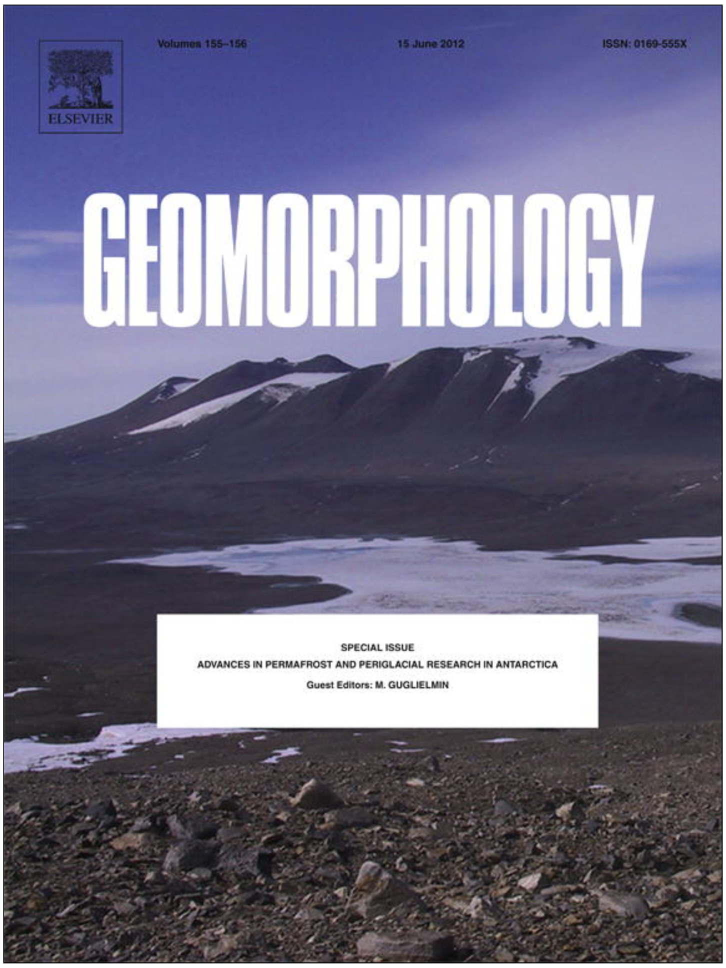
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Periglacial features in Patriot Hills, Ellsworth Mountains, Antarctica

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ABSTRACT

This work describes periglacial features identified at Patriot Hills, at the southernmost part of Ellsworth Mountains, Antarctica, during the 2008/2009 Brazilian Antarctic Expedition, and discusses their morphogenetic environment. Identified periglacial features were classified into: (a) rock glacier-like landform; (b) slightly creeping debris-mantled slopes; (c) steep debris-mantled slopes; and (d) rock falls. Results obtained from sediment sample analysis suggest activity and passive movement of a rock glacier-like landform, albeit minimal. Wind seems to play an important role in Patriot Hills local geomorphology. Periglacial features such as slightly creeping debris-mantled slope appear to have preferred slope orientation. They are commonly found onto slopes where the katabatic wind flows down. Slopewash and groundwater movement processes may be limited or non-existent since most snow disappears through sublimation

1. Introduction

Ground-ice is common in Antarctica, especially in the form of rock glacier (Bockheim and Hall, 2002). Rock glaciers have been identified in some areas of the coast and in subantarctic islands (Mayewski, 1979; Mayewski and Hassinger, 1980; Hassinger and Mayewski, 1983; Serrano and López-Martínez, 2000; Fukui et al., 2008), in the Transantarctic Mountains (Bockheim, 1995) and in some sectors of the McMurdo Dry Valleys (Rignot et al., 2002; McLeod et al., 2008; Shean and Marchant, 2010).

Although geological and geomorphological studies have been developed at Ellsworth Mountains, such studies in relation to identification and classification of rock glaciers and other periglacial features are rare.

The purpose of this paper is to describe periglacial landforms identified at Patriot Hills, located at the southernmost part of Ellsworth Mountains, and to discuss their morphogenetic environment. This work is based on satellite image interpretation and ground truth (measurements and sediment sample collection), carried out during the 2008/2009 Brazilian Antarctic Expedition.

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2. Regional setting

Patriot Hills are located at the southernmost end of the Ellsworth Mountains, at 80°18′ S/81°22′ W–80°30′S / 81°35′W, 50 km inland from the Ronne Ice Shelf grounding line (Jouguin and Bamber, 2005). Several BIAS (blue ice areas) have been identified on the leeward areas of the mountains (Swithinbank, 1987; Fogwill et al., 2011). They constitute a small mountain range approximately 8.5 km long, with extensive rock outcrops, especially on their northern flank, and the highest summit (1246 m) protruding about 400 m above the surrounding ice sheet (USGS, 1966). Patriot Hills comprise seven deglaciated valleys and two ice-filled valleys. The rocks consist predominantly of Cambrian limestone and recrystallized carbonate (Spörli and Craddock, 1992), which are folded about a NWW-SSE trending, sub-horizontal axis (Curtis and Lomas, 1999). Conglomerates underlie the limestone (Spörli and Craddock, 1992).

Patriot Hills is a very windy area with the presence of blue ice areas indicating the strength and persistence of the surface winds (Casassa et al., 2004). In addition, dry southerly katabatic winds can gust up to >30 m s^{-1} (Carrasco et al., 2000) and 50 m s^{-1}, but more generally blow at a steady 5–8 m s^{-1} (Turner and Pendlebury, 2008). Occasional frontal systems or rarely mesoscale cyclones can penetrate far into the Antarctic continent.

The mean annual temperature of the region was estimated to be −28 °C on the basis of a 10 m borehole at Patriot Hills, made between July 1989 and March 1990 (Dahe et al., 1994). Based on record from Teniente Parodi Station, during the summer season temperatures are around −15 °C (Turner and Pendlebury, 2008).

Mass balance surveys at Patriot Hills and Horseshoe Valley performed during 1995–1997 have shown that the ice sheet in the region is in near steady state (Casassa et al., 1998, 2004). Comparison GPS surveys in 2004/2005 and 2006 reveal a slight but significant ice elevation increase (Wendt et al., 2009).

Rutford (1972) and Rutford et al. (1980) divide the glacial history of the study area into two major phases: the first, corresponding to the valley glaciation, possibly initiated in the Upper Mesozoic and Lower Cenozoic, when the Ellsworth Mountains formed an archipelago or an island. The second phase involved the continental glaciation that covered the whole area, leaving only the higher peaks exposed as nunataks. Subsequently, the region has undergone partial deglaciation with the decrease in the ice sheet level.

Studies on the glacial history of Ellsworth Mountains indicate that the ice sheet previously reached much higher altitudes than today. Craddock et al. (1964) estimated an ancient ice sheet surface between 300 and 500 m above the present surface. Denton et al. (1991), with an ice sheet model constrained by the evidence from Ellsworth Mountains and other areas, suggest that ice sheet domes in West Antarctica were 450 to 600 m higher during the last glacial maximum (LGM). More recent studies (Todd and Stone, 2004; Bentley et al., 2010) show that the During the Last Glacial Maximum the ice cover was at least 430 m thicker, and that the West Antarctica Ice Sheet in the Ellsworth Mountains region has decreased its thickness up to 480 m in the past 15 ky.

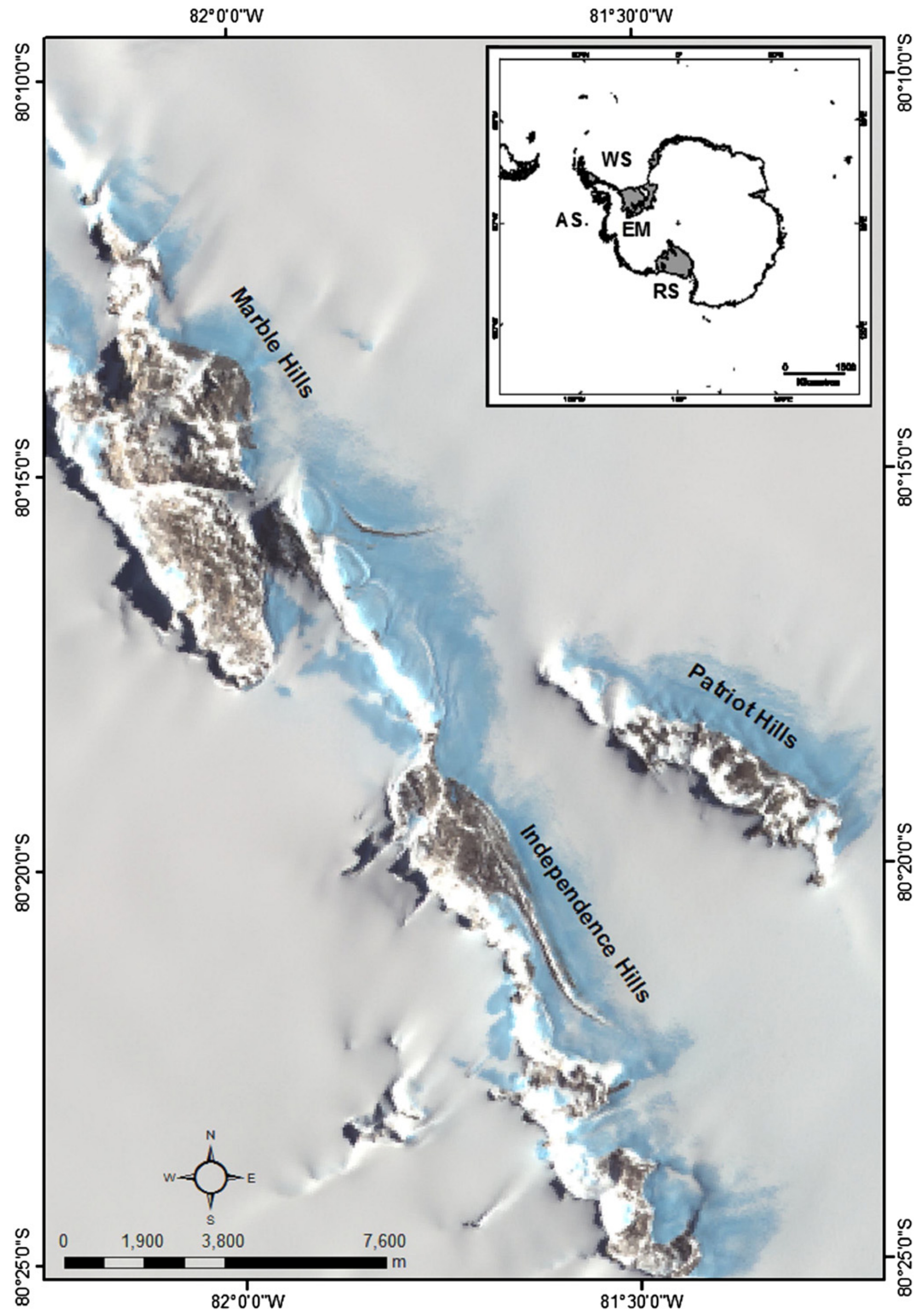

Fig. 1. Location map of the Patriot Hills area based on images from ASTER: EM—Ellswort Mountains, WS—Weddell Sea, AS—Amundsen Sea, RS—Ross Sea.

3. Materials and methods

This work combined images from Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER), (2004/2005; spatial resolution of 15 m), with GPS control-points in order to map the main geomorphological features.

These images were vectorized with Polar Stereographic coordinate and WGS84 geodetic reference system. Morphological features observed in Aster visible/near-infrared (VNIR) color composite images were georeferenced and identified during the field work using a portable GPS, with a margin of error of about 3 m. The newly detected morphological features were included in a geographical information system.

Landforms and deposits of periglacial and glacial features were identified and mapped.

At one elongated periglacial landform, a rock glacier like form, 400 m long, approximately, sediment samples were collected in seven different sites in the frontal area of the feature, on the surface, at each 50 m. Shallow, shovel-dug samples (100 g) were obtained down to the ice body.

Clast shape analysis and description of surface characteristics (striae, facets, and polish) at the pebble-and cobble-size fractions were carried out in order to identify the facies of the analyzed deposits (Fig. 1).

Roundness and sphericity of the clast were measured. The shape of the clasts was defined as the relative size of the three orthogonal axes: *a* (higher), *b* (intermediate), and *c* (lower) (Hubbard and Glasser, 2005).

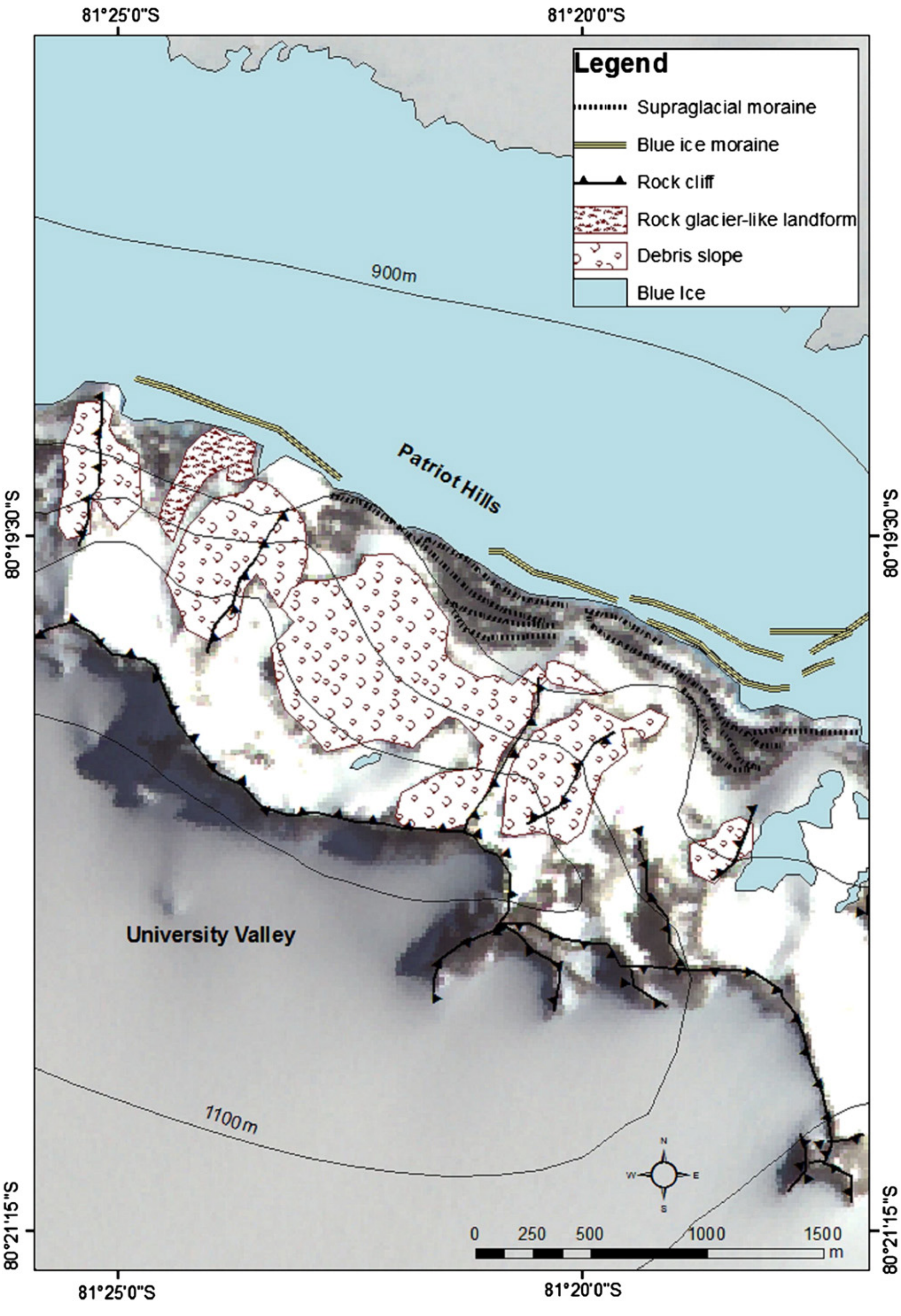

Fig. 2. Geomorphological map of Patriot Hills based on images from ASTER.

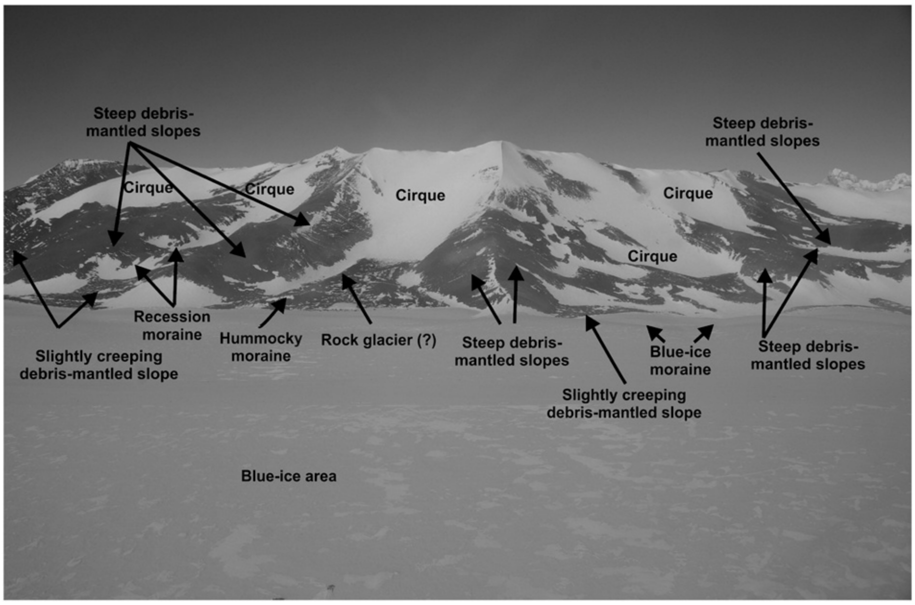

Fig. 3. Overview of the Patriot Hills area and of the main periglacial and glacial landforms.

Additionally, the RA index (% of angular clasts) was correlated with the C_{40} index (% of clasts which axis *c/a* is <0.4) according the method proposed by Benn and Ballantyne (1994). This method distinguishes sediments that were actively transported from those passively transported by the glacier (Benn and Ballantyne, 1994; Bennett et al., 1997).

4. Results

The periglacial environment in Patriot Hills can be described by distinct features: rock glacier-like landform, slightly creeping debris-mantled slopes: steep debris-mantled slopes, and rock falls (Figs. 2 and 3). Glacial geomorphology in Patriot Hills area is characterized by several types of moraines as hummocky moraines, blue-ice and supraglacial moraines.

4.1. Rock glacier-like landform

One rock glacier-like landform was identified in one of Patriot Hills valleys by its lobed shape, abrupt fronts and sides, and relatively flat tops. It presented a tongue-like mass of rock debris, extended 400 m down-valley from beneath the cirque headwall. The body has an arcuate plan form. Superficial ridges were observed on the upper surface down-slope (Figs. 3–5). The steep front of this rock glacier-like landform is connected with a set of ice-cored moraines.

Such features may be a result from distinct genetic processes associated with differential ablation. These hummocky-like moraines are located next to the blue-ice area and are intermixed in pool-like features (frozen-pools) (Fig. 5).

Superficially, with the exception of some exposed points, the ice is rarely visible. The surface debris is coarse, ranging from <10 cm to >40c m in diameter. All the size components are between angular and very angular (Fig. 6). Generally, at inner layers, medium-grained sediments can be observed.

The debris surface thickness increases slightly toward the frontal area, from 15 cm to >30 cm at a longitudinal transect down-slope, which could correspond to the superficial creeping over the ice.

Considering the particle size distributions of the sediment, the resulting histograms show bimodal and multimodal samples, predominantly pebble (≥ 2), followed by grains (≥ 1) and very coarse sand (>0).

According Benn and Ballantyne (1994) the high RA values and the radius *c/a* lower than 0.4 of the most of the clasts indicate a passive

Fig. 4. Fontal part of rock glacier-like landform, where ridges can be observed.

Fig. 5. Fontal part of rock glacier-like landform, connected with hummocky moraine. Frozen-polls are observed at the left side of the hummocky moraines.

Fig. 6. Debris cover with unsorted sediments and underlying ice.

Fig. 8. Steep debris-mantled slopes.

transport. Moreover, the samples showed a predominance of subangular clasts, characteristic of recent fragmentation of debris.

There are no flow velocity data, but sedimentary and morphological characteristics, such as abrupt front, medium-grained sediments underlying debris surface layer and thicker debris layer at the frontal area suggest that the rock glacier-like landform should be active.

4.2. Other periglacial features

Other periglacial features identified at Patriot and Independence Hills could be classified into: (a) slightly creeping debris-mantled slopes; (b) steep debris-mantled slopes; and (c) rock falls. (Figs. 7–9).

Slightly creeping debris-mantled slopes have been identified in some valleys of Patriot Hills (Fig. 7). Although no indication of fluid flow was observed, there is some deformation by gradual movements along the slope. These features appear to have preferred slope orientation, they are commonly found onto slopes where the katabatic wind flows down.

Steep debris-mantled slopes occur preferentially on rock walls separating the Patriot Hills valleys. They correspond to straight slopes developed on the bedrock. Despite occupying higher gradient slopes, there were no deformations indicative of motion (Fig. 8). Their development can be associated with in situ rock disintegration, and the consequent movement of debris downslope under gravity.

Rock falls are found on slopes of the Patriot Hills valleys, where there is availability of weathered material (pebbles and gravels) (Fig. 9).

5. Discussion and conclusions

The elongated body along the longitudinal axis of one of Patriot Hills valleys has morphological features that could be interpreted as a rock glacier. Nonetheless, there is no information on the internal structure, on the nature of the ice and the movement distribution within the investigated landform.

The lobate plan form and the thickest superficial debris layer toward the frontal area reflect down-valley movement of this feature. Results obtained from sediment sample analysis confirm the activity of this feature and its passive movement, albeit minimal. The angular clasts show the lack evidence for transport beneath ice (e.g. no striations, molding or polish) and/or modification from meltwater flow. Therefore the origin of the deposits could be related to snow avalanches descended from the upper slopes or to the sublimation till, produced via sublimation of underlying ice containing scattered debris. Sublimation is the main mechanism of ablation in Patriot Hills area (Casassa et al., 1998, 2004). Moreover, the sublimation tills are sufficiently thick (15–30 cm on the rock glacier-like feature surface) to prevent melting of the buried ice surface even with the constant

Fig. 7. Periglacial features: slightly creeping debris-mantled slopes.

Fig. 9. Rock falls in Patriot Hills.

and strong winds from the southwest-southeast quadrants that act intensively and continuously over the area, promoting sublimation but also transporting material for considerable distance and participate in the deposition process.

The definitive interpretation of the rock glacier-like landform as a true rock glacier is still problematic because unfortunately, there were no logistic conditions to drill a borehole through the debris ice layer to understand the internal structure and the nature of the ice. Thus, further field measurements, such as ground-penetrating radar, geodetic surveys, ice core-drilling, and flow-modeling efforts are required for a better understanding of the periglacial environment in this interior part of Antarctica.

The role of the water seems to be negligible, although the occurrence of exceptionally warm summer events, with deep (1 m) melt-lakes forming at the edge of Patriot Hills was identified in 1997 by Carrasco et al. (2000).

The presence of slightly creeping debris-mantled slopes could correspond to a location at the leeside of the Patriot Hills with respect to the katabatic winds from the polar plateau, and it could be due the combination of the wind action and the frost creep as suggested by French and Guglielmin (1999) for similar features found in Terra Nova Bay, Northern Victoria Land. On the other hand, the same authors do not exclude the role of the bedrock control, occurring only on slopes where the ablation till is thin that also in our case has to take account.

Slopewash and groundwater movement processes may be limited or non-existent since most snow disappears through sublimation.

Although debris-mantled steep slopes occupy the steeper rock walls between valleys, they indicate no deformation, so debris displacement downslope is slower and less noticeable. This could be due to their parallel position to the predominant winds.

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References

Benn, D.I., Ballantyne, C.K., 1994. Reconstructing the transport history of glaciogenic sediments—a new approach based on the covariance of clast form indices. Sedimentary Geology 91, 215–227.
Bennett, M.R., Hambrey, M.J., Huddart, D., 1997. Modification of clast shape in high-arctic glacial environments. Journal of Sedimentary Research 67, 550–559.
Bentley, M.J., Fogwill, C.J., Le Brocq, A.M., Hubbard, A.L., Sugden, D.E., Dunai, T.J., Stewart, P.H.T., Freeman, S.P.H.T., 2010. Deglacial history of the West Antarctic Ice Sheet in the Weddell Sea embayment: constraints on past ice volume change. Geology 38, 411–414.
Bockheim, J.G., 1995. Permafrost distribution on the Southern Circumpolar Region and its relation to the environment: a review and recommendation for further research. Permafrost and Periglacial Processes 6, 27–45.
Bockheim, J.G., Hall, K.J., 2002. Permafrost, active-layer dynamics and periglacial environments of continental Antarctica. South African Journal of Science 98, 83–90.
Carrasco, J.F., Casassa, G., Rivera, A., 2000. A warm event at Patriot Hills, Antarctica: an ENSO related phenomenon? In: Carrasco, J.F., Casassa, G., Rivera, A. (Eds.), Sixth International Conference on Southern Hemisphere Meteorology and Oceanography, 3–7 April, 2000, Santiago, Chile. Proceedings. American Meteorological Society, Boston, pp. 240–241.
Casassa, G., Brecher, H.H., Cárdenas, C., Rivera, A., 1998. Mass balance of the Antarctic ice sheet at Patriot Hills. Annals of Glaciology 27, 130–134.
Casassa, G., Rivera, A., Acuña, C., Brecher, H.H., Lange, H., 2004. Elevation change and ice flow at Horseshoe Valley, Patriot Hills, West Antarctica. Annals of Glaciology 39, 20–28.
Craddock, C., Anderson, J.J., Webers, G.F., 1964. Geologic outline of the Ellsworth Mountains. In: Adie, R.J. (Ed.), Antarctic Geology: Amsterdam. North-Holand, Amsterdam, pp. 155–170.
Curtis, M.L., Lomas, S.A., 1999. Late Cambrian stratigraphy of the Heritage Range, Ellsworth Mountains: implications for basin evolution. Antarctic Science 11, 63–77.
Dahe, Q., Petit, J.R., Jouzel, J., Stievernard, M., 1994. Distribution of stable isotopes in surface snow along the route of the 1990 International Trans-Antarctic Expedition. Journal of Glaciology 40, 107–118.
Denton, G.H., Prentice, M.L., Burkle, L.H., 1991. Cainozoic history of the Antarctic ice sheet. In: Tingey, R.J. (Ed.), The Geology of Antarctica. Clarendon Press, Oxford, UK, pp. 365–419.
Fogwill, C.J., Hein, A.S., Michael, J., Bentley, M.J., Sugden, D.E., 2011. Do blue-ice moraines in the Heritage Range show the West Antarctic ice sheet survived the last interglacial? Palaeogeography, Palaeoclimatology, Palaeoecology. doi:10.1016/j.palaeo.2011.01.027.
French, H.M., Guglielmin, M., 1999. Observations on the Ice-Marginal, Periglacial Geomorphology of Terra Nova Bay, Northern Victoria Land, Antarctica. Permafrost and Periglacial Processes 10, 331–347.
Fukui, K., Sone, T., Strelin, J.A., Torielli, C.A., Mori, J., Fujii, Y., 2008. Dynamics and GPR stratigraphy of a polar rock glacier on James Ross Island, Antarctic Peninsula. Journal of Glaciology 54, 445–451.
Hassinger, J.M., Mayewski, P.A., 1983. Morphology and dynamics of the rock glaciers in Southern Victoria Land, Antarctica. Arctic and Alpine Research 15, 351–368.
Hubbard, B., Glasser, N., 2005. Field Techniques in Glaciology and Glacial. Geomorphology. Wiley, Chichester UK. 400 pp.
Jouguin, I., Bamber, J.L., 2005. Thickening of the ice stream catchments feeding the Filchner–Ronne Ice Shelf, Antarctica. Geophysical Research Letters 32. doi:10.1029/2005GL023844.
Mayewski, P.A., 1979. Glaciology and glacio-geomorphology in Victoria Land and Queen Mound Mountains. Antarctic Journal of the United States 14, 53.
Mayewski, P.A., Hassinger, J., 1980. Characteristics and significance of rock glaciers in southern Victoria Land. Antarctic Journal of the United States 15, 68–69.
McLeod, M., Bockheim, J.G., Balks, M.R., 2008. Glacial geomorphology, soil development and permafrost features in central-upper Wright Valley, Antarctica. Geoderma 144, 93–103.
Rignot, E., Hallet, B., Fountain, A., 2002. Rock glacier surface motion in Beacon Valley, Antarctica, from synthetic-aperture radar interferometry. Geophysical Research Letters 29, 1607.
Rutford, R.H., 1972. Drainage system of the Ellsworth Mountains area. Antarctic Geology and Geophysics, International Union of Geological Sciences. Series B, Oslo, 1, p. 233.
Rutford, R.H., Denton, G.H., Anderson, B.G., 1980. Glacial history of the Ellsworth Mountains. Antarctic Journal of the United States 15, 56–57.
Serrano, E., López-Martínez, J., 2000. Rock glaciers in the South Shetland Islands, Western Antarctica. Geomorphology 35, 145–162.
Shean, D.E., Marchant, D.R., 2010. Seismic and GPR surveys of Mullins Glacier, McMurdo Dry Valleys, Antarctica: ice thickness, internal structure and implications for surface ridge formation. Journal of Glaciology 56, 48–64.
Spörli, K.B., Craddock, C., 1992. Stratigraphy and structure of the Marble, Independence and Patriot Hills, Heritange Range, Ellsworth Mountains, West Antarctica. In: Webers, G.F., Craddock, C., Splettstoesser, J.F. (Eds.), Geology and Paleontology of the Ellsworth Mountains, West Antarctica: Geological Society of America, Memoir, 170, pp. 351–364.
Swithinbank, C.W.M., 1987. Ice runways in the Heritage Range, Antarctica. Annals of Glaciology 14, 211–215.
Todd, C., Stone, J., 2004. Deglaciation of the southern Ellsworth Mountains, Weddell Sea sector of the West Antarctic Ice Sheet [abs.]. Proceedings, 11th Annual WAIS Workshop: Sterling, Virginia, West Antarctic Ice Sheet Initiative.
Turner, J., Pendlebury, S. (Eds.), 2008. The International Antarctic Weather Forecasting Handbook. http://www.antarctica.ac.uk/met/momu/International_Antarctic_Weather_Forecasting_Handbook/index.php. Accessed at August 27.
USGS (United States Geological Survey), 1966. Liberty Hills. Washington, DC, U.S. Department of the Interior. US. Geological Survey. (Reconnaissance Series, Scale 1250.000).
Wendt, A., Casassa, G., Rivera, A., Wendt, J., 2009. Reassessment of ice mass balance at Horseshoe Valley, Antarctica. Antarctic Science 21, 505–513.