Glacial geomorphology of the former Patagonian Ice Sheet (44–46 °S)

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ABSTRACT

We map the glacial geomorphology of the former Patagonian Ice Sheet between 44°S and 46°S. Building on previous work, our map covers a ~50,000 km² region of west-central Patagonia. The study area includes the eastward-flowing Río Pico, Río Caceres, Río Cisnes, Lago Plata-Fontana, El Toqui, Lago Cayt/Río Nirehuao, Simpson/Paso Cohiague, and Balmaceda palaeo-outlet glaciers, adjacent valleys, and the Andean Cordillera. The inventory contains >70,000 individual landforms mapped from remotely-sensed imagery and field surveys. Mapping was classified into ice-marginal (e.g. moraine ridges, trimlines), subglacial (e.g. glacial lineations, flutes), glaciolacustrine (e.g. palaeolake shorelines, perched deltas), glacio fluvi al (e.g. proglacial outwash plains, meltwater channels), and non-glacial (e.g. lake channels, landslides or slumps) landform groups. The new map will inform future interpretations of regional glacier dynamics, and the development of robust geochronological datasets that test the timing of glaciation and deglaciation.

1. Introduction

Patagonia, in southernmost South America, has undergone repeated glaciations since ~6 to 5 Ma (Mercer & Sutter, 1982; Rabassa et al., 2005, 2011; Rabassa, 2008). The former Patagonian Ice Sheet (PIS; Figure 1(a)), a temperate ice sheet with active and fast-flowing outlet glaciers (Darvill et al., 2017; Glasser & Jansson, 2005), covered most of Chile and western Argentina between 38° and 56° S (Cal denius, 1932; Davies et al., 2020; Glasser & Jansson, 2008). The Andean Cordillera is aligned north–south through western South America, intersecting the Southern Hemisphere Westerly Wind Belt and generating a marked west–east precipitation gradient (Aravena & Luckman, 2009; Garreaud et al., 2013). Arid conditions east of the Andean Cordillera have therefore preserved a unique, well-defined, record of terrestrial Quaternary glacier advances (Davies et al., 2020; Glasser et al., 2008). This makes Patagonia an ideal location to investigate the role of Southern Hemisphere mid-latitude paleoclimate on local palaeoglacier dynamics.

Until recently, glacial geomorphological mapping of the PIS focused on the largest and most distinctive landforms (e.g. Cal denius, 1932; Glasser & Jansson, 2008; Mercer, 1965), providing a broad-scale synthesis of ice extent and dynamics. Since ~2015, freely available high-resolution satellite imagery has offered new opportunities to refine our understanding of palaeoglaciological processes, but disparities in mapping extent and detail remain prevalent (cf. Davies et al., 2020). Most data are focused around the Northern Patagonian Icefield (Campo de Hielo Norte, 46–47.5 °S), Southern Patagonian Icefield (Campo de Hielo Sur, 48–51 °S), and Cordillera Darwin Icefield (Campo de Hielo de la Cordillera Darwin, 54–55 °S). To date, deglaciated areas north of the Northern Patagonian Icefield have received comparatively little attention. By generating comprehensive inventories of Patagonian glacial geomorphology (Bendle et al., 2017b; Darvill et al., 2014; García et al., 2014; Leger et al., 2020; Lovell et al., 2011; Martin et al., 2019; Soteres et al., 2020), we can begin to assess spatiotemporal variations in palaeoglaciological processes.

We provide detailed mapping across two degrees of latitude (44–46° S, Figure 1(b)). The main aim of this study is to identify and classify key glacial landform assemblages in west-central Patagonia. Our objectives are to: (1) produce a high-resolution map of glacial geomorphology using satellite imagery and field surveys and (2) group and characterise the key landform assemblages for this region of the former PIS. Mapping will provide the basis for subsequent...
reconstructions of glacier extent and dynamics based on morphostratigraphy (cf. Lukas, 2006), glacial land-systems (cf. Evans, 2003), and the generation of robust geochronological datasets (cf. García et al., 2020; Mendelová et al., 2020; Peltier et al., 2021; Sagredo et al., 2018; Strelin et al., 2014).

2. Study area

The mapping area is located at ~44–46° S and ~70.5–72.5° W. The area included at least eight eastward-draining outlet glaciers during the last glacial cycle (Figure 1). These were the Río Pico (~44.2° S), Río...
Caceres (~44.5° S), Río Cisnes (~44.6° S), Lago Plata-Fontana (~44.8° S), El Toqui (~45° S), Lago Coyt/Río Ñirehuao (~45.3° S), Simpson/Paso Coyhaique (~45.5° S), and Balmaceda (~46° S) glaciers.

The Andean Cordillera dominates the landscape in the west (Figure 1), with local summit elevations of up to ~2600 m a.s.l., before an eastward transition through the Patagonian foothills, which grade into the Argentine steppe. Ice originated from the Chilean highlands, advancing west towards the Pacific and east into present-day Argentina. During deglaciation, Atlantic-bound meltwater was stored in large proglacial lakes formed in overdeepened glacial troughs east of the ice divide (cf. Davies et al., 2020; García et al., 2019). Further ice recession then led to the opening of palaeolake drainage routes through the Andean Cordillera (cf. García et al., 2019). Today, ≥1482 glaciers remain in the region (Arendt et al., 2017); most of these are found adjacent to the Queulat ice cap (44.4° S, ~2000 m a.s.l.), and Mt. Hudson volcano (45.9° S, ~1900 m a.s.l.).

3. Previous mapping

Caldenius (1932) first mapped glacial landforms and glaciolacustrine sediments in the study area. Since this time, a number of early field surveys (e.g., Beltramone, 1991; Dal Molin, 1998; Lapido, 2000; Płoszkiewicz, 1987; Ramos, 1981) highlighted the largest and most extensive landforms, including moraine complexes or deposits, and proglacial outwash plains (Table 1 and Figure 2).

In the Río Pico valley, five moraine complexes were mapped in association with an eastward-draining outlet glacier (Beraza & Vilas, 1989 and Lapido, 2000 In: Rabassa et al., 2011). Likewise, in the Río Cisnes valley, García et al. (2019) mapped five main moraine complexes (Named: CIS 1, 2, 3, 4, and 5) and identified the limits of a proglacial palaeolake. Distinct palaeolake shorelines at 950-920 m a.s.l. and 860-850 m a.s.l. can be traced from the upper-to-middle Río Cisnes valley (Davies et al., 2020; García et al., 2019). A col located at ~920 m a.s.l. drained the palaeolake towards the Atlantic Ocean at this level (Davies et al., 2020), whilst the prominent Winchester Delta (Figure 3), south of the modern Río Cisnes, clearly marks the ~860-850 m a.s.l. lake level (García et al., 2019).

Beltramone (1991) identified multiple moraine complexes or deposits and moraines associated with the Simpson/Paso Coyhaique glacier (Figure 2). Dal Molin (1998) and Dal Molin and González Díaz (2002) further mapped broad moraine complexes and proglacial outwash plains from the Lago Coyt/Río Ñirehuao to Balmaceda valleys, east of the international boundary. Glasser and Jansson (2005) then used satellite remote sensing data to map in greater detail and presented the first indication of fast ice-flow in the region, evidenced by glacial lineations. Subsequently, Taylor (2019) provided thorough mapping of the Balmaceda outlet glacier (Table 1). This included the identification of previously unmapped moraine complexes and ridges associated with several glacial advances, proglacial outwash plains, and multiple palaeolake levels.

Within the Andean Cordillera, Mardones et al. (2011) mapped moraines deposited in tributary valleys of the main Balmaceda outlet glacier (Figure 2 and Table 1). Davies and Glasser (2012) then identified late-Holocene moraines and trimlines, allowing an assessment of recent ice extent. Multiple studies have now provided mapping within the Andean Cordillera (Glasser & Jansson, 2005, 2008; Mardones et al., 2011; Moreno et al., 2021), but at variable spatial scales.

The PATICE database compiled and generated new mapping (Table 1) for the entire PIS (Davies et al., 2020). In the area located between 44° and 46° S, detailed mapping has been limited to the Río Cisnes valley (e.g. García et al., 2019), and a regional, high-resolution, inventory is needed to assess palaeoglacio-logical processes.

4. Methods

Mapping of the eastern outlet glaciers was completed at 1:10,000–1:40,000 spatial scales, and a 1:1000–1:10,000 scale was used inside the Andean Cordillera. Landform identifications were undertaken according to descriptions outlined by Bendle et al. (2017b, pp. 660–661), Martin et al. (2019, pp. 114–115), and Leger et al. (2020, pp. 654–656), following protocols outlined in Chandler et al. (2018). Identification criteria were then modified for the study area (Table 2). Where possible, published landforms were re-mapped and incorporated into the new inventory (Table 1). River and palaeolake outwash plain shapefiles were adapted from the PATICE database (Davies et al., 2020), and modern glaciers were extracted from the Randolph Glacier Inventory (RGI v. 6.0, region 17; Arendt et al., 2017).

Mapping was completed with ArcGIS Pro using the Southern Hemisphere WGS-1984 UTM Zone 18S Projected Coordinate System. A ~50,000 km² area was mapped using an ASTER (v.3) 30 m resolution Digital Elevation Model (ASTER DEM). Composite ESRI™ DigitalGlobe World Imagery (1–2 m resolution) and Sentinel-2 (10 m resolution) imagery were used to identify landforms. Hillshade and Slope Digital Terrain Models were generated using the Spatial Analyst function and overlain onto the ASTER DEM to highlight topographic relief and elevation (Otto & Smith, 2013). Field surveys validated geomorphological interpretations at multiple locations (Figure 2).
Table 1. Relevant glacial geomorphological landforms and glacier inventories presented in studies from Figure 2, described using the terminology presented in this paper.

| Reference | Mapping Area Coverage | Mapping relevant to the new inventory |
|-----------|-----------------------|---------------------------------------|
| Caldenius (1932)* | Broad-scale | Moraine complexes or deposits and glaciolacustrine sediments. |
| Ramos (1981) | Lago Plata-Fontana | Moraine complexes or deposits and proglacial outwash plains. |
| Płoszkiewicz (1987) | East of the Río Cisnes valley | Proglacial outwash plains. |
| Beltramone (1991) | Central Simpson/Paso Coyhaique | Moraine complexes or deposits, moraine ridges, and glaciolacustrine sediments. |
| Dal Molin (1998) | Lago Coyt/Río Ñirehuao, Simpson/Paso Coyhaique, and Balmaceda | Moraine complexes or deposits, moraine ridges, and glaciolacustrine sediments. |
| Dal Molin and González Díaz (2002) | Lago Coyt/Río Ñirehuao, Simpson/Paso Coyhaique, and Balmaceda | Moraine ridges, proglacial outwash plains, and proglacial outwash terraces. |
| Escosteguy et al. (2003) | Eastern side of Lago Buenos Aires | Moraine complexes or deposits and glaciolacustrine sediments. |
| Smedley et al. (2016) | Eastern side of Lago Buenos Aires | Moraine complexes or deposits and glaciolacustrine sediments. |
| Martínez (2002) and Martínez et al. (2009) | Lago Coyt/Río Ñirehuao, Balmaceda and Andean Cordillera | Moraine ridges, glacially scoured bedrock, glacial lineations, and meltwater channels. |
| Gordon et al. (2020) | Eastern side of Lago Buenos Aires | Moraine complexes or deposits, proglacial outwash plains, and glaciolacustrine sediments. |
| Glasser and Jansson (2008) | Broad-scale | Moraine ridges, trimlines, meltwater channels, proglacial outwash plains, glacial lineations, palaeolake shorelines, and cirques. |
| Glasser et al. (2009) | Western margins of Lago Buenos Aires, inside the Anean Cordillera | Moraine ridges, trimlines, glacially scoured bedrock, cirques, glacial lineations, meltwater channels, proglacial outwash plains. |
| Haller et al. (2010) | Western edge of Simpson/Paso Coyhaique, Balmaceda, and inside the Andean Cordillera | Cirques, moraine ridges, moraine complexes or deposits, and palaeolake shorelines. |
| Besaza & Vilas (1989) cited in: Rabassa et al. (2011)* | Río Pico | Moraine complexes or deposits. |
| Martínez (2002) and Martínez et al. (2009) cited in: Martínez et al. (2011)* | Lago Palena/General Vintter | Moraine complexes or deposits and moraine ridges. |
| Lapido (2000) cited in: Rabassa et al. (2011)* | Río Pico | Moraine complexes or deposits and proglacial outwash terraces. |
| Davies and Glasser (2012) | Andean Cordillera | Moraine ridges, trimlines, and cirques. |
| Glasser et al. (2012) | Western edge of Lago Buenos Aires, inside the Andean Cordillera | Moraine ridges, trimlines, meltwater channels, proglacial outwash plains, palaeolake shorelines, glacial lineations, and cirques. |
| Miranda et al. (2013)* | Simpson/Paso Coyhaique and Balmaceda | Moraine complexes or deposits and moraine ridges. |
| Miranda (2013)* | Simpson/Paso Coyhaique and Balmaceda | Moraine ridges. |
| Smedley et al. (2016) | Eastern side of Lago Buenos Aires | Moraine ridges, palaeochannels, palaeolake shorelines, glaciolacustrine sediments, and proglacial outwash plains. |
| Bendle et al. (2017b) | Lago Buenos Aires | Moraine complexes or deposits, moraine ridges, trimlines, glacial lineations, glaciolacustrine sediments, perched deltas, palaeolake shorelines, proglacial outwash plains, catastrophic flood landforms, and meltwater channels. |
| García et al. (2019) | Río Cisnes | Moraine complexes or deposits, moraine ridges, palaeolake shorelines, perched deltas, and proglacial outwash plains. |
| Taylor (2019) | Eastern side of Balmaceda | Moraine complexes or deposits, moraine ridges, glacial lineations, meltwater channels, proglacial outwash plains, palaeolake shorelines, glaciolacustrine sediments, and perched deltas. |
| Vilanova et al. (2019)* | Simpson/Paso Coyhaique and Balmaceda | Moraine ridges. |
| Davies et al. (2020) | Broad-scale | Moraine ridges, trimlines, glacial lineations, meltwater channels, palaeolake shorelines, perched deltas, proglacial outwash plains, cols, and cirques. |
| Leger et al. (2020) | Lago Palena/General Vintter | Moraine complexes or deposits, moraine ridges, kettle holes, proglacial outwash plains, meltwater channels, palaeolake shorelines, perched deltas, glaciolacustrine sediments, glacial lineations, glacially scoured bedrock, and cirques. |
| Moreno et al. (2021) | Northern tip of Lago Rosselot, inside the Andean Cordillera | Moraine complexes or deposits and moraine ridges. |

*Indicates studies where detailed maps have not been available, where the original publication was not accessible, or where landforms have been described, but precise mapping locations are unknown and cannot be fully reviewed.

5. Mapped landforms

Mapping was classified into ice-marginal, subglacial, glaciolacustrine, glaciofluvial, and non-glacial landform categories (Table 2). Within these groups, a total of 27 landform types were digitised, which resulted in a database of >70,000 mapped features. We describe landforms mapped in the eight outlet valleys and the Andean Cordillera.

5.1. Ice-marginal landforms

5.1.1. Moraine complexes or deposits

Arcuate moraine complexes were deposited by the main outlet glaciers, and extend over tens of kms across the mouths of the individual valleys. Moraine complexes or deposits were mapped in multiple previous publications and have been re-mapped in greater detail. Herein, moraine complexes have...
been named to follow a standard nomenclature (Figure 3).

Moraines can be grouped into sets (moraine complexes) using morphostratigraphy to determine the relative ice-margin age (cf. Lukas, 2006) prior to developing geochronological datasets (Lüthgens & Böse, 2012). Moraine complexes or deposits were defined from satellite imagery based on geographic position, as well as moraine morphology and proximity. Where available, proglacial outwash plains were also...
used to identify the lateral and terminal extent of moraine complexes. However, the easternmost moraine complexes commonly lack distinct moraine ridges and are instead comprised of mounds or flat-topped and irregular terrain. In particular, the limits of older or proximal moraine complexes or deposits (e.g. Figure 3: SPC 1) can become difficult to define and should be field verified.

Figure 3. Broad geomorphological context of mapped valleys, including key moraine complexes. It is likely that the stratigraphically oldest moraine complexes span multiple glacial advances. Moraine complexes were mostly identified from remote mapping and should be field verified. Outlet glaciers: P: Río Pico, Ca: Río Caceres, C: Río Cisnes, PF: Lago Plata-Fontana, T: El Toqui, N: Lago Coyt/Río Ñirehuao, SP: Simpson/Paso Coyhaique, and B: Balmaceda. Location and extent of maps presented in Figures 4–6 have also been included (black boxes) and photos of glaciolacustrine sediments (red dots). Modern ice extent from RGI v. 6.0, region 17 (Arendt et al., 2017).
Figure 4. Ice-marginal landforms within the main outlet valleys and the Andean Cordillera. Raw satellite images (left) and mapped geomorphology (right). (a) Satellite image of central-northern sector of the Río Pico valley, including the location of (g). (b) Mapped landforms, including the PIC 6 moraine and an associated proglacial outwash plain. (c) Satellite image of a morainal bank, which is the lateral margin of the PIC 6 moraine, and a small isolated palaeolake basin in the northern Río Pico valley. (d) Mapped landforms surrounding the PIC 6 morainal bank, which is adjacent to ice-contact fans, and multiple, stepped, palaeolake shorelines. (e) Satellite image of the area southeast of the Queulat ice cap. (f) Mapped moraines and trimlines associated with the stratigraphically youngest glacier advances in the Andean Cordillera. (g) Ice-proximal view of the PIC 6 moraine in the field overlooking older moraines and terminating into a proglacial outwash plain. Satellite images are from ESRI™ DigitalGlobe World Imagery via ArcGIS Pro. Figure panel locations are shown in Figure 3.
Figure 5. Subglacial and glaciolacustrine landforms and sediments. (a) Satellite image of glacial lineations in the Simpson/Paso Coyhaique valley. (b) Mapped glacial lineations in the Simpson/Paso Coyhaique valley, dissected by proglacial outwash plains. Glacial lineations are aligned in a west-east and southwest-northeast direction, and adjacent to moraine complexes or deposits. (c) Satellite image of recently deglaciated ice cap south of Volcán Macá. (d) Flutes mapped within the Andean Cordillera which demonstrate multiple, diverging, local ice-flow directions. (e) Satellite image of the CIS 4 moraine, Río Cisnes valley. (f) Short-lived, narrow, palaeolake shorelines embedded on the CIS 4 moraine. (g) Laminated glaciolacustrine sediments located in the centre of the Río Pico palaeolake basin. (h) Glaciolacustrine sediments dissected by a tephra layer (cf. Stern et al., 2015) in the Río Cisnes valley.
Figure 6. Examples of glaciofluvial landforms in the study area. (a) Location of catastrophic flood landforms and direction of final palaeolake drainage in the Río Cisnes valley. (b) Mapped catastrophic flood landforms along the banks of the modern Río Cisnes, adjacent to the CIS 5 moraine. Includes the location of (c). (c) Catastrophic flood landform in the foreground, adjacent to the CIS 5 moraine. (d) Location and ice-flow direction at Lago La Paloma, the site of a tributary glacier of the main Balmaceda valley. (e) Mapping of the La Paloma glacier, including moraine ridges and proglacial outwash terraces. Proglacial outwash terraces indicate that glaciofluvial drainage from the La Paloma glacier was directed towards the main Balmaceda valley.
Table 2. Rationale, uncertainties, and identification criteria for ice-marginal, subglacial, glaciolacustrine, glaciofluvial, and non-glacial landforms mapped between 44 °S and 46°S. Total mapped landform numbers and/or areas are provided where applicable. Landform occurrence (✘) within the study region: P: Río Pico outlet glacier, Ca: Río Caceres outlet glacier, C: Río Cisnes outlet glacier, PF: Lago Plata-Fontana outlet glacier, T: El Toqui outlet glacier, N: Lago Coyt/Río Ñirehuao outlet glacier, SP: Simpson/Paso Coyhaique outlet glacier, B: Balmaceda outlet glacier, and A: landforms mapped within the Andean Cordillera. Identification criteria were modelled after Bendle et al. (2017b), Martin et al. (2019), and Leger et al. (2020): criteria were then modified and updated for the study area.

| Landform                         | Rationale                                                                 | Uncertainties                                                                 | Identification criteria                                                                 | Number of observations | Area (km²) | Landform occurrence |
|----------------------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------|------------|---------------------|
| Ice-marginal landforms           |                                                                           |                                                                               |                                                                                       |                        |            |                     |
| Moraine complexes or deposits    | Indicates lateral/terminal extent of a glacier. Represented by prolonged glacier stillstands or (re-)advances. | It can be difficult to differentiate between concomitant glacial advances from satellite imagery alone. May be confused with landslides or slumps when plastered onto the valley sides. | In satellite imagery, elongate ridges or crests found in close proximity. Older deposits may possess gently undulating mounds, with no distinct moraine ridges and which are sometimes heavily eroded. Can often be traced for long distances and may be found adjacent to proglacial outwash plains. | –                      | 1487       | ✘✘✘✘✘✘✘✘✘✘ellido                     |
| Moraine ridges                   | Indicates glacier lateral or terminal extent at the time of deposition. Moraine size may inform on the relative longevity of the ice-margin position. | Moraines lacking sharp or significant relief may be difficult to detect in satellite imagery. Small moraine ridges associated with younger glacial advances in the Andean Cordillera usually require mapping at a high spatial resolution (≤1:10,000). | In satellite imagery, elongate ridges or crests with consistent relief. Often steeply sloping or gently sloping on one side. May be flat topped in some cases. Likely to possess dark-light shading from relief. In the field, likely to also be topped with boulders and cobbles. | 11307                  | –          | ✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘✘� |
| Term                          | Description                                                                                                                                  | In satellite imagery, bedrock is often plastered with surficial sediments or interspersed with vegetation which may hinder identification. | In remote mapping, extensive areas of bedrock within former ice limits which appear smoothed. May appear streamlined in the direction of ice-flow. | In the field, may additionally be found overlain with perched boulders or interspersed with subglacial diamicet. |
|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|
| Glacially scoured bedrock     | May indicate former ice-flow direction, wet-based ice, or areas where ice was thick.                                                          |                                                                                                                               |                                                                                                                               |                                                                                                                               |
| Glacial lineations            | Will signal the direction(s) of former ice-flow. May be indicative of fast-flowing or streaming ice.                                        | May not be identifiable in highly vegetated areas. Could be confused with crag-and-tails or moraine ridges.                    | In satellite imagery, elongate ridges with sharp-to-gently tapering sides oriented in the direction of ice-flow. ≤2.5 km in length and ≤0.1 km in width, regionally. Often found aligned with moraine complexes or deposits. |                                                                                                                               |
| Flutes                        | Signal the direction(s) of local ice-flow. Indicates areas which were recently glacierised.                                                   | Flutes are only preserved near active or recently active glaciers. Requires high-resolution (≤ 1:10,000) mapping from satellite imagery to identify remotely. |                                                                                                                               |                                                                                                                               |
| Glaciolacustrine landforms    | Palaeolake shorelines: Indicative of palaeolake surface elevation, lake level longevity, and the lateral extent of the palaeolake.          | Difficult to distinguish when not continuous in satellite images. May be confused with low-relief moraines.                    | In satellite imagery 1) elongate, flat-topped ridges which may be traced for significant distances. May possess a steep lake-marginal slope or be found in association with perched deltas or ice-contact fans. 2) Short-lived, discrete, palaeolake shorelines are found in sets, and possess narrow terracing and closely spaced steps. Both shorelines are identifiable by dark-light shading in satellite imagery. | In the field, narrow shorelines with closely spaced steps are difficult to map individually. palateolake shorelines may possess a flat or gently undulating surface. |
| Perched deltas                | Can be used to indicate a proglacial palaeolake level. May help to infer the lateral extent of a palaeolake.                                 | May be misinterpreted as an alluvial fan in satellite imagery, particularly when the elevation change between the delta-top area and surrounding landscape is not sharp. | In satellite imagery, perched deltas possess a flat top, and sharp or gently sloping lake-marginal slope. Usually fan-shaped in plan view. Will be found pointing towards a lake or palaeolake basin, and may be associated with, or raised above, palaeolake shorelines. May preserve palaeochannels, gullies, or contain modern rivers. |                                                                                                                               |
| Ice-contact fans              | Indicative of ice-contact lake presence and surface elevation at the time of moraine deposition. May provide an approximate ice extent. | In satellite imagery, may be mistaken for proglacial outwash plains or perched deltas where topography is subdued or palaeolake/moraine evidence is not clear. | In satellite imagery, ice-contact fans possess a similar morphology to perched deltas. Additionally found on the ice-distal side of moraines and perched above the palaeolake basin. May preserve meltwater channels on their surface. |                                                                                                                               |
| Glaciolacustrine sediments    | Indicates the presence of a palaeolake. May provide further information on processes of glaciolacustrine sediment deposition.          | Requires field or laboratory verification to assess model of glaciolacustrine sediment deposition. May be difficult to identify in heavily vegetated areas. | In the field, possess a laminated or homogenous matrix. Likely to be exposed where rivers or runoff have incised older glaciolacustrine sediments. At the macro-scale, laminated glaciolacustrine sediments contain moderate-to-well-sorted |                                                                                                                               |

(Continued)
Table 2 Continued.

| Landform                    | Rationale                                                                 | Uncertainties                                                                 | Identification criteria                                                                                                                                                                                                 | Number of observations | Area (km²) | Landform occurrence |
|-----------------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|------------|---------------------|
| Palaeolake spillways (cols) | Indicative of palaeolake drainage outlet and direction of glaciofluvial drainage. | In satellite imagery, may be difficult to discern when landscape has been dissected by younger glaciofluvial drainage routes. May be mistaken for gullies. | Laminae comprised of clays, silts, and sands. In satellite imagery, usually appear beige or white in colour, and are located near a modern lake or within a palaeolake basin. By generating contours in GIS, and corresponding these with known palaeolake levels, drainage outlets may be identified at these levels. Will usually be marked by a large palaeochannel directed towards an area of lower relief. | 5                      | –          | × × × × × × × × × × |
| Glaciofluvial landforms     | Provides evidence for the occurrence of catastrophic floods. May also provide insight into the direction of flood drainage. | May be confused with river terraces in satellite imagery. Field verification is necessary for identification. | In satellite imagery, flat-topped landforms with steep scarp slopes which possess a similar morphology to river terraces. In the field, identifiable by presence of large boulders (≤3 m in height) which are located within and on top of a boulder bar. | 12                     | –          | – × × × × × × × × × × |
| Proglacial outwash plains   | Indicative of meltwater drainage direction. May inform on ice-margin extent. | Older proglacial outwash plains may be difficult to distinguish where glaciofluvial drainage routes meet. | In satellite imagery, usually possess extensive networks of braided meltwater channels. Usually found on the ice-distal side of moraines and moraine complexes or deposits. | –                      | 18144      | × × × × × × × × × × |
| Proglacial outwash terraces | May indicate the relative longevity of glaciofluvial drainage routes. | May be confused with river terraces near modern drainage routes. Difficult to delineate the limits of multiple terraces without field verification. | In satellite imagery, found within areas of proglacial outwash plains. Terraces are raised above surrounding proglacial outwash plains, and possess a steep scarp slope identifiable through light-dark shading. | 352                    | 93         | × × × × × × × × × × |
| Meltwater channels          | Indicates the direction(s) of glaciofluvial drainage. Preservation may reveal the relative age of drainage routes. May indicate the approximate and relative position of the ice-margin. | May be mistaken for palaeochannels (e.g. proglacial meltwater channels) or gullying in satellite imagery. May be occupied by modern drainage. In the field, proglacial meltwater channels within proglacial outwash plains are difficult to discern. | When mapping remotely, proglacial meltwater channels appear sinuous to braided, possess a dark-light shading, and are found in large numbers within proglacial outwash plains. Ice marginal and subglacial meltwater channels appear sinuous, and cross-cut moraines and moraine complexes or deposits. May be occupied by modern drainage or wetlands. | 31648                  | –          | × × × × × × × × × × |
| Kettle holes                | Indicative of an area of deposition. May suggest a stagnant ice margin. | When mapped remotely, kettle holes are easily confused with small lakes. | In satellite imagery, kettle holes possess an ovate or sub-rounded planform shape. Hullows may contain small lakes, and are found within proglacial outwash plains or moraine complexes or deposits. | 1572                   | –          | × × × × × × × × × × |
| Non-glacial landforms       | When present, may indicate reworking of underlying sediments. | Fans may be confused with perched deltas in satellite imagery, particularly when palaeolake shoreline evidence is not apparent. | Both in satellite imagery and in the field: fan shaped in plan view, may be gently sloping towards the main river channel or lake. May contain active or palaeochannels on their surface. | 1506                   | 263        | × × × × × × × × × × |
| Feature          | Description                                                                 | Patterns                                                                                     |
|------------------|------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Rivers           | Indicates the origin and direction of modern drainage routes.                | Straight, sinuous, or braided channels, which can be traced for a significant distance.      |
|                  | Smaller tributary rivers may be difficult to map in heavily vegetated areas. | Usually contain contemporary drainage.                                                      |
| Palaeochannels   | Indicates the presence and extent of past drainage routes.                  | Will usually be found next to active river channels, may retain water if recently abandoned.|
|                  | May be mistaken for proglacial meltwater channels when modern rivers are    | Sinuous-to-braided morphology.                                                              |
|                  | occupying proglacial outwash plains.                                        |                                                                             |
| River terraces   | Indicates the extent of the former floodplain and the possible re-working   | Flat-topped sediment accumulations which possess a steep scarp slope.                       |
|                  | of sediments.                                                                | Found adjacent to modern rivers, floodplains, or palaeochannels.                            |
| Major floodplains| Determines lateral extent of modern fluvial activity.                       | Will often be covered with low-lying vegetation. May appear waterlogged in satellite imagery.| |
|                  | May be misinterpreted as a proglacial outwash terrace where modern fluvial | Found adjacent to rivers.                                                                   |
|                  | drainage is cutting through proglacial outwash plains.                      |                                                                             |
|                  | Difficulties in distinguishing between floodplains and wetlands when these |                                                                             |
|                  | landforms coincide.                                                         |                                                                             |
| Lakes            | May indicate the presence of palaeolake shorelines or perched deltas.       | In satellite imagery, small water bodies may be mistaken for kettle holes in the main      |
|                  | In satellite imagery, small water bodies may be mistaken for kettle holes   | outlet valleys.                                                                            |
|                  | in the main outlet valleys.                                                 |                                                                             |
| Landslides or slumps | Indicates areas where underlying landforms and sediments have been re-mobilised. | In satellite imagery, slumped material containing irregular or undulating ridges.        |
|                  | When mapping remotely, landslides or slumps may be mistaken for lateral     | Usually found below a rounded hollow or scar which may be identified as the source of the  |
|                  | moraines, particularly when the source of the slope failure is not apparent. | slope failure.                                                                             |
| Wetlands         | May indicate areas of recent fluvial activity or re-working.                | In satellite imagery, usually appear green and saturated in comparison to the surrounding  |
|                  | May be mistaken for floodplains in satellite imagery when near modern rivers.| Covered with low lying vegetation. Found adjacent to rivers or lakes.                    |

**Total**: 72165 25073.9
5.1.2. Moraine ridges
Moraine ridges mark the extent of past glacial advances, readvances, or stillstands (e.g. Davies et al., 2020; Glasser & Jansson, 2008) and define the geometry of the glacier terminus (Ely et al., 2021). Moraine ridges were mapped in all outlet valleys and within the Andean Cordillera.

Strings of latero-frontal moraines cap the eastern margins of the former outlet glaciers. Moraine morphology varies between straight, arcuate, or meandering ridges (Figure 4(a,b)) or mounds, ranging from <0.01 km to ~50 km in length (Figure 3). In the field, the moraine crest/apex usually possesses an undulating morphology (Figure 4(f)) and are commonly overlain with sub-rounded, faceted boulders. The highest relief (ca 250 m) and most distinctive of these possess a sharp apex, steep ice-distal slope, and crosscut the Río Cisnes valley (CIS 3, 4 & 5; García et al., 2019). The longest moraine in the region is found in the Río Pico valley, a laterally continuous moraine (~50 km in length), with a sinuous morphology (Figure 3 and Figure 4(a,b)).

Within the Andean Cordillera, stratigraphically younger moraines are usually low-relief (<10 m), continuous ridges that possess an arcuate form and point down-slope of empty and occupied mountaintop cirques (e.g. Figure 3). Straight or winding, discontinuous ridges with close spacing are found nested upslope of larger latero-frontal moraines. The best preserved of these are found surrounding the Mt. Hudson volcano.

5.1.3. Morainal banks
A rounded wedge of sediment, possessing a steep ice-distal face, and gently tapering ice-proximal slope (44°03‘32.8” S, 71°34‘22.9” W) has been mapped adjacent to palaeolake shorelines and ice-contact fans in the northern Río Pico valley. This landform has been interpreted as a morainal bank (cf. Fitzsimons & Howarth, 2018; Rovey & Borucki, 1995), indicating a glaciolacustrine terminus with subaqueous deposition (cf. Davies et al., 2018; Martin et al., 2019). The morainal bank marks the northern lateral edge of the PIC 6 moraine (Figure 4(c,d)), aligned in a south–north direction, ~5 km in length, and terminating into a small (~12 km²), isolated, palaeolake basin (44°01‘56.7” S, 71°32‘57.0” W).

5.1.4. Trimlines
Trimlines were mapped within the Andean Cordillera (e.g. Figure 4(e,f)), and are concentrated around the remaining ice caps (e.g. Figure 3). Trimlines are found in two forms: the first is lobate landforms, which possess a sharp or gradational break between glacially scoured bedrock, sediment, or shrubs to the developed treeline, and point down-valley from active glaciers or abandoned cirques. The second possesses a sharp transition between underlying sediment/bedrock to low-lying shrubs and run parallel with the valley sides. According to criteria outlined by Rotes and Clark (2020), these are classified as glacial trimlines based on a clear contrast between surface age (e.g. developed vegetation, glacially scoured bedrock), proximity to moraines, or position down-slope of glaciers.

5.2. Subglacial landforms
5.2.1. Cirques
Landforms identified on mountain tops in the Andean Cordillera and marked by arcuate headwalls which taper into sub-rounded erosional hollows are mapped as cirques (Figure 4(e,f)). Many cirques in Patagonia still contain glaciers (e.g. Araos et al., 2018; Martin et al., 2019), though here we map abundant deglacierised cirques. Cirques can be identified in the surrounding landscape based on their position up-slope of ice-marginal (e.g. latero-frontal moraines) and subglacial (e.g. flutes, glacially scoured bedrock) landforms. The cirque bed will often appear overdeepened from subglacial erosion (Hooke, 1991), and sometimes contains a lake.

5.2.2. Crag-and-Tails
Crag-and-tails can be differentiated from other subglacial landforms by a resistant bedrock core on their up-ice (stoss) end, with a gently tapering lee slope composed of softer glacial sediments (Benn & Evans, 2014; Stroeven et al., 2013). Elongate ridges (individually ≤2 km in length, ≤0.4 km in width), only mapped in the Río Cisnes valley, are interpreted as crag-and-tails, aligned southwest–northeast and streamlined in the direction of local ice-flow.

5.2.3. Glacially scoured bedrock
Glacially scoured bedrock is distinguishable from the surrounding landscape by a smoothed bedrock surface often interspersed with vegetation, till, or found overlain with perched boulders. These glacial erosional landforms may indicate points of greater ice thickness, where basal ice has reached its pressure-melting point (Glasser & Bennett, 2004; Shaw, 1994). Similarly to the more northerly Río Corcovado, Río Huemul, and Lago Palena-General Vintter glaciers (Leger et al., 2020, ~43°S), the Río Pico valley possesses extensive areas of glacially scoured bedrock (~84 km²), and displays a broad-scale west–east streamlining in the direction of local ice-flow.

5.2.4. Glacial lineations
Glacial lineations are defined by an ovate or linear, elongate morphology, valley-floor position, and...
orientation in the direction of ice-flow. These landforms can be utilised as flow lines and may indicate areas of thick or warm-based ice that scoured and deposited sediment into linear ridges (Glasser & Jansson, 2005; Stroeven et al., 2013). Regionally, the most well-defined, elongate (≤2.5 km in length) and narrow (≤0.1 km in width) ridges occur in the Simpson/Paso Coyhaique valley (e.g. Figure 5(a,b)), aligned west–east and southwest–northeast reflecting local ice-flow directions.

5.2.5. Flutes
Narrow, elongate, and streamlined ridges (≤1.5 km in length) are a product of subglacial deformation (cf. Van der Meer, 1997), and were mapped as sedimentary flutes. Flutes are only preserved within recently deglaciated areas, and are useful in determining the direction(s) of local ice-flow (Gordon et al., 1992). We mapped 2521 flutes on mountaintops within the Andean Cordillera. The best example of these can be found south of Volcán Macá (Figure 5(c,d)), up-valley of glacial trimlines, and demonstrating multiple, diverging, ice-flow paths.

5.3. Glaciolacustrine landforms
5.3.1. Palaeolake shorelines
In Patagonia, during glacial maxima, erosion of sediment/bedrock beneath outlet glaciers formed glacial overdeepenings (cf. Cook & Swift, 2012), which were sometimes exposed subaerially during deglaciation. These overdeepenings commonly developed into proglacial lakes during deglaciation (e.g. García et al., 2019; Leger et al., 2020). In the study area, most of these lakes have now drained, leaving well-preserved palaeolake shorelines to study. In the study area, most of these lakes have now drained, leaving well-preserved palaeolake shorelines to study. In the study area, most of these lakes have now drained, leaving well-preserved palaeolake shorelines to study. In the study area, most of these lakes have now drained, leaving well-preserved palaeolake shorelines to study.

We mapped palaeolake shorelines in two common forms. The first is continuous, flat-topped terraces calved into valley sides, moraines, or associated with perched deltas. These shorelines represent the most long-lived lake levels in the region. The largest and most distinctive of these shorelines are found in the Río Cisnes valley at 950–920 m a.s.l., and 860–850 m a.s.l. (Davies et al., 2020; García et al., 2019), and the Río Pico valley at ~870 m a.s.l.

The second type is sets of multiple, discontinuous, shorelines found on moraines or eroded into valley-side deposits (Figure 5(e,f)). These are more difficult to discern in the field due to narrow terracing and closely spaced steps, and represent a punctuated lake level lowering through time (e.g. Bell, 2008; Thorndycraft et al., 2019a). These sets are found in the Río Pico (1010–910 m a.s.l.), Río Cisnes (790–650 m a.s.l.), Lago Coyt/Río Nirehuao (730–600 m a.s.l.) and Balmaceda (~600–610 m a.s.l.) valleys.

5.3.2. Perched deltas
Perched deltas formed when rivers met proglacial lakes and remained raised above the (palaeo-)lake basin as lake levels fell (e.g. Dulfer & Margold, 2021; Stroeven et al., 2016). Perched deltas are flat-topped or possess a gentle slope oriented towards, but elevated above, a palaeolake basin. Mapping the distribution and elevation of perched deltas, and comparing them with palaeolake shorelines, informs on the extent of former palaeolake levels (cf. Bell, 2008; Glasser et al., 2016; Turner et al., 2005). We mapped 91 perched deltas in the study area, the largest of these is the Winchester Delta (44°36’30.9′′ S, 71°27’08.4′′ W) in the Río Cisnes valley (García et al., 2019), marking a local palaeolake level of 860–850 m a.s.l. Large deltas are also found in the Río Pico valley (44°04’54.3′′ S, 71°35’34.1′′ W; 44°05’12.8′′ S, 71°33’07.0′′ W), associated with a ~850 m a.s.l. delta-top area.

5.3.3. Ice-contact fans
Ice-contact fans morphologically resemble perched deltas but can be distinguished based on their proximity to moraines. These landforms are composed of a build-up of glacioluvial outwash on the ice-distal side of moraines during a prolonged period of glacier stability (Dowdeswell et al., 2015), and indicate the former ice-contact lake level at the time of moraine formation. The largest ice-contact fan (~15 km²) is found adjacent to the southern lateral margin of the PIC 6 moraine (44°24’48.4′′ S 71°33’38.1′′ W), gently sloping into the Río Caceres palaeolake basin, and marking a ~900 m a.s.l. lake level.

5.3.4. Glaciolacustrine sediments
Caldenius (1932) first described glaciolacustrine sediments in the study region, but precise locations were previously unknown. Fine grained, well-sorted, and laminated glaciolacustrine sediments have accumulated in association with proglacial palaeolake formation during deglaciation (Figure 5(g,h)). At the macro-scale, these deposits resemble varved sediments studied at Lago Buenos Aires (Bendle et al., 2017a). Laminated glaciolacustrine sediments were field verified in the Río Pico, Río Cisnes, Simpson/Paso Coyhaique, and Balmaceda valleys.

5.3.5. Palaeolake spillways (cols)
We updated previous mapping of palaeolake spillways (cols) identified in the Río Cisnes, Lago Coyt/Río Nirehuao, and Balmaceda valleys (Davies et al., 2020; García et al., 2019), which are important for studying the switch between Atlantic-bound and Pacific-bound drainage routes during deglaciation (Thorndycraft et al., 2019a; 2019b). We mapped two additional cols
in the Río Pico valley at ~810 m a.s.l. and ~770 m a.s.l., by analysing contour elevations of known palaeolake shorelines in ArcMap. These data suggest that the Pico palaeolake drained east, towards the Atlantic, until the palaeolake level dropped below ~770 m a.s.l.

5.4. Glaciofluvial landforms

5.4.1. Catastrophic flood landforms
We identified Boulder bars in the middle Río Cisnes valley (~470–560 m a.s.l.), above the banks of the modern Río Cisnes, and in association with the CIS 5 moraine (Figure 6(a–b)). The boulder bars are characterised by steep scarp slopes with a flat-topped surface, interspersed with sub-rounded boulders (≤3 m in height) and cobbles. In the field, we interpreted one boulder bar (44°40′08″S, 71°49′06″W, 545 m a.s.l.) as an expansion bar with a fossa channel located on the southern edge of the deposit (Figure 6(c)). These landforms are similar to those identified by Benito and Thorndycraft (2020) further south in the Baker valley, which were interpreted as forming as the result of catastrophic floods (≥10⁵ m³/s) during palaeolake drainage.

5.4.2. Proglacial outwash plains
Proglacial outwash plains are characterised by broad, flat-topped expanses of glaciofluvial sediment, forming on the ice-distal side of moraines, or found nested between moraine complexes (e.g. Bendle et al., 2017b; Darvill et al., 2014). Similarly to moraine complexes, proglacial outwash plains may provide approximate ice-marginal positions but additionally indicate the direction(s) of glaciofluvial drainage. Mountainous areas to the east of the main outlet glaciers constrained the area of former glaciofluvial activity; beyond this, the landscape transitioned into the Argentine steppe, where proglacial outwash plains formed continental drainage networks (e.g. Clapperton, 1993).

5.4.3. Proglacial outwash terraces
Raised, flat-topped terraces of glaciofluvial sediment, located within the margins of proglacial outwash plains, are interpreted to form as a result of isostatic uplift (Maizels, 2002) or (glacio-)fluvial incision (Eilertsen et al., 2015). Stratigraphically younger terraces usually display well-preserved meltwater channels, whilst the surfaces of outwash terraces associated with the most extensive glacial advances appear homogenous. Based on geographic position, some of the stratigraphically youngest outwash terraces, oriented in a southwest–northeast direction, are found in a tributary valley of the Balmaceda glacier (Figure 6(d,e)).

5.4.4. Meltwater channels
Meltwater channels were mapped in the main outlet valleys, and in two main forms. The first are proglacial meltwater channels, which form extensive networks and are found on the ice-distal side of moraines, preserved on proglacial outwash plains (e.g. Bendle et al., 2017b; Leger et al., 2020). These are generally sinuous, discontinuous, channels with narrow spacing. The second are ice-marginal and subglacial meltwater channels that dissect moraine ridges (e.g. Figure 4(a,b)) or the valley floor. These channels are sinuous, vary in width from less than 50 m to over 150 m, and can only be traced for short distances. Where moraine complexes or ridges are heavily dissected, ice-marginal meltwater channels provide additional evidence for ice extent (Greenwood et al., 2007).

5.4.5. Kettle holes
Kettle holes were mapped inside proglacial outwash plains or nested within/between moraine complexes. Kettle holes are enclosed depressions with an ovate or sub-rounded planform shape and can be dry or contain small lakes. These landforms indicate regions where dead ice has been buried, melted, and left a residual pit (Evans & Orton, 2015). The largest kettle holes (~2 km²) are located between the N1R 1 and N1R 2 moraine complexes, in the Lago Coyt/Río Nir-huao valley.

5.5. Non-glacial landforms
Some non-glacial features were mapped in addition to glacial geomorphology. Holocene rivers, fans and deltas, palaeochannels, wetlands, and major floodplains determine the direction of modern or recent drainage routes and point to areas of possible post-depositional re-working. River terraces provide an indication of the relative age of drainage routes, and therefore the timing of continental drainage re-organisation. Mapping residual lakes can also be useful, particularly in determining the structure of palaeolake evolution in the main valleys.

Landslides or slumps were common following deglaciation, and particularly in the southern region (below 45.5° S) of the study area (cf. Pánek et al., 2021). Mapping landslides or slumps is important, as gravitational instabilities can be mistaken for moraines (e.g. Soteres et al., 2020). In particular, younger landslides or slumps appear to have overlaid segments of the Simpson/Paso Coyhaique and Balmaceda lateral moraine complexes.

6. Concluding points
We present a glacial geomorphological map covering a ~50,000 km² area of west-central Patagonia
(44–46° S), building on existing mapping in the region (Table 1). The map provides a detailed, georeferenced, inventory of glacial landforms mapped within eight outlet valleys and the Andean Cordillera. The inventory contains >70,000 features and 27 landform groups which were classified as ice-marginal, subglacial, glaciolacustrine, glaciofluvial, or non-glacial landforms. Our mapping reveals: (1) Multiple, previously unmapped, moraine complexes or deposits and ridges (Figure 3) spanning from the most extensive glacial advances to the stratigraphically youngest; (2) the widespread occurrence of palaeolake shorelines, perched deltas, ice-contact fans, and glaciolacustrine sediments in association with the main outlet glaciers informing on the existence and geolocation of multiple, large palaeolakes; and (3) the distribution of proglacial outwash plains, proglacial outwash terraces, and meltwater channels, which provide evidence for the extent, longevity, and direction of regional glaciofluvial drainage networks. Data will underpin future assessments of palaeo-glacier dynamics, the generation of geochronological datasets through direct-dating methods, and the basis for refining reconstructions of the Quaternary Patagonian Ice Sheet.

Software
Mapping was originally undertaken in ArcMap (v. 10.3) and completed in ArcGIS Pro. Full layout design for all maps was completed using ArcGIS Pro.

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Data Availability Statement
All shapefiles are available in the supplementary materials of this paper.

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Data Availability Statement
All shapefiles are available in the supplementary materials of this paper.

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