

Inventory of fossil cryogenic forms and structures in Patagonia and the mountains of Argentina beyond the Andes

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This article summarizes the most important observations of fossil cryogenic forms and structures in Patagonia and the mountains of Argentina beyond the Andes. The chronological history of cold episodes was based mainly on the dating of two important glaciations: the Great Quaternary Glaciation of 1.2 Myr ago, which represented a maximum of permanently frozen ground, and the expansion of permafrost during the last glaciation of 18–20 kyr ago. Special emphasis is given to those cryogenic indicators that irrefutably mark the occurrence of permafrost. In the earlier glaciation, the maximum expansion, which supposedly outreached the Río Colorado, left epigenetic ice wedge casts in North Patagonia, which penetrated soil profiles to a depth of over 3 m and express differences of up to 16°C from the present mean annual air temperature (MAAT). In the most recent glaciation, temperatures differed from MAAT by at least 14°C. The associated pseudomorphs are smaller in size than for the Great Quaternary Glaciation and so far have been found only in South Patagonia. They not only indicate a tundra environment near the glacial limits identified by Caldenius,¹ as in the area of the Río Deseado, for example, but are even to be found at the coast at the present day.

Introduction

The cryogenic processes of the Neogene left fossil traces in southern South America that are found in the Quaternary stratigraphy of Patagonia and may be observed clearly in mountain areas, particularly in the Andes. Meso- and microforms and structures indicate how the cold extended into the steppe. They also reveal the palaeoclimatic characteristics shaped by the cold episodes (cryomeres), when the extreme temperature minima of the Quaternary affected South America and even predominated at the higher latitudes of the southern part of the continent.

Both classic and recent publications on the Quaternary of Argentina describe, for example, the marine terraces of the Patagonian coast² and discuss the difficulty of their topographical or chronological interpretation.³ Many authors (see refs 1, 4–10, for example) have attempted to define the glacial environment at different times in the geological past, leaving many questions unanswered. The advance of the older glaciations has been intensively discussed.^{4,5,11,12}

Minor local glaciations (*glacioblastos* or *nidos glaciarios* in Spanish and in the terminology of Groeber) beyond the Andes are hard to imagine in Patagonia today, although an intensified aridity obviously prevailed in Patagonia, at least during the Last Glacial Maximum (LGM), but their occurrence cannot be ruled out completely for other glacial times. It is possible to define past glacial environments with certainty by means of end moraines,

which clearly mark the termination of cold episodes. Evidence is also derived from the great Andean glacial lakes, and landforms and structures that are characteristic of a glacial environment, such as drumlins and varves.

Trying to explain periglacial environments, however, is a more difficult task as such typical landforms are not always present. It is assumed that the periglacial structures in South America were the result of complex and sometimes atypical climatic, geological or regional conditions. This was certainly true for Patagonia and it may explain why periglacial environments in South America have hardly been taken into account by researchers concerned with the palaeoenvironment.

Czajka¹³ was one of the first to interpret fossil periglacial processes in South America in order to explain the Patagonian landscape, but his interpretations necessarily implied an extra-Andean glaciation. I have argued for a sequence of climatic denudation cycles, which display a tundra-loessic phase during the LGM, for example. This was when the netlike structures of Patagonian ice wedges were created, according to Czajka, and when the loess was deposited on the Pampean steppe and dunes and coarser sediments on its margins (the Pampean borders).

Clapperton, in his *Quaternary Geology of South America*,⁹ briefly summarized periglacial features. In order to establish a chronological order of cold episodes based on the interpretation of periglacial forms, Trombotto^{14,15} drew up the first inventory of cryogenic evidence. The present review is a new inventory of fossil cryogenic forms that may help to improve our understanding of the palaeoclimatic history of southern South America.

The periglacial and palaeoclimatic background

Today, South American permafrost (also called Andean permafrost) is a mountain permafrost type localized exclusively in the Andes. At the 31st International Geological Congress in Rio de Janeiro, Trombotto¹⁶ presented a preliminary regionalization of the main cryogenic areas in South America, including possible occurrence of permafrost. A more comprehensive study, however, allowed classification of Andean permafrost into a variety of subtypes.¹⁶ With the help of this taxonomy, it was possible to correlate permafrost types with hydrological and climatic conditions associated with global warming on the one hand and with the two great divisions characterizing the Andes of southern South America: the Dry (Desert and Central Andes) and the Wet Andes (Lakes Region and Patagonian Andes).

Permafrost occurs in equilibrium with environmental conditions. Thus, certain periglacial landforms are reliable indicators of climatic conditions such as temperature and precipitation. Morphogenesis within the ecosystem of fossil cryogenic environments is usually explained in terms of the characteristics and the morphodynamics of present cold environments.

The arid conditions, the dynamics of cryogenic processes as well as cryogenic mechanisms in volcanic petrology, and basaltic

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terraces in Patagonia in particular, raised many questions about the ambiguity of certain Patagonian structures and landforms. Their identification is complicated and the evolution of cryogenic processes in the past remains in doubt, so that further research is required.

Discontinuous (creeping) permafrost is found at 32–33°S in the Central (Arid) Andes of Mendoza, at 3600 m a.s.l., and island permafrost even persists at altitudes as low as 3450 m. In the Central Andes of San Juan at approximately 30°S, discontinuous permafrost is detected at 4150 m a.s.l. in the Dos Lenguas rock glacier, Agua Negra.¹⁷ In the 1990s, cryogenic phenomena combined with permafrost were registered 400 m below the 0°C isotherm.¹⁸ Regional arid conditions seem to reinforce the effectiveness of periglacial processes. Garleff and Stingl¹⁹ argued along these lines and introduce a de facto limit of 'quasi continuous permafrost' (a term that refers particularly to topography and exposure that creates landforms and important cryogenic activity). This limit is presently delimited by the –2°C to –4°C isotherms (4500 m at 33°S) in the Central Andes with an annual precipitation of 500–900 mm, and by the –1°C to –2°C isotherms with a precipitation of 300 mm in the Puna region of northwest Argentina.

At this limit of 4500 m a.s.l. and below, there is still a belt over 1 km wide that displays marked cryogenic phenomena. In the Southern or Humid Andes, permafrost was reported at 51°30'S in Santa Cruz between 1977 and 1978²⁰ at an altitude of 980–1100 m, while in the Lakes Region (between 35° and 45°30'S) in the province of Chubut, permafrost is today detected close to Lago Vintter (at c. 44°S) at an altitude of 2060 m (C. Bianchi, pers. comm.).

Garleff and Stingl²¹ have long insisted that there are different factors that distinguish and characterize cryogenic activity in the Arid and Humid Andes of southern South America. In the arid Central Andes it is temperature that determines the occurrence of permafrost and cryogenic phenomena, whereas in the Southern or Humid Andes precipitation plays a more decisive role. These differences imply that there may be disynchronicity in the evolution of the phenomena, and this must be taken into account when establishing palaeoclimatic and cryogenic chronologies. In contrast with current theories of Quaternary palaeoclimate and the circumstances which allowed cryogenic and morphodynamical activity, Garleff and Stingl²² and Garleff *et al.*²³ suggested that a temperature decrease during the LGM reinforced the growing aridity of the South American Arid Diagonal (the region between c. 25° and 45°S) and increased the influence of the westerlies without any shift of these western winds northwards as some authors argue. Groeber¹² pointed out the importance of westerly winds to explain the deposition of aeolian sediments in the Pampa region during the glaciations. But he based his assumptions about the atmospheric circulation on a model that is now questioned. Garleff and Stingl¹⁹ assumed that the mean annual air temperature (MAAT) today differed by approximately 15°C from that for the Central Andes and by 9°C for the Puna region during the LGM. Trombotto,¹⁵ based on the presence of ice wedge casts, calculated the depression of the MAAT during the LGM to be 14°C for South Patagonia. This value coincides with Garleff's estimates²⁴ of between 10° and 15°C for the region.

With evidence that included geomorphological data, the depression of the lower limit of the permafrost and strong cryogenic activity was calculated to be 2500 m in the northern part of the Humid Andes (in the Lakes Region), 2000 m in the Central Andes and 1000 m in the northwest of Argentina.^{19,25}

In the Central Andes around Mendoza, creeping permafrost

associated with rock glaciers supposedly reached down to 1200–1800 m a.s.l. at 32–33°S during the Great Quaternary Glaciation, in the sense of Mercer and when the Early Pleistocene glaciation reached its maximum expansion,^{6,26} whereas it is assumed that in the southern part of the province of Mendoza it penetrated as Patagonian permafrost (36°S) (Fig. 1).

During the Last Glacial episode (18–20 kyr), the surface covered by permafrost must have included the major part of the Patagonian steppe, possibly comprising more than the area that is affected by seasonal freezing today (Fig. 2).

During the Early Quaternary glaciation, temperatures were much lower, and the advance of the LGM limit was further north, occupying probably all of Patagonia and also lowering the altitude of the mountain permafrost limit. This doubtless occurred in earlier times too, according to the Neogenic advances reported by Schellmann.⁶⁶

Traces of past cold episodes

Fossil rock glaciers

The fossil rock glaciers of the Andes may be identified as landforms associated with active rock glaciers or as their geomorphological prolongation. Their activity is detected by means of geomorphology, geophysical prospecting and ground temperature profiles.¹⁸ Fossil debris rock glaciers are a direct link with present glaciers or Pleistocene ice-covered regions and their terminal moraines, as is often the case in the Central Andes. The talus rock glaciers, on the other hand, represent independent landforms.²⁷

Fossil rock glaciers have the following characteristics and associations:

- a) Traces of cirques and excavation hollows in mountainous areas subject to cryoweathering.
- b) Traces of snow-debris or nivodetritic channels on the slopes of the mountains, which functioned as a means of transport of cryoweathered material. These channels cut the cirque transversely and are of primary importance for the interpretation of talus rock glaciers, where the cirque is less significant or not recognizable with certainty.
- c) Lobe- or tongue-shaped relict forms. The rock glaciers left bulges as hanging tongues on the mountain slopes and piedmonts, and at the foot of the mountains with a post-frontal depression.
- d) Ridges of debris (*Haldenschutt*) left at the edges by the faster moving central channel of the glacier.
- e) Slopes with a predominantly southerly orientation.
- f) Rock glacier sediments may consist of large blocks and angular clasts on the surface but with a predominance of fine, angular sediments in their interior.
- g) Scanning electron microscopic analysis of superficial fine sediments, consisting of quartz grains of the size of medium and coarse sand by scanning electron microscopy (SEM), indicates a so-called glacier-like texture.^{27,28} These particles have the following general characteristics in an SEM: high relief, angular shape and conchoidal fractures, blocks, arch-like steps, and shattermarks. Deposition and dissolution of silica is also frequently found (see ref. 28) on the surface of the quartz grains.
- h) Sediments are sorted vertically at the front of a tongue.
- i) Blocks and clasts may be orientated with their major axis sloping downwards, but may also display marked surface damage and a subsurface of mixed orientation.
- j) The petrological component in talus rock glaciers may be monogenetic but frequently of varied petrology in debris rock glaciers with glacial origin.

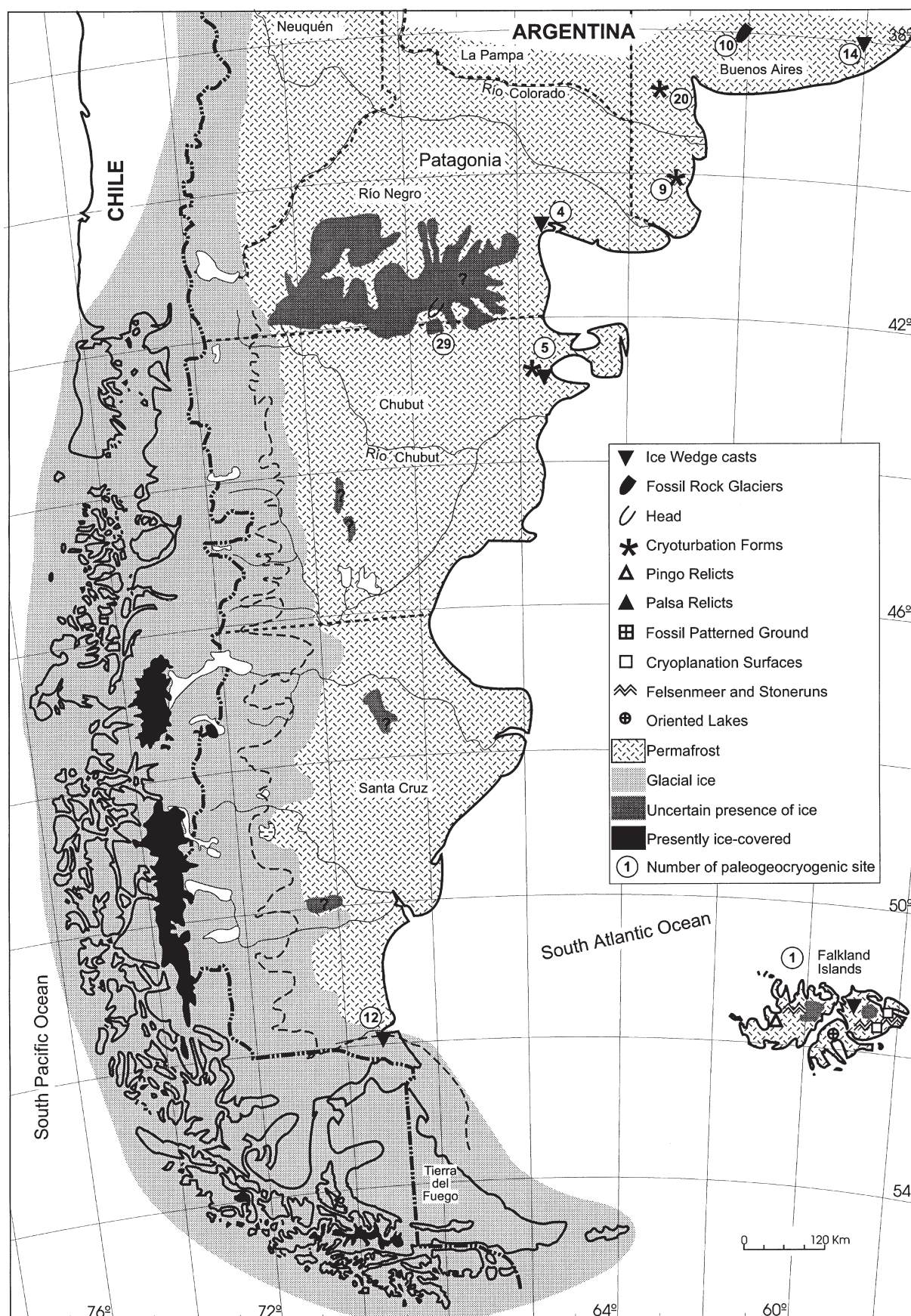


Fig. 1. Cryogenic structures and landforms in Patagonia assigned to the Great Quaternary Glaciation (c. 1.2 Myr ago), according to various authors. The numbered palaeocryogenic sites on this and the following map are: (1) Falkland Islands, (3) Pampa del Castillo, Holdich, (4) San Antonio Oeste, (5) Puerto Madryn, (6) Río Santa Cruz, (7) Tres Lagos, Río Chalia, (9) Stroeder, (10) Sierra de la Ventana, (11) Lago Cardiel, (12) Chimen Aike, Río Gallegos, (13) Río Deseado, (14) González Chávez, (20) Salinas Chicas, (27) Las Heras (North), (28) Cerro Kensel, (29) Somoncure, El Dinosaurio, (30) Río Santa Cruz and Río Deseado, (31) Lago Cami, (32) Meseta El Pedrero, (33) Romberg, area of the Meseta de las Lagunas Sin Fondo, (35) Puerto San Julián, (36) Telken.

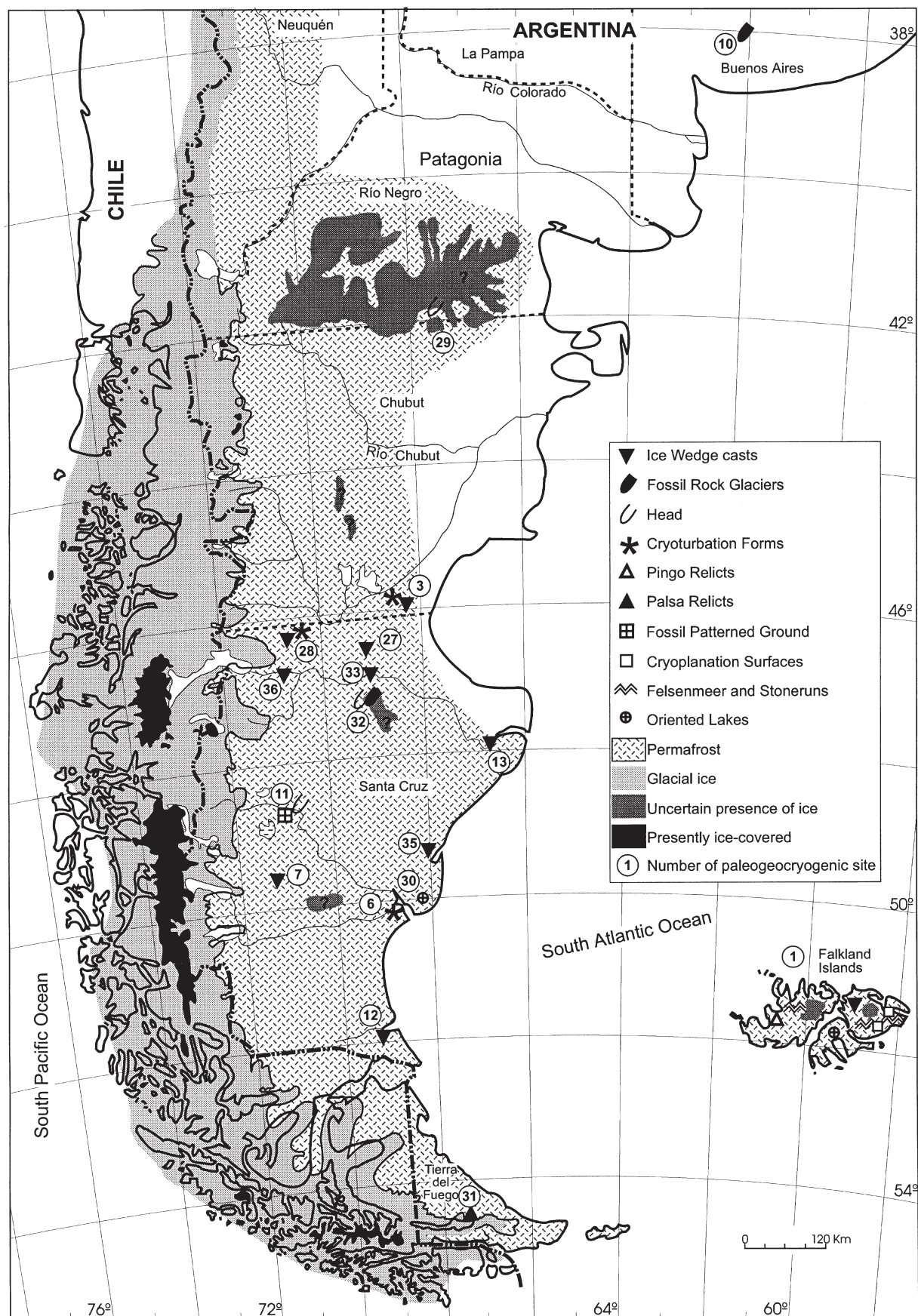


Fig. 2. Cryogenic structures and landforms in Patagonia assigned to the Last Glacial Maximum (18–20 kyr ago), according to various authors. Numbered sites as in Fig. 1.

Table 1. Examples of fossil rock glaciers in Argentina. The number in brackets indicates their location on the maps (Figs 1 and 2)

Palaeocryogenic sites	Altitude (m a.s.l.)	Latitude	Longitude	Assigned age	References
Sierra de Aconquija, Tucumán	2600	Approx. 27°S	Approx. 66°W	Pleistocene	37
Quebrada de los Árboles, Cerro El Áspero Precordillera, Mendoza	1100–1800	Approx. 33°S	Approx. 69°W	Period I: 1.2 Myr Period II: 700 kyr	28, 67, 68
Tomolasta, Sierras Pampeanas, San Luis	1750	Approx. 33°S		?	35, 28
Ventania (10), Sierras Australes, Buenos Aires	500–700	Approx. 38°S	Approx. 62°W	Pleistocene	13, 28, 35, 39, 67
Patagonia (32), Meseta El Pedrero, Region of the Meseta de las Lagunas sin Fondo, Santa Cruz (?)	c. 1000	47°S	69°W	?	14

k) Recurrence of the fossil rock glaciers in slopes of similar orientation.

The rock glaciers of the Cordón del Plata (at c. 33°S) show symptoms of inactivity at 3400 m a.s.l. Down to 3200 m, these glaciers may contain ice but below 3000 m they are considered to be fossil. At this altitude they were active only during the last glaciation.²⁹ Wayne and Corte³⁰ mentioned a sequence of fossil rock glaciers within the morainic Morenas Coloradas rock glacier at Vallecitos, Mendoza. Their interpretation is based mainly on the altitude, inclination and erosional modification of the fronts, weathering of surface clasts, and thickness of loess and vegetation cover. These parameters are not always clearly observable because of the disharmony in the permafrost creeping of different parts or identifiable bodies, which respond to subsurface ice. There may also be a superposition of the main body by talus rock glaciers, so that the main body presents active parts at lower altitudes, despite inactive parts at greater height.²⁹ This occurs frequently in such extensive Andean cryogenic forms as this one (over 4-km long and with an average width of 600–800 m). The inactive phase of a rock glacier often represents a state of transition that is hard to assess chronologically.

The so-called Dragon rock glacier at 34°S in the Cordillera Frontal of Mendoza, with a SE orientation, is one example of such a state. It has two different sectors: one is at an altitude of 3300 m and has a front tongue with an inclination of 28°; the other part at 3200 m has a front with an inclination of 26°. It is furthermore an example of glacial origin. The fossil part of it — easier to identify — begins at approximately 3175 m a.s.l. and has a maximum inclination of 15° at its front.

Fossil rock glaciers have also been sought in the geological regions Precordillera (province of Mendoza), Sierras Pampeanas [in this case the occurrence of cryogenic sedimentary slopes (*Schutthänge*) cannot be excluded²⁸], Sierras Australes and in the northwest of Argentina. Table 1 indicates the most important findings concerning the mountains of medium altitude.

The presence of fossil rock glaciers indicates a mean annual palaeoprecipitation of 500–600 mm; the termini of their tongues signify mean annual palaeotemperatures of around –1°C.

The surface textures of quartz grains (of sand size) from fossil rock glaciers were analysed by scanning electron microscopy by Trombotto.²⁸ Those cases listed in Table 1 indicate that the SEM technique detected textures of cryogenic origin in samples from Ventania, for example, whereas it was not satisfactory for specimens from Tomolasta, for which weathering and chemical processes largely obscure mechanically fashioned microtextures. In the case of the Quebrada de los Árboles fossil rock glacier it was

possible to identify typical evidence of mechanical working, such as the ‘washboard texture’. This was also obtained experimentally by compression,²⁸ although 70% of the samples displayed deposition or dissolution of silica.

Cryoplanations and relict nivation hollows

Keidel³¹ was one of the first in South America to mention cryoplanation surfaces, which he called *penillanuras cuspidales*. Although he did not give exact geographical positions, he emphasized their palaeoclimatic importance for the Puna region. More recently, Igarzábal and Rivelli³² reconsidered palaeocryogenic effects in the Cordillera Oriental, a geological region close to Puna, in order to explain the flattened land of the batholite of Tastil in a humid periglacial environment.

In the Andes in the province of San Juan, cryoplanation surfaces on mountain tops at 30°S can be found together with quasi-continuous permafrost at 5000 m and above, where temperatures are ≤4°C.³³ At the Lagunita del Plata (33°S, Mendoza), the cryoplanation surface starts to become inactive at 4000 m and below, with a mean annual temperature of about –2°C and a mean annual precipitation of c. 600 mm.

Cryoplanation surfaces are found throughout the Cordillera Frontal and Cordillera Principal regions of Mendoza. Fossil cryoplanation surfaces and relicts of tors are also known for the Falkland Islands, for example at Mt Kent at approximately 480 m, Mt Challenger and Wichham Heights.³⁴ The Falkland Islands, with their great variety of cryogenic fossil forms, indicate the significance of a past periglacial maritime climate (see ref. 9). Cryoplanation surfaces are closely related to nivation hollows. Nevertheless, they have been little considered for inventory-taking and their palaeoclimatic importance is underestimated.

Seasonal nivation hollows, with their inherited depressions from former perennial or more intense nivations, are frequently observed in the Central Andes between 3000 and 4000 m, depending on their orientation. The oldest forms display characteristic concavities with a threshold close to the cryogenic excavation. The bottom and centre of the nivation hollow accumulate fine sediments and more abundant vegetation.

Corte³⁵ reported on nivation hollows in the Sierras Pampeanas of San Luis. Clark³⁴ found them on the Falkland Islands at mounts Usborne, Adam and Maria (50°S); and Magnani³⁶ reported on such forms on the plateaus of South Patagonia near Lake Cardiel (48°S). In the basaltic region of the Meseta de las Lagunas sin Fondo at 47°S in Patagonia, relict nivation hollows have been identified with a southerly aspect.

Cryogenic sedimentary slopes, asymmetrical valleys and dells

Cryogenic sedimentary slopes were reported early in Argentina. Keidel³¹ called them detritic slopes (*pendientes de escombros*) and presented them as characteristic of the Puna region. It may be assumed that he also included rock glaciers under this term. He placed their lower limit at 4000 m without considering their degree of activity but he was conscious of their palaeoclimatic importance during previous cold episodes. Czajka (ref. 37, table 1) lowered the limit during the Pleistocene to 2600 m.

In the Sierra de Famatina (29°S), Richter denudation slopes (*Glatthänge*) are restricted in their activity to an altitude of 4000 m.⁴⁸ Detritic slopes (*Schutthänge*) and relict periglacial valleys abound in the Andes in Mendoza and San Juan, below or close to the present periglacial level, but further investigations are necessary for a detailed inventory.

Garleff *et al.*³⁸ made an inventory of dells for the elaboration of the geomorphological map of La Junta–Agua Nueva, interpreting morphodynamics and palaeoclimatic changes at the borders of the Andes at 35°S. Magnani³⁶ and Corte³⁹ reported on asymmetrical valleys in South Patagonia. The surface textures of quartz grains (sand size) from relict cryogenic sedimentary slopes were analysed by SEM by Trombotto²⁸ in an investigation of fossil cryogenic processes.

Solifluction forms, stone runs, blockfields and heads

Different types of solifluction forms in southern South America were described very early. Andersson⁷² was one of the first to mention this topic and to introduce the term solifluction to the international bibliography for the stone runs on the Falkland Islands. Blockfields (*Felsenmeer*) and stone runs (*Blockströme*) were investigated later by Clark,³⁴ Bellosi and Jalfin⁴⁰ and others in different parts of the Falklands.

Fossil solifluction layers have been reported in Patagonia where only seasonal frozen ground is recorded today. Magnani³⁶ described solifluction forms for the Patagonian *mesetas* but without mentioning any sites in particular. It should be remembered, though, that Caldenius, as early as 1940, referred to solifluction in order to explain the dispersion of the Patagonian Gravel (*Rodados Patagónicos*) (fluvial, fluvio-glacial or polygenetic gravels),⁷³ and Czajka¹³ questioned whether certain features, for instance in Pampa del Castillo, Patagonia, were solifluction or glacial phenomena (kames). Auer⁵ stated that the solifluction limit descended by 2000 m down to 2600 m at 27°S, while at 33° in the piedmont of the Cordillera Frontal, *Wanderblöcke* begin to become inactive only at an altitude of 2500 m.²⁸

Solifluction layers of Pleistocene age were also described by Regairaz at 2200 m for this site.⁷⁴ For Corte,^{35,41} however, the lower solifluction limit lies at 1500 m in the Precordillera of Mendoza and in the Sierras Pampeanas of San Luis and Córdoba. This limit extends even to 500 m in Ventania (Buenos Aires) at 38°S. Abraham de Vázquez and Garleff⁴² detected fossil solifluction layers at La Junta–Agua Nueva at approximately 1800 m a.s.l. (34–35°S).

The solifluction levels of the Patagonian profiles are recognizable but not as pronounced or as common as one would expect according to postulated palaeoclimatic models. This may be explained by petrology and the restrictions imposed by very low precipitation, which has characterized this area since the formation of the Andean chain. Nevertheless, solifluction layers of different undefined ages may be found from North Patagonia — on the southern slopes of the Meseta del Somoncuro, for example — and southwards.¹⁴

Auer⁴ mentioned evidence for solifluction in the Sierras

Australes (Buenos Aires), but played down the importance of solifluction in Patagonia⁵ because of few findings and insufficient precipitation there.

In South Patagonia at approximately 46°S there are several representative levels which are related to fossil ice wedge casts and were associated with the Last Glaciation^{39,43–45} (Figs 4, 6, 9 and 10). Corte³⁹ reported on fossil solifluction on the slopes of the southern Andes and Lake Buenos Aires.

On the Falkland Islands with their beaches from the pre-Holocene, Clapperton and Roberts⁴⁶ related solifluction layers to cryoturbation. Veit and Garleff⁴⁷ described solifluction layers with a thickness of 50–70 cm south of 42°S (72°20'W); north of this latitude such layers appear less frequently and are restricted to the SE part of the Valle Longitudinal and the Cordillera de la Costa (41°S, 72°20'W). The latter were assigned to the Llanquihue Glaciation (equivalent to the LGM).

Grèzes litées

Sedimentary layers of varying degrees of coarseness deposited by supra- or intranival processes were classified as relict *grèzes litées* and described by various authors, especially for the Central

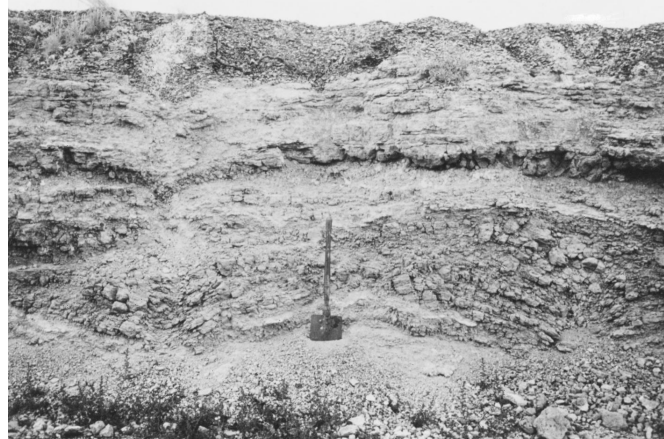


Fig. 3. Polygonal cryoturbation caused by epigenetic ice wedge casts which affected the sandstones of the Puerto Madryn Formation of the Upper Tertiary (Miocene), near the city of Puerto Madryn, Chubut; palaeocryogenic site no. 5, denominated Liß. Length of spade: 65 cm. The rest of the netlike structure with calcrete inside can be observed on the left. On the upper part of the profile are the *Rodados Patagónicos* (Patagonian Gravel), a fluvial conglomerate of acidic igneous rocks, which penetrated the cryogenic structure.



Fig. 4. Ice wedge casts from the Last Glacial Maximum, Holdich-Pampa del Castillo, Chubut; palaeocryogenic site no. 3. Length of hammer: 31.8 cm. The pseudomorphs penetrate up to 90 cm into the marine Oligocene and are filled with a solifluidal head (13–15 kyr?). The filling has more than 80% sandy material (quartz grains also show aeolian characteristics). On top of the ice wedge casts a palaeosoil indicates a warm episode (>15 kyr?).



Fig. 5. Cryoturbation, Cerro Kensel, Santa Cruz; palaeocryogenic site no. 28. Diameter of the camera lid: 5.4 cm. See Fig. 6.

Andes. Hitherto, however, it has not been possible to compile a detailed inventory or chronology.

The active deposition limit lies at approximately 3500 m a.s.l. according to Corte.³⁹ In the Precordillera of Mendoza, in Villavicencio at about 33°S, such fossil sediments appear at an altitude of approximately 2500 m.

Beyond the Andes, Corte³⁵ reported on *grèzes litées* for the Sierras Pampeanas (Cerro Pelado, San Luis) and Sierras Australes (Ventania, Buenos Aires) at 1500 m and 600 m, respectively, but they have not yet been studied in detail.

The quartz grain surface texture of *grèzes litées* was analysed with SEM by Trombotto.²⁸ These samples revealed not only a 'frost texture' characterized by conchoidal fractures and large blocks, ogival fractures on the edges, arch-shaped conchoidal fractures and irregular diagenetic surfaces to name a few, but also signs of subaquatic impressions due to nivofluvial activity.

Patterned ground and fossil cryoturbation

Stingl and Garleff⁴⁸ found evidence of fossil cryoturbation in the Sierras de Famatina (29°S) at 4200 m a.s.l. in the Central Andes of Mendoza, as well as at La Junta-Agua Nueva⁴² at 1880 m at c. 34°40'S. In Villavicencio, in the Precordillera of Mendoza at 33°S, it was detected at approximately 2500 m, marking an important lower limit of fossil cryogenesis.

Auer⁴ mentioned traces of cryoturbation in connection with the Patagonian Gravel, from Stroeder (40°S) southwards to 50°30'S and he also quoted cases from Ventania at 38°S. In general, these forms were reported together with indicators that support the argument for minor local glaciations. Czajka⁴⁹ associated the system of valleys at Pampa del Castillo (South Patagonia) with glacial processes (dead ice of kames). In 1967 Corte explained involutions and cryoturbation foldings in the area of Río Gallegos in terms of cryogenic criteria only. The cryoturbation forms affect Tertiary rocks — mainly sandstone — as in Salinas Chicas (southern part of the province of Buenos Aires) and Puerto Madryn (North Patagonia⁵⁰). From their stratigraphy, the forms at the sites of Holdich-Pampa del Castillo and Romberg (South Patagonia) were assigned to the LGM.^{14,43,44} Cryoturbation also affects the lower and upper and/or intermediate levels of the Patagonian Gravel.^{51,52}

Very few examples of relict, patterned ground have been found or reported. In the area of Vallecitos in the Central Andes of Mendoza, some examples were identified by Trombotto at 3000 m, but they are badly preserved. Magnani³⁶ reported on polygonal ground for the area of Lake Cardiel in South Patagonia (at c. 49°S) at 500 m a.s.l..



Fig. 6. Ice wedge cast from the Last Glacial Maximum, Cerro Kensel, Santa Cruz; palaeocryogenic site no. 28. Length of hammer: 31.8 cm. The filled material is rich in sand (c. 75%), whereas the host material is rich in CaCO₃, clay and gravel. The dark patches are indications of cryoturbations in a solifluidal layer. On the top of the pseudomorphs a palaeosol indicates a warm episode.

Less pronounced patterned ground with deformations due to inclination (*Kometenschweif* type⁵³), however, also appear in areas away from the Andes such as the Meseta El Pedrero, in the province of Santa Cruz.¹⁴

Fossil ice wedges and polygonal cryoturbation

Fossil ice wedges are the most important cryogenic structures in the Patagonian stratigraphy. Cryoturbation is also usually linked with ice wedge casts and polygon development.

Although mentioned previously by Auer^{4,5} Czajka^{13,37} and Corte,⁵⁴ fossil ice wedges were little considered in the interpretation of Patagonian stratigraphy and palaeoclimate. The discovery of fossil ice wedges, among other indicators, led to the belief in the extension of Pleistocene permafrost up to the Río Negro,³⁷ a limit that later was extended to the Río Colorado by Corte.^{26,39} The characteristics of very old epi- and syngenetic ice wedge casts in North Patagonia were described by Trombotto.^{51,52} The casts extend to a depth of nearly 3 m and indicate a temperature difference of at least 16°C compared to present MAAT and a much lower annual precipitation than today (500 mm/yr). Those

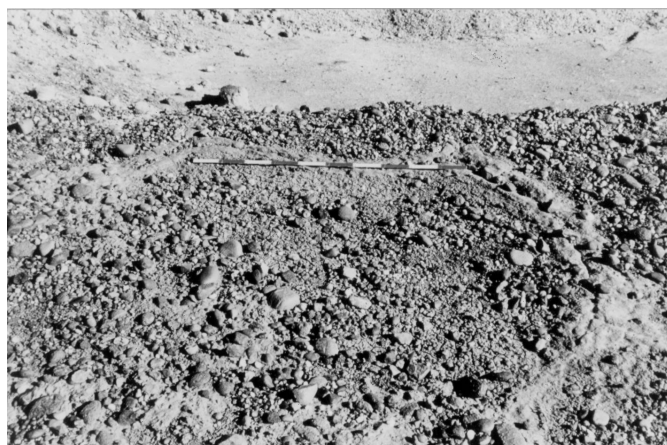


Fig. 7. Fossil polygonal network with upheaval on the borders (German *Randwülste*) indicating ice pressure. Las Heras (N), Santa Cruz; palaeocryogenic site no. 27. Length of the measure: 1 m. See Fig. 8.



Fig. 8. Ice wedge cast from the Last Glacial Maximum, Las Heras (N), Santa Cruz; palaeocryogenic site no. 27. Length of the measure: 50 cm. The pseudomorphs penetrate up to 70 cm of a sandy, calcareous layer with Patagonian Gravel. The sediments of the filling are composed mainly (c. 80%) of sand.



Fig. 9. Two generations of ice wedge casts from the Last Glacial Maximum (called the Romberg cryomere), vicinity of the Meseta de las Lagunas sin Fondo, Romberg, Santa Cruz; palaeocryogenic site no. 33. Length of pocket knife: 9 cm. The last generation of pseudomorphs cut a 40 cm solifluidal head with CaCO_3 and polyhedral structure. At the top a 10 cm horizon indicates another palaeosol with polyhedral structure but without CaCO_3 .

cold episodes apparently occurred during and after the deposition of the Patagonian Gravel. These cryogenic phenomena at Puerto Madryn were called Penfordd⁵¹ after the Welsh name of the site where they were found.



Fig. 10. Ice wedge casts from the Last Glacial Maximum in Telken, NW of the province Santa Cruz; palaeocryogenic site no. 36. Length of hammer: 31.8 cm. The dark polyhedral horizon outlines the cryogenic structures, indicating a palaeosol or warm episode.

Ice wedge casts assigned to the Last Glacial are less well developed. They have a maximum depth of 90 cm and a width of 30 cm and appear only in South Patagonia. The structures (at 46°S) indicate a temperature difference from the present MAAT of at least 14°C and are good examples of hexagons with convex borders (Fig. 7). The fine and medium sand that fills the wedges displays a certain inner orientation into thin vertical layers with little or no lateral pressure of adjacent sediments. The palaeocryogenic sites investigated were Holdich-Pampa del Castillo, Romberg, Las Heras and Cerro Kensel.^{43–45}

The northernmost cases of pseudomorphs were reported by González and Corte⁵⁵ at approximately 38°S, 60°W at 200 m a.s.l. in the province of Buenos Aires, and by Grosso and Corte⁵⁶ in the west of Argentina, with two generations identified in the area of Río Diamante (34°S, 825 m a.s.l.) in the province of Mendoza.

Pseudomorphs were also identified in the Sierras Azul and Media Luna (1640 m a.s.l.) at 38°16'S in the Cuyo region (Mendoza)⁴² at a critical altitude in terms of the cold Quaternary climate.

Table 2 summarizes the latitudinal permafrost advance in Patagonia characterized by ice wedge casts at important palaeocryogenic sites, some of which are illustrated in the photographs (Figs 3–10).

Other forms: pingo traces and orientated lakes

Although Clark³⁴ mentioned orientated lakes at Choiseul Sound and Lafonia as well as fossil pingos on the Doyle River (Falkland Islands), these forms are scarcely reported on for Patagonia, presumably for lack of investigation.

The so-called *pequeños bajos sin salida* (small basins without outlets⁵⁷) of Patagonia have sometimes been taken into account because of their genesis. Some authors considered them to be traces of the Patagonian periglacial environment of the Pleistocene. Certain *bajos sin salida* (German *Kaven*) in the province of Santa Cruz were interpreted as pingo traces by Garleff.²⁴ Corte²⁶ reported on a fossil pingo on basaltic rock at La Leonora in South Patagonia, but this has to be confirmed by further research. The same author³⁹ identified orientated lakes at the mouth of the Santa Cruz River and on the plains of the Río Deseado and mentioned fossil palsas near Lake Cami (Fagnano) in Tierra del Fuego.

A detailed inventory of peatlands (moor) or fossil *mallines* (a kind of anmoor with a genesis similar to a fenmoor) for a reconstruction of palaeoclimate still has to be compiled.

Conclusions and recommendations: towards a chronology of cold episodes in southern Argentina

Neogenic cryogenic processes left structures and fossil forms in Patagonia that may be observed in the stratigraphy and in the southern Andes below 2000 m a.s.l. at 44°S and even at 1000 m at 51°30'S. The limits of permafrost extension during the Neogene varied according to the cold episodes, and were particularly pronounced in southern South America. The exact permafrost limit, periglacial geomorphology and cryogenic structures, however, are still not well defined but hold important clues for understanding the climate in the Tertiary–Quaternary of Patagonia.

Two cold episodes have been examined that are based on datings with glacial, marine and other indicators:^{6,7,9,58–60} (a) the Great Quaternary Glaciation of 1.2 Myr ago, which represented a maximum of permanently frozen ground; (b) the expansion of permafrost during the latest glaciation of 18–200 kyr ago, which affected the uppermost parts of the geological profiles in the South Patagonian stratigraphy.

Corte,^{26,39} however, assigned the tills of South Patagonia of 3.5 Myr and 1.2 Myr (lower and upper till) to two generations of very old ice wedge casts in Río Gallegos–Chimen Aike. A third generation of pseudomorphs was assigned to the peak of the LGM 40 kyr ago. He compiled a first draft of a chronostratigraphical order of cryogenic events by applying different dating techniques. Cryogenic forms in Mendoza, for example, were assigned to an age of 450 ± 60 kyr (in relation to the 'pyroclastic pumice association', a volcanic, petrological sequence). In the case of the El Áspero fossil rock glacier, however, it was assumed that one part of it had been buried by volcanic ash of the age mentioned. The fossil ice wedge casts and cryoturbation in the area of Río Diamante were dated on this assumption and taking into account the sequence of fluvial terraces.⁵⁶

The ages of fossil ice wedges and cryoturbation in Puerto Madryn were questioned by Trombotto,^{51,52} who considered the structures to be much older (possibly of the Old/Oldest Pleistocene glaciation, called the 'Initioglacial') than those resulting from CaCO_3 datings of the ice wedge cast filling and their exterior CaCO_3 datings that were assigned to the cold maximum of the LGM (see refs 61, 62). Trombotto^{14,15} and Trombotto and Ahumada^{63,64} proposed that their age coincided with the most intensive cryogenic advance with increased humidity, the Penfordd cryomere, which even extended into North Patagonia.

Solifluction limits have been identified in Patagonia but they are less developed and not as common as expected, probably owing to the restrictions of low precipitation, which characterizes the regions since the rise of the Andean chain. Solifluction layers may nevertheless be observed in North Patagonia as, for example, on the southern slopes of the Meseta del Somuncura.

The conditions of the LGM approximately 20 kyr ago created significant cryogenic forms, such as ice wedge casts, only in South Patagonia.⁴⁵ The latter may probably be correlated with solifluction layers and cryoturbation recorded by Clapperton and Roberts⁴⁶ on the Falkland Islands, based on a palaeosol dated to approximately 26 kyr.

Whereas the Falkland Islands display the most varied periglacial forms of a past oceanic climate, the Patagonian periglacial is influenced by very low precipitation and extremely low temperatures very different from today.

Pingo traces and a possible fossil rock glacier have been reported in the area of the basalt Meseta El Pedrero and require further research.

The most recent pseudomorphs in South Patagonia are covered by solifluction layers assigned to a cold episode in the Last Glacial of the Upper Pleistocene (13–15 kyr ago), accompa-

Table 2. Palaeocryogenic sites with ice wedge casts. The number in brackets indicates their location on the maps (Figs 1, 2).

Palaeocryogenic site	Latitude	Longitude	Assigned age	Reference
San Antonio Oeste (4) Río Negro	40°50'S	65°30'W	GQG	4, 37
Puerto Madryn (5) (minimum 2 generations) Fig. 3 Chubut	42°40'S	65°W	LGM	4, 5, 39, 63, 64, 69
Pampa del Castillo, Holdich (3), Fig. 4 Chubut	45°50'S	68°W	LGM	37, 43, 44, 49
Cerro Kensel (28) Figs 5, 6 Santa Cruz	46°05'S	70°31'W	LGM	43, 44
Las Heras Sur (27) Santa Cruz	c. 46°30'S	c. 68°55'W	?	43, 44
Las Heras Norte (27) Figs 7, 8 Santa Cruz	46°30'S	68°55'W	LGM	39, 70
Romberg (33) 2 generations, Fig. 9 Santa Cruz	46°40'S	68°50'W	LGM OIS 2 (c. 13–30 kyr) OIS 4 (c. 58–73 kyr)	14, 45
Telken (36) Fig. 10 Santa Cruz	46°48'S	71°46'W	LGM	This article
Río Deseado (13) Santa Cruz	47°52'S	66°35'W	LGM	5
Tres Lagos, Río Chalia (7) Santa Cruz	49°35'S	71°25'W	LGM	4
Río San Carlos, Falkland Islands (1)	51°30'S	59°W		34
Chimen Aike– Río Gallegos (12) (2 or 3 generations) Santa Cruz	51°40'S	69°20'W	Lower till: 3.5 Myr (?) Upper till: GQG 40 kyr (and/or 24 kyr)	26, 39, 54, 71

LGM, Last Glacial Maximum (c. 18–20 kyr); GQG, Great Quaternary Glaciation in sense of Mercer⁶ (c. 1.2 Myr); OIS, oxygen isotope stage.

nied by a glacial advance reported by Mercer^{58,65} that follows an interstadial represented by a palaeosol frequently found in South Patagonia.^{15,43,44} A characteristic profile at the penultimate fluvial terrace of the Río Deseado, however, reveals that the structures supposed to be of pleniglacial age also cut across an older solifluction layer and extend downwards. Towards the lower part of the profile there even appear relicts of structures or even older pseudomorphs. The sequence of sedimentary structures and forms coincides closely with the last oxygen isotope stages but absolute datings are required to confirm this.

The most recent events¹⁴ are called the Romberg cryomere after the name of the *estancia* near the profile. Recently, Shellmann⁶⁶ dated Last Glacial ice wedge casts from San Julián, which are cryoturbating coastal levels containing molluscs. These pseudomorphs share the same characteristics as those found at Romberg, Kensel, Holdich, Las Heras and recent findings at Telken (province of Santa Cruz).

The palaeoclimatic history of southern South America remains poorly known. The dating of cryogenic structures and landforms in Patagonia in particular will make an important contribution to our understanding of this history.

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