Glacial geomorphology of the Marinelli and Pigafetta glaciers, Cordillera Darwin Icefield, southernmost Chile

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1. Introduction

Patagonia contains some of the longest and best-preserved glacial records in the world (Clapperton, 1993). The region is of interest for palaeoclimatic research because of its position in relation to important atmospheric and oceanic circulation systems, including the Southern Westerly Winds (westerlies) and the Antarctic Circumpolar Current (Ackert et al., 2008; Boex et al., 2013; Kaplan et al., 2008; Moreno, Francois, Villa-Martinez, & Moy, 2009; Murray et al., 2012; Strelin, Kaplan, Vandergoes, Denton, & Schaefer, 2014). The southern reaches of Patagonia extend closer to Antarctica than any other continent and so researchers have targeted the region to understand interhemispheric glacial (a) synchrony at the end of the last glacial termination, 18,000 years ago (Denton et al., 2010; Garcia et al., 2012; Moreno, Jacobson, Lowell, & Denton, 2001; Severinghaus, 2009; Sugden et al., 2005).

Contemporary glaciation in Patagonia is restricted to three major icefields: the North and South Patagonia Icefields and the Cordillera Darwin Icefield (CDI) on Tierra del Fuego (Figure 1(A)). In recent years, several studies have reconstructed recession of the former Patagonian Ice Sheet into the Cordillera Darwin mountain range during the last glacial termination (Boyd, Anderson, Wellner, & Fernández, 2008; Fernández, Anderson, Wellner, & Hallet, 2011; Hall, Porter,...

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a climatologically significant part of the world and can be used as the basis for future chronological campaigns.

2. Study area and previous work

The Cordillera Darwin mountain range in southernmost Patagonia includes peaks exceeding 2000 m a.s.l. and is host to the CDI, covering approximately 50% of the range (Holmlund & Fuenzalida, 1995). At ~2300 km² (Bown et al., 2014), the icefield is the third largest ice mass in South America and includes both tidewater glaciers calving into fjords and former land-terminating glaciers, many of which are now calving into proglacial lakes. Our study focuses on two of these different types of glaciers. The Marinelli marine-terminating glacier and Pigafetta, former land-terminating, now freshwater-terminating glacier (Figure 1 C) are selected to represent different glacial regimes producing different geomorphological histories under similar climatic conditions (Boyd et al., 2008).

Figure 1. (A) Map of Patagonia showing the three modern icefields: Northern Patagonia Icefield (NPI), Southern Patagonia Icefield (SPI) and Cordillera Darwin Icefield (CDI). (B) Landsat image mosaic of the CDI and the study area. The inset map shows the approximate present extent of the modern Southern Westerly Wind system (orange shading) and the Antarctic Circumpolar Current (ACC; blue dashed line). (C) Contemporary glaciers around the study area. Marinelli (tidewater) and Pigafetta (land-terminating with proglacial lake) glaciers are highlighted in blue and orange. Shaded-relief digital elevation model (DEM) was derived from a radiometrically terrain-corrected ALOSPALSAR image (August 2010). Glacier outlines are taken from the Randolph Glacier Inventory (Arendt et al., 2015), updated here using 2016 optical satellite imagery.
The CDI is located in the present-day core of the southern westelries. The region receives relatively uniform precipitation throughout the year, which can reach up to 5000 mm/yr at the top of the icefield (Garreaud, Lopez, Minvielle, & Rojas, 2013). Mean daily temperature patterns indicate a regional control, with temperatures varying between 0° and 15°C at sea level (Fernández et al., 2011). The E–W orientation of the CDI creates an orographic effect with greater precipitation on southern and western glaciers and drier conditions around northern and eastern glaciers (Holmlund & Fuenzalida, 1995; Lopez et al., 2010). The Marinelli and Pigafetta glaciers are located on the northern edge of the CDI. Due to their close proximity (5 km apart), the temperatures and precipitation experienced by each glacier are similar.

### 2.1. Marinelli and Pigafetta glaciers

Glaciar Marinelli (54°36’ S, 69°36’ W) is the largest glacier in the CDI and in 2016 drained an area of 129 km² north of Monte Shipton, the highest peak in the mountain range (2569 m a.s.l.). The glacier flows for 19 km before calving into the Fiordo Marinelli, south of Bahía Ainsworth. Historic observations suggest the glacier terminus once held a stable position at the mouth of the fjord (de Agostini and de Gasperi in 1913), calving directly into shallow water in Bahía Ainsworth until the first half of the twentieth century (Agostini, 1956; de Gasperi, 1922). Evidence for this position remains in the form of a large terminal moraine that likely marks the culmination of an advance during the LIA (~AD 1870) (Davies & Glasser, 2012; Porter & Santana, 2003). Subsequently, Glaciar Marinelli has retreated at one of the highest rates in South America; at an average of 153 m/a (Bown et al., 2014). Overall, the glacier has receded by around 15 km between 1913 and 2011, with the greatest annual retreat between 1984 and 1985 (923 m; Bown et al., 2014). In 2016, the tidewater calving terminus was 3.3 km wide and divided in two by the exposure of a bedrock knoll.

Glaciar Pigafetta (54°36’ S, 69°34’ W) is presently a freshwater-calving glacier located to the northeast of Glaciar Marinelli. In 2016, it drained an area of 23.6 km² over a distance of 10 km, north of Monte Yagán (2158 m a.s.l.). The glacier terminates in a proglacial lake dammed by a terminal moraine, which drains first into Ensenada Pigafetta and then Bahía Ainsworth. Between 1945 and 2016, Glaciar Pigafetta retreated by around 1.4 km at an average rate of 20 m/a, with an associated expansion of the proglacial lake (Bown et al., 2014).

### 2.2. Previous mapping

Our mapping focuses on part of the Cordillera Darwin mountain range where glacial geomorphological mapping remains largely absent. At the last glacial maximum (LGM), ~24,000 to 18,000 years BP, ice extended from Cordillera Darwin and coalesced to form the southern reaches of the former Patagonian Ice Sheet (Hall et al., 2013; Kaplan et al., 2008; McCulloch, Fogwill, et al., 2005). To the north and east of our study area, extensive mapping has been conducted of geomorphology related to the maximum ice extent around the Strait of Magellan and northern Tierra del Fuego (e.g. Clapperton, Sugden, Kaufman, & McCulloch, 1995; Bentley, Sugden, Hulton, & McCulloch, 2005; Darvill, Stokes, Bentley, & Lovell, 2014). However, this work did not extend into the centre of the mountain range. Cordillera Darwin was included in a regional map of Patagonian glacial geomorphology (Glasser & Jansson, 2008; Glasser, Jansson, Harrison, & Kleman, 2008). However, this mapping was conducted at a necessarily coarse scale and recorded only the largest landforms in the study area, such as glacial cirques and trimlines in Fiordo Marinelli and an arcuate terminal moraine in Bahía Ainsworth. In addition to Glasser et al.’s (2008) map, small regions of the Holocene glacial geomorphology have been mapped in detail for the Monte Sarmiento massif area (Strélin et al., 2008) and Fiordo Pia area (Kuylenstierna et al., 1996). To date, high-resolution (10 m) mapping of the Marinelli and Pigafetta glacial geomorphology has been lacking.

### 2.3. Chronological constraints

It is unclear how quickly glaciers retreated during the last deglaciation from the Strait of Magellan area southward towards the present positions of the Marinelli and Pigafetta glaciers. McCulloch, Fogwill, Sugden, Bentley, and Kubik (2005) suggested that ice might have stabilised during retreat at the northern tip of Dawson Island, roughly halfway between LGM extents and the Cordillera Darwin mountain range. They identified this stabilisation as ‘Stage E’, between ca. 15.5 and 11.8 ka, making it synchronous with the Antarctic Cold Reversal (ACR, 15.3–12.2 ka; Sugden et al., 2005). The evidence for stabilisation is supported by the evidence for two large proglacial lakes situated at this time between LGM moraine limits to the north and ice to the south (McCulloch, Bentley, Tipping, & Clapperton, 2005). By contrast, basal ages from peat cores close to the heart of Cordillera Darwin indicate ice-free areas by ca. 16.8 ka (Hall et al., 2013, 2017). These results complement a marine core age in Fiordo Almirantazgo, offshore from Bahía Ainsworth, which suggests ice-free conditions by at least 14.3 ka (Bertrand et al., 2017; Boyd et al., 2008). Hence, an alternative argument is that ice did not stabilise or re-advance during the ACR. With respect to the study glaciers, Hall et al. (2013, 2017) concluded that there was no evidence for re-advance of the Glaciar Marinelli after
ca.12.5 ka (Boyd et al., 2008; Fernández et al., 2011; Koppes et al., 2009). Likewise, the adjacent Ensenada Pigafetta was likely ice free by ca. 8.0 ka (Boyd et al., 2008). Chronological constraints relating to the Holocene history of Glaciar Marinelli and/or Glaciar Pigafetta are limited to more recent neoglacial ice front positions. Bertrand et al. (2017) used marine sediments from the Fjordo Almirantazgo to reconstruct a potential re-advance of land-based CDI outlet glaciers at 7.3–5.7 ka followed by periods of rapid retreat at 3.3–2.7 ka and 2.0–1.2 ka. There is a good evidence that the prominent terminal moraine in Bahía Ainsworth dates to the LIA (Fernández et al., 2011; Holmlund & Fuenzalida, 1995; Koppes et al., 2009; Porter & Santana, 2003). Dendrochronological ages obtained by Porter and Santana (2003) confirm that Glaciar Marinelli advanced during the late nineteenth century and both the Marinelli and Pigafetta glaciers are presently retreating.

3. Map production

We conducted geomorphological mapping using a combination of remote sensing analysis and fieldchecking. Aerial photographs and satellite imagery were used to provide the most rigorous interpretation of the glacial geomorphology before selected areas were examined in the field.

3.1. Imagery

Our initial mapping used Landsat ETM+ (2012–2014) and OLI scenes (2015–2016) from the USGS Global Visualization Viewer (GLOVIS: https://glovis.usgs.gov/). These cover an area of 185 × 185 km and have a spatial resolution of 30 m, increased to 15 m using the panchromatic band 8. Landsat imagery was then supplemented with ESA Sentinel-2 images from 2016 (spatial resolution of 10 m in four visible and near-infrared bands), downloaded from the Alaska Satellite Facility (VERTEX; https://vertex.daac.asf.alaska.edu/). Terra ASTER images from the NASA’s Earth Observing System Data and Information System (EOSDIS; https://reverb.echo.nasa.gov/reverb/) were also used, covering an area of 60 × 60 km, with a spatial resolution of 15 m.

Where possible, we used aerial photographs in preference to satellite images and these revealed features that were absent from previous mapping. A total of six vertical aerial photographs was used (all scanned hard copies with ~5 m resolution from the Servicio Aerofotogramétrico de la Fuerza Aérea de Chile). Where aerial photographs were not sufficiently clear, BingMaps® often provided freely-available 2013DigitalGlobe images of only slightly lower resolution (up to ~5–15 m).

Geomorphological mapping was overlain on Digital Elevation Models constructed from Shuttle Radar Topographic Mission (SRTM) data (3 arcsec data, 90 m resolution) from the USGS EarthExplorer depository, ASTER Global Digital Elevation Map (GDEM) data (1 arcsec data, 30 m resolution) from the NASA Reverb depository and Radiometric Terrain-Corrected (RTC) ALOS PALSAR Global Radar Imagery (12.5 m resolution) from the VERTEX depository. The elevation models provided topographic context and were also used to identify some features only visible as subtle changes in topography.

A field campaign in April 2015 allowed us to cross-check features mapped from remote imagery. Fieldwork was conducted using sea kayaks to access the forelands of the two glaciers. The remote and challenging nature of the field area meant that it was not possible to cover the entire ~350 km² study area on the ground and so we targeted key elements of the geomorphological sequence (Figure 1(C)).

3.2. Geomorphological mapping

In total, 12 different glacial features were mapped as line and/or polygon symbols using QGIS software (version 2.14.7). These were: contemporary glaciers, glacial cirques, ice-scoured bedrock, glacial lineations, morainic complex or deposits, moraine ridges, outwash plains, trimlines, ice-contact slopes, former shorelines, glaciolacustrine deposits and meltwater channels. Rivers, lakes, alluvial fans, mountain peaks, ridgelines and scarps were also mapped to provide a broader physiographic context.

4. Glacial geomorphology

The glacial geomorphological features mapped in this study (Main Map) are summarised in Table 1 in terms of their morphology and appearance (colour, structure and texture). In this section, we briefly describe these different features.

4.1. Contemporary glaciers

Contemporary glaciers were identified using the most current version 6.0 of the Randolph Glacier Inventory (RGI; http://www.glims.org/RGI/rgi60_dl.html). However, manual corrections were applied to update the outlines to 2016 extensions and delimit debris-covered ice. In particular, we distinguished glaciers from ice patches and/or patches of relic ice to avoid confusion. The outlet glaciers in the study area are the Marinelli tidewater calving glacier – the largest glacier in the CDI – and the adjacent Pigafetta freshwater calving glacier (Figure 2).

4.2. Glacial cirques

Glacial cirques are large- to medium-sized amphitheatre-shaped hollows on mountain flanks or incised into plateau edges, showing sharp boundaries with the
Table 1. Criteria used for the identification of the geomorphological landforms by satellite imagery (adapted from Bendle et al., 2017; Darvill et al., 2014; Davies & Glasser, 2012; Glasser et al., 2005; Glasser et al., 2008).

| Landform/feature       | Morphology                                                                 | Colour/structure/texture                                      | Possible identification errors                                                                 | Glaciological significance                                             |
|------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------|--------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| Mountain peaks         | Mountain peaks, often pyramidal in shape due to glacial and periglacial erosion on two or more sides | Dark colours with possible shading and rough texture           | Possible misplacement due to snow or ice on the summit. A DEM helps to pinpoint the exact summit. | Divides one or more present or former ice masses                         |
| Ridgelines             | Steep-sided ridges separating two valleys or glacial cirques, commonly descending from peaks to mountain passes | Linear shading due to sharp relief, usually standing out against surrounding snow or ice.            | May be covered with snow, although shading is highly distinctive.                               | Indicate glacial erosion or basal weakening on rocky slopes             |
| Scars                  | Abrupt steps on slopes                                                      | Shading, with dark colours highlighting bare and rough bedrock. | Possible overestimation without contours. Often occur in association with ridges and cirques.     | Indicate glacial erosion or basal weakening on rocky slopes             |
| Contemporary glaciers  | Bare ice, snow and debris. Surface structures such as crevasses and seracs are common | Snow and ice appear white to light blue in colour, with smooth to rough surfaces. Debris-covered ice is grey to black in colour. | Possible overestimation in glacier extent if confused with snow cover.                          | Foci for ice discharge from the contemporary icefield                  |
| Glacial cirques        | Large amphitheatre-shaped hollows on mountain flanks or incised into plateau edges | Sharp boundaries with surrounding terrain, including cliffs   | Possible confusion with mass-movement or landslip scars.                                         | Indicate the presence of localised or restricted mountain glaciation   |
| Ice-scoured bedrock    | Widespread exposures of bare or lightly vegetated bedrock, often containing small lake basins and open joints | Grey to light pink when vegetation cover is present. Bedrock structures and faults often present. Upper surface often has a rough, irregular texture. | Possible underestimation where bedrock is obscured by vegetation.                               | Evidence for extensive areas of former ice at pressure-melting point. |
| Glacial lineations     | Parallel features with a characteristic linear or oval-shaped morphology. Formed from sediment moulding or glacial erosion of bedrock | In bedrock, change in surface structure compared to surrounding terrain. In debris cover, different colour compared to surrounding terrain due to change in vegetation cover. | Possible underestimation in areas of thin debris cover. Bedrock landforms may be confused with bedrock structures in certain lithologies. | Show former ice-flow direction and may indicate high former ice velocities, especially when highly attenuated. |
| Morainic complex or deposits | Undulating topography within which distinctive moraine ridges occur      | Texture/colour difference from adjacent terrain. Presence of moraine ridges. Elevated above surrounding terrain. | Extent of morainic material difficult to delimit on imagery.                                    | Marks approximate extent of ice-marginal deposition.                  |
| Moraine ridges         | Prominent, cross-valley single or multiple ridges with positive relief. Linear, curved, sinuous or saw-toothed shape in platform | Shading due to change in relief and change in colour where moraines are vegetated.                   | Possible confusion with trinelines where moraines have low relative height.                    | Mark former positions of outlet glaciers.                              |
| Outwash plains         | Valley floor accumulations of sediment, commonly dissected by a braided stream pattern | Flat appearance, mainly light red areas with medium grey where there is thin vegetation cover. Erosional scars and sharp boundaries with surrounding terrain due to change in vegetation cover. | Possible confusion with delta or ice-contact deposits.                                          | Show major drainage routes from glaciers and glacier-fed streams.      |
| Trimlines              | Sub-horizontal lines on valley sides separating areas of non-vegetated and vegetated land or areas covered by different types of vegetation. | Sharp altitudinal change in surface colour and texture due to change in vegetation cover.           | Possible confusion with other sub-horizontal or horizontal features such as glacial lake shorelines. | Delimit the former vertical dimensions of glaciers.                    |
| Ice-contact topography | A steep escarpment of predominantly glaciofluvial sediment that was deposited against the wall of glacier ice, marking the position of relatively static ice margin; an irregular scar against which glacier ice once rested. | Homogeneous surface texture with flat upper surfaces, erosional scars and sharp boundaries with surrounding terrain. | Possible confusion with morainic complexes or outwash plains.                                   | Sediments deposited by streams draining tributary valleys onto/against glacier ice. Indicate thickness and extent of ice. |
| Former shorelines      | Raised terraces, often running parallel or sub-parallel to modern coastline or lake shoreline. | Shading due to change in height or relative relief. Change in colour if former shorelines are vegetated. Many shorelines mirror the shape of existing coastlines or lake margins | Possible confusion with moraines, especially around major lakes where both shorelines and moraines may be present and have similar orientations. May be missed where the location of a paleo-lake is not previously known. | Indicate former lake or sea levels. Some lake shorelines indicate the presence of a former ice-dammed lake. |
| Glaciolacustrine deposits | Broad, flat accumulations of fine-grained glaciolacustrine sediment around former ice. | Distinctive white colouration of terrain on satellite images, distinct from | Underestimation of spatial extent on imagery. Best identified in the field. | Indicative of glacial lake existence and former lake levels. |

(Continued)
surrounding terrain (Davies & Glasser, 2012). The features are common in the mountainous parts of the study area beyond the perimeter of the icefield and are particularly well-developed in former tributary valleys such as Fiordo Marinelli, Pigafetta valley and Fiordo Almirantazgo. Cirques are concentrated in areas that have been deglaciated since the LGM and follow the direction of the main ridgelines, which show considerable local variation relating to geotectonics and glacial erosion (Glasser & Ghiglione, 2009).

4.3. Ice-scoured bedrock

Outcrops of ice-scoured bedrock comprise a large part of the Fiordo Marinelli but only a small area in front of the Glaciar Pigafetta, close to the current glacier margin. The bedrock lithology in the Fiordo Marinelli is dominated by Palaeozoic metamorphic rocks, Cretaceous granitoids and Jurassic gneiss (Sernageomin, 2003), where glacial erosion has been widely imprinted. These outcrops are heavily abraded and in places covered with a thin layer of glacial sediments, suggesting glacial erosion by Glaciar Marinelli along the main valley (Figure 3). (Glasser & Ghiglione, 2009).

4.4. Glacial lineations

Glacial lineations usually occur within glacial valleys where wet-based ice has scoured bedrock or deposited sediments. The features show the direction of former, warm-based ice flow. Lineations in the study area have been primarily identified on satellite and aerial imagery, although those located in the inner part of the Fiordo Marinelli were identified in the field in front of Glaciar Marinelli (Figure 3). By comparison, Glasser et al. (2008) mapped only a few lineations in the southern part of Fiordo Almirantazgo, north of our study area.

4.5. Moraine ridges and complexes

Moraine ridges are linear or curvilinear, elongate features exhibiting positive relief that demarcate the limits of former glacier margins. The mapped moraine ridges are mainly single, cross-valley ridges exhibiting ~10 to 30 m relief. A clear example is the sharp-crested outer moraine of the Pigafetta valley. Additionally, there are also complexes of closely spaced multi-ridge systems. These morainic complexes exhibit undulating topography within which distinctive moraine ridges occur (Bendle, Thorndycraft, & Palmer, 2017), such as to the west of the large arcuate terminal moraine of Bahía Ainsworth (Figure 4). The morainic complex has been shown to have formed by pulses of the Glaciar Marinelli during the Holocene (Boyd et al., 2008; Koppes et al., 2009).

4.6. Outwash plains

Outwash plains are large, flat areas consisting of well-sorted glaciofluvial sediment. Braided rivers often develop across the plains, such as in the dry eastern valleys of continental Patagonia. However, the cool, wet climate of western Patagonia and Tierra del Fuego usually leads to the development of peat bogs that can mask former outwash plains. For example, it is likely that contemporary peat bogs overlie an outwash plain in the Pigafetta valley (Figure 5). Nonetheless, the outwash

Table 1. Continued.

| Landform/feature | Identification criteria | Possible identification errors | Glaciological significance |
|------------------|-------------------------|--------------------------------|---------------------------|
| Meltwater channels | margins, lake embayments or valley sides Channels, often without contemporary drainage | Possible confusion with contemporary drainage routes | Indicate the routes of former meltwater drainage. Channels may indicate the position of a former ice margin, especially when in association with moraines |
| Lakes | Freshwater bodies within enclosed basins. | Lakes appear as blue to black, with sharp boundaries with surrounding terrain. Variety of shapes possible | Areas in the shadow of high relative relief or clouds may be mistaken for lakes | Indicate impeded drainage and can result from rock basins formed by glacial overdeepening |
| Rivers and streams | Channels of water draining a valley | Colours vary from blue to black, with sharp boundaries with surrounding terrain | Indicate contemporary drainage routes and may be sourced from modern glaciers |
| Alluvial fans | Sub-horizontal fans on valley sides and on distal parts of the outwash plains, often fed by meltwater channels or streams | Fan shaped accumulations with sharp boundaries with surrounding terrain due to change in vegetation cover. Often possess a pattern of braided streams on upper surfaces | Possible misinterpretation as ice-contact deposit | Reworking of unconsolidated material by contemporary meltwater channels and streams |
plain retains many of its characteristics when viewed in satellite and aerial imagery. The plain appears as a large, relatively flat area without major topographic constraints, downstream of a prominent moraine, which might give evidences of the former land-terminating dynamic of the Glaciar Pigafetta since its Early Holocene position in Bahía Ainsworth. Where clear meltwater channels can be identified within the outwash, these have been mapped separately.

4.7. Trimlines

Trimlines mark the erosive boundaries of formerly thicker ice. The features are identified as sub-
horizontal boundaries on valley sides separating vegetated and non-vegetated surfaces or areas covered by different types of vegetation (Glasser et al., 2008). A trimline on the eastern side of Fiordo Marinelli merges with a large arcuate moraine extending northwards into Bahía Ainsworth, likely marking recent glacier recession since the LIA (Porter & Santana, 2003) (Figures 2 and 4). Trimlines are also developed around the former tributary valleys of the Glaciar Marinelli and along Lago Pigafetta, which has been expanding with the frontal retreat of the Glaciar Pigafetta. There is generally good agreement between our mapping of trimlines and that of Glasser et al. (2008).

4.8. Ice-contact topography

Primary ice-contact slopes are identified as gently sloping or hanging deposits of glaciofluvial sand and gravel perched below trimlines on valley sides or at valley confluences (Bendle et al., 2017). These accumulations represent ice-contact glaciofluvial deposits that have been (de-)formed over low-lying bedrock outcrops and steep fjord- or lake-sides in the study area. The topography marks former terminal or marginal positions of both Marinelli and Pigafetta glaciers. Examples can be seen on both sides of Lago Pigafetta and Fiordo Marinelli, where steep slopes have triggered erosion of these hanging deposits (Figure 2). It is possible that mapped ice-contact topography represents (reworked) kame terraces, but we do not have sedimentological evidence from the field to support this hypothesis.

4.9. Former shorelines

Former shorelines were identified as raised, linear terraces that showed no positive relief and often continued unbroken around present fjords and lakes. We interpret these features to be wave-cut scarps and benches formed by previously higher lake levels (Glasser et al., 2008). The most prominent shorelines occur west of Fiordo Marinelli, perpendicular to
former ice flow of the Glaciar Marinelli and indicate the presence of four former ice-dammed lakes following the LIA advance. Based on our mapped shorelines, the four lakes would have covered between 0.4 and 1.3 km² and reached depths of around 45–110 m above the base of the former lakes. It is possible to identify former lakes on Alberto de Agostini’s 1913 photograph and 1945 USAF Trimetrogon aerial imagery (Agostini, 1956). Additionally, de Gasperi (1922) described the draining of one of these lakes – the second from the North – when mapping Glaciar Marinelli during de Agostini’s 1913 expedition: ‘In the second of those valleys, at the time of my visit (February 16, 2018) was formed a peripheral lake dammed by the glacier, partly dried due to the lake water break out between the rock and the ice’. Such observations lend support to our mapping of former shorelines in the study area.

4.10. Glaciolacustrine deposits

Glaciolacustrine deposits are inferred based on their appearance in satellite and aerial imagery and location within the bounds of former shorelines. These stratigraphic units are mapped because they appear as broad, relatively flat areas with a distinctive white colouration around former ice margins, particularly in the valley embayments on the western side of Fiordo Marinelli. However, we add the caveat that it was not possible to check the sedimentology of these features in the field and so cannot be certain that they were formed in a former glaciolacustrine environment.

4.11. Meltwater channels

Due to the proximity of contemporary glaciers and associated drainage, few former meltwater channels
were mapped in the study area and these likely mark recent glacial recession. Some meltwater channels are associated with large terminal moraine complexes, for example, those in the Pigafetta valley morainic complex. In contrast, there are no similar meltwater channels associated with recession of the marine-terminating Glaciar Marinelli.

5. Summary and conclusions

This paper presents a new glacial geomorphological map for two glaciers in the remote CDI at a level of detail greater than previous glacial geomorphological mapping in the study area. Mapped features include contemporary glaciers, glacial cirques, ice-scoured bedrock, glacial lineations, morainic complexes, moraine ridges, outwash plains, trimlines, ice-contact topography, former shorelines, glaciolacustrine deposits and meltwater channels. Many of these features have not been previously recorded. Our mapping highlights two principal glacial landform groups:

1. An assemblage of marine-terminating landforms in the Fiordo Marinelli area dominated by a large arcuate terminal morainic complex, glaciolacustrine landforms (shorelines) and extended ice-contact topography.
2. An assemblage of sequential frontal moraine ridges and outwash plains that formed when the formerly land-terminating Pigafetta glacier retreated from Bahía Ainsworth.

The contrast in landform assemblages between the Fiordo Marinelli area and Pigafetta valley is attributed to a difference in the glacial regimes of each glacier, which produced different geomorphological histories under similar climatic conditions.

The landforms around the Fiordo Marinelli were likely produced during relatively recent (LIA) glacial fluctuations during the neoglacial. Given than Glaciar Marinelli had a tidewater margin, the geomorphology may have been produced during retreat that was, to some extent, climatically independent (Holmlund &
Similar assemblages are described for marine-terminating glaciers in Patagonia, Svalbard, Alaska and the Canadian High Arctic where warm-based glaciers moulded and striated underlying bedrock and delivered large volumes of sediment and meltwater to the ice margin (Dowdeswell & Vasquez, 2013; Ó Cofaigh, Lemman, Evans, & Bednarski, 1999; Ottesen & Dowdeswell, 2006; Powell & Molnia, 1989). Since 2011, glacial activity in the fjord has generally decreased, due to the relatively stable position of Glaciar Marinelli.

The absence of surficial frontal moraines for 9 km between Bahía Ainsworth and the Pigafetta valley may indicate constant ice retreat of the Glacial Pigafetta towards the heart of the mountain range, likely as a former land-terminating glacier. The foreland is dominated by a large outwash plain that extends north of the marked moraine ridges in the inner part of the Pigafetta valley. These ridges were deposited when the glacier was still considerably more extensive than present – likely in the mid-Holocene and/or the LIA. A subsequent period of overall recession has resulted in the formation of a proglacial lake and a switch in ice dynamics from a land-terminating to a freshwater-calving glacier. Similar patterns have been described for the land-terminating Exploradores and Soler glaciers in the Northern Patagonia Icefield, both of which have large outwash plains in front of their LIA moraines (Aniya & Naruse, 1999; Aniya, Barcaza, & Iwasaki, 2007; Glasser, Jansson, Harrison, & Rivera, 2005).

This map is intended to underpin further work on the glacial history of glaciers in the region. The glacial geomorphological map provides the necessary context for dating former glacial limits and testing numerical ice-sheet models of glacial retreat in the heart of the CDI.

Software
Mapping and image processing was conducted using QGIS (2.14.7) and GRASS (6.4) software. The final geomorphological map was produced in Adobe Illustrator CS6.

Acknowledgements
E.I. would like to thank Rodrigo Bahamón and Coté Marchant for their assistance and companionship in the field, in the addition to Cruceros Australis Expedition Cruises, Erratic Rock Patagonia Expeditions, Marypaz II Turismo and Uncharted project. The authors are grateful for constructive comments by reviewers Dr Esteban Sagredo and Dr Juan Luis Garcia and editor Dr Kasper Knight.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This research was funded by Fondo Nacional de Desarrollo Científico y Tecnológico [FONDECYT-Chile; 1130381], awarded to J.C.A. at Universidad de Magallanes.

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