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## Short Communication

# Cryogenic Landforms in the Sierras de Alvear, Fuegian Andes, Subantarctic Argentina

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### ABSTRACT

A preliminary survey of periglacial landforms found in the Monte Alvear region of the Fuegian Andes, subantarctic Argentina has revealed the presence of nivation hollows, subnival 'boulder' (clast) pavements, protalus ramparts, debris lobes, patterned ground and cryo-ejected clasts. With the exception of debris lobes and cryo-ejected clasts, all the landforms show some degree of activity and are, therefore, considered as indicators of present-day cryonival morphodynamics at higher elevations in these mountains. A number of small tors, while not necessarily periglacial in origin, are also apparently experiencing cryogenic weathering. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: cryogenic landforms; cryonival morphodynamics; Fuegian Andes; Argentina; subantarctic

## INTRODUCTION

Existing knowledge of cryogenic landforms above tree-line in the Fuegian Andes is very limited and highly generalised. Auer (1970), referring to the area around Ushuaia (lat. 54° 50′S), cited the occurrence of landforms related to seasonal soil freezing and frost penetration to a maximum depth of ~0.3 m at elevations that approached sea level. At Monte Louis Martial, near Ushuaia, he placed the lower boundary of small-scale patterned ground at 750 m a.s.l., and that of large polygonal nets above ~900 m a.s.l. In the central sector of the Fuegian Andes, Garleff (1977) located the lower limit of solifluction phenomena and patterned ground at ~700 m a.s.l. Corte (1997) included Tierra del Fuego in the Argentine Andean region in which the lower boundary of permafrost was estimated to be at 900 m a.s.l., using a combination of observations of sorted freeze-thaw structures of ~1 m in diameter, and an estimate of the 0°C mean annual air isotherm at ~950 m a.s.l.

This short communication describes the variety of cryogenic landforms found at higher elevations in the vicinity of Monte Alvear, Andes of Tierra del Fuego, subantarctic Argentina. The survey was undertaken as the first step in a multi-year study in which many of the cryogenic landforms in this little-studied area are being investigated and monitored.

## STUDY AREA

The study area is located in the Sierras de Alvear (lat. 54° 40′ 30″S; long. 68° 02′ 30″W), at elevations between 1000 and 1077 m a.s.l., and is about 25 km

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NE of the city of Ushuaia (Figure 1). The location is an unnamed, flat summit located close to Monte Alvear and the Alvear Este glacier, NW of Cerro Krund. The topography of this mountain sector is characterised by medium to steep slopes, in which sub-horizontal benches are preserved, as well as by an extensive, sub-horizontal summit. The bedrock consists of strongly deformed, Late Jurassic porphyrites, basalts and slates of the 'Lemaire Formation' (Olivero and Martinioni, 2001). At the last glacial maximum the summit area was a nunatak, separating the basins of the glaciers Alvear Este (to the W and S) and Tristén (to the E), both tributaries of the Beagle outlet glacier, and also that of the Río Alvear glacier (to the N), which was a tributary of the Fagnano outlet glacier (Coronato, 1995). These alpine glaciers eroded hanging valleys and rock basins. Quarried rock steps and abraded surfaces with striae, both sets of features highly modified by frost-shattering, have been preserved.

The climate of southern Tierra del Fuego is cold-temperate and wet, with a strong oceanic influence and limited seasonality (Tuhkanen, 1992). To date we have recorded air temperatures in the study area at an elevation of 1050 m a.s.l. from February 2005 to January 2006. During this period, the mean air temperature was $-2$°C and absolute minimum and maximum temperatures were $-11.7$°C and 15.6°C, respectively. Presently there are no precipitation data from the study area. At Ushuaia, near sea level, mean annual precipitation for the period 1961–70 was 550 mm (Linares, 1984), although this must be considered a weak indication of precipitation in the study area itself. In the Sierras de Alvear snowfall is recorded between April and October, but may also take place during the summer months. Vegetation in the study area is essentially restricted to communities of mosses and lichens.

## CRYOGENIC LANDFORMS

The following cryogenic landforms were identified during the geomorphological survey carried out in the southern summers of 2004 and 2005: nivation hollows, subnival 'boulder' (clast) pavements, protalus ramparts, debris lobes, patterned ground and cryo-ejected clasts. Small tors are also found in the study area; while they are undoubtedly affected by cryogenic processes in this location, they are not inherently a cryogenic landform.

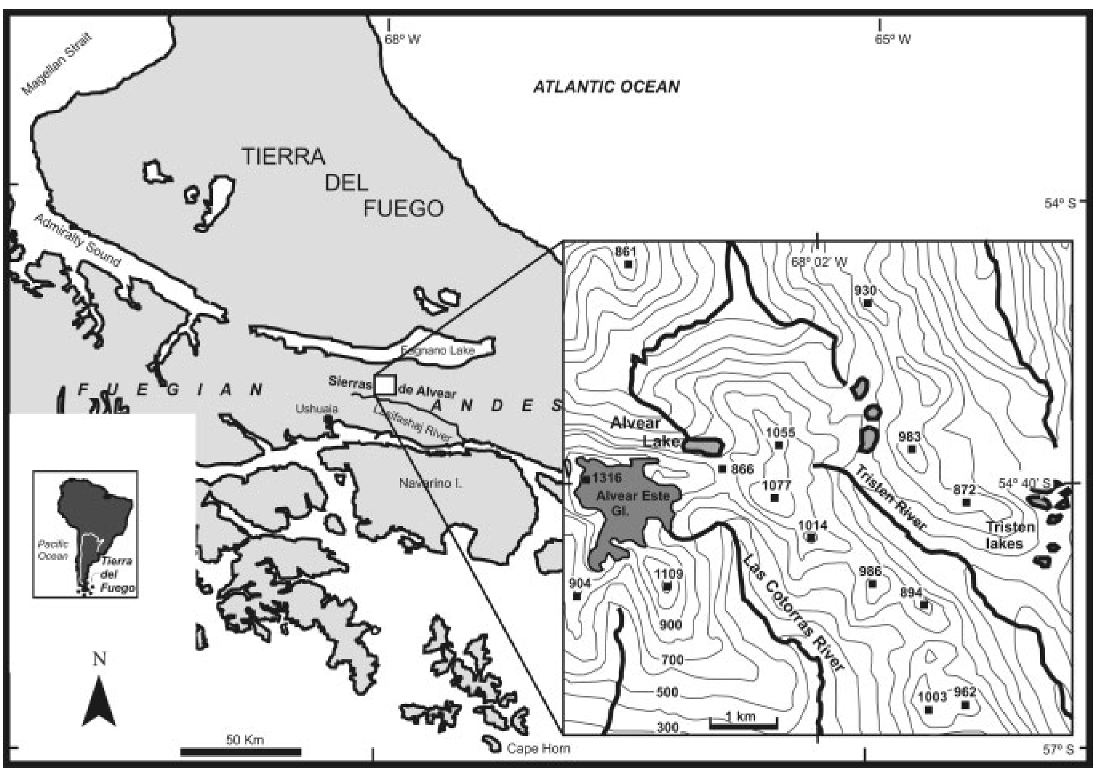


Figure 1 Location of the study area.




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## Nivation Hollows

These landforms, related to a group of geomorphic processes falling under the general term 'nivation', occur in places in which snow accumulates over extended periods. They are small hollows or depressions on the slopes, which are progressively deepened by the standing snow mass. Snow creep, summer subnival melting and the subsequent meltwater erosion, as well as solifluction, seem to play dominant roles in their genesis (Thorn, 1988). In the study area nivation hollows mostly occur along the E-facing, leeward slopes, between 1000 and 1050 m a.s.l., on slaty substrates. They are elongated transverse depressions, with a concave cross-section, closed in their lower portions by a marked change in slope and occupied by snow patches. During our brief study period the snow patches appear to be perennial; however, whether they occasionally melt-out is presently an open question. The preferred location of the nivation hollows on the lee-side slopes appears to be mostly due to a combination of copious snow blown from the summit surface, which assures the existence of snow patches thick enough to survive the summer melt, and the occurrence of highly fractured (and thus readily disrupted) slates. We assume that rapid weathering of the slate provides suitable hollows for snow accumulation which are then in turn subjected to even more intensive development by nivation processes.

## 'Boulder' (Clast) Pavements

'Boulder' (clast) pavements occur on low gradient surfaces of E-facing slopes, always above 1050 m a.s.l. They are formed by platy rock fragments, varying in size from cobble- to boulder-sized, and embedded in a silty-sandy soil and closely packed. The long axes of the clasts tend to be aligned with the local slope direction. Pavement occurrence is related to the existence of a thick snow-pack, the weight of which pushes down rock fragments emerging from the soupy matrix of fines. Meltwater action, solifluction and snow creep may also contribute to their formation.

## Protalus Ramparts

These landforms are located at the lower edge of perennial snow patches along the NW-facing slope, at ~1040 m a.s.l. These are windward locations, but snow patches accumulate at the base of rock faces. The ridges are up to 2 m high and composed of coarse, poorly sorted clasts and fines. The clasts appear to be detached by frost wedging and gravity processes from a highly friable, porphyritic wall upslope of snow patches. Transport appears to be supranival: the detached rock fragments slide, or roll down the sloping snow patch surface and accumulate at its foot. Clasts of varying size have frequently been observed on the surface of the snow patches. The dense fracturing pattern within the porphyrites undoubtedly facilitates frost wedging and, consequently, enhances the debris supply to the protalus ramparts. It also provides an unusually rich source of fine material which can also be seen on the snow patch surfaces and in the protalus ramparts. The combination of both fines and coarse debris in protalus ramparts appears not to have been widely reported. Here it is clearly rock-specific.

## Debris Lobes

Debris lobes are lobate accumulations, composed of abundant fines, as well as cobbles and small blocks. They are located along the NW-facing slope, at ~1010 m a.s.l., under a porphyritic wall which is the source area for the debris. The longitudinal axis of the lobes is aligned with the direction of the maximum slope. Their fronts and flanks are steep (Figure 2). The largest lobe measures 8 m long, 5 m wide and 3 m high. Considering the size and morphometric characteristics of the lobes, especially their steep fronts and flanks, it is thought that their origin may be permafrost related. The lobes may be, or may have been, ice-cemented and they may have moved downslope from the deformation of this ice. At present, it has not been determined whether they are more akin to small rock glaciers or solifluction lobes, nor whether they are currently active.

## Patterned Ground

Patterned ground features are the most abundant and varied cryogenic landforms found in the study area. On benches and low gradient slopes, they occur as stone circles, gradually grading into sorted stone stripes as slope angles increase. Consideration of their morphology and sorted nature reveals three of Washburn's (1956, 1979) proposed categories to be dominant: (1) sorted stone circles, (2) nonsorted stone circles and (3) sorted stone stripes.

The sorted stone circles only occur on the summit surface, above 1050 m a.s.l., on basalt areas of minimal or no gradient. They are composed of a ring or exterior border, formed by coarse clasts up to 50 cm long, colonised by lichens and mosses, and frequently in almost vertical positions. This border encloses a raised inner sector, mostly composed of sands and silts, in which, isolated, larger clasts also occur (Figure 3). Small polygons, outlined by coarse sands

 
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Figure 2 Debris lobes at the foot of a porphyrite wall. This figure is available in colour online at www.interscience.wiley.com/journal/ppp.

and gravels, have developed on the silty matrix of the inner sector. These forms as a whole can attain a diameter up to 2 m. Frost heave is currently active within the finer material. Steel nails 15 cm long and 0.8 cm in diameter, totally inserted into the fines, experienced heaving ranging from 1.8 to 2 cm in a single year. The development of patterned ground on the summit surface may possibly be explained by deep and intense wintertime freezing promoted by a locally thin seasonal snowpack due to exposure to high wind speeds.

The nonsorted stone circles occur on sub-horizontal benches on the NW- and N-facing slopes, between 1000 and 1030 m a.s.l., and preferentially on basaltic substrate. They do not contain a fine-grained inner sector. Nonsorted circles are formed of poorly sorted debris and frequently show boulder-sized clasts along their outer margins. They can attain 1 m in diameter.

The sorted stripes occur preferentially on the E-facing, lee-side slope, above 1000 m a.s.l., on slaty and basaltic substrates. They are formed by parallel bands 5 to 8 cm wide and up to 6 m long, composed of coarse sands, gravels and small pebbles, aligned with the direction of the maximum slope, alternating with silty-sandy strips 10 to 15 cm wide. Sorted stripes occur on gradients ranging from 8° to 15°. These landforms seem to have been formed by repeated freeze-thaw cycles in the uppermost soil layers. On this lee-side slope, the accumulation and persistence of the snow may be important, as demonstrated by the occurrence of perennial snow patches. Thus development of sorted stripes may be restricted to the snow-free period. Moreover, it is possible that the seasonal snow cover modifies them in winter, due to the dragging action of snow creep.

## Tors

Small tors occur on flat bedrock benches on the NW-facing slope, at ~1020 m a.s.l. They are residual basaltic and porphyritic protuberances, standing up to 1.7 m above the overall bedrock surface. They show angular, joint-bounded faces. Frost wedging is considered to be the main process responsible for their present development. The abundance of fresh, densely cracked and angular rock fragments observed at the base of the tors strongly suggests that they are presently being actively weathered.

## Cryo-ejected Clasts

Cryo-ejected clasts occur in highly fractured slate and basalt outcrops of the summit surface and on low gradient slopes, always above 1050 m a.s.l. (Figure 4). The clasts, usually boulder-sized, appear to have been detached from the bedrock by frost wedging, and to have been raised above the surrounding surface by

Figure 3 Sorted stone circle on the summit surface. This figure is available in colour online at www.interscience.wiley.com/journal/ppp.

Figure 4 Cryo-ejected macroclast on the summit. This figure is available in colour online at www.interscience.wiley.com/journal/ppp.



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heaving caused by the freezing of water in rock discontinuities. The largest observed clast protrudes 72 cm from the general surface. According to Dionne (1983), these landforms require the existence of permafrost for their genesis. However, it has yet to be proven that the features found in the study area are presently active or underlain by permafrost.

## CONCLUSIONS

Most of the meso- to micro-scale cryogenic landforms observed in the Sierras de Alvear, with the possible exception of the cryo-ejected macroclasts and the debris lobes, seem to be active under current climatic conditions.

Seasonal snow cover plays a substantial role in the genesis and evolution of many of the landforms. In areas of high snow accumulation, the insulation effect of the snow cover significantly reduces the period in which the ground is exposed to frost action. Nivation hollows, subnival 'boulder' (clast) pavements and seasonal patterned ground are the most common landforms developed in these zones. Frost action is much more intense and persistent on the windswept summit surfaces due to the absence of a deep seasonal snow cover, permitting the development of large patterned ground features and cryo-ejection phenomena. Moreover, the melting of the seasonal snow cover is the most important source of moisture for many geomorphic processes. Variability in rock type (basalt, porphyrite, slate) also appears to play a significant role in the landforms produced.

This landform survey constitutes the preliminary step of a research project focused on present-day cryonival morphodynamics in the higher levels of the Fuegian Andes. Cryogenic processes (e.g. frost heaving, solifluction and snow creep) and landform development (e.g. protalus ramparts, debris lobes and patterned ground) are being studied at selected sites. A monitoring programme comprising local air climate, ground temperatures and moisture, rock temperatures, as well as seasonal snow cover depth and duration is also being carried out.

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