Ashton and Moore (1978) from immediately below the summit of Mt William (12) which is the highest summit (1167 m asl) in the Grampians Range of central Western Victoria. This site has been observed by the author who supports its likely periglacial origin due to the sites altitude, the blocky nature of the boulders and the location on moderate slopes with no significant headwall indicative of slow downslope movement processes. This block slope of likely periglacial origin is the only periglacial site documented from the highlands of western Victoria. Its existence suggests that other periglacial landforms are likely to be present in western Victoria.

## 4.2. Periglacial deposits of NSW and the ACT

### 4.2.1 Introduction

Periglacial landforms have been documented throughout the Australian Alps, and to a lesser extent the Central Tablelands and Canberra districts (Figure 4.1). The widespread distribution of periglacial landforms in the region contrasts with the minimal extent of landforms presently active in the highest areas of the Australian Alps. This suggests that periglacial conditions were far more widespread in the past than at present. The extensive distribution of periglacial landforms compared to the very limited extent of glaciation (Barrows *et al.* 2001, 2002) may indicate that the Australian Alps where too dry during past glaciations for the development of extensive glacial ice.

### 4.2.2. Periglacial landforms of the NSW Alps

Amongst the earliest documented periglacial landforms in Australia were solifluction deposits described as boulder ridges and mounds by Browne and Vallance (1957). These were part of a study into a suite of landforms that suggested plateau ice glaciation once was present over much of the Main Range (13). Galloway (1963) suggested that the majority of the features described by Browne and Vallance (1957) indicating past glaciation were likely to be of periglacial origin. He was amongst the first to describe solifluction lobes, sorted terracettes and boulder deposits found on the Main Range as being of periglacial and not glacial origin. While this early work recognised many periglacial landforms were present in vicinity of the Main Range not many of the periglacial landforms have been morphologically described. An exception is the study by Costin *et al.* (1967) on non-sorted steps that are found on the highest slopes of the main range between Mt Kosciusko (2228 m asl) and Mt Tate ((14) 2068 m asl). Dating of organic material buried by the solifluction deposits indicate that the deposits date to a cool climate shift during the late Holocene with dates of 2500 – 3000 yr BP for activity of the lower solifluction lobes rising to dates of less than 200 years before present for lobes immediately below the summit slopes. This suggests that periglacial processes are active during the present climate, or at least until the warming of recent decades. Woody material buried by a fossil block stream found on the Toolong Range (15) above 1680 m asl, 50 kilometres north of Mt Kosciusko was radiocarbon dated by Caine and Jennings (1968, 1969) to (35±2 yr BP). The block stream generated from a steep headwall production zone leading to a low angle concave deposit between 6 – 12 degrees was suggested by Jennings (1969) to have formed through one of three processes.

1. Solifluction of a pre-glacial deep weathering profile and associated removal of fine grained material from the deposit.

2. A diamicton formed by frost weathering and solifluction with post glacial removal of interstitial fine material.

3. Glacial age frost wedging of coarse material and slope processes influenced by presence of interstitial ice.

North of the Toolong Range, Barrows *et al.* (2004) dated block streams at Ravine (16) using (SED) techniques and indicated block stream activity during the LGM with ages of 12 -24 kyr. The block streams at Ravine originated from bedrock outcrops and are strongly suggestive of mechanical breakdown of bedrock and downslope movement by periglacial frost shatter and ground ice processes. During the early 1970's a number of papers where produced detailing slope landforms described as being of periglacial origin from the NSW Australian Alps. Slope deposits consisting of coarse angular sediment displaying preferential downslope orientation of clasts were described by Costin and Polach (1971) and Costin (1972) as extending to altitudes as low as 1000 m asl in the Snowy Mountains. These include a deposit at Munyang where wood buried by slope deposits at 1370 m asl was dated to approximately 31,000 yr BP. Dates of 26000 and 33700 yr BP where obtained by Costin (1972) at two nearby mid-altitude sites (Island Bend 1160 m asl and Geehi 1370 m asl) where woody debris was buried beneath periglacial deposits. The ages of 31-34,000 yr BP, indicate that these deposits were probably related to periglacial conditions prevalent in the Australian Alps during the initial onset of the Last Glacial Maximum. The 31-34,000 yr BP ages for these slope deposits compare favourably with similar deposits indicating substantial destabilisation of hill slopes in Tasmania around this period (McIntosh *et al.* 2012) suggesting a regional SE Australian cold phase at around 30 to 34 kyr BP.

The climatic interpolation of the previous two studies were summarised by (Costin 1972) as indicating that during the last glaciation periglacial processes were active at elevations of 1000 m asl in the Australian Alps which correlated to a decrease in annual temperatures of 8 – 10°C below present, this was based off the observed altitude of periglacial deposits and the extrapolated modern altitude of likely strong periglacial development loosely based off the current modern permanent snow line ELA. Costin's (1972) interpretation of more extensive solifluction activity on the Main Range approximately 3000 – 1500 years ago indicates a temperature drop of 2-3°C during the late Holocene.

Studies by Jennings (1979, 1982) documented the development of the Cooleman Plains Karst (17) in the northern part of Kosciusko National Park. Where Jennings described the interaction of periglacial solifluction deposits and freeze-thaw talus accumulations with the development on one of Australia's only sub-alpine karst systems. Jennings indicated that solifluction and talus accumulations may have played a direct role in the formation of underground drainage systems by blocking pre-existing stream swallets. However, Jennings (1982) did not describe the slope deposits in detail and a periglacial origin for these deposits was assumed based on general characteristics, proximity to small block streams, altitude  (1200 m asl) and the valley topography that generates frequent sub-zero temperatures linked to cold air drainage.

#### 4.2.3. Periglacial landforms of the Central Highlands

The Brindabella Range (18) rises to 1913 m asl at Bimberi Peak and contains a number of high altitude peaks with steep rocky slopes. The Snowy Flats forms a flat bench of open boggy ground to the immediate east of the high summit of Mt Gingera (1855 m asl). This flat floored valley was investigated by Peterson (1977) for evidence of glaciation. He observed boulder deposits and a possible lake that had been in-filled with organic material and accounted some of the morphology of the area to periglacial processes however did not describe the landforms in detail. Periglacial block streams are known from the Mt Kelly area (19), the Tidbinbilla Range (20) and Mt Coree (21) (Webster 1974, Land Management and Planning Division 2010) these deposits are remote and have not been described in any detail.

A study by Heimsath *et al.* (2001) of the age and associated exposure of tors in the Bredbo River Valley (22) on the eastern edge of the Monaro Plains utilising SED. Suggested that while the tors were old, at least one period of rejuvenation and erosion in the vicinity of the granite tors were readily identifiable and that there may have been multiple periods of erosion between 20 and 160 kya BP. They associated the periods of rapid tor exhumation with the rapid stripping of laterite under periglacial climatic conditions.

On the eastern slopes of Black Mountain in the ACT (23) at an altitude of 590 m Costin and Polach (1973) located a paleosol containing carbonised wood lying beneath thick slope deposits composed of course angular cobbles and gravels within a fine grained matrix. They interpreted the slope deposits to be of periglacial origin based on the preferential orientation of the clasts downslope, and by association with similar much higher elevation deposits located in the Australian Alps to the southwest. The origin of the deposit was later challenged by Wasson (1979) on the grounds that there was no clear evidence for periglacial action. However, the author takes the view of Costin and Polach (1973) that for the deposits to form, vegetation cover was minimal. Considering the moderate altitude (590 m asl) and inland setting of the site, cold and moderately dry conditions under a periglacial climate would be the most likely explanation for the sites lack of vegetation cover and slope processes. While Wasson's (1979) challenge to the origin of this deposit is valid; the deposit is still described in modern literature as indicating periglacial activity in the Canberra region (Finlayson *et al.* 2008). Radiocarbon dating of the wood produced an age of approximately 27,800 yr BP indicating that the overlying periglacial deposit postdates the early last glacial, Costin and Polach (1973) inferred that temperatures sufficient to produce periglacial deposits at this altitude on Black Mountain were likely to have been between 9°C and 12°C colder than the present annual minimum / maximum mean temperatures of 6.5 – 19.7°C (BOM 2012b) these temperatures are consistent with the likely LGM temperature depression calculated by Galloway (1965).

Lake George (24) is a large ephemeral lake about 30 kilometres northeast of Canberra lying at an altitude of 670 m asl. The lake bed has formed as an impoundment adjacent an active fault scarp that has produced a north-south 200 m tall escarpment locally known as the Lake George Range which rises to an altitude of (900 m asl). Talus accumulations consisting of coarse angular gravels forming hilltop and fan deposits on the slopes of the Lake George Range were first recognised by Taylor (1907). Coventry and Walker (1977) suggested a periglacial origin for these deposits based on the morphology of the fan complexes and the radiocarbon ages of deposits dated to a corresponding dry period in the nearby lake bed at approximately 27,000 yr BP.

#### 4.2.4. Periglacial landforms of northern NSW.

North of Lake George periglacial landforms have received only cursory documentation, although the likelihood of periglacial landforms in the higher parts of the Blue Mountains and New England Tablelands was suggested by Galloway (1965). His study was based from observations of periglacial landforms in the Australian Alps and extrapolations of the regional snow lines and modern temperature records to indicate that parts of the New England Tablelands may have been cold enough for periglacial environments to be present during the LGM. However no periglacial landforms from New England were described in his study. Evidence for periglaciation north of Lake George appears to be limited to two documented and dated sites at the Wombeyan Karst (25), an incised valley slope karst on the southern extremities of the Blue Mountain Plateau. Here scree deposits interpreted as being of relict periglacial origin partially infill the Basin Cave (W4) entrance at an altitude of 660 m (Osborne and Branagan 1988). The deposit consists of a 7 meter thick accumulation of angular pebble to cobble grade clasts of Wombeyan Marble. A radiocarbon age of 27,850± 1100 yr BP from a charcoal layer 3 meters from the top of the deposit suggest a last glacial age for deposition. Osborne and Branagan (1988) indicates that present freeze thaw activity in the Wombeyan Karst is limited and that the coarse angular deposits have no modern analogue. A slope deposit composed of angular pebbles and cobbles at a nearby site in the Wombeyan Creek Valley was radiocarbon dated by Jennings *et al.* (1982) to 19700± 1500 yr BP. They suggested that the deposit is indicative of active periglacial processes in the vicinity of Wombeyan at altitudes of 600 – 700 m during the last glacial maximum further studies of slope deposits in the region have not been undertaken. On the north-western slopes of the Blue Mountains alluvial and lacustrine deposits inter bedded with carbonate flowstones were dated at several cave sites in the Wellington area (Frank 1975). Dates of 27900 ± 1500, 27300 and 27760 ± 3370 yr BP were obtained from flowstone layers interbedded with alluvial deposits inside the arch and tunnel caves at Borenore, indicate a dry period where the stream flowing through the caves was either absent or its flow was severely reduced. Frank attributed the development of swamp deposits in the nearby Wellington caves at around 22,500 yr BP to indicate a resumption of a wetter climate during the LGM. These results while not dealing specifically with periglacial deposits indicate a dry and possibly cold period in the region of the Blue Mountains at ~27,000 yr BP.

North-west of Newcastle the high summit area of the Barrington Tops rising to an altitude of 1586 m at Brumlow Top. In a study of streams flowing across the sub-alpine peat bogs Nanson (2009) suggested that the bogs dated to no more than the early Holocene with radiocarbon dates of 11,000 yr BP for basal layers. Nanson (2009) inferred that immediately underlying the organic materials was a compact layer of cobbles and boulders related to periglacial solifluction during the last glacial.

### 4.2.5. Summary

Block deposits are common in the high country in Victoria and in the higher elevation regions of southern NSW and the ACT. Several of these deposits have been described in detail by Jennings (1969), Webster (1974) Ashton and Moore (1978) and Barrows *et al.* (2004) and there is strong evidence in the location, structure and age of these deposits that these deposits most likely formed by bedrock frost shatter and ground ice processes under prevailing late Last Glacial periglacial conditions. These landforms are far more widespread than glacial deposits in the Australian Alps and suggest that moisture balances were not positive enough for extensive glacier growth in the high country. The inferred temperature declines of c. 8-11°C derived from the lowering of block deposit elevations suggest that periglacial activity could have extended much further north along the ranges. This was suggested by Galloway (1965) but has yet to be documented and this possibility is examined in the next chapters. The concentration of boulder ages in the latter part of the last glaciation (e.g. Barrows *et al.* 2004) is curious but matches the apparent lack of pre-last glacial moraines on the SE Mainland (e.g. Barrows *et al.* 2001). In contrast to the Tasmanian geomorphic literature, the documentation of scree and possible relict solifluction / slope deposits at mid to low elevations on the Southeast Mainland is almost entirely lacking. The exceptions are the slope deposits documented from the Canberra District and Central Highlands of NSW. While these deposits have all been described as 'periglacial' the lack of detailed descriptions and study of mid altitude slope deposits more generally requires a degree of caution in designating the deposits as reliable indicators of past periglacial conditions. It is noteworthy that thick angular scree deposits at altitudes of 1100 m asl in the Bogong High Plains were observed by the author during this thesis (Figure 4.2) and may indicate the potential for mid-low altitude evidence of periglacial processes in the Victorian Alps. However to date no potential mid-low altitude relict periglacial slope deposits have been studied in Victoria.

Figure 4.2) Scree deposits within road cuttings at 1100 m asl in the Bogong High Plains.

# Chapter 5. The age and morphologic characteristics of relict periglacial block streams on the New England Tablelands, Australia.

## 5.1. Abstract

This chapter describes block deposits of periglacial origin present in the Great Dividing Range of New South Wales, Australia as far north as latitude 29.5°S. Previously described block deposits had been limited to the Australian Alps and highlands of Tasmania with no documented deposits north of 35°S. Surface exposure dating from four block deposits reveal periglacial activity was present during much of the last glacial cycle. Based on modern temperature data, the higher parts of the Northern Tablelands of northern New South Wales are susceptible to limited freeze-thaw processes today and they would have been much stronger under lower mean annual temperatures during glacial times. The surface exposure ages obtained from the four block deposits are internally consistent but vary between sites. At Malpas, block stream ages range from 14 kya at the top of the deposit to 54 kya on the northern lobe of the deposit. At Mt Temi, the head-wall yields ages of 11 and 15 kya while block stream boulders range from 3 to 14 kya.

Two samples from a block slope at Mt Bin Ben in the Wollemi Region also indicate likely block development during the LGM with ages of 30 and 20 kya. At Guyra a block stream and adjacent boulder deposit has ages ranging from 40 to 70 kya indicative of development during marine isotope stages 3 and 4. In summary, freeze-thaw and ground ice processes are likely to have been the primary drivers of block stream development throughout much of the last glaciation and most likely earlier glaciations of the late Quaternary. These results build on the widespread evidence of periglacial activity in SE Australia at the LGM but indicate that more northerly sites were less affected by LGM reworking. This suggests different climate forcing in northern New England than in the high ranges of south east Australia.

## 5.2. Introduction

The distribution of relict block streams, block fields and associated landforms including screes and solifluction lobes have been widely used as indicators of periglacial processes affecting the geomorphology of mountain landscapes during cold stages of the late Quaternary (e.g. Galloway 1965, Karte 1983, Clarke and Ciolkosz 1988, Harris 2007,Park Nelson *et al.* 2007). In Australia there has been limited research on the distribution and climatic significance of periglacial block deposits. Barrows *et al*. (2004) determined the approximate age of some of these deposits using Surface Exposure Dating (SED) on block deposits in the Australian Alps and Tasmania. For the Australian mainland, their study yielded only LGM ages while a wide range of ages was determined from Tasmania.

The New England Tablelands comprise an extensive plateau in north eastern New South Wales, forming a section of the Great Dividing Range. Most of the plateau falls between 1000 and 1500 m and comprises the largest contiguous area of highland in Australia with approximately 32,000 square kilometres above 1000 m. The tablelands are bordered to the east by the Great Escarpment that drops 1000 m to the coastal plains. The tablelands merge westward into the slopes that lead to the Murray-Darling Basin. The crest of the tablelands marks a major drainage divide between short (steep) east flowing rivers and the main catchments for the Murray-Darling system that drains about 1/6 of Australia. The climate on the New England Tableland is classified as cool temperate (Stern *et al.* 2000). The central regions of the New England Tablelands form high rolling hill country with local relief of generally less than 300 m. Night time temperatures on the New England tablelands are known to drop to below -5°C regularly in winter (BOM 2014) promoting extensive frosts. These frosts are locally amplified by cold air drainage with temperatures below -10°C common in frost hollows and valley floors.

Mapping using Google Earth and aerial photograph interpretation supported by field reconnaissance of block streams, block slopes and block fields (aka felsenmeer: Marquette *et al.* 2004, Hargitai 2014) indicates that block deposits are present on the New England Tablelands generally within 30 kilometres of the Great Divide (Slee and Shulmeister 2015). The deposits commonly take the form of small block slopes at or near breaks in slope that generally extend tens of meters downslope from source areas. More extensive block deposits are present in the forms of extensive block slopes measuring hectares in extent and /or elongated block streams. The northernmost block deposits are observed at approximately 29°50'S (near Glen Innes - see Figure 5.1). This paper presents a description of some of the better developed block streams in the New England Tablelands and provides the first age constraints on their formation using Surface Exposure Dating (SED) based on $^{36}Cl$.

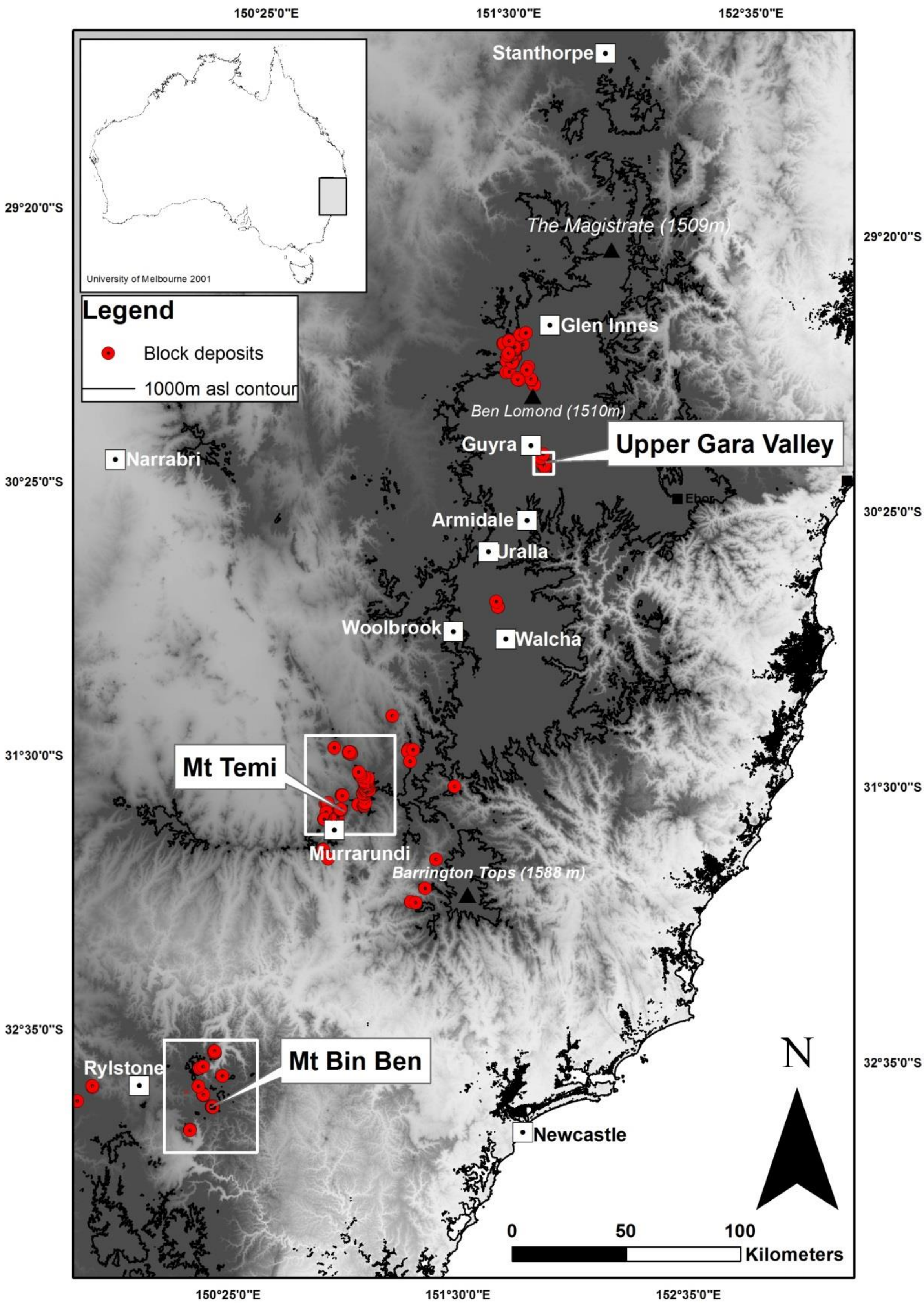



Figure 5.1) Distribution of block deposits in northern NSW, with key sites located.

## 5.3. Methods

### 5.3.1. Survey

Block streams were initially mapped on Google Earth and ground truthed in the field. For all sites described, general field descriptions were undertaken. Follow-up fieldwork involved producing profile surveys of two deposits, Malpas 1 and Guyra 1 at Urandangie near Guyra (hence forth the Guyra site), using compass and clinometer measurements. At key locations 50 blocks were measured for A-axis and B-axis lengths, dip and strike measurements. The dip and strike data were then plotted using the Stereo net program (Allmendinger *et al.* 2013, Cardozo and Allmendinger 2013).

### 5.3.2. Temperature monitoring

The Guyra site was monitored from March 2012 to December 2013 giving two full winter seasons of temperature observations, for the purpose of determining the potential for modern freeze-thaw processes at the site and to use as baseline data for paleoclimate reconstructions. Maxim DS1922 miniature temperature loggers were established in pairs at 1 cm and 60 cm above the ground at 4 locations on the hill slope in the vicinity of the Guyra 2 Block stream including top, bottom and mid-slope locations. The loggers where initially shaded, however the plastic covers disintegrated or where destroyed by animals (sheep, kangaroos and foxes) during the study. The locations were the valley floor adjacent the channel of Urandangie Creek (30°15'54.76S: 151°43'02.08E), the lower mid slope (30°15'52.32S: 151°43'06.80E), the upper mid-slope adjacent to the back sloping lower bench of the Guyra 2 block stream (30°15'48.24S: 151°43'14.44E) and the top of the slope adjacent to a bedrock outcrop that forms the source of the block stream (30°15'46.44S: 151°43'14.89E) (see Figure 5.11). Two loggers were lowered 40 cm depth into voids between the boulders of the Guyra 1 and Guyra 2 block streams with the aim of observing the temperature regime at shallow depths within the block streams to those of the surface (Figure 5.11). A final logger was inserted 15 cm into a horizontal crack within a bedrock outcrop at the top of the study site to gauge the potential for ice development within bedrock cracks in line with Grab (2007). The loggers were covered in thin plastic bags to make them waterproof. Temperature data was recorded on an hourly basis. The data were downloaded utilising the Thermodata viewer program every 90 days.

### 5.3.3. 36^Cl Surface exposure dating

Age and/or erosion data for boulders and rock outcrops were determined using cosmogenic ($^{36}$Cl) dating of Ca rich mafic minerals in basalt. Samples were collected from the crests of large (mostly > 1 m diameter) stable basalt boulders. Boulders that showed evidence of spallation were avoided. The average thickness of samples was less than 5 cm. At least 500g of sample were collected for each site. Shading angles were calculated in the field using a clinometer. Nine samples were collected from the Malpas block stream, while five were collected at the Guyra site, two from a boulder ridge that impounds a back-basin on the top of a landslide deposit and three from the Guyra 1 block stream. A further six samples were collected from the Mt Temi block stream. Four of the samples were collected in a transect down the Mt Temi block stream while two more samples were collected from the headwall above the Mt Temi block stream at (31°41'07"S: 150°51'41"E). The final two samples collected for this study are from the north-eastern block deposit on Mt Bin Ben (32°52'21"S: 150°19'06"E). All of these samples were collected following similar procedures to those detailed at the Malpas site.

Cosmogenic targets were prepared at the University of Exeter SED preparation laboratory following procedures detailed in Barrows *et al.* (2013). Total $^{36}$Cl was measured on the whole rock because the fine-grained nature of the basalts prevented effective mineral separation. The concentrations of major target elements for $^{36}$Cl production was determined using X-ray fluorescence. The concentrations of trace elements with large neutron capture cross sections (Gd, and Sm) and neutron-producing elements (U and Th) were measured by inductively-coupled plasma mass spectrometry. Chlorine content was determined by isotope dilution. The isotopic ratios $^{36}$Cl/Cl were measured by accelerator mass spectrometry on the 14UD accelerator at the Australian National University (Fifield *et al.* 2010). Major and Trace element abundances and neutron capture cross sections are listed in Tables 2 and 3.

Chlorine-36 exposure ages are calculated as detailed following Barrows *et al.* (2013). The ages were corrected for changes in the geomagnetic field (Barrows *et al.* 2001). The production rates were scaled using the scheme of Stone (2000). All analytical errors are fully propagated on individual ages. All ages in the text are reported at one standard deviation.

## 5.4. SED Results

Table 5.1) SED chemical data and results

| Chemical data | | | | | | Exposure ages | |
|---|---|---|---|---|---|---|---|
| Sample | [K2O] (wt%) | [CaO] (wt%) | [TiO2] (wt%) | [Fe2O3] (wt%) | [Cl] (ppm) | Exposure age (ka) | Apparent erosion rate (m/Ma) |
| **Guyra** | | | | | | | |
| GUY-01 | 1.3 ± 0.05 | 8.89 ± 0.08 | 2.25 ± 0.06 | 9.68 ± 0.15 | 3.31 ± 0.23 | **54.2 ± 4.0** | 11.8 ± 1.0 |
| GUY-02 | 1.29 ± 0.05 | 9.15 ± 0.08 | 2.28 ± 0.06 | 9.77 ± 0.15 | 3.04 ± 0.23 | **47.1 ± 3.6** | 13.9 ± 1.2 |
| GUY-03 | 1.34 ± 0.05 | 8.57 ± 0.08 | 2.27 ± 0.06 | 9.86 ± 0.15 | 3.63 ± 0.23 | **51.8 ± 3.8** | 12.5 ± 1.0 |
| GUY-04 | 1.26 ± 0.05 | 9.05 ± 0.08 | 2.37 ± 0.06 | 10.22 ± 0.15 | 3.26 ± 0.25 | **56.0 ± 4.2** | 11.4 ± 0.9 |
| GUY-05 | 1.32 ± 0.05 | 9.13 ± 0.08 | 2.32 ± 0.06 | 9.41 ± 0.14 | 4.48 ± 0.41 | **73.3 ± 5.5** | 8.4 ± 0.7 |
| **Malpas** | | | | | | | |
| MAL-01 | 1.33 ± 0.02 | 9.02 ± 0.08 | 2.54 ± 0.06 | 10.7 ± 0.16 | 7.45 ± 0.34 | **26.2 ± 1.5** | |
| MAL-02 | 1.33 ± 0.02 | 9.27 ± 0.08 | 2.53 ± 0.06 | 9.92 ± 0.15 | 6.22 ± 0.27 | **18.6 ± 1.1** | |
| MAL-03 | 1.41 ± 0.02 | 8.91 ± 0.08 | 2.57 ± 0.06 | 10.51 ± 0.16 | 6.56 ± 0.27 | **55.4 ± 3.1** | |
| MAL-04 | 1.41 ± 0.02 | 9.37 ± 0.08 | 2.55 ± 0.06 | 10.12 ± 0.15 | 10.3 ± 0.33 | **38.8 ± 2.3** | |
| MAL-05 | 1.31 ± 0.02 | 9.08 ± 0.08 | 2.45 ± 0.06 | 10.05 ± 0.15 | 6.33 ± 0.29 | **31.7 ± 1.7** | |
| MAL-06 | 1.33 ± 0.02 | 9.23 ± 0.08 | 2.62 ± 0.06 | 10.47 ± 0.16 | 10.5 ± 0.33 | **29.0 ± 1.5** | |
| MAL-07 | 1.33 ± 0.02 | 9.2 ± 0.08 | 2.49 ± 0.06 | 9.81 ± 0.15 | 4.51 ± 0.2 | **14.2 ± 0.9** | |
| MAL-08 | 1.43 ± 0.02 | 9.3 ± 0.08 | 2.58 ± 0.06 | 9.31 ± 0.14 | 5.67 ± 0.21 | **15.4 ± 0.9** | |
| MAL-09 | 1.03 ± 0.01 | 9.48 ± 0.08 | 2.6 ± 0.06 | 8.77 ± 0.13 | 129.1 ± 2.71 | **15.9 ± 1.4** | |
| **Mt Temi** | | | | | | | |
| TEM-01 | 2.56 ± 0.04 | 5.66 ± 0.05 | 2.57 ± 0.06 | 9.43 ± 0.14 | 19.2 ± 0.53 | **11.4 ± .07** | 68 ± 5 |
| TEM-02 | 2.49 ± 0.03 | 5.91 ± 0.05 | 2.68 ± 0.07 | 9.03 ± 0.14 | 13.12 ± 0.44 | **15.3 ± .09** | 49 ± 4 |
| TEM-03 | 2.51 ± 0.04 | 5.86 ± 0.05 | 2.69 ± 0.07 | 9.37 ± 0.14 | 13.37 ± 0.53 | **11.9 ± .07** | |
| TEM-04 | 2.58 ± 0.04 | 5.96 ± 0.05 | 2.74 ± 0.07 | 8.33 ± 0.13 | 8.75 ± 0.41 | **7.1 ± .04** | |
| TEM-05 | 2.69 ± 0.04 | 5.67 ± 0.05 | 2.63 ± 0.07 | 7.98 ± 0.12 | 7.45 ± 0.36 | **2.9 ± .02** | |
| TEM-06 | 1.18 ± 0.05 | 8.62 ± 0.08 | 2.81 ± 0.07 | 9 ± 0.14 | 10.69 ± 0.41 | **14.3 ± .07** | |
| **Mt Bin Ben** | | | | | | | |
| BIN-01 | 1.4 ± 0.05 | 12.6 ± 0.11 | 3.19 ± 0.08 | 11.45 ± 0.17 | 10.93 ± 0.44 | **30.4 ± 1.8** | |
| BIN-02 | 1.26 ± 0.05 | 11.96 ± 0.11 | 3.01 ± 0.07 | 12.57 ± 0.19 | 14.64 ± 0.49 | **20 ± 1.2** | |

Data are normalised to the GEC standard ($^{36}Cl/Cl = 444 \times 10^{-15}$).
Carrier $^{36}Cl/Cl = 1 \times 10^{-15}$
$^{36}Cl$ decay constant $2.3 \times 10^{-6}$ $yr^{-1}$.
1. C = cosmogenic component.
2. R = background nucleogenic component

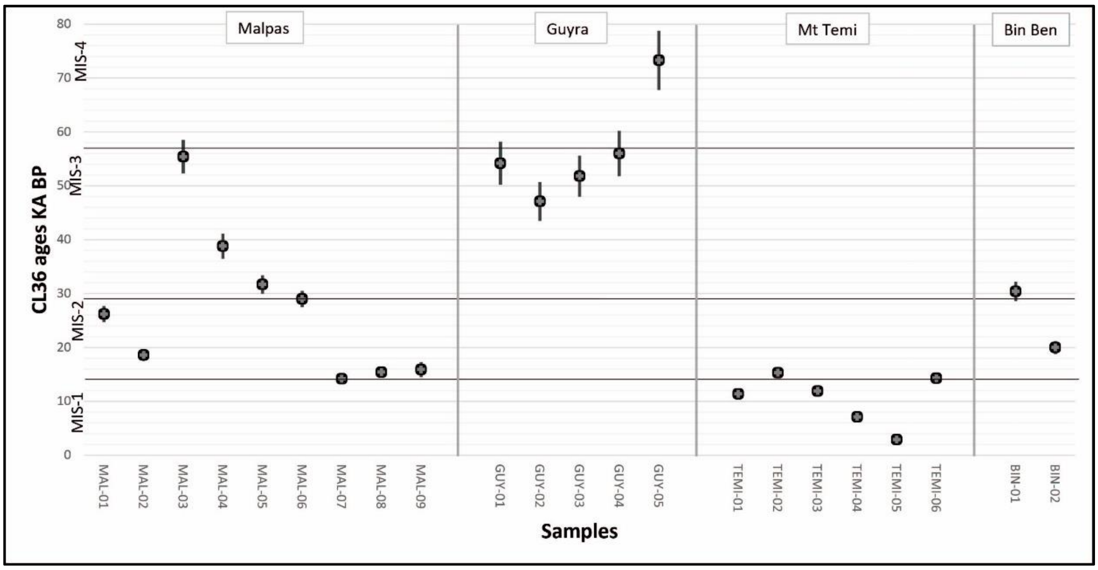



Figure 5.2) Spread of $^{36}$CL SED ages from northern NSW.

The Guyra deposit is notable not only due to its older MIS 3 and late MIS 4 dates, but for their strong clustering that suggests inheritance may not be an issue at this site, or that the blockstreams have reworked an older deposit. Apart from the three samples taken from the upper lobe the remainder of samples from the Malpas deposit have an intermediate spread of ages probably indicating some inheritance or later exposure of boulders by roll-over, however their spread still indicates that the deposit most likely formed during MIS 2 and MIS 3 between 17-37 kyr BP. The Mt Temi and Mt Bin Ben dates as well as the upper lobe of the Malpas deposit appear to have little inheritance and indicate development during MIS 2 particularly during the MIS 2 de-glacial period with ongoing boulder instability at Mt Temi during the Holocene.

### 5.5. Climate monitoring results

Two full winter cycles at the Guyra study site reveals a number of climatic trends. The climate graphs for the top and base of the slope locations are shown in Figure 5.22. From these data mean winter temperatures from the top of slope location indicate that the 2012 winter mean temp of 5.25°C (June to August) was cooler than the 2013 winter temp (6.81°C) by 1.94°C. Two notable local climatic factors are apparent when comparing the figures for the top and bottom of the slope; the first is that there is a clear variation in the magnitude and frequency of sub-zero temperatures recorded. The top of the slope recorded 65 and 40 days with minima less than <0°C during 2012 and 2013 winters respectively. At the base of the slope, the number of nights with temperatures <0°C were 108 and 80 days respectively. This suggests significant temperature inversions and strong effects from cold air drainage down a slope of only 60 m. These observations are also reflected in the mean annual temperatures recorded, with the valley floor location being on average 1.4°C cooler (10.6°C) than the top of the hill (12°C). This trend is slightly stronger in summer than winter with a variation 0.8°C between the mean winter temperature at the base of the hillslope of 5.0°C and a mean winter temperature at the top of hill of 5.8°C.

The second factor is the very significant diurnal oscillation. Diurnal temperature oscillations of between 25° and 32°C are common throughout the year at the base of the slope and during summer at the top of the hill. However, what drives the temperature inversion within the valley is the trend towards long periods at or near the daily minimum (>12 hours) and peaked daily maximums that during winter may only last 4-6 hours. Reduced temperature oscillations of 10 - 15°C during the winter months at the top of the hill may be related to the exposure of this face to westerly winds during this season reducing the effect of radiative cooling.

While bedrock and ground (soil) temperatures were not recorded at the site, observations of the site indicate that periglacial activity is restricted or inactive under the current climatic conditions. This contrasts with the significant evidence of mechanical breakdown of bedrock most likely by periglacial processes in the past. The “frost cracking window” is associated with air temperatures under which freeze-thaw processes have been shown to be active (Anderson 1998, Hales and Roering 2005, 2007, Delunel *et al.* 2010, Andersen *et al.* 2015). It lies between temperatures of -3 and -8°C. While I acknowledge that internal bedrock temperatures would be ideal, these were not collected at this site in the study. Air temperatures have been shown to be indicative of the frost shatter window in regions that have mean annual temperatures in excess of 0°C which has been show to induce shallow but active freeze-thaw in the outer layers of bedrock. These thermal conditions are particularly relevant to cool temperate environments similar to the current prevailing climate of the New England Tablelands and air temperatures have been utilised as proxy indicators of the frost shatter window by Hales and Roering (2005), at moderate elevation locations in the New Zealand Alps and by Dewez *et al. (*2015) to explain observed frost shatter events associated with anomalously cold conditions during the winter of 2009 at a coastal outcrop in France. Other studies including Bartlett *et al.* (2006), Van Manen and Wallin (2012) and Anderson *et al.* (2013) have measured the rates of thermal heat transfer into bedrock surfaces and have found that temperatures within the outer surface of bedrock to depths of approximately 0.5 m correlate well with short term air temperature oscillations. Bartlett *et al.* (2006) also observe correlations between diurnal air temperature oscillations and ground temperature oscillations of 0.97 and 0.89 at depths of 10 cm and 1 m respectively. The site detailed by Bartlett *et al.* (2006) is particularly relevant to the Guyra study site owing to a similar climatic regime of winter temperatures recorded as low as -13°C and summer maximum temperatures in excess of 30°C. The observations by Bartlett *et al.* (2006) spanned a period of a number of years and indicated that warm summer temperatures led to a average background temperature at the bedrock surface of approximately 2.47°C above that of the measured air temperatures. Projecting the potential of ground temperature estimates of the Guyra site with consideration to the observations of Bartlett *et al*. (2006) the potential for ground temperatures <0°C at both the Guyra top and bottom of the hill indicate that temperature conditions would still currently lie occasionally within the frost shatter zone. With a temperature reduction of 9 – 10.5°C

(Galloway 1965, Slee and Shulmeister 2015) and a source of moisture there is little doubt that the prevailing temperature regime would have facilitated frost shatter processes and active generation of the blocks that constitute the block deposits at Guyra, Malpas and sites elsewhere in the New England Region**.**

Observations from the Guyra Hospital Weather station (BOM 2014b) which is located on a plateau at an elevation of 1330 m asl (30°21S: 151°68E) (Figure 5.3) do not show such extreme temperature fluctuations. The data reveals that the Guyra Hospital recorded 51 and 25 days recording temperatures <0°C during 2012 and 2013 respectively and higher minimum recorded temperatures during the 2012 and 2013 winters of -4.7°C and -4.5°C. This is 1.5°C warmer than the hill top site at Guyra and much (8-9°C) warmer than the Guyra valley floor. Temperatures more comparable with the Guyra field site are seen in other weather stations on the New England Plateau where Glen Innes and Armidale have official record minimums of -12.5°C and -11.5°C respectively and Woolbrook located at a lower altitude of 910 m asl but also in a valley floor location (30°97S: 151°35E) has a record minimum of -14.5°C (BOM 2014b). A key point is the strong diurnal oscillations on the Northern Tablelands are exacerbated in valley floor settings. These effects are highlighted in Figure 5.3.

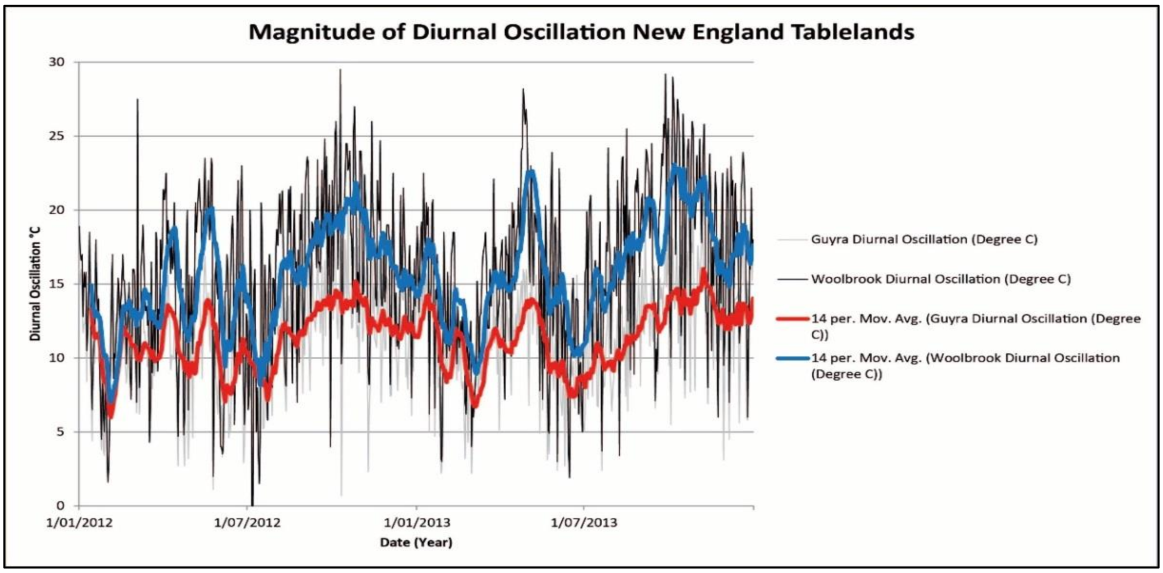



Figure 5.3) Diurnal oscillation values for Guyra Hospital (red) and Woolbrook post office (blue), weather stations for 2012 and 2013.

## 5.6. Study area description

In the northern New England tablelands the most impressive block deposits are centred on a small gorge (30°17’44S: 151°44’38E) of the Gara River downstream of the Malpas Reservoir impoundment (called the Malpas site). A second area of block deposits are associated with large mass movement landforms on south-west facing hill slopes in the Urandangie Creek Valley immediately upstream of the Malpas Reservoir (30°15’52S: 151°43’14E). Detailed mapping reveals 19 block deposits varying in length from 40 m to almost 400 m in length and covering areas of up to 3.6 ha (see Figure 5.4). The three deposits studied in depth were the 340 m long Malpas 1 block deposit (30°17”9’S: 151°44’17’E) located to the south of Malpas Reservoir on the western slopes of the Gara River Valley and the Guyra 1(30°15’52S: 151°43’14E) and Guyra 2 (30°15’42S: 151°43’14E) block deposits located on the eastern valley slopes adjacent to Urandangie Creek. Adjacent to the Malpas 1 deposit an angular scree deposit provides further evidence of cold climate processes at the site. Elsewhere in the greater New England region block fields occur intermittently in other parts of the Great Dividing Range (see Figure 5.1). Block deposits at Mt Temi in the Liverpool Ranges (31°43’37”S: 150°49’34”E) and at Mt Bin Ben in the Northern Wollemi Region (32°49’50”S: 150°16’20”E) present a representative selection of the range of morphologic forms identified within the broader extent of block deposits found in the Great Dividing Range. The morphology of these deposits and their regional context are described.

### 5.6.1. Upper Gara Valley

The 19 mapped block deposits of the upper Gara River Valley vary in area from c. 40 x 30 m (.1 ha) to 260 x 170 m (~ 3.6 ha). The block deposits are distributed between altitudes of 1280 m and 1140 m asl and notably, no major block streams were observed on the flanks of the higher summits that rise to >1450 m. The majority of the block deposits have developed on slopes with southerly and/or westerly aspects. Block fields found on flat summit plateaus are partially buried by weathering products and soil. They are consequently obscured but may be very extensive on the tops. Patterned ground in the form of ~1 m wide depressions that reflect relict stone circles (see cover page) are a feature of the flat summits.

### 5.6.2. Malpas 1 block stream description

The Malpas 1 block stream is a c. 340 m long block stream fed from two headwalls (Figure 5.5A), both at a starting elevation of c. 1270 m asl. The upper block streams merge about half way down (at c. 170 m). The block stream ranges from 5 to 30 m wide and covers 1.24 ha on an E to SE facing slope (orientation 87° above the confluence of the block streams and 140° below the confluence). The southern source has a more pronounced embayed (cirque like) form and the deposit below this headwall is topographically pronounced and un-vegetated for the upper 200 m and lightly vegetated on the lower 140 m of its length.

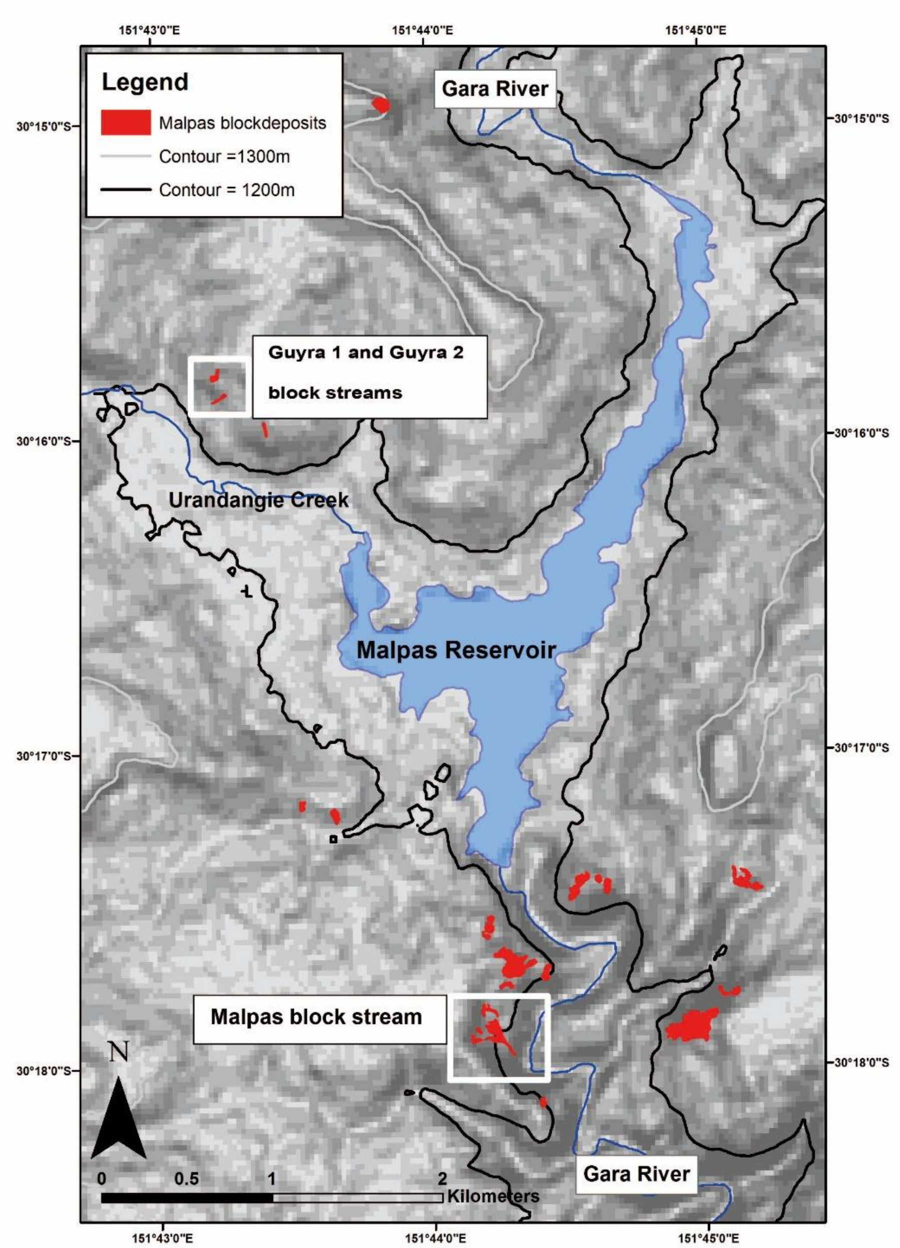



Figure 5.4) Hill shade map of the Malpas Reservoir and surrounds of the Upper Gara Valley. The 1200 and 1300 m contours are black and white respectively. Openwork block deposits that are elongated downslope and are of likely periglacial origin are shown in red.

At the confluence the block stream narrows into a single ridge of boulders 2 to 3 m tall bordered by lateral trenches incised into the slope (Figure 5.5B). The block deposit drops 85 m in altitude over its length from ~1255 m to 1170 m asl. This is a minimum extent as prior to track construction at the base of the deposit; it is likely the deposit flowed to the valley floor at a bend of the Gara River at an altitude of 1145 m asl. Surface pits up to 1.5 m wide and 1 m deep pockmark the surface of the upper part of the deposit. Boulder thicknesses range from 2 m in the lower section (measured at the track cut) and were observed to be at least 2 m but likely thicker in the upper parts.

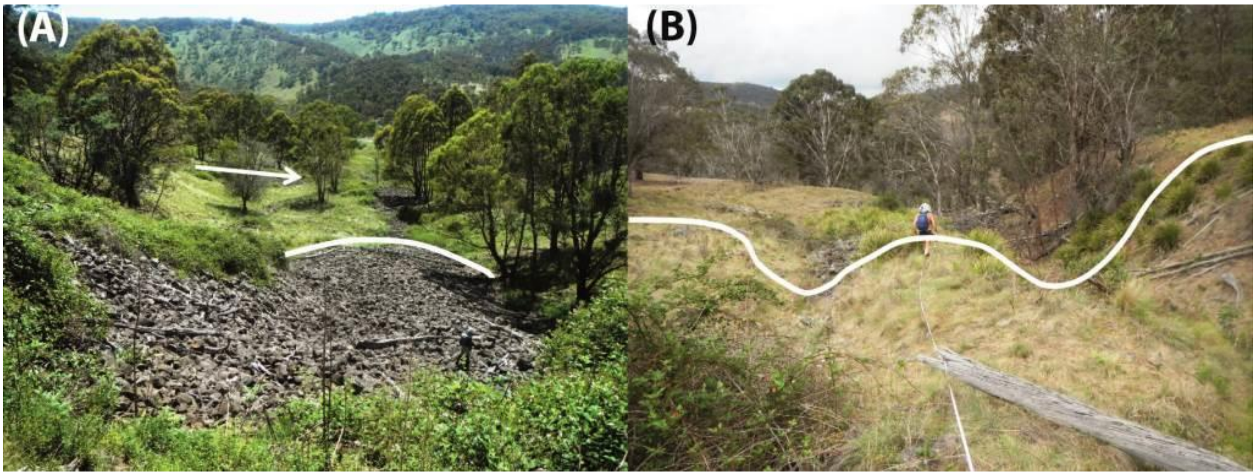



Figure 5.5) (A) Photograph looking from the back wall down over the upper lobe of the Malpas 1 block stream the dotted line indicates the upper edge of the lobes frontal riser. The arrow indicates the direction of flow of the northern arm of the deposit. (B) Lower Malpas 1 block stream below the confluence of its northern and southern flows; note the ridged and partially grassed but low gradient profile of this lower 100 m.

### 5.6.3. Geologic control

The Malpas 1 block deposit is sourced from basalts but largely deposited on Sandon Beds, which are Palaeozoic metasediments of the New England Fold Belt (Voisey 1963). This is clearly observed in the road cutting (30°17’59S: 151°44’16E) where Sandon Beds and associated stratified screes are located immediately to the south of the deposit (see Figure 5.8). The deposit is confined in a narrow channel for the lower 100 m of its length and it lies adjacent to and partially caps a 3 m thick outcrop of compacted fine mottled sediments containing 79.8% fine silts and clays and 20.2% of courser clasts of >2 mm (See Appendix 14). The sediments are generally yellow 10YR 8/4 with mottles of 10YR 8/8, 10YR 9.5/1 and Gley 1 7/10Y. This silty-clay appears to be deeply weathered Sandon Beds.

### 5.6.4. Block stream profile and sedimentological measurements

A transect of the Malpas 1 deposit was undertaken. Three distinct sections of the deposit were noted. The uppermost part of the deposit is approximately 72 m long and starts on the 30 m tall head wall which is at an angle of about 38°. Within 30 m the slopes have dropped to around 17° and this upper section ends in a distinct lobate topographic step that has a slope of 19° over a distance of 18 m. Fifty sub-rounded boulders with average a and A-axis lengths of 41 and 28.3 cm and a maximum a-b axis length of 65 x 42 cm were sampled for A-axis dip and dip direction measurements. The A-axis dip and dip direction orientations within this upper section (Figure 5.6B) reveal no strong clast orientation and a wide range of dips averaging 24.7° (range 0° to 65°). The middle section of the deposit (Figure 5A) features a reduction in the overall slope to about 11°. There are a number of steps and lobate forms that have slopes varying from flat benches to 22 fore-slopes (see Figure 5.6A). A-axis dips taken from sub-rounded boulders with average A and B-axis lengths of 39 and 24 cm and a maximum boulder size of 75 x 45 cm on the top of the lower large lobate step on a slope of 15° (Figure 5.6C) reveal a bi-modal imbrication of boulders with a strong downslope trend of 130°SE and a secondary trend of around 73°NE. Secondary boulder orientations to the west (230° and 326°) are associated with reverse-imbricated boulders. Below the confluence of the northern arm of the block stream the lower section of the block stream is in general characterised by gradients of less than 11° (Figure 5.6A),

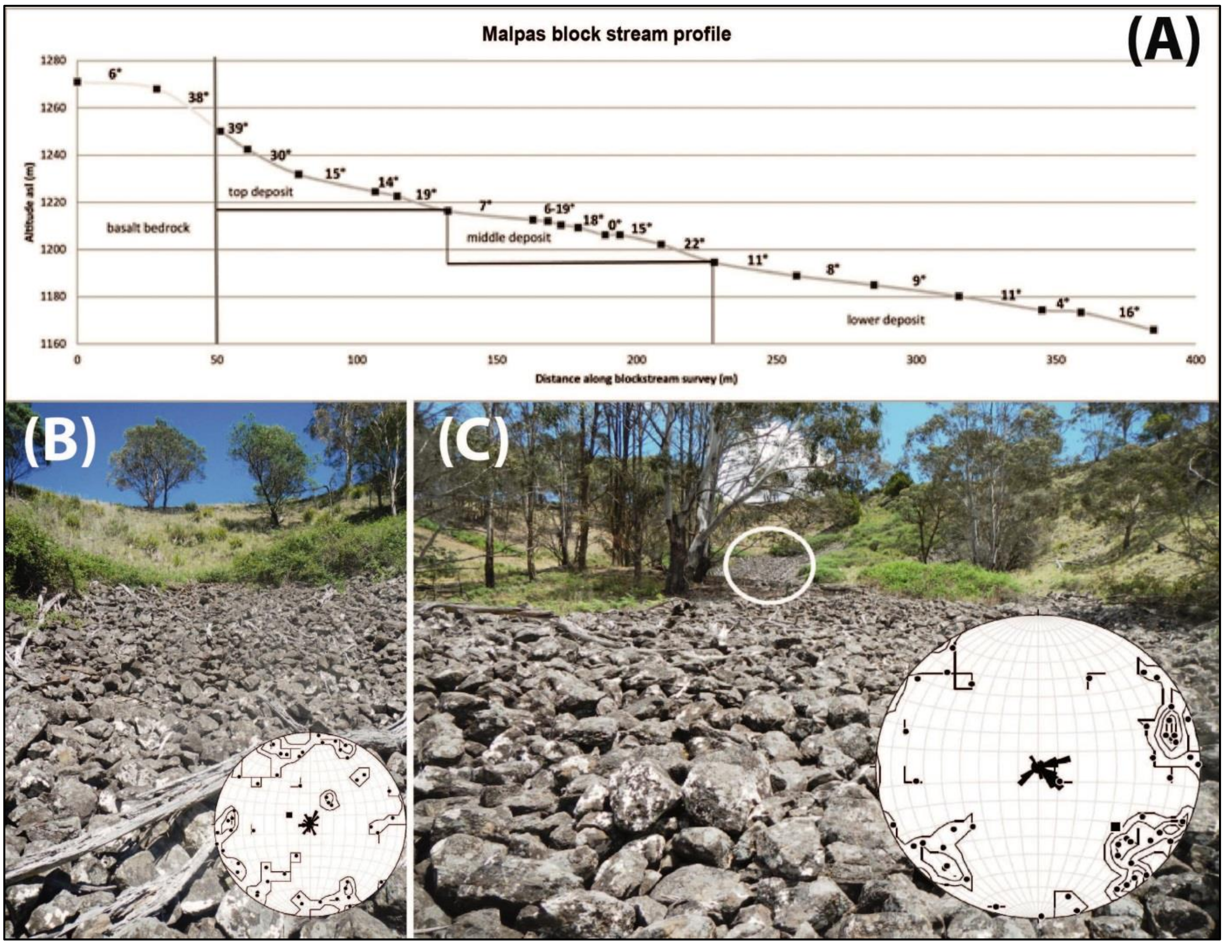



Figure 5.6) (A) Profile of the Malpas 1 block stream separated into three distinct topographic units associated with changes in slope and block stream morphology. (B) View of the top of the deposit with stereo net of clast orientation. (C) View of the middle section of the deposit with stereo net of clast orientation, note the preferred orientation compared to (B), the location of which is circled in the background.

### 5.6.5. Age control

The transect of the Malpas 1 block stream (Table 5.1) shows ages that span the period from the late MIS 2 to early MIS 3. The results reveals that the upper western lobe was likely formed during the Last deglaciation as evidenced by the MAL-7 14.2±0.9 kyr, MAL-08 15.4±0.9 kyr and MAL-09 15.9±1.4 kyr ages. The lower section of the block stream appears to be formed of boulders that have been sourced from the back-wall between 26.2±1.5 kyr and 38.8±2.3 kyr. The MAL-02 date of 18.6±1.1 kyr is out of sequence but may be exhumed or more likely rolled over. The older MAL-03 date of 55.4±3.1 kyr was sampled from the northern arm of the deposit which has a different and most likely less active source area. This age suggests older block deposit formation on site.

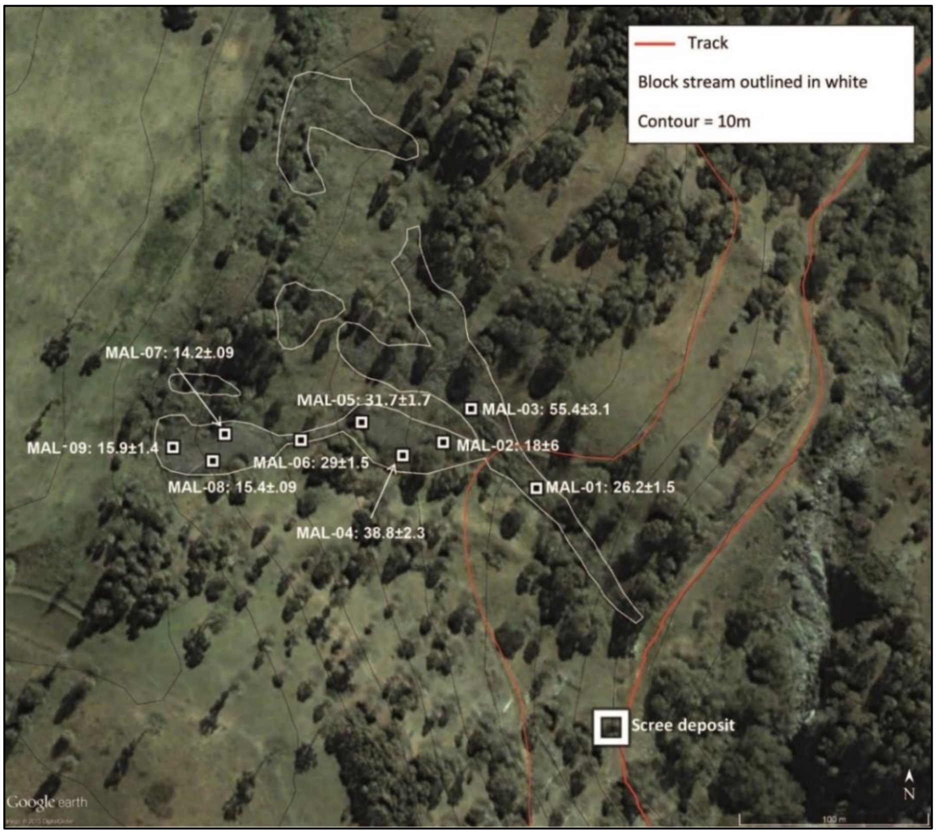



Figure 5.7) Google Earth Pro image of the Malpas 1 deposit with locations and (SED) ages of sampled boulders.

### 5.6.6. Interpretation of Site

The site remains an openwork block deposit suggesting that block stream producing processes are either still active, which is unlikely given the vegetation of the source scarp, or that there is a mechanism to prevent soil development. The rose diagrams in Figure 5.6 strongly suggest that the dominant process in this upper lobe of the deposit is the accumulation of boulders eroded off the back-wall by simple down slope gravitationally driven mass movement. The boulders are rounded and as a consequence the freeze-thaw processes that originally detached them from the headwall are likely to be relatively old as bedrock exposures elsewhere in the Gara Valley indicate that the fine grained basalt of the area cracks into angular clasts. I acknowledge that thermal shatter can result in angular deposits occurring in semi-arid to arid environments (Hall *et al.* 2002) as can salt weathering that is efficient at weathering rock in arid and coastal localities (e.g. Goudie 1970, Viles and Goudie 2007). However neither of these processes have extensive block deposits documented in Australia. It is also noteworthy that observations of back wall source areas for the block deposits indicate marginal to no weathering under the current warmer and drier Holocene climate. Conditions that should be more suitable to both thermal and salt weathering if these processes where a major component of landscape denudation of the 'periglacial' sites. The age of block deposits suggest main activity during cold periods of the last glaciation and the lack of modern denudation is significant ancillary evidence for the freeze-thaw and ground ice origin of these deposits. The small hollows found in the upper part of the deposit may be ice melt-out pits. While tree roots have been shown to produce hollows in landscapes (Clinton and Barker 2000) there is no evidence for large trees growing on the deposit under current climatic conditions despite the surrounding forest cover. In addition the depressions have a problematic morphology for root stock depressions (tree fall) as they are circular in form and do not have the common hump associated with root ball rotation and uplift of the soil associated with tree fall (Beattie and Stone 1985). Another critical observation is the presence of the lobate and stepped forms that include transverse ridge and furrows of 0.5-1 m amplitude which is inconsistent with simple mass movement, and suggests a flow. Since there is no matrix in the boulders, the most likely candidate for flow is seasonal ice. The low gradients on the lower part of the deposit also suggest a mediated flow.

The SED ages are consistent with activity at this site during MIS 2 and MIS 3. The change in age between the top of the southern lobe and the lower sections of this lobe are consistent with the change in morphology of the lobe and supports the concept of multiple phases of formation. The main issue is the question of inheritance. Without samples from the headwall, which was unsuitable for dating due to the limited exposure of bedrock mantled under slope deposits and vegetation, dating is reliant on the ages coming from the lobes. The deglacial age at the top of the southern lobe indicates that inheritance may not be significant at this site. It can therefore be assumed that the upper lobe most likely developed late in MIS 2 and most likely 14-17 kya. The middle section of the deposit appears to indicate blockstream development during the late MIS 3 with dates from 27 to 38 kya. Below this two younger dates of 26 and 19 kya may indicate LGM activity. They are out of sequence with the late MIS 3 ages further up the block stream. Given the strongly ridged form of this lower section of the blockstream there is the potential that these boulders have been overturned and/or exhumed. This may not be a problem as it may reflect ice mediated movement of the lower lobes during the LGM, while blocks on the higher slopes move under simple gravity processes. There is also one age that suggests that part of the northern lobe was active in MIS 4. With this in mind there appears to be activity on the site spanning MIS 4 to late MIS 2, however there is an indication of three peaks of development with a MIS 2 deglacial age for the top of the upper lobe, a mid- to late- MIS 3 age to the lower parts of the upper lobe and LGM activity (MIS 2) in the lower lobe and base of the upper lobe. The sampling does extend to the lowest part of the block stream and therefore I cannot exclude the possibility of older ages from the lowest part of the lower lobe. In fact, most likely only the most recent phases of development have been dated, and it is likely that the feature developed over multiple phases of activity in during the late Quaternary.

#### 5.6.7. Angular scree

A slope deposit formed of angular mudstone / siltstone pebbles with a fine yellow silty matrix is exposed in the Gara River track cutting immediately south of the Malpas 1 block stream (Figure 5.8). This scree appears to have a local source from the Sandon Beds immediately upslope of the deposit and the pebbles within the deposit exhibit a moderately strong imbrication with A-axis orientations preferentially dipping to the East with an average imbrication of 107° east (downslope) and a dip of 24.7°. The average A-axis length of individual clasts is in the range of 10-30 mm with occasional larger pebbles up to 100 mm. The deposits are crudely stratified.

The crude stratification, angularity of clasts and lack of organic material all suggest that this deposit formed when there was little or no woody vegetation on the valley slopes above it, as the vegetated slopes under the current climate would inhibit the fracturing of clasts and transportation of this material. The deposit supports the inferences of the neighbouring Malpas 1 block stream that the slopes of the Upper Gara Valley were sparsely vegetated and impacted by significant frost shatter and local solifluction / gelifluction processes (Hétu and Gray 2000) during the period of formation of the mass movement deposits.

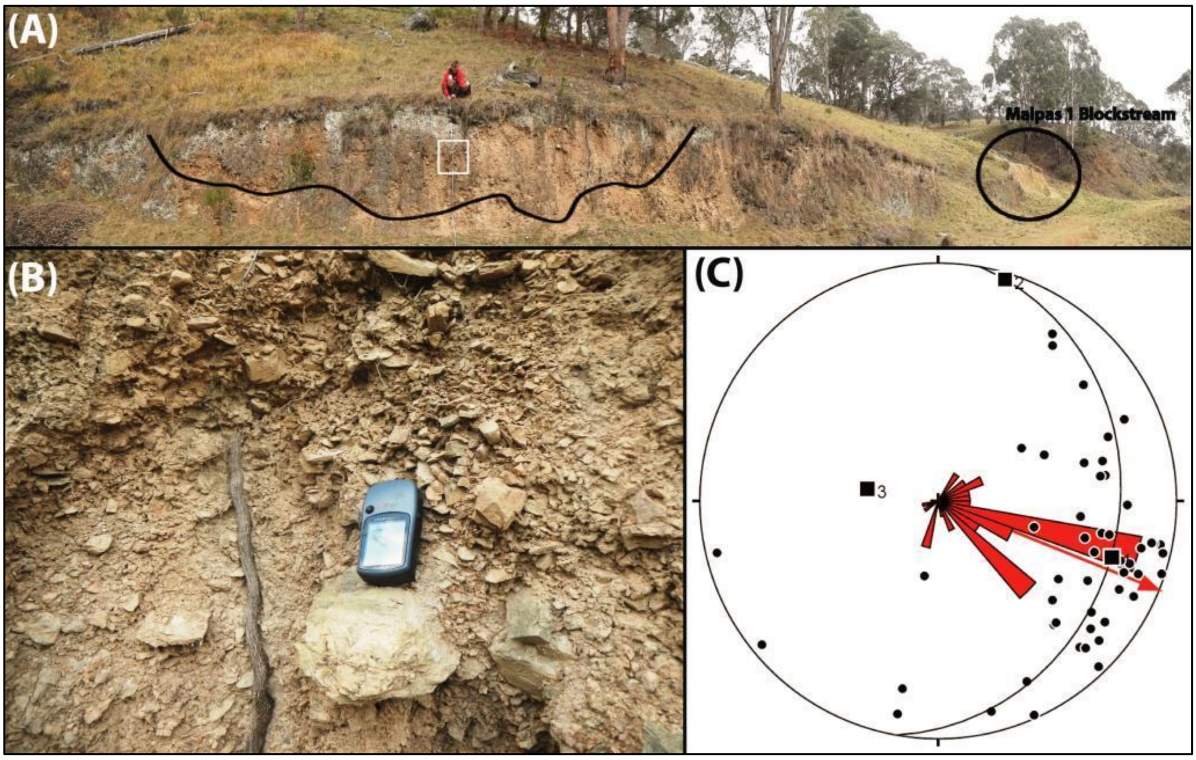



Figure 5.8) (A) The location of the scree deposit in relation to the end of the Malpas 1 block stream (circled). (B) Close up of the angular scree deposit. C: Stereo net showing preferred orientation of A-axis downslope and to the east 112°.

## 5.7. Guyra1 block stream

### 5.7.1. Description

The Guyra 1 block stream is approximately 90 metres long (Figure 5.9). It is located on a west-south west (236°) facing hill slope and has a headwall source at the top of the hill that is disconnected from the current blockstream by many tens of metres. The upper 15 m section of the deposit has a slope of around 30° before shallowing to slopes of 9-15° in the middle 50 m. The slope steepens again to 18-25° over the lower 25 m at the toe of the deposit. The toe of the deposit lies immediately above a spring seep (see Figures 5.9, 5.10). The total vertical drop of the deposit is 29 m from an elevation of about 1240 m asl. The deposit is composed of basalt boulders with a typical A-axis length in the range of 30-60 cm. An excavation of the lower part of the deposit approximately 15 m from its toe, revealed that it is in excess of 1 m deep and is reverse graded with small boulders and cobbles with a-axes of 10-20 cm, at a depth of >1 m. These grade up through the block stream, to the >50 cm boulders that commonly mantle the surface of the deposit. A -axis dips and strikes from the centre and lower reaches of the block stream to reveal a moderately strong clast imbrication downslope and towards the southwest (220°). In the lower 40 m of the deposit there is an incipient gully in the middle of the block stream

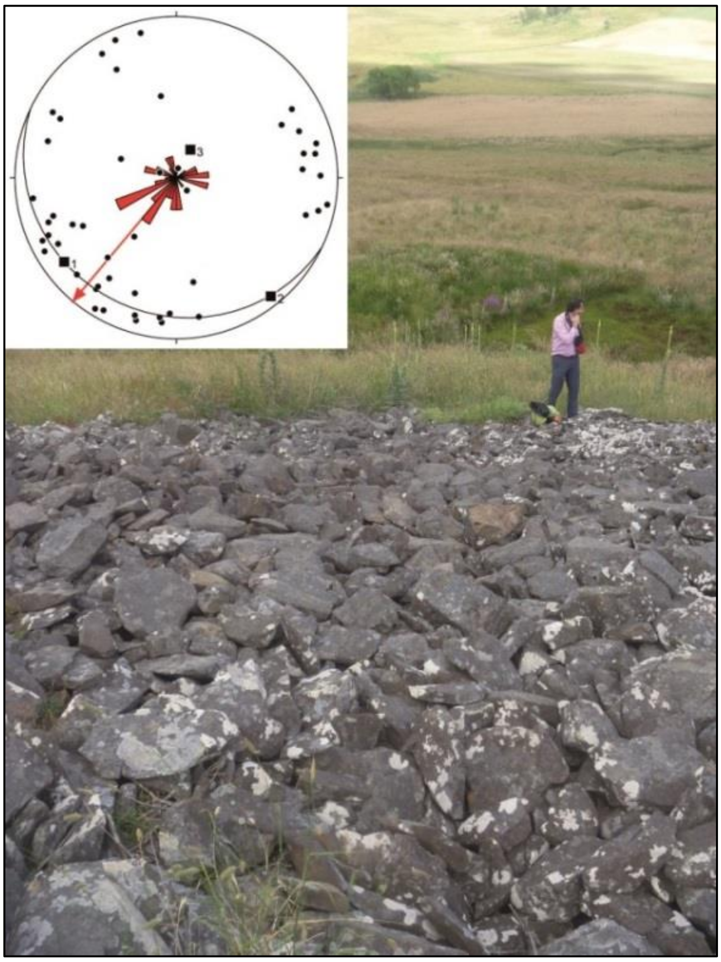


Figure 5.9) View of the lower section of the Guyra 1 block stream, note the seep at the base of slope evidenced by the dark green vegetation behind the figure in the resplendent shirt (which cannot be missed). The stereo net show the general downslope orientation of 50 boulders on the lower section of the deposit.

### 5.7.2. Geologic control

In the vicinity of the Guyra 1 block stream all slopes and valley floors are composed of Tertiary basalts, however, there is strong variation in the basalt. The upper unit of basalt capping the summit plateau is composed of fine grained, regularly jointed, columnar to massive basalt. This unit is the source area of the block deposits. Below this a unit dominated by weathered vesicular basalt, tens of metres thick. These weathered horizons contain springs near the base of the slope and due to their clay rich weathering mantle appear to have promoted significant landslide and possible solifluction lobe development on southern and western facing slopes.

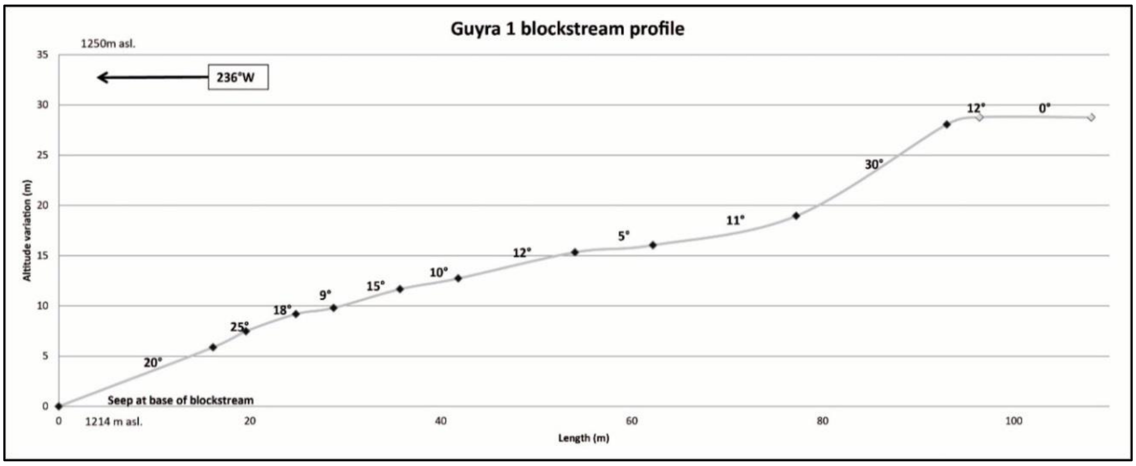



Figure 5.10) Guyra 1 block stream profile

### 5.7.3. SED results

The three samples from the Guyra 1 block stream (Figure 5.11) yield results that are nominally early MIS 3 in age (51.8 ± 3.8; 56± 4.2, 73.3 ± 5.5 kyr). Alternatively if the SED results are used to calculate an erosion rate, rates of 8.4-13.9 m per MYA are achieved. Ages were also recovered off a boulder ridge that partly encloses a back basin and which is interpreted as a pronival rampart (see Chapter 6). This yielded ages of early MIS 3 (54.2 ± 4 and 47.1 ± 3.6 kyr) and is consistent with the ages from the block stream.

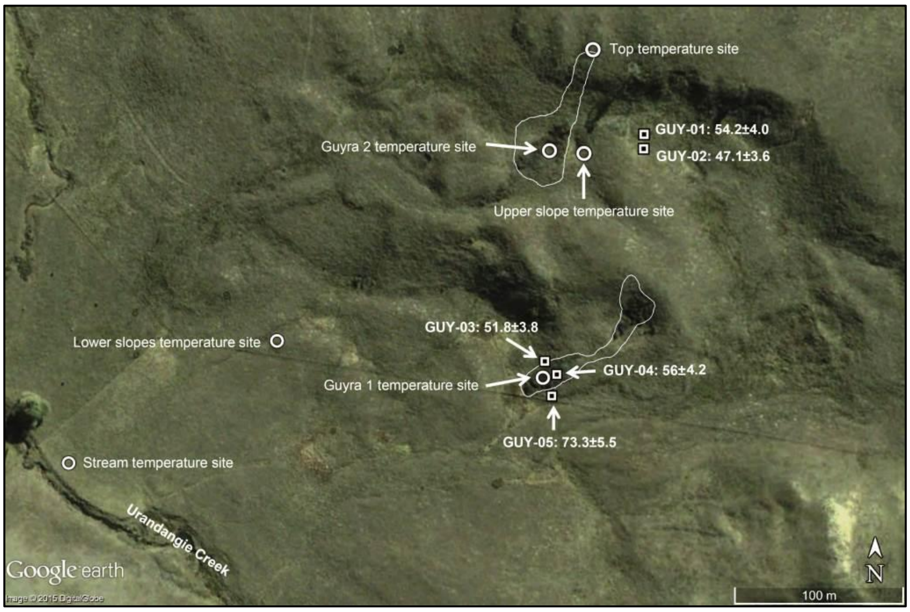



Figure 5.11) Map of SED sample sites and the locations where temperature loggers were established during 2012 and 2013.

### 5.7.4. Interpretation

The block stream is again openwork indicating that there are processes maintaining the freshness of the deposit. At this site, the presence of an incipient trench in the lower part of the deposit suggests recent slumping and indicates through-flow of water through the block stream. This is the most likely mechanism to prevent soil build up in these features. Again very low slopes are recorded and pure gravitational movement down slope is unlikely except in the immediate vicinity of the head wall. The reverse-graded profile is typical of many periglacial block streams (e.g. White 1976, Caine 1983, André *et al.* 2008, Wilson 2013, Gutiérrez and Gutiérrez 2014) and is thought to be promoted by ice segregation within the deposit differentially heaving larger boulders towards the surface. In addition this opens voids in the deposit that upon melting, promote the collapse of finer clasts into the voids between the larger clasts (André *et al.* 2008). The headwall is largely vegetated and the feature is inactive at the present day. One key feature of this block stream is that the local headwall is not part of the main slope but part of a detached block. It is likely that the blocks in the block stream were originally generated when this area was still part of the main hill slope. The formation of the blockstream itself post-dates the formation of the detachment as it is unaffected by the detachment.

The SED ages are consistent with a simple interpretation of an early to mid MIS 3 age of formation. However it is challenging to explain why these boulders are consistently older than boulders from Malpas which is only 5km to the south sourced from a similar lithology. One notable difference is detachment of this blockstream from the main slope. If the blocks were formed when this area was part of the main slope and then recycled into the block stream this might account for the significant age of this feature. There is a thick felsenmeer on the top of the main hill and material eroded from this source is likely to yield ages with significant inheritance. However, it should also be noted that the boulder ridge yields ages that are indistinguishable from the block stream and its boulders are derived from the main hill scarp. All evidence suggests activity early in MIS 3.

## 5.8. Mt Temi block stream

### 5.8.1. Introduction

Block deposits are common in the upper Hunter River Valley adjacent to and on the upper slopes of the eastern Liverpool Range and western slopes of the Barrington Tops and Woolooma Range. Notable block deposits can be found below Crawney Mountain, Mt

Tamarang, Big Jack White Mtn, Mt Helen and Mt Temi and occur from immediately below the summit of Crawney Mtn (1444 m) to altitudes of around 700 m asl (Figure 5.12). Two deposits that lie immediately below the western face of the pyramid shaped peak of Mt Temi (1254 m) (at or about 31°41’04S: 150°51’41E, altitude 1225 – 1090 m asl.) were investigated and 6 samples were recovered for SED from the larger feature (see Figure 5.15A) for sample location and map of the deposits). Here the main deposit has its source in a 4 m tall headwall formed of massive basalt. The block stream is a 300 m long triangular shaped deposit that tapers down slope. The deposit has a westerly aspect of 292° and covers approximately 1.6 ha. The boulders and cobbles of the upper section of the main deposit have a slope near that of the angle of repose at ~30°. This gradient decreases through the middle of the deposit to 20° and the lower 50m of the deposit has a gradient of 15° with topographic steps in the form of small (<30 cm) terraces and a <1m tall frontal lobe. The deposit consists of sub-rounded to sub-angular cobbles to small boulders of 15-30 cm A-axis (90%) and sub-rounded boulders up to 2 m A-axis length (10%). The deposit is connected to the source headwall by a scree of sub-angular to angular clasts (A-axis <10 cm long).

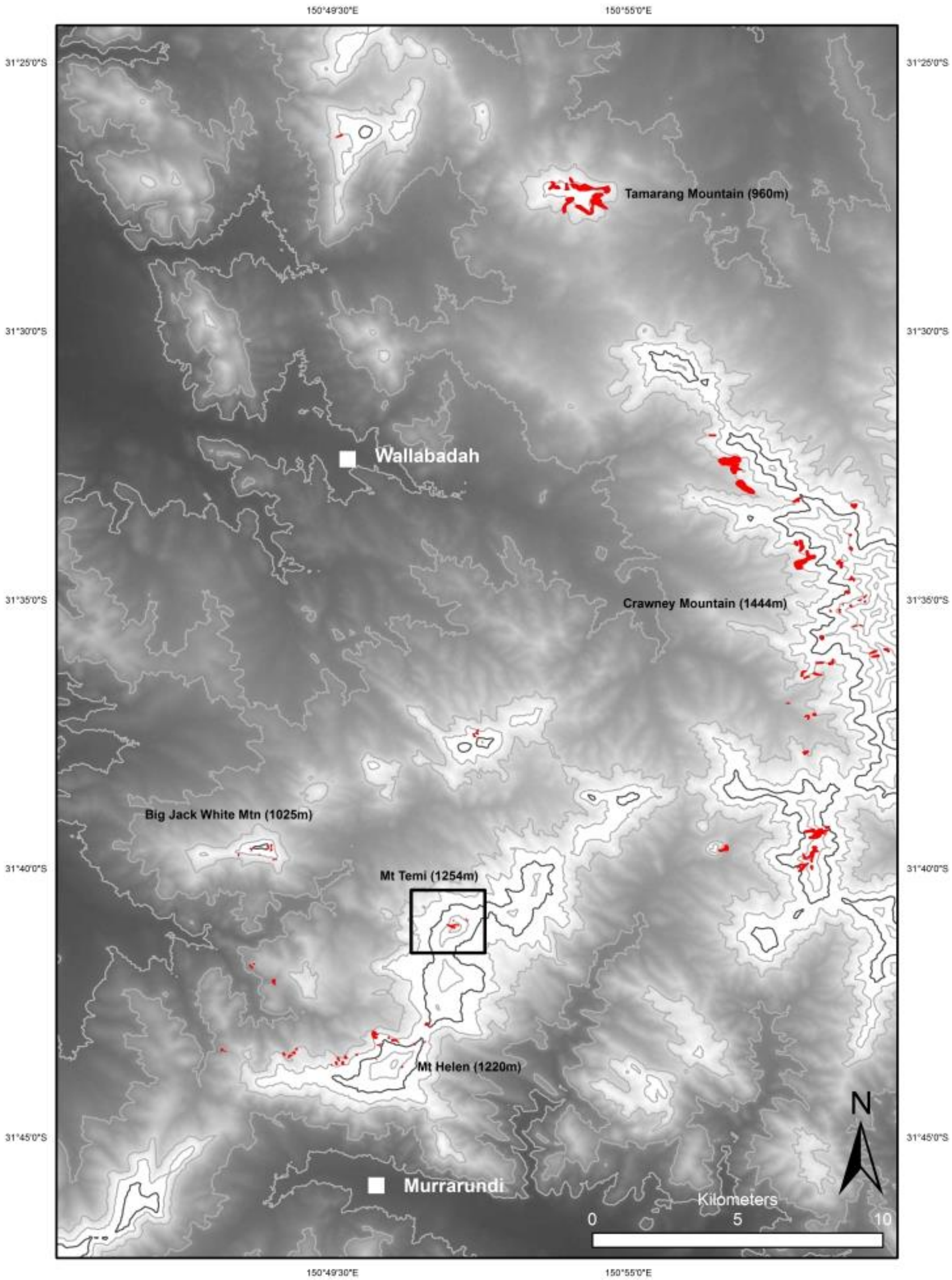



Figure 5.12) Map of the eastern Liverpool Ranges in the upper Hunter Valley. Block deposits are highlighted in red.


Figure 5.13) (A) Basalt bluff at the top of the Mt Temi deposit, showing the site of TEMI-01 sample (immediately above man). (B) Large boulders 1-2 m long constitute c.10% of the Mt Temi deposit sample TEMI-04 was taken from the large column on the right.

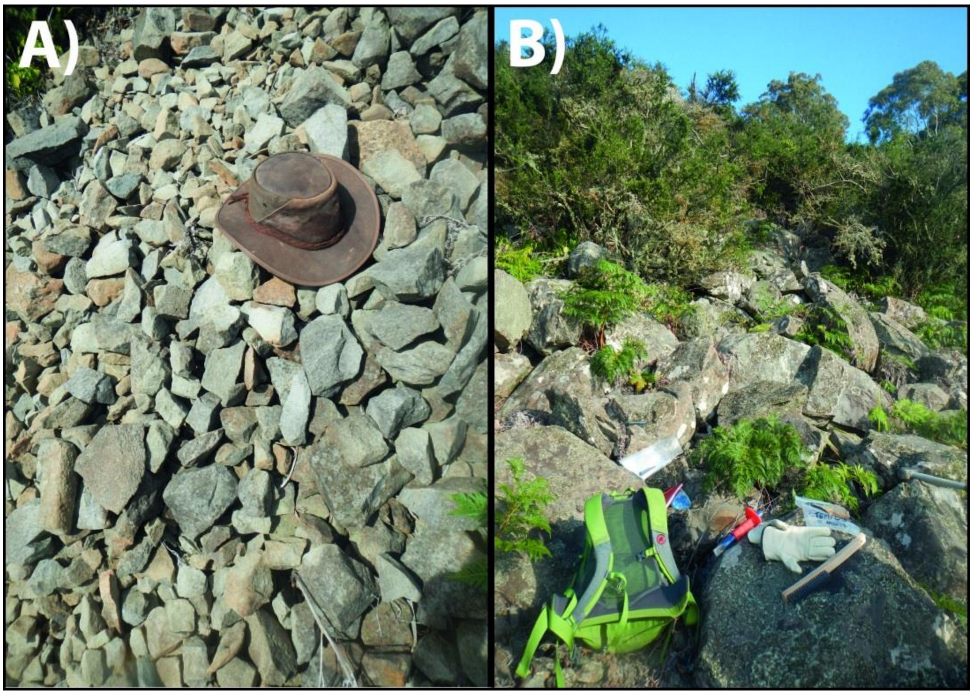



Figure 5.14) Comparison of the fine loose scree on steep slopes near the top of the Mt Temi Deposit (A) and the boulders located on the blockstream below at the Temi-03 sample site (B).

### 5.8.2. Age control

The two samples (Temi-01 and Temi-02) taken from the free face at the top of the deposit returned dates of 11.4±0.7 and 15.3±0.9 kyr respectively. The other 4 samples returned dates that range from 2.9 ±0.2 kyr to 14.3 ± 0.7 kyr from the block stream deposit.

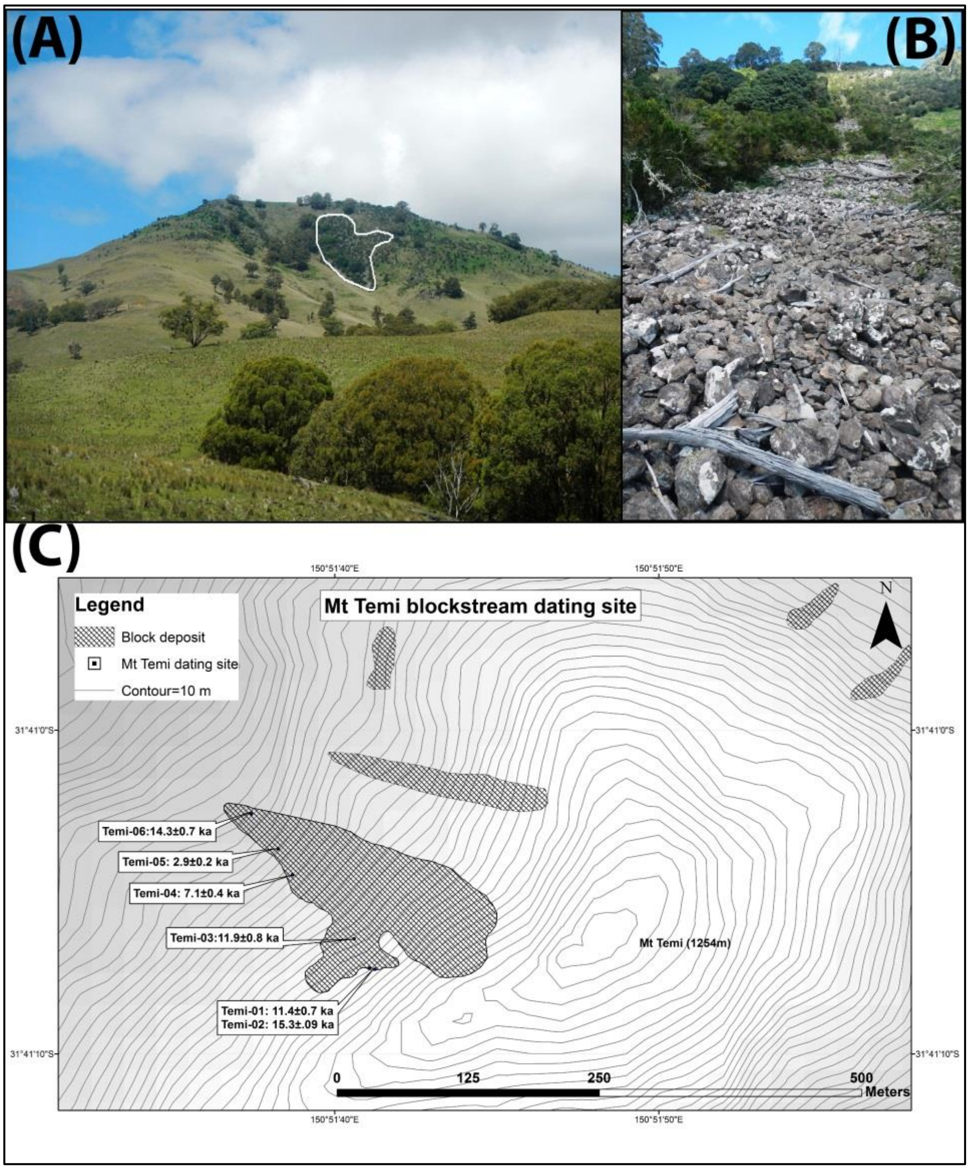



Figure 5.15) (A) View of Mt Temi summit with Mt Temi block stream highlighted. (B) Shallow steps located on the middle section of the blockstream. (C) Google Earth Pro image of the Mt Temi Blockstreams (outlined) and the locations and ages of SED results.

### 5.8.3. Interpretation

The deposit is mainly inactive but there is small scale erosion of the headwall producing fine angular scree the scree indicates that the site is still active however the variation between the finer scree and the sub-rounded boulders and cobbles located on the main block stream (Figure 5.14) indicates that the processes currently effecting Mt Temi do not relate to those that produced the blockstream during the late stages of MIS 2. A feature of this deposit is that it is constrained by two prominent lateral ridges of 2-3 m relief. The lateral ridges along with further boulder deposits downslope of the well-defined deposit (Figure 5.15C) undated boulders) may be indicative of an earlier more extensive phase of block stream and / or landslide mass movement on this slope.

The simplest interpretation is that the ages from this deposit are effectively modern or at least Holocene. This is based on using the rock-face ages as an indicator for inheritance and subtracting the inheritance age from the ages on the block stream. This would yield ages that are modern for almost all samples. An alternative model is that there was a significantly larger source area when the block stream was active and that the blocks on the slope are largely sourced from areas of the rock face that were 1.5 m or more below the surface. This would provide material with little inheritance for the block streams and yield maximum ages of last glacial termination for the block stream. The geomorphological evidence suggests that the block stream is only weakly active at the present day. Therefore it can be concluded that a late deglacial glacial age is quite likely but also note that the deposit is clearly geologically young and is unlikely to even reach an LGM age.

## 5.9. Mt Bin Ben blockfields

### 5.9.1 Introduction

Mt Bin Ben (1098 m; 32°52’28S: 150°18’57E) is one of several isolated basaltic pyramid shaped peaks and rounded plateaus that rise to altitudes in excess of 1000 m asl about 300 m above the sandstone plateau of the northern Wollemi Region in the southern Hunter Valley (Figure 5.16). These summits feature block fields with the largest examples (i.e. those on Mt Kelgoola, Nullo Mtn (Figure 5.16) located on south and south easterly slopes. Block fields can be found on all sides of Mt Bin Ben to a minimum altitude of approximately 915 m (Figure 5.17). These deposits comprise steep block fields giving way to flatter apron areas at the foot of the slope. They are strongly concave in plan form. The two block fields investigated on Mt Bin Ben were Bin Ben 1 on the northeast slope (3.22 ha; 32°52’21S: 150°19’6E) from which two samples were taken for surface exposure dating and the

Southern Bin Ben 2 block deposit (1.64 ha; 32°52’30S: 150°18’49E). Bin Ben 1 consists of an extensive accumulation of small boulders extending around the northern and eastern slopes of Mt Bin Ben. This deposit has upper- slopes of between 25-35° that end in low angle frontal lobes.

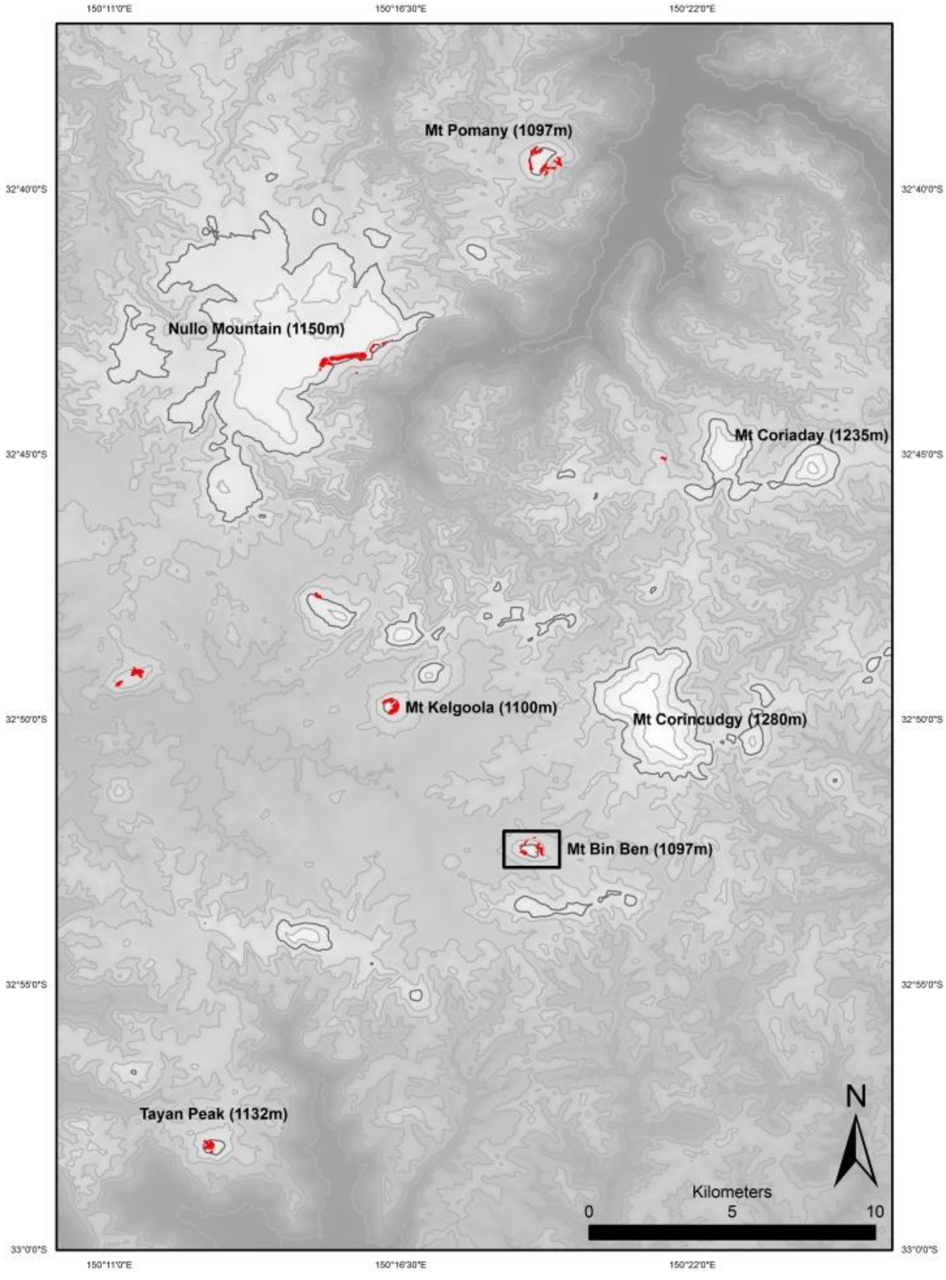



Figure 5.16) Block deposits associated with basalt summits >900 m asl in the northern Wollemi region. The Mt Bin Ben deposits (boxed) were studied due to their comparatively easy access.

The deposit is formed of large cobbles to small sub-rounded boulders, generally 20-60 cm in A-axis length the two sampled boulders BIN-01 and BIN-02 were sampled from near the outer edge of the lower lobate bench at the northern end of the Bin Ben 1 deposit (Figure 5.19). The boulders were approximately 15 m apart and were selected for their size, shape and their location within the deposit. Bin Ben 2 exhibits a well-defined break in slope, from a 26-35° slope in the upper section, to a lower terrace with 5-10° slopes and minor (c. 30 cm high) ridges. This lobate lower terrace is fronted by a 1-2 m tall riser (Figure 5.18). Boulders in both deposits are formed of equant shaped; sub-rounded basalt blocks most (90%) of which have A-axis lengths of 15-30 cm with the remainder comprising larger boulders with A-axis length of up to 60 cm.

### 5.9.2. SED Results

The two Bin Ben samples BIN-01 and BIN-02 returned ages of 30.4 ± 1.8 kyr and 20 ± 1.2 kyr respectively (see Table 5.1).

### 5.9.3. Interpretation

These deposits are distinct from block streams and block slopes observed elsewhere in New England as neither block deposit has a distinct head wall. Hence while the upper section of the block fields are near the angle of repose and could be defined as coarse screes, there are no cliffs from which the boulders comprising the deposits could be sourced and which would drive normal gravity induced mass movement. The lower sections of both deposits feature low angle benches and lobate outer risers and a concave plan form profile (Figure 5.20). While two samples means that only a preliminary age interpretation can be provided, the samples indicate block production during MIS 2 at this site.

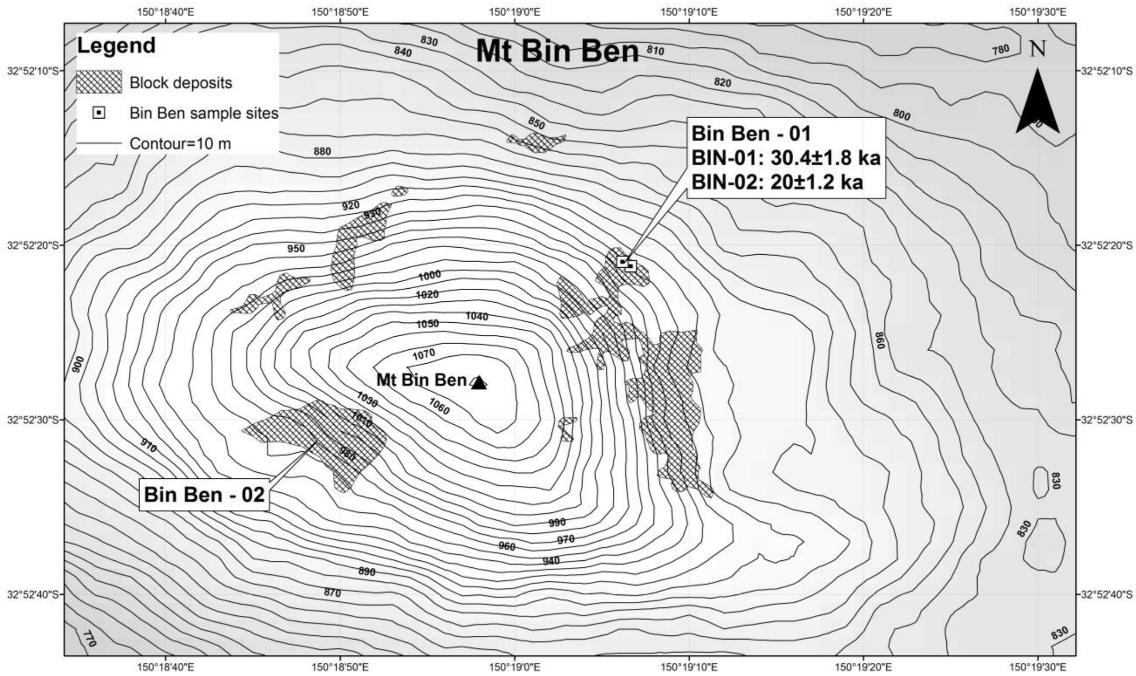



Figure 5.17) Map of the block deposits at Mt Bin Ben (highlighted in white)

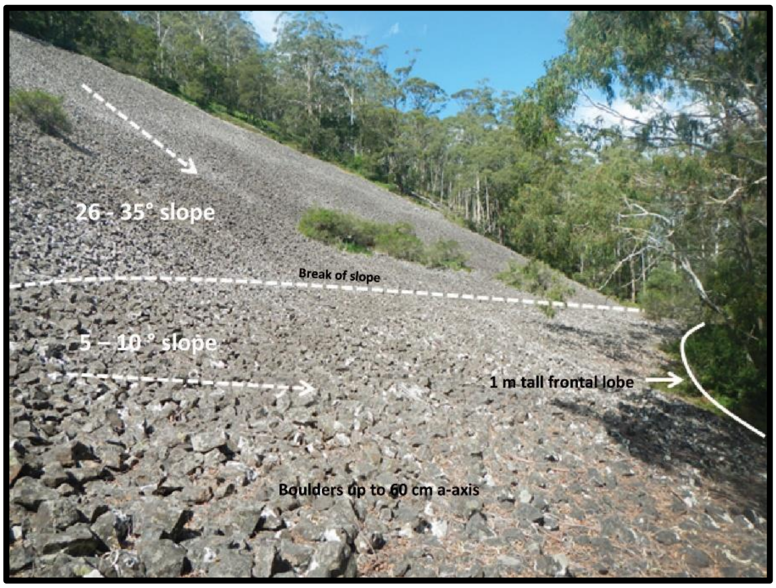



Figure 5.18) View of the Bin Ben-02 block deposit, this deposit forms a half-moon concavity in the southern slopes of Mt Bin Ben, its upper reaches have slopes of 26-35° with an abrupt change of slope to 5-10° at the basal area which ends in a 1-2 m tall lobate front giving the deposit a concave plan profile that contrasts strongly with gravitationally sorted scree deposits.

Figure 5.19) The BIN-02 sample came from this 40 cm long block on the lower slope of the Bin Ben 1 block deposit.

Figure 5.20) View of Bin Ben deposit 1 viewed from near the top of the lower lobe riser. This view shows the low angle slopes in the foreground. Behind the figure lies the upper steeper section of the deposit.

### 5.10. Landform discussion

The Malpas, Guyra and Mt Temi deposits all have morphologic characteristics that indicate that they have developed as a result of block formation and ground-ice mediated movement in a periglacial environment. The preferred orientation of boulder A-axes downslope and towards the direction of block stream development within the Malpas and Guyra deposits suggest that the clasts are a further indication of downslope movement of the block streams. At the Malpas 1 block stream small pits 1-2 m wide within the upper layers of boulders are suggestive of minor collapse possibly due to ice-melt in the underlying deposit. Tree throw producing root ball depressions have been shown to form surface pitting within a landscape. However with tree root throw the pits formed generally are not circular but half-moon in shape with a raised hump in the direction that the tree lay once fallen. The Malpas deposit has the largest pits and it is noteworthy that while the deposit is located within a forest, no large trees grow directly on top of the deposit suggesting that tree throw is not the likely process for the formation of the surface pits at the site. Pressure ridges are also present at all three sites. At Guyra and Mt Temi these features consist of slightly raised ridges and terraces up to 40 cm high that cut parallel to the main axis of block deposit flow. At Malpas, well defined ridges and terraces in the middle section of the deposit are indicative not only of a slow mass flow of the deposit but also of the likely presence of an interstitial matrix facilitating the movement. Considering the deposit is likely to be several metres thick and is composed entirely of clast supported boulders to generate ridging parallel to the main angle of the deposit it appears likely a matrix enabling the boulders to form ridges was present at the time of last movement. It is apparent that seasonal interstitial ground ice was present at this site. The prominent pressure ridge at around 2-3 m tall on the lower Malpas deposit coupled with the notable change in the orientation of the deposit within its lower reaches are further evidence that the deposit flowed as a block stream and it is not coincidental that the age of this section of the deposit is LGM.

The gradient and length of the Malpas deposit, the ridging and pitting evident on its surface and the relatively small height of its back-wall of no more than 25 m, the lack of any noticeable downslope size sorting of the deposit and the change in orientation of the lower section of the deposit clearly indicate that this deposit once flowed and that ground ice either within the interstitial voids of the deposit or forming within the clay layers at the base of the deposit promoted slow mass movement. Both the Guyra block stream and Mt Temi deposit are significantly smaller and steeper than the Malpas deposit. However the lack of a significant headwall cliff necessary for simple scree cone formation coupled with the downslope orientation of the blocks, reverse sorting of the clast supported boulders at depth and surface pitting at Guyra point to a process similar to Malpas. The Mt Temi deposit has what may be active modern scree near the top of the slope and much of its upper section is formed on slopes at or approaching 30° and could be described as a simple scree. However, it is notable that clasts in the active scree are no larger than cobble size whereas boulders up to 2 m long are found in the main deposit. The low angle of the lower 100 m of the deposit features terraces and small depressions that suggest ground ice has promoted movement. In summary, there is widespread evidence for both frost shatter and ground ice mediated flows at all these sites. Periglacial processes were operative throughout the Great Dividing Range of northern NSW to relatively low elevations during cold periods of the last glacial cycle.

### 5.11. Temperature discussion

Modern climatic measurements support the evidence for a prevailing LGM periglacial climate that provided the ground ice for block formation. The denudation of bedrock exposures by frost cracking and heave processes that result in the formation of the blocks that form block streams require temperatures regimes that oscillate diurnally significantly above and below freezing point (Matsuoka 2001b). The mean annual temperature of a region is important, in that frost cracking is only effective in environments that have mean annual air temperatures above 0°C (Boelhouwers 2004). Mean annual temperatures <0°C would promote the development of permafrost that would impede frost cracking processes due to reducing the availability of free moisture in the bedrock surface (Hales and Roering 2007). While ground ice (including needle ice) and minor periglacial forms such as sorted stone patterns can be promoted by temperatures barely below freezing. Observations and experiments have shown that a temperature of 0°C is generally not cold enough for frost cracking processes associated with shallow ground ice and deeper segregation ice to be important (Matsuoka 1990a, Hallet *et al.* 1991, Hallett *et al.* 2004). Observations suggest sustained periods with air temperature minimums of below about -3.5°C are needed for thermal expansion of moisture within rock surfaces to initiate the frost cracking process (Matsuoka 2001, Hallett *et al.* 2004). At the other extreme once temperatures drop below -8°C (Anderson 1998, Hales and Roering 2005) or alternatively -6°C (Walder and Hallett 1986, Hallett *et al.* 2004), thermal expansion slows due to the lack of moisture movement in the rock leading to reduced segregation ice (Matsuoka 1991). The effective frost cracking process is restricted to a band of temperatures that has been referred to as the “Frost Cracking Zone” and has been the focus of several studies (e.g. Hales and Roering 2005, 2007) in the New Zealand Alps where the altitudinal distribution of scree deposits and climate data were utilised to determine the modern limits of the frost cracking zone and the lower limits of the frost cracking zone (and scree production) during the Last Glaciation.

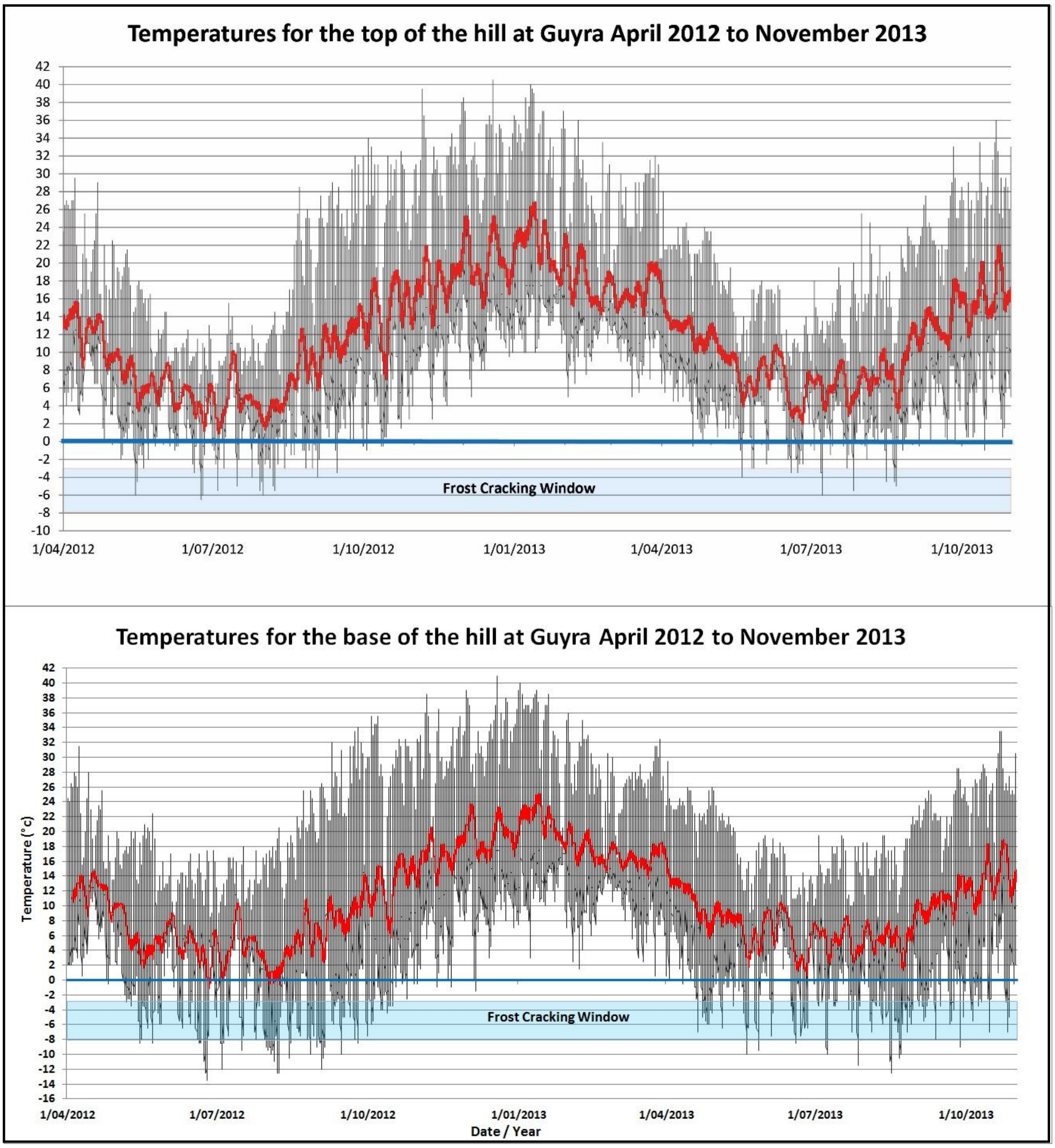



Figure 5.22) Temperature records for the top and lower slope locations at the Urandangie site for April 2012 till October 2013. Note the variation in temperature and diurnal

oscillation from the top to bottom of slope and the number of nights that fall within the frost cracking window. 0°C is represented by the thick blue lines.

The New England Region is a substantially different environment to the eastern New Zealand Alps. The key difference between the New England region of Australia and the New Zealand Alps is the continentally the New England Region and the effect of an extensive, low relief but high elevation plateau. While the mean annual temperatures in New England (10-12°C) are substantially warmer than that of the eastern Canterbury Alps (5-6°C at a 1000 m) due to the strong diurnal oscillation and warm summer months experienced on the northern New England Tablelands, the frequency of minimum temperatures that fall within the frost cracking window is actually higher than the eastern Canterbury Alps.

While the climate data reveals that minor frost cracking and heave activity is possible under modern conditions in northern New England evidence for modern activity is very limited. Temperature reconstructions (Galloway (1965) and (see Chapter 7) suggest that during the LGM winter temperatures were between -8°C to -11°C colder than present in eastern Australia. Extrapolating a -8°C temperature depression on the 2012 /2013 winters clearly indicates that during the LGM substantial periods of the winter months were available for diurnal temperature oscillations between the frost-cracking window (-3 to -8°C) and above freezing. With these enhanced diurnal frost cracking rates, enhanced headwall erosion led to the accumulation of sub-angular to sub rounded boulder accumulations that in turn moved down slope. The high porosity of block deposits has been shown to promote significantly colder ground conditions than in fine grained slope deposits. Venting associated with the 'Balch effect' within block deposits can enhance convection and heat transfer at depth (Balch 1900, Sawada *et al.* 2003). Rough surface topography and surface boulder convective heat transfer can lead to block deposits also having reduced snow cover (Sawada *et al.* 2003, Juliussen and Humlum 2008). Snowmelt can drain into the deposit and re-freeze upon encountering cooler temperatures at depth, while the thin snow cover permits cold air drainage into voids in the block deposits and enhanced freezing conditions (Sawada *et al.* 2003). It has been shown that coarse block deposits may be between 1.4 – 7°C cooler than the surrounding land surfaces, the order of magnitude dependant on regional climate and local topographic effects (Harris and Pederson 1998, Gorbunov *et al.* 2004, Juliussen and Humlum 2008) and that seasonal ground ice can develop at locations that experience mean annual air temperatures (MAAT) of up to 5°C (Gorbunov *et al.* 2004). Supporting this evidence is the observation by Sawada *et al.* (2003) that the circulation of air drainage through a block deposits triggers the venting of warm air at the top of the slope 'the chimney effect' (Harris and Peterson 1998) and the preferential development of ground ice conditions towards the base of block slopes. The study by Gorbunov *et al.* (2004) also suggests that the lower temperature thermal regime of block deposits can affect surrounding terrain to a distance of 15 m. Fine grained sands and clays have been observed at the base of the Malpas deposit, block deposits on Mt Wellington in Tasmania and the Bogong High Plains in Victoria during this study, these basal sand and clay horizons have been recognised as a feature of many block deposits (Wilson 2013). The potential for enhanced ground ice conditions within this material, adjacent to the block deposits may well play a role in downslope movement via solifluction and wash through of fine interstitial material (Caine 1983). The local thermal characteristics of the block deposits may therefore explain the mechanism of downslope movement of associated fine sediments and boulders within block deposit. Data collected from block deposits at the Guyra site indicate reduced diurnal oscillation, reduced MAAT inside block deposits and likely enhanced potential for ground ice conditions during cold phases of the Last Glacial Cycle. The temperature monitoring of the Guyra 1 block stream during the winter of 2013 reveals that at a depth of 40 cm the diurnal oscillation is reduced to <5°C and the overall temperature of the block stream closely follows the winter average air temperature on the surface. The results of Figure 5.23 clearly indicate that with a temperature depression of -8°C on the modern average temperature of the block stream, which currently does not reach freezing, would stay below 0°C for about 2 months a year. With an estimated temperature depression of 9°C (Galloway 1965) at the LGM, the blockstreams at the Guyra site would have had experienced internal temperatures below freezing for up to 5 months a year. With evidence of enhanced moisture availability at the LGM at the nearby Little Llangothlin Lagoon (Ellerton unpublished, Slee and Shulmeister 2015) these block streams would have been prime candidates for ground ice formation. By association, the better developed block deposits at Malpas and other deposits mapped throughout Northern New England were also associated with seasonal ground ice. The temperature data recorded from the crack within a bedrock bluff at the top of the Guyra deposit (Figure 5.24) reveals minimums as low as -2.5°C during winter and a mean temperature of 5-6°C during the months of June and July. This demonstrates the potential for water in cracks and joints to freeze at the site under modern conditions and clearly demonstrates the strong degree of freezing potential under temperature conditions up to 10.5°C colder than present during the LGM.

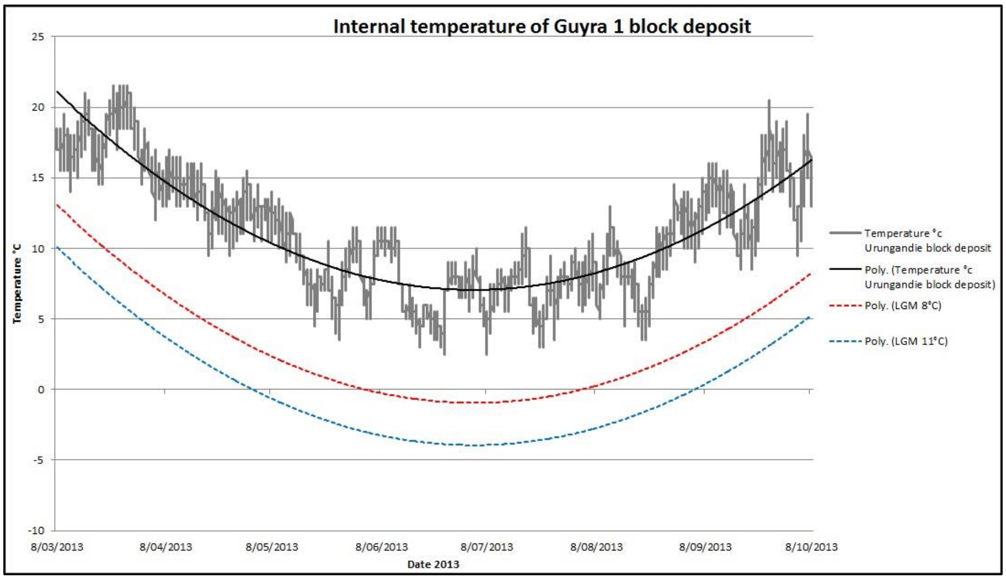



Figure 5.23) Temperature records for the winter of 2013 from -40 cm within the Guyra 1 block deposit. Note the supressed diurnal oscillation compared to the surface temperatures shown in Figure 5.22. Block line represents the polynomial mean for the period red and blue lines show temperatures with 8 and 11°C reductions to account for possible LGM conditions on the site.

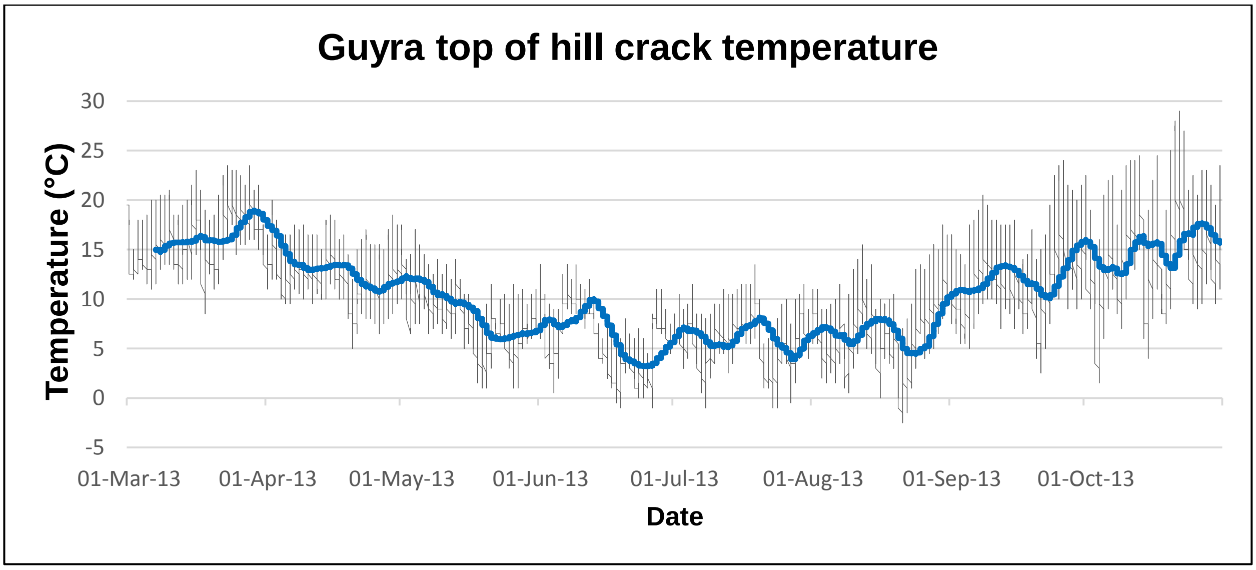



Figure 5.24) Winter 2013 temperature records from 15 cm into a horizontal 2 cm wide crack within a bedrock bluff at the top of the Guyra study site. The blue line is the weekly moving average.

## 5.12. Age of the deposits

The oldest block streams are recorded from the Guyra site which appears to be consistently early MIS 3 in age. The consistency of ages between the two Guyra sites and the fact that the boulder ridge near the top of the slope is attached to a modern scarp support the concept that these may be true ages for the deposits with little or no inheritance. The inferred erosion rates support this idea. The oldest age, from the northern block stream at Malpas indicates that that site may be active at roughly the same time. These ages contrast with the findings of Barrows *et al*. (2004) who produced LGM ages of 17 – 24 kyr from the Ravine block stream and the one of two dated deposits at Mt Little Higginbotham both of which lie in the Australian Alps. The second deposit at Mt Little Higginbotham has a single age of 58.9±2.8 kyr effectively corresponding with the early MIS 3 ages at both the Guyra and Malpas sites. However, it is clear that both the New England and Australian Alps studies have block deposits that fall within the Last Glaciation. This contrasts to the Tasmanian dates published by Barrows *et al.* (2004) that include ages of up to ~500 kya for block deposits at Ben Lomond and Mt Wellington suggesting that block deposits in Tasmania have developed over multiple glacial cycles.

The Malpas site reveals significant frost breakdown of the bedrock source and periglacial induced downslope movement of the deposit from late MIS 3 through MIS 2 and into the deglaciation. At Malpas, there is a suggestion that scree processes dominated during the MIS 3/MIS 2 transition and during the deglaciation with ice mediated movement on lower slopes was focussed in the LGM. At Mt Temi block stream development occurred during the deglaciation and possibly into the early Holocene while at Bin Ben the limited data suggest LGM activity. In summary, block streams were active somewhere on the New England Tablelands almost continuously between about 45 kyr and 10 kyr ago. This suggests that blockstream formation is a common process under colder climate conditions in New England. Furthermore, the absence of pre-last glacial cycle ages or indeed anything except relatively young dates, mitigates against long inheritance in this landscape and suggests considerable landscape rejuvenation in glacial times.

It is likely that the prevailing moisture balance may have been more positive during glacial periods and especially during late MIS3/early MIS 2 and late in MIS 2 as enhanced breakdown of bedrock exposures by frost shatter is controlled by the moisture availability in the rocks (Matsuoka 1991, Sass 2004). At the moment, the winters are dry and this may inhibit frost shatter more than temperature constraints. The enhanced moisture balance does not necessarily imply high precipitation. Decreased evapotranspiration, under cooler conditions, possibly combined with the enhanced run-off generated by snow banks and consequent snowmelt (e.g. Reinfelds *et al.* 2014) and loss of forest cover (Woodward *et al*. 2014) would generate more moisture availability especially in spring and autumn.

### 5.13. Conclusions

The block deposits of the New England region, northern NSW, Australia exhibit morphological and sedimentological characteristics indicative of their formation under periglacial conditions. The modern climate that features strong diurnal temperature fluctuations around freezing supports frost conditions at the present day. However, while small talus deposits are forming, none of the block deposits are currently active. SED ages from four block deposits yield consistent ages within each of the block deposits but there are significant variations between the different block deposits. Cumulatively there is strong evidence for periods of movement during early MIS 3, at the MIS 3/MIS 2 transition, in the LGM and during the deglaciation. This pattern contrasts with work by Barrows *et al.* (2004) in the Australian Alps to the south which show such strong LGM activation of block deposits that older episodes are overprinted. This is perhaps unsurprising as northern New England, while cool temperate sits well within the sub-tropical anticyclonic belt as opposed to sites further south that are progressively more under the control of westerlies.

# Chapter 6. Mass movement landforms in the vicinity of Guyra, Northern New South Wales, morphologic characteristics and paleoclimate implications.

### 6.1. Abstract

Basalt terrain in the Upper Gara Valley of the New England Tableland in northern New South Wales harbors abundant large relict landslides. Modern activity in the area is limited to small rotational slumps and flows. Both these modern features and relict block streams and blockfields (felsenmeer) on the valley mid-slopes and adjacent plateau respectively, which represent mass movements under colder previous climates, are superimposed on much larger rotational and complex landslides that date to >80 kyr. The scale of the larger landslides and their

association with spring seeps on the lower valley slopes, coupled with the relative inactivity of landslide processes under modern climate conditions, indicate that the peak of landslide activity in the Upper Gara Valley occurred under climate conditions wetter than Today. A colder but still wetter than contemporary climate during the last glaciation, promoted the development of block streams, solifluction lobes and a possible nivation hollow. Mass balance modelling of potential snow pack constrains an upper limit for cooling during glaciations at -11°C whereas the existence of periglacial landforms themselves supports a minimum likely cooling of 8-9°C. Limited size and extent of modern mass movement landforms indicate that climate through the Holocene has been too warm for significant periglacial processes and too dry for the re-mobilisation of the large landslides.

## 6.2. Introduction

The New England Tableland is an elevated plateau that forms part of the Great Dividing Range. The plateau covers an area of approximately 32,000 $km^2$ above 1000 m asl, rising to a maximum elevation of 1608 m near its eastern edge, and comprises the largest area of high elevation land in Australia. The plateau is capped by a mixture of Permian granitic rocks, Carboniferous sedimentary sequences and extensive Miocene flows of the Central Province Flood Basalts. Where Miocene basalts are present they have infilled existing topography.

This study examines landforms on hill slopes in the Upper Gara Valley which is part of the northern New England Tableland (Figure 6.1). The Gara Valley lies 1100 m above sea level, while the local topographic relief is generally less than 150 m. This low relief setting makes the study more broadly valuable because the investigation of mass movement in areas of low relief has received limited attention in the literature (e.g. Safran *et al.* 2011) but is globally widespread. In Australia, most mass movement research has focused on modern processes and hazard identification (e.g. Nyman *et al.* 2011) and there has been very little work undertaken on relict landforms.

A review of the literature of landslide deposits documented in eastern Australia reveals that very few relict landslide deposits have been studied outside those of Tasmania (McIntosh and Barrows 2011, McIntosh *et al.* 2012), the Illawarra district of New South Wales (Walker 1963, Young 1976) and the Cairns area of far north of Queensland (Michael-Leiba *et al.* 2001, 2003, Nott *et al.* 2001, Nott 2003). These three regions of Australia are also the most studied for modern landslide processes. While modern landslides have necessitated the study of mass movement in the Cairns area, work by Nott *et al.* (2001) has shown that the peak of landslide activity in the form of earthflows and alluvial fan growth was during the Last Glacial Maximum for a period of approximately 10 kya between 27 kya to 14 kya. They imply that the landslide activity was enhanced during this period by overall colder and drier conditions in North Queensland promoting a reduction in vegetation type and forest extent. However Nott *et al.* (2001) also suggest that heavy precipitation events where still frequent occurrences in this otherwise drier regime and the heavy precipitation events coupled with reduced vegetation cover led to the overall enhancement of slope instability.

In Tasmania research on large relict complex landslides on the Mt Nicholas Range have revealed evidence for major landslide activity during MIS stage 5b, and more than likely MIS stages 2, 3 and 4, but by the Holocene the large scale mass movement appears to have stabilised (McIntosh and Barrows 2011, T Barrows pers.comm., 2011). They interpret these landslides as being morphologically uncharacteristic of modern landslides and imply that they were active under a very different prevailing climate than the present; probably with significantly enhanced moisture availability due to enhanced precipitation or spring snow melt (McIntosh and Barrows 2011). Utilising weathering and morphologic characteristics of relict landslides on the Illawarra escarpment, Walker (1963) suggested that there are two periods of major landslide activity; an older period represented by deeply weathered debris avalanches that he suggested related to a very wet climate in the past and landslides related to a second younger period of enhanced moisture conditions.

The lack of landslide dating in Australia has recently been noted by Panek (2015) in his global overview of landslide dating. This paper highlights the relative paucity of landslide dating studies outside mountain orogeny belts globally and calls for future research into areas including tablelands within continental interiors. This paper constitutes the first attempt to define the geomorphic processes operating on the New England Tableland during the late Quaternary and focuses on mass-movement landforms at all scales.

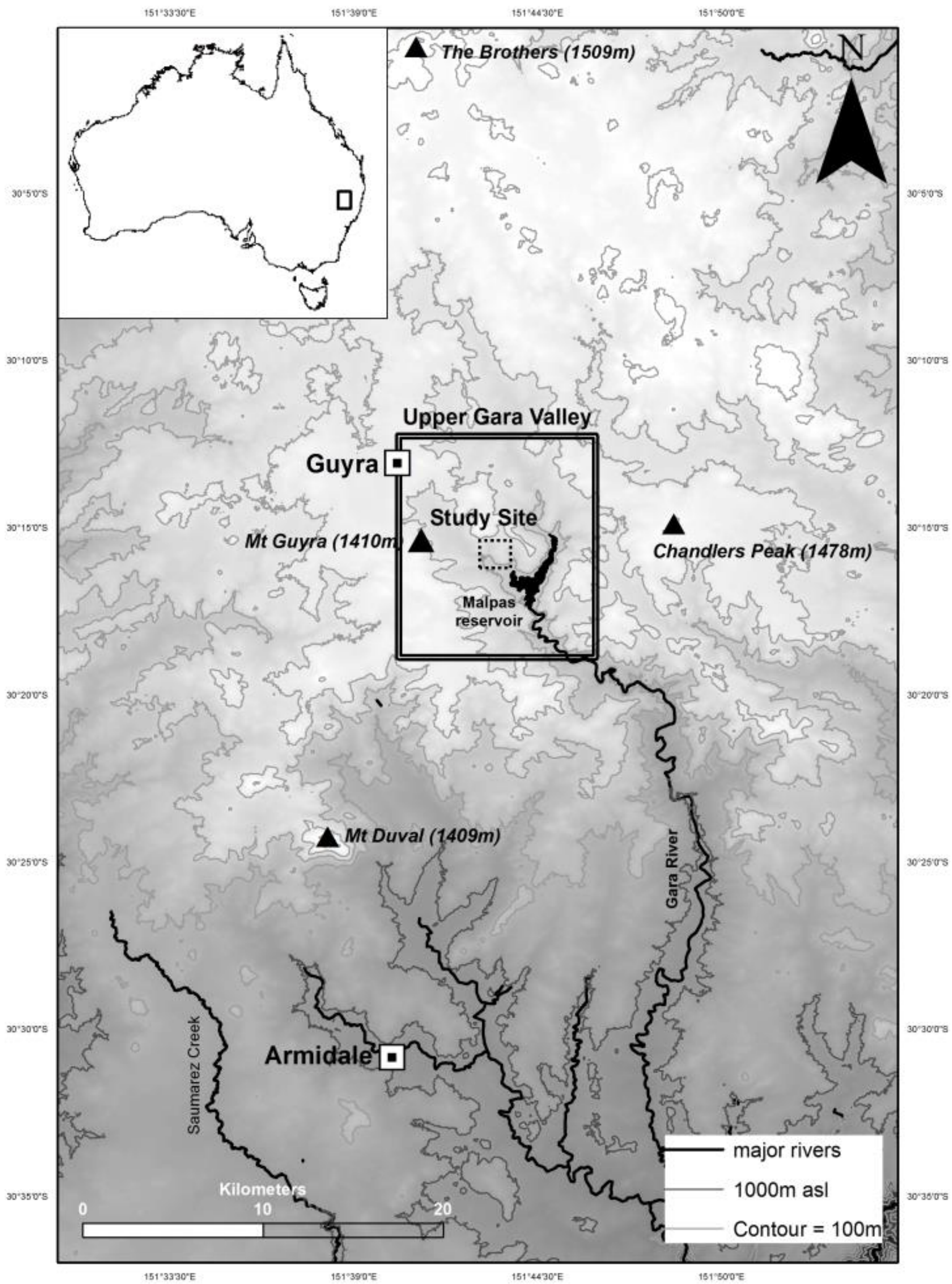



Figure 6.1) Gara Valley and surrounds, part of the central New England Tableland showing the Upper Gara Valley and study site. Contours are at 100 m intervals with the dark grey contour being 1000 m asl. Inner box is Figure 6.2 and outer box is Figure 6.5.

### 6.2.1. Study site and visual observations

The study area lies in the Upper Gara River Valley (30°15’48S: 151°43’17E) upstream of the Malpas Reservoir along the tributary valley of Urandangie Creek and the main investigations were focussed on the northern slopes of this valley (Figure 6.1). The Gara River is sourced at the Great Dividing Range drainage divide near the town of Guyra (1330 m asl) and drains south via a series of gorges and before feeding into the Macleay River and eventually to the Tasman Sea. As such it constitutes one of the short east coast drainages rather than a tributary of the extensive Murray-Darling system that drains west of the divide. The entire Gara catchment lies at altitudes in excess of 1100 m asl. with the highest mountains in the catchment Ben Lomond (1510 m asl) and The Brothers (1509 m asl) marking the northern limits of the drainage system (Figure 6.1). The local relief in the study area along Urandangie Creek extends from 1140 m to 1410 m asl.

The bedrock geology of the study area is entirely composed of Miocene-Oligocene basalt flows associated with the Central Province flood basalts (McDougall and Wilkinson 1967). Numerous mass movement landforms are visible on the hillslopes within the study area (see Figures 6.3 and 6.5) including rotational slumps, block streams and solifluction lobes. Active mass movement appears to be restricted to small scale spallation on back-wall scarps and small rotational slumps only a few meters in diameter and runout. Historical aerial photographs reveal no visible changes on the hillslope in the 70 year period between 1943 and 2015 (Figure 6.2). This lack of evidence for erosion is surprising given the ongoing changes in land use in the study area, as indicated by the clearance of forest from a landslide deposit between 1943 and 2015.

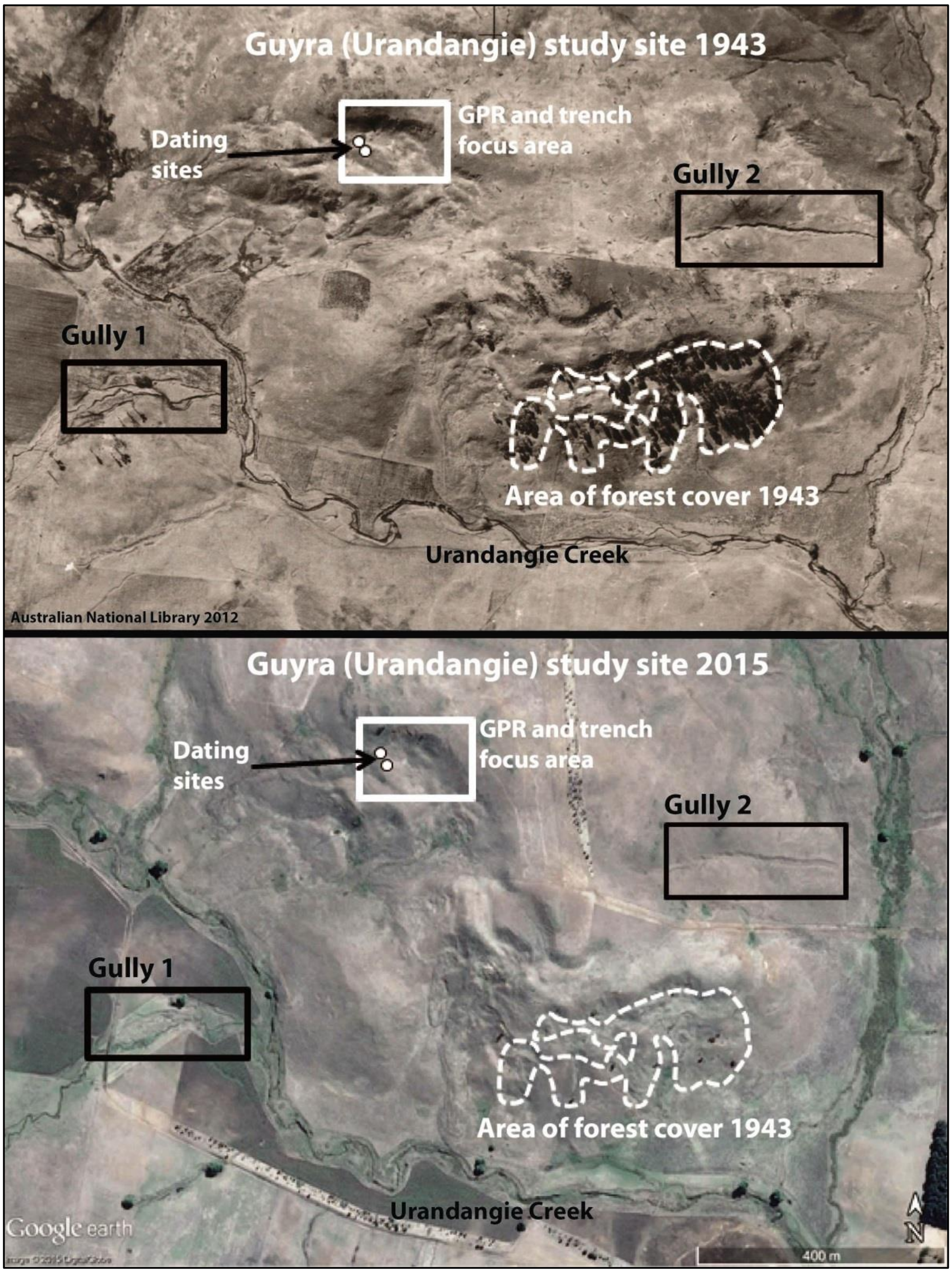



Figure 6.2) A comparison of Historic aerial imagery of the Guyra study site between 1943 and 2015. The large scale mass movement deposits pre-date 1943 and do not appear to show any significant activity. Further evidence for the relative stability of the area since European clearance are the two deep Gullies that appear to have not progressed over the intervening 72 years between photographs.

The largest of the relict mass movement complexes located in the study area are associated with mid-slope positions on south to south-western aspects between elevations of 1200-1300 m asl (see Figure 6.5). Mass movements are not confined to this orientation but those found on northerly aspects are along shallow planes of weakness. A number of small but well developed block streams and periglacial pavements occupy parts of the upper parts of the slope, while the lower third of the slope has a lobate morphology consistent with solifluction lobes (Figure 6.3). In addition to the rotational slumps, block slopes and solifluction lobes, a putative nivation hollow and pronival rampart was identified. This feature has an exposed back wall with angular clasts at the foot of the scarp. The floor of the feature is a small swamp while the ridge that impounds the swamp is openwork in its top 20-30 cm. The total height of the enclosing ridge is c. 2 m.

## 6.3. Methods

### 6.3.1. Mapping

The site was mapped using 1:5000 black and white aerial photographs (1943 Aerial photographs National Library of Australia Guyra Run 31. 12 July 43) and Google Earth Pro images. The 1943 photographs provide the best resolution of any series. Extensive field mapping was undertaken to verify the aerial photograph interpretations. Geomorphic maps were produced in Arc-GIS. Sediment characteristics were observed in the field, grab samples were taken and where appropriate, dry sieved with the fine grained content determined by a Mastersizer3000 laser particle size analyser.

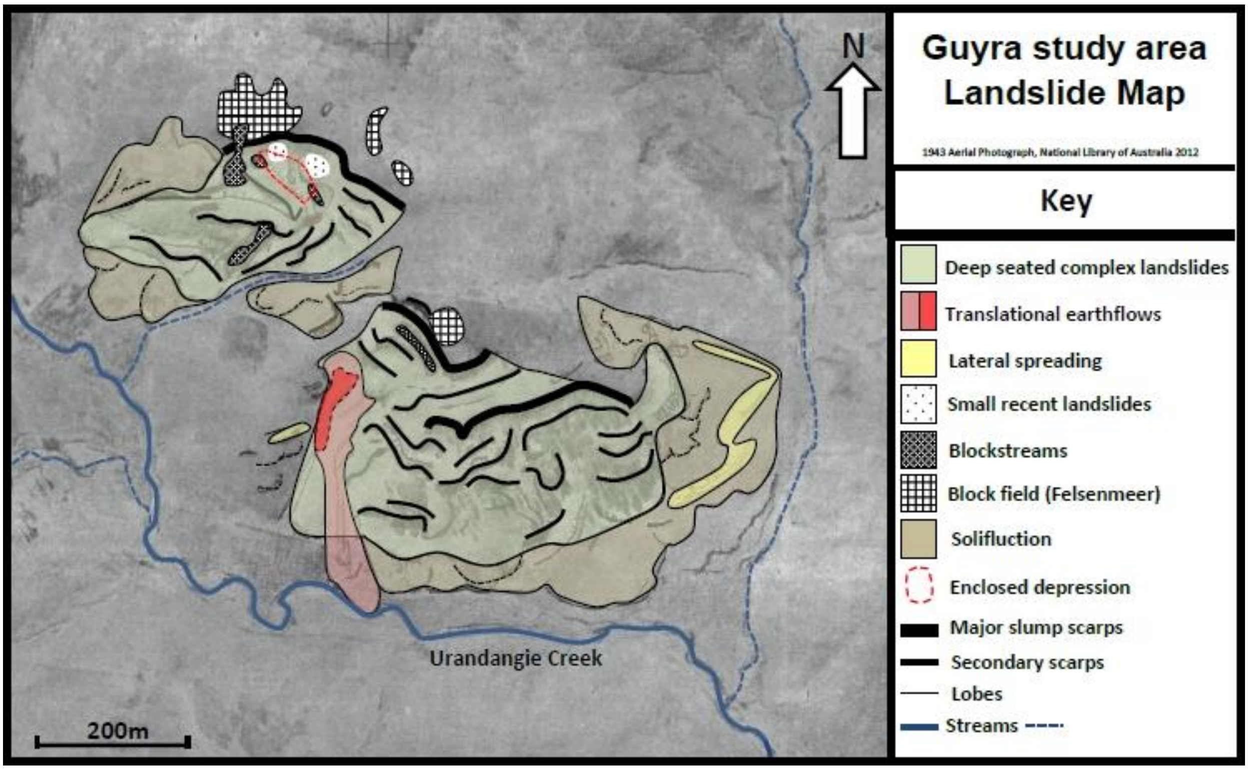



Figure 6.3) Geomorphological map of the study area about 3 km SE of Guyra. Mass movement deposits including solifluction lobes, block slopes, earth flows and rotational slumps. A boulder field (felsenmeer) that displays large >1 m diameter stone circles, covers parts of the summit of the hills.

### 6.3.2. Surface Exposure Dating

Five basalt boulders where sampled for Surface Exposure Dating (SED).Two basalt boulders were sampled from the northern end of the upper ridge (30°15’45”S: 151°43’15”E see Chapter 5, Figure 5.11) while three samples were collected from a 90 m long block stream (Guyra 1 block stream) on the mid slope of the landslide deposit at (30°15’52S: 151°43’14E). The rocks were selected on the basis of their large size (> 60 cm) and stable location. Thin samples (<5 cm thickness) were collected from prominent crests on the boulders to minimize effects of post-movement weathering on SED ages. Sky angles were measured to correct for shielding. Because the lithology is basaltic, these samples were prepared for surface exposure dating using $^{36}Cl$ at the University of Exeter laboratory using the methods discussed in Chapter 5.3.3.

### 6.3.3. GPR Surveys

One of the large rotational landslides and an area of shallow land sliding and block fields was surveyed using a MALA ProEx ground penetrating radar (GPR) system with a 500 MHz antenna and integrated high-resolution GPS. GPR has proven effective at determining the depositional process in alpine and periglacial sediments (Sass 2007, Monnier *et al.* 2011). The GPR data were collected in transects forming a rough grid, and were subsequently processed (DC drift; user-defined signal gain; bandpass lo=350, hi=650; background removal) using GPR Slice software. Individual profiles were converted to depth-distance, from which sediment thicknesses as well as subsurface architecture were estimated.

To validate the GPR data two 1 -1.5 m deep trenches were excavated through sections of the upper ridge adjacent the landslide back basin. The trenches were located to best document the relationships between boulders on a ridge crest, the back basin and the foot of the landslide back wall. Sedimentary structures within the exposed sides and face of the trenches were logged and sketched. These data were supplemented by an augur survey of the main back basin.

### 6.3.4. Mass balance modelling

At present, although snowfalls occur annually near Guyra, accumulation is transitory and usually melts within a few days. In order to test the climatic requirements for the formation of the putative nivation feature, a degree-day snow mass balance model (Alexander *et al.* 2011) is applied. The model is based on 30-year averaged daily mean temperatures and precipitation from the Guyra Hospital meteorological station (1329 m asl), the closest location of a long-term climate record to the study site. It is used to determine the temperature depression required to allow a snow bank of up to 2 m to form. At present, the mean annual air temperature at Guyra is 10.5°C while precipitation is c.900 mm $a^{-1}$, with maximum precipitation occurring during summer months. Three scenarios are developed using a cooling of 9°C from present to simulate inferred temperatures at the LGM (Galloway 1965, Costin and Polach 1971); combined with three distinct precipitation patterns: (1) The present day (30-year averaged) Guyra meteorological station precipitation distribution; (2) Hartz Mountain (Tasmania) precipitation. Hartz Mountain, which has a similar precipitation total to Guyra (900 mm $a^{-1}$) but with a precipitation peak in winter; and (3) Hartz Mountain precipitation increased by 100% to simulate both cooler and substantially wetter Pleistocene conditions.

The basis of the degree-day model is to calculate the amount of snow melt based on temperature and precipitation (e.g. Braithwaite 1985). The proportion of precipitation *P* that falls as snow *S** is prescribed as a linear function of air temperature (Legates and Bogart, 2009):

$$S^* = P\big(0.5 - (0.05T_a)\big),$$

Where $T_a$ is the air temperature. Taking into account that the density of water is 1000 kg $m^{-3}$ and a typical compacted snow density on the order of 350 kg $m^{-3}$ (Morris and O'Loughlin, 1965, Marcus and Moore 1983), the following conversion from water equivalent to snow equivalent *S* is required

$$S = S^* \left(\frac{\rho_w}{\rho_s}\right).$$

Surface ablation *b* is calculated as follows:

$$b = PDD_{sum}(k), T_a > 0°\mathrm{C}$$

Where $PDD_{sum}$ is the sum of positive degree-days and *k* is the empirical degree-day factor. For the Australian Alps, the degree day factor has been empirically estimated as 2.9 mm $d^{-1}$ $K^{-1}$ (Whetton *et al.* 1996). In addition, the rainfall heat flux $Q_r$ causes melt:

$$Q_r = \rho_w C_w V_r (T_w - T_s)$$

where the specific heat capacity of water is $C_w$ ($2.1 \times 10^3$ J $kg^{-1}$ $K^{-1}$), the volume of rain water is $V_r$, $T_w$ is the water temperature approximated by $T_a$ and $T_s$ is the surface temperature (0°C; Hock and Holmgren 2005). The evolution of the snow bank depth $H_s$ (which is always positive) throughout the season then becomes

$$\frac{\partial H_s}{\partial t} = H_s + S - b - \frac{Q_r}{L\rho_s}$$

where *L* is the latent heat of fusion of ice ($3.34 \times 10^5$ J $kg^{-1}$).

## 6.4. Results

### 6.4.1. Landslide characteristics

The majority of mass movement features in the Upper Gara Valley catchment are located on southern and western facing hillslopes (Figure 6.5), and comprise six types of mass movement forms following the classifications of Varnes (1978) and Hungr *et al.* (2014).

They are:

1) ***Deep –seated complex landslides***

   These landforms are the largest scale features in the valley and are up to 40 – 160 Ha in extent. They have back walls generally >5 m and in many cases >15 m high (Figure 6.4). The landslides are dominantly rotational with subsidiary lateral slumping and may extend downslope for 200 – 300 m. A trench dug through a boulder ridge near the top of a large landslide (Figure 6.9) indicates that the main body of the landslide is composed of deeply weathered clays with very few boulders (core stones).

2) ***Translational earthflows***

   Earthflows, also described as shallow regolith landslides (Gao and Maro 2010), feature well developed head-wall scarps leading to elongated chute zones in some cases featuring downslope oriented berms and prominent lobate toe risers. They are often associated with the plastic deformation of clay-rich soils (Hungr *et al.* 2014). In the study site the largest earthflows are about 100 m long and feature longitudinal ridges and well defined lobate toe risers. The deposits appear to overlie the larger and presumably older complex landslides.

3) ***Lateral spreading (lateral flows)***

   Lateral flows are extensive contour-parallel ridge and trench topography on low-angle slopes with subtle back walls of limited topographic relief usually associated with a rigid geologic unit capping a weaker unit (Rohn *et al.* 2004, Crozier 2010, Pasuto and Soldati 2013). The lateral spreading forms in the study area are small in scale; they have low back-walls of at most 3-4 m tall and usually form single contour-parallel ridges generally <1 m tall, with elongate broad back depressions.

4) ***Translational and rotational landslides***

Small rotational slumps and translational landslides are indicated by fresh back wall scarps, soil scars and partially vegetated toe areas. These landforms are located on or adjacent to the main back-walls of the deep-seated mass movements. They are mostly <20 m wide and display recently active headwall scarps.

5) ***Block streams***

Along the flanks of the plateau, basalt scarps are currently only marginally active, but below the scarps, and often separated by several metres of vegetated terrain, lie angular block streams. These block streams are tens of metres long and 10-20 m wide. The block streams extend onto and also occur within the type 1 landslides. The block streams that occur within the landslide zones are derived from small scarps that represent basalt cap rock that moved downhill with the landslide. A ridge of openwork basalt blocks occurs at (30°15’45”S: 151°43’15”E). GPR results (Figure 6.6) suggest that in the sub-surface the ridge encloses a pre-existing landslide back basin.

6) ***Solifluction lobes***

These landforms are low lobate deposits forming skirts around the hillslopes with no obvious back-wall source areas. The solifluction forms found in the Gara Valley are turf banked lobes associated with movement of saturated soils and possibly enhanced by ground ice development beneath vegetation (Costin *et al.* 1967**,** Benedict 1970, Gorbunov and Seversky 1999, Matsuoka 1999). These features can be discerned in the field by variations in vegetation cover and the larger deposits may be 100 m wide and have 30-40 cm tall overturned toes indicative of modern movement (Hugenholtz and Lewkowicz 2002). The lobes that appear to be currently active lie below the seep lines near the valley floor. Other lobes located further around the hillslope form a continuous skirt on the mid slope of a small conical hill. There is no indication of large seeps in the area and these may be relict features.

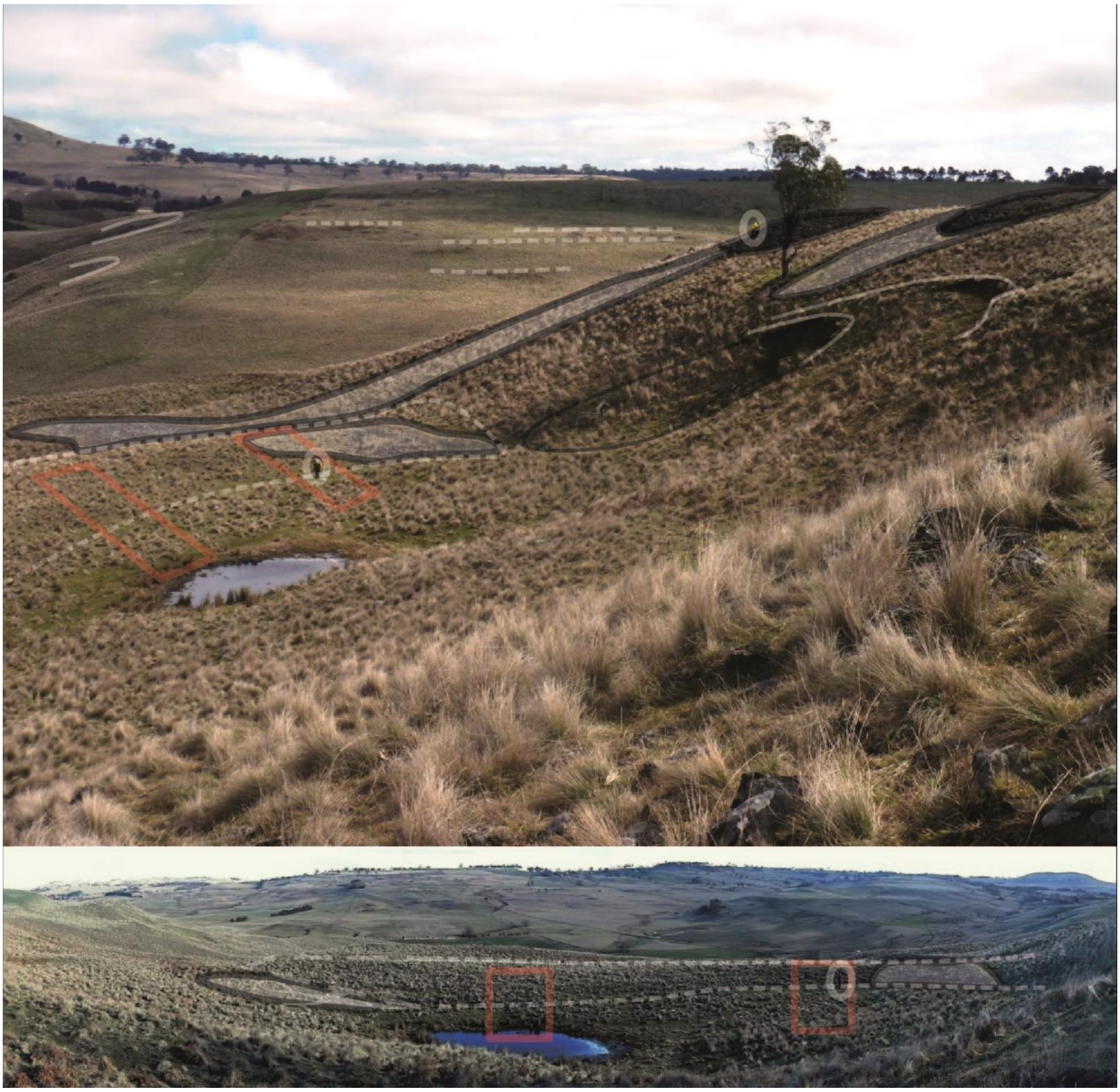


Figure 6.4) Views facing NW (top) and W (bottom) over the back-wall and back-basin of the landslide. The prominent ridge that defines the outside of the back basin is indicated by the white dotted line. The red squares mark the locations of the trenches 1 (left) and 2 (right). Small parasitic scarps (white lines) and a small fan (black line) are visible in the back-wall and appear to be historic. Block deposits are represented by the shaded white areas. GPR surveys indicate that the background paddocks contain block fields (felsenmeer) obscured by modern soil development up to ~1.5 m thick in places and extensional mass movement in the form of elongate contour-parallel ridges

### 6.4.2. Aspect control

Mapping of hillslopes in the vicinity of Malpas Reservoir and around the principle study site (Figure 6.5) reveals that of the 10494 hectare study area 904 hectares or 8.6% has been affected by visible landslide processes. Landslides on southerly facing slopes constitute 600 hectares or 67% of the landslide area, with landslides on westerly, northerly and easterly facing slopes contributing 25%, 5% and 3% respectively. The landslide distribution map therefore indicates a strong aspect control of the development of landslides. Slope angle does not appear to be a strong factor on landslide development with northerly facing valley side slopes having similar gradients (20-35°) to their southerly facing counterparts. Structural control could be the reason for dominant southerly aspects, however, the basalts in the area are flows and are generally flat lying to gently dipping. Elsewhere on the New England Tablelands remotely sensed landslide deposits on basalt terrain appear to favour southerly or westerly aspects, indicating that local geologic controls may not be the dominant cause of landslide development. Further south Blong and Dunkerley (1976) described landslides preferentially developed on the southern slopes of the Razorback Ridge near Picton NSW and linked this distribution to enhanced moisture availability on south facing slopes. Local aspect and topography appear to be a significant driver in the distribution and type of landslides in the Upper Gara Valley with the shaded southerly aspects being favourable for higher soil saturation and therefore spring-line sapping and associated mass movement than the drier northern slopes (Figure 6.5). These observations are supported by the morphology of the landslides were almost all of the complex deep seated (Type 1) landslides occur on southerly and south-westerly facing slopes, while the landslides found on northerly slopes appear to be shallow (type 3) landforms.

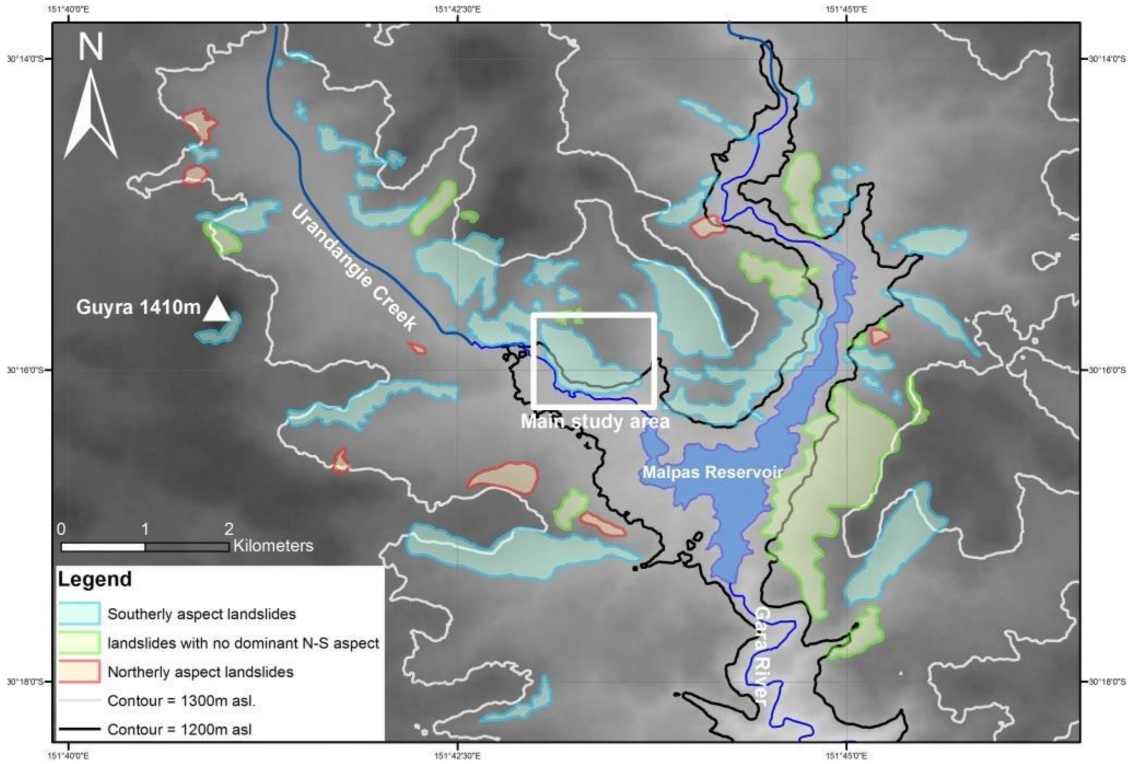



Figure 6.5) Landslide aspect map of the Gara Valley surrounding Malpas Reservoir. The main Guyra study area is highlighted. The majority of the largest and most complex landslides are found on south facing slopes.

### 6.4.3. Possible evidence for a pro-talus rampart

During the course of the GPR study a series of arcuate boulder ridges within the upper landslide basin of the principal study site were identified (Figure 6.6) adjacent to a boulder pavement composed of boulders with low A-axis dips. GPR analysis supported by trenching of the deposit and an auger transect of the back basin of the landslide were compiled to investigate the origins of these landforms and sediments. The basin is enclosed by an openwork gravel berm that is strongly defined as a 2 - 2.5 m tall ridge at its northern end but becomes subtle at its southern end. Three buried, open-work berms occur inside the main berm and each partly encloses the basin. The berms show strong morphologic asymmetry, with a steep face on the headwall side and a low angle ramp on the valley side (Figure 6.6). As determined by the GPR survey, the hollow hosts a variable thickness of fine sediment ranging from 0 cm to 150 cm. Boulders (up to 15 cm A-axis) are scattered on the surface of the basin but appear to lie on top of fine clay material and are likely to be associated with minor sporadic rock fall activity.

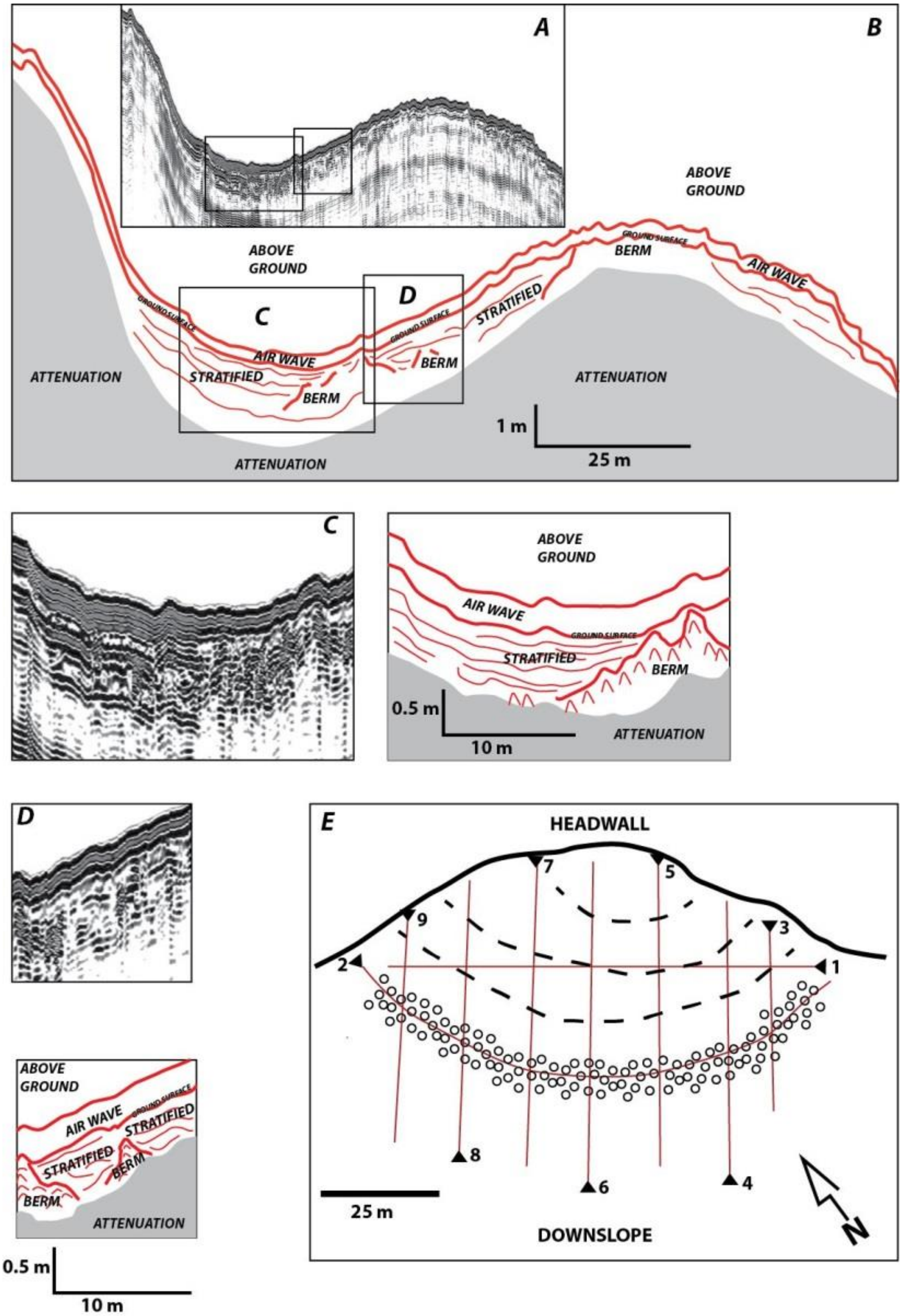



Figure 6.6) Cross-section GPR line through the proposed pronival rampart feature. A) Raw GPR line 7 oriented from the headwall of the feature parallel to the fall line (See Figure 3.E for location). B) Interpretation of GPR line 7 showing prominent stratigraphic boundaries between facies interpreted as stratified infill and coarse berms with minor

reflections within each facies (See Figure 3.E for line location). C) Raw and interpreted enlargement of the stratigraphic relationship between facies interpreted as stratified infill and coarse berms. Note the stratified infill facies laps onto the berm facies (See Figure 3B for location). D). Raw and interpreted enlargement of minor berm and stratified facies further down slope, but within the basin. Note the down-lap relationship of the stratified facies with respect to the basin and the berm facies (See Figure 3B for location). E). Interpretative map of the pronival rampart feature with GPR survey lines (solid red) and buried features interpreted as berm facies (dashed black) and exposed open work boulder berm (black open circles).

### 6.4.4. Trench observations

*Trench 1*

Trench 1 was excavated through the inner edge of the ridge back approximately 12 m into the back-slope and floor of the enclosed depression to a depth of 1.2 m. The trench was aligned approximately to line 6 in the GPR survey. The trench revealed 3 units (Figure 6.7):

Unit 1: 0-30 cm. Fresh clast-supported basalt boulders overlie outcropping jointed basalt with clay interbeds.

Unit 2: This is a deeply weathered brown clay/silt (see appendix 15) 10YR 4/4 with dark (7.5YR 2.5/1 and lighter 7.5YR 6/8) mottles. This unit caps Unit 1 but thins rapidly before lensing out towards the top of the ridge.

Unit 3: This is a clast supported sub-rounded cobble to boulder (basalt) with a clay/silt (see appendix 16) grey-brown 10YR 3/2 matrix. This deposit thickens into the back-basin.

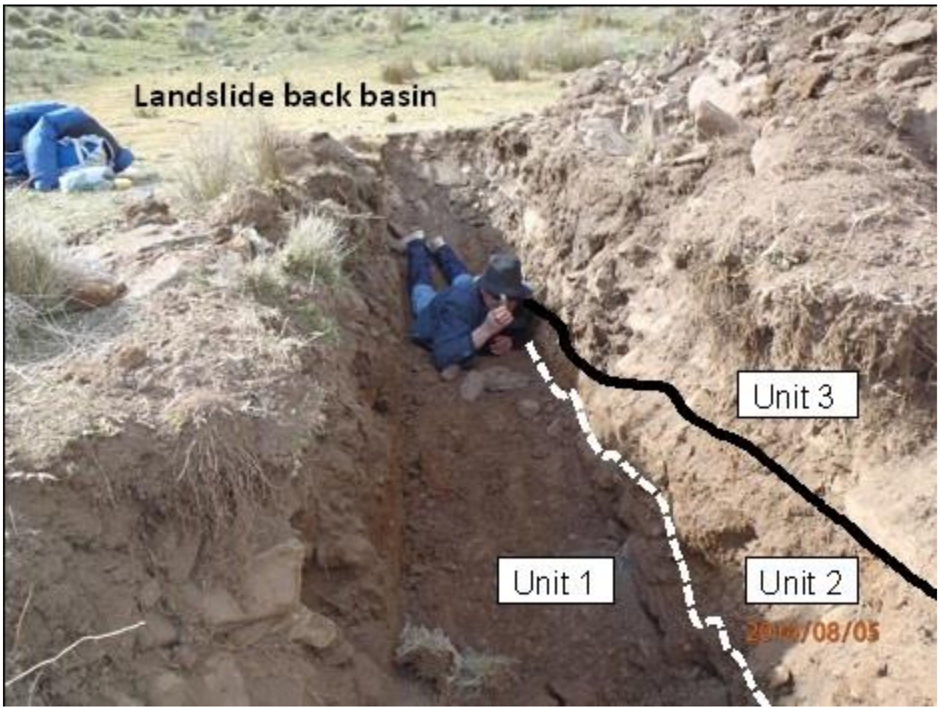



Figure 6.7) Trench 1, the unit 2 and unit 3 deposits are demarcated by the black line, Unit 1 comprises part of the floor of the trench below dotted line, note that the clast supported boulders of Unit 3 thickens into the back basin.

*Trench 2.*

Trench 2 was excavated through a steeper section of the ridge near its northern terminus with the back wall of the landslide, adjacent to an area of the ridge that is composed of sub-rounded clast supported boulders and close to the two CRN dated boulders on top of the ridge. The trench exposed two units (Figure 6.8):

Unit 1: The lower 85 cm of the trench is composed of fine clayey-silts10YR 4/4 with dark brown (7.5YR 2.5/1) and lighter yellow mottles (7.5YR 6/8) with no basalt clasts.

Unit 2: The upper 35 cm is composed of clast-supported sub-rounded basalt cobbles to boulders with a light brown (10Yr 4/2) clayey-silt matrix that has formed loose sandy aggregates.

There is a strongly defined contact between Units 1 and 2, and no suggestion that the boulder clasts of unit 2 are related to the clay unit beneath it. Unit 2 thickens into the back-basin and there is a step change in thickness on the inner margin of the ridge (see Figure 6.8).

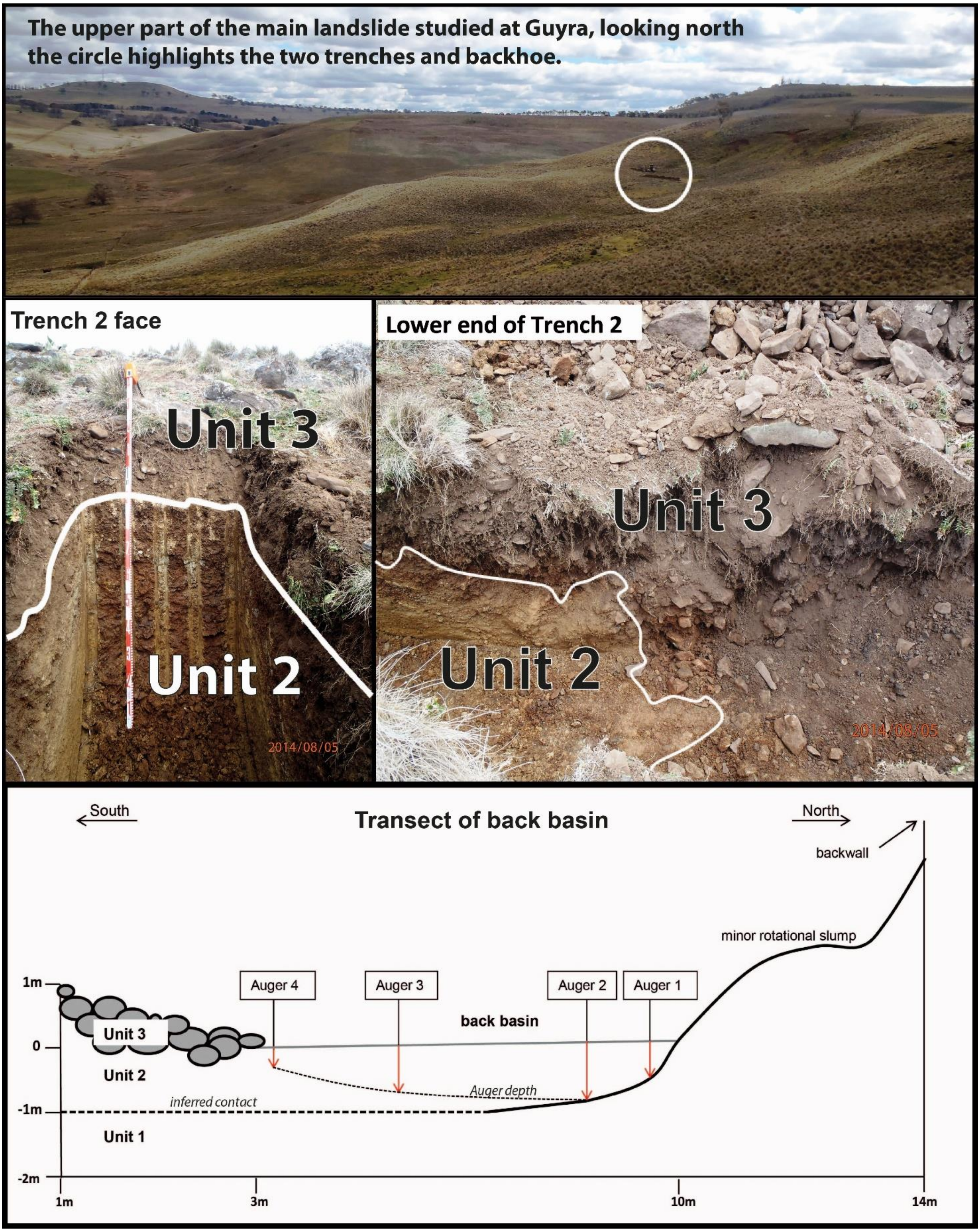



Figure 6.8) Overview of the upper landslide deposit with the trench sites circled. The lower photos show two aspects of Trench 2 with the trench face (left) displaying the strong boundary between Unit 1 and Unit 2. The photo on the left shows the thickening of the

upper clast supported Unit 1 and a benched step in the lower Unit 2 which may be an erosion cut. As it appears to form a benched drop off between the Unit 2 clays and the overlying boulder deposits of Unit C. The transect highlights the structure of the landform and the principle units.

### 6.4.5. Auger survey of back basin

The auger transect of the landslide back-basin on a line adjacent to trench 1 reveals that the upper boulder accumulation documented in trench 1 pinches out into the back-basin. Auger holes 2 and 3 display a minimum of 80 cm of fine clay material most likely the equivalent of Unit 2 in trench 1 (Figure 6.8).

### 6.4.6. Surface exposure dating

The SED ages obtained from the two sample sites on top of the landslide deposit are given in Table 6.1. The ages demonstrate that the major landslide on which they sit pre-dates MIS 3 and is likely to be >50 kya. The dates from the block stream are contemporaneous or slightly older than those from the upper ridge. This suggests that the upper ridge and the block streams formed under the same climate regime.

Table 6.1)

| **Chemical data** | | | | | | **Exposure ages** | |
|---|---|---|---|---|---|---|---|
| Sample | [K2O] (wt%) | [CaO] (wt%) | [TiO2] (wt%) | [Fe2O3] (wt%) | [Cl] (ppm) | Exposure age (ka) | Apparent erosion rate (m/Ma) |
| **Guyra** | | | | | | | |
| GUY-01 | 1.3 ± 0.05 | 8.89 ± 0.08 | 2.25 ± 0.06 | 9.68 ± 0.15 | 3.31 ± 0.23 | **54.2 ± 4.0** | 11.8 ± 1.0 |
| GUY-02 | 1.29 ± 0.05 | 9.15 ± 0.08 | 2.28 ± 0.06 | 9.77 ± 0.15 | 3.04 ± 0.23 | **47.1 ± 3.6** | 13.9 ± 1.2 |

### 6.4.7. Mass balance

The degree-day model results highlight that under a present-day precipitation regime, there is insufficient snowfall to generate a seasonal snow bank of up to 2 m in thickness under temperatures 7–11°C less than present, even when precipitation is moved into the winter quarter (as per Mt Hartz) (Figure 6.10).The maximum modelled snow depth is 0.5–1.0 m. No further reduction in temperature is reasonable because this would cause permanent snow to form year-round, which would result in the development of glaciation at this site. To obtain a modelled snow bank height consistent with field observations (e.g.

1.5–2.0 m), precipitation would need to be nearly doubled (Figure 6.10). Consequently, the feature cannot be formed by cooling alone and some enhanced snow delivery is required suggesting a long snow accumulation season and either higher absolute precipitation or snow focussing (drift) into the hollow promoted by periods of easterly weather conditions (Slee and Shulmeister 2015, Ellerton *et al.* unpublished).

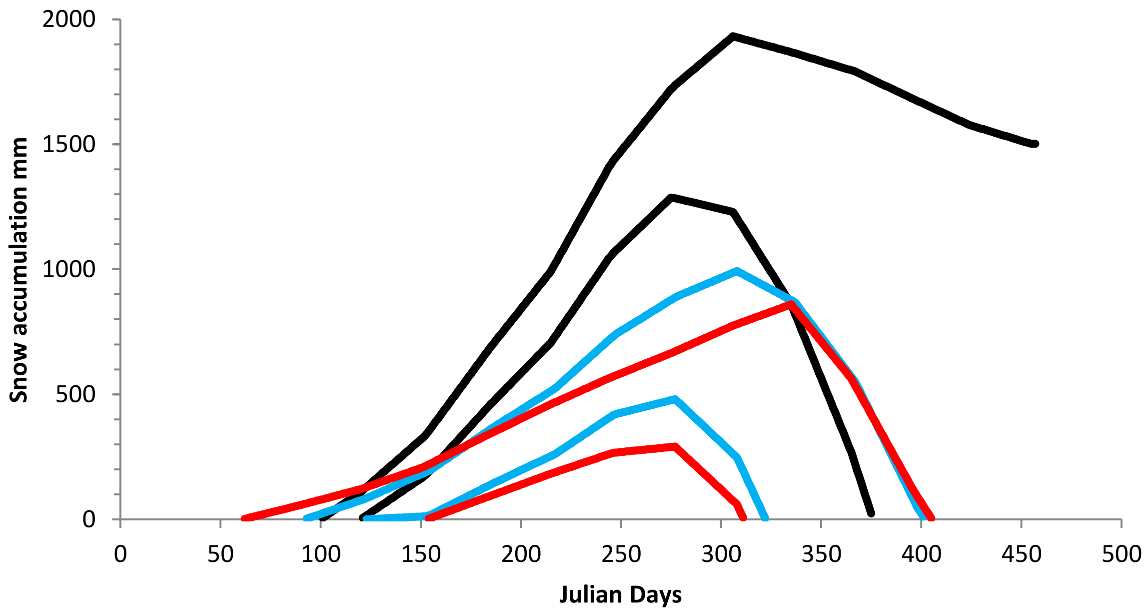



Figure 6.9) Modelled snow accumulation ranges from three different precipitation scenarios tested for temperatures between -7°C and -11°C less than present for a nivation hollow in Guyra, northern New South Wales, Australia. A snow density of 350 kg m–3 has been assumed (see text). Under the present precipitation regime from either Guyra (red) or Mt. Hartz (Tasmania) (blue), there is insufficient precipitation to obtain a 2 m seasonal snow bank. Such accumulation is only attained when the Mt. Hartz precipitation volume is doubled (black).

### 6.5. Discussion

The largest landslides in the Upper Gara Valley are the large deep seated complex landslides that are associated with the seep lines at changes in valley slopes. They are the oldest mass movement landforms because all the other deposits are superimposed on top of them. The earthflows appear to be superimposed on top of the rotational slumps and may represent a distinct period of mass movement activity related to wetter conditions. The block streams also are superimposed on the landslides and in one case a block stream has originated from a landslide block. Although most of these deposits appear to be relict, modern rotational landslides and marginal solifluction processes can be found throughout the study area. However, the small scale of these active mass movements hints to the relative stability of the slopes in the Upper Gara Valley during the late Holocene.

The abundance of mass movement landforms in an area of very limited local relief can be attributed to the bedrock structure of the basalts in the Upper Gara Valley and in particular the ability of the basalts to act as perched aquifers. The upper columnar and massive basalt units are underlain by comparatively highly weathered vesicular basalt units which in turn, appear to lie on a second more impermeable unit near the base of the hill-slope. At this break in slope springs seep from perched water tables 5-20 m elevation above the regional water table as represented by Urandangie Creek. The largest landslides have failed along this break in slope most likely as a result of the increased pore water pressure at the geological contact. This process is widely described in literature (e.g. Van Asch *et al.* 1999, Lebourg *et al.* 2005, Eeckhaut *et al.* 2007, Crozier 2010 and Prokešová *et al.* 2013). The deep seated complex landslides buried the original springs and forced the water to drain through their lower toe sections and rise as seeps at the base of the landslide toes. These springs along the lower toes of the large landslides are associated with saturated soils at and below the seepage line, which is inferred to have caused both solifluction and soil creep creating shallow turf banked lobes (Type 6 deposits) on the lower slopes. These lobate features appear to be active under modern conditions.

The large landslides also provide the parent material for block streams (Type 5) deposits which are sourced both from the back-wall bedrock face and from detachment blocks within the landslides. These block streams flowed across and onto the large landslides indicating that at the time of the block stream formation the deep seated mass movement was already in place and because they are not deformed, it suggests that the large landslides were fully stabilised.

### 6.5.1. Sequence of events and Age of landslides

Overall, our results indicate three phases of mass movement. This sequence is further summarised in Figure 6.11.

**1) Deep seated rotation slumps and earthflows**

These landslides represent the parent material on which all other deposits have been developed or superimposed. These landslides are currently inactive but association of these features with spring seeps in their toe areas suggest that these landforms formed during a period of enhanced moisture availability and high groundwater pore-pressures. Although the springs are active under modern climatic conditions, it is apparent that there has not been enough pore water pressure to maintain deep seated mass movement on these slopes. A trench dug through a boulder ridge near the top of a large landslide (Figure 6.8(B)) suggests that at least part of the main body of the landslide is composed of deeply weathered clays with very few boulders (core stones), a result of deep chemical weathering. More importantly, the initial fill of the back basin that is associated with a putative nivation feature is also dominated by weathered clays, which are consistent with slope wash, suggesting warm, wet conditions and a vegetated head scarp.

2) **Cold climate mass movement phase**

While the block streams maintain an openwork structure, all the freeze-thaw deposits are largely inactive at present except for some minor solifluction on the lower parts of the hill slopes and very minor spallation of clasts from headwall scarps (see below). The block streams are frequently detached from the headwall sources and separated by vegetated ground. Several of the block streams are superimposed on the larger landslides. Consequently, they are clearly stratigraphically younger than the main landslides. Apparent SED ages from these deposits suggest their age is early MIS 3.

**3) Modern mass movement**

Modern ongoing mass movement appears to be limited to minor landforms. These include small parasitic slumps on the back-walls of the landslides as indicated by fresh scars in the regolith and small slump blocks located on the upper and mid slope locations. Below the spring lines low lobate landforms are related to modern flows across slopes of limited gradient. These turf-banked lobes are generally subtle features in the landscape. The larger examples show signs of loose soil scars and rollover in the toe areas indicative of ongoing mass movement. Very small scale (clast-by-clast) spallation of rocks from basalt outcrops is also apparent.

### 6.5.2. Mass movement landforms associating with deep seated landslides

Landslide-prone slopes are regarded as uncommon in the Australian environment (Panek 2015). The Upper Gara Valley therefore offers an unusual opportunity to study a diverse range of landslide and cryonival landforms in a locality where it has not been previously recognized. The landslides have most likely formed as a result of spring sapping and enhanced discharge during periods of the late Quaternary when soil moisture / precipitation was greater than today leading to enhanced drainage in the perched aquifers of the area. The surface exposure ages coupled with the advanced degree of deep weathering to clays of much of the regolith suggest that the major period of landslide activity pre-dates MIS 3 (>50 kya) and could conceivably relate to the last interglacial when the climate was warmer and wetter than present. McIntosh and Barrows (2011) dated landslides by SED to 80-90 kya on the Mt Nicholas Range in Tasmania. They suggested that landslide development that may have been a result of enhanced moisture availability during the last interglacial period. However the morphology and setting of these landslides differ significantly to those of the Upper Gara Valley.

Enhanced deep-seated landslide activity in temperate mid-latitude locations has been shown to be promoted by saturated ground conditions after sustained periods of heavy precipitation (Zêzere *et al.* 1999, Chowdhury and Flentje 2002, Leventhal and Withycombe 2009). At a broader scale the documentation of the temporal distribution of relict landslides may indicate periods of increased landslide activity. This activity has been facilitated by periods of enhanced moisture availability leading to increased groundwater recharge, storage and discharge at spring locations. In turn the enhanced groundwater discharge has promoted spring sapping and the movement of landslides along planes of weakness during the late Quaternary (Borgatti and Soldati 2010).

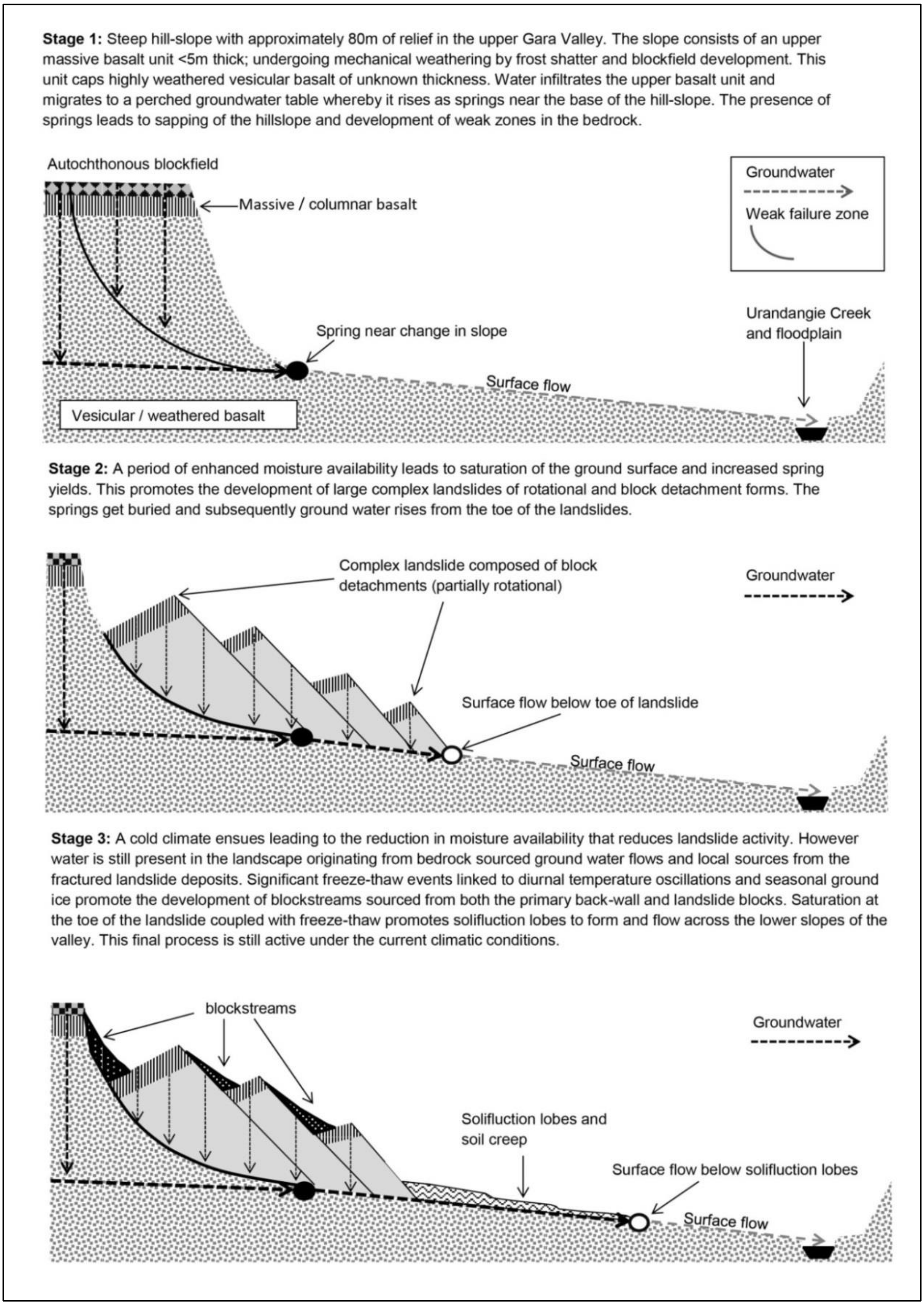



Figure 6.10) Development of mass movement landforms near Guyra.

Paleoclimate reconstructions linked to relict landslide activity are an established method of indicating periods of high moisture availability. The enhanced moisture availability may have been due to either reduced evaporation, increased humidity (Bookhagen *et al.* 2004) or enhanced precipitation that in turn led to increased landslide frequencies. Investigation of landslides in the Argentinean Andes clearly links enhanced late last glacial landslide activity to periods of enhanced precipitation notably that between 40 to 25 kya BP (Trauth *et al.* 2003) which is similar to what is observed here. While it is apparent that research into relict mass movement processes is generally lacking in an Australian context it is even more apparent that the suite of landforms located in the Guyra area are of both geomorphic and paleoclimate significance.

### 6.5.3. Mass movement landforms of periglacial origin

Mapping of all block streams in New England indicates that they are most strongly developed in basalts and to a lesser extent in metasedimentary rocks. Block streams occur between 670 m and 1450 m asl and the presence of some of the largest block deposits at moderate elevations of around 1200 m asl indicates that altitude is not the sole control on block stream distribution or size. The block streams are confined to a north-south oriented belt 15-30 km west of the escarpment of the Great Dividing Range (see Chapter 7, Figure 7.7). The study infers that the presence of long lived snow cover during the winter months may explain the lack of block deposits as insulation from snow cover inhibits sub-surface freezing and resultant freeze-thaw processes (Anderson *et al.* 2002) where duration of winter snow cover is a principal controlling factor in ground freezing, frost shatter and solifluction processes (Goodrich 1982, Jaesche *et al*. 2003). Stronger vegetation cover might also limit freeze-thaw action. The study makes no claims about the absolute precipitation required for block streams to form but note that weak to moderate freeze thaw action is active in the same general areas today as where the main freeze-thaw features occurred during the Last Glaciation.

### 6.5.4. Mass movement landforms associated with nivation processes

Interpretations of pronival ramparts are often controversial (e.g. Ballantyne 1987, Shakesby 1997) and the feature recognised here is neither particularly large nor from surface exposure, distinctive. The primary formation process for ramparts is the sliding of individual clasts across a steep and icy surface (Hedding *et al.* 2007). However, many modern active pronival ramparts have slopes at considerably less than the angle of repose (e.g. Shakesby 1997) with other processes such as debris flows across the snow field and slush avalanches allowing ramparts to form at these lower angles (Ballantyne 1987). In Guyra, the inferred snow slope would clearly be less than angle of repose for the highest, distal most berm, but depending on the geometry of the reconstruction, near angle of repose slopes are possible for the lower proximal berms. Nevertheless, the existence of these concentric openwork-clast supported berms in a strongly freeze-thaw setting strongly favours the presence of long-lived snow-pack in the basin behind the berms. It is apparent that in this strong freeze-thaw environment refreezing is a critical process and rocks will slide at angles well under the angle of repose.

The morphology of the hollow and the GPR stratigraphy of the berms is consistent with a nivation origin for the feature and cannot easily be reconciled to other origins. In particular, the contour parallel orientation of the berm, the isolation of the berm from the headwall, and the clast supported to openwork nature of the berms exclude mass movement processes which are the other most likely candidates.

While the presence of small slumps on the back-wall imply ongoing mass movement at the site, there is a general lack of boulders infilling the back hollow. This could indicate that there was snow and ice accumulation in this hollow during the peak of periglacial conditions at the site considering that nearby block streams have developed from bedrock exposures on the back-wall. There seems little doubt that enhanced mass movement processes acting on the back-wall would have led to the infilling of the depression with a mixture of coarse and fine material rather than solely fine laminated clays.

### 6.5.5. Precipitation volume and source

The presence of a possible pronival rampart at the Guyra site indicates that cold-season precipitation was sufficient for a relatively thick snow bank to form and that conditions were cold enough such that the snow bank persisted long enough so that the berms could be constructed. The rampart shows evidence of snow pack contraction from a maximum extent. The morphology of the berms, buried and exposed, suggests ice contact on the headwall side and the slightly lower elevation of each successive berm indicates gradual shrinking of the snow bank. A noteworthy observation is that it is challenging to achieve the highest relief berm elevations (2 m) strictly from direct precipitation and requires some additional sources of snow. The broad plateau above the site would act as a snow field catchment and therefore some snow additional mass would likely be derived from wind drifting. However, we also note that the site is on a SW slope and thus is not particularly favourable for wind-blown snow unless the blown snow is from an easterly source.

A key question is whether there would be enough cold season snow to generate the nivation feature. Central to this discussion is the source of the moisture. Based on modern data, the dominant source of snowfall at Guyra is not associated with the passage of Southern Ocean (westerly) fronts in winter (e.g. Hobbs 1971, Hobbs 1998). Instead modern snowfall occurs when east coast lows track through the region. These are formed when a blocking high extends south-east of the region and a trough forms along the NSW coast. The lows drag relatively warm, moist air from the Tasman Sea onto the coast. As this air mass moves inland and upslope, it strikes cold air sitting on the New England Plateau. The interaction of these air-masses produces strong precipitation and snowfall at high elevations. The following recent snowfall events provide two examples. On the 12th to 13th of October 2012, a strong moisture bearing east coast low over the Tasman Sea interacted with a slow moving upper atmospheric cold pool over central NSW. This system promoted snowfall over an extensive area of Northern NSW and the SE Queensland high country with falls in excess of 15 cm at Guyra (BOM 2013). Similarly a series of five snow bearing East Coast Lows occurred in June 2007 resulting in snow falling and settling on the New England Tablelands (Figure 6.12)

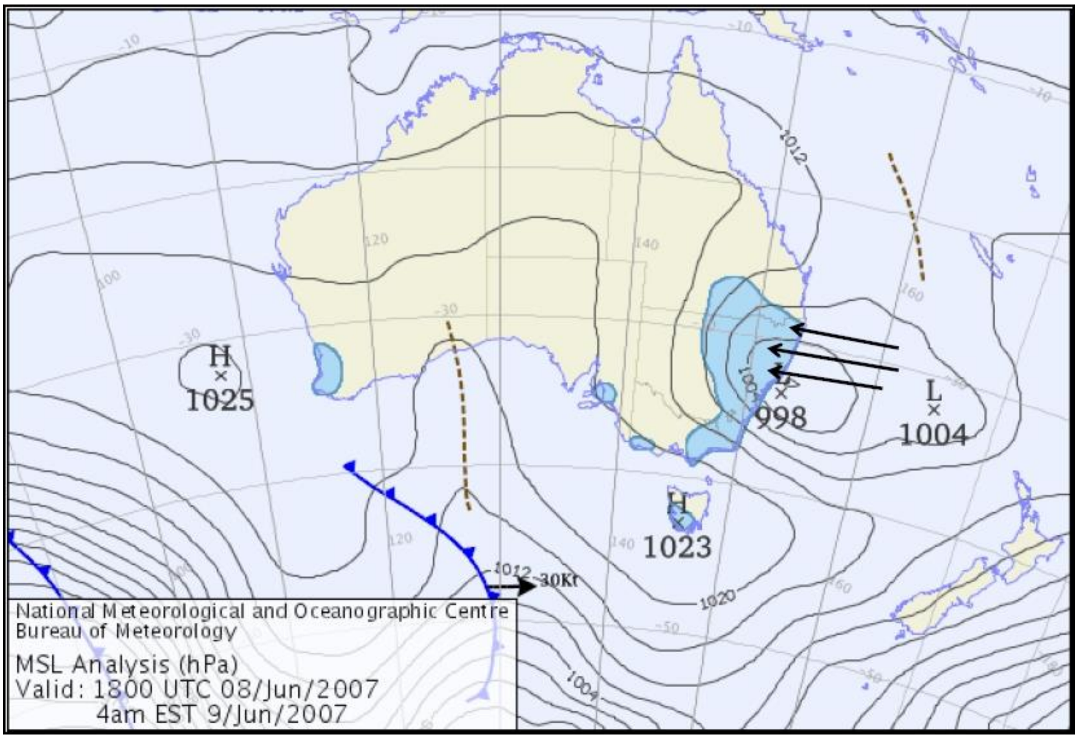



Figure 6.11) BOM precipitation map for 8/9th June 2007. This map shows the impact of an east coast low on precipitation including snowfall over the New England Tablelands (BOM 2007).

As noted earlier, it is widely regarded that mean annual temperatures in SE Australia were significantly cooler than present at the LGM, typically in the range of 7-9°C (Galloway 1965, Miller *et al.* 1997, Williams *et al.* 2009). Our modelling of realistic temperatures required for snow bank formation at Guyra suggests a very similar range. Conversely, reconstructions of temperatures for the East Australia Current which runs along the eastern coastline of Australia, indicate that water temperature cooled only moderately at the LGM as the present day at these latitudes (within 4-6°C) (Bostock *et al*. 2013). In addition, the extension of the Australian landmass to connect Tasmania to the mainland at lower sea-levels meant that warm water could penetrate several degrees of latitude further south before encountering Southern Ocean waters. This situation implies that the temperature gradient along the east coast of Australia in glacial times was significantly stronger than the present day. East coast lows may or may not have been more common during glacial times, but there was significantly more energy available for them because of the enhanced pressure contrast and the likelihood of snow falling was greatly enhanced because of the generally lower temperatures. In short, for a narrow north-south band of land from the escarpment to just west the main divide, significantly enhanced snowfall is a reasonable expectation. Note that the easterly snowfall source for Guyra does not contradict generally prevailing westerly conditions during winter months in glacial times. Some minor snowfall was almost certainly derived from this source also.

The significance of substantial snowfall in a band along the escarpment is that it challenges a universally dry glacial climate in SE Australia. It does not imply, or even suggest, widespread wet conditions at the LGM but it helps in the delivery of water to the headwaters of west flowing rivers and can assist in reconciling dry conditions on the riverine plains and western slopes of the dividing ranges with the observations of greater flow in the rivers close to the LGM (e.g. Kemp and Spooner 2007, Kemp and Rhodes 2010). Here are the winter snowbanks to feed spring melt flows.

## 6.6. Conclusions

The landslides and cryonival features on the basalt slopes of the upper Gara Valley represent a complex history of mass movement processes during the late Quaternary. Three distinct phases of slope activity have occurred with 1) major deep seated mass movement associated with a warm wet period occurring most likely during MIS 5. This early episode contrasts with widespread block field and block stream formation promoted by mid-late last glacial cold periods contributing to periglacial processes and enhanced freeze-thaw. Earthflows overlying and presumably post-dating the MIS4 deep-seated landslides imply local precipitation events, but not prolonged periods of enhanced precipitation required to increase the perched water tables and reactivate deep-seated movement on these landforms. The Holocene appears to have been too warm for significant periglacial activity and not wet enough to promote enhanced spring seepage and the re-mobilisation of the major deep seated landslides. Instead minor shallow mass-movement is an ongoing process that may relate in part to European vegetation clearance.

Our study confirms the inferences of Galloway (1965) of the presence of block streams and other freeze-thaw features in far northern New South Wales at 29°30’S. The features are concentrated on the colder south and west facing slopes. The presence of a possible nivation hollow and associated pronival (protalus) ramparts strongly suggest the accumulation of thick winter snow pack during glacial times in this area and mass balance modelling demonstrates that cooling alone cannot explain the presence of this feature. Instead it requires an enhanced snow accumulation period and modest to significant increased snowfall. At the present time, winter snowfall is associated with East Coast lows and we argue that this is the most likely source of enhanced winter precipitation during glacial times, driven by increased temperature gradients between the east coast air masses and cold air sitting over the Tablelands. The findings may help resolve the enigma of drier conditions in much of SE Australia at times when river flows are stronger as the freeze-thaw zone coincides with the headwaters of the major rivers.

# Chapter 7. The distribution and climatic implications of periglacial landforms in eastern Australia.

This chapter forms the thesis version of the paper: **Slee, A.** and Shulmeister, J., The distribution and climatic implications of periglacial landforms in eastern Australia. Published in the *Journal of Quaternary Science* 30(8):848-858 (see appendix 3). Note this paper was revised and updated after the submission of the Thesis and includes new climate data not incorporated in this thesis but referenced in several locations within the thesis.

## 7.1. Abstract

Mapping of over 3500 mostly relict block deposits and hundreds of large scree slopes along the length of Eastern Australia has been undertaken to determine the extent of past periglacial activity. Modern climatic, topographic and geologic parameters have been described for all of the mapped deposits. Periglacial landforms are common in the high country as far north as 30°S. There is a clear relationship between the locations of relict periglacial landforms with areas that receive more than 50 days of frost annually under modern conditions.

An unexpected observation is the importance of precipitation in the distribution of block deposits north of 35°S. Here, almost all block deposits have a southerly or westerly aspect, but also lie in a narrow modern precipitation band of c. 850 – 1000 mm. We infer that to the east of this band high elevation areas appear to have received too much snow to permit strong freeze-thaw, while to the west; well-developed block deposits are absent, most likely due to insufficient moisture to drive strong freeze-thaw processes. We cannot define specific last glaciation precipitation but the maintenance of a strong east-west precipitation gradient during glacial times is inferred for areas between 35 and 30°S.

## 7.2. Introduction

The focus of this study is on the distribution of a suite of periglacial landforms associated with freeze-thaw processes operating in the mountains of south-eastern Australia during the late Quaternary. The principle landforms mapped in this study are block deposits that represent ground ice conditions (Caine and Jennings 1968, Boelhouwers *et al.* 2002, Sawada *et al.* 2003) and scree deposits that are associated with more marginal freeze-thaw conditions (Hales and Roering 2005).

Periglacial landforms can range in form and scale from minor patterned ground formations only a few cm in diameter and limited to the top few centimetres in the uppermost soil horizons to permafrost promoted rock glaciers. Relict rock glaciers, block streams, block fields and large mountain screes have been collectively described as block deposits (Barrows *et al.* 2004) or as rock-ice features (Millar and Westfall 2008) and we follow the terminology of Barrows et al. Block deposits including rock glaciers, block streams, block slopes and block fields (felsenmeer) have been recognised as developing under conditions that promote frost shatter of bedrock followed by downslope movement of the deposit under the influence of interstitial ice, either within the boulder matrix (Jennings 1969, Harris *et al.* 1998, Wilson 2007) or beneath the blocks in an underlying fine grained sediments (Caine 1983). Screes may form in environments impacted by marginal freeze-thaw conditions and can be important indicators of the lower limits of past and modern freeze-thaw (Librecht *et al.* 2000, Hales and Roering 2005, 2009).

The morphology, distribution and age of these features have been utilised for paleoclimate interpretation by numerous authors worldwide (e.g. Oguchi and Tanaka 1998, Boelhouwers 1999a, b, Van Steijn *et al.* (2002), Wilson *et al.* 2008). In Australia there is no evidence of modern block deposit activity, however, researchers, notably Webster (1974), Caine (1983) and Barrows *et al.* (2004), have documented numerous relict block deposits in the Australian Alps and highlands of Tasmania.

The documentation and mapping of the distribution of periglacial landforms on a sub-continental scale has been rarely addressed. In the United States the most notable was the work by Park Nelson *et al.* (2007) who mapped the distribution and elevation of 96 relict periglacial block deposits in the Appalachians along a north to south transect, to determine past climatic trends. In the Sierra Nevada of California, Millar and Westfall (2008) constructed an inventory of 421 rock glaciers and block deposit landforms using their distribution to calculate the range of Pleistocene cooling. In New Zealand, mapping of scree deposits along a transect of the Southern Alps by Hales and Roering (2005) revealed a regional trend in scree development linked to tectonic uplift and frost susceptibility. In Europe, many studies have documented the distribution of block deposits (Firpo *et al.* 2006, Gutiérrez and Gutiérrez 2014) as well as rock glaciers (Urdea 1992, Baroni *et al.* 2004 and Scotti *et al.* 2013). However, most of these studies are more local in scale and mapping projects targeting the distribution of relict periglacial landforms for the purpose of defining past climatic conditions are mostly lacking. The one notable exception is the work by Hughes *et al.* (2006) who summarise both the glacial and periglacial landform distribution around the Mediterranean.

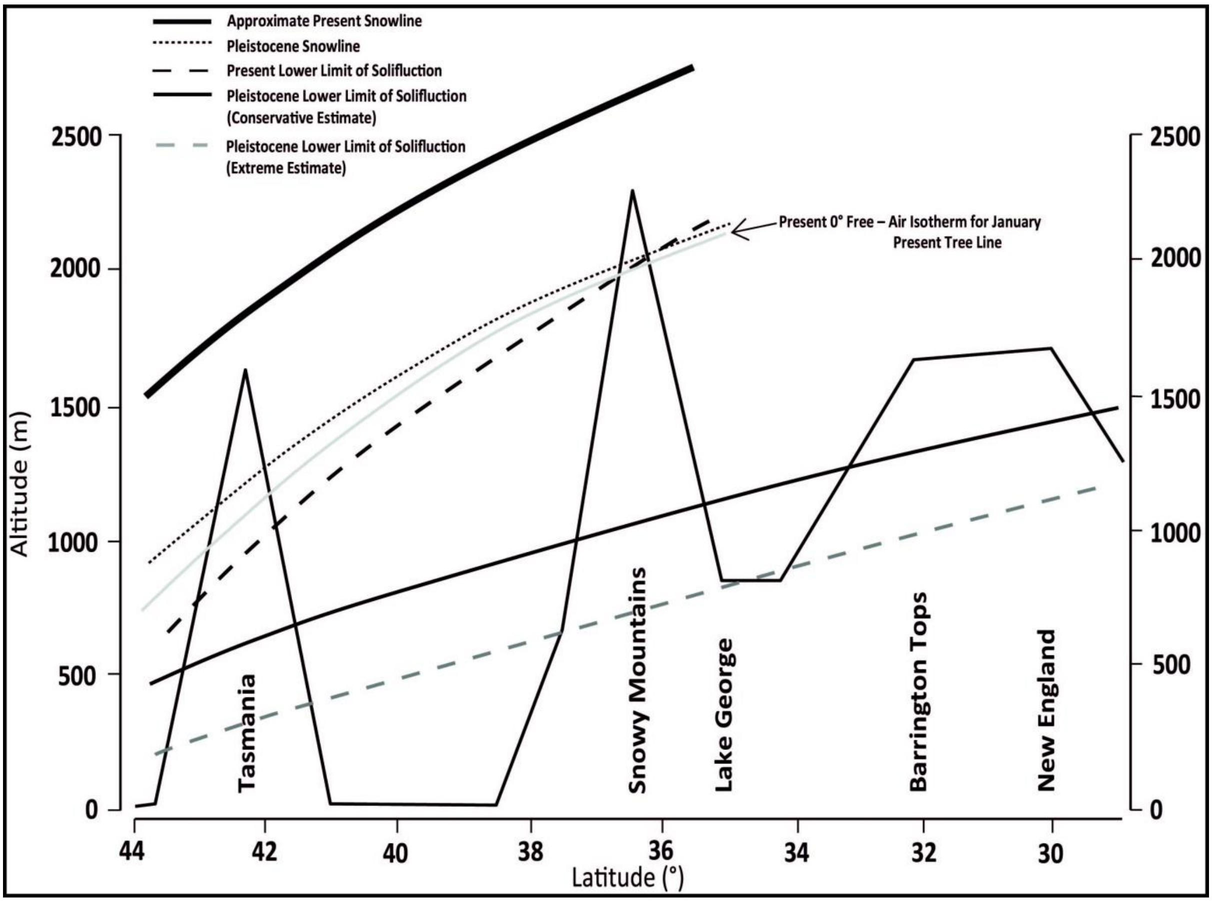



Figure 7.1) Galloways (1965; Fig 2 p.605) estimates of glacial / periglacial altitudes during the LGM in SE Australia.

Within Australia, Galloway (1965) utilised the then known distribution of block deposits to estimate the limits of periglacial climatic conditions during the Last Glaciation in eastern Australia (Figure 7.1) He suggested that parts of the New England Tablelands as far north as c. 30°S and as low as 1100 m above sea level fell within the lower limits of periglacial activity. No actual deposits are reported from these northern regions in his paper. The other major periglacial studies in Australia are by Webster (1974) who described block deposits in the Australian Alps and Caine (1983) and Kiernan (2008) who documented the morphology of periglacial deposits in Tasmania.

This paper presents the results of an extensive survey of periglacial landforms in the highlands of eastern Australia using remotely sensed data and an extensive field program. The main research aims are.

- To determine the distribution and altitudinal range of relict freeze-thaw landforms in eastern Australia with the aim of producing a map of the extent of Quaternary freeze-thaw / periglacial environments.

- To determine modern and infer paleo-climatic parameters controlling the distribution of periglacial landforms.

## 7.3. Methods

### 7.3.1. Study area

The research is focused on the uplands of the Great Dividing Range and Tasmania between 26° and 44°S. The Great Dividing Range consists of extensive plateaus broken by dissected ranges formed from Tertiary volcanism. The general elevation of the Great Dividing Range varies from 700 – 1800 m asl. The highest summits are located in the Australian Alps in southern New South Wales and north-eastern Victoria, where they rise to 2228 m asl at Mt Kosciuszko, the only area of the Great Dividing Range that was glaciated during the Quaternary (David *et al.* 1901, Barrows *et al.* 2001). The mountains of Tasmania are lower (Mt Ossa 1617 m asl is the highest peak) but due to their higher latitude they are much more extensively covered in periglacial deposits.

### 7.3.2. Mapping

Initially a literature review was used to establish the topographic and climatic distribution of known block deposits in Australia. This was followed by a systematic search for block deposits on all mountain ranges in South-eastern Australia and Tasmania utilising Google Earth Pro, which permits landform documentation and analysis of dispersed features located in large/remote study areas unsuitable for systematic ground investigation (Goudie 2007, Brown *et al.* 2011, Fu *et al.* 2013 and Pearce *et al.* 2014). Sites determined from Google Earth Pro were subsequently examined using aerial photographs from the following sources

Six Maps NSW (https://maps.six.nsw.gov.au/)

Alpine Shire Interactive Mapping System (AIMS) (http://www.alpineshire.vic.gov.au)

Land Information System (LIST) Tasmania
(https://www.thelist.tas.gov.au/app/content/home)

Ground truthing of deposits was undertaken across the entire region and included both systematic descriptions of key block streams and roadside observations of the mapped sites. Because the focus of the original project was on defining the limits of block deposit formation, surveys were most intensive on the northern (warmer) limits of the block deposit observations.

All mapped deposits were either fully digitised (block deposits) or their central location was marked (scree) on Google Earth, extracted as kmz files and converted to shape-files in Arc-GIS. As the surface expression of a deposit may vary between different Google Earth Images due to variances in the azimuth of the image when it was taken (Smith and Wise 2007), care was taken to identify the image that gave the most detail of the deposits prior to digitising their locality and extents. It is recognised that the extent of some small block deposits will be underestimates because features are obscured by vegetation.

### 7.3.3. Arc-GIS and data extraction

Various parameters related to the distribution of the bock deposits and screes were calculated in Arc-GIS and these are discussed below along with the data-sources.

*Topographic Parameters*

The topographic parameters of block deposit area, slope, aspect and altitude were calculated using the National Shuttle Radar Tomography Mission derived 3 second (~90 m) and 1 second (~30 m) Digital Elevation Models (DEMs) obtained from Geoscience Australia (http://www.ga.gov.au/scientific-topics/geographic-information/topographic-maps-data/digital-elevation-data). Due to the wide variety of shapes of block streams there was a need to calculate the block stream attributes from the central geographic data point. Therefore, given the scale of many deposits with respect to the scale of the DEMs, the coarser 3 second DEM was considered to give parameters more representative of the overall extent of the block streams than the finer scale 1 second DEM, which was utilised specifically for the calculation of block deposit slopes. Block deposit aspects were summarised onto rose diagrams.

*Geologic Parameters*

The best available digital geology information for eastern Australia comes from the 1:1 000,000 geologic shape file (Raymond *et al*. 2012). This was accessed as a downloadable vector shape file, from which the general (non-specific) geologic units of individual block deposits and scree were mapped in Arc-GIS.

*Climate Parameters*

Climatic parameters were calculated using Bioclim climate grids (Hijmans *et al.* 2005) available from WorldClim-Global Climate Data (http://www.worldclim.org/). Species Distribution Models (SDM) of which Bioclim was the first developed (Booth 1985, Booth *et al.* 2014). Bioclim utilises gridded datasets (Nix 1986), usually derived from a DEM coupled with mathematical surfaces (Hutchinson *et al.* 1984, Busby 1986) of a range of climatic variables, to describe the climatic parameters of a locality of specific interest. BIOCLIM was initially set up for mapping the distribution of flora and fauna based on known localities and therefore to infer the climatic ranges of taxa (see Busby 1986, Booth 1990). The dataset comprises of 17 climatic variables interpolated from the distribution of climate stations. The grid maps were generated utilising mathematical surfaces in the ANUSPLIN modelling package (Hijmans *et al.* 2005). The data are represented as a raster DEM with 1km$^2$ climate grids. The resolution of the climate grid is generally adequate for classifying our deposits because the topography is not overly complex. Clearly 1km$^2$ grids are problematic when applied to areas of extreme relief such as the great escarpment. Of the 17 climatic parameters available in Worldclim, eight were utilised for describing the climatic characteristics of the Australian periglacial landscape (see Table 7.1). Eight variables where chosen as initial work using the Bioclim variables identified these parameters as the most relevant to the identification of geographic variations in the block and scree deposits. In addition to the Worldclim data, raster grid maps displaying the average annual number of frost days below 2°C, an obvious control on freeze-thaw activity, was used as an additional climate input (BOM 2012).

| Table 7.1) Variables reported for bioclimatic mapping |
|---|
| Mean Annual Temperature (MAT) |
| Mean Diurnal Range (Mean of monthly maximum temperature – monthly minimum temperature) |
| Minimum temperature of coldest month (MinT) |
| Mean temperature of coldest (Winter) quarter (MTW) |
| Mean Annual Precipitation (MAP) |
| Precipitation Seasonality (PS) |
| Mean Precipitation of the warmest (Summer) quarter (PSQ) |
| Mean Precipitation of the coldest (Winter) quarter (PWQ) |
| Mean annual frost days <2°C |

The area of all block deposits was calculated from the polygon files converted from Google Earth kmz files in Arc-GIS. After this, the central co-ordinates of all block deposits and screes was utilised to calculate climatic, topographic and geologic variables associated with the input datasets. The output variables were produced by using the ‘extract multi-values to points’ tool in the Arc-GIS Spatial Analyst toolset.

## 7.4. Results - Topographic and geologic variables

In total 3524 block deposits and 637 scree deposits where digitised in Google Earth and mapped in Arc-GIS; these deposits are presented in Figures 7.2 and 7.3 and as supplementary data in the appendix 7 to 15. The distribution of the block deposits reveals a number of significant observations.

### 7.4.1. Area (Hectares)

The total area of block deposits in eastern Australia is approximately 18,769 Ha, of which 17,332 Ha or 92.3% of this area is located in Tasmania. Of the 784 mapped block deposits covering 1437 Ha found on the Australian Mainland, the majority of the deposits are small, with only 23 deposits being >10 Ha in size. Large deposits are located on the Bogong High Plains (36°56’25S: 147°13’12E) and near Mt Howitt (37°12’22S: 146°39’56E) in Victoria, and on the Tidbinbilla Range (35°26’47S: 148°51’34E) near Canberra. In northern NSW the largest blockfield is located on the northern face of the Woolooma Range (32°02’13S: 151°12’24E) in the upper Hunter Valley. In contrast, 332 block deposits have areas >10Ha in Tasmania and several very large block deposits with extents of several hundred hectares of continuous boulder cover are present at locations including Ben Lomond (41°33S: 147°40E), Western Bluff (41°37’29S: 146°17’39E) and the Snowy Range (42°56’33S: 146°39’30E).

### 7.4.2. Regional distribution of block deposits

Prior to this study the northern most block deposits documented in literature were those of Mt Coree (35°18’25”S) near Canberra (Webster 1974). The results place the most northerly block deposits of likely periglacial origin at 29°46’25’’S some 670 km north of the previous mapped limit, but within the predicted zone of Galloway (1965). Block deposits in Tasmania are the dominant alpine landforms of the mountains of central and eastern Tasmania, and they form an almost continuous cover around the base of the mountains in north-eastern Tasmania (Caine 1983) and in the Great Western Tiers. They also cover much of the northern Central Plateau. In western Tasmania the distribution of block deposits is strongly associated with the limits of former glaciation. For example, mountains in south-western Tasmania such as Mt Anne (Kiernan 1990) and the Denison Range (Kiernan *et al.* 2014) have been impacted by significant Last Glacial Maximum glaciation on the leeward (eastern) slopes, leading to the presence of extensive block deposits only on the windward western slopes of the ranges.

### 7.4.3. Altitude of block deposits

The distribution of block deposits suggest that there is no significant rise in the minimum elevation of block deposits between the Australian Alps and northern New South Wales. The lower elevation of block deposits at 30°S lies at approximately 800-1100 m asl (Figure 7.3). It is apparent that local topographic effects, and notably cold air ponding, lead to enhanced diurnal freeze-thaw oscillations at mid – lower slope locations, and play a significant factor in the distribution of block deposits. In Tasmania, well developed block deposits can be located to altitudes of 550 m asl in the east of the state.

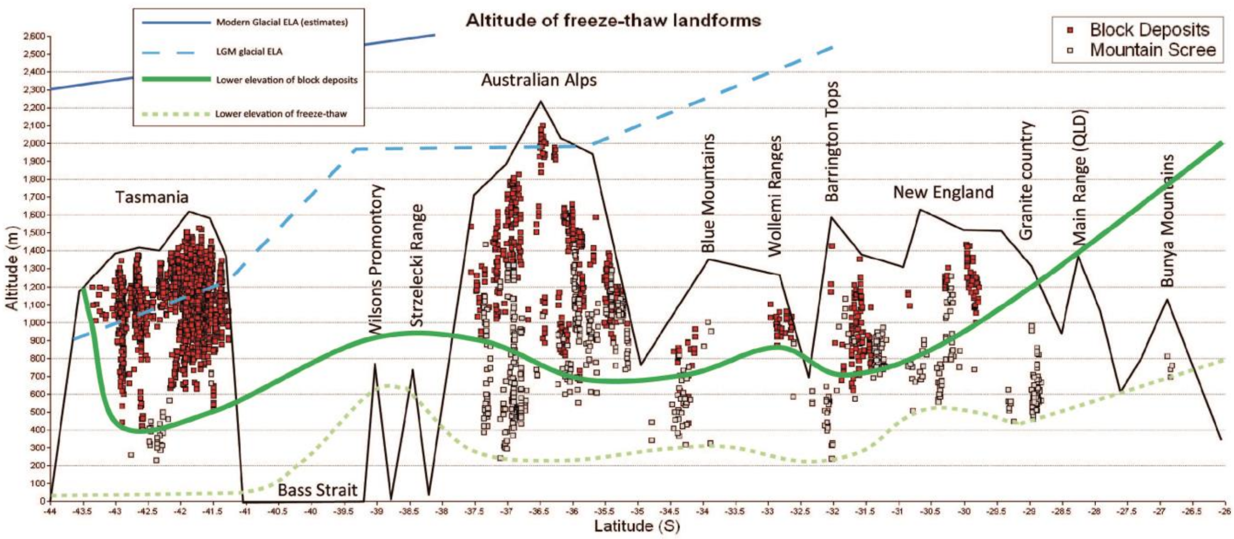



Figure 7.2) This is a general profile of the Great Dividing Range and Tasmania from 36° to 44°S, with the elevations of block deposits and mountain scree deposits superimposed. The dark blue line represents the approximate ELA for glacial ice under modern climatic conditions. The light blue line is the approximate ELA during the LGM. Both are based off estimates from Colhoun (1985) and Barrows *et al.* (2001). The dark green line is the lower elevation of well-developed block deposits as mapped during this study. The green dotted line indicates the lower estimated elevation of freeze-thaw landforms, Note that in Tasmania small scale landforms suggested to be of freeze-thaw origin reach to close to present day sea level (Colhoun 1979, Kiernan 2008, McIntosh *et al.* 2009, Slee *et al.* 2015). Further north the scree and block deposits appear to have varying lower altitudes largely due to the effects of cold air drainage in extensive gorge terrain.

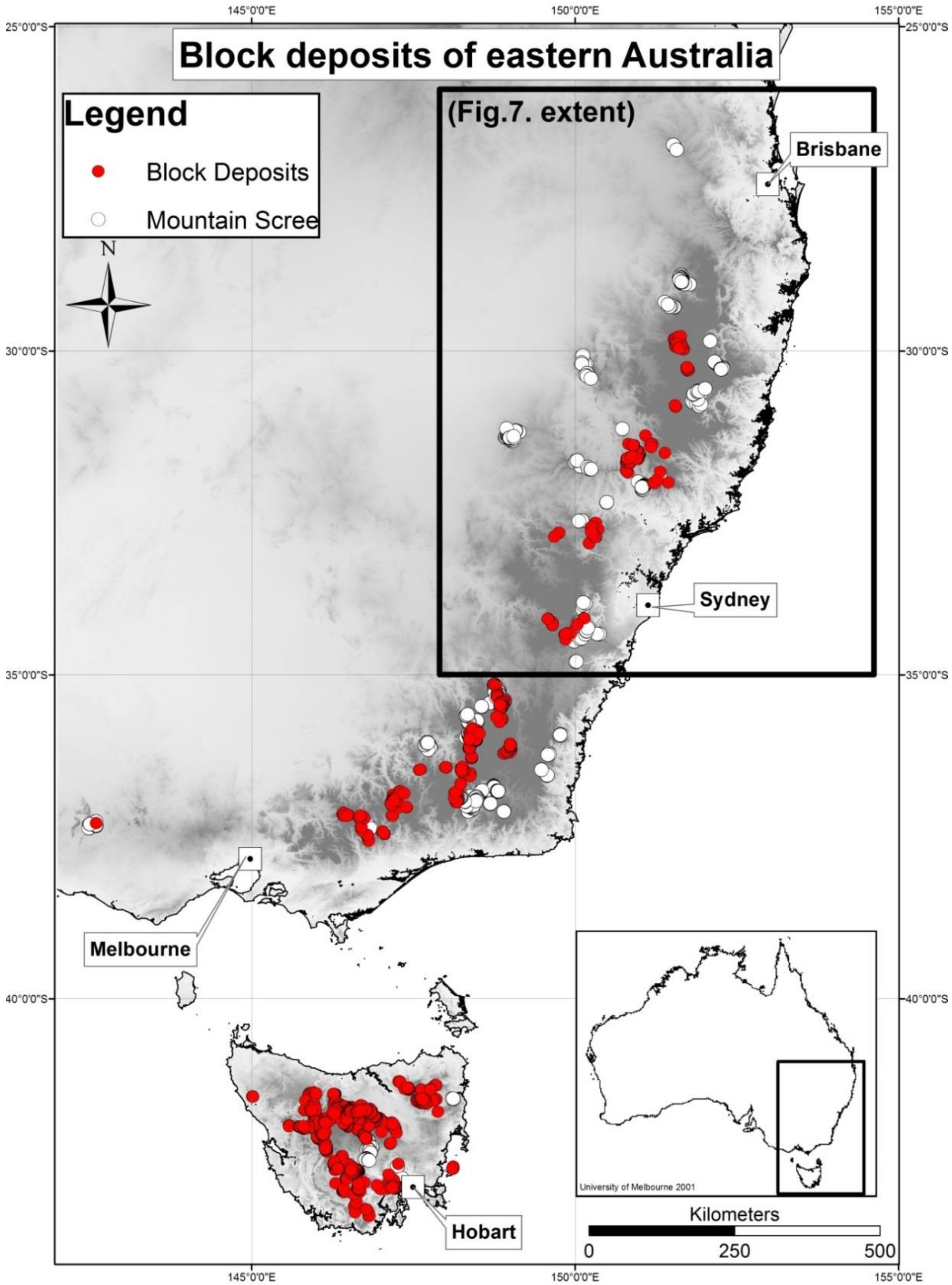



Figure 7.3) Distribution of block deposits and scree deposits in south-eastern Australia.

### 7.4.4. Geologic control on block deposits

On the Australian mainland; the majority of block deposits are formed in well jointed basalt (Figure 7.4 A-D), this is particularly the case in northern New South Wales, where the only other lithology to produce block deposits are the outcrops of slaty Carboniferous Sandon Beds (Figure 7.4B). To the south, there is a greater diversity of lithologies forming block deposits. Large block streams in rhyodacites can be found in the Cobberas Range of Northern Victoria (Webster 1974, Ashton and Moore 1978). Block deposits formed in granitic rocks occur at Mt Jaithmathang (Figure 4C) and are present on the higher slopes of the Main Range and Bogong high plains above altitudes of 1700 m asl. The greatest diversity of block deposit lithologies is in Tasmania where block deposits (Figure 7.4E, F) are formed in dolerite, conglomerate and quartzite. The geologic units of both block deposits and screes are mapped in Appendix 4 and 5.

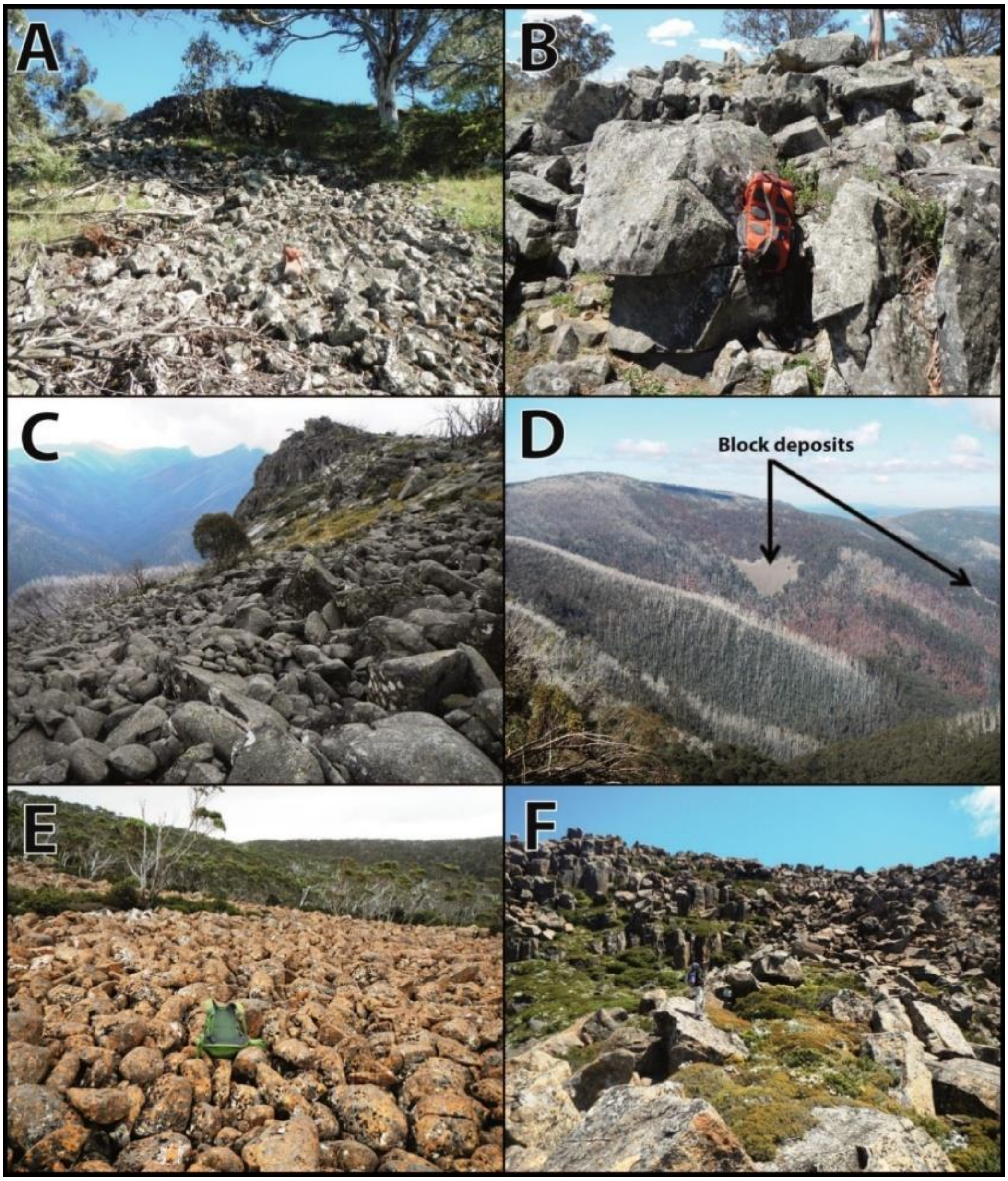



Figure 7.4) Examples of Australian block deposits (a) Basalt block stream near Guyra northern NSW (30°17’12”S: 151°43’39”E) (B) Block deposits formed of angular boulders in Sandon metasediment beds near Uralla northern NSW (30°50’19”S: 151°32’39”E) (C) Granite block stream on Mt Jaithmathang, Victorian Alps (36°53’25”S: 147°11’10”E) (D) Basalt block deposits near Mt Hotham, Victorian Alps (37°00’45”S: 147°10’28”E)(E) Low gradient dolerite blockstream on Mt Wellington, Tasmania (42°53’13”S: 147°13’26”E) (F) Steep blockstream composed of large angular boulders below the summit cliffs of Mt Olympus (42°02’45”S: 146°07’10”E) this deposit lies above the glacial trim line associated with the Lake St Clair glacier, Tasmania.

### 7.4.5. Aspect

On the Australian mainland block deposits in the Australian Alps have a strong northerly aspect with a secondary north-westerly aspect (Figure 7.5). The deposits of central and northern NSW have a dominant westerly aspect, although it is notable that many of the larger block streams have south to south-easterly aspects. This westerly bias was not predicted due to the expectation that periglacial processes would be the most active on the more shaded southern slopes. Within the Australian Alps, the large number of deposits on the Bogong High Plans and upper Tumut Valley in the northern NSW Alps that have northerly aspects, but lie in areas of marked cold air drainage on frost susceptible basalt geology, may skew the regional trends. As noted previously, on unglaciated mountain tops in Tasmania periglacial block deposits have no strong aspect orientation. The lack of aspect control is also evidenced by the occurrence of block and scree deposits that have developed on low elevation sites such as Mt Maria (710 m asl) (Slee and Kiernan 2014).

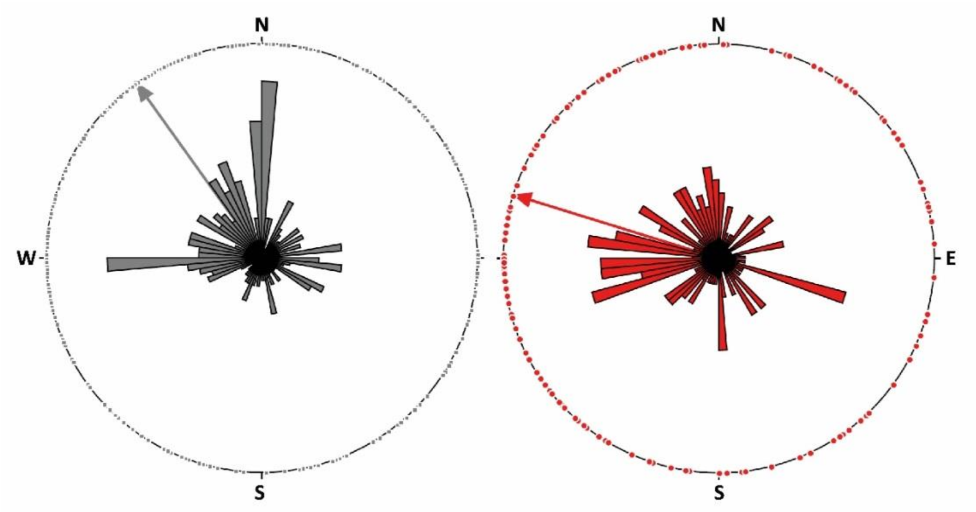



Figure 7.5) Aspect of block deposits in (left) the Australian Alps and (right) Northern New South Wales. Note that in the Australian Alps there are a strong concentration of block deposits with northerly aspects and a secondary westerly concentration. In northern New South Wales the dominant aspect of block deposits is to the west and northwest although observations indicate that a number of the largest deposits have formed on south or south-east facing slopes.

### 7.4.6. Slope

Calculated block deposit slopes vary from 1° to 43° in northern New South Wales where the average slope of the block deposits is 21.4° with a one sigma range of 9°. The modal slope is 24° but the data shows a broad range of slopes from 7 - 33°. In the Australian Alps slope angles varied from 2 - 45° with a mean of 22.7°, the slopes showed a weak bi-modal distribution with the mode at 29° and a secondary peak at 15°. Tasmania showed the widest range of slope angles from <1° to 61°. The mean for Tasmania was 18.3° with a s.d. of 10.2° and the mode was 17.9°. Both values are lower than the mainland.

### 7.4.7. Distribution of scree

Scree deposits generally occur at lower elevations than block deposits, with scree deposits found at altitudes of ~250 m asl on the southern Australian mainland and close to sea level in Tasmania (this study and Colhoun 1977, Kiernan 2008, McIntosh *et al.* 2009, 2012). Further north scree deposits are also common in mid-altitude river gorge settings at altitudes of 450-900 m asl to both the east and west of the New England Plateau. Small screes found below cliff faces at altitudes of 700 – 850 m asl on the upper western slopes of the Bunya Mountains in Queensland (26°50’36”S) most likely mark the northern limits of marginal periglacial activity in Australia.

## 7.5. Results - Bioclimatic variables

### 7.5.1. Annual Number of frost days

There is a very strong relationship between the Mean Annual Number of frost days and the distribution of block deposits in Australia (see Figure 7.6). 99% of block deposits on the Australian Mainland are located in areas with at least 50 frost days a year and no site records less than 30 days of frost a year.  In Tasmania, 99.3% of block deposits are also in areas with more than 50 frost days, the exceptions are Mt Maria on Maria Island off the east coast of Tasmania and the summits of the Norfolk Range of north-western Tasmania. The majority (88%) of scree deposits are found in locations that receive a minimum of 50 frost days a year although on average they receive 92 frost days which is significantly less than the 158 frost days received on average by block deposits.

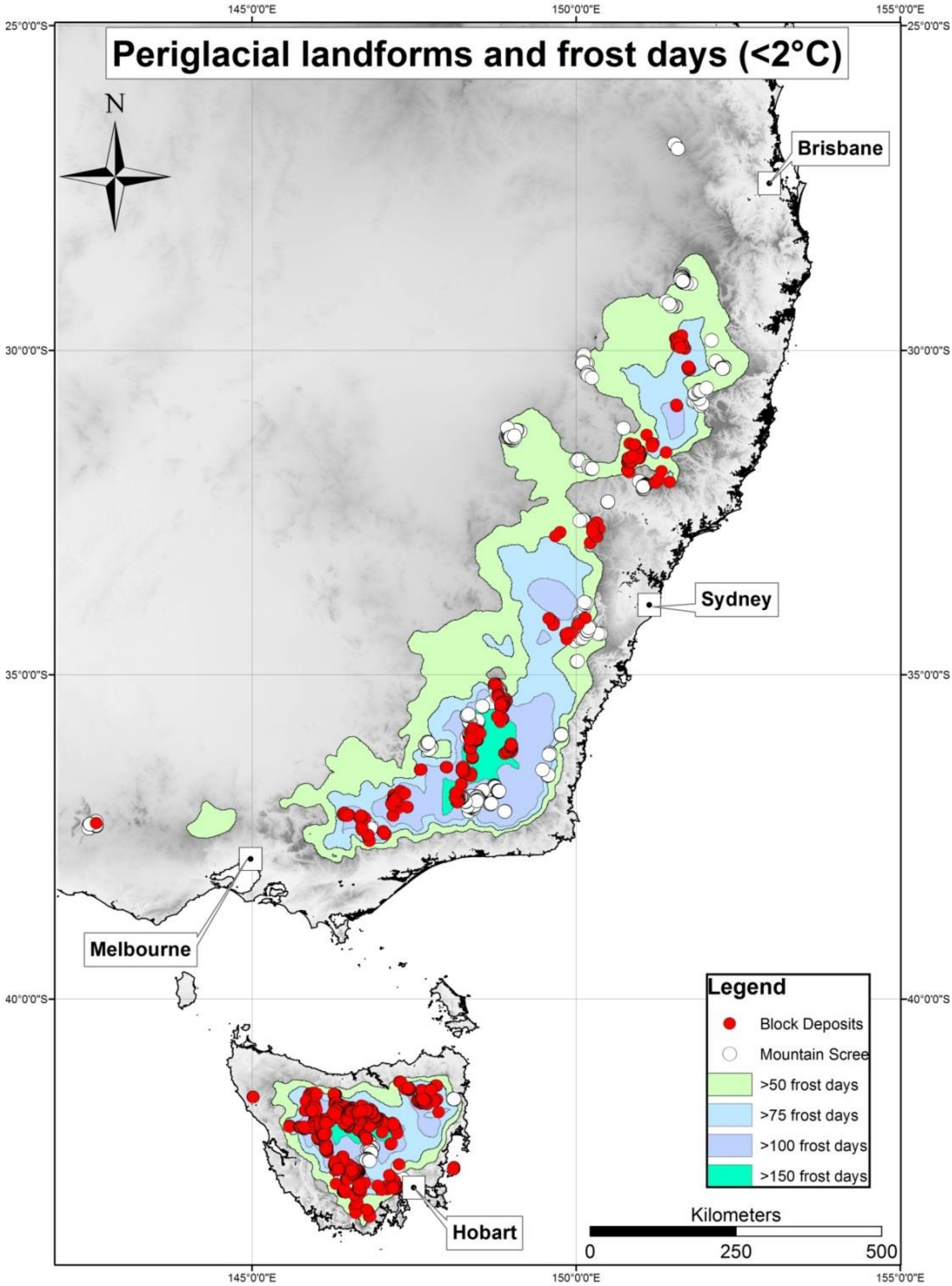



Figure 7.6) This figure maps the association of block and scree deposits with areas which experience >50 frost days annually under the current climate in eastern Australia.

### 7.5.2. Mean Annual Precipitation

In Tasmania block deposits display a wide range of modern precipitation values from 800 mm to >3200 mm. On the SE Australian Mainland the block deposits of the Australian Alps lie generally within a precipitation band between 1500 and 2200 mm. Further north the 1500 m high plateau of the Barrington Tops (32°01'58": 151°26'17") has an annual precipitation of >1500 mm, block deposits have been observed by the authors and Nanson (2009) underlying peat bogs on the plateau . The plateau lies immediately south of the New England Tablelands but further to the east of other documented periglacial landscapes in northern NSW.

North of 35°S the majority of block deposits lie in a narrow precipitation band between 850 and 1000 mm with occasional outliers located in areas receiving up to 1150 mm (see Figure 7.7). Screes around the Australian Alps and other main ranges on the Mainland and also on Tasmania are mainly located in areas of lower rainfall associated in general with the rain shadow effects to the east and southeast of the highest peaks. In this case, the main distribution is to the west and north of the block deposits, but scree deposits are also common on the escarpment.

*Mean precipitation of the winter quarter vs Mean precipitation of the summer quarter*

Winter precipitation in the Australian Alps and Tasmania is associated with westerly frontal systems and promotes weeks to months of snow cover above altitudes of 1200 m asl (Whetton *et al.* 1996). In contrast, the ranges of northern NSW, particularly those north of 32°S, have very little rainfall during the winter months and higher rainfall during the summer months, associated with the arrival of tropical air masses in summer leading to increased precipitation by thunderstorm activity (Sumner 1983, Crapper *et al.*1999, Schuster *et al.* 2005). These observations of a latitudinal switch in rainfall seasonality are well known (e.g. Sumner 1983) and are readily observable on precipitation maps of NSW (BOM 2013).

### 7.5.3. Mean Diurnal Oscillation

Trends in the mean diurnal oscillation indicate that scree deposits have, on average, located in drier areas this also means they have a greater diurnal variability in temperature.

## 7.6. Discussion

There is a strong relationship between the location of periglacial block deposits, screes and modern climatic conditions that promote sub-zero air temperatures and frost days. This observation supports the idea that there is no major change in overall climatic patterns during glacial times, just overall colder conditions.

In northern NSW, two zones are associated with ground ice conditions, an inner zone that includes block deposits and (though this paper does not document them) patterned ground, solifluction lobes and stratified screes. This zone reflects significant ground ice conditions. The second outer zone is a scree zone that indicates more marginal freeze-thaw conditions. Both the mean annual and minimum daily winter temperature results indicate that the inner zone is significantly colder than the outer zone under modern conditions and there is no reason to expect the pattern to vary in the past. However, not all modern cold areas of the eastern highlands have block deposits. The most notable exception is the escarpment that marks the eastern limit of the New England Tablelands, and the elevated lands up to around 30klm inland (west) of the escarpment edge.

The precipitation data shows that winter westerly frontal systems and orographic rain shadow effects operate in both the Australian Alps and Tasmania. In contrast, the mountains of northern New South Wales have a summer precipitation maximum associated with onshore easterly weather systems. This precipitation regime produces a strong East to West precipitation gradient across the New England Tablelands from >2000 mm in the coastal ranges behind Coffs Harbour to c.650 mm on the western slopes near Narrabri (BOM 2013; see Figure 7.7). Figure 7.7 highlights the narrow north-south aligned band of block deposits between 35 and 29°S. These block deposits are formed in Tertiary basalt rocks, of which there are abundant outcrops throughout the higher parts of New England, while summits in excess of 1200 m asl are present both to the east and west of the block deposit zone. To the east lies the highest tracks of land on the New England Plateau in the vicinity of Round Mountain (1611 m asl) and Point Lookout (1578 m asl, Figure 7.7). To the west, high basalt, trachyte and granitic summits are present as far west as the Wurrumbungles (Figure 7.7). In these western ranges, scree deposits are present at the base of cliffs above altitudes of ~750 m asl are likely to be associated with periglacial processes in this range but no block deposits have been identified.

New evidence indicating high lake levels and a positive moisture balance on the northern New England Tablelands at the last glaciation maximum (Ellerton *et al.* submitted) support the concept of a humid zone close to the east coast. This is reinforced by the presence of rainforest taxa in the pollen record from their site, which highlights the persistence of rainforest along the coastal escarpments.

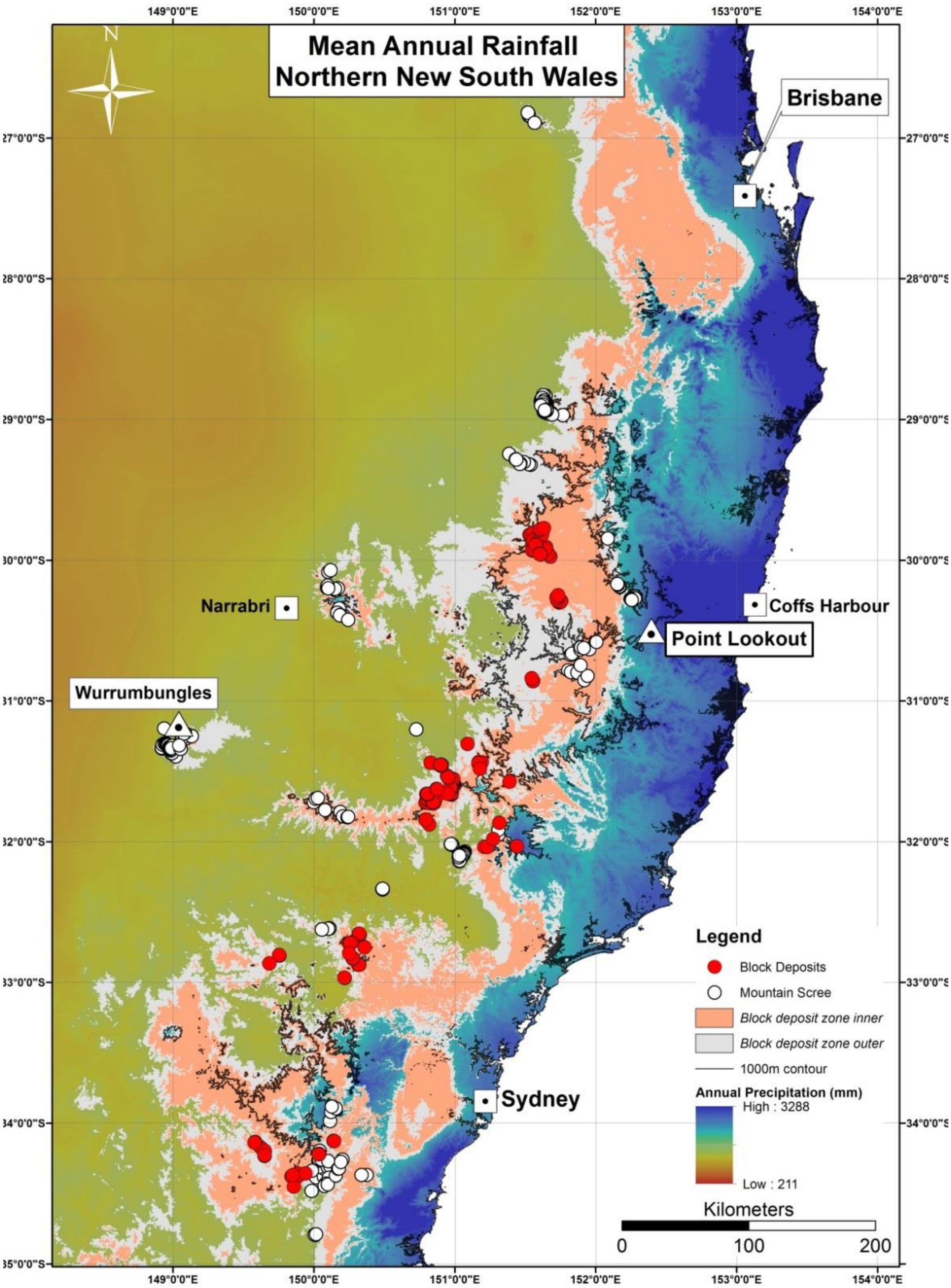



Figure 7.7) Map of the mean annual precipitation in coastal Northern NSW and southeast Queensland, centered on the New England Tablelands. The inner zone and outer zone represents 1 and 2 σ respectively from the estimated mean annual precipitation (938 mm) of the region that correlates with most of the block deposits. The high altitude block deposit free band along the eastern escarpment that receives significant annual precipitation under modern climatic conditions is also highlighted.

Also of note, Little Llangothlin Lagoon currently lies in a region of modest moisture deficits and the lagoon did not become a permanent lake until European settlement, when forest clearance changed the local hydrological balance in favour of runoff (Woodward *et al*. 2014). The LGM at this site had a positive moisture balance and even allowing for hydrological changes due to loss of forest cover, was at least as moist as the present day. Critically, Little Llangothlin Lagoon (c. 1350 m asl), falls within the zone of block deposits. The implication is that both a modern easterly dominated flow occurred at the time of block deposit formation and that the area was at least sub-humid and possibly humid during glacial times. The observations that suggest a shift towards enhanced winter precipitation along the eastern and central regions of the New England Tablelands are similar to those of Mills *et al*. (2012) from South Africa. The study by Mills et al. (2012) utilised glacial reconstructions from the Lesotho Highlands to interpret periods of enhanced precipitation and changes in seasonality in eastern South Africa during the LGM. However Mills *et al.* (2012) do not directly suggest enhanced easterly weather systems rather they suggest that increases in the frequency of westerly frontal systems are the most likely cause of enhanced moisture availability during the LGM.

Temperature reconstructions from Galloway (1965) indicate a likely temperature depression of -8 to -11°C in south eastern highlands of Australia during the LGM, with a lesser decline of about -4°C suggested for Tasmania (e.g. Fletcher and Thomas 2010). Galloway estimated his temperature depression based on his inferences of the distributions of periglacial landforms. Our study reconfirms the general patterns suggested by Galloway and, in fact, indicates that he somewhat under-estimated the lower limits of periglacial activity in northern areas. Other work by us (e.g. chapter 6) suggests that the lower limits are largely a function of cold air drainage and we reconfirm the general inferences of Galloway.

We argue that the temperature decline and the precipitation gradient helps explain the absence of freeze-thaw features on high ground east of the block deposit zone. Under the modern climate, snow is uncommon on the New England Tablelands, but it does occur, and is usually associated with East Coast Lows in the Tasman Sea in winter and early spring (Browning and Goodwin 2013, BOM 2007). The snow develops as moist air masses off the Tasman Sea interact with cold air pooled over the Tablelands. The development of block deposits requires a strong diurnal temperature variability to drive the freeze-thaw process. Under glacial conditions, the relatively warm and moist onshore air masses sourced from the Tasman Sea would rise by orographic forcing and push onto the eastern edges of the New England plateau, where they would interact with the cold air mass sitting on top of the plateau. This interaction would produce heavy winter snow fall that would insulate the ground. Even if the precipitation fell as rain, cloud cover and raised soil moisture would limit the diurnal oscillation and frost days (Dai and Trenberth 1999, Liu *et al.* 2008) in areas close to the divide.

In the block deposit zone a reduction of -8°C to -11°C would result in 150 – 200+ days of frost activity over large areas of the New England Tablelands as estimated by modifying modern temperature records (BOM 2013) by a conservative 8°C. We choose this lower value because the local evidence for positive moisture balances suggests a somewhat cloudier climate than modern. Observations by the authors indicate that diurnal oscillations of over 30°C and temperatures regularly below -5°C are common during modern winter and we recorded values of down to -13.5°C. Glacial age minima may have been as low as -20°C in sheltered locations. This strong decline in temperature combined with the enhanced availability of moisture may have provided environmental conditions conducive for strong frost-action processes that resulted in widespread block deposit formation on the Tablelands. To the west of the 'block deposit zone', scree deposits demonstrate that temperatures where still cool enough for the frost shatter processes to occur. We speculate that for at least the higher areas, the absence of block deposits demonstrates soil conditions too dry to allow ice segregation mechanisms to dominate.

## 7.7. Summary

This paper provides the first comprehensive map of block deposits and screes in Eastern Australia. The distributions give insights into prevailing climatic conditions on the eastern highlands during glacial times. The paper details a number of key findings including the following;

1. Currently active periglacial landforms are likely to be restricted to the higher summits in Tasmania and the Australian Alps where modern patterned ground and solifluction deposits are currently or where active during the late Holocene. However none of these deposits are associated with the activity that promoted the development of the block deposits. This indicates that the block deposits are relict features associated with significantly enhanced ground ice conditions during the

late last glaciation, when mean annual temperatures where significantly colder than at present.

2. Relict landforms suggestive of past periglacial conditions are present throughout the eastern highlands as far north as 29°S and landforms suggestive of mild periglacial conditions extend as far north as the Bunya Mountains (26°S) in southern Queensland. The former limit reflects the northern penetration of block deposits, while the latter is based on screes. The distribution is largely consistent with the predictions of Galloway (1965) and extends his limits both latitudinally and altitudinally.

3. The distribution of relict block deposits occurs almost solely in areas that are currently subject to at least 50 days of frost (<2°C) a year. There is no apparent change in the pattern of distribution of features but a clear implication of colder conditions at glacial times. We have no reason to revise Galloway's estimate of -8 to -11°C peak cooling in winter during the last ice age.

4. In marginal areas, block deposits are lithologically controlled with basalts providing the most favourable lithology for block formation. In the highest areas of the Australian Alps and Tasmania where periglacial conditions have been most severe almost all lithologies can produce block deposits.

5. Large block deposits in northern New England occur preferentially on western and southern slopes. This appears to reflect shading for southern slopes but the western aspect may reflect the preferential accumulation of snow banks behind wind fences to the lee of the easterlies. However smaller block deposits can be found commonly on westerly and northerly slopes. Aspect appears less critical in the Australian Alps and Tasmania.

5. There is a narrow (c. 30 km wide) band of block deposits in northern New England (35-29°S) in an area subject to summer easterly rainfall. This band is aligned with modern precipitation gradients and comprises regions with modern precipitation of 850-1000 mm. It is not associated with changes in elevation, aspect or rock type. We conclude that a 'block deposit zone' occurs where thermal and moisture conditions are ideal for block deposit formation with cold temperatures, large diurnal oscillations and adequate moisture for freeze-thaw to dominate. To the east we conclude that precipitation was too high and temperature oscillations too

muted for significant ground ice to develop. To the west, arid conditions limited freeze-thaw activity. The findings support the concept of a humid zone along the east coast in glacial times.

# Chapter 8. Summary of research

## 8.1. Principle results of thesis

This thesis presents a significant contribution to the knowledge of periglacial geomorphology in Australia. The thesis links Australia's active and relict periglacial landform assemblage with paleoclimate interpretations throughout the Last Glaciation. The principle questions and studies investigated and answered by this thesis are summarised below.

**Are periglacial processes active in Australia under the current climate?**

Yes. In Western Tasmania landforms associated with marginal frost action are found to elevations of c.200 m asl in thick glacial and alluvial deposits where vegetation clearance has been maintained by either natural or anthropogenic means.

At higher elevations landforms that can be defined as periglacial sorted stone-banked lobes associated with ground ice and solifluction processes are found on Mt Rufus. These features can generate up to 40 cm of surface (boulder) movement over one average winter season. There is little doubt that similar stone banked and soil banked solifluction lobes observed during the course of this study and documented by other authors are likely to be active under the modern climate.

**Galloway 1965 predicted relict periglacial landforms as far north as 30°S in northern NSW, was he right?**

Yes. This study proved the existence of well-developed block streams and block slopes to 29-30°S indicative of periglacial climatic conditions on the New England

Plateau of Northern New South Wales. The surface exposure dating of some of these deposits indicates that periglacial conditions were present in the New England Region during several stages of the Last Glacial.

**How old are periglacial landforms in Australia? Relative dating of the block deposits of the New England Region.**

Four deposits from the ranges of Northern New South Wales were dated by SED techniques. This data produced ages indicative of block deposit formation in the late Last Glacial spanning MIS 2 to late MIS 4. The dataset of 22 exposure ages returned surprisingly robust and clustered age estimates.

This project represents the second time SED has been utilised to obtain relative ages from periglacial block deposits in Australia after the work by Barrows *et al.* (2004) in the Australian Alps and Tasmania.

This fact coupled with the detailed documentation of the morphology and distribution of periglacial deposits of Northern New England signifies a significant advancement in knowledge regarding the distribution and paleoclimate significance of freeze-thaw landforms within Australia.

**Evidence for moisture playing a significant role in the development of periglacial landforms.**

Mapped block deposits in northern New England form a narrow block deposit band lying adjacent to the Great Divide but to the west of the highland associated with the Great Escarpment. These observations show that both altitude (associated with temperature) and geology do not appear to be the drivers of this well-defined distribution of block deposits.

Mapping and observations using Worldclim and BOM climate raster data suggest that precipitation appears to be an important driver of block deposit formation.

To the west of the block deposit zone it may have been too dry and moisture deficient for frost shatter processes to be significant. To the east it appears to have been too mild, cloudy and possibly snowy for the promotion of strong diurnal freeze-thaw cycles that would promote the development of block deposits.

These observations coupled with lacustrine and fluvial evidence produced by colleagues working on other projects within the ARC-grant indicates the existence of a zone of comparatively high moisture availability and possibly enhanced precipitation along the eastern seaboard during the latter stages of the Last Glaciation. This moisture was likely to have been associated with an onshore easterly moisture source sourced from the Tasman Sea, most probably related to the interaction of strong east coast low pressure systems with the cold air-masses pooled on the New England Tablelands.

**The documentation of mass movement (landslides) near Guyra. Large relict landslide deposits near Guyra with block streams superimposed on top of them indicate that there are at least three stages of slope development at this site linked to changes in prevailing climatic conditions during the late Quaternary.**

Stage one.

Initially there appears to have been a warm-wet period promoting the development of deep seated mass movement triggered by groundwater discharge and subsequent weathering of these deposits to clays.

Stage two.

The first stage was followed by cold climate periglacial conditions during the last glaciation promoting block fields (felsenmeer), block streams, and solifluction lobes.

Stage three

During the Holocene, warmer conditions led to small scale mass movement and very mild ground ice processes. While deforestation and farming activity has occurred since European settlement there appears to be no evidence that European settlement has triggered large scale mass movement at the site, and these observations are particularly relevant to the past 70 years.

## 8.2. Areas of future research into Australian periglacial geomorphology.

This thesis presents a general overview of the extent of periglacial landforms in Australia. However, there is obvious scope for further research on this topic. In particular, cold climate landforms such as examining the distribution of stratified and non-stratified angular scree deposits. The very large number of block deposits and scree deposits mapped during the project means there is substantial scope for further in depth field descriptions of individual groups of sites.

Due to time constraints and the remote location of most scree deposits mapped these were not visited in the field and warrant further investigation. In particular, the extensive mid-altitude scree deposits located in some of the river gorges draining the New England Plateau, and the small deposits on the western slopes of the Bunya Mountains that may lie close to the northern limits of LGM periglacial activity. This thesis presents mapped *scree* deposits as being of likely periglacial origin; however, I do not indicate that these deposits are direct evidence of past periglacial conditions. I only indicate that their distribution 'fits' with the modern climate observations and the distribution of the more robust evidence of periglacial conditions in the form of the block deposits and other associated landforms. Further investigations of these scree deposits and the processes of bedrock weathering promoting their formation will likely go a long way to determining their climatic significance.

Several block deposits in Tasmania and at least one block deposit in the NSW Alps have been described as relict 'rock glaciers' by past authors. This PhD did not focus on differentiating these features from block streams but I do believe that some of these features are likely to have contained interstitial ground ice (permafrost). Remote sensing and observations in the field indicate that in addition to the 'rock glaciers' proposed by past authors on some Tasmanian Mountains (Derbyshire 1973, Caine 1983) several other block deposits mapped during this thesis have morphologies suggestive of flow induced by permanent ice. The most notable of these occur on the northern Central Plateau near Great Lake and Western Bluff. At these locations extensive block deposits feature elongated cross slope ripple crevices and prominent lobate toes, features that are characteristic of modern rock glaciers in alpine zones. The description of these 'rock glacier' landforms would justify a specifically focused project.

This project focused on the most readily identifiable periglacial landforms i.e. block streams and associated landforms. Tors have only been briefly described in this study (see Appendix 16). One notable issue with marginal periglacial environments is the process of granite breakdown under freeze-thaw conditions. The block deposits of northern New England are found in basaltic terrain, however high elevation land extends into south eastern Queensland in the Granite Belt at 28°S. Here apart from the occasional well developed tor there is no strong evidence of freeze thaw processes despite the fact that temperatures are known to drop below -10°C under the modern climate. It is apparent that frost shatter may not work to create blocks in these granites and individual granular spallation may be the primary sediment produced by frost shatter. These cold climate granite landforms warrant further study.

Furthermore, chemical weathering in tropical environments can produce extensive boulder deposits and nubbin hills in granite terrain. The morphology of the landforms in the granite belt suggest that physical weathering from freeze thaw may be the major factor in landscape development whereas further north chemical weathering is dominant. The impact and rates of denudation by both freeze-thaw and tropical chemical weathering processes in mid-latitude environments has not been thoroughly examined in the global literature recently and presents a major line of enquiry for future research.

Chapter 7 discusses the use of relict landslide deposits as paleoclimate indicators. To date there has been very little description of relict landslides in Australia outside a few coastal urban areas. It is obvious that there is future potential research in this subject throughout the Great Dividing Range and the potential of exploring the relationship of major landslide events to both cold climate and wet warm periods of the late Quaternary. Indeed large scale land sliding, while not presently a major landscape process, may have been a major driver of the morphology of much of the Great Dividing Range. Evidence for these processes has been observed in locations including the Bogong High Plains the Barrington Tops and the Main Range and Macpherson Ranges in Queensland. These deposits have been largely overlooked and need investigation.

The results of the SED are robust indicators of the development of periglacial block deposits during the late Last Glaciation in Northern New South Wales. However the results of this project and those of Barrows *et al.* (2004) who documented sites in the Australian Alps show a marked contrast in the ages of periglacial landforms between those of the Australian Mainland and Tasmania. In Tasmania, block deposits have been dated by Barrows *et al.* (2004) to 500 kya, these dates indicate that the periglacial deposits of Tasmania have developed through multiple Quaternary glacial cycles. In contrast the oldest date obtained from northern New South Wales is 73.3±5.5 kya at the Guyra site indicative of late MIS 4 block production.

The age and morphology of the mainland sites documented in this thesis and those of Barrows *et al.* (2004) show no indication of extensive older deposits lying outside the limits of Last Glacial deposits, as would be expected if penultimate and older glaciation deposits were present. This trend corresponds with the lack of glacial deposits on the Australian Mainland older than MIS 3 whereas glacial deposits dating from MIS 6 to MIS 10 and earlier glacial cycles are recognized in Tasmania (Colhoun *et al.* 2010). This anomalous disparity in ages between the periglacial and glacial deposits of the Australian mainland and those of Tasmania present a major unanswered question. That is, what are the climatic or geological drivers for this variation in landscape history?

Is this disparity the result of erosion by deep chemical weathering reducing older periglacial deposits on the Australian mainland during a warm stage, which may represent a climatic event that did not have the same impact on weathering in Tasmania? Or, more simply were periglacial and glacial processes on the Australian mainland limited to the last glacial cycle and for an unknown reason absent or severely reduced during the penultimate glaciation and those preceding it?

In summary this thesis presents a new understanding of the climate and processes active on the highlands of Eastern Australia during the Last Glacial Cycle. It also raises a host of new geomorphological and climatic problems to solve.

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# 10. Appendix

Appendix 1: Published version of Chapter 2.4 in *Geographical Research* **53**(2)

Slee, A., Kiernan, K. and Shulmeister J., 2015. Contemporary Sorted Patterned Ground in Low Altitude Areas of Tasmania. *Geographical Research* **53**(2): 175-183

DOI: 10.1111/1745-5871.12110

Accessible at: http://onlinelibrary.wiley.com/doi/10.1111/1745-5871.12110/abstract

Appendix 2: Published version of Chapter 3.6 in *Quaternary Australia* 31(2)2014

Research Note: A reconnaissance of low elevation block deposits on Maria Island, Tasmania, *Quaternary Australasia* **31**(2):40-44

Accessible at:
http://aqua.org.au/?page_id=103

Appendix 3: Published version of Chapter 7 Journal of Quaternary Science

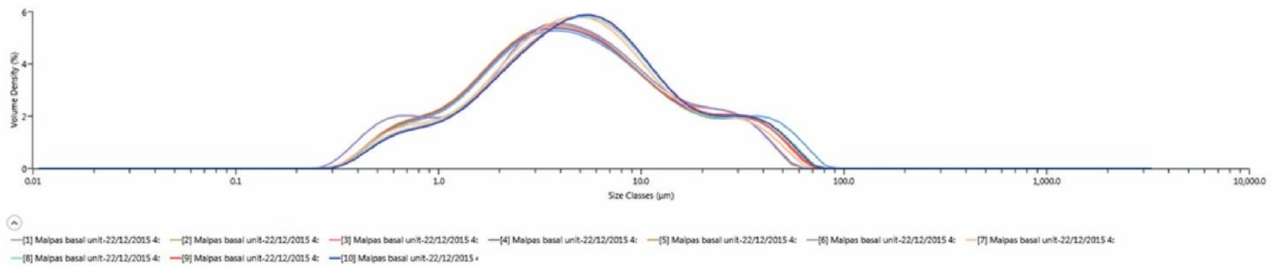
Slee, A. and Shulmeister, J., 2015. The distribution and climatic implications of periglacial landforms in eastern Australia. *Journal of Quaternary Science* **30**(8):848-858,

DOI: 10.1002/jqs.2823

Accessible at: http://onlinelibrary.wiley.com/doi/10.1002/jqs.2823/abstract

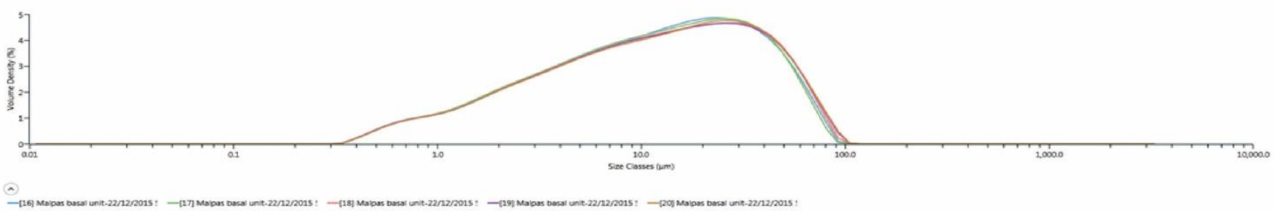
## Appendix 4: Mastersizer3000 clay/silt results for basal Malpas deposit.

| Analysis | | Result | |
|---|---|---|---|
| Particle Name | Soil | Concentration | 0.0016 % |
| Particle Refractive Index | 1.520 | Span | 6.057 |
| Particle Absorption Index | 1.000 | Uniformity | 1.686 |
| Dispersant Name | Water | Specific Surface Area | 2297 m²/kg |
| Dispersant Refractive Index | 1.330 | D [3,2] | 2.61 µm |
| Scattering Model | Mie | D [4,3] | 9.89 µm |
| Analysis Model | General Purpose | Dx (10) | 1.04 µm |
| Weighted Residual | 0.83 % | Dx (50) | 4.54 µm |
| Laser Obscuration | 5.08 % | Dx (90) | 28.6 µm |



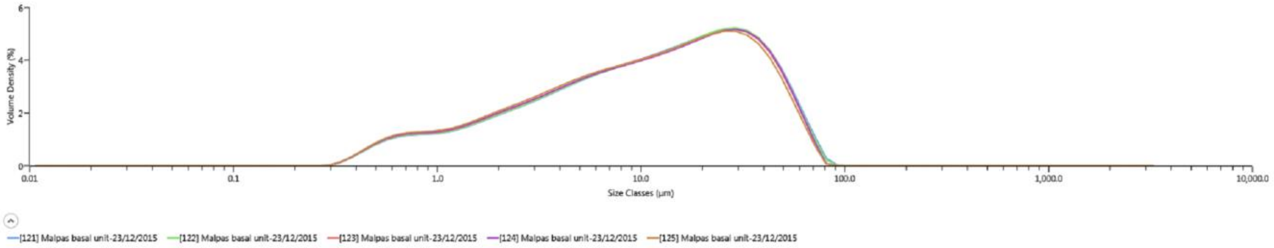

## Appendix 5: Mastersizer3000 clay/silt results Unit B of the Guyra 1 trench.

| Analysis | | Result | |
|---|---|---|---|
| Particle Name | Soil | Concentration | 0.0038 % |
| Particle Refractive Index | 1.520 | Span | 3.614 |
| Particle Absorption Index | 1.000 | Uniformity | 1.106 |
| Dispersant Name | Water | Specific Surface Area | 1337 m²/kg |
| Dispersant Refractive Index | 1.330 | D [3,2] | 4.49 µm |
| Scattering Model | Mie | D [4,3] | 18.1 µm |
| Analysis Model | General Purpose | Dx (10) | 1.73 µm |
| Weighted Residual | 0.65 % | Dx (50) | 11.9 µm |
| Laser Obscuration | 7.00 % | Dx (90) | 44.7 µm |

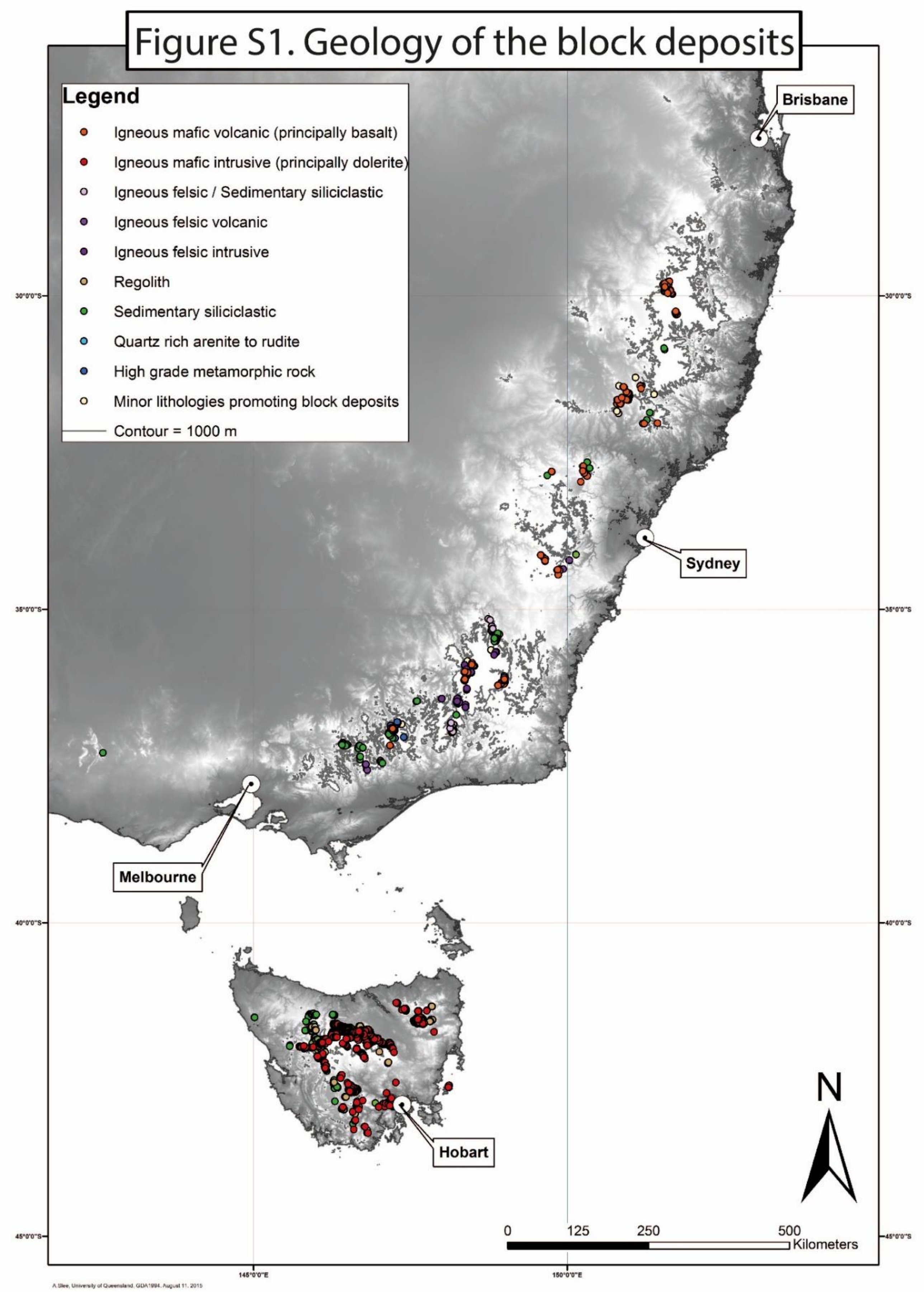


Appendix 6: Mastersizer3000 clay/silt results for Unit C of the Guyra 1 trench.

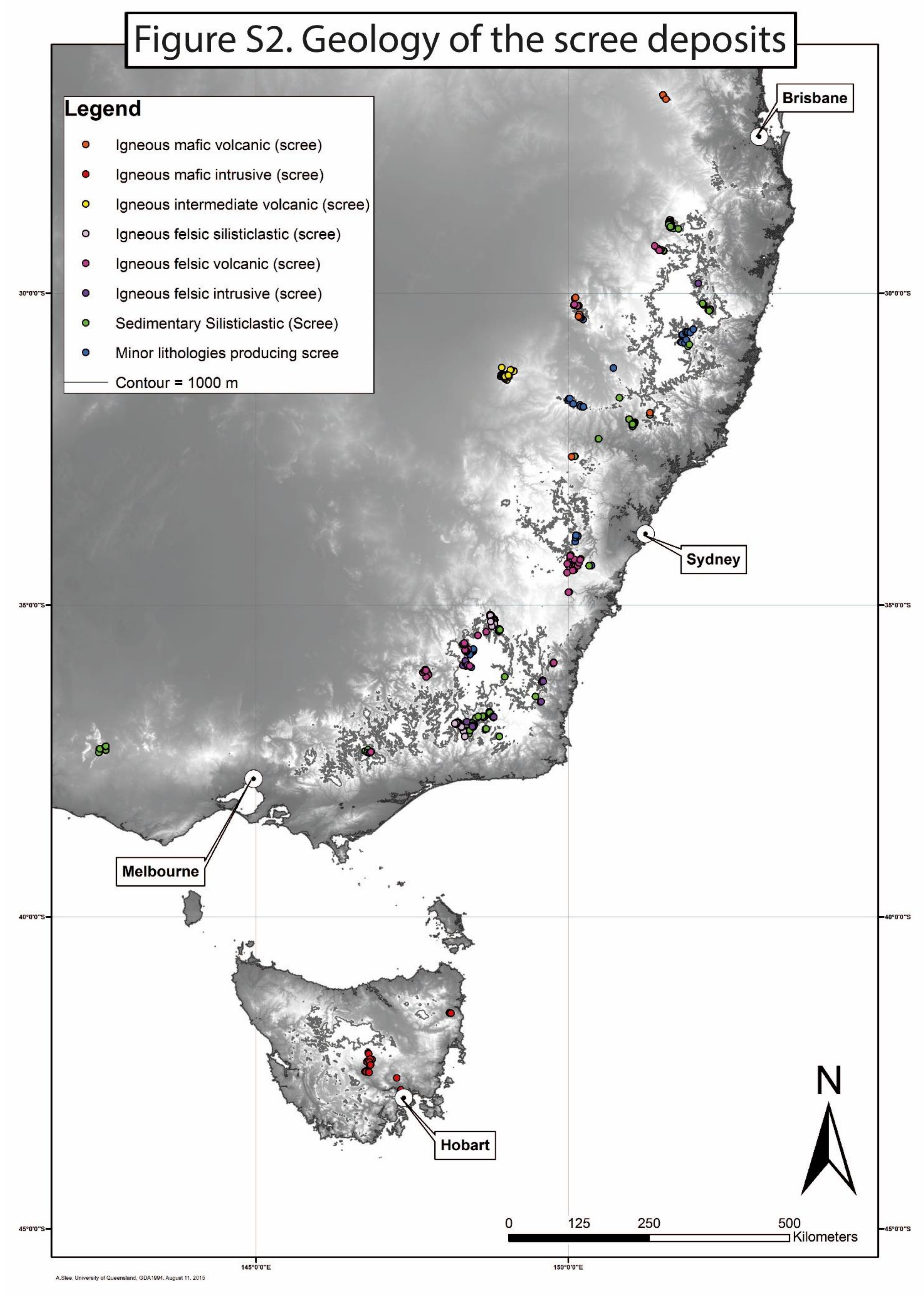
| Analysis | Result |
|---|---|
| Particle Name Soil | Concentration 0.0061 % |
| Particle Refractive Index 1.520 | Span 3.416 |
| Particle Absorption Index 1.000 | Uniformity 1.058 |
| Dispersant Name Water | Specific Surface Area 1461 m²/kg |
| Dispersant Refractive Index 1.330 | D [3,2]4.11 µm |
| Scattering Model Mie | D [4,3]17.7 µm |
| Analysis Model General Purpose | Dx (10) 1.53 µm |
| Weighted Residual 0.75 % | Dx (50) 12.1 µm |
| Laser Obscuration 12.01 % | Dx (90) 43.0 µm |



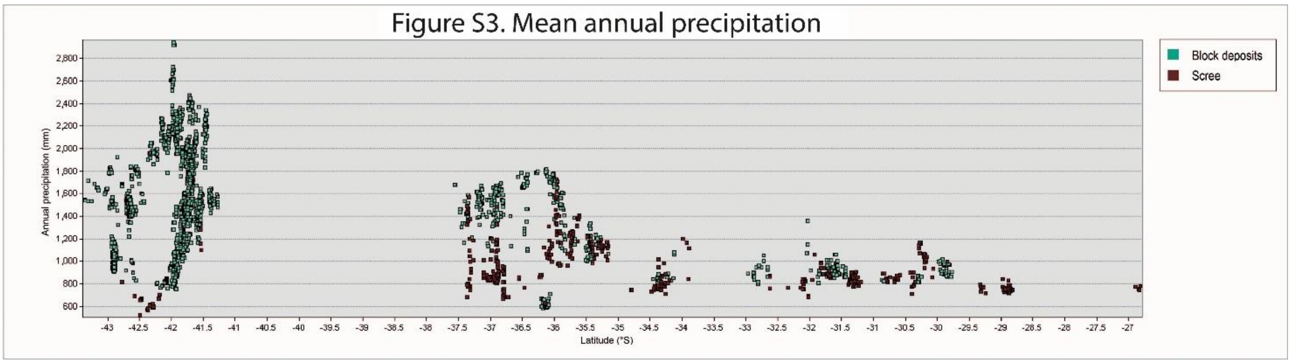
Appendix 7: Geology of block deposits (Figure S1, Slee and Shulmeister 2015)



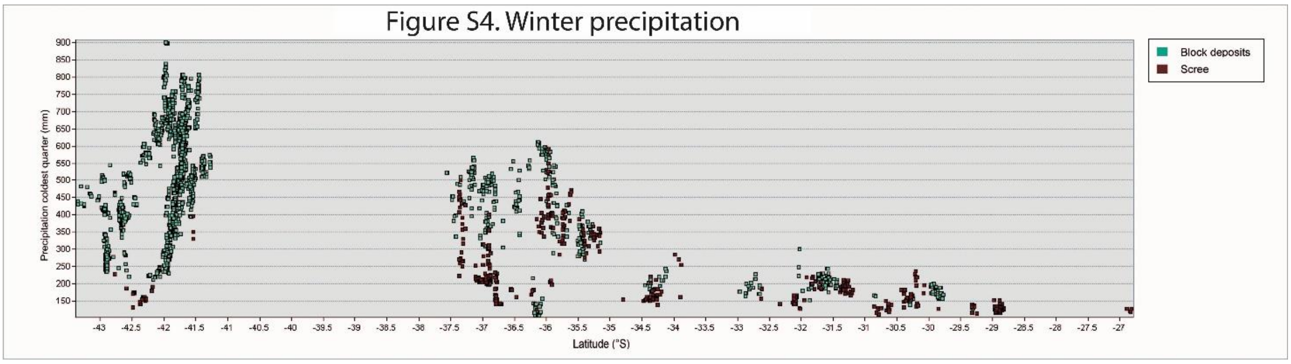
Appendix 8: Geology of scree deposits (Figure S2, Slee and Shulmeister 2015)



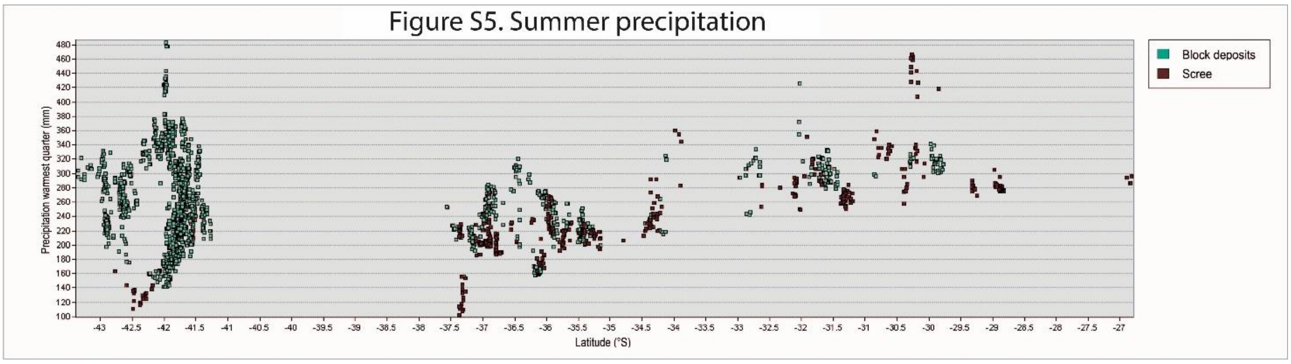
Appendix 9: Mean Annual Precipitation (Figure S3, Slee and Shulmeister 2015)



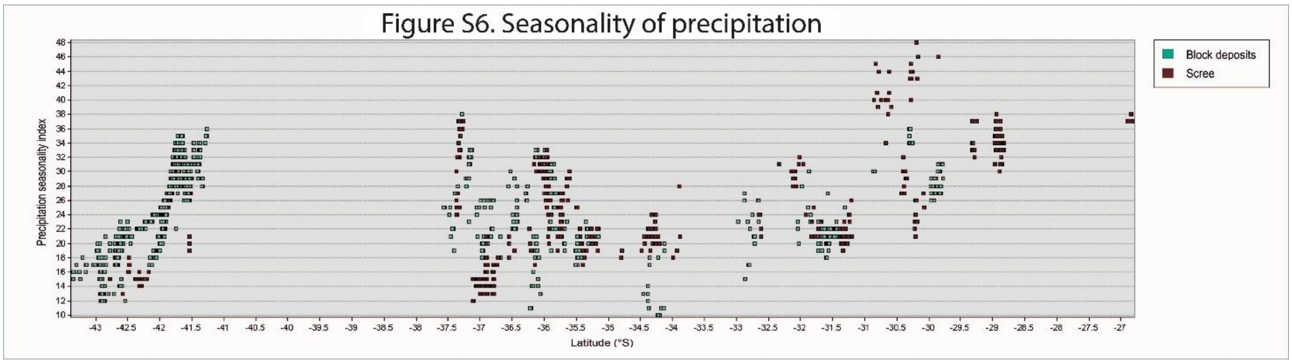

Appendix 10: Winter precipitation (Figure S4, Slee and Shulmeister 2015)



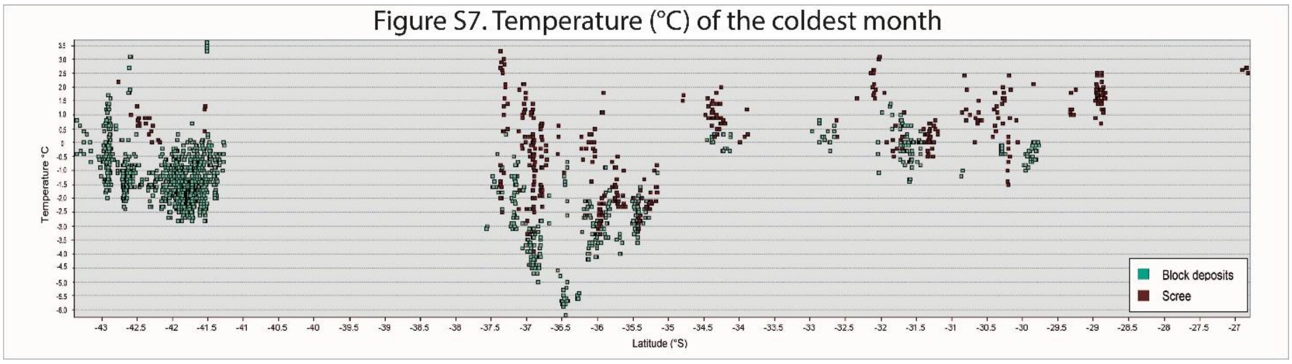

Appendix 11: Summer precipitation (Figure S5, Slee and Shulmeister 2015)



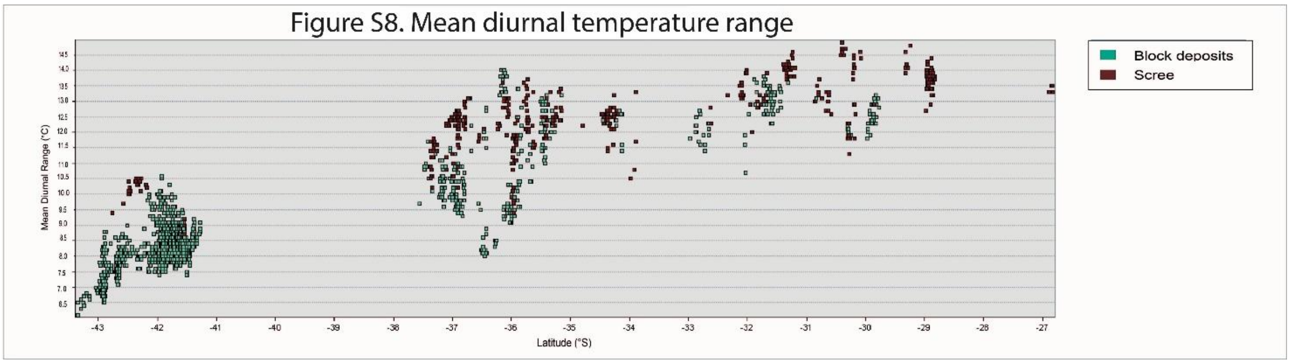
Appendix 12: Seasonality of precipitation (Figure S6, Slee and Shulmeister 2015)




Appendix 13: Temperature (°C) of the coldest month (Figure S7, Slee and Shulmeister 2015)




Appendix 14: Mean diurnal temperature range (Figure S8, Slee and Shulmeister 2015)

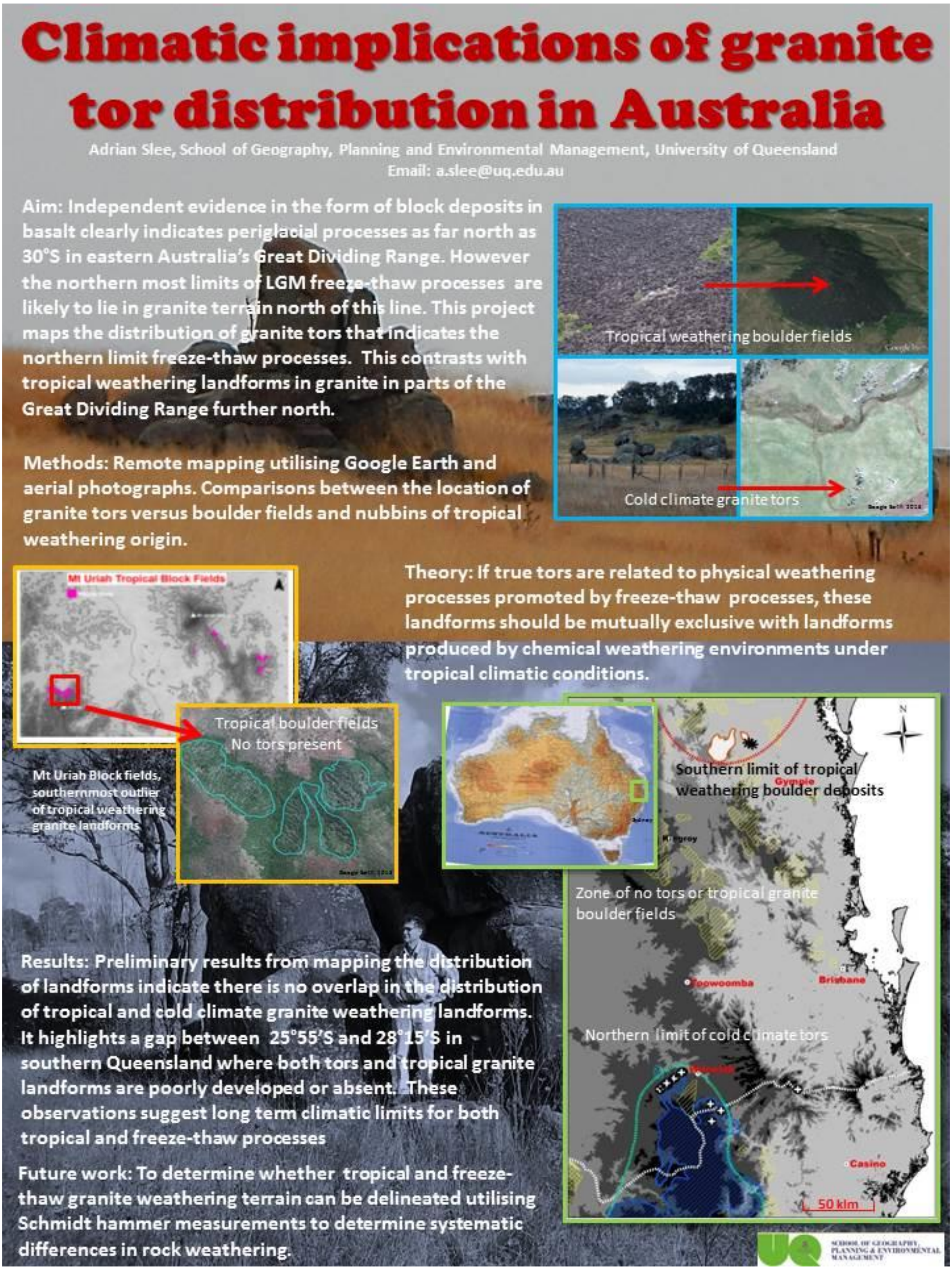


# Appendix 15: Metadata analysis of block deposits documented in south-eastern Australia (Figure S9, Slee and Shulmeister 2015)

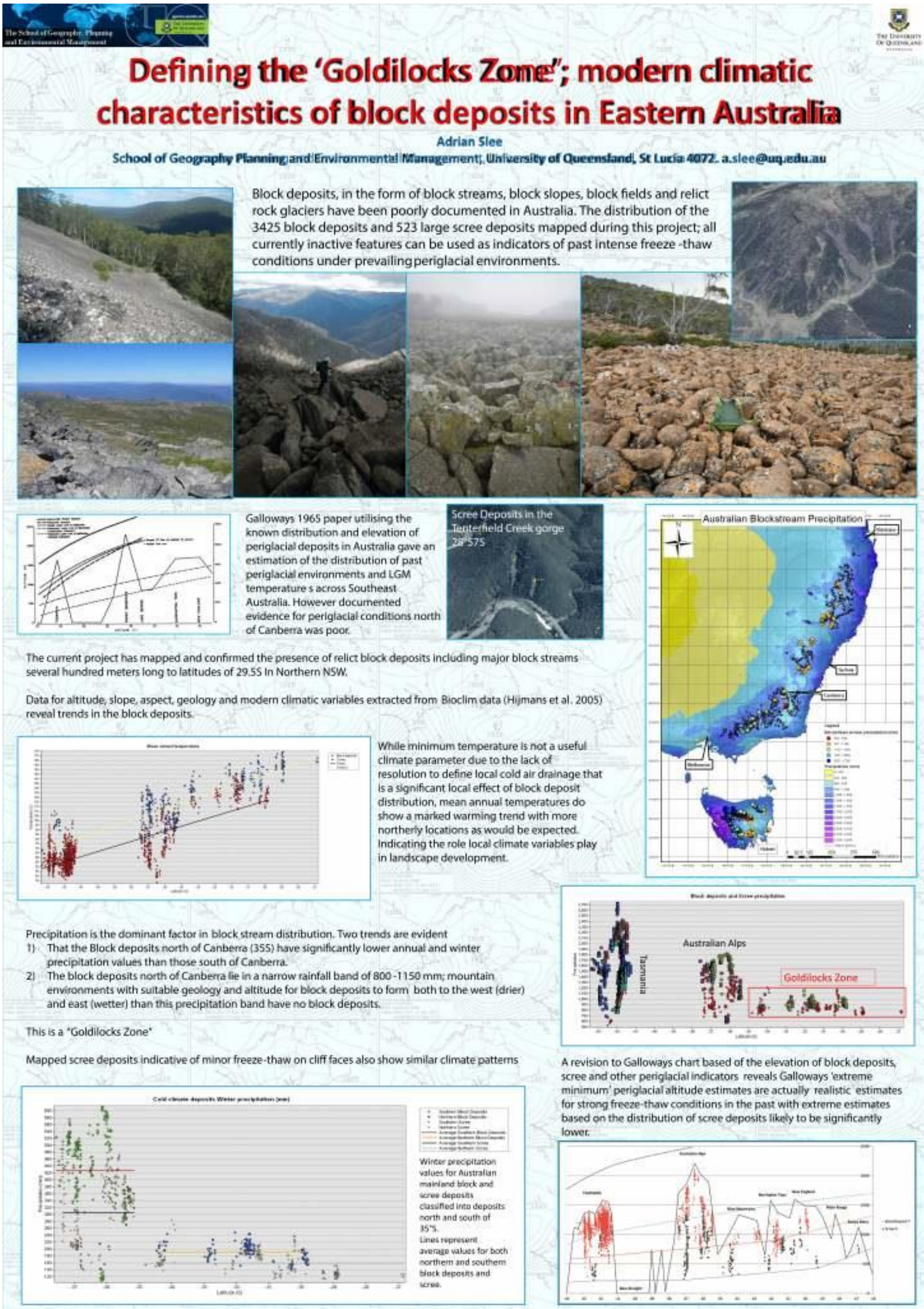
**Table S1. References used for locating and characterising block deposits in southeastern Australia**

| State | Location (as reported) | Altitude | Ground truthed for this paper | Authors | Author's description |
|---|---|---|---|---|---|
| **Tasmania** | | | | | |
| Ben Lomond (Plateau) | 41°33'00S: 147°39'00E | 800-1550 m | Yes | Caine 1967,1968a, 1969, 1983 | Extensive low angle (as low as 2°) block fields and block streams of both autocthonous and allochthonous development. |
| Ben Lomond (Carvilla) | 41.5133S:147.7272E | 1250-1360 m | Yes | Barrows *et al.* 2004 | Extensive dolerite blockslope on the northern slopes of Ben Lomond |
| Ben Lomond (Denison Craig) | 46.2700S:147.7200E | 1285 m | | Barrows *et al.* 2004 | Extensive dolerite blockslope on the southern slopes of Ben Lomond |
| Mt Barrow (Plateau central blockstream) | 41°23'17"S:147°24'52"E | 950-1350 m | Yes | Caine 1967, 1968a,c, 1972, 1983 | Extensive low angle block fields and block streams of both autocthonous and allochthonous development. |
| Mt Barrow (south) | 41°24'29"S:147°25'36"E | 1000-1300 m | Yes | Caine 1967, 1983 | Possible rock glaciers, and undifferentiated talus and block deposits |
| Mt Victoria | 41°20'06"S:147°50'22"E | 850-1200 m | Yes | Caine 1983, Sharples 1994, 2001 | Periglacial block deposit landforms including blockfield and block streams |
| Mt Young | 41°21'35"S:147°57'25"E | >850 m | | Caine 1983, Sharples 1994, 2001 | Extensive suite of periglacial block deposit landforms including blockfield and block streams covering 50% of the plateau |
| Mt Albert | 41°20'55"S:147°52'20"E | >850 m | | Caine 1983, Sharples 1994, 2001 | Periglacial block deposit landforms including blockfield and block streams |
| Mt Blackboy | 41°24'00"S:147°52'00"E | >850 m | | Caine 1983, Sharples 1994, 2001 | Periglacial block deposit landforms including blockfield and block streams |
| Tower Hills | 41°32'24"S:147°49'50"E | 850-1100 m | | Caine 1983, Sharples 1994, 2001 | Periglacial block deposit landforms including blockfield and block streams |
| Ben Nevis | 41°24'43"S:147°37'03"E | 1050-1300 m | | Caine 1983, Sharples 1994, 2001 | Periglacial block deposit landforms including blockfield and block streams |
| Mt Saddleback | 41°24'00"S:147°45'46"E | 1020-1200 m | | Caine 1983, Sharples 1994, 2001 | Periglacial block deposit landforms including blockfield and block streams |
| Mt Wellington (Plateau) | 42°54'18"S:147°12'32"E | 550-1250 m | Yes | Davies 1958, Sharples 1995, 2001, Bradbury 1995 | Numerous blockfields related to what Davies describes as a cryoplanation surface, Sharples notes the most extensive periglacial terrain to have not been glaciated in Tasmania. |
| Mt Wellington (Thark Ridge) | 42.9000S:147.2000E | 1220 m | Yes | Barrows *et al.* 2004 | Dated block deposits (block field) |
| Dissapearing Tarn solifluction colluvium | 42°55'28"S:147°12'32"E | 575-1000 m | Yes | Sharples 1995 | Solifluction colluvium (block fields of very large scale) |
| Mt Dromadary | 42°42'56"S:147°07'16"E | 550-900 m | | Sharples 1997, 2001 | High altitude periglacial erosion features (blockstreams observed from air) |
| Mt Maria | 42°37'00"S:148°06'20"E | 450-709 m | Yes | Slee and Kiernan 2014 | Low elevation blockfields and associated scree deposits. |
| Mt Field (above karst on W and SW slopes) | 42°41'32"S:146°31'54"E | 1050-1420 m | Yes | Kiernan *et al.* 2001 | Extensive areas of the plateau mantled by dolerite diamictons interpreted as periglacial solifluctate |
| Mt Field (Lake Fenton blockstream) | 42°40'43"S:146°37'53"E | 920-1020 m | Yes | Lewis 1921, 1922, Colhoun and Peterson 1986, Sharples 1992, McIntosh *et al.* 2012 | Noted on the TGD as "an outstanding example of a periglacial block stream first documented as 'Tasuls' by Lewis (1921) |
| Mt Field (Rodway Range) | 42°40'43S: 146°37'53E | 1080-1380 m | Yes | Webster 1974 | Description of two low angle block deposits on the Rodway Range |
| St Pauls Dome | 41°44'00"S. 147°53'15E | 900-1020 m | | Sharples 1995 | Terraced scree deposits identified in the field |
| Pine Lake (Central Plateau) | 41°44'41"S:146°42'09"E | 1050-1300 m | Yes | Colhoun and Peterson 1986 | Extensive block fields on slopes of <7° |
| Mt Weld | 43°00'26"S:146°34'39"E | 1000-1340 m | | Colhoun and Geode 1979 | Notable block deposits on the upper slopes |
| Mt Picton | 43°09'24"S:146°36'15"E | 1000-1320 m | | Webster 1974, Colhoun and Geode 1979 | Notable block deposits on the upper western slopes |
| Mt Olympus | 42°02'20"S:146°05'18"E | 1150-1450 m | Yes | Derbyshire 1973 | Relict rock glaciers |
| Mt Gell | 42°09'13"S:146°01'16"E | 1100-1440 m | | Derbyshire 1973 | Reict rock glaciers |
| Mt Rufus | 42°07'29"S:146°05'55"E | 1250-1410 m | Yes | Derbyshire 1973 | Block deposits |
| Great Pine Tier | 41°55'27"S:146°25'33"E | 1050-1200 m | | Sharples in McIntosh *et al.* 2012 | Unconfined blockfield |
| Denison Range | 42°32'58"S:146°16'19"E | 900-1200 m | | Webster 1974 | Block deposits identified by aerial photographs formed from metamorphic rocks |
| King William Range | 42°18'00"S:146°08'15"E | 1020-1330 m | Yes | Webster 1974 | Block deposits identified by aerial photographs |
| Mt Anne | 42°57'00"S,146°25'12"E | 870-1400 m | Yes | Webster 1974 | Block deposits identified by aerial photographs primarily located on the western slopes |
| Mt Ossa (and surrounding peaks) | 41°52'17"S:146°01'52"E | 1150-1600 m | Yes | Webster 1974 | Block deposits identified by aerial photographs |
| Walls of Jerusalem | 41°49'10"S:146°17'04"E | 1200-1480 m | Yes | Webster 1974, Colhoun 2002 | Block deposits identified by aerial photographs, low angle block streams <5-20°. |
| Mt Campbell | 41°39'25"S:145°58'18"E | 1000-1245 m | Yes | Colhoun 2002 | Quartzite block fields |
| Mt Emmett | 41°42'34"S:145°58'50"E | 950-1410 m | Yes | Colhoun 2002 | Extensive summit and upper slope boulderfield |
| Poatina Road Quarry (Camps Bay) | 41°53'43"S:146°50'57"E | 1160-1170 m | | J. Kirkpatrick pers.comm. June 2015 | Blockfield with reverse graded openwork boulders exposed in quarry face. |
| | | | | | |
| **Victoria** | | | | | |
| Mt Little Higginbotham (LHB-05) | 37.0000S:147.1600E | 1680 m | Yes | Barrows *et al.* 2004 | Block aprons (proximal to source) block fields |
| Mt Little Higginbotham (LHB-06) | 37.0000S:147.1600E | 1680 m | Yes | Barrows *et al.* 2004 | Block aprons (proximal to source) block fields |
| Mt Little Higginbotham (LHB-07) | 36.9900S:147.1600E | 1520 m | | Barrows *et al.* 2004 | Block aprons (distal from source bedrock) block fields, elongation downslope. |
| Mt Cobberas | 36°50'11"S:148°11'24"E | 1200-1800 m | | Ashton and Moore 1978, McRae-Williams *et al.* 1981 | Elongate block streams clasts 10cm - 1m length, with smooth profiles and moderate gadients of <30° (18-26°) |
| Mt Wombargo | 36°55'49"S 148°10'55"E | 1150-1600 m | | Webster 1974, Ashton and Moore 1978 | Large 1 klm long block stream elongated downslope from a source outcrop near the summit. Webster (1974) also documented other block streams in area. |
| Big Hill | 36°54'35"S:148°09'56"E | 1400-1600 m | | Ashton and Moore 1978, | Elongate blockstreams 18-26° |
| Moscow Peak (Mt Cobberas No. 2) | 36°49'11"S:148°09'37"E | 1400-1700 m | | Webster 1974 | Elongate block streams 18-26° |
| Bogong High Plains (Cobungra/Bundarra River) | 36°56'22"S:147°13'10"E | 1450-1800 m | Yes | McRae-Williams et al. 1981 | Blockfields and elongated block streams |
| Dinner Plain | 37°00'46"S:147°10'28"E | 1320-1550 m | | Webster 1974 | Large blockfields |
| Mt Hotham | 36°59'10"S 147°08'58"E | 1500-1700 m | Yes | McRae-Williams et al. 1981 | Block streams and blockfields |
| Mt Jaithmathang | 36°53'27"S:147°11'07"E | 1500-1800 m | Yes | McRae-Williams et al. 1981 | Block streams identified in granodiarite, visited as part of the present study by the primary author |
| Red Rag Range | NA | 1600- 1700 m | | McRae-Williams et al. 1981 | Block streams identified |
| Howitt Plains (Mcalister Valley) | 37°11'00"S: 146°41'E | 1300-1600 m | | Webster 1974, McRae-Williams *et al.* 1981 | Extensive blockfields descibed in detail by Webster (1974) |
| Wellington Plains | 37°21'00"S: 146°41'26"E | 1000-1500 m | | McRae-Williams *et al.* 1981 | "Periglacial boulder deposits" and extensive scree slopes |
| Mt Loch | 36°57'46"S 147°09'44"E | 1620-1780 m | | Webster 1974 | Extensive blockfields and blockstreams described in detail by Webster (1974) |
| Mt Battery | 37°02'36"S:147°23'41"E | 1000-1250 m | | Webster 1974 | Extensive blockfields described in detail in Webster 1974. |
| Mt Buller | 37°08'34"S: 146°25'27"E | 1518-1620 m | | Webster 1974 | Blockstreams in basalt |
| Corn Hill | 37°09'42S: 146°28'45"E | | | Webster 1974 | Several block streams in sedimentary rocks in the vicinity of the summit of Com Hill |
| Gattamurgh Creek (upper Snowy River valley) | Vicinity of 36°54'S: 148°27E | 400-750 m | | McRae-Williams *et. al.* 1981 | Proposed block streams apparently never visited google earth and aerial photograph observation suggests that they are more likely to be very large scree deposits |
| Mt William (Grampians) | 37°17'23"S:142°35'49"E | 1050-1100 m | Yes | Ashton and Moore 1978 | Sandstone block field |
| | | | | | |
| **New South Wales and the ACT** | | | | | |
| Ravine | 35.8333S:148.4167E | 1170-1200 m | | Barrows *et al.* 2004 | Elongate basalt block streams up to 300m long with ridges indicative of flow |
| Mt Stilwell | 36°26'41"S:148°19'27"E | ~1900 m | | Costin *et al.* 1979, Coyne 2001 | Periglacial block stream |
| Toolong Range | 36°07'52"S:148°21'14"E | 1680 m | | Caine and Jennings 1968, Jennings 1969 | Elongated low angle (6-12°) concave boulder diamicton suggested by Jennings (1969) formed by periglacial processes |
| Rougth Creek | 36°00'38"S: 148°24'08"E | 1480 - 1685 m | | Caine and Jennings 1968, Webster 1974 | Some features described by Caine and Jennings as "small relict rock glaciers" |
| Coolman Plains | 35°37'15"S:148°40'40"E | ~1250 m | | Webster 1974, Jennings 1982 | Small block streams |
| Mt Coree | 35°18'25"S 148°48'21"E | 1115 -1175 m | | Webster 1974 | Small block streams |
| Tidbinbilla Range | 35°26'28"S:148°51'22"E | 1200 - 1600 m | | Webster 1974 | Webster awknowledges the presence of block deposits but does not detail further. |
| Mt Kelly Spur and Mt Namadgi | 35°40'35"S:148°52'09"E | 1300-1500 m | | Land Management and Planning Division 10/0386 | Block streams |
| Barrington Tops | 32°01'57"S: 151°26'21E | ~1400-1500 m | Yes | Nanson 2009 | Basalt periglacial block deposits buried under peat bogs that post date 11 ka. |

Appendix 16: Poster presented at the 2013 International conference on Geomorphology (IAG) Paris, France.



Appendix 17: Poster Presented at the 2014 Australian New Zealand Geomorphology Group Conference (ANZGG), Mt Tamborine QLD.



Appendix 18: Poster Presented at the 2015 European Geosciences Union General Assembly.