Characteristics and geomorphological implications of the periglacial environment of Craig Cŵts, Patagonides, Chubut, Argentina

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Abstract

Glaciations and cold episodes, which shaped the current Humid Andes (regional name Andes Ap Iwan) as well as the Patagonian steppe, developed mainly during the Quaternary. In this work, a geomorphological and paleoclimatic study of the region called Craig Cŵts in the Patagonides mountain range in Patagonia, is carried out. Through parameters obtained from active, inactive and fossil landforms, it was possible to develop a preliminary climatic reconstruction from the present to the Last Glacial Maximum, given that records of the most important Pleistocene glaciations were also detected. Identified Holocene events (cryogenic and glacial) were assigned to the Andean Neoglacials. These cryogenic scenarios are well represented everywhere in the Craig Cŵts range. Numerous different cryoforms that interact with the lithology, structures and hydrology of the region were found. Regional isotherms were calculated and mountain permafrost or permanently frozen ground was discovered in the highest part of the area, from 1970 m ASL upward to 2019 m ASL (the summit of Mount Edwin). The data were applied to a preliminary isotherm model to calculate possible and probable permafrost distribution scenarios. The model was also successfully compared to other models as the "Continental Permafrost Distribution Model for the South American Andes" of Arenson et al. (2021). For the first time, the Craig Cŵts region is analyzed in detail for its periglacial environment and permafrost in the present day and in the past to transform it into a key area for the Patagonides. The identified cryogenic geoforms have been shaping the current periglacial landscape until the present.

1.0 Introduction

Glaciations and cold episodes, which shaped the current Humid Andes (regional name Andes Ap Iwan) as well as the Patagonian steppe, developed mainly during the Quaternary. In this work, a geomorphological and paleoclimatic study of the region called Craig Cŵts is carried out (Figure 1). Through parameters obtained from active, inactive and fossil landforms, it was possible to develop a preliminary climatic reconstruction from the present to the Last Glacial Maximum. There, records of the most important Pleistocene glaciations have also been found. Identified Holocene events (cryogenic and glacial) were assigned to the Andean Neoglacials (see Mercer 1985). These cryogenic scenarios are well represented everywhere in the Craig Cŵts range. Numerous different cryoforms that interact with the lithology, structures and hydrology of the region were found. For the first time, the Craig Cŵts region is analyzed for its periglacial environment and permafrost in the present day and in the past to transform it into a key area for the Patagonides. The identified cryogenic geoforms have been shaping the current periglacial landscape until the present, but they also have been conditioning the regional hydrology.

2 Study Area

The study area Craig Cŵts (Figure 1) is located in the Patagonides, Precordillera of the province Chubut, Argentina, an extra Andean mountain massif between parallels 43° and 43°40'S in Patagonia (also called Celtic Patagonia, because of Welsh colonization). The area is quite unexplored and unknown from a geological and geomorphological point of view. A first regional map with original names by Ap Iwan (1888) is used. Peaceful coexistence between Welsh people and Aóni Kenk and Gününa Küne ethnic groups from southern and northern Patagonia respectively, is shown on this type of map, that included many of indigenous names and help us to understand the landscapes, as well as relatively unknown zones. The calculated mean annual air temperature (MAAT) of the study area at the temporary measurement station Craig Cŵts (43°27'48''S, 70°55'17''W, 1670 m ASL) on a moraine between the glacial lakes Ogwen and Hughes, for the period between 2017 and 2022, was 2.7 °C. The precipitation regime was taken from the nearby locality Gwyndy (43°16'35''S,71°09'22''W, 710 m ASL) between 1988 and 2018, for which a mean of 315.5 mm is recorded per annum.

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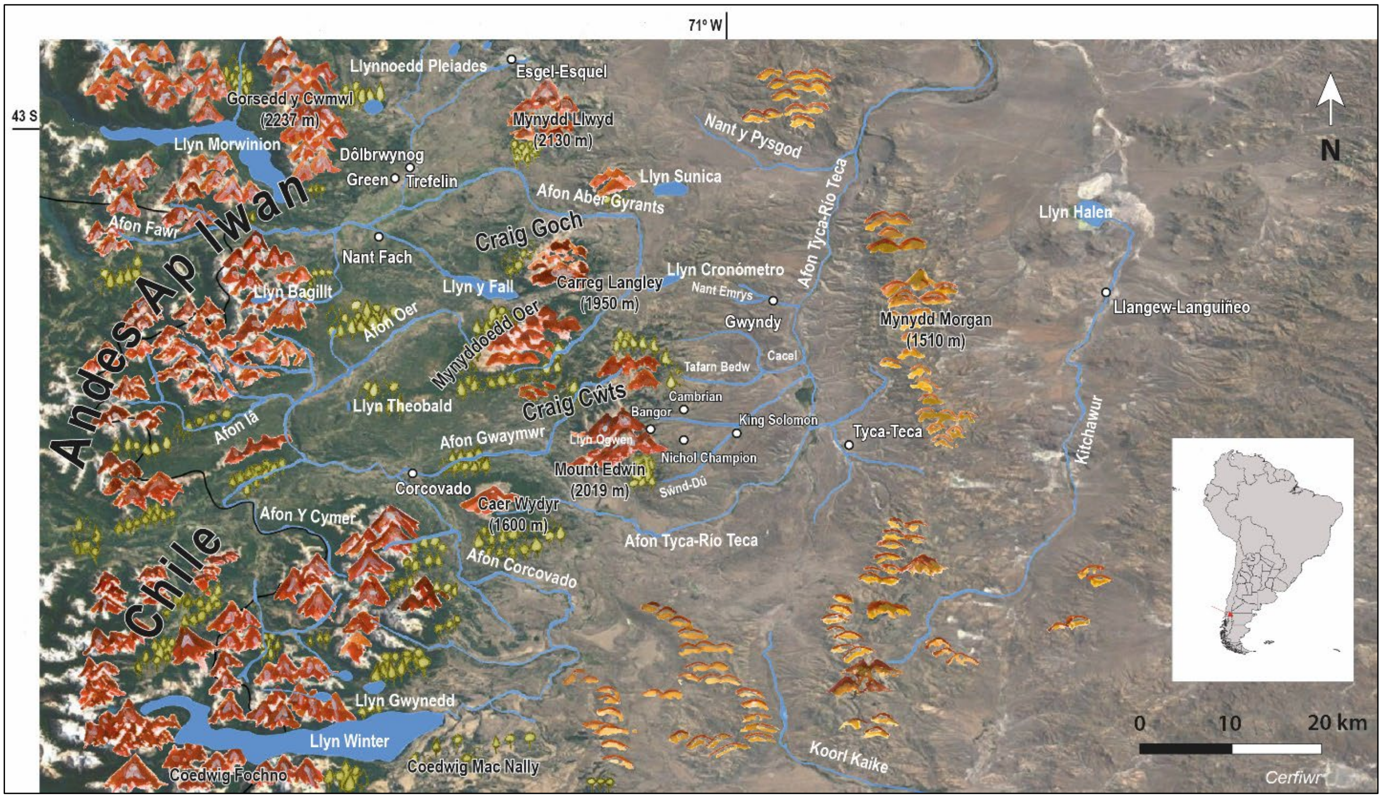

Figure 1. Study area and cryogenic landforms (Trombotto Liaudat, 2021).

The climograph (Figure 2) indicates in black the months (between May and September) when the average daily minimum and they average daily temperatures are below 0 °C. The remaining months are with absolute minimum below 0 °C. While the absolute minimum was -15.42 °C (July 2020), the daily average minimum of the coldest month was -6.4°C (July 2022). The upper limit of the forest with intense seasonal freezing cycles, cryoweathering and solifluction without permafrost reaches up to 1500 m.

The weather station at Esquel Airport (see Esgel, Figure 1) shows no long-term trend in MAAT in the period of record between 1931 and 2022. However, there is decadal variability and particularly the period between approximately 1950 and 1975 shows on average a MAAT that is about 1 °C colder than in the period from 2017 to 2022.

This implies a c. 150 m lowering of the zero isotherm at that time. The upper elevation of the tree line at Craig Cŵts is located at approximately 1510 m ASL, and descends to the east and north to approximately 1200 m. To the west and south, the forest may descend farther down, for instance to elevations of 900 and 1000 m ASL respectively. Then, the forest descends in "gallery" accompanying the creeks. Above the tree line, the landscape is largely shaped by current cryogenic processes.

The lithology of the study area is composed mainly of Early Mesozoic (Jurassic) andesitic and dacitic rocks (Massaferro 1998; Haller et al. 2010). However, from the same age, pyroclastic rocks such as tuffs, lapilli and breccias as well as clastic and carbonate rocks appear (Table 1).

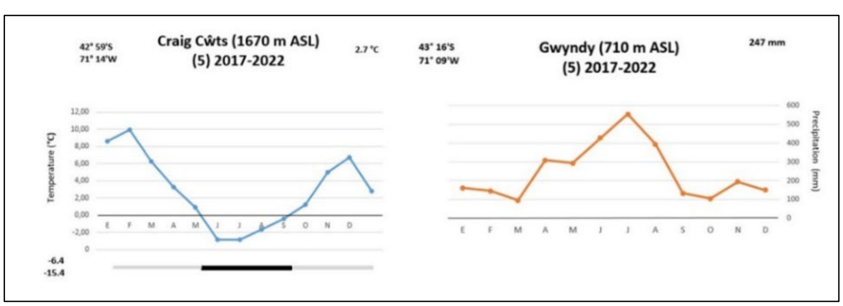

Figure 2. Walter Lieth climograph of the study area.

Given the effects of cryoweathering at Mount Edwin (2019 m ASL), unconsolidated Pleistocene to Holocene age periglacial sediments cover slopes as colluvium on surrounding slopes. Former creeping permafrost forms, such as fossil rock glaciers, carried volcanic cryoclasts (i.e., andesites, Jurassic, Lago La Plata Formation; Haller et al. 2010) below 1500 m ASL. Other clastic periglacial sediments are transported through contemporary processes including rock falls and active nivodetritic channels are also involved. Till, in the form of Pleistocene and Holocene moraines, is present around lakes Ogwen and Hughes. These are clearly seen given the absence of vegetation up to 1500 m ASL (Figure 1). Holocene fluvial and alluvial sediments are deposited in the creeks.

Table 1. Geology of the region based on Turner (1982), Massaferro (1998) and Haller et al. (2010)

Age			Geological Units	Litology
Cenozoic	Holocene			Unconsolidated periglacial, fluvial, alluvial and colluvial deposits
	Ptc.	L, M		Unconsolidated glacial, periglacial, fluvial, alluvial and colluvial deposits
		E	Huaiqui Formation	Polymictic conglomerates
	Miocene		La Mimosa Formation	Tuffaceous siltstones, limestones
	Eocene		Huitrera Formation	Dacitic dykes, tuffs, breccias, sandstones and siltstones
Mesozoic	K		Río Hielo Granitoid	Granitoid
			Divisadero Group	Andesitic dykes and rhyodacites
	J		Lago La Plata Formation	Andesites, rhyodacites, limestones; pyroclastic, epiclastic and bioclastic rocks
			Lepá Formation	Conglomerates, sandstones and siltstones

3 METHODOLOGY

Mapping of landforms was carried out in two steps. First, from the processing and visualization of satellite images and digital elevation models (DEMs), with which it was also possible to obtain the contour lines and streams. The results were drawn into a Geographic Information System (ArcGIS). Such mapping was controlled and corrected through field surveys. Periglacial landforms (Hughes 2023) were classified according to their present state of activity, namely:

1. Paleo-permafrost landforms;
2. Landforms/Cryoforms with current permafrost; and
3. Macro and microforms related to seasonal freezing and thawing cycles.

Each landform was visited during different fieldtrips (2016–2023). Pits were made in order to find cryogenic phenomena in the stratigraphy, or specific cryogenic indicators of the active layer.

The region has no recorded instrumental weather information given the absence of weather stations. To know the in situ current climatic conditions and isotherm positions, the area has been equipped with UTL data loggers since 2017. In this way, the data were used to calculate the regional isotherms. A value of 2.7 °C (MAAT) from the lake Ogwen moraine meteorological station was established, from which the 0 °C isotherm (cf. Ruiz and Trombotto 2012a) and other isotherms at higher elevations. For this aim, two different methodologies were used.

The first method consists of using an algorithm, relating both the MAAT with altitude, and a variation gradient of the MAAT with altitude. We considered a standard adiabatic gradient for a relatively dry atmosphere of -0.65 °C/ 100 m:

$$\mathrm{Iso0^oC(m)} = \mathrm{MAAT} / c + h0 \qquad [1]$$

where MAAT is the mean annual air temperature, h0 is the height of the station and c the thermal gradient.

To locate the position of isotherms other than 0 °C, the following linear regression was used:

$$Z1\ (m) = \frac{(T1 - T0) - (c \times Z0)}{-c} \qquad [2]$$

where Z1 is the height of the 2 °C/4 °C isotherm; Z0 is the height of the Cŵts station, T1 is 2°C or 4 °C, T0 is the average annual temperature at the weather station and c is the thermal gradient.

The second method involved generating isotherms from a model consisting of a continuous field of MAAT values (Raster) interpolated from a GIS software using data from the nearest meteorological stations. As the weather stations are located at different altitudes, it was necessary to calculate a homogeneous surface using an H-reference, as well as a MAAT-reference.

$$\Delta H = \text{H-reference} - \text{H-weather station}$$

For the H-reference, the H of the Craig Cŵts weather station at 1670 m ASL was used. The calculation of the MAAT-reference was made as follows:

$$\text{MAAT-reference} = \text{MAAT- weather station} + (c \times \Delta H)$$

The TMAA-reference was used as the Z coordinate corresponding to a station marked in the GIS software. The reference surface obtained was projected onto a DEM (Fries et al., 2012; Tapia and Trombotto, 2015). The work used the Natural Neighbor interpolation method to calculate a desired isotherm. This is calculated in a GIS software with a Raster calculator under the expression:

$$\text{MAAT-isotherm} = \text{MAAT-interpolation} + (c\ (\text{DEM}\ (xyz) - \text{H-reference}))$$

Where the expression (DEM (xyz) – H-reference) represents the altitude value of all the other points of the

DEM that are not contained on the reference surface, it is possible to obtain a new Raster whose Z coordinate represents the average annual air temperature estimated all over the DEM.

Once the height of the isotherms was known through the two methods used, three cryogenic zones with different probabilities of permafrost occurrence were defined according to the following MAAT thresholds (Ruiz and Trombotto 2012b; Tapia and Trombotto 2015):

- < 0 °C = Periglacial zone, likely permafrost (LP)
- 0 °C to < 2 °C = Periglacial zone, possible permafrost (PP)
- 2 °C to < 4 °C = Periglacial zone, no permafrost (NP), with periglacial phenomena due to strong seasonal freezing
- > 4 °C = No periglacial, seasonal freezing

The model was also successfully compared with other models such as the "Continental Permafrost Distribution Model of Arenson et al. (2021). Permafrost, perennial snow patches and regional glacierettes were mapped following geocryological classical methodologies (Washburn 1979; Karte and Liedtke 1981; Garleff and Stingl 1986; Trombotto et al. 1999; Bolch and Schroeder 2000).

4 RESULTS

4.1 Periglacial Geomorphology

The Craig Cŵts region (Figure 3) shows typical erosive and depositional glacial landforms, such as nearby U-glacial valleys, cirques, sheepback rocks, moraines and outwash plains. Today there are glacierettes in the region, but from the glacial point of view they are of little importance. However, they permanently occupy 10 highly visible nivation niches in the remaining Little Ice Age cirques (Figures 4 and 5; Table 2). Furthermore, in order to corroborate the existence of permafrost in Craig Cŵts, pits to 2.5 m depth were made in the area of perennial snow patches, and permafrost was found underneath. However, the most numerous periglacial landforms are those left by Holocene paleo-permafrost, such as stone runs, blockfields, kurums, solifluction lobes and terraces, as well as fossil rock glaciers (Figures 6 and 7). Some of these landforms are interrupted or hidden under Nothofagus forests. The most important fossil rock glacier is 800 m long in its visible part.

Above 1850 m ASL the landforms are associated with present permafrost. They include patterned ground, cryoplanation surfaces, cryogenic sedimentary slopes, nivation hollows, soli and gelifluction lobes and terraces (e.g., terracettes and garlands), protalus lobes and both active (up to approx. 80 m long) and inactive rock glaciers (Figures 3, 7 and 8).

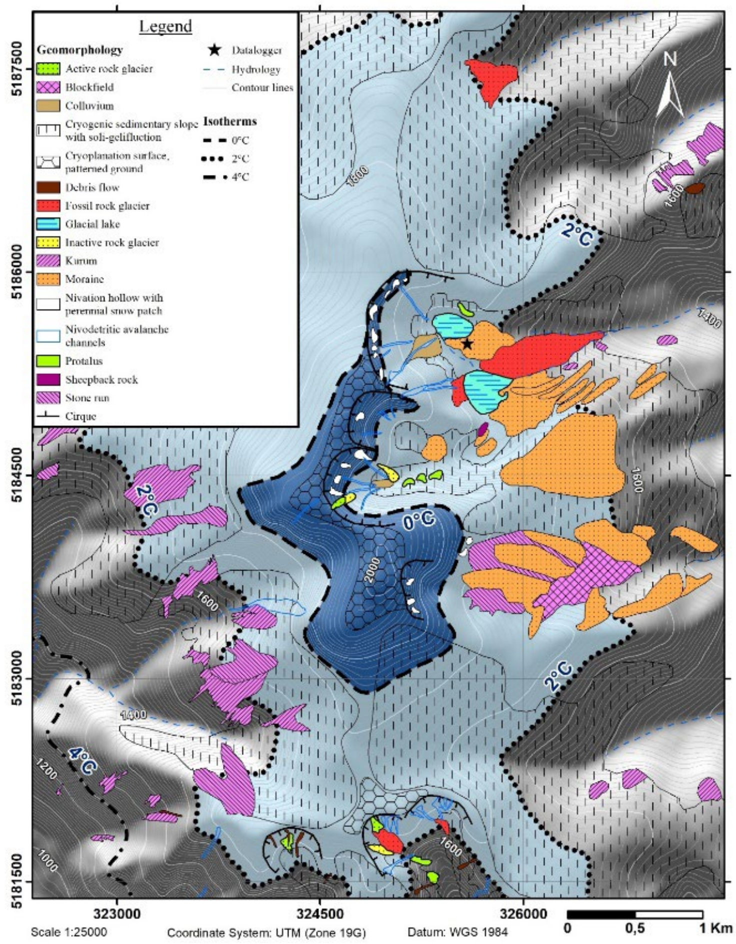

Figure 3. Cryogenic Geomorphology at Craig Cŵts.

Table 2. Comparison of present glacierette areas in the region with those indicated in the National Inventory of Glaciers for the year 2015 (software QGIS 3.28.8).

2015		2021	
Number	Area (m2)	Number	Area (m2)
1	21770.92	1	4250.92
		2	5029.9
2	26584.64	3	5776.26
		4	2882.03
3	33276.24	5	3984.44
		6	4370.96
	0	7	1734.94
4	14774.39	8	1621.95
5	27319.76	9	9790.58
6	15969.69	10	8929.98

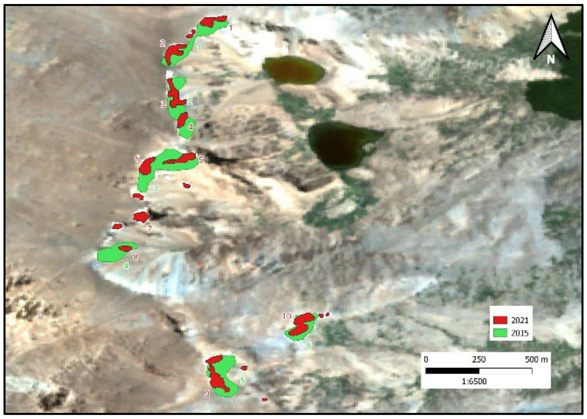

Figure 4. Image Sentinel 2A from January 30, 2021. Snow patches without number are < 1000 m^2.

Figure 5. Pits made in glacierette: a) general view of the glacierette number 2, 2021; b) section in snow patch showing structure and uppermost permafrost layer (tip of red shovel) c) firn/névé found in the section, sample at 1.6 m depth.

Figure 6. a) tor; b) and c) former stone runs; d) kurum.

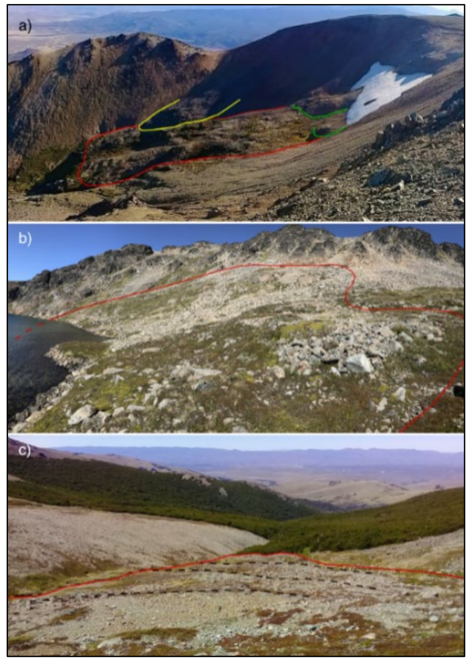

Figure 7. Fossil rock glaciers: a) active embryonic rock glacier and protalus lobes (green), inactive (yellow) and fossil (red) rock glaciers; b) and c) fossil rock glaciers.

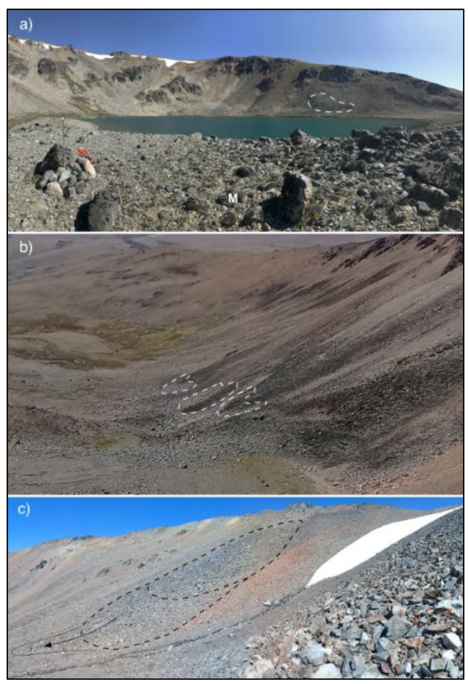

Figure 8. a) Data logger at Lake Ogwen, glacierettes, M = moraine, protalus lobe; b) Protalus; c) Active (upper) and inactive (bottom) rock glacier.

Due to the topographic shadow of Mount Edwin to the S and SW, cryogenic processes produce these landforms approximately 100 m below. Inactive rock glaciers are up to 150 m long. They are made of vulcanites from regional lithology (Lago La Plata Formation, Haller et al. 2010). The environment is exposed to many cycles of freezing and thawing that promote strong cryoweathering (formation of tors, Figure 6). The cryogenic sedimentary slopes show natural ruggedness due to the soli and gelifluction lobes (Figures 3 and 9).

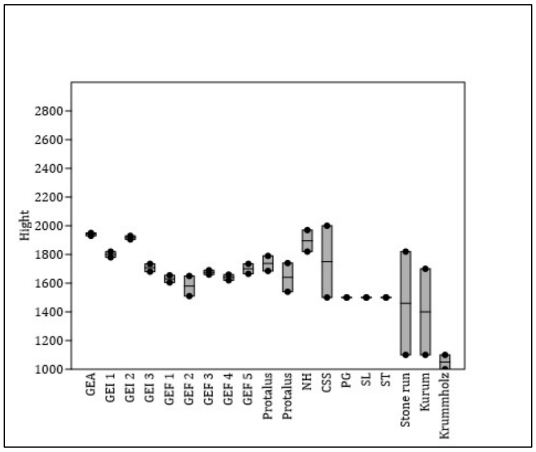

Figure 9. Lowest and highest altitudes of the most important cryogenic landforms. GEA = active rock glacier, GEI= inactive rock glacier, GEF = fossil rock glacier, NH = nivation hollow, CSS = cryogenic sedimentary slopes, PG = patterned ground, SL= solifluction lobes, ST = solifluction terraces.

Figure 9 with "boxes" shows the lowest and highest altitudes of the main cryogenic landforms. The elevations of the landforms allow the identification of fossil and currently active cryoforms.

4.2 Looking for the 0 °C isotherm through indirect ways

The position of the 0 °C isotherm following the thermal gradient and a linear regression today lies between approximately 2000 and 2100 m ASL.

However, if we use isotherms from the model consisting of a Raster of MAAT, values interpolated from a GIS software, using other data from nearby weather stations, the 0 °C isotherm somewhat lies lower, as follows:

- iso0 °C Raster = 1970 m ASL
- iso2 °C Raster = 1640 – 1650 m ASL
- iso4 °C Raster = 1300 – 1400 m ASL

4.3 Comparison with another permafrost model

Figure 10 shows the Continental Permafrost Distribution Model by Arenson et al. (2021). In this model, the 1800 m ASL contour line was drawn. It is observed that the curve covers most of the area interpreted with permafrost in our model and supports our earlier mentioned interpretation.

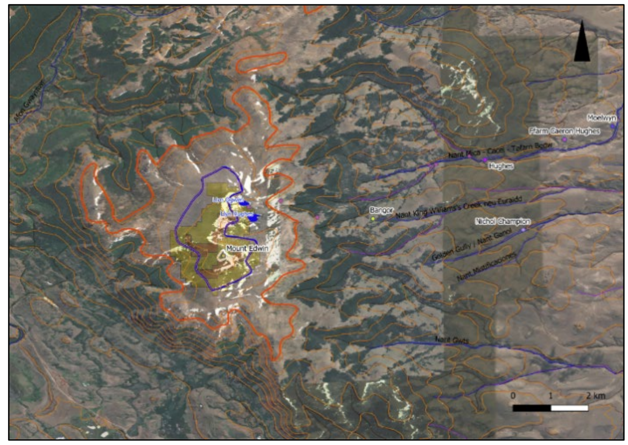

Figure 10. Permafrost distribution model according to Arenson et al. 2021. Orange = likely permafrost; yellow = possible permafrost; circle around Mount Edwin (2019 m) = contour of 2000 m ASL; violet line = contour of 1800 m ASL; and orange line = 1600 m ASL, representing lowest altitude of intense cryoweathering.

5 Discussion

5.1 Permafrost altitude

Regionally, Reato et al. (2023) analyze the meteorology that favors the periglacial environment with permafrost in the touristic region of La Hoya, Esquel (with clear indicators of anthropization in the cryogenic landscape). However, we observe from our presented data (cf. Hughes 2023), that the results and climatic regime differ when we move to the S. We believe that the mentioned climate seems to have differentially influenced cryogenic processes and landform genesis.

Looking for the 0 °C isotherm, according to the thermal gradient, two results are notable. The first is for the period until 2019, which places the isotherm of 0 °C at the summit of Mount Edwin (approximately 2000 m ASL). However, the second result places the 0 °C isotherm above it. If we add the warmest temperatures obtained between 2020 and 2023, we obtain an annual average of 2.7 °C at Lake Ogwen, which would not support permafrost.

The warm mountain permafrost found from an altitude of 1850 m ASL upwards, is associated with permanent snow patches. Active cryogenic landforms such as cryogenic lobes and active cryogenic sedimentary slopes are in patchy or island mountain permafrost areas which extent to the summit of the Craig Cŵts (2019 m ASL). On southern slopes, the permafrost altitude is approximately 1850 m ASL, but would be at 1950 m on northern slopes, as found through models. The models agree fairly closely with the most important cryogenic landform indicators (Figures 3 and 9).

The calculated area for the likely permafrost zone is 1.92 km^2 and 16.21 km^2 for the possible permafrost zone.

It may be assumed that current permafrost is in an unstable state and may soon disappear. However, island permafrost can persist in the biggest and most elevated cryoforms for many more decades.

5.2 Age of old periglaciation in the Patagonides

After and during the last ice age, strong periglaciation and rock glacier formation was likely in the region. The glacial geomorphology consists of notable cirques and moraines. These landforms are ‘fresh’ in appearance and easily distinguishable. They suggest that during the Greenlandian Age (11.7–8.3 ka), Craig Cŵts would have been glaciated and that the paleo-periglacial landforms essentially appeared later, starting probably from the Meghalayan Age (4.2–0 ka). Important glaciers occupied the region until the end of the Little Ice Age and left the freshest moraines close to the cirques (Figure 8a). The rocks present clean surfaces, without oxidation patina; and so there is no organic soil or vegetation development. Regional investigations on glacial advances, that also indirectly involve Craig Cŵts, are mentioned by several authors (i.e., Caldenius 1932: Glasser and Jansson 2008).

The number, diversity, and large fossil periglacial landforms would indicate that there was a significant mountainous periglacial environment with intense cryoweathering activity, creeping permafrost, and in situ permafrost.

Through a recent work in Craig Goch, Patagonides (Fröjd et al. 2022), with similar geological and climatic characteristics and proximity, it is possible to transfer identified Neoglacials and cryogenic processes to Craig Cŵts. On this basis we identify two ages associated with soli and gelifluction lobes and terraces and an outwash plain delimited by a moraine. They are cryomeres belonging to the Little Ice Age and the previous Neoglacial known as the “*Pessimum der Völkerwanderung”* in Germanic literature (see Table 3).

Table 3. Dating old cryogenic processes at Craig Goch,

Profile	Altitude (m)	Age cal 14C yr BP	Environment and Processes	Neoglacials, other connotations	Horizont Depth (cm)
CG T1-1	1625	614	solifluction	Little Ice Age	30-36
CG T1-2	1633	1550	Stabilized solifluction	PV = Pessimum der Völkerwanderung, Dark Ages	22-28
CG T2-3	1731	1559	Outwash plain	PV = Pessimum der Völkerwanderung, Dark Ages	38-39

Patagonia (Fröjd et al. 2022).

6 Conclusions

Island permafrost appears until present in mountain ranges beyond the Andes at altitudes below 1900 m ASL and 42°S due to special topo-climatic conditions (sufficient altitude, narrow and shady valleys), southern aspect and sedimentary/volcanic lithology. However, clear indicators of rapid warming (size of glacierettes, rise of the isotherm of 0°C) are detected and coincide with the increase in MAAT since 2017.

A good example of the Patagonian cryogenic environment is the previously unknown area Craig Cŵts located in the Patagonides, Precordillera of the province Chubut, Argentina, an extra Andean mountain massif between parallels 43° and 43°40' in Patagonia, which is being studied for the first time in detail.

A rich periglacial geomorphology is present in Craig Cŵts, with active and inactive rock glaciers, nivation hollows, cryogenic sedimentary slopes, patterned ground, soli- and gelifluction lobes and terraces.

7 Acknowledgements

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