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Geomorphological evidence of different glacial stages in the Martial cirque, Fuegian Andes, southernmost South America

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Abstract

The geomorphological features of a cirque partially occupied by receding ice bodies are presented as evidences of different glacial stages in the Fuegian Andes summits since the Last Glaciation (IOS 2). A glacierization scheme involving: (i) regional glacier accumulation basin; (ii) glacier individualization from a main regional; (ii) a stillstand during the general retreat and (iii) two advancing stages are suggested. Geomorphic and sedimentary units, named Martial I, II, III and IV, have been distinguished as a consequence of the glacial scheme. Unfortunately, the lack of datable materials has impeded establishment of an absolute chronology. Recognized glacier advances in the region are discussed. The palaeoclimatic framework for the surroundings, based on previous studies, is presented. © 2001 Elsevier Science Ltd and INQUA. All rights reserved.

1. Geographical setting

The Martial Glacier is a receding cirque glacier, located in the Montes Martial, Fuegian Andes (54°46′/54°48′S; 68°22′/68°25′W), along the northern coast of the Beagle Channel, in the Argentine portion of the Isla Grande de Tierra del Fuego (Fig. 1). This sector of the Fuegian Andes is located on the Scotia Plate and it is composed of a metamorphic set of dark shales with chert layers, and associated turbidite beds and andesitic tuffs, known as the Yaghan Formation. Slaty shale and graywacke sequences, of Upper Jurassic-Lower Cretaceous age, with isoclinal folding and strong axial plane cleavage, are also included in these units (Caminos et al., 1981; Olivero et al., 1999). The mountain belt has a west–east strike and the slopes are oriented towards the east–southeast. The elevation of the mountain summits does not surpass the 1250 m a.s.l., whereas the cirque floor is found between 500 and 600 m a.s.l.

The humid–temperate climate of these regions is determined by the influence of Antarctic and Subantarctic air fronts, moving out from the Southern Pacific Anticyclone, generating the prevailing winds from the South–Southwest quadrant (Tuhkanen, 1992). The mean annual temperature at sea level is 5.9°C and 2.4°C at the upper forest limit, at an elevation of 600 ± 100 m, with mean temperatures below 0°C during 109 days a year, between the end of April and the beginning of September (Puigdefábregas et al., 1988).

Mean annual rainfall at sea level is 546 mm/yr. Although there are no rainfall instrumental records at high elevations, statistical calculations suggest that at an elevation of 535 m, precipitation is three-fold that at sea level (Iturraspe et al., 1989). Snowy precipitation is dominant between June and September, although snow storms occur all year around, as is the case with frost events. The high index of cloudiness keeps evapotranspiration very low, favoring the forest development even under low annual rainfall. Soil freezing is seasonal, reaching 0.30 m depth at sea level (Iturraspe et al., 1989). These characteristics define the regional climate as moderate, sub-humid, but permanently cold, without seasonal extreme conditions.

The *Nothofagus pumilio* forest covers the lower slopes and the bottom of the valleys up to 600 ± 100 m a.s.l. From here to 1000 m a.s.l., the High Andean desert is found, dominated by *Bolax gummifera* vegetation accompanied by grasses, lichens and mosses (Roig, 1998). The soils are quite shallow and the impeded drainage areas allow the genesis of peaty environments. Most of this area is covered by rocky outcrops and debris.

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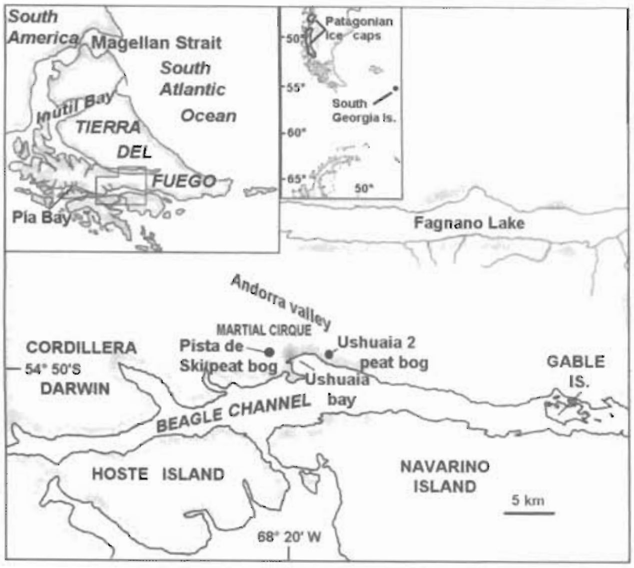

Fig. 1. Location map of Martial cirque and the surrounding area of Beagle Channel.

This area is a mountain tourist resource as a ski center. Ushuaia city is located at the foot of the Montes Martial, in the Ushuaia Bay, Beagle Channel (Fig. 1).

2. Geomorphology of the Martial cirque

The geomorphology of this area has been studied by aerial photo interpretation and field work. The geomorphological map (Fig. 2) shows the spatial distribution of the glacigenic, periglacial, fluvial and mass-movement processes and landforms recognized in the study area.

2.1. *Erosional glacigenic features*

Among the erosional landforms, the arêtes, which form the rocky summit line and which separate the Martial cirque from other major glacial valleys, define the boundaries of the cirque along the Bridges (S) and Godoy (N) mountain ranges.

The principal cirque is composed of five smaller cirques, separated by eroded rocky outcrops that would have occurred at the surface when the glacial ice thinned and divided into different ice bodies. Fig. 2 shows the remnant ice bodies as they occur today, with a prevailing orientation to the ESE, whereas the cirque with snow fields is oriented towards the NE. In neighboring valleys of the Fuegian Andes, it has been observed that the cirques which are oriented towards the SE are the most abundant. Glacial ice is preserved in these due to the limited exposure to sunlight and the effects of humid air masses. In contrast, in cirques oriented to the east, the presence or absence of glacial ice would depend on structural or topographic factors (Coronato, 1996).

The confluence of the water courses proceeding from the smaller cirques (B–E) defines the upper part of the cirque floor. The A cirque has a higher topographic position (approximately 900 m a.s.l.), separated by glacial accumulation landforms (Fig. 2). It has a slope of 7% from 560 m elevation, steepening to 12% down to 500 m a.s.l. Downslope from the point where it merges with the Monte Godoy cirque, a high-altitude glacial valley of reduced longitudinal development is formed with a slope of 15% above the 300 m a.s.l. contour line, at the site of the parking lot of the ski complex. Roche-moutonnées are visible above tree-line on the slopes of Monte Bridges and in the surroundings of the ice bodies.

2.2. *Accumulation glacial features*

Moraines are the most frequent accumulation landforms in this area, although the presence of glaciofluvial deposits at the valley outlet show the existence of an eroded glaciofluvial plain. The erratic boulder distribution around 800–900 m a.s.l. at Monte Bridges slopes and at the cirque floor are additional evidence of glacial accumulation processes.

The observed moraines have been classified according to their position respective to the ice body (Dreimanis, 1989). The following types have been distinguished.

2.2.1. *Lateral, central and end morainic complex*

Located at higher and outer positions, the lateral moraines form a continuous belt, clearly visible on the lower slopes of the Bridges and Godoy summits. The morainic belt of this later peak is united with that of the slope in front, forming a central moraine, which may have acted as a closure for the Arroyo Godoy valley, non-existent today. The easternmost lateral moraine of the Arroyo Godoy valley merges with the westernmost lateral moraine of the Monte Bridges, forming the central morainic arc of the system. Evidently, during the formation of these moraines, the Martial Glacier integrated a single ice mass, in both high altitude valleys. The morainic belts are located from 700 m a.s.l. along the slopes down to 290 m a.s.l. in the frontal position at the bottom of the valley. The sediments observed in the very rare outcrops show rounded and striated boulders and gravels in a fine sand and silt matrix. Lithology is varied and heterogeneous, with a high frequency of allochthonous particles in the central part of the morainic arc. The deposit type that forms the morainic belt is interpreted as an ablation till. In the terminal zone, above these deposits, sand, gravel and stratified silt beds of possible glaciofluvial origin are found.

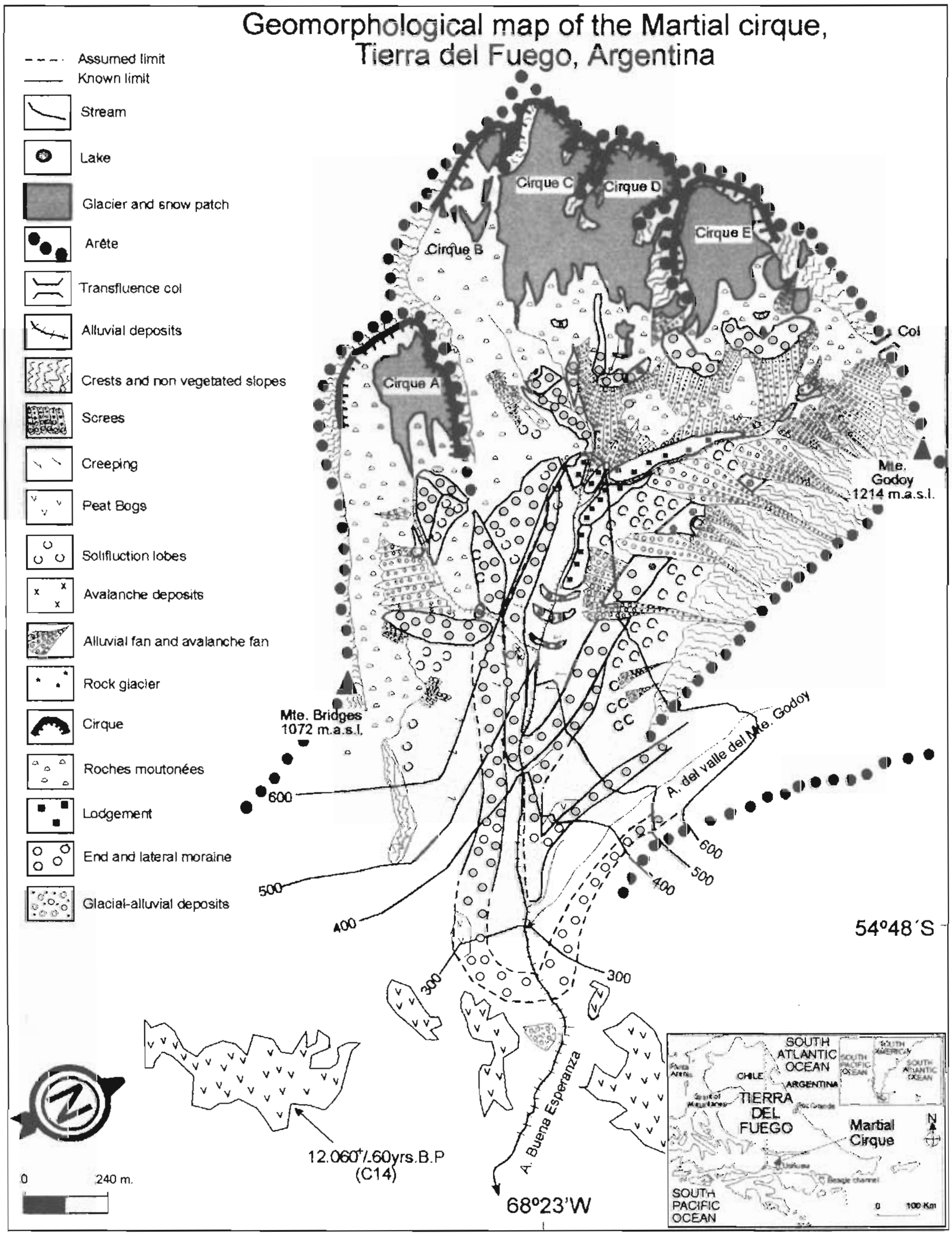

Fig. 2. Geomorphological map of Martial cirque area, in the Fuegian Andes.

2.2.2. Second latero-frontal morainic belt

A morainic arc extends laterally in both slopes of the main cirque, with a frontal closure at 400 m a.s.l., between pillars 4 and 6 of the ski lift. Laterally, they are found between 500–600 m a.s.l. on the western margin. In the Monte Godoy slope, the longitudinal development is clear, superposed with the outermost lateral moraine of the central sector, at 605 m a.s.l., and obliterated by debris cones in the higher portions (Fig. 3). The morphology of the moraines located at elevations lower than 650 m a.s.l. is difficult to analyze, due to the forest cover, which allows only observation of the changes in slope. Outcrops which may permit the description of the sediment within these moraines have not been found. However, gravels and angular clasts of local lithology within silty matrices are present on the surfaces. On the Monte Godoy slope moraine, very large erratic boulders are observed (Fig. 3), but with a lesser frequency at higher elevations, disappearing above 632 m a.s.l.

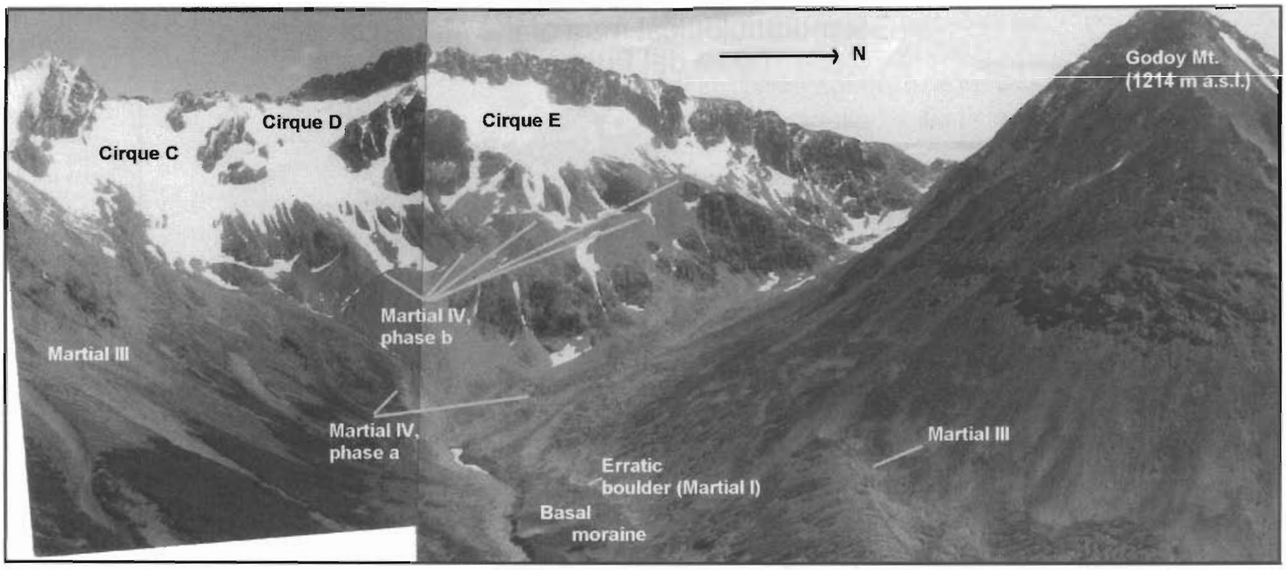

Fig. 3. Aerial view of Martial cirque showing ice-bodies and glacial and slope landforms. Glacial features are named in relation to the proposed depositional model.

2.2.3. *Cirque A latero-frontal moraine*

Is the outermost morainic belt of this cirque and its small hanging trough to the Martial valley. Two elongated belts, symmetrical with respect to the bottom of the valley, are distinguished, with a steeper slope in the inner faces. The frontal arc reaches 600 m a.s.l., extending upslope beyond the forest tree-line, being colonized by cushion-like vegetation. The slopes with higher inclination show soil movements due to gravity processes. The outermost lateral moraine is partially "interrupted" by the frontal sector of this high-elevation moraine. The absence of outcrops has not allowed analysis of its sedimentary content, although the existence of sediments with silty and clayey fractions is superficially dominant; this is interpreted as a consequence of periglacial dynamics modifications.

2.2.4. *Recessional morainic arcs*

At the bottom of the valley (500–540 m a.s.l.), three small recessional arcs are located, generating a series of minor convex hills, eroded by the water course in their western slopes. No lateral continuity of the lateral arcs along the higher slopes of the valley has been observed. Each morainic belt is coincident with a larger highly rounded boulder and frequent clasts of allochthonous lithology, found both in the creek channel and in the interior and surface of the moraines. The till of these moraines is very compact, with a high content of sub-angular and rounded clasts ranging from granules to boulders, with no apparent internal structure. The size of the boulders diminishes up valley. Outwash deposits overlie the till, ending the sedimentary section.

2.2.5. *Basal moraine*

This landform is exposed with a plain topography up valley from the recessional arcs, from 540 to above 600 m a.s.l. elevation (Fig. 3). The exposed till is composed of compact, greyish-blue (locally brownish by oxidation) clays. The incorporated clasts have angular shapes but they are not abundant. Some boulders are scattered over the surface. In several exposed outcrops, the development of clast beds with little matrix and fluvial structure has been observed. These layers overlie very shallow palaeosoils, with very low organic matter content, interbedded with clayey and sandy strata.

2.2.6. *Moraines closer to the present ice body, outer phase*

They are clearly observed in the A and D cirques, between the 600 and 800 m a.s.l. They are distinguishable from the outermost moraines of the cirque due to their fresher morphology and grassy vegetation cover. The landforms correspond with small convex hills, with higher slope down valley. In some cases, they are represented as patches of remnant till along the slopes, visible at the erosional cuts generated by the water courses. They are massive sedimentary bodies, composed of till with abundant angular clasts and superficially covered by boulders and pebbles, removed by periglacial processes. In the B, D, and E cirques, no moraines of this type have been observed. They are probably buried by mass-movement debris, or may have been eroded by younger glacial advances.

2.2.7. Moraines closer to the present ice body, inner phase

Morainic accumulations of the "push-moraine" type are present between 800 and 900 m a.s.l., as semi-circular arcs that dam runoff, forming small ponds and holding ice and snow (Fig. 3). These are irregular landforms, with asymmetrical slopes, that in some places form belts which are exposed as parallel or superposed belts, making difficult their spatial reconnaissance and identification. The number and size of the moraines is variable in each cirque. No outcrops have been found. Superficially, granules and pebbles are dominant, and the few boulders are angular in interstitial matrix. In the cases when deflation processes are intensively active and materials are removed by gravity and frost, only a very compact, gravelly clayey till is superficially outcropping. The depressed areas in between the arcs are favorable sites for the deposition of clasts removed by periglacial processes. Plant colonization is incipient along these moraines; notwithstanding, very young colonies of *Rhizocarpon* sp., mosses and a few grasses have been observed growing amidst the boulders. Although a general tendency towards a lichen-colony size diminution on the higher elevation landforms has been observed, the lack of a regional lichen growth curve-type and the absence of sufficient materials have not encouraged lichenometric studies so far. Between these moraines and the present front of the ice bodies, convex landforms of reduced size in the shape of ill-defined arcs, composed of very angular gravels, boulders and pebbles, have been identified. These landforms are subject to strong erosional processes by the meltwater streams coming out from the ice bodies or even from the interstitial ice from the interior of the most recent sedimentary bodies. Most likely, these small landforms indicate recent (last 100 or 50 years?) positions of the ice front.

2.3. Periglacial features

In the proximity of the col, in the northern portion of the arête, a periglacial landform, apparently inactive and interpreted as a rock glacier, is found. It has a sinusoidal shape, formed at least by three convex lobes. In its farther end, next to the slopes with angular debris, a change in slope is observed. The inner structure of the sediments that compose this landform was not observed, and features indicating recent activity have not been detected. Therefore, this is interpreted as a fossil landform, a result of the periglacial activity during certain climatic stages colder than today. Landforms of similar characteristics have been mentioned in other cirques of the Fuegian Andes (Coronato, 1995a).

The metamorphic rock outcrops of this site are undergoing severe gelifraction processes along the joint and other fractures. This process occurs continuously today during at least seven months each year, although the regional climatic conditions enable frost episodes even during the summer.

The frost selection of materials is another common feature in the surfaces with clasts with silty–clayey matrix and whose cushioned vegetal cover is scattered or non-existent. On the sloping morainic surfaces it is possible to observe patterned ground in the shape of coarse bands of finer sediments alternating with thinner stripes of angular, pebble-size clasts, and transit channels of coarse materials with zones that act as a source of cobbles and cone-shaped accumulation zones. These landforms are very similar, in scale, to true mass-movement complexes such as those that are present in the slopes. Frequently, they are interconnected, giving a peculiar aspect to the surfaces where they occur.

2.4. Slope features

The slopes of the Bridges and Godoy peaks are composed of stratified metamorphosed sedimentary rock outcrops, dipping and fractured in their upper portions. They present evidence of glacial polishing and abrading in various places. The intermediate and lower rocky slopes are covered by debris that form detrital sheets in unstable equilibrium, or form debris cones in the lower portions. The cone development reaches higher exposure in the western slope of Monte Godoy, where the transport funnels have eroded the fractures of the rocky outcrops and achieve a larger length, because they have their origin near the higher summit line. Debris cones are partially obliterating some areas of the lowermost older moraines of the Martial II Group (Fig. 3).

Evidence of slower and more rapid movement processes in the slope deposits is shown at different locations. Creep is produced in the slopes with shallower soils developed on clayey silts coming from the morainic till deposits. The effect of down-slope inclination on the base of *Nothofagus* sp. trunks is noted nearby the mountain refuge.

Faster movements such as rock and ice falls or landslides are seen on the moderately to strongly dipping slopes of both sides of the principal cirque. On the slope that connects cirque A with the bottom of the valley, at the elevation of the mountain refuge, evidence exists of an event occurred in the 1960s, during which the forest biomass covering the slope was mobilized, bringing boulders and debris to the bottom of the valley.

2.5. Fluvial features

From the front of the ice body located in cirque C, little meltwater streams flow, which merge with the creek coming from cirque E to form the Arroyo Buena

Esperanza (Fig. 2). This is the main outlet of the cirque complex and the Arroyo Godoy valley, which joins at 300 m a.s.l. It flows into the Ushuaia Bay of the Beagle Channel, after 7 km within an entrenched stream bed, with an approximate average discharge of 200–300 l/s, with minimum yields of 40 l/s and a maximum of 4000 l/s during the annual spring flows (R. Iturraspe, CADIC, personal communication). Erosional processes of stream bed deepening and bank undermining are dominant, especially in the till deposits located at the valley bottom, such as basal moraines, and recessional and latero-frontal arcs. The clast grain size of the stream bed varies between cobbles and boulders, with shapes ranging from angular to sub-rounded, depending upon their origin in slope processes, or erosion of basal or ablation till. Above tree-line, the angular clasts lying on the higher moraines and slopes are undergoing gelifluction movements, due to the existence of seasonal permafrost. Clasts subject to these processes accumulate forming lobes and terracettes.

3. Evidence of glacial advances

During the Last Glacial Maximum (IOS 2), a huge mountain ice-cap covered both the Southern and the Fuegian Andes and many outlet glaciers spread in all directions. The main glaciers flowing down from the Cordillera Darwin were the Magellan and Fagnano, which covered the Magellan Strait coasts, the Bahía Inútil and Bahía San Sebastián depression and the surroundings of Lago Fagnano. To the south, the alpine glaciers flowing down the inland of the Tierra del Fuego and Navarino islands joined the Beagle Glacier, the main trunk glacier that flowed 200 km eastwards along a longitudinal valley at latitude 54°S (Fig. 1). Due to its geographical and topographical position, the Martial Glacier was within the accumulation basin of the Beagle Glacier, and joined it at an altitude of 400 m a.s.l.

According to landform placement, altitude, morphogenesis, sediments, soil development and kind of vegetation cover, the occurrence of different glacial stages into the cirque are interpreted as follows:

- Stage I: during the maximum ice cover development, the erosional morphology of the mountain summits prevailed in both margins of the Beagle Channel. The ice thickness would have reached a minimum of 1000 m a.s.l. along the slopes of the main valley. The alignment of erratic boulders on the slopes of Monte Bridges, between 800 and 900 m a.s.l., indicates depositional processes at high elevations. Due to the transversal section of the ice body, it is possible to consider that the center of the Beagle Glacier would have surpassed the present 1200 m a.s.l., at its northern margin, reaching a total thickness of at least 1380 m, if the present bathymetry of the Beagle Channel is considered. Such a minimum thickness would have enabled the penetration of the main glacier into the Martial basin, providing ice mass and detrital load to the glacier that finally rested within the cirque. The evidence of the detrital transferency is the abundance of large granitoid boulders in the interior of the cirque, which could never entered through another section of the cirque basin, considering that it is a semi-closed amphitheater, with bordering summits that show no evidence of transfluent glacial activity. The lithology of the erratic boulders is allochthonous to the surrounding valleys, but coincident with that of the plutonic massif of the Cordillera Darwin. Similar ice penetration into the inner valleys of the mountain front has been previously demonstrated by Coronato (1990, 1995b) in the Andorra Valley, Ushuaia Bay (Fig. 1). During this phase, arêtes, horns, nunataks and erratic boulders were abundant features in the high elevation landscape. This is considered as the Martial I stage.
- Stage II: the Martial Glacier started to develop an independent glaciological behaviour from the Beagle Glacier, forming its latero-frontal moraines of the Martial I phase, at 300 m a.s.l. elevation, when it was still a single ice mass together with the Arroyo Godoy valley glacier. A stabilization phase would have formed the latero-frontal morainic complex, at 400 m a.s.l. altitude, in the interior of the high valley. During this same event, the ice body which occupied the cirque A would have separated from the remainder, leaving a latero-frontal morainic arc hanging at the side of the valley. The presence of erratic boulders in these moraines is explained considering that, in the depositional processes of this phase, the ice would have incorporated and re-deposited the allochthonous boulders brought into the basin by the Beagle Glacier during Stage I. The basal detrital load of the ice body would have formed the basal moraine located up-slope from the recessional arcs. This is considered as the Martial II stage.
- Stage III: the general recession of the ice towards the cirque headwaters was interrupted, perhaps by general climatic cooling, resulting in ice stabilization pulses which generated the three smaller morainic arcs, between 510 and 540 m a.s.l. This is considered as the Martial III stage.
- Stage IV: morainic belts, named phase "a", show a younger glacier advance. Push morainic topography close to the present ice-front, phase "b", indicates a very recent event, perhaps during the last centuries. This is considered as the Martial IV stage.

4. Final remarks

The existence of different frontal morainic arcs indicates different glacial advances, which might be caused by the occurrence of several climatic deterioration phases, since the Last Glacial Maximum. Unfortunately, neither datable material nor lichens were found in order to obtain precise chronological data in this cirque: similar problems characterize other cirques of the Fuegian Andes. Geomorphological features appear as the unique tool available to suggest a glacierization scheme, as the following: (i) cirque glacier separation from a main regional trunk glacier and deposition of down valley lateral and end moraines at 280 and 400 m a.s.l., at 2 and 1 km away from the present ice front, respectively; (ii) stillstand phase in the upper valley during the general ice retreat, depositing recessional moraines at the bottom of the valley between 500 and 550 m a.s.l., at 9 km away from the present ice front; (iii) one advance phase generating morainic belts above 600 m a.s.l., between 180 and 350 m away from the present ice front, presently covered by grassy and mossy vegetation; (iv) a second advance phase depositing push-moraines between 20 and 6 m from resent ice front, with very scarce lichen and moss occurrence only on some boulders.

The chronological framework in which these glacial advance and stabilization phases occurred cannot be established because of the absence of absolute data in the locality. Cosmogenic isotope dating is being performed on samples from the Martial I boulders (T. Cerling, personal communication). It must be considered that the basal peat age of Pista de Ski (Figs. 1 and 2) indicates that the Beagle Glacier had receded from the 300 m a.s.l. at least 12,060 ± 60 yr BP (Rabassa et al., 1990, 2000; Heusser, 1998). The disappearance of the confining pressure of the main trunk glacier allowed the high altitude glaciers to achieve independent behaviour, making possible their expansion, deposition of sediment, and genesis of accumulation landforms. According to this hypothesis, the end and lateral moraines (Martial II), should be related to the Late Glacial times and should be considered as the older glacial landforms of the system. Recessional moraines (Martial III) and younger moraines (Martial IV) located up valley and in the cirque floor, respectively, must have formed since the post Late Glacial up to the present.

The palynological analysis from Pista de Ski (300 m a.s.l.), and Ushuaia 2 (80 m a.s.l) peat bogs (Fig. 1) indicates that the climate was cold during the Late Glacial, the Younger Dryas, and the late Holocene (Heusser, 1998). The shift towards a cooler and humid climate since 5 ka BP was regionally observed in the inner Fuegian valleys and along the Beagle Channel up to its eastern mouth (Heusser, 1989a, b, 1990, 1995; Borromei, 1995). Unfortunately, peat bogs located adjacent to the Martial morainic complex have not been found.

Palaeotemperature analysis performed in marine waters of Ushuaia Bay (Fig. 1), show several periods of cooling (Gordillo, 1995; Obelic et al., 1998) from which the mean annual temperature at the base of the Martial cirque can be roughly estimated at 2.2°C in the first two cold periods and at 1.2°C during the glacial advance of recent centuries. Dendrochronological studies in the southern Fuegian forest, based on summer temperatures, have allowed recognition of cold periods around AD 1750–1780, 1820, 1875–1880, 1900–1945 and 1950. (Boninsegna et al., 1989). This data offers a first environmental approach for the development of the Little Ice Age in this part of South America.

Palaeoclimatic studies and radiocarbon dating in the Andean region of South America and the Subantarctic islands have distinguished at least three cold periods, including the equivalent of the Little Ice Age of the Northern Hemisphere, in the sense of Grove (1988). The reconnaissance of three cold periods with noted glacier advances, as defined by Mercer (1968, 1970, 1976, 1982) in some Western Patagonia calving glaciers and East Patagonia land-ended glaciers, was partially confirmed by Geyh and Röthlisberger (1986) in the western O'Higgins and Huemul glaciers, the former being a calving ice body. However, glacier advances older than 3 ka BP have not taken place in the Subantarctic islands, although expansion during the Little Ice Age seems to have been more important than in the South American Andes (Clapperton and Sudgen, 1988), beginning at the end of the XIIIth century and, with more clear evidence, in the XVIIIth, XIXth and XXth centuries in South Georgia (Clapperton et al., 1989).

Westwards, in northern Beagle Channel coast, Glacier Bahía Pía (Fig. 1) discharges the Cordillera Darwin mountain ice cap. Two Neoglacial advances and the Little Ice Age were defined there: (i) before 3060 yr BP; (ii) before 0.940 yr BP and (iii) in centuries XI–XIII, respectively (Kuylenstierna et al., 1996).

In spite of the nearness and similar glacier orientation, the Bahía Pía glacial sequence is not considered similar to Martial glacial scheme due to the tidewater condition that Pía Glacier would exhibit during the Early to Middle Holocene. The differential behaviour showed by the Patagonian glaciers, according to their orientation, temperature and/or precipitation influence on mass-balance, topography, and especially due to the typology of the ablation zone, are noted in glacier behaviour today (Warren, 1993; Warren et al., 1995; Aniya and Enomoto, 1986; Winchester and Harrison, 1996). They might have affected the glaciers' mass-balance during the Holocene as well, forcing their reaction to the climatic changes. According to Porter (2000), the available Holocene glacier chronology must be considered provisional until absolute dates are obtained for a large number of glaciers, avoiding those with calving or rock-avalanche influence.

The glacial geomorphological analysis of Martial cirque offers a tool for the knowledge of the glacial problem since the Last Glaciation. Further research in other cirques and high altitude valleys of the Fuegian Andes will be helpful to compare the glacial landforms systems and to establish absolute chronologies allowing determination of the influence of climatic changes in the high altitude landscapes in southernmost South America. The Fuegian Andes are strategically located in an intermediate location between Southern South America and the Subantarctic islands.

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