Glacial geomorphology of the central and southern Chilotan Archipelago (42.2°S–43.5°S), northwestern Patagonia

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ABSTRACT

We present a geomorphic map of the glacial landforms associated with the Golfo Corcovado ice lobe in northwestern Patagonia. Built upon prior studies, our map elaborates on the central and southern sectors of Isla Grande de Chiloé and neighboring islands. Through a combination of remote sensing techniques and exhaustive fieldwork, we identified a suite of ice-marginal, subglacial, and glaciofluvial features created by the Golfo Corcovado ice lobe during four maxima within the last glacial cycle, in none of which the ice-front reached the Pacific coast of Isla Grande de Chiloé. Our mapping builds a foundation and provides insights for future interdisciplinary research on the Late Quaternary sequence of glacial and paleoclimatic events in this key sector of northwestern Patagonia.

1. Introduction

Isla Grande de Chiloé (IGC) constitutes the largest island of the Chilotan Archipelago, which is composed by ~40 islands located in the Chilotan Inner Sea, just south of the Chilean Lake District (CLD) and west of Chiloé Continental, in northwestern Patagonia (40°S–44°S; Figure 1). This region has been central in the study of former glacial fluctuations and paleoclimatic conditions in the middle latitudes of the southern hemisphere (e.g. Denton et al., 1999; Heusser, 1990; Lowell et al., 1995; Moreno et al., 2015; Villagrán, 1985; Villagrán, 1988).

During the last ice age, locally known as the Llanquihue glaciation (Heusser, 1974), the region was covered by multiple piedmont glacier lobes that extended from Cordillera de los Andes (Figure 1; Davies et al., 2020) which produced a suite of well-preserved glacial landforms and sedimentary deposits. Previous studies have reconstructed the glacial history of CLD during the Last Glacial Maximum (LGM: 35–18 ka, ka = 1000 calibrated years before present) by mapping the extent of glacial landforms, particularly between Lago Ranco and Seno Reloncavi (e.g. Denton et al., 1999, 1976; Laugénie, 1982; Lowell et al., 1995; Mercer, 1972; Porter, 1981; Figure 2). Mapping efforts in the Chilotan archipelago have focused on the central-northern half of IGC, with fragmentary work on its southern third and some islands to the east (Andersen et al., 1999; García, 2012; Figure 2).

Our study seeks to fill the gap in glacial geomorphic and stratigraphic studies in the central and southern sectors of IGC and adjoining archipelago. This contribution is intended as an initial effort to expand our knowledge into a virtually unmapped sector, build a geomorphic framework integrating new sectors with previous site- or sector-specific studies, and laying the foundations to unravel the structure and timing of local glacial fluctuations during the last glacial cycle.

2. Previous work

The earliest sketch of former glacier limits in IGC was published by Caldenius (1932). Subsequently, Heusser and Flint (1977) mapped the landforms-sedimentary associations in glacial drift packages along the northern and central sectors of IGC (Figure 2). They distinguished three glacial limits based on surface morphology and weathering criteria, which they named San Antonio, Intermediate, and Llanquihue drifts, from outermost to innermost. These glacial
limits were correlated to the Colegual, Casma, and Llanquihue drifts (Table 1), previously identified by Mercer (1972, 1976) in the CLD area. Within the latter, and several years later, Porter (1981) defined and mapped four glacial drifts in the Lago Llanquihue area, he termed Caracol, Río Llico, Santa María, and Llanquihue, from outermost to innermost (Table 1).

Andersen et al. (1995, 1999) published the first comprehensive geomorphic map of northern IGC (Figure 2), developed in the context of an interdisciplinary effort to reconstruct the glacial, vegetation, and climate history of CLD during the LGM (Denton et al., 1999; Lowell et al., 1995). They identified at least two glacial drifts, composed by nested moraine ridges

Figure 1. (a) Location of the study area in southern South America. Former limit of the Patagonian Ice Sheet according to Davies et al. (2020) is outlined as a white polygon. Present Patagonian Ice Fields are depicted in grey. (b) Overview of the Chilean Lake District and the Chilotan archipelago showing the coverage of used aerial photographs (dark blue dots: centroids of GEOTEC images) and satellite imagery (light green boxes: Sentinel 1 imagery; blue light boxes: ALOS PALSAR digital elevation model). Field-checking areas (solid red line: inspected on the ground; dashed red line: helicopter inspection). (c) Digital elevation model of Isla Grande de Chiloé region highlighting the main sites of the study area.
they termed Casma/Colegual and Llanquihue drifts, from outermost to innermost (Table 1). More recently, García (2012) mapped the glacial landforms of central IGC (Figure 2), which he tentatively correlated with the Santa María and Llanquihue drifts (Table 1).

The initial glacial chronologies from the CLD and IGC relied on relative dating techniques, including morphostratigraphy and weathering rinds (e.g. Heusser & Flint, 1977), followed by a generation of studies that benefited from the advent of the radiocarbon dating technique (e.g. Heusser, 1990; Mercer, 1972; Porter, 1981). Subsequently, Lowell et al. (1995) and Denton et al. (1999) developed a glacial chronology based on an extensive radiocarbon-dating effort based on multiple minimum and maximum bracketing dates obtained from numerous stratigraphic sections and sediment cores from lakes and
Table 1. Stratigraphic names of the glacial drift hosted in the Chilean Lake District and Isla Grande de Chiloé according to Mercer (1972, 1976), Heusser and Flint (1977), Porter (1981) and Denton et al. (1999) Golfo Corcovado ice lobe drift sequence labeled by Mercer (1972, 1976) and Denton et al. (1999).

| Mercer (1976) | Heusser and Flint (1977) | Porter (1981) | Andersen et al. (1999) | Morphostratigraphic position | Age |
|---------------|--------------------------|---------------|------------------------|----------------------------|-----|
| Llanquihue    | Llanquihue               | Llanquihue    | Llanquihue             | Inner                      | Younger |
| Casma         | Intermediate            | Santa Maria   | Casma                  |                           | Older  |
| Colegual      | San Antonio             | Rio Llico     | Colegual               | Outer                      |       |
| Rio Frio      | ?                        | Caracol       | Pre-Casma/Colegual     |                           |       |

bogs associated to the Llanquihue drift. They concluded that ice lobes in the CLD achieved maxima during the last glacial cycle at ~33.9, ~30.9, ~27.0, ~26.2 and ~18 ka (Moreno et al., 2015). In IGC they show that the Golfo Corcovado ice lobe advanced to the outermost Llanquihue moraine prior to ~53.0 ka (Figure 2; Denton et al., 1999; Heusser et al., 1999), predating the LGM. More recently, Garcia et al. (2021) used a combination of radiocarbon, infrared stimulated luminescence and $^{10}$Be depth profiles to conclude that the outermost Llanquihue glacial limit of the Golfo Corcovado ice lobe was formed at ~57.8 ka, in agreement with previous findings. Subsequent ice advances occurred prior to ~34.5 ka, after ~26.7 ka, and shortly after ~18.1 ka (Figure 2; Denton et al., 1999; Heusser, 1990). They suggested that the final advance of the Golfo Corcovado ice lobe was the most extensive event of the LGM, contrasting with the behavior of ice lobes in the CLD (Denton et al., 1999). The westernmost extent of the Golfo Corcovado ice lobe in the southern third of IGC, however, was unaddressed by these studies. The demise of the Golfo Corcovado ice lobe is constrained by basal radiocarbon dates from multiple lakes and bogs inboard or atop the innermost Llanquihue moraine yielding close minimum-limiting ages of ~17.8 ka. Radiocarbon dates for the onset of ice-free conditions in Chiloé continental of ~16.7 ka (Figure 2; Moreno et al., 2015) indicate sustained glacier recession across ~100 km eastward through the Chilotan Inner Sea within ~1000 years or less.

3. Setting

The Chilotan archipelago spans from ~41.8° to ~43.5° S in the Pacific shore of southern Chile. The western sector of IGC is dominated by Cordillera de la Costa (CC) running N-SE. Two topographic gaps corresponding with the Canal de Cahao and Lago Huilinco-Cucao basin divide the range into Cordillera PiuChén (~900 m a.s.l.) in northern IGC, and Cordillera Pirulil in central-southern IGC. The interior-eastern sector of IGC is characterized by a flat to smooth hilly topography extending eastwards to the inner sea (Figure 1(c)).

The CC consists of Paleozoic metamorphic and Miocene sedimentary rocks, which limit with Quaternary glacial, glaciolacustrine, and glaciofluvial deposits toward the interior and eastern sectors of IGC (SERNAGEOMIN, 2003). The tectonic setting is dominated by the subduction of the Nazca Plate under the South American Plate and the Liquiñe-Ofqui Fault Zone in the continent, accounting for several stratovolcanoes located ≥70 km east of IGC. These have produced numerous tephra layers interbedded within local soil sequences in the Chilotan archipelago, Chiloé continental, and east of the Andean divide (Alloway et al., 2017a, 2017b, 2018) and seismic activity, such as the recent (AD 2016) Mw 7.6 earthquake that occurred offshore south of Tantauco (Ruiz & Madariaga, 2018; Figure 3).

The climate of northwestern Patagonia is controlled by the annual cycle of the southern westerly winds, which promotes maximum precipitation during winter and minimum during summer (Garraud et al., 2013). From west to east, meteorological stations distributed across IGC show annual precipitation values that range from ~2500 to ~1600 mm and a mean air temperature fluctuating between ~14°C in summer and ~7°C in winter (data retrieved from www.explorador.cr2.cl). Satellite data indicate offshore sea surface temperatures ranging between ~15°C in summer and ~11°C in winter, whereas the Chilotan Inner Sea follows a similar pattern but slightly colder during the entire year (Saldías et al., 2021).

4. Map production

We present a glacial geomorphic map of central and southern IGC (~42.2°~43.5°S) that encompasses areas within and beyond previous mapping efforts (Figure 2; Andersen et al., 1999; García, 2012; Heusser & Flint, 1977). We developed descriptions and interpretations from raw observations, extending our analysis into neighboring islands and sea floor whenever pertinent.

We conducted an initial identification of major glacial landforms (Figure 1(b)) using aerial photographs (1:70,000) and satellite imagery from Google Earth (2016 Cnes/SPOT, ~15 m spatial resolution), SENTINEL-2 (~10 m spatial resolution), and ESRI Imagery (2017, TerraColor, ~15 m spatial resolution and SPOT, ~2.5 m spatial resolution). We analyzed
minor topographic features using images from the Advanced Land Observation Satellite (ALOS PALSAR, ∼12 m spatial resolution). Submarine landforms were examined with the General Bathymetric Chart of Oceans 2019 (GEBCO 2019, ∼0.6 km/pixel spatial resolution). We ground-truthed the preliminary interpretations based on glacial geomorphologic mapping through field campaigns between 2016 and 2019 (Figure 1(b)). While the more accessible locations in central IGC and adjacent islands were covered on the ground, the southern sector, corresponding to the Tantauco area, was scouted from a helicopter.

5. Results

We summarized the glacial landforms identified throughout central and southern IGC in Table 2, indicating their corresponding: (i) morphological description, (ii) identification criteria, (iii) potential uncertainties, (iv) interpretation, and (v) previous mapping efforts of the individual landforms recognized in IGC.

We divided the study area in four sectors (Figure 1(c)) to facilitate the descriptions, which we present from north to south.

5.1. Castro-Dalcahue sector

This sector extends between Río Butalcura to the mouth of Estero Castro (Figure 1(c)). To the west, the CC reaches its maximum elevation in IGC (∼900 m a.s.l.). Plastered against the eastern flank of the range, we recognize a sequence of diffuse ice-contact slopes (Table 2) accompanied by poorly-defined till deposits running at elevations of ∼370 m a.s.l. Immediately to the east, we identify at least three
Table 2. Summary of glacial landforms, identification criteria, uncertainties, and previous mapping of the geomorphology of the Golfo Corcovado ice lobe (adapted from Bendle et al., 2017; Darvill et al., 2014; Leger et al., 2020; Lovell et al., 2012; Soteres et al., 2020).

| Landform                | Morphology                        | Identification criteria                                                                 | Uncertainties                                                                 | Interpretation                                                                 | Previous mapping          |
|-------------------------|-----------------------------------|----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|---------------------------|
| Ice-marginal landforms  | Moraine ridge                     | Medium to large positive relief with plan morphology ranging between conic to linear and composed of glacial sediments with large boulders of Andean lithologies (granites, tonalites, metasedimentary) periodically protruding. | Sharp and continuous feature elevated above surrounding topography. Often aligned in the same direction. Limited by marked slopes on DEM. | Generally, it marks the former position of the glacier margin. In some cases, it could also reflect minor standstill positions of the ice-front. | Andersen et al. (1999) Garcia (2012) |
| Moraine terrain         |                                   | Irregular topography composed by rounded hills made of glacial sediments. Sometimes, it is possible to identify large boulders (erratics) on the surface of these landforms. | Diffuse pattern without significant slope breaks on DEM. | When subdued, difficult to differentiate from outwash plains. It can also be hard to distinguish from bedrock promontories, especially in the Tantauco sector. | Andersen et al. (1999) Garcia (2012) |
| Ice-contact slope       |                                   | Prominent linear to arcuate slopes with homogeneous inclinations extending for tens to hundreds of meters. The top of this landform often exhibits moraine ridges and/or the headwater of an outwash plains. Locally, the slope is heavily incised by fluvial channels. | Extensive and sharp breaks on the slopes on DEM. | Extensive linear-to-sinuous features delimited by smooth slope breaks and sub-horizontal valley floors forming U-shaped valleys on DEM. | Marks the former position of the glacier margin. | Andersen et al. (1999) Garcia (2012) |
| Subglacial landforms    | Subglacial channel                 | Linear or sinuous long depression reaching several tens of km with smooth slopes and flat bottoms. Usually ends abruptly in lithological boundaries. Frequently occupied by lakes or wetlands. Punctually delimited by moraine ridges. | Extensive linear-to-sinuous features delimited by smooth slope breaks and sub-horizontal valley floors forming U-shaped valleys on DEM. | Potential misidentification with meltwater channels. | Garcia (2012) but labeled as glacial trough. |
| Ice-sculpted bedrock    |                                   | Major bedrock outcrops with rounded plan form and smooth surface. Minor moraine ridges and ice-contact slopes are often attached to bedrock flanks. | Extensive rounded features of contrasting color within surrounding landscape in satellite imagery. Delimited by marked slope breaks in DEM. | When covered by vegetation, difficult to distinguish from moraine ridges or moraine terrain. | Indicative of former ice coverage. | Unmapped |
| Rock lineation          |                                   | Minor bedrock outcrops with a linear plan form reaching ~1 km in length and usually nearby the Cordillera de la Costa. | Linear features with contrasting colors with adjacent landscape on satellite imagery. Parallel and subdued slope breaks on DEM. | Potential misidentification with moraine ridges. | Indicative of former ice-flow direction. | Andersen et al. (1999) Garcia (2012) |
| Glaciofluvial landforms  | Outwash plains                     | Extensive gently inclined surfaces (0°–5°) grading from ice-marginal features. Frequently composed by sequences of distinctive terraces. | Areas of homogeneous color imprinted by linear to undulating features in aerial and satellite. | Potential misclassification when appear in contact with subdued moraine terrain. Surface. | Indicative of former meltwater drainage pathways. Headwaters might mark a | Andersen et al. (1999) Garcia (2012) |

(Continued)
| Landform                          | Morphology                                                                 | Identification criteria                                                                 | Uncertainties                                                                 | Interpretation                                                                 |
|----------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Glaciolacustrine landforms        | Paleodeltas (0°–5°) with fan-like plan form, commonly associated to outwash plains or fluvial channels ending in depressions. | Small flat surface with fan-like limits and homogeneous fine-grained texture in DEM. | Minor features, difficult to identify in aerial and satellite imagery. Potential misinterpretation with outwash plains Fieldwork and stratigraphic analysis are required for confirmation. | Marks the maximum height of former glacial lake levels. Unmapped |
| Glaciolacustrine irregular terrain | Irregular topography, heavily incised by fluvial channel. Associated to the proximal portion of ice-contact slopes located at the eastern coastline of the main island. | Distinctive fluvial erosion pattern in aerial and satellite imagery. Irregular pattern with no significant slope breaks in DEM. | Potential misidentification with moraine terrain. Fieldwork and stratigraphic analysis are needed for confirmation. | Delimits the extent of former glacial lakes. Heusser and Flint (1977) |
| Fluvial landforms                 | Fluvial channel Linear and deeply incised channel ranging from 1 to 10 km in length and V-shape profile. Elongated and deep valleys in aerial and satellite imagery. Sharp and steep breaks on the slope, marked V-shaped profile in DEM. | Difficult to differentiate from meltwater channel when located at mountainous areas. | Marks modern drainage pathways. | Garcia (2012) identified this feature as Holocene riverbed. |
| Coastal landforms                 | Sea cliff Linear and continuous scarps of steep slopes and tens of m in high above the coastline. | Sharp and linear breaks in the slopes of the coastline on DEM. Areas of homogeneous light colors close to the coastline. Sandy bars are often visible in aerial and satellite imagery. Fine grained texture with flat | Potential misidentification with ice-contact slopes. Difficult to delimitate when associated with outwash plains. | Indicates areas dominated by marine processes. Marks areas dominated by marine processes (sandy beaches) or the between fluvial to marine processes (estuaries). Unmapped |
| Coastal features                  | Nearly horizontal surfaces (0°–3°) located at sea level on the coastline. Often composed by sandy beaches delimited by sea cliffs. | | | Garcia (2012) mapped sandy to gravel beaches mostly in the western shore of the main island. |

(Continued)
outwash terraces (Table 2), extending from CC to the Pindapulli community, that descend in elevation toward the NW from the Dalcahue-Castro coastline through the Mocopulli-Pupetra sector into the Río Butalcura channel. The lower outwash plain extends for ∼10 km ranging from ∼180 m a.s.l. at its headwaters to ∼100 m a.s.l. at its distal portion, the upper subsidiary outwash terraces reach ∼190 and ∼200 m a.s.l. at their headwaters, respectively.

To the east and south of the outwash plains, the landscape is characterized by irregular morainic topography (Figure 4; Table 2) extending to the eastern coast of IGC (Andersen et al., 1999; García, 2012). In this area, we distinguish remnants of nested, and relatively sharp moraine ridges (Table 2) oriented from NE to SW between Dalcahue and Río Butalcura. These ice-marginal features are partially buried by the outwash plain that mantles the Mocopulli and Pupetra area (Main map).

Another distinctive feature in the east coast of IGC corresponds to a continuous and steep ice-contact slope (Table 2) that runs between Dalcahue and Castro. At its proximal side, the slope presents an irregular topography with smooth hills accentuated by minor creeks. Numerous stratigraphic exposures in this area reveal a sequence of laminated sands with discrete lenses of silts and clays and occasional dropstones, which we interpret as glaciolacustrine beds.

### Table 2. Continued.

| Landform                  | Morphology                                                                 | Identification criteria                                                                 | Uncertainties                                                                 | Interpretation                                                                 | Previous mapping |
|---------------------------|----------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|------------------|
| Subaqueous landforms      | Subaqueous moraine                                                        | Linear-to-arcuate positive relief in the sea floor associated with terrestrial ice marginal features. | Topography on DEM.                                      | Hard to differentiate from morainal banks or grounding zone wedges. Difficult to field check. | Unmapped         |
|                           | Subaqueous channel                                                        | Linear-to-sinusoidal depressions delimited by marked subaqueous scarps reaching several tens of km. | Continuous depression with linear-to-sinusoidal plan form marked by sharp brakes on the slope of the sea floor in bathymetry DEM. | Potentially indicative of former meltwater drainage. | Rodrigo (2006)    |
|                           | Subaqueous lineation                                                       | Long and linear positive relief reaching ∼10 km in the bottom of the sea floor.          | Long linear feature with 10 km in length and delimited by sharp brakes on the slope of the sea floor in bathymetry DEM. | Indicative of former ice flow direction. | Rodrigo (2006)    |

### Figure 4.

Oblique aerial photographs of the morainal topography and moraine ridge near Castro (Figure 1(c)).
These deposits were first described by Heusser and Flint (1977), who inferred the presence of a proglacial lake during the last deglaciation we name, informally, ice-dammed lake Castro. At the top of this ice-contact slope, we identify moraine ridges and/or the headwaters of the outwash plain terraces discussed above, as well as a mayor channel that dissects the lower outwash (Table 2; Main map). This channel starts at ~100 m a.s.l. east of Dalcahue and presents a sinuous plan flowing northward into the Mocopulli-Pupetra outwash plain and ending in Río Butalcura. This channel, which is currently inactive, likely evacuated meltwater from its respective ice-front or functioned as the spillway of lake Castro during the final phases of the last glaciation (Heusser et al., 1995).

To the southeast of the Castro-Dalcahue ice-contact slope, we distinguish a suite of continuous and sharp moraine ridges running N-S in Peninsula Rilán. The interior of the peninsula features an outwash plain that descends northward from an elevation of ~120 m a.s.l. at its headwater (Main map). Its distal portion shows a tilted sequence of sand and gravel layers capped by horizontal layers of sands and gravels we interpret as the topsets and foresets, respectively, of a Gilbert-type delta (Table 2). The paleodelta reaches ~100 m a.s.l., marking a maximum level for the glacial lake that deposited the glaciolacustrine sediments discussed in the previous paragraph, which most likely discharged through the channel located east of Dalcahue.

We recognize several ice-margin features further east on Isla Quinchao, including groups of moraine ridges running NW-SE in the island interior, and ice-contact slopes forming its northern shore, where glaciolacustrine beds in natural outcrops are ubiquitous (Main map).

The small islands to the east exhibit irregular morainal topography lacking sharp and laterally continuous ridges that would indicate former ice-front stabilization in the archipelago following withdrawal from the LGM margins.

### 5.2. Lago Cucao – Isla Talcán sector

From north to south, this sector spans from the southern limit of Peninsula Rilán to Lago Tepuhueico. The most conspicuous topographic feature is a wide valley that crosses CC from east to west, where Lago L. Cucao and Lago L. Huillinco are located (Figure 1(c)).

We observe two levels of outwash plains sloping westward, north and south of L. Cucao (Figure 5). The upper outwash plain ranges between ~150 and ~60 m a.s.l. from its headwaters to its distal portion, and the lower between ~120 and ~30 m a.s.l., respectively. We recognize moraine remnants partially buried by the upper outwash south of L. Cucao (Main map). A well-defined ice-contact slope immediately west of Lago Quilque (Figure 5) separates both outwash plains. Further evidence supporting our interpretation of this landform comes from a road cut near its culmination revealing a stratigraphy composed by massive sands with gravel lenses in discordant contact with a sequence of horizontal layers of sand and gravels we interpret as a glaciofluvial deposit (Figure 5(b); Turbek & Lowell, 1999).

Further east of L. Cucao, along its northern shore, we identify a sequence of ice-contact slopes between ~200 and ~300 m a.s.l. resting on the eastern slope of CC (Main map). These features can be traced southward to a narrowing located between L. Cucao and L. Huillinco, where we find minor moraine ridges and ice-moulded bedrock outcrops (Table 2).

Eastwards, the area between L. Huillinco and the eastern coast of IGC features an irregular morainal topography with discontinuous moraine belts. The most distinctive moraine ridges occur on the eastern shore of L. Huillinco. These ice-marginal features appear to correlate with some isolated moraine fragments located north of the meltwater channels that originate from the Quinched area (Main map). Inboard from these moraines, we recognize numerous parabolic-shaped valleys reaching ~10 km in length and ~120 m in depth, occasionally occupied by lakes, and abruptly ending when changes in bedrock lithology occur, we interpret as subglacial channels (Figure 6; Table 2). These landforms were previously identified by Garcia (2012), who interpreted as glacial troughs formed in a subglacial environment and reworked during subsequent glacial incursions.

To the east of IGC, we identify an ice-contact slope and moraine ridges running N-S along the eastern coast of Isla Lemuy. To the north, this ice-contact slope can be correlated with the moraine ridges and ice-contact slopes of Peninsula Rilán and Isla Quinchao; to the south, this landform is aligned with submerged geomorphic ridges that cross Bahía Yal toward IGC, landforms we interpret as subaqueous moraines (Table 2; Batchelor & Dowdeswell, 2015). The continuity of this feature matches the ice-contact slope that establishes the eastern coast of IGC between L. Tarahuin and Queilen (Main map).

The rest of the Chilotan islands to the east of Isla Lemuy consist of irregular morainal topography and outwash deposits lacking clear ice-marginal features, suggesting that the Golfo Corcovado ice lobe did not stabilize during deglacial retreat in the interior archipelago.

### 5.3. Lago Tepuhueico – Estero Compu sector

This sector extents from L. Tepuhueico in the north to L. Yaldad in the south (Figure 1(c)). From west to east, the first distinctive glacial landforms correspond to a
A group of outwash plains occupying east-to-west trending valleys that dissect the core of CC and descend toward the western coast of IGC. The most extensive of these originates west of L. Tepuhueico and ranges in elevation from 150 to 50 m a.s.l. We also detect multiple subtle ice-contact slopes between ∼350 and ∼250 m a.s.l. on the eastern flank of CC, adjacent to L. Tepuhueico. Immediately east of that lake, we recognize a group of small outwash plains that descend to the west and follow a N-S direction (Main map).

The interior of IGC is dominated by several subglacial channels imprinted over irregular morainal topography with occasional moraine ridges (Figure 6). These channels flow westwards reaching ∼50 km in length, and originate from ice-contact slopes or former U-shaped valleys currently flooded by the sea, such as Estero Compu, along the eastern coast of IGC.

A prominent ice-contact slope culminating ∼120 m a.s.l. rims the east coast of IGC between Bahía Yal and Queilen, where it curves westward forming the slopes of Estero Compu. Closely inboard, intermittent moraine ridges occur near Queilen following a N-S direction. These moraines can be traced to submarine ridges, we interpret as subaqueous moraines, towards Isla Tranqui. South of Isla Tranqui, we find NW-SE trending ice-contact slopes running along the east coast of IGC that match the direction of subaqueous moraines (Main map).

Figure 5. (a) Overview of the sequence of outwash plains nearby Lago Cucao and ice-contact slope of Lago Quilque (Figure 1(c)). (b) Detail of a stratigraphic exposure at the culmination of the Lago Quilque ice-contact slope.
This sector corresponds to the southern tip of IGC (Figure 1(c)) and has a landscape dominated by the CC, which, at this latitude, curves towards the east occupying most of the island. To the west, close to the Pacific shore, we observe extensive and westward-dipping outwash plains (Figure 7(a)) enclosed in the valleys excavated on the Miocene sedimentary rocks of CC (SERNAGEOMIN, 2003). Northwest of L. Chaiguaco, imprinted over the outwash plains, we detect a well-preserved ice-contact slope topped by sharp moraine ridges in the Río Medina valley (Figure 1(c) and Figure 8). The next valley to the south exhibits remnants of moraine ridges located at similar morphostratigraphic positions.

East of L. Chaiguaco, the landscape exhibits a smooth topography mainly composed by ice-moulded knobs of the Paleozoic metamorphic rocks from CC. We identify a subtle ice-contact slope running N-S at an elevation of ~300 m a.s.l. south of L. Chaiguaco and west of L. Chaiguata (Main map). The east coast of IGC exhibits a well-defined ice-contact slope culminating at ~130 m a.s.l. from Estero Yaldad, near Quellón, to the north of Isla San Pedro (Figure 1(c)). In the latter, massive bedrock outcrops present a rounded ice-sculped plan form, occasionally
resulting in parallel rocky lineations of hundreds to thousands of meters in length following a SE-NW direction (Main map), indicative of former ice flow.

The south coast of IGC is characterized by a well-preserved ice-contact slope running E-W at ~150 m a.s.l. (Main map). Its culmination is associated to moraine terrain accompanied by scattered moraine ridges, which turn towards the Pacific Ocean south of L. Huillin.

In general, the distribution of ice-marginal landforms in the Tantauco sector suggests that glacier flow occurred along a SE to NW axis along Canal Moraleda (Figure 1(c)), where Rodrigo (2006) mapped large-scale subaqueous mega-lineations reaching ~15 km in length.

### 6. Discussion

#### 6.1. Glacial limits of the Golfo Corcovado ice lobe

The predominantly discontinuous and poorly preserved nature of ice-marginal landforms in central and southern IGC allow us to address a first-order interpretation of the behavior of the Golfo Corcovado ice lobe. The distribution and morphostratigraphic relations of the most distinctive moraine ridges, ice-contact slopes, and outwash plains, suggest at least four potential glacial limits associated to the Llanquihue glaciation. We named these positions as Corcovado (COR) 1–4, from outermost to innermost (Figure 9).

The outermost glacial limit, COR 1 (Figure 9), is defined by the Butalcura moraines which were first mapped by Andersen et al. (1999), and subsequently recognized by García (2012). These ice-marginal features are morphostratigraphically associated with the sequence of diffuse ice-contact slopes running at the eastern flank of CC distal to L. Pastahué. To the south, in the L. Cúcao area, COR 1 appears as the ice-contact slope of L. Quильke, which continues southward along the eastern slope of CC in the L. Tepuhueico sector. In the Tantauco sector, we correlate this ice margin with a series of ice-contact slopes and moraine ridges associated to the outwash plains hosted in valleys that dissect CC. Except for the L. Cúcao area, the distribution of deposits and landforms suggests that the Golfo Corcovado ice lobe remained buttressed against CC without reaching the west coast of IGC, at least, during the Llanquihue glaciation. This conclusion validates previous hypotheses based on the southward extrapolation of ice marginal features from the CLD and central IGC (García, 2012).

COR 2 (Figure 9) is represented by a diffuse ice-contact slope along the eastern flank of CC distal to Laguna Pastahue, closely inboard of COR 1. To the south, this ice marginal feature can be tentatively traced to the narrowing connecting L. Cúcao and L. Huillínco, further south these landforms can be associated with an ice-contact slope plastered along the eastern slope of CC in the L. Tepuhueico sector, at broadly the same elevation. We could not identify ice marginal features attributable to COR 2 in the Tantauco sector of IGC, possibly due to fluvioglacial erosion on the narrow sectors of the valleys traversing the CC, outwash burial, or, alternatively, to the deposition of moraines on the western slope of CC. Hence, the extent of this glacial limit remains elusive in the Tantauco sector of IGC.

The next glacial limit is COR 3 (Figure 9), which is represented by a group of subtle moraine ridges inboard the Butalcura moraines recognized by Andersen et al. (1999) and García (2012). To the south, near Quinched, COR 3 follows a group of moraine ridge remnants heading west toward the eastern shore of L. Huillínco. Further south, in the L. Tepuhueico area, we did not recognize any distinctive ice-marginal features. We hypothesize that the Golfo Corcovado ice lobe could have reached the headwaters of the outwash...
plains located east of CC between L. Tepuhueico and L. Yaldad. In the Tantauco sector, COR 3 is represented by an ice-contact slope and minor moraine ridges running N-S between the west shore of L. Chaiguata and south of L. Huillín, where they originate outwash plains that drain toward the Pacific Ocean.

The innermost glacial limit, COR 4 (Figure 9), comprises prominent ice-contact slope and moraine ridges extending along the eastern and southern coast of IGC, from Punta Tenaún in the north to the Tantauco shore in the south. This ice marginal feature appears to be associated through subaqueous moraine ridges with ice-contact slopes and moraine ridges.
hosted in Isla Quinchao, I. Lemuy and I. Tranqui. This ice-front position could account for the formation of ice-dammed lake Castro in the Castro-Dalcahue area (García, 2012; Heusser et al., 1995; Heusser & Flint, 1977) and suggests that the Golfo Corcovado ice lobe experienced a stepwise retreat from the east coast of IGC following withdrawal from COR 3, as opposed to a single irreversible pulse.

Overall, the northern and central-southern sectors of IGC present different glacial landform types. To the north of the Castro-Dalcahue area, distinctive moraine ridges associated to extensive outwash plains clearly delineate former ice lobe boundaries (Andersen et al., 1999), whereas to the south of Lago Cucao-Huillinco, ice-marginal and glaciofluvial features are diffuse and the landscape is mostly dominated by ice-moulded CC hills furrowed by subglacial channels (Main map). This finding suggests that (i) glaciers in northern IGC advanced over a soft sedimentary bed, whereas, in southern IGC the Golfo Corcovado ice lobe mostly advanced over bedrock outcrops; and (ii) the differences in CC topography between the northern (absence of CC) and central-southern (high and low relief, respectively) sectors of IGC established topographic barriers that affected local glacial dynamics and hydrology. Based on our
mapping, which covers for the first time the southern half of IGC, we infer that the Golfo Corcovado ice lobe did not surpass the CC toward the west coast in central and southern IGC, at least, during the last glaciation.

7. Concluding remarks

We present a new map of the landform-sediment associations sculpted and deposited by the Golfo Corcovado ice lobe in the central and southern thirds of IGC and the adjoining archipelago, including the seafloor of the Chilotan Inner Sea.

We distinguish four marginal positions of the Golfo Corcovado ice lobe in IGC (Figure 9), defined by successive glacial and glaciofluvial landforms along a west-to-east axis. Our results suggest that (i) the Golfo Corcovado ice lobe was mostly butted against the CC during the last glaciation without reaching the Pacific coast of IGC, and (ii) that disappearance of the Golfo Corcovado ice lobe proceeded in a step-wise manner during the initial portion of the Last Glacial Termination (∼17.8–16.8 ka) forming the ice-dammed lake Castro. Our map, thus, provides constraints for further empirical and modeling developments in a key area of the middle latitudes of the Southern Hemisphere.

Software

Spatial information analysis was carried out using ArcGIS 10.4 software. World image in the inset map was composed in MATLAB 2017. Final map production was completed with Adobe Illustrator CC 2020.

Open Scholarship

This article has earned the Center for Open Science badge for Open Data. The data are openly accessible at 10.17632/hzg2tvvxk8.1

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

ESRI shapefiles (*.shp) for visualizing the map produced in this study are freely available, as long as original publication is properly cited. A folder with twenty-four shapefiles can be downloaded from a Mendeley Data online repository using the following doi:10.17632/hzg2tvvxk8.1.

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