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Distribution and palaeoenvironmental significance of mountain blockstreams in the southern hemisphere

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ABSTRACT: Openwork mountain block deposits (blockfields, blockstreams) have received much research interest globally given their visual appeal as prominent cold-region landforms. However, studies have shown that these landforms in both glaciated and non-glaciated environments are probably of considerable age (pre-Quaternary), yet the environmental conditions of their formation (such as the presence of permafrost) and associated processes remain poorly understood. This paper focuses on consolidating and critically analysing current knowledge on mountain blockstreams found in the southern hemisphere. This is achieved by reviewing past published work on such landforms, from the Falkland Islands, Marion Island, southern Africa and southeastern Australia. By presenting a variety of previously proposed landscape evolutionary models, we demonstrate that southern hemisphere blockstreams are products of a range of weathering and material mobilization processes over long multiple warmer/wetter and colder/drier pre-Quaternary and Quaternary climatic cycles. Although most southern hemisphere mountain blockstreams have some association with periglacial processes, they are not exclusively periglacial in their developmental history. This can be tested through field geomorphic, sedimentary and ecological methods; the use of remote sensing; radiometric and relative-age dating; seismic and other subsurface methods; and modelling. However, many research questions remain unanswered, such as the potential role of permafrost in blockstream formation and dynamics, or their sensitivity to ongoing climate change.

KEYWORDS: blockstreams; mountain glaciation; periglacial processes; permafrost; southern hemisphere

Introduction

The aim of this study is to consolidate and critically analyse current knowledge on southern hemisphere blockstreams, based on evidence on their locations and properties as described in the literature. This comparison has not been done previously. The motivation behind this analysis is that, unlike blockfields, blockstreams have been less commonly examined, especially in the southern hemisphere, but are potentially useful for interpreting processes and phases of environmental change, particularly given their longevity in mountain landscapes that were not (completely) affected by Quaternary glaciation.

A wide variety of weathering processes (e.g. chemical, biochemical, physical, biophysical) operate in non-glacial mountain environments and these are major mechanisms by which bedrock exposures disintegrate *in situ* (Thorn et al., 2001; Dixon and Thorn, 2005; Strømsøe and Paasche, 2011). The outcome of weathering over long (10^4–10^7 year) timescales is the formation of disaggregated and dispersed surface boulder litters that can be many square kilometres in area over mountain summits and plateaus, and in high-latitude regions. Morphological and site-contextual attributes of surface boulder landforms can potentially provide important evidence for the processes, rates and timing of environmental change on mountains from the pre-Quaternary to present, where relative age-dating is possible (Rea et al., 1996; André, 2003; Darmody et al., 2005; André et al., 2008). However, there is still an incomplete understanding of the properties and distributions of different boulder landforms, both globally and regionally, and this is a limitation when it comes to correctly interpreting environmental change and landscape evolution in mountains or their sensitivity to climate change (Wilson et al., 2002; Fjellanger et al., 2006; Goodfellow et al., 2008; Knight and Grab, 2021). Regolith (weathered debris) cover in many mountain and cold region environments globally has been termed 'mountain-top detritus' (Ballantyne, 1998) or 'rock rubble veneers' (French, 1996). These general terms effectively describe the surficial and spatial extent of weathered materials. Such detrital cover may constitute a variety of forms, such as openwork block deposits characterized by large boulder- to cobble-sized materials (including air-filled pore spaces) near the surface, underlain by progressively finer-textured sediments with depth, and eventual bedrock (Goodfellow et al., 2009). Other forms of summit block deposits include single boulders of similar sizes distributed uniformly across an eroded or weathered bedrock surface; or blocks of different sizes located in clusters or distributed unevenly across the bedrock surface (Firpo et al., 2006; Goodfellow et al., 2014; Denn et al., 2018). In addition, summit blocks may also vary from rounded to angular, and this property has in some studies been used as a diagnostic indicator of climatically influenced weathering processes (Hopkinson and Ballantyne, 2014). Rounded boulders have been interpreted as reflecting physical (granular disintegration) and chemical weathering over long time periods under warmer and wetter conditions, or as being associated with coarse-grained rocks (Rea et al., 1996; Goodfellow et al., 2014; Hopkinson and Ballantyne, 2014), whereas angular boulders have generally been associated with physical weathering by

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frost shattering under cold climate conditions (Matsuoka and Murton, 2008; Nicholson, 2008). These latter accumulations have largely been viewed as 'periglacial' in origin and collectively termed as 'blockfields' (Ballantyne and Harris, 1994; Ballantyne, 2010), or 'felsenmeer'/'blockmeer' in Germanic literature (e.g. Präger, 1987) and 'kurums' in Russian literature (e.g. Romanovski and Tyurin, 1986).

The varied morphological characteristics of mountain block deposits, and their probable ages of formation, have resulted in a wide variety of more detailed terms being used to describe these deposits, some morphological, some spatial and some genetic in origin. Blockstreams are at times confused or conflated with block slopes, blockfields and rock glaciers, possibly given the difficulty to distinguish or separate various forms of block deposits in cases where they may spatially merge into one another or represent different forms that develop over time (Giardino and Vitek, 1988; Wilson, 2013). Although the term 'blockfield' is at times used to include openwork block deposits on both plateaus (near-flat surfaces) and on slopes, the terms 'block slope' and 'block stream' are typically used where such openwork deposits occur on slopes of different gradient (Embleton and King, 1975; White, 1981). A wide range of gradients has been suggested to distinguish blockstreams from blockfields, apparently active from as little as two-degree slopes (e.g. Tyurin, 1983); however, such a distinction may be arbitrary where the process origins are similar and where there might be a landform continuum from blockfields to blockstreams. In more detail, a major distinction between the use of the terms 'blockfield' and 'blockstream' is their spatial footprint and relationship to local relief. Blockfields tend to be located on summits or plateaus that have relatively low local relief and where the width and length of the 'field' are relatively similar. By contrast, blockstreams tend to occur in topographic depressions that usually extend downslope, and thus have a 'stream'-like outline shape with a narrow width but much greater length. This means the terms 'blockfield' and 'blockstream' largely refer to different spatial morphologies without any specific genetic interpretation. There are also relationships between blockstreams, rock glaciers and other (massive and stratified) slope deposits (scree, grèzes litées, rockfall) (André et al., 2008). For example, rockfall deposits may be a debris source to both blockstreams and rock glaciers.

Although blockstreams and blockfields belong to a similar suite of openwork block landforms, their genetic, spatial and temporal relationships are not always clear. For example, in some places, blockstreams on a slope are spatially connected to a blockfield on a plateau above; at other times they are not. In some instances, blockstream boulders are derived from a blockfield or plateau edge source above the blockstream, but not always.

Notwithstanding this at-times challenging separation, our focus is on blockstreams given their prominence in several southern hemisphere mountain environments. Blockstreams have also been referred to as 'rock-streams' (Small et al., 1970), 'rubble streams' (Richmond, 1962), 'rock rivers' (Costin, 1955), 'stone rivers' (Stone, 2000), 'boulder streams' (Whittecar and Ryter, 1992), 'boulder pavements' (Hara and Thorn, 1982) and 'stone runs' (André et al., 2008; Wilson et al., 2008). Although both terms are used in the literature, for consistency herein we use the term blockstream (one word) rather than block stream (two words) and in a morphological rather than in a genetic sense. The linear morphology of blockstreams is a common diagnostic property, located along topographic drainage lines and valley axes. Reported dimensions of blockstreams are highly variable but typically range from a few tens of metres to several hundreds of metres in width, and tens of metres to over 10 km in length (e.g. Williams, 1968; Whittecar and Ryter, 1992; Wilson et al., 2017). Boulder accumulations at the blockstream surface are usually 1–3 m thick but may be up to 9–10 m thick in some cases (Wilson, 2013). Boulders making up the blockstreams often show downslope orientation and hence past/present mobility of the landform or of elements within it (Harris, 2016).

Openwork block landforms may be controversial given the difficulties of determining their ages and relative activity through time, and the range of suggested formative processes involved. Two primary modes of debris accumulation on mountain summits are recognized. *Autochthonous* openwork block deposits originate from *in situ* weathering which supposedly includes frost heaving of rock from the regolith (White, 1981; Rea et al., 1996; Ballantyne, 2010). By contrast, *allochthonous* openwork block deposits result from downslope accumulation of materials that have originated from an upslope source (e.g. scarp outcrops) (White, 1981). In some high latitudes of the northern hemisphere, openwork block deposits (including blockstreams) are relatively common and were previously thought to have largely originated from Neogene regolith cover and then altered through frost action during the Quaternary (e.g. Nesje, 1989; Whalley et al., 2004; Fabel et al., 2012). It has also been suggested that such deposits of considerable antiquity were protected (preserved) by cold-based ice during periods of glaciation, which thus promoted their longevity (e.g. Rea et al., 1996; Fjellanger et al., 2006; Fabel et al., 2012; Marr et al., 2022). However, some studies based on granulometry and secondary mineral fingerprinting of chemical weathering have argued against these being products of Neogene (or pre-Quaternary) weathering profiles, but rather as having been produced by physical weathering during the Quaternary (e.g. Goodfellow, 2012; Goodfellow et al., 2014; Hopkinson and Ballantyne, 2014). Active blockstreams in the Kunlun Shan (China) have developed in areas of negligible snow cover where permafrost beneath the surface blocks apparently permits sliding downslope (Harris et al., 1998). This would imply that at least *some* blockstreams have: (i) been mobile over time and space; (ii) developed through mechanisms associated with permafrost at some stage of their activity; and (iii) properties that make them difficult to separate from rock glaciers (Jones et al., 2019).

The global distribution (including latitudinal limits) of apparently active blockstreams was mapped by Harris (1994) (see Fig. 1), which suggests their widespread occurrence in northeastern Alaska (USA) and large parts of Russia, including sub-Arctic Novaya Zemlya Island (Kara Sea), the Ural Mountains, and mountainous eastern and central parts of Russia. A literature search has also found numerous publications reporting on inactive blockstreams from many northern hemisphere mountain regions, as denoted in Fig. 1. It is likely that many more (formerly) cold regions host blockstreams, but that these have yet to be documented in the literature. The known distribution includes parts of western and eastern USA (e.g. Clark and Ciolkosz, 1988; Degenhardt et al., 2007), southwestern Europe (e.g. Iberian mountains; Gutiérrez and Gutiérrez, 2014), the Mediterranean mountains (e.g. Firpo et al., 2006), and in regions of central (e.g. Borowicz and Żurawek, 2003; Rypl et al., 2014), eastern (e.g. Șerban et al., 2019) and northern (e.g. Wilson et al., 2017; Marr et al., 2018) Europe. Inactive blockstreams are also known from the Eurasian zone (e.g. Turkey, Iran; Mokhtari, 2010), central Asia (e.g. Tibet; Harris et al., 1998), and mountains of South Korea (e.g. Seong and Kim, 2003) and Japan (e.g. Seto, 2010). The wide latitudinal distribution of blockstreams in a host of mountain climate types and glaciological/tectonic settings, ranging from Mediterranean/oceanic to continental and sub-Arctic, indicates that blockstreams have developed or presently occur in a variety of cold climate regimes.

For over a century, blockstreams have also been reported from the southern hemisphere (e.g. Darwin, 1839; Thomson, 1877). Possibly the first published scientific mention of blockstreams

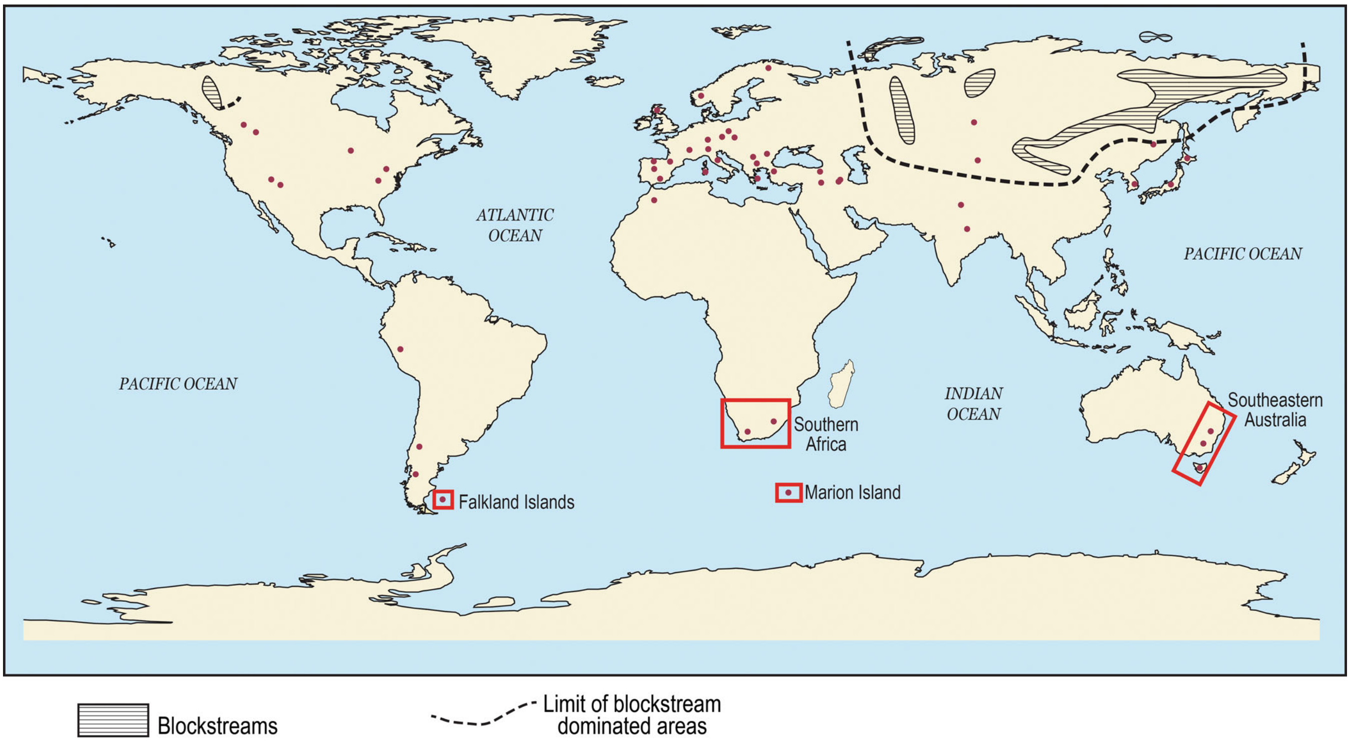

Figure 1. Global distribution of: (i) inactive mountain blockstreams (dots on map) as reported in the scientific literature and (ii) active mountain blockstreams (shaded parts on map) and their latitudinal limits (dotted lines on map) according to Harris (1994, his fig. 12, p. 187).

('stone rivers', 'stone runs') in the southern hemisphere was by Charles Darwin, who noted the 'myriads of great angular fragments of quartz rock' on the Falkland Islands, which were described as 'a stream of stones' (Darwin, 1839, p. 254). Since then, southern hemisphere blockstreams have been reported from the sub-Antarctic Marion Island (e.g. Holness, 2003), South America (Trombotto, 2000), southern Africa (e.g. Boelhouwers et al., 2002) and SE Australia (e.g. Slee and Shulmeister, 2015). Although autochthonous blockfields are known from currently unglaciated parts of the NE Antarctic Peninsula (James Ross Island) (Davies et al., 2013), these have not yet been examined in detail. In addition, Ruiz-Fernández and Oliva (2016, p. 352) report the occurrence of lichen-covered (inactive) 'blockstreams' from Livingston Island (South Shetland Islands) which are described as 'ridges of boulders and gravel separated by fine particles'. Such a morphology, however, is more typical of large varieties of sorted stripes, rather than belonging to the suite of openwork block deposits as described earlier. Despite a large variety of glacial and periglacial landforms (e.g. rock glaciers, blockfields, solifluction lobes and other slope depositional phenomena) reported from New Zealand (Augustinus, 2002), there is no published work on openwork block deposits in that country, and notably absent is any mention of blockstreams.

In detail, this study provides for each southern hemisphere region where blockstreams have been examined: (i) an outline of its past and present climatic/environmental setting; (ii) the key characteristics (i.e. distribution, size, morphology and sedimentology) of blockstreams within these regions; (iii) a summary of suggested modes of blockstream formation based on site and morphological characteristics; and (iv) the relative age and significance of southern hemisphere blockstreams. The locations of these study regions are shown on Fig. 1 and include the Falkland Islands, Marion Island, southern Africa and Australia. Specific mention of blockstreams in South America is notably absent, apart from Trombotto (2000) who provides a review of periglacial landforms in South America and mentions the occurrence of 'rock streams' in the Cerro Hermoso Valley, southern Andes [47°34'S; 1365 m above sea level (asl)] (Figs. 2 and 3). Hence, although blockstreams are known to South America, there is insufficient information to justify a review of these landforms from this region. The outcome of this analysis is an enhanced understanding of blockstreams as a mountain phenomenon in the southern hemisphere, and their potential usefulness as an indicator of past climatic and environmental conditions and changes.

Blockstream locations and their present climates in the southern hemisphere

Falkland Islands

The Falkland Islands host a variety of openwork block phenomena referred to collectively as 'stone runs' (Joyce, 1950; Clapperton, 1990; André et al., 2008; Wilson et al., 2008), but which are referred to hereafter as blockstreams. The blockstreams occur on relatively gently sloping terrain (1–10°) or along valley floors (André et al., 2008). The Falkland Islands (51–52°30'S; 60–61°30'W; Figs. 1 and 2) are made up of two main islands, East and West Falkland, which cover ~5000 and 3500 km^2 respectively (Clapperton, 1990). Bedrock geology mostly comprises Palaeozoic and Mesozoic quartzites and sandstones (Stone, 2016), and with a variety of surficial Quaternary periglacial mass-wasting deposits (Clark et al., 1998). Blockstreams are found only on quartzite lithologies and are absent in areas identified as formerly glaciated (Clapperton, 1975, 1990). The climate is primarily influenced by the Patagonian Andes (South America) to the west and northern extension of the Antarctic Circumpolar Current (Lister and Jones, 2015). The cool maritime climate annually averages temperatures of 5.5°C (2.2°C in July to 9.1°C in February) and rainfall of 500–800 mm in Stanley at the coast (Wilson et al., 2008; Lister and Jones, 2015). A more intense periglacial climate, conducive to substantive solifluction, was likely at 36–14k ^{14}C a BP and also prior to 36k

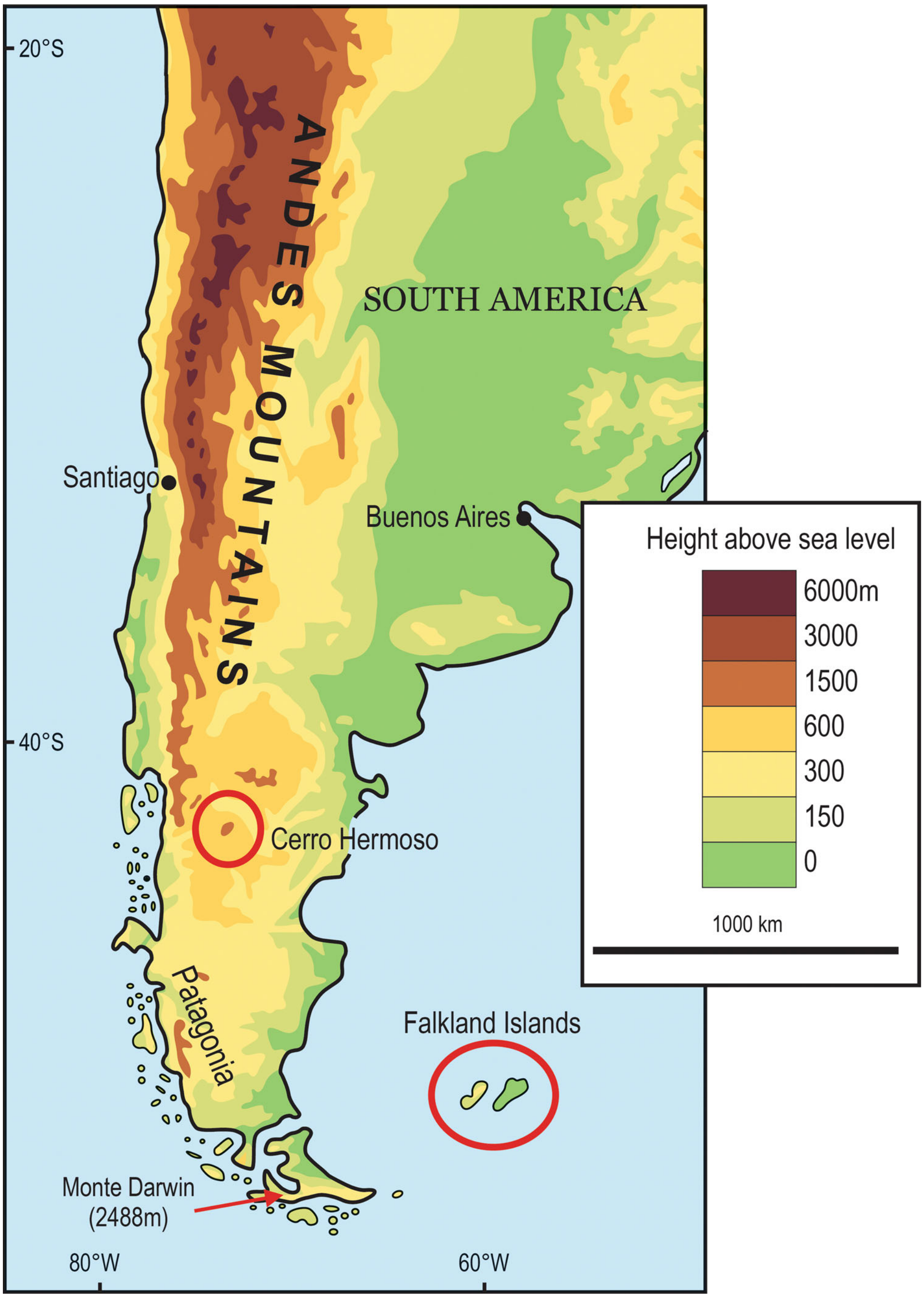

Figure 2. Location of South American Andes, Cerro Hermoso and Falkland Islands, across which blockstreams have been reported.

^{14}C a BP (Wilson et al., 2008). The islands experienced limited glaciation (cirque glaciers and small ice caps) during Quaternary cold periods (Clapperton and Suggern, 1976; Clapperton, 1990; Hodgson et al., 2014). Overviews of periglacial processes and landforms in the Falklands have been provided by Clark (1972, 1976) and Wilson et al. (2002).

Marion Island (sub-Antarctic)

Blockstreams occur at high elevation (~ 750 m asl) on Marion Island, below the edges of plateaus or on low-angle slopes, but are of limited distribution (Holness, 2001, 2003). The ~293-km^2 Marion Island is located just north of the Antarctic Convergence at 46°54′S; 37°45′E (Fig. 1), reaching a maximum elevation of 1240 m asl (Hedding, 2008). Thick late Pleistocene deposits of basalt-derived till cover about a third of Marion Island (Hall, 1978), while the remaining areas host more recent volcanic deposits (Holness, 2003). Dominant geological cover includes older pre-glacial (Pleistocene) grey basalts (where the blockstreams are located), and younger (Holocene) black lavas and scoria cones (Hedding, 2008). Marion Island's complex glacial history has recently been summarized by Rudolph et al. (2024). The 'hyper-maritime' climate is strongly linked to the frequent overpass of mid-latitude westerlies (Hedding and Greve, 2018), which have also had a direct influence on the island's maritime periglacial regime (e.g. Boelhouwers et al., 2003; Nel, 2012). Mean annual precipitation is high (~ 2000 mm), but has decreased in recent decades (Rudolph et al., 2020). Mean annual air temperature (MAAT) is ~6°C but rapid warming (2.4°C per 100 years) has been measured over the period 1950–2021 (Nel et al., 2023).

Southern Africa

Although openwork block deposits have been reported from a variety of environmental contexts in southern Africa, including

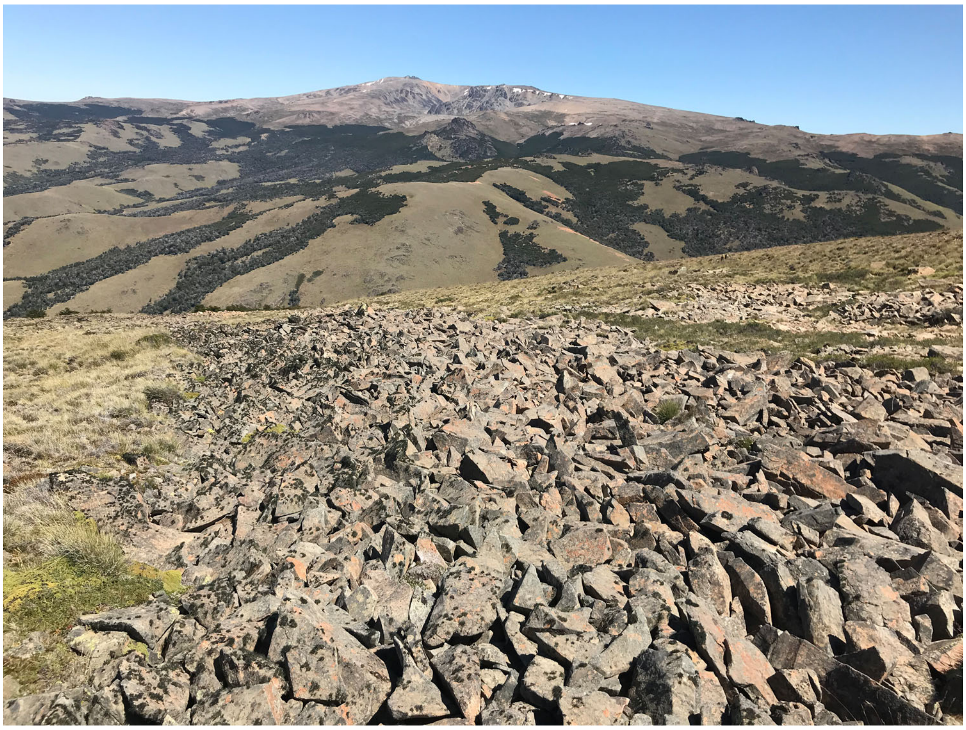

Figure 3. A blockstream in the Cerro Hermoso region (photo provided by Dario Trombotto).

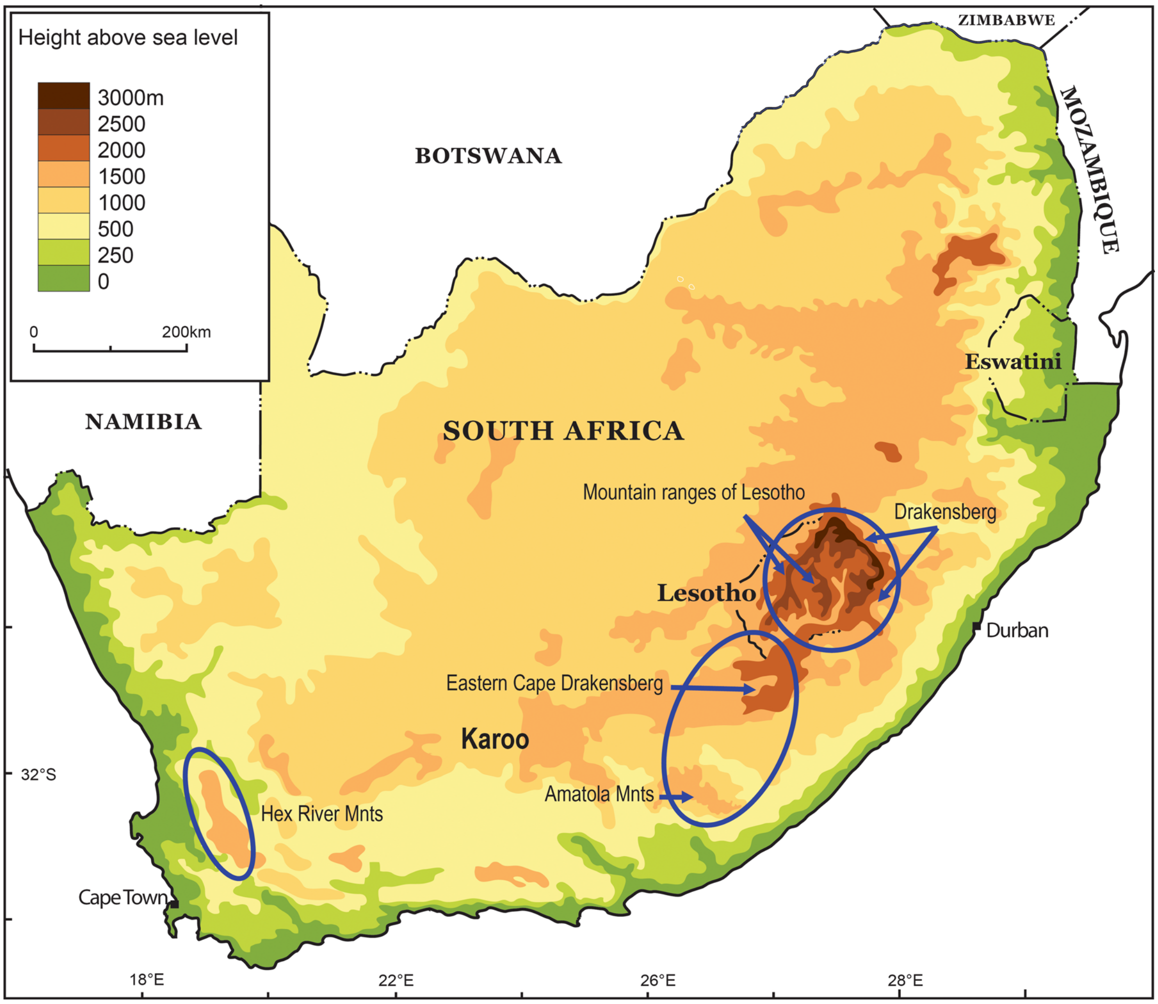

Figure 4. Core regions where blockstreams have been reported in southern Africa.

the arid Namib desert and semi-arid Karoo (Boelhouwers, 1999a; Boelhouwers and Sumner, 2003), most detailed work and information stems from three key high-elevation regions along the Great Escarpment (Knight and Grab, 2021) (Fig. 4). The first is the high Drakensberg which forms a natural border between the landlocked country of Lesotho and KwaZulu-Natal Province of South Africa (~28°40′S to 29°50′S; 28°40′E to 29°50′E). The Drakensberg is a product of basaltic fissure outpourings ~183–105 Ma (Eales et al., 1984) and reaches elevations of 3482 m asl. The second area is the Eastern Cape Province Drakensberg and Amatola Mountains farther south, comprising predominantly basalts and Karoo dolerites respectively (Sumner and de Villiers, 2002; Mills et al., 2017). The region broadly extends from ~30°40′S to 32°40′S and 26°50′E to 28°00′E, reaching maximum elevations of 3001 m asl in the north and 2016 m asl in the Amatola Mountains. The third area is the Hex River Mountains in the southwestern Cape (~33°25′S; 19°30′E; maximum elevation of 2249 m asl), comprising mostly folded quartzitic sandstones and occasional argillaceous bands of shale (Boelhouwers, 1998). The high Drakensberg receives most (80%) of its annual precipitation (~1000 mm) during the austral summer months (Sene et al., 1998). At 3100 m asl, mid-summers are mild (mean temperature of 11°C) and mid-winters are cold (mean temperatures of 0°C) (Grab, 1999). In contrast, the Hex River Mountains receive predominantly winter precipitation (often as snow), with MAATs ranging between 7 and 10°C at highest elevations (Boelhouwers, 1998, 1999b). The limited Quaternary niche glaciation in the high Drakensberg and southern African periglacial environments are summarized by Grab and Knight (2016).

Australia

Australia has two core regions well known for past glaciation and past/present cryogenic activity and associated landform development (including blockstreams), namely the Great Dividing Range (Southern Tablelands of SE Australia, in New South Wales and Victoria), and the Tasmanian highlands (Fig. 5) (e.g. Barrows et al., 2002; Slee and Shulmeister, 2015; Slee et al., 2016). The geology of these locations is diverse and complex across the mountainous regions, with highest elevations in SE Australia consisting of granites of Ordovician and Early Devonian age (Packham and Day, 1969), while large

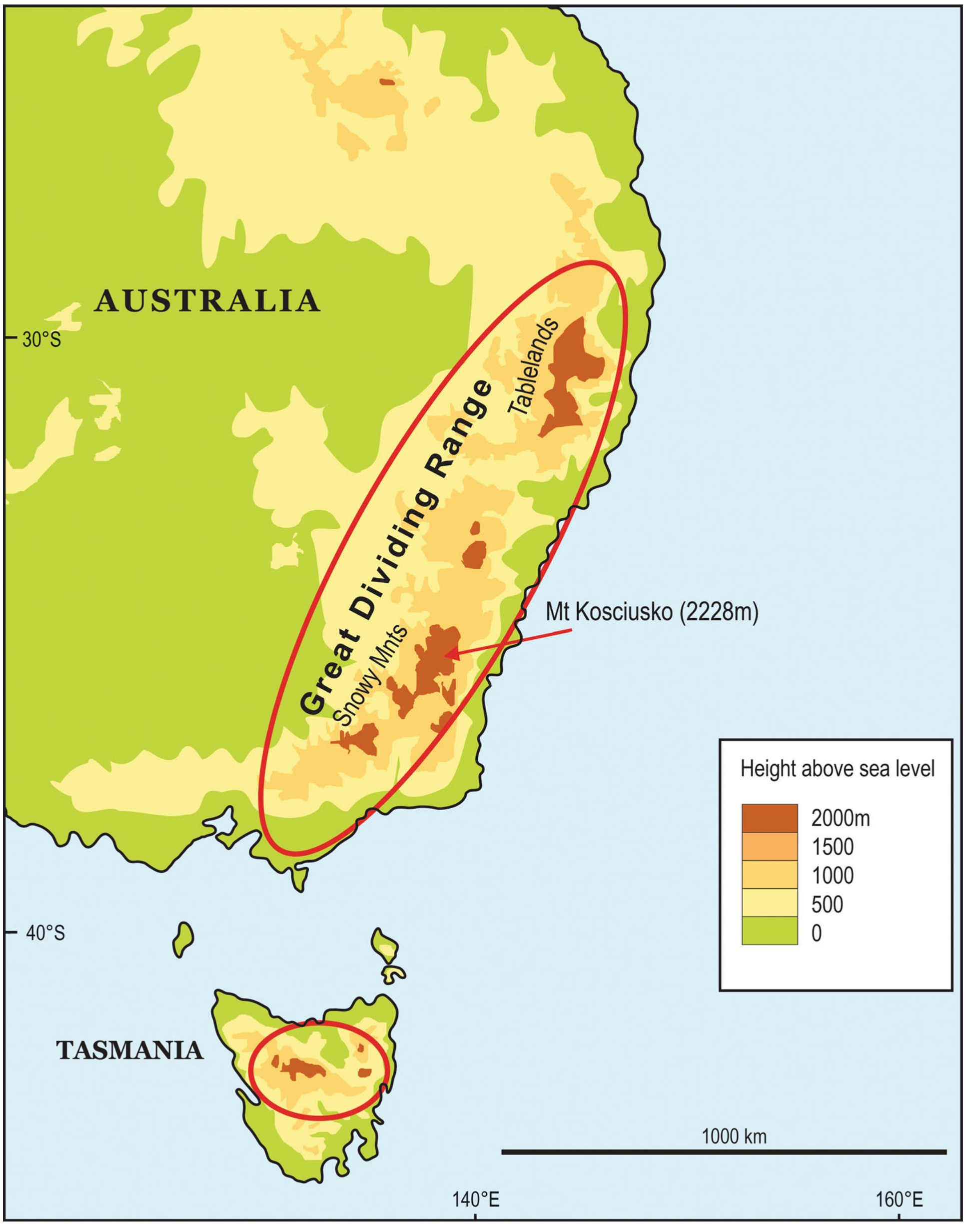

Figure 5. Core regions where blockstreams have been reported in SE Australia.

parts of the higher Tablelands and summits of Tasmania consist of Jurassic dolerite intrusions (Burrett and Martin, 1989). Climates are equally diverse, with more southerly regions (Tasmania and the Australian Alps) impacted by mid-latitude cyclones (westerly frontal systems). These bring winter precipitation during colder months, and consequent snow cover >1200 m asl, which can last several weeks to months on higher summits (Whetton et al., 1996). The more northerly extensions of the Tablelands have increasing inputs from tropical airflow and thus are also influenced by summer precipitation. In the Snowy Mountains at Perisher Valley (1735 m asl), the MAAT measured over the period 1976–1993 was ~5.6°C and ranged from 12°C (January) to −1.4°C (June), while annual precipitation averaged 1950 mm (Happold, 1998). Tasmania has a pronounced west to east rainfall gradient, with annual values ranging from 2500–3500 mm in the southwest to <600 mm in the east (McIntosh et al., 2012). With a MAAT of ~4.5°C at Mt Wellington (1260 m asl) (McIntosh et al., 2012), the extrapolated MAAT for the highest summit (~1600 m asl) is ~2.7°C. Late Pleistocene [Last Glacial Maximum (LGM)] glaciation was restricted to the Snowy Mountains and Tasmanian Highlands (Barrows et al., 2002). However, based on cosmogenic ^{36}Cl and ^{10}Be dating applied to moraine boulders, this glaciation was brief (~17 000–20 000 years) (Barrows et al., 2002). This may mean that these regions have been subject to episodic periglacial and cryonival conditions over a long time, both before and after Quaternary glacier development.

Key general blockstream features in the southern hemisphere

Falkland Islands

A variety of 'stone-run' types which include 'stone patches', 'stone fans', 'stone stripes' and 'stone rivers' (i.e. blockstreams) (Fig. 6) have been described (André et al., 2008). It is likely, however, that these are simply different variants of the same landform type, and thus some of these variants may merge or feed into each other as is evident in Fig. 6, or extend from summit crests where they may be linked to blockfields (André et al., 2008).

Blockstreams occupy both gentle slopes and valley floor locations, measuring 0.1–4 km in length and up to 2 km in width (Andersson, 1907; André et al., 2008; Wilson et al., 2008). Block *a*-axis lengths average 0.5–1.5 m (maximum 9 m) and accumulate to depths (minimum measured thicknesses) of 2–3 m (Wilson et al., 2008). The blocks are mostly imbricated and dip upslope, whilst those along the margins tilt outwards (Clapperton, 1975; André et al., 2008). Grain size and micromorphological analyses of sediments underlying the blocky surface material has been interpreted as colluvial quartzitic in make-up and is derived from underlying bedrock (André et al., 2008).

Marion Island

Blockstreams are up to 160 m in length and contain openwork material with a distinct clast orientation accompanied by downslope and lateral sorting (Holness, 2003). Blockstream clasts are angular and platy in morphology, with *a*-axes pointing in a downslope direction (Holness, 2003). More detailed information on such blockstreams is not provided. However, 'poorly developed' autochthonous blockfields have been described from lower elevation areas (<750 m asl) where the insulating effects of the former snowline would not have been a limiting factor to rock weathering (Sumner and Meiklejohn, 2004). Here, the predominantly platy blocks are variably angular to subrounded and form a shallow single layer above the bedrock surface (Sumner and Meiklejohn, 2004).

Southern Africa

Blockfields and blockstreams are common features in the Drakensberg and Hex River mountains, and have been described in several publications (e.g. Boelhouwers, 1999b; 2004; Grab, 1999; Boelhouwers et al., 2002; Boelhouwers and Sumner, 2003; Sumner, 2004; Mills et al., 2017; Bregman and Knight, 2022). Blockfields and blockstreams mapped in the southern Drakensberg show a strong spatial preference to south-facing slopes (median of 180°) above ~3050 m asl (Grab et al., 2009). However, several blockstreams have also been identified on northerly slope aspects at higher elevations (>3350 m asl) (Grab et al., 2009). Despite blockstreams in the high Drakensberg predominantly occurring on cold south-facing slopes, they do not have a strong association with areas of most prolonged contemporary snow longevity (Grab et al., 2009).

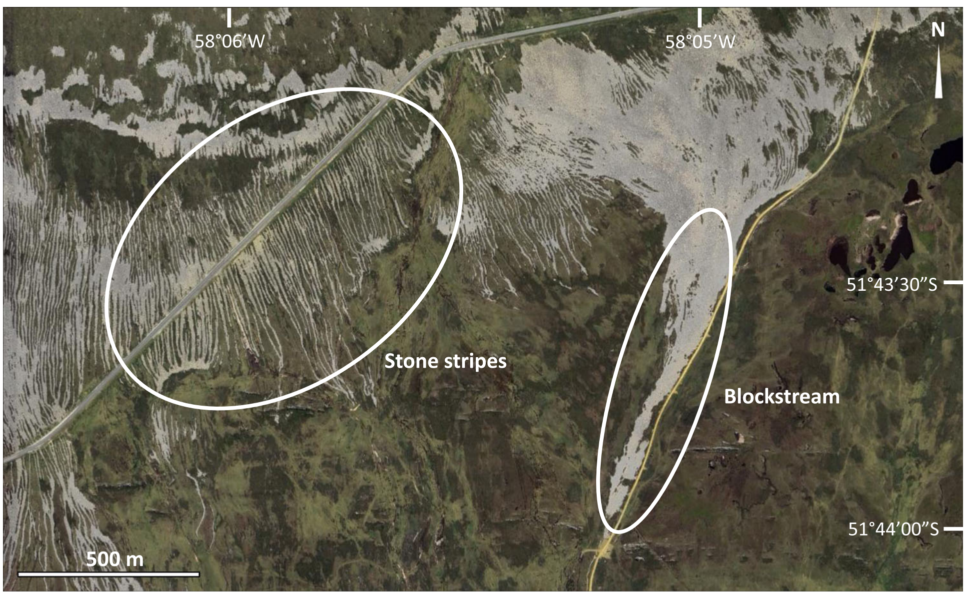

Figure 6. Stone stripes and blockstreams in easternmost East Falkland Islands (sourced from Google Earth, image date 1 August 2023).

Figure 7. The longest blockstream in the Drakensberg, Lesotho (length 1.1 km; maximum width 75 m) (photo: S. Grab).

Blockstreams in the Hex River Mountains likewise occur on south-facing slopes (Boelhouwers, 1999b).

Smaller blockstreams are axially aligned downslope and in places extend from highly weathered (disintegrated) scarps and summit blockfields, while larger varieties occupy central valley floor positions (Boelhouwers, 1999b; Grab, 1999; Boelhouwers et al., 2002; Sumner, 2004; Bregman and Knight, 2022). Blockstreams on valley slopes usually represent an upraised (ridge-like) topographic expression (Boelhouwers, 1999b; Grab, 1999, Bregman and Knight, 2022). Some blockstreams in the Hex River Mountains have lobate fronts up to ~3 m in height (Boelhouwers, 1999b). Measured blockstreams in the high Drakensberg are of variable dimension, ranging from 15 m in length and 3 m in width (Grab, 1999) to ~1.1 km in length and 75 m in width (Boelhouwers et al., 2002) (Fig. 7). Boulder sizes vary depending on site location and micro-topographic position along the blockstreams, but *a*-axis lengths typically average between 60 and 122 cm in the Drakensberg (Boelhouwers et al., 2002; Bregman and Knight, 2022) and range between ~40 and 300 cm in the Hex River Mountains (Boelhouwers, 1999b). Drakensberg boulders range from subangular to rounded in shape, in many cases displaying bi- or trimodal *a*–*b* plane fabrics; these are primarily aligned parallel to the micro-site slope gradient and reflect the downslope direction of the blockstream (Boelhouwers et al., 2002; Sumner, 2004; Bregman and Knight, 2022). Similar downslope fabric alignment has been described for the more platy/elongate blocks found in the Hex River Mountain blockstreams (Boelhouwers, 1999b). Little is known about the internal (vertical) stratigraphy of blockstreams, largely due to blocks being too large to displace for such analysis. However, a small, sectioned mountain summit blockstream indicated considerable stratigraphic variability (Grab, 1999). Where the blockstream 'overflows' the rock scarp, the ~50-cm layer of openwork blocks is underlain by tightly packed horizontally layered (weathered) rock slabs ~70 cm in depth, below which is bedrock. Downslope from the rock scarp, openwork block material ranges between 60–70 cm in depth, below which is an ~9-cm gravel layer with interstitial fines, which rests unconformably above fine sand and silt of unknown depth (Grab, 1999). Similar stratigraphies have been described from these same regions from more common stratified slope deposits (Knight and Grab, 2021).

Australia

Australian block deposits occur in a variety of lithologies, including basalt, slaty Carboniferous Sandon Beds, rhyodacites, dolerite, conglomerate and quartzite (Caine, 1983; Colhoun, 2002; McIntosh et al., 2012; Slee and Shulmeister, 2015). The occurrence of such 'block deposits' ranges from ~30°S in the New England Tableland to ~43°30′S in Tasmania (Slee and Shulmeister, 2015). Despite the considerable latitudinal extent of block deposits (across 13° of latitude), this seems to have had limited impact on their lower elevational occurrence (at ~550 m asl in Tasmania and ~800 m asl in the New England Tableland), notwithstanding considerable elevational extent above the deposits in the respective regions (Slee and Shulmeister, 2015). Although many of the larger blockstreams occur on southerly slope aspects, block deposits are also reported from other slope aspects and have a strong north-facing occurrence in the Australian Alps (Slee and Shulmeister, 2015). In western Tasmania, block deposits are closely associated with the limits of former glaciation, and hence only occur in non-glaciated areas (Colhoun, 2002; Slee and Shulmeister, 2015). Here, blockstreams typically occur on slope gradients of 5–10° (Caine, 1983) and are extensive on mountains above ~900 m asl (Colhoun, 2002). Single large blockstreams tend to occupy the axes of valleys, but in uppermost reaches, several blockstreams originating from doleritic plateau edges may become confluent; thus, they merge to become single large blockstreams occupying the axes of valleys below (Colhoun, 2002). This suggests multiple phases and mechanisms of blockstream evolution.

Unfortunately, the >4000 block deposits described and mapped by Slee and Shulmeister (2015) are not morphologically separated, making it impossible to isolate specific examples of blockstreams. Nonetheless, most of such deposits cover <10 ha in area but may extend over several 100 ha in parts of Tasmania, where the Ben Lomond blockfield covers 1591 ha (Caine, 1983; Slee and Shulmeister, 2015). New England Tableland and Snowy Mountain blockstreams are 40–400 m in length and 10–20 m in width (Barrows et al., 2004; Slee et al., 2023). Mean block sizes in Tasmania are 25–60 cm (Colhoun, 2002). Measurement of surface block fabrics in Tasmanian blockfields and blockstreams has confirmed a dominant alignment parallel to the slope direction and that the strength of alignment increases with distance downslope (Caine, 1972). This suggests slope-influenced block mobility typical of blockstreams. The blockstream stratigraphy usually consists of openwork block material ranging from 0.5 to 3.0 m in depth, below which are layers of variable thickness including blocks, cobbles and finer sediments, and which ultimately rest unconformably above deeply weathered clays (Caine, 1968, 1983; Caine and Jennings, 1968).

Key features that may provide evidence of blockstream origins, and suggested models of formation

Falkland Islands

In the Falkland Islands, Sir Wayville Thomson described vast accumulations of quartzite blocks resting irregularly upon one another and noted the association between blockstreams at the valley bottom and quartzite outcrops (ridges) above gently inclined slopes surrounding the features (Thomson, 1877). The hypothesis was thus one of: (i) weathering and denudation of exposed cliffs, (ii) accumulation of rock fragments (blocks) at the base of scarps which become embedded in vegetated soil, (iii) subsequent slope mass transfer (creep) downslope through forces of periglacial expansion and contraction, (iv) the eventual accumulation of blocks at the bottom of the valley, and (v) subsequent washout of finer interstitial materials by the stream, leaving behind only the larger blocks. This hypothesis was later supported by Andersson (1907) who, unlike Thomson, considered the features as inactive given the evidence of vegetation partly covering the 'stone-rivers'. In addition, Andersson noted that (i) the 'stone-rivers' outlined small river systems beneath the rocks (flowing water could be heard at depth) and that (ii) along the periphery of the 'stone-rivers' similar large rocks had been deposited but were now imbedded within finer rock detritus not yet washed out through fluvial action. The 'stone-rivers' were considered evidence for a more severe past climate with heavy winter snow and summer melt causing superficial mud flows (Andersson, 1907).

Joyce (1950, p. 106) later argued that given the enormous weight of blocks detached from the bedrock, these would 'surely have sunk, under gravity, to the bottom of any viscous mass' and thus inhibited any lateral transport as suggested by Andersson (1907). Instead, Joyce emphasized the role of frost action along the heavily folded and highly jointed/bedded quartzite outcrops with intervening softer shales. The evolutionary model (Fig. 8) for 'stone run' formation presented by Joyce (1950) is thus one emphasizing the role of *in situ* weathering and denudation, without blocks being transported any great distance from their point of origin. Nonetheless, Joyce postulated that a combination of 'hill creep, freeze and thaw, frost heaving, and solifluction' contributed to the eventual formation of 'stone runs'. However, Joyce's model came under scrutiny, and particularly so by Clapperton (1975) who emphasized evidence that downslope movement of blocks was involved (e.g. merging of stripes into blockstreams). Instead, Clapperton favoured the views of Andersson, namely frost shattering of bedrock and solifluction (see Clapperton's model; Fig. 9).

More recently, based on field measurements and laboratory analyses of sediments beneath a blockstream, André et al. (2008) argued against these 'classical' and long-held views of a periglacial origin. Instead, they hypothesized a five-stage temporal model for blockstream development on the Falkland Islands (Fig. 10). This comprises:

1. Tertiary: regolith formation caused by chemical weathering under subtropical conditions.
2. Late Tertiary–early Quaternary: regolith stripping due to mass movement processes.
3. Early–Middle Quaternary: soil formation under more temperate climatic conditions, with a forested vegetation cover.
4. Late Quaternary cold stages: further regolith denudation, downslope material accumulation and reworking as a result of periglacial slope processes, with interstitial material subsequently washed out under permafrost conditions.
5. Late Quaternary warm stages including the Holocene: biological and chemical boulder weathering, with limited if any boulder movement.

The above hypothesis presented by André et al. (2008) is, however, highly speculative as it is unlikely that the region was 'subtropical' at any stage during the Tertiary given its high latitude and proximity to Antarctica (which has been glaciated for tens of millions of years).

Marion Island

Holness (2003, p. 72) proposed that the Marion Island blockstreams formed through the downslope movement and accumulation of a diamicton comprising weathered detritus 'under a periglacial environment', with subsequent removal of fines, and are thus allochthonous in nature. However, the precise periglacial mechanisms involved have not been considered. Monitoring of potential clast movement of the blockstreams today, the occurrence of vegetation growth, and moss and lichen growth on block surfaces suggest that these are relict landforms and stable under contemporary environmental conditions (Holness, 2003). The absence of stratification has been used to propose that the blockstreams formed as a single phase of movement associated with deep seasonal freeze, and/or possibly permafrost (Holness, 2003). However, this is not in itself diagnostic of any particular process or period given that blockstreams can develop and then move downslope as a body when under a range of climatic conditions.

A proposed mechanism (although incomplete) is that autochthonous blockfield development on Marion Island may, in part, be associated with pressure-release (dilatation) fracturing on deglaciation of bedrock surfaces (Sumner and Meiklejohn, 2004). However, given their poor development and absence of finer products (clay/silt-sized minerals produced by chemical weathering/past glaciation), both mechanical and chemical weathering rates are said to have been insufficient to produce a substantive surficial blocky layer through time (Sumner and Meiklejohn, 2004). To this end, the 'pre-conditioning of bedrock by deep chemical weathering' would have been deemed a probable necessity for more enhanced blockfield development on Marion Island (Sumner and Meiklejohn, 2004, p. 130). This may also account for the limited number and seemingly poorly developed (i.e. thin surficial blocky layer) blockstreams on the island.

Southern Africa

It is widely argued that the high mountain blockstreams described across southern Africa are allochthonous in origin (Boelhouwers, 1999b; Boelhouwers et al., 2002; Sumner, 2004; Bregman and Knight, 2022). Pseudokarst weathering forms associated with warm, humid times (e.g. Tertiary, contemporary) have been reported from the Hex River Mountain quartzites

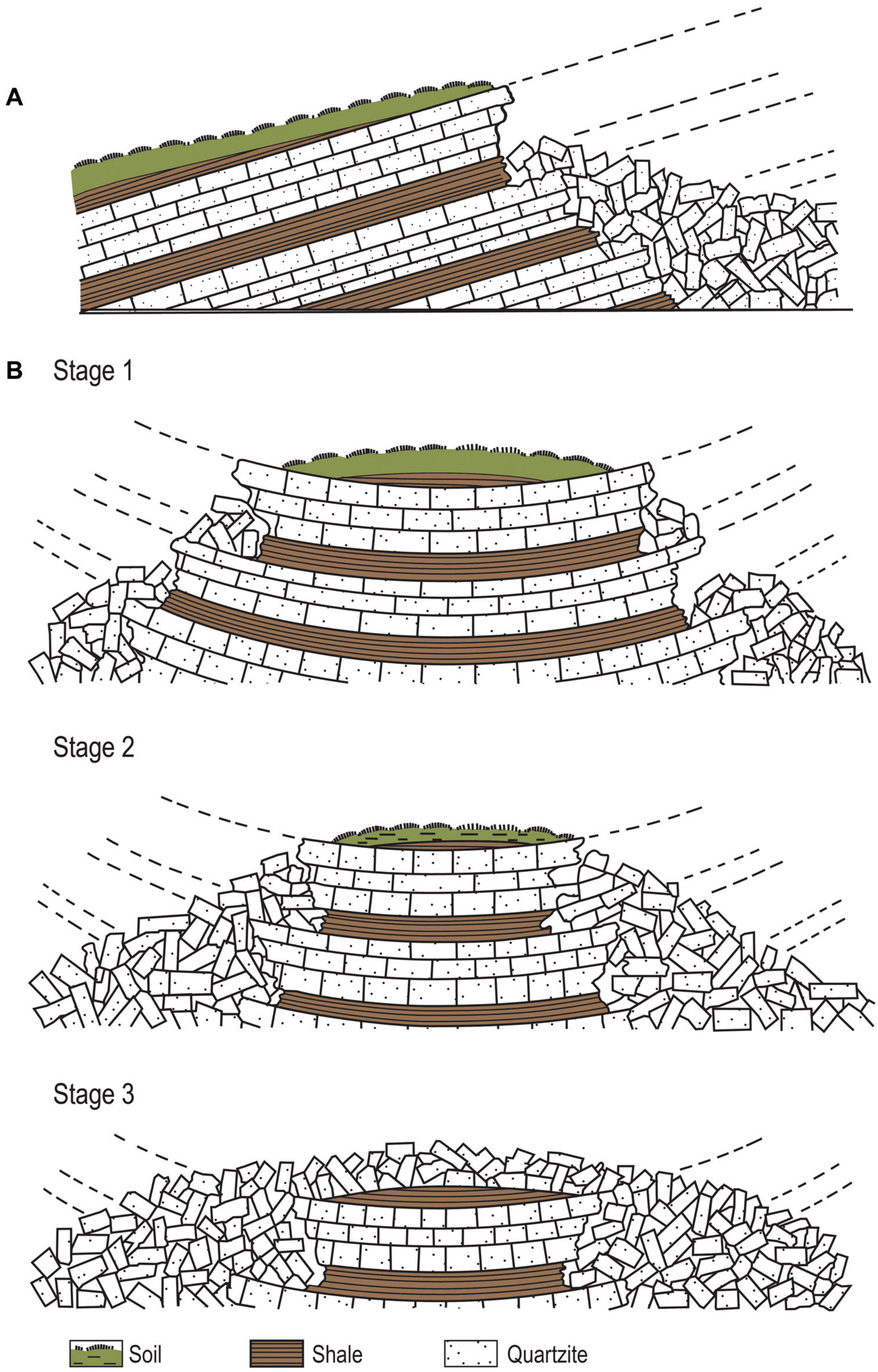

Figure 8. Evolutionary model for 'stone run' formation on the Falkland Islands (according to and redrafted from Joyce, 1950, his fig. 3, p. 113). (A) No detachment of quartzite on the dip slopes and thus absence of 'stone runs'. (B) Various stages for a gentle syncline and relationship of stone runs to minor tectonic features (Joyce, 1950, pp. 113–114).

(Boelhouwers, 1999b) and Drakensberg basalts (Knight and Grab, 2022). It has thus been suggested that chemical weathering played an important role in pre-conditioning exposed mountain summit bedrock for subsequent ongoing weathering mechanisms, especially those associated with cold climate phases (e.g. Boelhouwers, 1994, 1999b, 2004; Boelhouwers et al., 2002). The exposed rock scarps consequently have a long weathering history that may date back to the late Tertiary (Boelhouwers et al., 2002). Emplaced blocks and smaller weathered products from bedrock scarps have been subject to mostly slow mass movement processes since this time, which would have included deep seasonal frost (possibly 1–2 m in depth) during cold periods (e.g. the LGM and earlier stadials), thus permitting segregation ice development, frost creep (solifluction) and thaw-failure under high porewater pressure conditions (Boelhouwers et al., 2002; Bregman and Knight, 2022). Processes of rockfall and boulder rolling/sliding have also been proposed for steeper slopes (Bregman and Knight, 2022). Such mechanisms of debris transfer down mountain slopes (primarily on colder south-facing slopes) is supported by a variety of landforms including lobate solifluction terraces, blockstreams with lobate fronts, and stone-banked

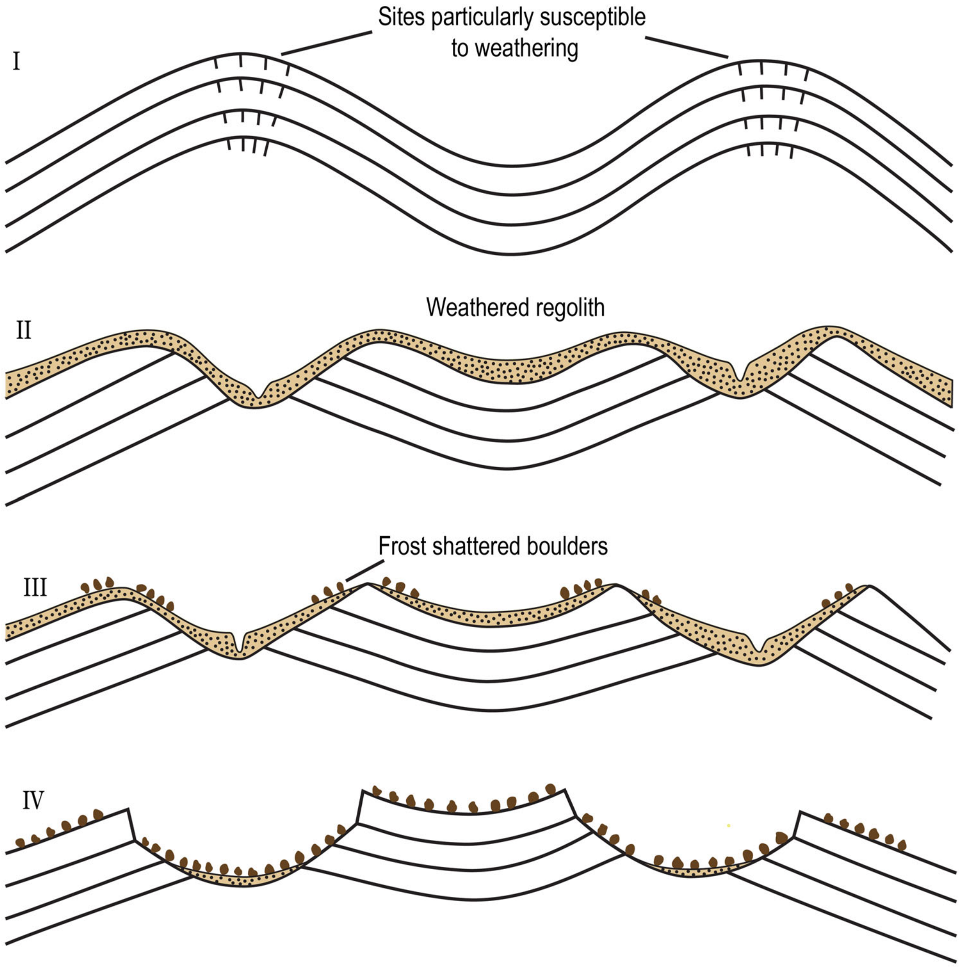

Figure 9. Evolutionary topographic stages for 'stone run' development on the Falkand Islands (according to and redrafted after Clapperton, 1975, his fig. 3, p. 215). (I) Anticlines and synclines of quartzite, sandstone and shale. (II) Inverse relief produced by prolonged denudation during the Tertiary era and a regolith of chemically rotted bedrock. (III) Onset of periglacial conditions leading to the exposure of fresh bedrock; development of stone runs and other slope phenomena aided by regolith of rotted bedrock. (IV) Present situation with well-developed stone runs; much of the Tertiary regolith has been removed (Clapperton, 1975, p. 215).

lobes (Boelhouwers, 1999b; Grab, 1999, 2000; Boelhouwers et al., 2002; Grab et al., 2021). This has yielded extensive colluvial debris mantle accumulations (with incorporated blocky material) on lower slopes of the high mountain catchments (Grab, 1999; Boelhouwers et al., 2002), some of which have been dated to at least ~43k ^{14}C a BP (Grab and Mills, 2011; Knight and Grab, 2021). The openwork deposits aligned along valley axes and infilling the base of valleys (rather than being a feature with positive relief) imply the subsequent washing out of finer matrix material, leading to downward movement and settling of the interlocking boulders (Boelhouwers, 1999b; Boelhouwers et al., 2002).

Australia

Caine (1983) believed the blockfields and blockstreams of the Tasmanian plateau mountains to be allochthonous in origin. In some parts, debris production was influenced by past glaciation which contributed to mass transfer of debris to valley floors, while areas not impacted by glaciation had more limited debris production (Caine, 1983). However, debris production along cliffs through *in situ* mechanical weathering over long time periods is also recognized (Colhoun, 2002). Subangular to subrounded corestones are in places encased (Caine, 1983; Colhoun, 2002). This highlights the potential importance of pre-Quaternary (non-periglacial) deep weathering as a condition for block supply in this region.

Caine (1983) proposed that blockfields and blockstreams are a product of sliding failure in remoulded clays beneath the overlying blocky surface. In addition, mechanisms associated with seasonal ground freezing (segregation ice development, 'frost-heaving', 'frost creep'), viscous flow and subsequent washing out of interstitial fines are considered important mechanisms at times of active landform development (e.g. Caine, 1983; Colhoun, 2002; Slee and Shulmeister, 2015). McIntosh et al. (2012, p. 23) argued against the likelihood of interstitial material encasing the boulders, but postulated that boulders were packed by 'interstitial perennial ice' (i.e. permafrost) and are thus 'genetically linked to rock glaciers'. These authors further proposed that blockstreams in Tasmania indicate viscous flow over considerable distances and could represent a landform type that is intermediate between rock glaciers and blockfields, similar to Berthling's (2011) argument for the development of rock glaciers. This may be further supported by the occurrence of pits, lobes and steps (including transverse ridges and furrows) in some block deposits that may indicate different periods of localized block movement, related to interstitial and/or permafrost ice development (Slee et al., 2023). Although Colhoun (2002) mentioned the occurrence of rock glaciers and permafrost above 1000 m asl in Tasmania, no other work has conclusively established such phenomena. Slee et al. (2023, p. 131) attributed such surface morphology to 'ice-mediated flow of the boulders' but acknowledge that not all Australian openwork block deposits are necessarily periglacial in origin. Nonetheless, 'frost-weathering' is considered the primary

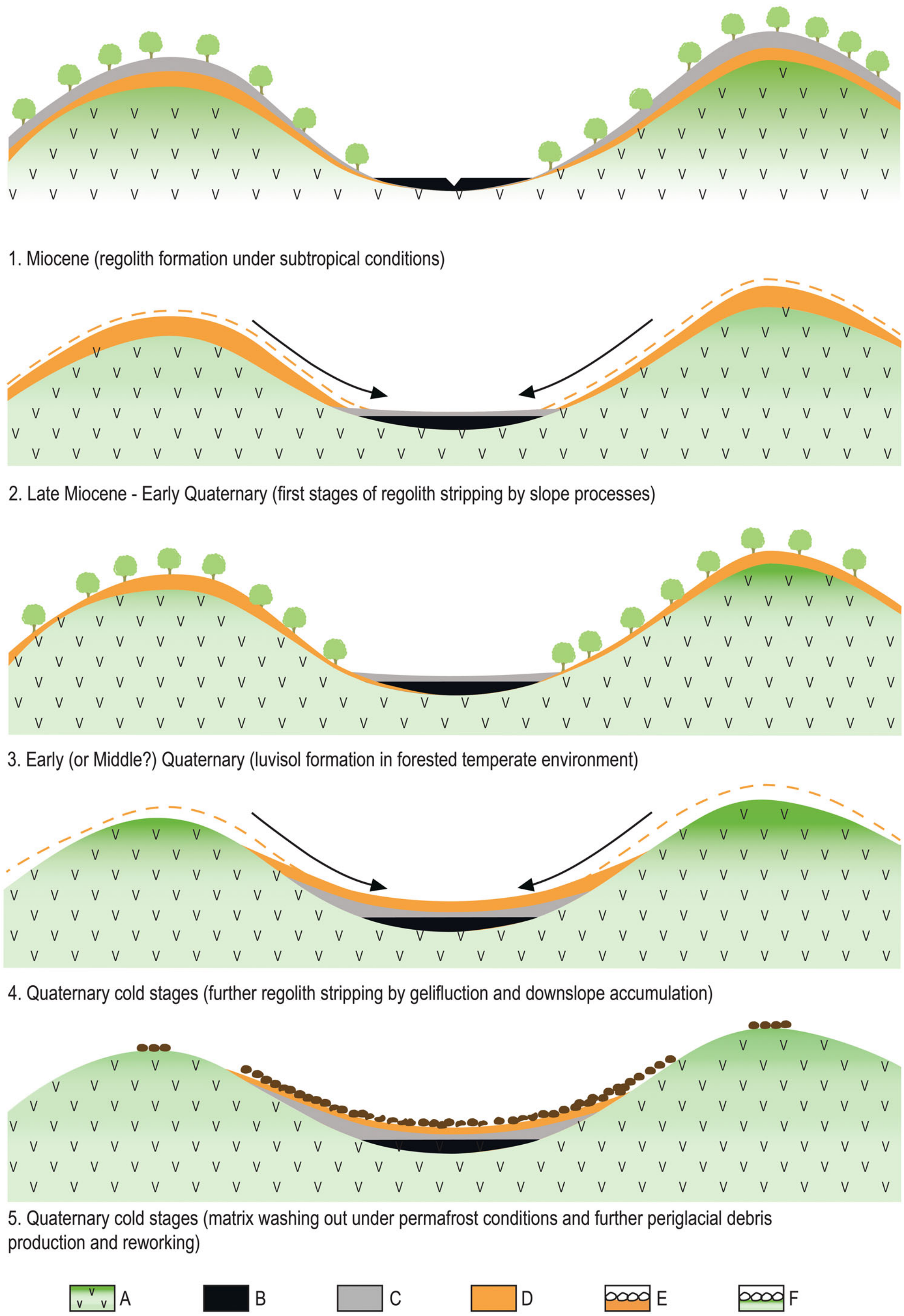

Figure 10. Proposed model for 'stone run' formation on the Falkland Islands (according to and redrafted after André et al., 2008, their fig. 14, p. 537). Key: (A) bedrock (mainly quartzite, with interbedded siltstones and mudstones); (B) alluvial deposits; (C) grus (initially top of regolith); (D) block-rich material with fine-grained matrix (initially bottom of regolith); (E) valley-bottom blockstream with stone run pavement derived from matrix washing-out of the upper part of unit 4; (F) hillslope blockfield.

mechanism for blocky-debris production, with thermal stress suggested as an additional likely weathering mechanism, and at least some of the blockstreams are believed to be 'lag deposits' (Slee et al., 2023).

Relative age and significance of southern hemisphere blockstreams

Falkland Islands

Available cosmogenic exposure ages from blockstream rock samples indicate ^{10}Be ages of 700 000–800 000 years for valley-axis blockstreams (Wilson et al., 2008), while optically stimulated luminescence dating of sediments beneath two blockstreams indicate ages of >54 000 to ~16 000 years (Hansom et al., 2008). Such large age differences may be a function of blockstream locality (e.g. valley-axis, hillslopes, hillcrests) (Wilson et al., 2008; Wilson, 2013). These findings support suggestions that past Quaternary glaciation was restricted to upland areas of the Falklands (e.g. Wilson et al., 2008; Hodgson et al., 2014). The ages also indicate that the blockstreams did not originate as a product from the LGM, but according to Wilson et al. (2008), they developed over several cold (periglacial) stages including prior to the LGM. Although the findings of André et al. (2008) suggest that the

Falkland Island blockstreams developed in various phases since the Tertiary, this would probably have happened under a range of environmental conditions and not necessarily restricted to either cold Quaternary stadials or solely under periglacial process regimes. This complicates any attempt to associate blockstream formation to a specific climatic regime. There are few detailed studies on Falkland blockstreams and their surrounding geomorphic environments and stratigraphic contexts, so the interplay between different process regimes (e.g. periglacial versus pedogenesis) remains unclear.

Marion Island

Thus far, there are no radiometric ages on the blockstreams or indeed on blockfields themselves, and there are limited quantitative data on the morphology of these landforms or on the blocks contained within them. Some possible constraint on the ages of exposed rock surfaces can be deduced from the probable LGM extent of Marion Island ice masses, which covered ~80% of the island and were separated by narrow bedrock ridges (Rudolph et al., 2022, 2024). However, the 'Grey lava' regions in which the blockstreams developed seem already to have been ice free prior to the LGM (Rudolph et al., 2024), placing further temporal constraints in providing a relative age-date for these landforms.

Southern Africa

The morphology and fabrics of southern African blockstreams on slopes below rock scarps, and also those aligned along valley floors, suggest that these have been variably developed and mobile over time, but are today considered relict (i.e. no longer actively forming) landforms given evidence such as vegetation growth upon and along the margins of the blockstreams (Boelhouwers, 1994, 1999b; Boelhouwers et al., 2002; Sumner, 2004; Bregman and Knight, 2022). Cosmogenic nuclide exposure ages for blocks in an Eastern Cape Drakensberg blockstream returned ages of ~12.7k to 49.3k a BP (Mills et al., 2017). The large scatter of ages implies that blocky material was already mobile at times pre-dating the LGM and thus have inherited ages, but that blockstreams have probably been inactive (stable) since the early Holocene (Mills et al., 2017). A model for non-glaciated mountain slope sediment systems, applicable to southern Africa, suggests that variations in slope sediment supply and sediment mobility result from progressive changes in climate, especially humidity, and slope properties (Knight and Grab, 2021). The outcome of this is the capturing of sediment bodies, including blockstreams and solifluction sheets/lobes, as relict landforms in mid-slope locations. The episodic movement of these landforms, as evidenced by spatial patterns in block morphology and relative weathering status (Bregman and Knight, 2022), shows there is not a deterministic 'on/off' mode of blockstream development under cold and warm conditions, respectively. Rather, there is differential boulder movement within blockstreams, resulting in areas of expansion and compression through which ridges, lobes and depressions are formed, as have been noted on southern African blockstreams (Bregman and Knight, 2022).

Given that blockstream formation probably required deep seasonal freeze throughout their most active stage of development during the LGM with a temperature depression of 6–8°C relative to the present, this implies an absence of the deep insulating effects of snow cover at such a time (Boelhouwers et al., 2002). To this end, southern African blockstreams have been used as evidence to refute previous suggestions of localized late Quaternary glaciation in the Hex River Mountains (Boelhouwers, 1999b) and high Drakensberg (Sumner, 2004). The suggested formative mechanisms for southern African blockstreams do not imply permafrost as a requirement, but rather are viewed as landforms indicative of past deep seasonal freeze (Boelhouwers, 1999b; Boelhouwers et al., 2002; Sumner, 2004; Bregman and Knight, 2022). However, given that southern African blockstreams are located in different geologies, elevations and climate regimes, it is not necessarily the case that they all formed at the same time or under the same climatic triggers, as has been assumed in previous studies (e.g. Boelhouwers and Sumner, 2003). This hypothesis requires further testing against field geomorphic and dating evidence.

Australia

The first reported indication for possible blockstream age in Australia is based on a buried *Nothofagus* stump in the Snowy Mountains, dated to ~35k ^{14}C a BP and interpreted to indicate a 6°C temperature depression at that time (Caine and Jennings, 1968). Based on ^{14}C-dated soil and peat development below a blockfield in Tasmania, and on weathering rind thicknesses of the blockfield clasts, Caine (1983) proposed that blockfields in the region have been stable (inactive) for the past ~13 000 years. More recently, cosmogenic ^{36}Cl block exposure ages for blockstreams in the Snowy Mountains have indicated age ranges of 17 200–22 700 years, suggesting relatively quick and brief development during the LGM and stability since then (Barrows et al., 2004). However, blockstreams from the Ben Lomond Plateau (Tasmania) indicate much older block exposure ages (22 000–49 800 years), leading Barrows et al. (2004) to infer that the slope was also episodically active as a rock glacier (implying also permafrost or interstitial massive ice). These ages are very similar to those reported from the Falkland Islands (Wilson et al., 2008). Based on the findings of Barrows et al. (2002), it has more recently been proposed that the block deposits developed episodically over long periods, including by freeze–thaw when interstitial ice was absent (i.e. blockstream) and other times of mass viscous flow when interstitial ice was present (i.e. rock glacier) (McIntosh et al., 2012). However, the specific mechanisms of 'freeze–thaw' and how these might contribute to landform development remain unexplained.

Based on a strong relationship between locations receiving at least ~50 contemporary frost days per annum and those hosting block deposits, Slee and Shulmeister (2015) inferred that such landforms must thus be 'periglacial' in nature and a product of freeze–thaw during Quaternary cold periods. This would have required substantial cooling of ~10.5°C in the northernmost parts of the Tablelands (~30°S) (Slee and Shulmeister, 2015). Further south (Southern Tablelands; ~35°S), screes, alluvial valley fills and fans at relatively low elevations (~700 m asl), dated to 13–66k ^{10}Be a BP, have likewise been interpreted as products of frost action, implying a temperature depression of 8.2 ± 0.5°C (Barrows et al., 2022).

Discussion

Several northern hemisphere studies on blockstreams have associated development of such landforms with cold, dry climates and permafrost during the late Pleistocene (e.g. Harris, 1994; Firpo et al., 2005; Șerban et al., 2019; Viana-Soto and Pérez-Alberti, 2019). Although Harris (1994) places blockstream formation within a MAAT range of −6 to −20°C (Fig. 11), other studies have proposed palaeotemperature requirements of between 0 and −2°C (Firpo et al., 2005; Viana-Soto and Pérez-Alberti, 2019). These rather largely contrasting temperature requirements, obtained from location-

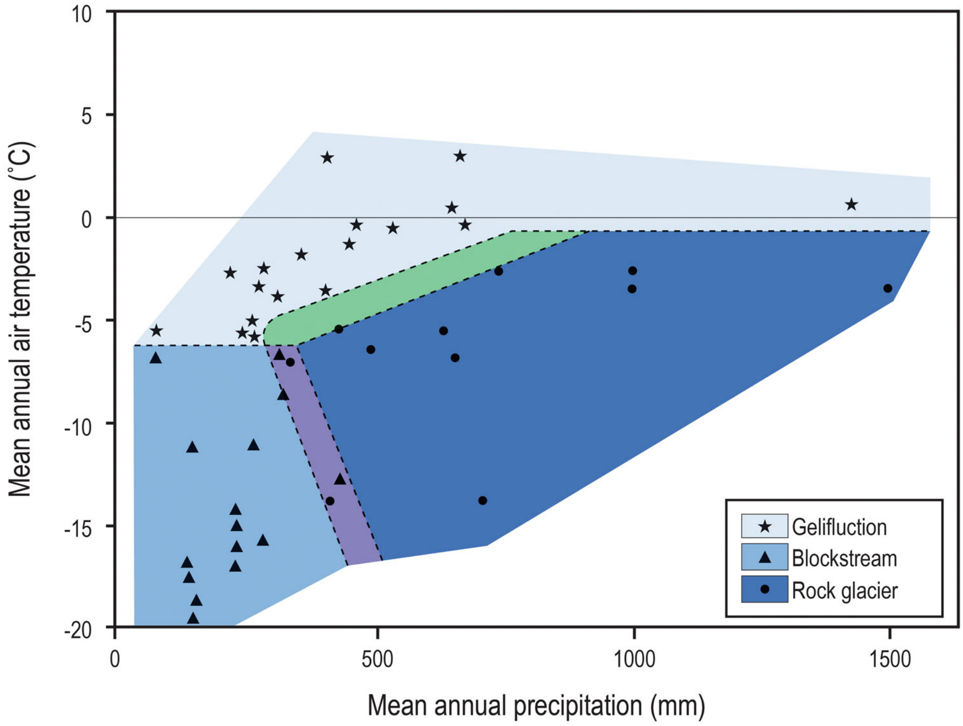

Figure 11. Climatic parameters (mean annual air temperature; mean annual precipitation) for mountain regions dominated by active blockstreams, active rock glaciers and active gelifluction deposits. Green = climatic zone hosting both gelifluction deposits and rock glaciers; purple = climatic zone hosting both blockstreams and rock glaciers (according to and redrafted after Harris, 1994).

specific investigations and under different conditions of moisture availability, demonstrate the difficulty with advocating strict climate-controlling parameters for blockstream formation. French (1996) identified two primary challenges when using blockfields or blockstreams as palaeo-climatic/environmental indicators; namely (i) uncertainty of *when* the landforms were actively forming through time, and (ii) uncertainty about the climate–geomorphic (and hence *process*) context for their development. These remain key questions today but are particularly pertinent given the specific climatic properties of the southern hemisphere. Recent work examining temperature and precipitation changes in the southern hemisphere, into and out of the global LGM, shows that southern hemisphere cooling preceded that of the northern hemisphere from at least 32k a BP, with maximum southern hemisphere cooling by at least 21k a BP (Petherick et al., 2022). Throughout, both decreased and increased moisture availability is recorded across the southern hemisphere, and this probably has implications for block formation and mobility and thus the switching on/off of blockstream movement. Thus, it is probable that, at the large scale, blockstream development in the southern hemisphere had different timings and controls to those in the northern hemisphere. The proximity of Southern Ocean moisture sources, and the importance of ocean-derived weather systems, to all southern hemisphere mountains where blockstreams are recorded, may suggest that moisture availability is the primary control on blockstream activity in the southern hemisphere. Morphological evidence, Schmidt hammer rebound values and cosmogenic dating studies all suggest multiple periods of blockstream activity spanning both late Quaternary warmer and cooler phases (e.g. Bregman and Knight, 2022). Barrows et al. (2004) argued that block deposits in southeast Australia were active before ice advance, rather than in the period of maximum cold during the regional LGM. The relative longevity of southern hemisphere blockstreams compared to those in the northern hemisphere may reflect the higher preservation potential under conditions of glaciation (Wilson et al., 2008). However, the interplay between glacial and periglacial process regimes across a changing landscape has not been examined in detail except Marion Island (Rudolph et al., 2022). More detailed geochronological studies on southern hemisphere blockstreams may be able to clarify these phasing relationships.

As is evident from this review, work on southern hemisphere blockstreams has also proposed variable modes of formation and associated palaeoenvironmental (climatic) conditions. Some strongly argued alternative (to predominantly periglacial) perspectives have also been proposed, which imply that blockstreams may represent landforms that developed over a range of climate types given their long temporal developmental history (e.g. André et al., 2008). When considering the palaeoenvironmental significance of blockstreams, three lines of their formative processes require consideration: (i) the primary weathering/erosional origin of block production; (ii) the mode of debris transport to the blockstream site (for allochthonous blockstreams); and (iii) mechanisms operating within the blockstream for their longer-term morphological evolution, including their possible movement and preservation potential. Each of these mechanistic components are explored in some further detail.

Weathering and material production

Boelhouwers (1999a, p. 20) urged that 'for a correct interpretation of autochthonous blockfield [stream] origin, the local weathering history through time must be considered by means beyond simplistic indicators such as clast angularity'. Sumner and Meiklejohn (2004) subsequently raised the important point of identifying mechanisms of block production (i.e. weathering and dislodgement from underlying bedrock), which may not necessarily be 'periglacial' (i.e. frost-action) in origin and which may pre-date subsequent periglacial activity of block emplacement (including mechanisms of clast uplift, sorting, frost creep, solifluction). Earlier views, based strongly on climatic geomorphology, held that the dominant weathering mechanism in cold environments is mechanical in nature (especially by frost-shattering) (Peltier, 1950). However, several studies have since advocated the importance of chemical (including biochemical) weathering in such environments (e.g. Meiklejohn and Hall, 1997; André, 2003; Whalley et al., 2004; Knight and Grab, 2022). Further, it has been argued that even where freeze–thaw cycles may be operative, these would probably require chemical action to enhance rock disintegration (Whalley et al., 2004). More recent work has demonstrated that rock crack development is in most instances a product of chemical and physical (i.e. chemophysical) weathering in combination (Eppes and Keanini, 2017). Chemical processes may include stress corrosion in silicate minerals (especially quartz) (Eppes and Keanini, 2017) and oxidative dissolution of iron (Fe) along mineral surfaces (Goodfellow and Hilley, 2022). The importance of chemical weathering under relatively warm, humid environments for blockfield and blockstream development in Tasmania was already recognized in the 1960s (Caine, 1968). It is widely supported that a prolonged phase of deep chemical weathering during warmer, humid Tertiary times was an important requirement for regolith production of corestones embedded in finer materials (including clays) (Caine, 1983; Boelhouwers, 1999a, 2004; Colhoun, 2002; André et al., 2008; Ballantyne, 2010; Bregman and Knight, 2022). However, unequivocal evidence confirming (i) specific palaeo-chemical weathering mechanisms during the Tertiary and (ii) that such processes are indeed of such antiquity remain absent.

Angular debris production in cold environments is oftentimes deemed to be a product of freeze–thaw. However, without unequivocal evidence that rock temperature fluctuations and rock moisture conditions were conducive to causing mechanical rock alteration, would constitute a largely 'unsubstantiated qualitative judgement' (Hall, 1995, p. 79). In addition, according to Hall and Thorn (2011, p. 83), 'the whole notion of frost-weathered debris having a specific form is also highly spurious', especially given that angular clasts may be a product of numerous weathering mechanisms (Hall, 1995; Knight and Grab, 2014). To this end, the assumption that many of the openwork block deposits in SE Australia owe their origin to 'frost action' or 'freeze–thaw', and that the deposits are thus 'periglacial' landforms (Slee and Shulmeister, 2015; Barrows et al., 2022), is not yet proven. This then also raises concerns when establishing palaeotemperature reconstructions based on *assumed* past 'freeze–thaw', which in the case of SE Australia implies substantial cooling (10.5°C) (Slee and Shulmeister, 2015). Interestingly, the locational characteristics (including climate) and morphological attributes of openwork blocky screes described by Sumner and de Villiers (2002) from the Amatola Mountains in South Africa, are similar to those from parts of SE Australia described by Slee and Shulmeister (2015). Furthermore, Sumner and de Villiers (2002, p. 600) emphasize the importance of geological and topographic factors influencing a variety of mechanical and chemical weathering types for the production of blockstream source material.

A variety of weathering types are now recognized for cold environments or during past colder periods such as the LGM, including chemical weathering (e.g. Meiklejohn and Hall, 1997), dilatation (e.g. Martel, 2017) and thermal shock (e.g. Hall and André, 2001, 2003). In addition, Knight and Grab (2014) have demonstrated the importance of lightning in high-elevation mid-latitude mountain regions for rapid and substantial bedrock destruction and debris production, most especially along exposed scarp edges, and which produce highly angular shattered debris. Even should freeze–thaw be a proven mechanism, it is unlikely that it (or any other mechanism) would operate in isolation—it then becomes a question of which mechanism(s) were the dominant ones. Therefore, southern hemisphere blockstreams cannot be represented as diagnostic 'periglacial' landforms based on past *assumed* weathering on its own.

Debris transport and deposition for allochthonous blockstreams

There is wide support from work undertaken in the Falkland Islands, southern Africa and SE Australia/Tasmania that weathered products on slopes generally became mobile through a variety of mass-transfer mechanisms through time (especially during late Quaternary cold periods), but with emphasis on mass movements which may include one or more of rockfalls, frost heave and creep, solifluction, surface mud flows, and sliding failure (e.g. Andersson, 1907; Caine, 1983; Boelhouwers et al., 2002; Holness, 2003; Slee and Shulmeister, 2015; Bregman and Knight, 2022). The general predominance of blockstreams on locally coldest topographic positions (e.g. south-facing slopes), and in some cases below other periglacial mass movement phenomena (e.g. stone-banked lobes, smaller 'feeder' blockstreams with lobate fronts), further supports periglacial solifluction as key mass transfer mechanisms to the block accumulation sites. Such periglacial slope processes do not necessarily require permafrost and are currently active in areas of seasonal ground freeze (e.g. Harris et al., 2008; Ballantyne, 2013). In addition, it is also understood that wetter/warmer climates (with snowmelt) are important for boulder-dominated landform development through debris-flow transport mechanisms (Marr et al., 2022), or the washing out of finer interstitial material. Thus, although many of the block accumulations forming southern hemisphere blockstreams may, at least in part, be a consequence of periglacial mass transport and deposition during Quaternary cold phases, permafrost was not a necessity.

Processes operating within blockstreams

It is generally understood that any accumulated surficial debris eventually has its finer matrix material 'washed out' (e.g. Caine, 1983; Boelhouwers, 1999a; Boelhouwers et al., 2002; André et al., 2008), leaving behind large accumulations of blocky material. Work on southern hemisphere blockstreams in the Falkland Islands, Marion Island, southern Africa and Tasmania has documented common blockstream attributes of block imbrication and fabrics aligned parallel to the local slope (e.g. Caine, 1972; Boelhouwers, 1999a; Boelhouwers et al., 2002; Holness, 2003; Bregman and Knight, 2022). This suggests mobility of debris within the blockstream (vertical and lateral), and/or downslope movement of the blockstream as a unit either before or after 'washing out'. Lobate fronts, ridges and furrows have also been reported for apparent blockstreams in SE Australia, for which 'interstitial perennial ice' (i.e. permafrost) has been suggested (McIntosh et al., 2012). Collectively, this would have entailed 'periglacial reworking' during Quaternary cold stages (André et al., 2008). However, the proposed environmental requirements for post-depositional southern hemisphere blockstream activity are varied, with suggestions that deep seasonal freeze was sufficient (Boelhouwers et al., 2002), permafrost *might* have been involved (Holness, 2003) or that the matrix material was washed out under permafrost conditions (André et al., 2008). Elsewhere, it has been demonstrated that large contemporary solifluction landforms, some of which have surface expressions including ridges, furrows and ~3-m-high lobe fronts (and thus similar in geometry to rock glaciers), are products of deep seasonal freeze in non-permafrost areas (Matsuoka et al., 2005;

Table 1. Proposed multi-stage processes for blockstreams and other mountain slope deposits in the southern hemisphere since the Neogene (pre-Quaternary).

Time period	Dominant environmental conditions	Dominant weathering processes and products	Mountain sediment dynamics	Morphological outcomes
Neogene (pre-Quaternary)	Warm and humid	Deep weathering, regolith production with corestones, clay mineral matrix	Development of surface weathering mantle, may be episodic mass movement and downslope sediment accumulation, export of fines though snowmelt or water throughflow	Formation of summit bedrock scarps by mass movement, spalling, rockfall Formation of summit block deposits by weathering
Quaternary	Cool/dry: Deep and long-lasting seasonal freeze (sporadic/alpine permafrost possible in some places)	Diverse weathering processes (dominated by mechanical, cryogenic, thermal stress, wetting/drying, dilatation)	Slope sediment movement by gelifluction and solifluction processes, other cryogenic mass transfer processes may also operate, e.g. sediment sliding Glacier retreat (in some instances), debris deposition; periglacial slope processes Snow melt, debris flows, rockfalls, rock slides	Formation of periglacial slope landforms and deposits: formation and movement of stone-banked lobes, blockstreams Formation of glacigenic slope landforms and deposits: formation and movement blockstreams, rock glaciers
	Warm/wet: Shallow and/or brief seasonal freeze (possibly only diurnal freeze)	Diverse weathering processes (dominated by chemical, biochemical processes)	Removal of fines though snowmelt and other water flow dynamics	Periglacial slope deposits experience decreased activity (reduced rates of movement, decreased footslope sediment yield, stabilisation of the surfaces of stone-banked lobes, blockstreams, rock glaciers
Holocene	Warmer, wetter periods	Diverse weathering processes (dominated by chemical, biochemical processes)	Fluvial action, slopewash, washing out of interstitial materials; stabilisation of the land surface by ecological succession; changes in land surface properties and processes by human activity	Blockstreams and rock glaciers (if/where they may have existed) become inactive
	Short Neoglacial cool/dry periods	Phases of enhanced mechanical weathering (cryogenic, thermal stress, wetting/drying, dilatation processes)	Solifluction, other cryogenic mass transfer processes triggered by climate deterioration	Periglacial slope deposits: Short-term and limited reactivation of slope landforms by solifluction and creep

Matsuoka, 2010). Further, Wilson's (2013) overview on blockstreams supports mechanisms associated with snow melt and deep seasonal freeze. Implications are that even where southern hemisphere blockstreams may at some stage have contained permafrost, this was not a necessity for their internal movement processes.

Conclusions

Southern hemisphere blockstreams, as large (10^1–10^3 m scale), enigmatic landforms, have attracted much research attention in a variety of settings ranging from maritime sub-Antarctic to mid-latitude high-elevation sites. However, they remain less studied and understood than northern hemisphere examples. For the most part, the age of southern hemisphere blockstreams has been difficult to determine, especially given that origins of debris production (weathering) may date back to warmer, humid Tertiary times, and since then, have involved processes of debris movement, accumulation, eventual removal of finer interstitial material and ongoing subsequent internal process dynamics (Table 1). It is thus recognized that blockstreams are products of a variety of processes operating across multiple stages of landform development over long periods of time (pre-Quaternary to present) (Boelhouwers, 1999a; André et al., 2008; Wilson, 2013). Given such a lengthy multi-stage process, blockstreams are thus outcomes of varying climates over time and are not *exclusively* 'periglacial' in domain, as demonstrated in our proposed model (Table 1). In fact, some southern hemisphere blockstreams may have no historical 'periglacial stage' (see Boelhouwers and Sumner, 2003). Blockstreams may therefore be viewed as landforms of equifinality, where similar looking landforms may have developed through dissimilar mechanisms under different climatic regimes (Harris, 2016). Consequently, 'the parameters that governed block stream development in one location are unlikely to have been identical to those that operated elsewhere' (Wilson, 2013, p. 521). In summary, southern hemisphere blockstreams cannot thus be used to indicate a specific past climate, unless it is possible to *conclusively* demonstrate distinct processes during specified past temporal frameworks. Nonetheless, it would seem, based on our review of work from respective southern hemisphere regions, that at least the majority of blockstreams owe a considerable portion of their origins, evolution and activity to periglacial (cryogenic) processes within contexts of weathering (debris origins) and sediment mobilization (mass sediment transfer, deposition and erosion). This would have been most strongly the case during colder late Quaternary times (Table 1).

Future research directions for block landforms in southern hemisphere mountains may include: (i) their relationships to upslope and plateau blockfields; (ii) the relative role of warmer pre-Quaternary weathering versus cooler Quaternary weathering in block formation; (iii) the environment of initial blockstream formation; (iv) the rates and processes of block movement within blockstreams, including differential movement giving rise to changes in the blockstream form; and (v) the role of permafrost or seasonally active frost heave—if any—in blockstream dynamics. Addressing these research questions may be challenging but could be informed through: (i) grain size analyses (clay/silt ratios) of sediment beneath openwork block deposits to establish chemical weathering intensity, clay geochemistry and chemical index of alteration (CIA) ratios (e.g. Goodfellow, 2012; Goodfellow et al., 2014; Andersen et al., 2018); (ii) greater engagement with rock mechanics/structural geology to develop mechanics of rock cracking for application if establishing surface exposure durations; (iii) assessing the influence of topographic stress controls on bedrock fracture dynamics and block development (e.g. Moon et al., 2020; Li and Moon, 2021); (iv) numerical and/or chemophysical modelling of weathering and subcritical cracking processes in block production; and (v) applying techniques such as electrical resistivity tomography (ERT) and structure from motion (SfM) photogrammetry to better understand the internal and surface structures of blockstreams (e.g. Stan and Stan-Kłeczek, 2014).

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Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Abbreviations. a, years; Be, Beryllium; BP, Before Present; C, Carbon; Cl, Chlorine; K, thousand; LGM, Last Glacial Maximum; Ma, million; MAAT, Mean Annual Air Temperature; m asl, meters above sea level; OSL, Optically Stimulated Luminescence; yrs, years.

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