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Rock glaciers in the Jutulsessen, Dronning Maud Land, East Antarctica

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Abstract: Rock glaciers are lobate or tongue-shaped landforms which consist of rock debris and have either an ice core or an ice-cemented matrix. Characteristics such as the landscape setting, morphology, material and current geomorphological state are universally used to classify rock glaciers. In Antarctica, rock glaciers have only been surveyed on the Antarctic Peninsula, Ellsworth Mountains and in Victoria Land. This paper presents the first data on the identification and description of rock glaciers in the Jutulsessen nunataks, Dronning Maud Land, East Antarctica. The rock glaciers in the Jutulsessen exhibit a variety of morphologies and states. Our data suggests that the rock glaciers in Brugdedalen and Jutuldalen are active, while the features at Vassdalen and Grjotlia are considered inactive, and a feature at Grjotøyra is considered relict. The described rock glaciers do not fit into existing classification systems and appear to be different to alpine, Arctic and Andean rock glaciers. They further present examples that fit both the 'glaciogenic' and 'permafrost' development theories.

Key words: East Antarctica, Jutulsessen, rock glacier, permafrost, climate change.

Introduction

The term "rock glacier", coined by Capps (1910), is described by Giardino *et al*. (2011) as "a lobate or tongue-shaped landform consisting of rock debris and either an ice core or an ice-cemented matrix". Characteristics such as (i) topographic setting (valley-floor, valley-side) (Outcalt and Benedict 1965), (ii) morphology (tongue shaped, lobate or spatulate) (Wahrhaftig and Cox

1959), (iii) sediment texture (pebbly or bouldery) (Ikeda and Matsuoka 2006), (iv) genetic: (ice-cemented/permafrost or ice-cored/glaciogenic) (Potter 1972; Haeberli 1985; Whalley and Martin 1992; Barsch 1996) and (v) movement rates (active, inactive, relict) (Barsch and King 1975) are commonly recorded to classify rock glaciers. Although there have been efforts to standardise classification, no consensus has been reached; see Martin and Whalley (1987) and Janke *et al*. (2013). In addition, rock glacier origin and development are still contested topic (see Clark *et al*. 1998), but are often referred to as either 'glaciogenic' (*e.g*. Dzierzek and Nitychoruk 1987; Potter *et al*. 1998), 'cryogenic' (permafrost-related) (*e.g*. Barsch 1992), or a combination of both (*e.g*. Whalley 2009).

Increased use of remotely sensed imagery has improved the efficiency of developing rock glacier inventories (Kääb 2005). Individual rock glaciers can be identified from high-resolution satellite imagery and surveyed in detail with minimal need for fieldwork (*e.g*. Trombotto Liaudat *et al*. 2012; Falaschi *et al*. 2014). Classification is then based on field observations which focus on rock glacier surface characteristics that can successfully distinguish a rock glacier from stable talus on mountain slopes (Burger *et al*. 1999). Other than mere identification, surface characteristics are helpful indicators of rock glaciers' activity and internal composition. For example, active rock glaciers can be identified through a typically narrow concave upper zone with loose material, especially where there are high rates of debris input, leading into a broad convex body and steep front toe (Kääb 2007; Janke *et al*. 2013). Conversely, inactive rock glaciers usually have coarser debris surfaces at the head and concave lower profiles with obvious drainage pathways (furrows) and thermokarst, due to the melt-out of interstitial ice or ice-core and subsequent removal of fines (Humlum 1982; Kääb 2007). Morphological observations during field surveys are also used to infer the internal structure of rock glaciers and protalus lobes. For example, field observations of a spoon-shaped depression at the head, filled with snow, ice or debris, can indicate a body of buried glacial and/or interstitial ice (White 1981). Similarly, furrows, transverse ridges or patterned ground could be an indication of an active-layer covering an ice core, or permafrost within a rock glacier (Chinn and Dillon 1987; Serrano and López-Martínez 2000; Haeberli *et al*. 2006; Kääb 2007; Guglielmin *et al*. 2018). Vegetation cover, rock hardness of clast surfaces and radionuclides (^{137}Cs) in sediment are useful measures to determine rock glacier relative or absolute age and movement rates (Sumner *et al*. 2002; Haeberli *et al*. 2003).

Temperature and moisture conditions (aridity) are commonly considered to be strong influences on rock glacier development, and are therefore, useful to assess climate change (Hassinger and Mayewski 1983; Barsch 1988). Consequently, rock glaciers can be used as proxy indicators of climate change (Humlum 1998; Frauenfelder and Kääb 2000) and have been documented globally in a range of climates and geological settings (see Janke *et al*. 2013). However, apart from geomorphological surveys on the Antarctic Peninsula (Strelin and Sone 1998; Serrano and López-Matrínez 2000; Fukui *et al*. 2008), in the Ellsworth Mountains (Vieira *et al*. 2012), and in Victoria Land (Hassinger and Mayewski 1983; Rignot *et al*. 2002; Swanger *et al*. 2010; Guglielmin *et al*. 2018), no other rock glaciers have been documented on the Antarctic continent.

The aim of this study was to identify and provide field descriptions of rock glaciers in the Jutulsessen, Dronning Maud Land. This information provides a baseline for determining climate change responses in continental East Antarctica. Since contemporary permafrost decay, through climate warming, may result in the loss of palaeo-climatic records captured within rock glaciers (Kennicutt *et al*. 2015), it is imperative that their existence and current state are documented. Furthermore, improved knowledge of climatic and dynamic controls on rock glaciers can improve our understanding of their distribution, rheology and origin (Haeberli *et al*. 2006; Kääb 2007; Janke *et al*. 2013).

Study area

The study area is located in Dronning Maud Land, Antarctica, 200 km south of the Fimbul Ice Shelf (Fig. 1). A number of rock glaciers were identified on the Jutulsessen nunataks in the Gjelsvik Mountains of Fimbulheimen, in the vicinity of the Norwegian Research Station, Troll (72°01’S, 02°32’E; 1290 m a.s.l.). The north western edge of the nunataks is bordered by lower lying ice-flats: Grjotlia and Sætet (Dallmann *et al*. 1990). Glacial cirques of various sizes are particularly evident in the region and slopes are covered with till, scree material, or ice from different origins. Underlying bedrock comprises metamorphic-igneous units with a series of dyke intrusions. Rocks vary from felsic to migmatitic gneiss, and are medium to coarse grained (Dallmann *et al*. 1990). Permafrost thickness is approximately 650 m for the exposed ice and snow-free areas of these portions of Dronning Maud Land (Hansen and Meiklejohn in prep.). The annual ground freezing index approaches 6000, reflecting the annual frost environment. Sorted patterned ground, indicating an active layer, is only found at isolated locations in the region. In comparison, landforms such as thermal-contraction-crack polygons, associated with permafrost, are common. The mean annual air and ground temperatures are -17.7°C and -17.3°C respectively (Hansen and Meiklejohn in prep.), and the maximum active-layer depth near Troll Station is 38 cm (Kotzé 2015). No local precipitation data are available, but glacier-ice-cores suggest an average snow accumulation of <100 mm/y over the last 50 years (Monaghan *et al*. 2006).

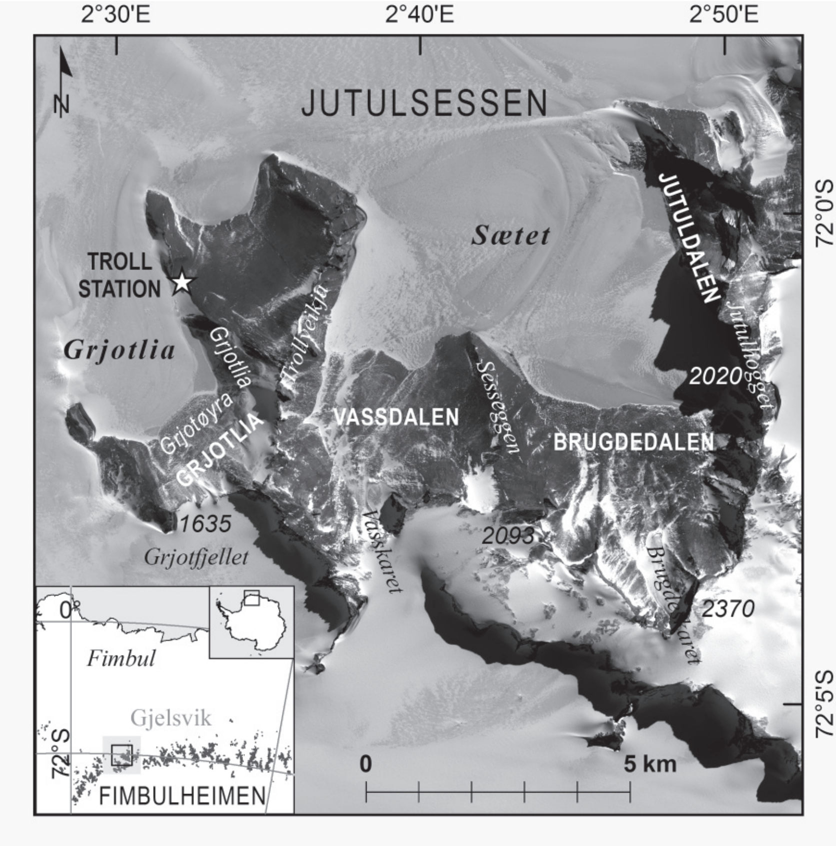

Fig. 1. The location of the study area within the Jutulsessen, Dronning Maud Land, East Antarctica. Satellite imagery: GeoEye Digital Globe Foundation.

Methods

Rock glaciers were initially identified and surface features mapped from orthorectified high-resolution GeoEye I satellite imagery. The imagery, obtained from the GeoEye Foundation, is from 2009 with a resolution of 0.61 m and 2.4 m for the panchromatic and multispectral imagery, respectively. The topographic setting, morphology (shape and surface topography) and material characteristics (clast and sediment) of five rock glaciers were determined: two within the Grjotlia cirque (Grjotlia and Grjotøyra) and one each in Vassdalen, Brugdedalen and Jutuldalen (Fig. 2). Field surveys and verification took place during the 2013/14 and 2014/15 Austral summers. Two of the features, Grjotøyra and Vassdalen were mapped using handheld GPSs (Garmin® GPSMap 62Csx) with a<10 m horizontal accuracy and ±3 m vertical accuracy. A digital elevation model (DEM) of both Grjotøyra and Vassdalen was generated using the inverse distance

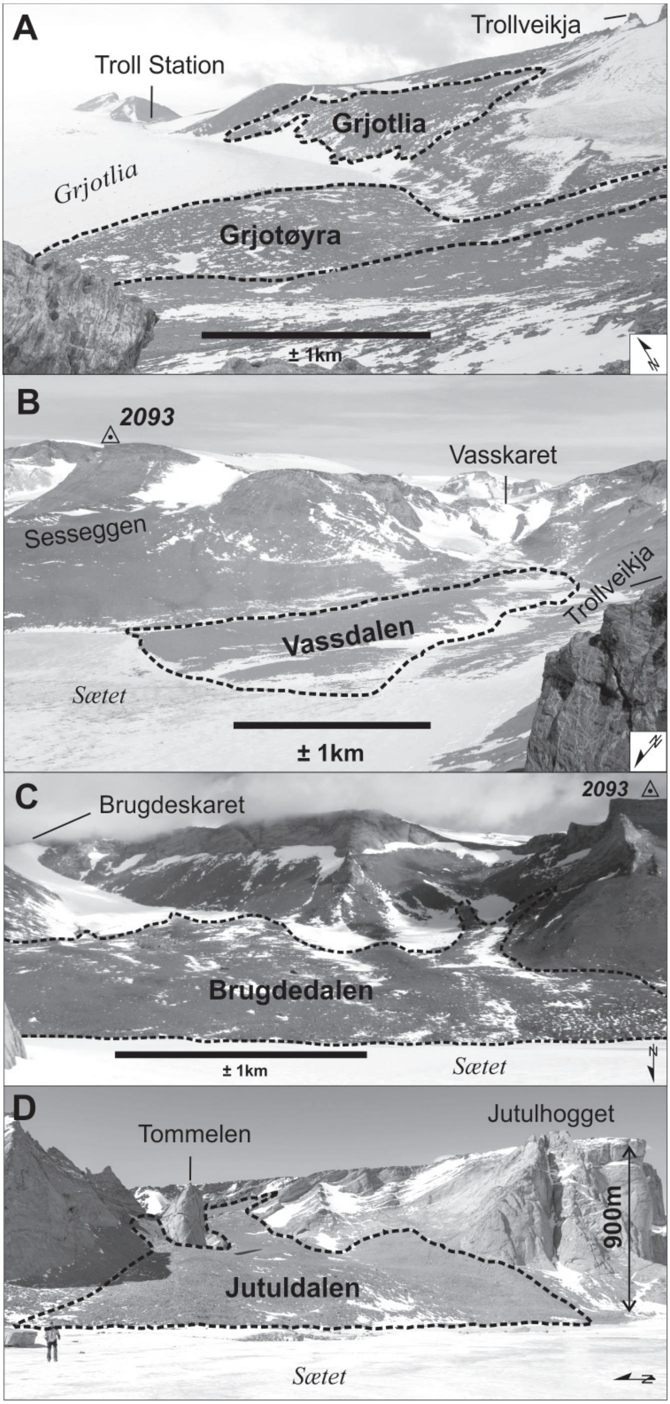

Fig. 2. The location of the rock glaciers within their respective cirques: (**A**) Grjotlia and Grjotøyra, (**B**) Vassdalen, (**C**) Brugdedalen and (**D**) Jutuldalen. *Photo A&D: J. Näränen.*

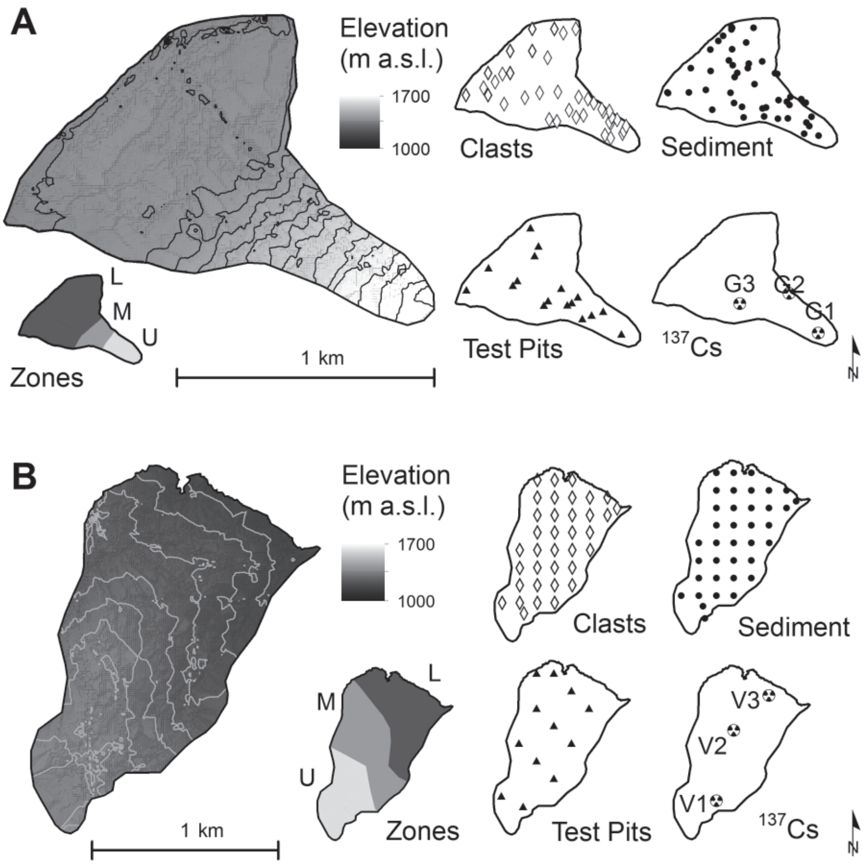

Fig. 3. The distribution of various sampling points on Grjotøyra (**A**) and Vassdalen (**B**), and the interpolated elevation used to delineate altitudinal zones.

weighting tool in ArcMap™ 10.3 (10 × 10 m cell size). The DEM was used to delimitate the rock glaciers into three altitudinal zones: upper, middle and lower, based on observational topographical change, to match head, body or toe structures as defined in literature (Kääb 2007; Janke *et al*. 2013) (see Fig. 3).

Substrate samples were collected from Grjotøyra and Vassdalen rock glaciers for comparative purposes. The Grjotøyra rock glacier was sampled using stratified-random sampling and systematic sampling took place in 200 m^2 grids on Vassdalen (Fig. 3). Sample points for Grjotøyra and Vassdalen are reported as n_g and n_v respectively.

To investigate sediment texture and movement, samples were collected for particle size analysis (n_g=49; n_v=39) (after Briggs 1977) and ^{137}Cs count ($n_{g\&v}$=3) (after Godoy *et al*. 1998). Fallout radionuclides, such as ^{137}Cs, are used as tracers to determine sediment transport and deposition rates since peak fallout 50–60 years ago (Zapata 2003). The rate of geomorphic processes can be determined by the concentration and distribution of ^{137}Cs within a landscape profile. For example, the spatial distribution of ^{137}Cs concentrations can be used to indicate the rate of large scale processes, such as erosion and slope movement (Gaspar *et al*. 2013), as well as sediment movement related to cryoturbation and active-layer process (Lacelle and Vasil'chuk 2013). Concentrations of ^{137}Cs were measured by an ORTEC® gamma ray spectrometer and normalised to the specific surface area of particles within the <63 μm fraction. Specific surface area laser granulometry was determined with a Malvern Mastersizer3000 after Blott *et al*. (2004).

Rock hardness values of surface clasts were recorded for relative age-dating determination similar to the investigations done by Haeberli *et al*. (2003). Three surface clasts with an a-axis larger than 0.3 m were selected at each sampling point (n_g=114; n_v=108) (Fig. 3). A Proceq Equotip® was used to obtain 15 single impact readings, from which the mean value was used as representative rock hardness for each clast, following Sumner and Nel (2002) and Aoki and Matsukura (2007). In addition, test pits were dug (n_g=17; n_v=12) to determine the depth of frozen ground, using the presence of ice as an identifier.

Results

A summary of the rock glaciers' dimensions and other significant observations are presented in Table 1, while the geomorphological map derived from field observations is presented in Fig. 4. The geomorphological map presented here supplements the geomorphological map (Fig. 2) of Dallmann *et al*. (1990).

Table 1

The rock glaciers' size, shape and other significant observations.

Feature	Length (m)	Width (m)		Toe Slope	Shape	Texture	Location			Status
		Head	Toe				Cirque	Talus	Valley	
Grjotlia	200	–	900	n.a.	Lobate	n.d.	in	–	wall	Inactive
Grjotøyra	1500	200	1200	8°	Spatulate	Pebbly	in	base	wall	Relict
Vassdalen	1800	300	100	n.a.	Tongue	Pebbly	below	base	floor	Inactive
Brugdedalen	2700	200 & 400	1900	10°	?	Bouldery	in	–	–	Active
Jutuldalen	900	170 & 300	1700	20°	?	Bouldery	in	–	–	Active

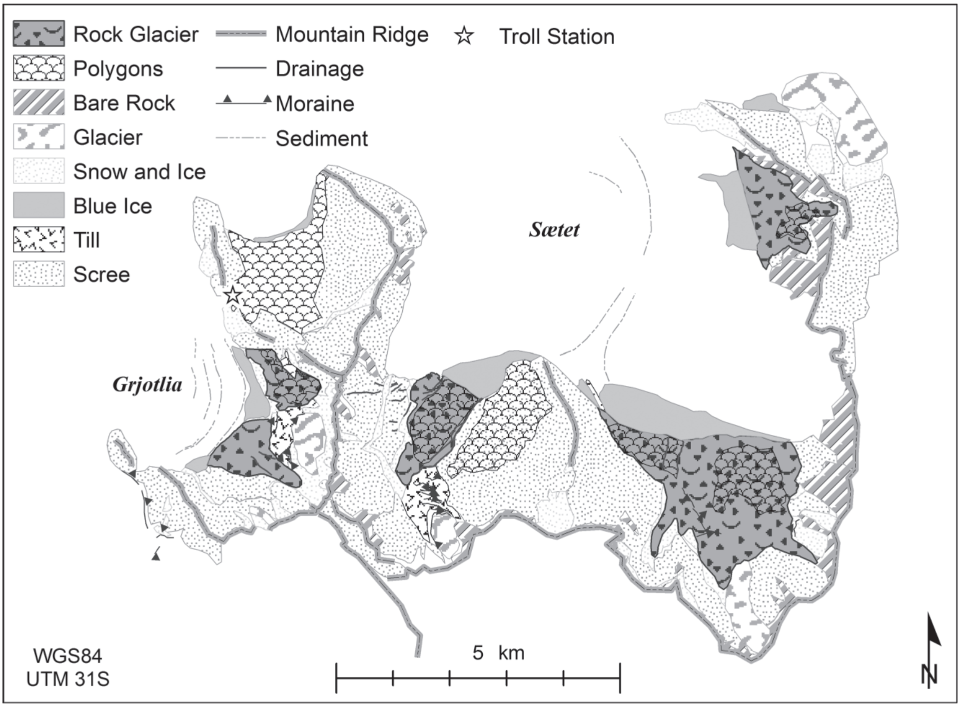

Fig. 4. A geomorphological map of the Jutulsessen nunataks, Dronning Maud Land, Antarctica.

The Grjotlia cirque contains two rock glaciers: the first, Grjotlia, is located below the eastern cirque wall; and the second, Grjotøyra, extends over the Grjotlia ice-flat. Grjotøyra was previously described as an "ablation moraine" (Dallmann *et al*. 1990) or "a feature of indeterminate type" (Stewart 2011), but is now considered the 'toe' of the rock glacier. The slope of the Grjotlia rock glacier is convex and thermal-contraction-crack polygons can be found on its upper reaches. The occurrence of polygons dissipates in a down-slope direction as the slope gradient increases, and the lower parts border a steep snow bank as the slope merges with the Grjotlia ice-flat. The slope's surface is permanently frozen (Goodwin 2014, personal communication).

The head of the Grjotøyra rock glacier emerges from a spoon-shaped depression where snow accumulates, and it is disconnected from the headwall, which may represent a former outlet glacier. A cirque glacier is located at the eastern edge of the rock glacier head, and a talus slope lies to the west. The rock glacier head extends into a steeper, narrow convex middle portion that slopes down to a fan-shaped toe. Drainage pathways are visible along the middle and upper zone, where surface water was occasionally observed during field surveys. The lower extent of the feature is undulating with ridges of ±5 m elevation change. These 'ridges' have no preferred orientation, but usually surround water ponds of varying sizes, visually typical of the topography associated with melt-out till (Evans *et al*. 2006), and potentially indicating a past presence of glacial ice. Some of the ponds were observed to be frozen, resembling lake ice blisters (see Guglielmin *et al*. 2009), while others had liquid water during Austral summers, and exhibit exposed beaches of fine sediment. From a terminal crest, the toe of the rock glacier slopes down over a distance of 70 m at an 8° gradient to meet the Grjotlia ice-flat.

The Vassdalen rock glacier is located along the length of a valley floor in a NNE direction, meeting the Sætet ice-flat below. Its upper reaches adjoin till deposits to the south and a frozen pond to the west. The middle and lower zones have transverse ridges and furrows on the surface. Snow covered depressions on either side of the rock glacier separate it from the valley walls, and although liquid water was not observed, drainage lines are visible. Beyond the lower end of the landform towards the western valley wall, sediment mounds with a circumference of *ca*. 3 m protrude by *ca*. 1.2 m from the ice and excavation revealed ice cement at a depth of *ca*. 0.1 m (Hansen *et al*. 2016). Thermal-contraction-crack polygons were observed across the extent of the landform. The density of these polygons decreases towards the head and toe, with the best-defined features found in the middle zone; similar to those documented by French and Guglielmin (2000) in Victoria Land, Antarctica.

The rock glaciers documented at Jutuldalen and Brugdedalen are similar in morphology: both rock glaciers are located in cirques, surrounded by cliffs, have multiple head sources and their toes form steep banks of material that exhibit a series of prominent bulging ridges and undulating surface topography. Both terminate with a linear-concave edge against the Sætet ice-flat. The key difference in topographic setting between these rock glaciers is that a glacier is located at the head of north-facing Brugdedalen, whereas west-facing Jutuldalen has no glacier feeding into the valley. In addition, on Brugdedalen, dark discoloration of clasts and snow-filled depressions in the lower zones provide evidence of drainage pathways. Similar drainage features are conspicuously absent in the Jutuldalen cirque. Jutuldalen is much smaller and steeper and the debris is perceived to be more unstable and unconsolidated than at Brugdedalen.

Substrate analyses from Grjotøyra and Vassdalen indicate that the sediment from both rock glaciers is poorly to very poorly sorted and the largest proportion of particles fall within 500–250 μm (1–2 phi) sizes with no significant change ($p>0.4$) between altitudinal zones. The measured ^{137}Cs concentrations were higher in the uppermost samples of both Grjotøyra and Vassdalen, whereas the lower samples had no detectable ^{137}Cs (Table 2). Rock hardness decreases significantly with an increase in elevation ($p<0.05$). This trend, although not strong ($r<-0.2$), is consistent on both Grjotøyra and Vassdalen. Further, rocks on Grjotøyra averaged 200 L-hardness values lower than on Vassdalen (Table 3). The depth of frozen ground was more varied on Grjotøyra than Vassdalen, with both maximum (0.43 m) and minimum (0.09 m) depths recorded in Grjotøyra's lower zone (Fig. 5). On Vassdalen, the average depth of the frozen substrate increased with a decrease in altitude. Although sparsely distributed, lichens were observed across the extent of Grjotøyra and Vassdalen.

Table 2

The ^{137}Cs concentrations from Grjotøyra and Vassdalen show higher concentrations in the upper altitudinal zones (U) compared to the middle (M) and lower zones (L). Results were normalised to specific surface area (SSA) of <63 µm sediment fraction.

Feature	Zone	ID	Lat.	Long.	Detected ^{137}Cs (mBq/g)	SSA	Normalised ^{137}Cs (mBq/g)	Error
Grjotøyra	U	G1	-72.0405	2.5647	0.85294	115.2843	0.0074	0.0035
	M	G2	-72.0373	2.5572	0.99555	188.4476	0.0053	0.0016
	L	G3	-72.0380	2.5442	0.00000	224.7621	0	0
Vassdalen	U	V1	-72.0373	2.6316	0.25379	326.0898	0.0008	0.0009
	M	V2	-72.0302	2.6375	0.00000	245.5297	0	0
	L	V3	-72.0266	2.6492	0.00000	165.2231	0	0

Table 3

Rock hardness of clasts decreases significantly with an increase in elevation ($p<0.05$) and were on average 200 L lower on Grjotøyra than on Vassdalen. U stands for the upper altitudinal zones, M for the middle and L for lower zones.

Feature	Zone	n	Mean	Min.	Max.	Std. Dev.
Grjotøyra	U	36	621	385	812	136
	M	24	652	407	838	114
	L	54	685	411	861	110
Vassdalen	U	30	796	669	875	52
	M	36	819	720	915	48
	L	42	822	696	904	44

Discussion

The movement rates of the documented rock glaciers were not determined and, thus, no direct conclusions can be drawn on whether the current geomorphological state of these features are 'active' (*i.e.* moving), 'inactive' (*i.e.* stagnant, but ice-core or ice lenses remain) or 'relict' (interstitial ice has melted out),

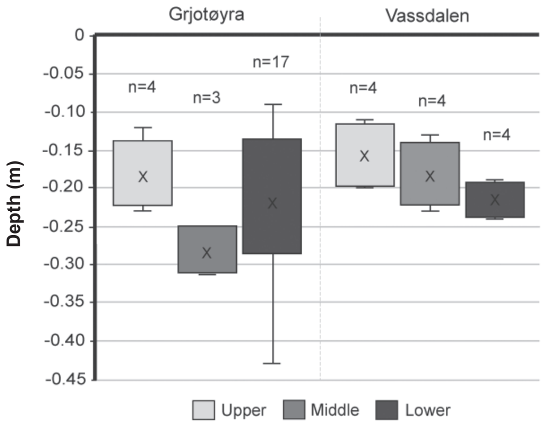

Fig. 5. The mean (x) depth of frozen ground at test pits from the respective zones on Grjotøyra and Vassdalen. Depths were more varied on Grjotøyra than on Vassdalen.

when compared to rock glaciers documented elsewhere (Janke *et al*. 2013). Nevertheless, the observed morphology and substrate characteristics allow for a description of relative state of the rock glaciers on the Jutulsessen nunataks.

Grjotlia. — Grjotlia's overall morphology does not resemble either a snow avalanche deposit (Haeberli 1985), nor a pronival rampart (Hedding *et al*. 2010). Instead, it is considered a lobate valley-wall rock glacier or protalus lobe. Since the presence of thermal-contraction-crack polygons indicate a permafrost environment, slow permafrost creep may be responsible for the movement of material (Haeberli 1985). However, in light of the recent findings of Guglielmin *et al*. (2018), creep of buried glacial ice should also be investigated.

Grjotøyra. — The spoon-shaped ablation depression at the head of Grjotøyra, along with the upper and middle zones' convex shape, mimics that of a rock glacier with a glacial ice-core (Potter *et al*. 1998; Guglielmin *et al*. 2018). The morphology of the upper and middle zones suggest that the Grjotøyra rock glacier is 'active' (Haeberli 1985; Kääb 2007), however, sediment and clast analyses suggest a more 'inactive' upper zone. Moreover, the lower zone's morphology matches that of melt-out till (Evans *et al*. 2006; Fukui *et al*. 2008), or of a 'relict' rock glacier with evidence of a past ice-core (Ikeda and Matsuoka 2002; Kääb 2007). Ice blisters, exposed beaches, and undulating 'ablated' surface suggests the possibility of thaw and drainage of interstitial ice, but also hints at the possibility of liquid water existing underneath the surface (Chinn and Dillon 1987; French and Guglielmin 2000; Haeberli *et al*. 2006; Kääb 2007), or the previous presence of glacial ice. The middle convex body may have a glacial ice-core which extends from the depression at its head. Guglielmin *et al*. (2018) also ascribed a glacial origin of an Antarctic rock glacier with a similar geographical setting. A shallow permafrost table observed in test pits gradually deepens with a decrease in altitude. The toe is interpreted to be a mixed matrix of ice and sediment with an active-layer of varied thickness. The shape of the feature is typical of a spatulate rock glacier (*e.g*. Wahrhaftig and Cox 1959).

Vassdalen. — The surface morphology of Vassdalen suggests compressional movement (Haeberli 1985). However, a steep ridging toe of sorted material, which is often associated with active rock glaciers (Wahrhaftig and Cox 1959; Humlum 1982), is absent. Nevertheless, the occurrence of thermal-contraction-crack polygons confirms the presence of a permafrost environment. Due to the absence of evidence of extreme melt, this rock glacier is argued to be an 'inactive' tongue-shaped rock glacier. Additionally, the surface drainage lines could reflect subsurface hydrology (Whalley and Martin 1986), and be indicative of a remnant glacial ice core which has been preserved in a permafrost environment.

Brugdedalen and Jutuldalen. — Dark discoloration observed on clasts at Brugdedalen are believed to represent precipitates from drainage pathways. Since snowfall and melt is limited in the lower zone, this observation suggests the presence of interstitial ice at higher elevations, or subsurface drainage and resurfacing of glacial melt water, or warmer past climates where melting of ice resulted in significant surficial drainage. The rock glaciers here partly fit Corte's (1987) and Parson's (1987) 'complex', or 'transitional' rock glacier classification. However, the linear, instead of tongue-shaped, toe and the steep angle of repose do not fit these models. Nevertheless, these rock glaciers are suggested to be 'active' due to their steep, unstable surfaces.

Synthesis. — Classifiers commonly used for Arctic, alpine or Andean rock glaciers do not comfortably apply to the Jutulsessen rock glaciers documented above. Using climatic parameters and movement rates from published research findings (*e.g*. Janke *et al*. 2013), all of the features investigated should be classified 'inactive' or 'relict'. However, according to morphology and hydrological observations a dual classification could be assigned to some, as they occasionally exhibit characteristics of both 'active' and 'inactive' features. For example, the Grjotøyra rock glacier appears to be the 'relict' of the documented features, yet it is the only landform with convincing evidence of a glacial ice-core as it appears to occupy a former outlet glacier valley. Similar to the suggestion by Guglielmin *et al*. (2018), the extreme aridity, together with the relatively colder Antarctic continent, may result in rock glacier forms and processes that are different to those in other environments. Cognisance of such observations is important if researchers are to correctly interpret the often-subtle differences in landforms and associated processes in continental Antarctica. For example, Guglielmin *et al*. (2018) have, using different geophysical investigations and borehole stratigraphy, reinterpreted the origin of two rock glaciers in Victoria Land, Antarctica from 'cryogenic' (permafrost creep) to 'glaciogenic'. A better understanding of the climatic history and deglaciation sequence of the Jutulsessen nunataks may shed light on the climatic controls and development of these rock glaciers. Future research using absolute dating techniques, *e.g.* cosmogenic nuclides, will shed light on these timelines and geophysical surveys will elucidate the various characteristics of internal composition. Such studies would be significant because ice, of different origin, preserved under and within these rock glaciers holds valuable records of the climatic controls of landscape development (Frauenfelder and Kääb 2000; Rignot *et al*. 2002; Kennicut *et al*. 2015; Guglielmin *et al*. 2018).

Conclusions

The rock glaciers in the Jutulsessen nunataks are the first to be documented from Dronning Maud Land and amongst only a few identified in continental Antarctica. A variety of morphological forms and geomorphological states were recorded. While considerable difficulty exists in determining the activity of these forms, our observations are that the rock glaciers at Brugdedalen and Jutuldalen are active, Vassdalen (tongue-shaped) and Grjotlia (lobate) are considered to be the less active, and Grjotøyra (spatulate) is viewed as being relict. The rock glaciers in the Jutulsessen, which represent examples of both 'glaciogenic' and 'permafrost' development, do not fit existing classifications and clearly differ from Arctic, alpine, and Andean forms. The geomorphological map presented provide a valuable baseline for further investigations into Antarctic rock glacier development, palaeo-climatic reconstructions, and to monitor the future impacts of climate change.

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