LATE PLEISTOCENE ICE FLUCTUATIONS AND GLACIAL GEOMORPHOLOGY OF THE ARCHIPIÉLAGO DE CHILOÉ, SOUTHERN CHILE

JUAN L. GARCÍA

Instituto de Geografía, Facultad de Historia, Geografía y Ciencia Política, Pontificia Universidad Católica de Chile, Santiago, Chile

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ABSTRACT. Most of the last glacial maximum (LGM) glacier record west of the southern Andes (40–55° S) is today submerged under the Pacific Ocean and therefore the Archipiélago de Chiloé (42–43° S) provides an unusual opportunity to study local sediment and landform associations to help understand paleoglacial features of the former *Patagonian ice sheet* (*PIS*). In this context, this work presents the first comprehensive glacial geomorphologic mapping of the central region of the Archipiélago de Chiloé, which is located in a transitional geomorphic region between the *Chilean Lake District* (*CLD*, 39–41° S, 73° W) and northwest Patagonia (~43–48° S, 74° W).

The Chilotan glacial geomorphology and sediment associations resulted from a warm-based glacier that characterizes a typical *active glacial temperate landsystem*, which in central Chiloé combines deposits and landform units originated in subglacial and subaerial environments. Paleoglacial features that occur in central Chiloé are characteristic of an ice-sheet style of glaciation, which differentiates it from a typical Alpine glacial style defined previously for the CLD. Therefore, the Archipiélago de Chiloé represents a geographical break point where the PIS became the large ice mass that occupied the Patagonian Andes during the last glacial period (Llanquihue Glaciation).

A double ice-contact slope on the east face of the Cordillera de La Costa provides evidence for the most extensive Early Llanquihue glacial advance on Isla Grande de Chiloé. The most prominent LGM advance in the area occurred at 26 000 cal yr BP, coincident with regional stadial conditions, and is defined by a big moraine along the east coast of the island.

Key words: Patagonian ice sheet, Llanquihue Glaciation, glacial geomorphology, Chiloé, glacial landsystems

Introduction

The former *Patagonian ice sheet* (*PIS*) extended from 38° S to 56° S along the southern Andes (e.g. Glasser *et al*. 2008). Last glacial maximum (LGM) climatic and topographic conditions along the Pacific slope of the southern Andes determined the existence of a typical 'Alpine style of glaciation' in the northern part of the PIS (e.g. *Chilean Lake District*, *CLD*, 39–41° S; Laugénie 1982; Andersen *et al*. 1999), whereas to the south (i.e. Patagonia Occidental; Steffen, 1844) an 'ice-sheet style of glaciation' was present (e.g. Hulton *et al*. 2002). As a consequence, PIS outlet glaciers included a wide range of termini with a variety of *glacial landsystems* defined in a broad geographical and climatological range (e.g. Glasser *et al*. 2008). The local morphological and geological record provides an excellent opportunity to define the geographical area where the PIS changed from an Alpine into an ice sheet type of glacial system. This question has important implications for understanding the glaciological attributes of the former PIS and paleoclimate reconstructions. In this work, the term Alpine refers particularly to glaciated mountain valleys (cf. Benn *et al*. 2005) where ice was constrained by topographic barriers, which in turn defined discrete ice lobes along a mountain range, today usually represented by deep, elongated lake bodies. However, ice-sheet glaciation refers to continuous ice expanding without major topographic constraints and therefore covering a relatively extensive region. A detailed study of the glacial sediment and landform associations can provide important paleoglacial information about this geographical transition in style of glaciation along the southwestern Andes. Most of the LGM record of former terminal ice positions in the western PIS is now submerged under the Pacific Ocean, except in the CLD (e.g. Denton *et al*. 1999) and Archipiélago de Chiloé (42–43° S). The glacial record at Peninsula de Taitao (46° S; Heusser 2002) remains mostly undated but probably postdates the LGM (e.g. Glasser *et al*. 2008). This work focuses in the Archipiélago de Chiloé and provides the first substantial glacial geomorphologic mapping of its central region. The main goal of this study is to define the local style of glaciation in the study area and to contrast our findings with those defined for the CLD (e.g. Laugénie, 1982; Andersen *et al*. 1999).

The Chilotan paleoglacial record represents the first opportunity to apply the *glacial landsystems* approach (e.g. Evans 2005; Benn and Evans 2010) to this area and describe the glaciological and climatological aspects of the last glaciation, regionally known as the Llanquihue Glaciation (*Marine Isotopic Stages*, *MIS* 4-2; Heusser 1974). This approach is in line with that used by Andersen *et al*. (1999) and Laugénie (1982), who built detailed geomorphologic maps for the CLD that included main morphologic units and their lithologies. The association between landforms and sediments by Andersen *et al*. (1999) resulted in detailed knowledge of the ice environments and ice fluctuations that characterized the last glaciation in the CLD.

This work aims to answer the following research questions. What glacial environments existed during the last glacial period in the central region of the Archipiélago de Chiloé as inferred from the sediment–landform associations present there? How does the glacial geomorphology inherited from the Llanquihue glaciation in central Chiloé compare to that in the CLD as defined by Andersen *et al*. (1999)? What was the maximum glacial extent of the Golfo de Corcovado Lobe on the central region of Isla Grande the Chiloé? When did this and other less extensive glacial pulses occur in the area? By applying the *glacial landsystems* approach (Evans 2005 and references therein; Ó Cofaigh and Stokes 2008; Glasser *et al*. 2009; Benn and Evans 2010) this work aims to define former proglacial and subglacial bed conditions and glacial dynamics that affected Chiloé during the last glaciation.

The Archipiélago de Chiloé, together with its landmark Isla Grande de Chiloé, occurs at present in the geographical and climatological transition between the Mediterranean climate regime of central Chile and the colder and wetter maritime regime of the fjords in west Patagonia (Patagonia Occidental). Chilotan glacial landforms and deposits are unique given that there are restricted LGM glacial records west of the southern Andes, and they comprise the distal part of major ice bodies flowing in a transitional geomorphological region.

Previous work

The Llanquihue Glaciation takes its name from the big lake that occurs in the southern part of the CLD and has been used to differentiate barely weathered deposits (Porter 1981) linked to the last glacial period from older glacial drifts in the CLD and Isla Grande de Chiloé (e.g. Heusser and Flint 1977; Porter 1981; Laugénie 1982; Denton *et al*. 1999).

The mapping and dating of the last glacial cycle record west of the southern Andes is a work in progress, particularly south of 41° S. On Isla Grande de Chiloé, Heusser and Flint (1977) recognized three major Pleistocene glaciations in Isla Grande de Chiloé (Fuerte San Antonio, Intermediate Drift and Llanquihue) but did not delimit glacial extent and only provided a general chronology. In the CLD and northern Isla Grande de Chiloé, Llanquihue glacial advances have been dated using stratigraphic sections and few moraine ridges have been dated directly (e.g. Mercer 1976; Porter 1981; Denton *et al*. 1999). For example, there is no direct dating on the outermost wide moraine belt both in northern Chiloé and CLD. Based on morphological and geographical aspects, this moraine was probably built after a regional, yet unknown, climatic event and its age could be MIS 4 (Porter 1981; Laugénie 1982; Mercer 1983; Denton *et al*. 1999).

The geomorphology inherited from the Llanquihue Glaciation in the CLD can be referred to as an Alpine system (e.g. Laugénie 1982; Andersen *et al*. 1999), and this has important implications for defining paleoglaciological and climatological conditions that characterized the northern PIS during the last glacial period. Today, eight prominent lake bodies closely expose the former extent of piedmont lobes that flowed from the Andes into the Depresión Intermedia (the tectonic graben that separates the Cordillera de Los Andes and Cordillera de La Costa). Each of these former glacial catchments include, overall, the same morphologic features concentrated in discrete basins, which altogether characterize the style of glaciation at the CLD. Three consecutive steep ice-contact slopes and associated moraine belts enclose present-day lakes (e.g. Porter 1981; Laugénie 1982; Andersen *et al*. 1999). The same triple pattern is found in northern Isla Grande de Chiloé (Andersen *et al*. 1999), nonetheless the latter ice marginal landforms can be traced for more than 50 km displaying rather straight north to south moraine ridges, which contrasts with the concentric arc-shaped geometry of the moraine systems enclosing the big lakes at the CLD. A west–east transect across the moraine field in the CLD and north Chiloé reveals this stepwise topography, punctuated by distinct ice-contact slopes, composite moraines and associated outwash plains (Andersen *et al*. 1999; Denton *et al*. 1999). Prominent ice-contact slopes, modified by erosion, occur at present lake margins (e.g. Lago Llanquihue) in the CLD where piedmont glaciers built kame terraces fringed on their distal sides by inner moraines (Andersen *et al*. 1999). Glaciers buttressed against the same ice-contact slope during different glacial pulses (Denton *et al*. 1999), when distinct moraine ridges were formed. The main outwash plain (i.e. tens of kilometers long and wide) grades from the outermost moraine belt. Erosional subsidiary outwash terraces grade from the inner moraine system and are incised in the main glaciofluvial plain. Preservation of landforms is very good and it is possible to trace most of the major outwash plains from their sources on moraine flanks to where they converge into the present fluvial drainage system. Meltwater channels cut subsidiary outwash plains and grade to present lake basins. These channels were active when piedmont glaciers were at the inner moraine belts and served as meltwater conduits as well as spillways for ice-dammed lakes during deglaciation (Denton *et al*. 1999). Ice-marginal channels can be traced between former ice margins and ice-contact slopes. Their small topographic gradient commonly does not allow recognition of paleoflow direction (Andersen *et al*. 1999).

For the LGM time period, Denton *et al*. (1999) documented the timing of at least four glacial advances in the CLD and northern Isla Grande de Chiloé. From their exhaustive radiocarbon chronology they defined the timing of the local LGM between 34 300 and 18 000 cal yr. BP (all ages presented in this work are ^{14}C ages converted to calendar years using Calib 6.0 by Reimer *et al*. 2009; infinite ^{14}C ages were not converted). During this glacial stage, the regional *equilibrium line altitude* (*ELA*) in the CLD was depressed ~1000 m relative to that at present (Porter 1981; Hubbard *et al*. 2005). This corresponds to an estimated drop of 6–8°C in mean summer temperature and precipitation ~2000 mm greater than present (Villagrán 1988a, 1990; Heusser *et al*. 1996, 1999; Moreno 1997; Moreno *et al*. 1999; Moreno and León 2003). The end of the LGM was marked by abrupt glacial retreat after 18 000 cal yr BP (Lowell *et al*. 1995; Denton *et al*. 1999).

This study builds on previous work by Denton *et al*. (1999) and Andersen *et al*. (1999) in North-east Chiloé and CLD by extending the detailed mapping program to the region just south of their study area; producing a glacial landsystem model on the northern PIS dynamics and fluctuations during the Llanquihue Glaciation; and providing new ^{14}C data that add to the local glacial chronology of the Archipiélago de Chiloé. A transect along the CLD reveals that LGM ice lobes were progressively bigger and reached farther distant areas to the west with higher latitude. The colder and wetter LGM climate at the latitude of central and southern Chiloé (Villagrán 1990; Heusser *et al*. 1999) produced large ice lobes (e.g. Golfo de Corcovado Lobe; Denton *et al*. 1999), which left a distinct glacial geomorphological imprint. By constructing a sediment–landform model, this work contrasts the paleoglacial attributes of northern PIS glaciation by comparing the sediment and landform associations in the CLD (Laugénie 1982; Andersen *et al*. 1999; Denton *et al*. 1999) and those in central Chiloé.

Physical setting

Isla Grande de Chiloé (Fig. 1) is separated from the mainland by the Golfo de Ancud and Golfo de Corcovado, where seawaters reach >400 m depth in some areas, due to the combined effects of tectonics and Pleistocene glacier erosion. Here, seawaters have inundated the Depresión Intermedia, a flat relief unit that to the north occurs on land. The Andes facing the southern half of the island are wider and have higher relief than in the lake district to the north, with ice caps on peaks >2000 m a.s.l. (e.g. Cerro Barros Arana, Macizo Nevado). During the Quaternary ice ages glacier ice eroded the preglacial fluvial landscape, replacing it by small, deep and wide glacial valleys (Glasser *et al*. 2008). During the Llanquihue Glaciation, and previous glaciations, the Chilotan Piedmont Glacier (Heusser 1990) drained these Andean glacial catchments, crossed the seaway, and expanded into the study area. The Golfo de Ancud and Golfo de Corcovado Lobes (Denton *et al*. 1999) advanced over the northern and southern regions of the island, respectively.

In the central region of the Archipiélago de Chiloé (42° 12′–43° 00′ S, 74° 15′–73° 13′ W, ~100–300 m a.s.l., Fig. 2), the Cordillera de La Costa, a prominent mountain range occurring all along Chile between ~20 and 46° S, decreases abruptly in elevation and tends to disappear to the south. Whereas north of Lago Huillinco this coastal

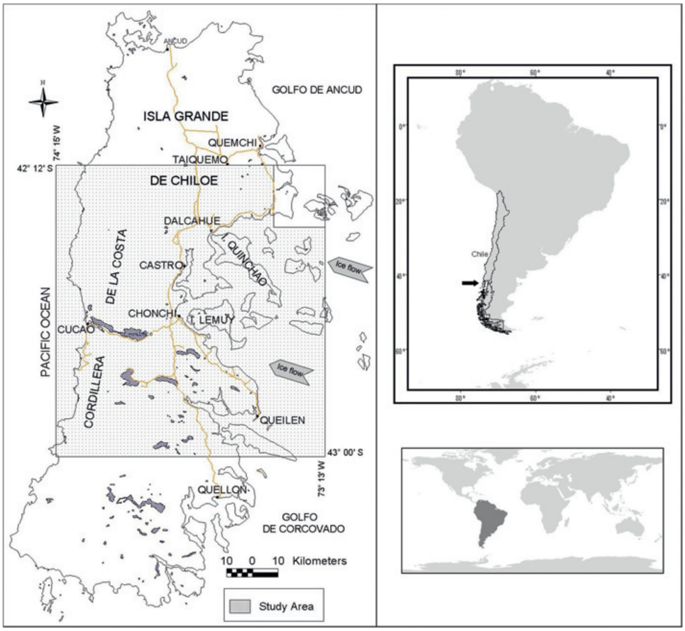

Fig. 1. Location of the Archipiélago de Chiloé (black arrow and left panel) and the study area (box) in the global and regional geographical context.

range reaches elevations ≥800 m a.s.l. to the south, where it is locally known as Cordillera de Piuché, elevations vary between 250 and 350 m a.s.l., with some peaks at ~550 m a.s.l. The Huillinco-Cucao Lake interrupts the continuity of the Cordillera de La Costa and allows a connection between eastern and western regions of the island. This area, together with the Estero Mocopulli in the north of the study area, formed the main westward meltwater drainage of central Isla Grande de Chiloé during the last glacial period.

Isla Grande de Chiloé is located at the northern margin of the westerly wind belt and *Antarctic Circumpolar Current* (*ACC*) (Strub *et al*. 1998). Here the ACC shows the steepest thermal latitudinal gradient and separates in the northward Humbolt Current and the southward Cape Horn Current. This abrupt change in ocean waters temperatures is linked with the westerly northern boundary (Lamy *et al*. 2004). These prevalent winds occur in a zone constrained mainly by the effect of the Pacific Anticyclone and the Atmospheric Polar Front and today produce a precipitation peak at 45–47° S (Miller 1976; Luebert and Pliscoff 2006). Although winters today in Chiloé are very humid, with ~1000 mm of precipitation between May and August in Castro (Luebert and Pliscoff 2006), during summer (December–March) the effect of the Pacific high-pressure cell impedes the ingression of storm tracks (Miller 1976). During the LGM, the westerlies migrated northward (e.g. Heusser 1989), bringing higher snow accumulation rates and wetter conditions to lower latitudes.

Materials and methods

Geomorphologic features of the Archipiélago de Chiloé presented here are the result of stereoscopic analysis of aerial photographs (Vuelo OEA, 1961, 1:50 000; Vuelo GEOTEC 1998, 1:70 000) covering the entire field area (>1000 km^2) and work during two field campaigns. Given the presence of widespread forest and limited access to some areas, the fieldwork was concentrated mainly in those zones with accessible roads. This issue limited direct examination of some areas, resulting in some generalizations. The field campaigns included the interpretation of stratigraphic sequences exposed in sediment sections at road-cuts, borrow pits and coastal cliffs located in the morphologic units to help understand former glacial dynamics, processes and environments. When possible organic materials were collected for radiocarbon dating. Discrimination between Llanquihue age and older landforms/

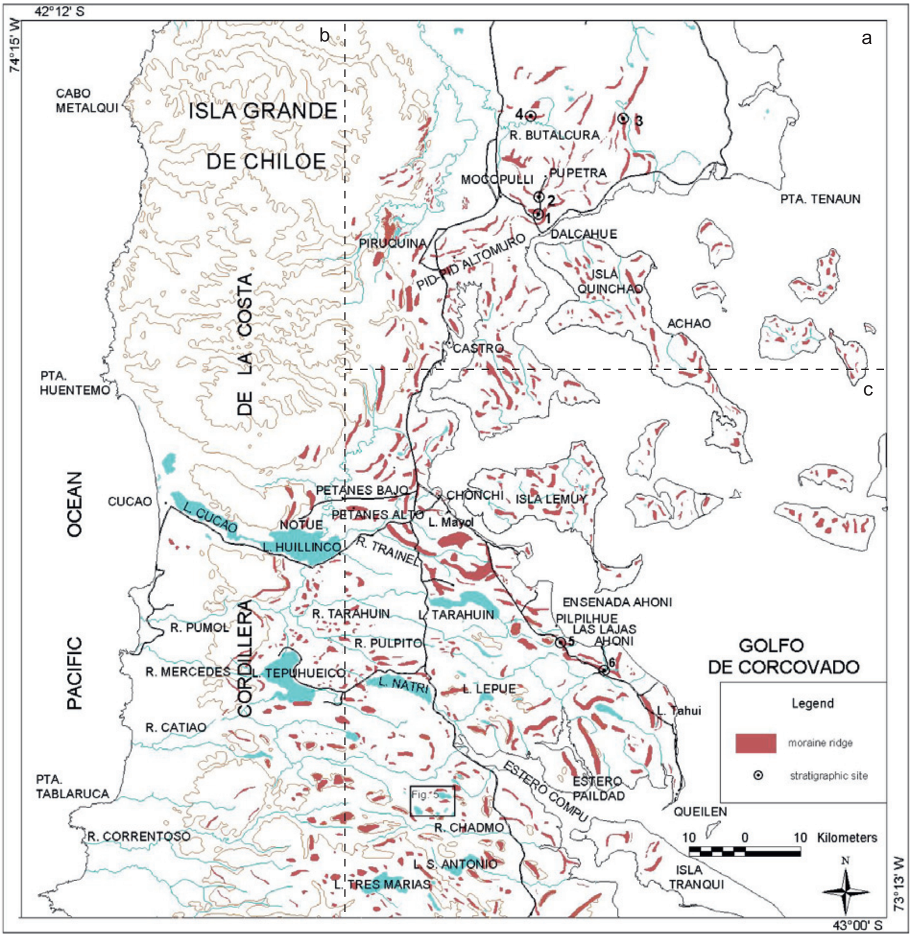

Fig. 2. Map of the central region of the Archipiélago de Chiloé showing moraine ridges of the Llanquihue Glaciation and other physiographical attributes. Dashed line boxes refer to the areas described in the text: (a) Castro-Dalcahue Area, (b) Cordillera de La Costa Area and (c) Eastern Margin Area. The black circles indicate the location of stratigraphic sites discussed in the text: (1) Dalcahue Site, (2) Pupetra Site, (3) Tehuaco Site, (4) Butalcura Site, (5) Las Lajas Site, (6) Ahoni Site.

sediments is based on weathering criteria as applied by Porter (1981) in the CLD. For instance, Llanquihue age volcanic clasts display weathering rinds < 0.5 mm (Porter 1981) and the overall Llaquihue landform preservation is excellent.

The analysis of topographic maps (1:50 000) and of landscape elements, including relative and absolute elevation of morphologic units, slope, dissection of landforms, landscape obliteration, water divides and hydrologic networks, played a key role in the construction of a sediment–landform associations model of the Llanquihue Glaciation in central Chiloé. For instance, I utilized these landscape elements to better understand the temporal sequence of glacial events in the study area, the distribution and connectivity of topographic depressions associated with the paleo and present drainage network, and the location of ice-marginal positions. The glacial geomorphologic map (Fig. 3) that resulted from the mapping program depicts the most representative morphological units and the overall glacial landscape inherited from the Llanquihue Glaciation in the central region of the Archipiélago de Chiloé. Names of moraines, meltwater channels and other units are given here to facilitate description and geographical comparisons. They follow names of the location where they occur.

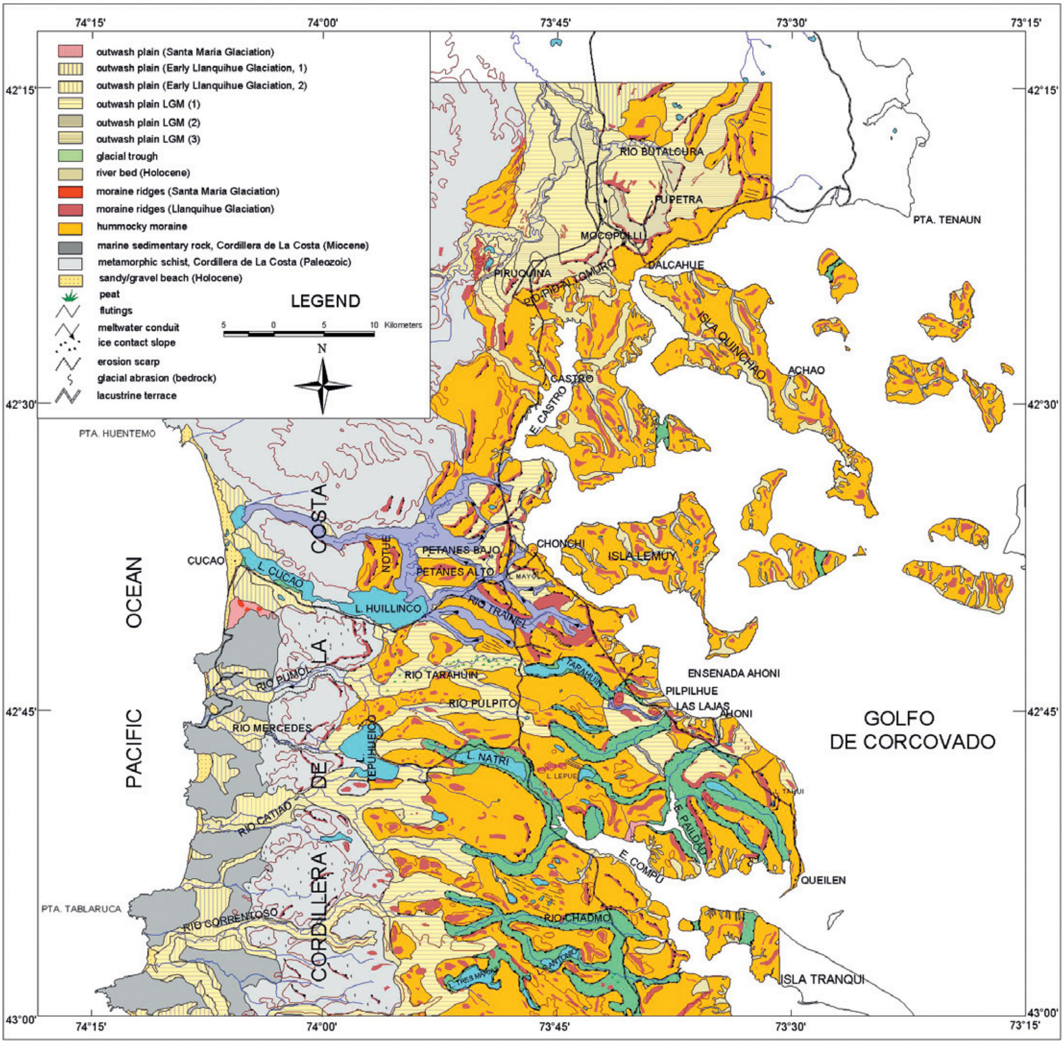

Fig. 3. Glacial geomorphological map of the central region of the Archipiélago de Chiloé.

Results

Based on the location of distinct glacier terminal positions during the last glaciation, the study area was divided into three areas (Fig. 2), which facilitates the understanding of the glacial attributes presented here: (a) *Castro-Dalcahue area*, in the north, where terminal ice positions of Early and Late Llanquihue age are well preserved; (b) *Cordillera de La Costa area*, where the Golfo de Corcovado Lobe reached its outermost position likely during the Early Llanquihue Glaciation; (c) *Eastern Margin area*, where LGM glacial margins are located (Fig. 2). This section first goes through the landforms present in each of the three areas defined above; second, it describes the different types of glacial sediments that crop out in different morphological units in the study area; and third, it gives a detailed description of key sediment sections that expose common sediment associations present in central Chiloé. Table 1 provides a summary of the sediment–landform associations occurring in the study area.

Castro-Dalcahue area landforms

Ice-contact slopes and moraines In this sector, it is possible to infer as many as five glacial marginal

Table 1. Summary of the sediment–landforms associations and their attributes as interpreted from the central region of the Archipiélago de Chiloé.

Sediment–landform association	Area	Units[a]	Observations
Ice-contact slope	Castro-Dalcahue, Cordillera de La Costa	CDA: Piruquina, Alto-Muro, Dalcahue and Pupetra Moraines CCA: Notue, Lago Tepuhueico	In the CDA, they form a stepwise system with three abrupt topographic breaks that define the LGM ice fluctuations. A double ice-contact slope on the CCA defines the most extensive glacial pulse during the Early Llanquihue
Moraine ridge	Castro-Dalcahue, Cordillera de La Costa, Eastern Margin	CDA: Butalcura, Piruquina, Alto-Muro, Dalcahue and Pupetra Moraines CCA: Notue, Lago Tepuhueico EMA: eastern composite moraine belt	In the CDA and CCA, they occur associated with ice-contact slopes. Moraine cores commonly include outwash and lodgement tills but flow tills and lacustrine sediments also may be present
Ground moraine	Castro-Dalcahue, Eastern Margin	Widespread in CDA and EMA, including the group of big and small islands to the east of Isla Grande de Chiloé	Occupies the higher moraine relief deposited during the Early Llanquihue Phase, where LGM deposits are incised in. Present in between LGM moraine ridges and present coastline. Hilly surface and mostly composed of lodgement and meltout tills
Outwash plain	Castro-Dalcahue, Cordillera de La Costa, Eastern Margin	Widespread in the northern part of the CDA, both sides of the Cordillera de La Costa south of Lago Cucao and distal to inner LGM moraines north of Chonchi	They are widely developed at the northern part of the CDA. In the CCA and EMA, they appear intercalated and incised in older landforms
Meltwater channel/spillway	Castro-Dalcahue, Cordillera de La Costa	CDA: Mocopulli Meltwater Channel CCA: Lago Tepuhuieco, projection of the Río Tarahuin into the Cordillera de La Costa and Río Bravo Meltwater channel between Lago Tepuhuico and Lago Huillinco	The Mocopulli Channel cut subsidiary outwash terraces and served as a spillway for a glacial lake during LGM ice retreat. In the CCA, the two low-gradient channels are carved in bedrock and conducted meltwaters west. Río Bravo meltwater channel run parallel to the ice front and conducted waters to the Lago Huillinco
Bedrock knobs	Cordillera de La Costa	Eastern Cordillera de La Costa	Small-scale knobs eroded on the Paleozoic schist of the mountain range
Drumlinoid/ whaleback hills	Cordillera de La Costa	CCA: Eastern foothills of the Cordillera de La Costa	Semi-rounded hills shaped by the overriding ice during the Early Llanquihue glacial phase
Ice troughs	Eastern Margin	Southern EMA	Elongated depressions (up to 100 m deep and hundreds of meters wide), carved in glacial sediment, some occupied today by lakes. Probably first formed as subglacial troughs and later reworked by LGM ice incursions
Lacustrine terrace	Eastern Margin	EMA: restricted to Lago Natri Basin	A set of lake terraces is present in the northeastern half of Lago Natri Basin. They define paleolake levels associated with fluctuations of ice occupying Estero Compu
Fluting	Eastern Margin	Scattered in EMA	NWW trending subglacial linear flutes shaped on glacial sediments appear in three deforested locations. They indicate fast-flowing and warm-based temperate ice during the Llanquihue Glaciaton
Lodgement till	Castro-Dalcahue, Cordillera de La Costa, Eastern Margin	EMA: north of Lago Tarahuin, vicinity of Petanes Alto, eastern composite moraine belt.	Compact diamicton sediment with silty matrix supporting faceted clasts, some striated. It may include fissility structures or boudins and sandy lenses. In the EMA, commonly appear overlaying outwash sediments and capping moraine ridges
Flow till	Eastern Margin	EMA: Las Lajas and Ahoni Sites	Gravelly rich coarsely bedded diamictons associated with debris flows from the ice margin. Clasts are subrounded to subangular and not striated
Deformation till	Eastern Margin	EMA: limited distribution	Outwash and debris flow deposits compressed, folded and deformed by overriding ice
Meltout till	Eastern Margin	EMA: Petanes Alto, Isla Quinchao, Isla Lemuy	Massive to coarsely bedded loose silty sand diamicton. Usually the sediment includes sandy gravel pockets
Outwash	Castro-Dalcahue, Cordillera de La Costa, Eastern Margin Area	CDA: Dalcahue and Pupetra Sites EMA: Distal part of the eastern moraine belt; sections at the southeast coast of the Lago Huillinco	They form thick (5–10 m) sequences of parallel-bedded Andean sandy gravels and pebbles. In the EMA, they appear forming part of the core of moraine ridges
Glaciolacustrine	Castro-Dalcahue, Eastern Margin Area	CDA: Estero Castro, Castro-Dalcahue road EMA: Ahoni Site, west of lago Tarahuin	They occur as (1) muddy, finely laminated sediments; (2) thin and parallel laminations of sediments ranging from fine sand to gravel, and (3) parallel and well-laminated clayey, silty sand

[a] CCA: Cordillera de La Costa area; CDA: Castro-Dalcahue area; EMA: Eastern Margin area.

positions from moraine ridges and ice-contact slopes. The stepwise topography left on the landscape here is the same found to the north part of Isla Grande de Chiloé (Andersen *et al*. 1999) and suggests an extensive, uninterrupted ice front. The outermost moraine trends north–south and is continuous for several tens of kilometers in northern Isla Grande de Chiloé (Andersen *et al*. 1999). North of Taiquemó Mire (42° 10′ 25″ S, 73° 35′ 50″ W, 170 m a.s.l), which is located in an inner position and therefore younger than this moraine, the outermost Llanquihue moraine curves southwest (Denton *et al*. 1999). South of Taiquemó Mire this wide arcuate moraine appears buried and breached by outwash deposits that grade to the inner, younger moraine arcs. The last prominent expression of the outermost Llanquihue moraine south of Taiquemó and east of the Cordillera de La Costa is the Butalcura Moraine (42° 17′ 25″ S, 73° 39′ 20″ W, 205 m a.s.l., Figs 2 and 3). In aerial photographs, this moraine appears as a remnant of a formerly larger landform. On the Cordillera de la Costa the outermost Llanquihue moraines appear as a group of small ridges deposited at a similar elevation as, and to the west of, the Butalcura Moraine (Fig. 3). Barely weathered Andean clasts (Porter 1981) that make up the outer moraine provide evidence for its construction during Llanquihue times.

The inner moraine arcs in the *Castro–Dalcahue area* (Fig. 2) extend several tens of kilometers to the north of the Isla Grande de Chiloé (Denton *et al*. 1999), parallel to the outermost moraines. Near Dalcahue, the moraines turn west abruptly following the coastline (Fig. 3). Two prominent ice-contact slopes and associated moraine ridges are very distinctive here; to the east, the Pupetra moraines and the Dalcahue moraines represent the outer and inner marginal positions, respectively, and appear reworked by post-depositional erosion. To the west, the Piruquina moraines describe the outer ice position, and the Pidpid–Alto Muro (the latter meaning ‘high wall’) marks the inner ice position in this sector (Fig. 3). The moraine system here shows steep ice-contact slopes as much as 30 m high, breached by subsequent glaciofluvial activity. An eroded innermost ice-contact slope that defines the present coast geometry marks the last position of the ice on this part of Isla Grande de Chiloé (Fig. 3).

Hummocky moraines are characterized by an irregular, low relief topography. Local creeks accentuate the hilly morphology. This topography is well developed on top of ice-contact slopes, among moraine ridges and between the innermost eroded ice-contact and present coastline (Fig. 3).

Outwash plains The main outwash plain (Early Llanquihue Glaciation 1, Fig. 3) is associated with the outermost moraine and appears incised by extensive erosional subsidiary outwash terraces (Early Llanquihue Glaciation 2; LGM 1–3; Fig. 3) that in some cases can be traced to the inner moraines. Some of the outwash plains grade directly to ice-contact slopes without the presence of distinct moraine deposits. The outwash subsidiary terraces are incised in higher glaciofluvial topography. Main and subsidiary outwash terraces merge in the distal end of the main glaciofluvial plain, before they converge with the modern Río Butalcura fluvial drainage system. At least three subsidiary erosional terraces are evidence of changing glacial dynamics as they can be traced to inner ice-marginal positions (Fig. 3).

Meltwater channels and spillways The Mocopulli Channel (115 m a.s.l.) was the main meltwater conduit when the ice terminated at the innermost ice-contact slope. The channel is ~500 m wide and grades to inner moraine belts. It both cuts and contains subsidiary outwash terraces. The Mocopulli Channel served as a spillway during glacial retreat for a large glacial lake (Heusser *et al*. 1995) documented by extensive glaciolacustrine sediments in the area. During the Llanquihue glaciation the whole meltwater system in this part of Isla Grande de Chiloé drained northwest via the Butalcura River (Fig. 3) to the Pacific Ocean.

Cordillera de La Costa area landforms

Ice-contact slopes and moraines On the eastern flank of the Cordillera de La Costa, between 200 and 300 m a.s.l., subtle moraine ridges and a double system of ice-contact slopes mark the outer positions of ice during the Llanquihue Glaciation. North of Lago Huillinco, in the vicinity of Notue, this double ice-contact slope occurs at 200 and 250 m a.s.l. (Fig. 4) and represents lateral ice-marginal landforms produced by a sub-lobe flowing west through the Río Notue Valley (Fig. 3). South of Lago Huillinco, aerial photographs also show a double system of prominent ice-contact slopes roughly at the same elevations as those at Notue. Where the glacier butted against the mountain, aerial photographs depict distinctive bowl-shaped features such as in front of Lago

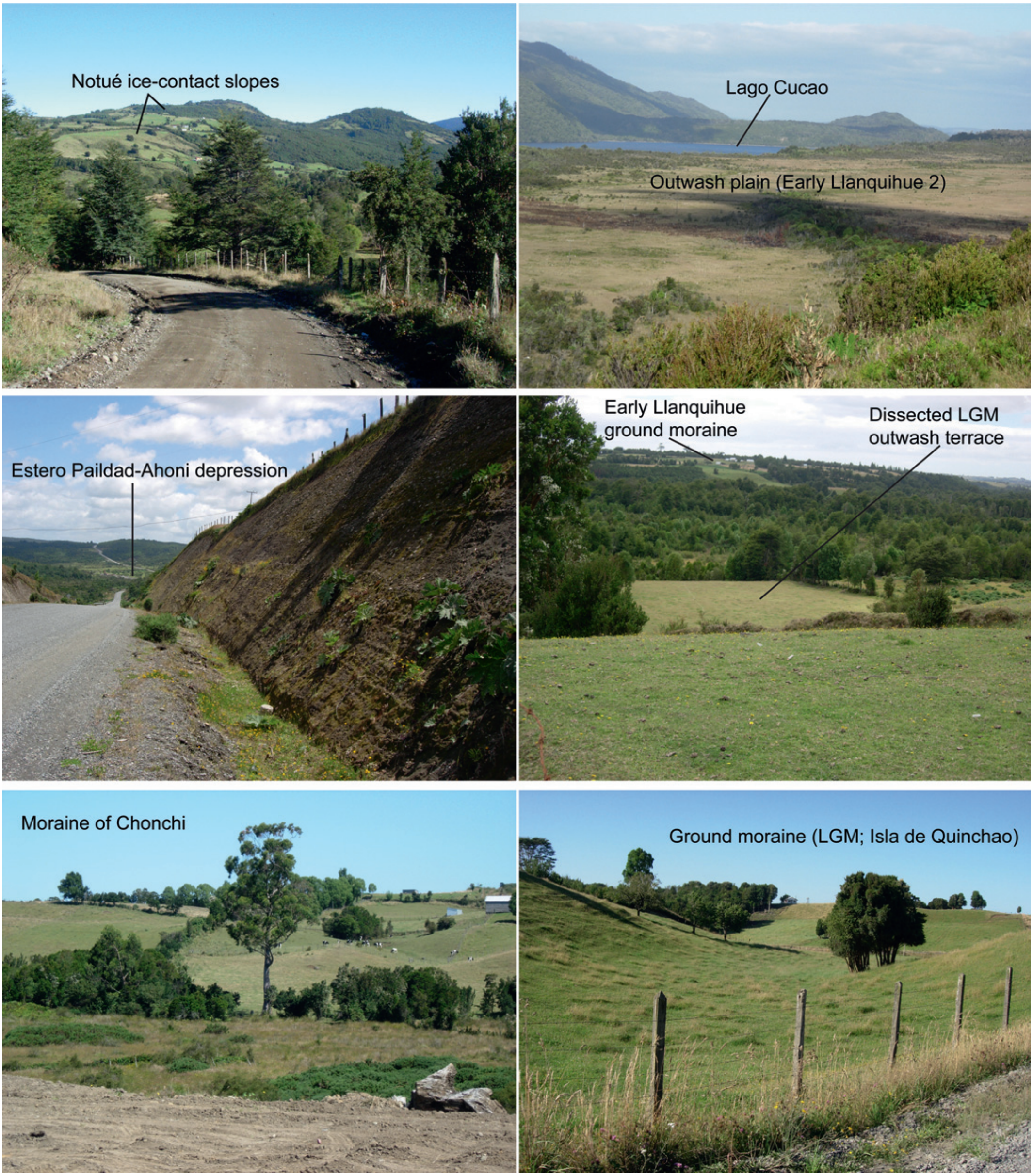

Fig. 4. Photographs of main landforms units in central region of Archipiélago de Chiloé (see text for details). Top panel: (left) Early Llanquihue: ice-contact slopes in the vicinity of Notué and (right) lower outwash terrace south of Lago Cucao. Intermediate panel: (left) distal section of the eastern margin moraine belt, exposing outwash sediments; Estero Paildad-Ahoni ice trough in the background; (right) LGM dissected outwash terrace incised in Early Llanquihue moraine. Lower panel: LGM moraines: (left) proximal reworked ice-contact slope of the Chonchi moraine; (right) hilly ground moraine in the Isla de Quinchao. LGM: last glacial maximum

Tepuhueico (Fig. 3). No moraine ridges or other indication of ice-marginal positions were found to the west of the Cordillera de La Costa at this latitude.

Meltwater channels Deep meltwater channels emerge from the central sections where the ice buttressed against the mountain relief in front of Lago Tepuhueico and where the Río Tarahuin meets the Cordillera de La Costa (Fig. 3). The channels are cut in bedrock and maintain water divides close to their central sections, and low elevation gradient on either side (~1%). During the glacial peak phase, these channels conducted meltwaters to the west flank of the Cordillera de La Costa. During the glacier retreat phase, meltwater flowed between the ice front and the eastern flank of the Cordillera de La Costa through the south-north Río Bravo meltwater channel to Lago Huillinco (Fig. 3), which at that time served as the main meltwater route to the Pacific Ocean.

Outwash plains Two outwash terraces (about 100 and 70 m a.s.l.) develop from the meltwater channel mouths and incise the sedimentary rocks west of the Cordillera de La Costa (Fig. 3). The glaciofluvial plains appear geographically discontinuous along a north–south transect interrupted by higher bedrock relief and are only present when a meltwater channel connects them with ice-contact slopes and moraines to the east. Another double set of outwash terraces occurs at the southern coast of Lago Cucao (Figs 3 and 4), and is only partially visible to the north of the lake. The glaciofluvial plains are larger and more continuous to the south where the mountain relief is lower. Here, they still preserve relict braided drainage channels.

Bedrock knobs and drumlinoid landforms Small-scale knobs cropping out in the Cordillera de La Costa are evident in aerial photographs (Fig. 3). These features probably were formed by ice abrasion on bedrock. At the foot of the proximal slope of the Cordillera de Las Costa NWW trending drumlinoid landforms developed on bedrock and/or sediment are apparent as well (Fig. 3). Limited access in the field to these areas does not allow more description or details.

Eastern Margin area landforms

Ice-contact slopes and moraines Up-ice from the Cordillera de La Costa, a wide and prominent end moraine occurs along the eastern margin of Isla Grande de Chiloé (Fig. 3). The moraine complex is massive and might be a composite feature representing several glacial advances. This eastern inner moraine belt forms a second, local, water divide in Isla Grande de Chiloé (Fig. 3). Its proximal side has been obliterated by postglacial creek erosion, which makes it difficult to track. Two subtle ridges are usually distinguished here, as in the vicinity of Chonchi (Fig. 4) and Ahoni (Fig. 3), and occasionally small ponds occur between them (Villagrán 1988a; Abarzúa *et al*. 2004) (Fig. 3). In some locations, moraines are inconspicuous (Heusser *et al*. 1995) and occur separated and eroded by meltwater channels. The most prominent ice-contact slope in the area is that north of Río Trainel, which was subsequently breached by meltwaters (Fig. 3). To the south, lateral moraines occur on the flanks of Estero Compu and Estero Paildad, and frontal moraines close to the west end of Lago Natri depression (Fig. 3). As in the Castro-Dalcahue area, the hilly topography that characterizes hummocky ground moraines is widespread (Figs 3 and 4).

Outwash plains As along the western flank of the Cordillera de La Costa, outwash plains in the Eastern Margin area are discontinuous and intercalated in an older moraine landscape (Figs 3 and 4). The terraces grade directly from the eastern moraine ridges and are interpreted from laminated glaciofluvial sediments and/or from well developed flat plains. Some outwash terraces appear dissected by meltwater channels (such as in Petanes Bajos, Fig. 4) and others, as described below, by ice troughs (e.g. Estero Paildad-Ahoni depression, Fig. 4). Glaciofluvial plains are better developed in the vicinity of Chonchi and Petanes Bajos (Figs 3 and 4); nevertheless they are restricted in surface area if compared with the outwash plains at the Castro-Dalcahue area (Fig. 3).

Ice troughs Distal to the eastern moraines, major and minor depressions (between a hundred and several hundreds of meters wide and several tens to a hundred meters depth) form a distinct pattern (Fig. 3). Some depressions are occupied by low-gradient underfit streams, which flow westward and gradually disappear halfway towards the Cordillera de La Costa. These depressions are excavated into glacial sediments and mostly follow a SEE–NWW trend. Elongated water bodies, such as lakes Tarahuin, Natri and Pio Pio (Fig. 3), occupy major depressions, some of which have steep sidewalls, as well as lateral and end moraines. For example, the western margin of Lago Natri basin is fringed by three moraine ridges (Fig. 3). The Estero Compu depression, today inundated by the sea, has a gentle 'U' shape with lateral moraines and ice-contact slopes (Fig. 3). The Estero Paildad-Ahoni depression is open to Estero Compu and heads close to the

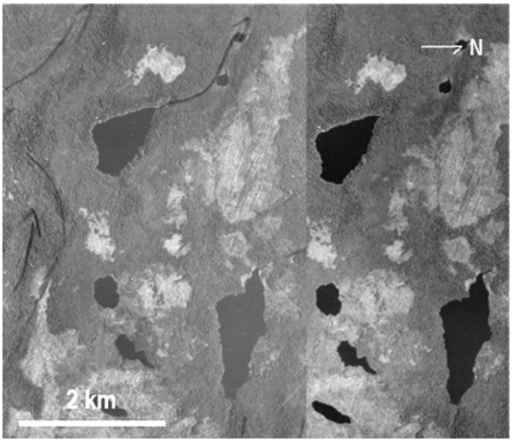

Fig. 5. Stereoscopic pair (Vuelo OEA 1961, 1:50 000, line 520, photos 2428–29) showing small lake basins, channels and flutings formed in a soft-bedded subglacial environment during the most extensive glacial expansion of the Golfo de Corcovado Ice Lobe. See text for details.

Ahoni Site (Fig. 4). Lateral moraines and ice-contact slopes are well defined on the sidewalls of the Estero Paildad depression (Fig. 3).

Paleolake terraces On the northeastern half of Lago Natri basin a set of lake terraces is present (Fig. 3). They define paleolake levels associated with fluctuations of ice occupying Estero Compu.

Meltwater channels Meltwater channels are well developed to the north of the Eastern Margin area (Figs 3 and 4). They occur distal to inner end moraines and cut outwash terraces. The meltwater channels form an intricate pattern that converges radially into Lago Huillinco, the main drainage route to the Pacific Ocean in this area of Isla Grande de Chiloé (Fig. 3). To the south of this point, some of the ice troughs described may have been occupied and reworked by meltwaters as well.

Flutings NWW trending subglacial linear flutes on till appear in three deforested locations (Figs 3 and 5). A similar ice-flow direction is also shown by drumlinoid and whaleback hills closer to the Cordillera de La Costa, and by the overall NWW imprint on the landscape (Fig. 3), following bedrock structure (Quiroz *et al*. 2004). The NWW direction of fluting in this area differs from the SWW direction shown by landforms north of Taiquemó Mire, but is the same as those occurring south of this point (Andersen *et al*. 1999). Some flutings to the south of the study area are associated with steep-sided-wall small lake basins scoured in glacial sediments (Figs 3 and 5).

Sediments

Tills There are probably at least four types of till in the central Chiloé region: lodgement till, flow till, deformation till and melt-out till (e.g. Benn and Evans, 2010; Fig. 6). Lodgement till in the area occurs as highly compact and indurated diamicton sediment with silty matrix supporting faceted and commonly striated clasts. Clasts are semirounded and reach 50 cm at their maximum axis. Their crystalline and volcanic lithologies indicate an Andean source. In the Eastern Margin area lodgement tills expose fissility structures and overlie outwash. Fissility features have been interpreted as pervasive shear deformation at the ice sole (Denton *et al*. 1999). Lodgement till commonly caps moraine ridges and underlies postglacial soil. This type of till is mainly massive in appearance, such as in Petanes Alto vicinity (Fig. 6), but may include boudins and sandy lenses in some areas, such as north of Lago Tarahuin (Fig. 3).

In the study area it is possible to find the whole granulometric range from gravel-poor to gravel-rich, faintly bedded diamictons, with the latter usually exposing better sorting. Gravel-rich coarsely bedded diamictons may be associated with debris flow deposits from the ice margin, and are interpreted here as flow tills. Clasts present in this type of sediment are of Andean origin, as in lodgement tills, but normally are of smaller size, subrounded to subangular in form and not striated. This sediment is associated with moraine ridge landforms in the Eastern Margin area, such as in Las Lajas and Ahoni Sites (Figs 7 and 8).

Gravelly and sandy sediments appear glaciotectonically folded in places. Deformed sediments include intercalated sand and well sorted open gravel beds or exclusively gravel-rich sediment, interpreted as outwash and debris flow deposits, respectively, which were compressed and deformed by the weight of overriding ice. This sediment type is interpreted as deformation till but is the least common of the glacial diamictons present in the study area.

Meltout till is present in central Chiloé at some specific locations and is interpreted from massive to coarsely bedded loose, silty sand diamicton (Fig. 6). Usually the sediment includes sandy gravel pockets. This type of till is widespread near

Fig. 6. Photographs of main sediment types and associations in central region of Archipiélago de Chiloé (see text for details). Top panel: (left) meltout till: sandy gravel sediment in the vicinity of Petanes Alto; (middle) lodgement till: massive, indurated sediment with silty matrix supporting faceted, commonly striated Andean clasts; (right) Las Lajas Site: detail of the organic bed overlain by glaciolacustrine clays and glaciofluvial sands (till sediment, not shown, overlies the sandy unit). Lower panel: (left) section in the Eastern Margin Area exposing a common sediment association made up of parallel-bedded outwash sediments uncomformably overlain by lodgement till; (right) well-laminated sand and gravel beds interpreted as proximal glaciolacustrine sediments.

Petanes Alto (Fig. 6), Isla Lemuy and Isla de Quinchao, where it commonly crops out topping or occupying entire sediment sections making up hummocky moraines. Sediment thickness in sections can be several meters.

Outwash Glaciofluvial sediments are widespread in the distal side of the eastern moraine and are made up of thick sequences (5–10 m) of parallel-bedded Andean sandy gravels and pebbles (Figs 4 and 6). The presence of coarser materials is rare, but may occur. Where present in morainic landscape, outwash sediments commonly appear underlying till separated by sharp surface contacts, such as in the Eastern Margin area moraine (Fig. 6) and northern Dalcahue and Pupetra moraines (Fig. 3).

Glaciolacustrine sediments Fine-grained (e.g. silt and clay) glaciolacustrine sediments are limited in the central Chiloé region, cropping out mostly close to present coastlines, such as in Estero Castro, and in proximal ice-margin deposits (e.g. see Ahoni Site described below). Nevertheless, thick sediment sections (a few to tens of meters) exposing thin and parallel laminations of sediments, ranging mostly from fine sand to gravel may have been deposited in glacial lakes (Fig. 6). Laminae can have lateral development of several tens of meters. Impermeable layers of gravels in yellowish indurated pyroclastic sand most likely expose debris flow from the glacial front associated with Andean volcanic events. To the north, parallel and well laminated clayey, silty sand is widespread

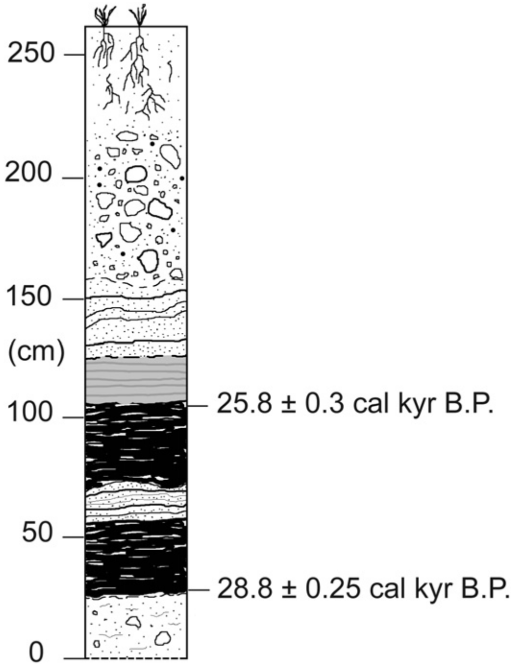

Fig. 7. Las Lajas Site stratigraphic sequence in the distal side of the moraine belt in the Eastern Margin Area. The calibrated ages at the base and top of the organic deposit provide limiting ages for two bracketing till units. See text for more details.

along the road connecting Castro with Dalcahue and presumably indicates the existence of an important glacial lake in the area draining through the Mocopulli Spillway (Fig. 3).

Sediment sections

There are two key sediment sections in the *Castro–Dalcahue area*: the Dalcahue site (42° 22′ 36″ S, 73° 39′ 17″ W, 158 m a.s.l.; Fig. 2), described before by Laugénie (1982), Mercer (1984) and Denton *et al*. (1999) (Site 98), located in the vicinity of the Dalcahue Moraine, and the Pupetra Site (42° 21′ 37″ S, 73° 39′ 12″ W, 185 m a.s.l., Fig. 3), described by Denton *et al*. (1999) (Site 99). In both sequences well laminated sandy gravel is overlain by till, indicating a glacial advance over the site. This sediment association is also common along the east margin of Isla Grande de Chiloé. The Dalcahue Site is located in an inner ice-contact slope that exposes a dark-brown silty organic bed resting on top of compact lodgment till and overlain by laminated sand and gravel, which in turn, are capped by compact and thin diamicton. Dating of wood pieces from the organic sequence provided limiting ages of 34 800 and 18 000 cal yr BP (Denton *et al*. 1999) for the beginning and termination, respectively, of organic sedimentation in

Fig. 8. Ahoni Site stratigraphic section in the distal side of the moraine belt in the Eastern Margin Area. The codes in the photograph are as follows: A, debris flow sediments; B, massive glaciofluvial sands; C, clayey silt glaciolacustrine rhythmites; D, lodgement till with fissility structures. See text for interpretation and details. Scale is only correct for the center of the photograph.

Table 2. Radiocarbon samples attributes, Las Lajas Site (this study).

Sample CAMS #	Stratigraphic context	$\delta^{13}C$	$D^{14}C$	±	Age[a]	
					^{14}C yr BP	Calendar yr BP (1σ range)
125361	cm above lower till unit	–25	–949.6	0.8	24 000 ± 130	28 580–29 085
125362	cm below higher till unit	–25	–931.3	1.5	21 510 ± 180	25 450–26 055

[a] Age uncertainty = 1σ; calibration based on Reimer *et al*. (2009).

the site. The Pupetra Site is in an ice-contact slope that marks the outer position of the ice during the LGM (Denton *et al*. 1999), 1.5 km north of the Dalcahue Site. Most of the section is composed of laminated sandy gravel capped unconformably by ice-contact gravels. Denton *et al*. (1999) obtained a maximum age of 18 000 cal yr BP for the advance represented here.

In the Cordillera de La Costa, Andean sediments brought by the Golfo de Corcovado Lobe mantle the local Paleozoic schist (Muñoz *et al*. 1999; Quiroz *et al*. 2004) to elevations of ~350 m. Scattered sediment sections in the area show a <1 m thick mantle of scarcely weathered and poorly sorted Andean-derived sediments, ranging from sands to boulders of volcanic and crystalline lithologies. Diamictons composed of compact fine silty sand supporting scattered pebbles and cobbles occur at the eastern flank of the Cordillera de La Costa. Diamictons composed of local material (i.e. schist) are also present.

Las Lajas Site (42° 45′ 36″ S; 73° 37′ 55″ W, 127 m a.s.l.; Figs 2 and 7) is located in the distal part of a moraine, 25 km south of Chonchi, in the Eastern Margin area. A stratigraphic section displays an organic deposit between two diamictons, the lower interpreted as lodgement till and the upper as flow till. The organic deposit, as much as 80 cm thick, extends laterally several meters and contains vegetal fibers and macrofossils probably from a peat environment. The organic bed shows an interbedded 10 cm thick sand unit and grades upwards into grey clay-rich glaciolacustrine sediments and then to laminated brownish, compact sands, overlain by diamicton containing subrounded to cobble-size clasts of Andean and organic origin. Clay-rich, brownish volcanic soil overlies the diamicton.

Two radiocarbon ages from close to the base (CAMS #125361) and close to the top of the organic deposit (CAMS #125362) bracket the organic deposition between 28 800 ± 250 and 25 800 ± 300 cal yr BP (1 sigma, Table 2), which respectively provide a minimum and a close-maximum age for two glacial advances into central Chiloé as recorded by the till units occurring in the section.

Several kilometers south of the Las Lajas Site, at the junction of the Chonchi-Queilen road and that going to Ahoni, sediments in a section (Ahoni Site, 42° 46′ 39″ S, 73° 33′ 52″ W, 51 m a.s.l.; Figs 2 and 8) in the distal part of the same moraine as Las Lajas Site, are inferred to represent an ice-marginal position. The sequence is 7 m thick and exposes a grayish, fine-matrix diamicton made up of Andean pebbles and gravels of <8 cm in size. This unit is uncomformably overlain by massive sandy gravels and pebbles (3 cm at long axis) and then by diamicton containing subrounded gravels and pebbles supported by a compact sandy silt matrix. A piece of wood (60 cm) was encased in the diamicton. The diamicton is overlain by massive coarse sand gravel supported in finer matrix, which shows interbedded ~5 cm thick beds of silty clay. This unit is uncomformably overlain by sandy gravels and pebbles that grade to massive sands at the top of the section.

Fig. 8 shows a lateral extension of the Ahoni section described above, where some of the units occur with thicker dimensions and better expose the ice-marginal deposits in the distal side of the eastern moraine belt. Here, glaciolacustrine rhythmites (C) infill a small basin that was eroded in a glacial debris flow deposit (A) and massive glaciofluvial sands (B). A thick lodgement till unit (D) displaying fissility features overlays these units with an erosive basal contact surface. An erosive contact also separates the lodgement till from the debris flow that caps the section.

Discussion

As stated before, the main goal of this work is to define the style of glaciation in the central region of the Archipiélago de Chiloé and discuss if it corresponds better with an Alpine style of glaciation

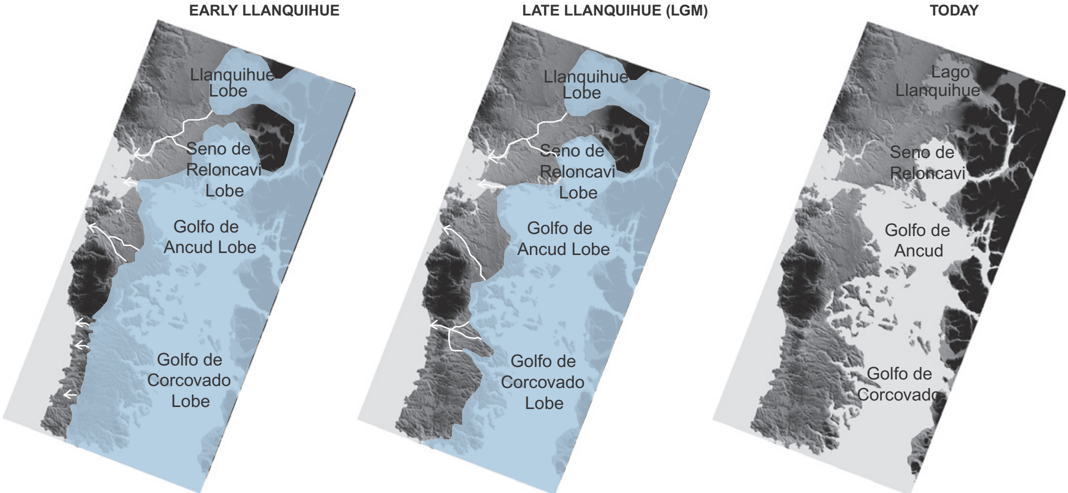

Fig. 9. Ice extent on the Archipiélago de Chiloé throughout the last glacial period. Left panel: Early Llanquihue Phase; central panel: Late Llanquihue Phase (LGM); right panel: present time. White arrow lines in left and middle panels indicate meltwater routes. Darker tones in image represent higher elevation. Note the glacial channelized topography in the southern half of the main island (right panel). Base map: SRTM image displaying a gray-scale elevation data (SRTM from the ESDI, University of Maryland).

present in the CLD (Laugénie 1982; Andersen *et al*. 1999) or with an ice-sheet style that characterized the southern section of the former PIS (e.g. Hulton *et al*. 2002; McCulloch *et al*. 2005; Sugden *et al*. 2005). This section discusses each of the research questions defined above regarding the ice extent and ice dynamics in central Chiloé, former glacial environments, and then attempts to define the local style of glaciation. Our results suggest that the well defined Alpine style of glaciation in the CLD is no longer present to the south in Isla Grande de Chiloé, where prominent subglacial features and extensive, mostly uninterrupted ice-marginal positions denote an ice-sheet style of glaciation.

Ice extent

Defining the ice extent is key for understanding the magnitude of the last glaciation in the southern Andes. This knowledge has main climatological, geomorphological, and paleoecological implications that help us understand remarkable short-term landscape shifts. The central region of Isla Grande de Chiloé preserves the most extensive Llanquihue glacial advance in the region, as defined by the outermost double moraine/ice-contact slope, best represented at the Cordillera de La Costa locations (e.g. Notue, front of Lago Tepuhueico ice-contact slopes; Figs 3 and 4), and by some isolated moraines to the north of the study area (e.g. Butalcura moraines; Fig. 3). The outermost moraines in Isla Grande de Chiloé occur more than a hundred kilometers west of the Andean catchments. To produce these landforms, the ice infilled and crossed what is today the Golfo de Corcovado basin and overrode the Archipiélago de Chiloé, giving it most of its present physiographic attributes. During the LGM, the ice seems to have fluctuated mostly at the eastern margin of the Isla Grande de Chiloé, where ice marginal positions are well defined by a north–south moraine relief and sediment sequences.

The Golfo de Corcovado Lobe did not reach the Pacific Ocean at this latitude during the Llanquihue Glaciation (Fig. 9). Moreover, no cirque landforms are present in the Cordillera de La Costa, indicating that the summit of the Cordillera de La Costa north of Lago Huillinco (≥ 800 m a.s.l.; Fig. 3), and the west coast along northern and central Isla Grande de Chiloé remained ice free during the last glacial cycle. As inferred from the mapping, the double moraine/ice-contact slopes on the eastern slope of the Cordillera de La Costa represent the outermost ice position during the Llanquihue Glaciation. Beyond this ice-marginal position, meltwater channels carved the bedrock and fed a double system of outwash terraces (Figs 3 and 9). Therefore, the Cordillera de La Costa was a significant obstacle for the Golfo de Corcovado Lobe expansion and was only ice covered on its eastern flanks during the last glaciation (Figs 3 and 9).

The geomorphological units present to the north in the Castro-Dalcahue area (Fig. 2), such as ice-contact slopes, moraine ridges and outwash plains, were deposited at the ice margin and proglacial environments. Here, distinct moraine belts can be tracked for several tens of kilometers and appear associated with a stepwise morphology that records the main ice-marginal positions during the last glacial period. This area is a continuum of the glacial landsystem developed in the northern half of Isla Grande de Chiloé as defined by Denton *et al.* (1999) and Andersen *et al.* (1999), and contrasts sharply with glacial features found to the south, where a different glacial geomorphological pattern exists. (e.g. Eastern Margin, Cordillera de La Costa areas; Figs 2 and 3). A likely explanation that could account for the glacial geomorphological differences between northern and southern Isla Grande de Chiloé is the ice extent during the Early Llanquihue glacial phase. Everywhere the Early Llanquihue moraine is the most distal moraine set, but in central Chiloé, it occurs much further west (up to 40 km) from the LGM moraines than in northern Chiloé, where in some locations the whole Llanquihue moraine system is only a few kilometers apart (Andersen *et al.* 1999; Fig. 9). Therefore, in central Isla Grande de Chiloé the Early Llanquihue phase seems to have been considerably more important than the LGM. To the north, both phases, Early and Late Llanquihue (i.e. LGM), were not very different, and the LGM glaciofluvial deposits infilled and breached older deposits, as evident at the northern Castro-Dalcahue area (Fig. 3) and northeast Chiloé (Andersen *et al.* 1999). Although the reasons for a greater Early Llanquihue glacier extent in central Chiloé are unknown, one possibility is that increased precipitation and colder conditions associated with a relatively southern position of the westerly winds directly affected the southern part of the Golfo de Corcovado Lobe during the Early Llanquihue period. In addition, a lower ELA associated with higher latitude and wider and higher Andes in front of southern Chiloé may have played an important role. Potentially, a geomorphological factor including increased glacial erosion, deepening and widening of glacial valleys in the Andes in front of southern Chiloé during the Early Llanquihue could also have facilitated different glacial extent during the main two phases of the last glaciation (cf. Kaplan *et al.* 2009).

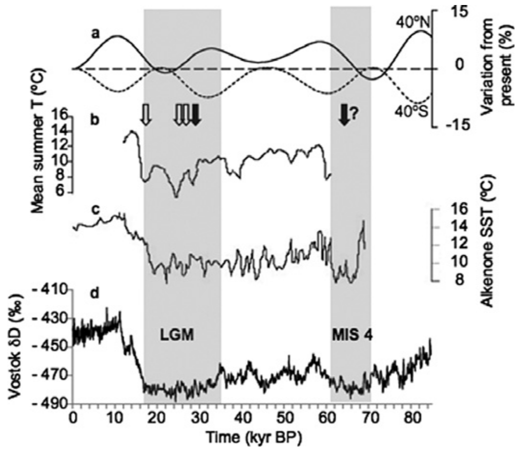

Fig. 10. Summary of glacial advances into Isla Grande de Chiloé during the Llanquihue Glaciation and paleoclimate context. Empty arrows represent close-maximum ages for a glacial advance; solid black arrows represent close-minimum ages for a glacial advance. Data from Denton *et al.* (1999) and this work. (a) Insolation at mid latitudes (40°) for both hemispheres (Berger and Loutre 1991); (b) last glaciation temperature reconstruction based on Taiquemó paleoecological record, Isla Grande de Chiloé (Heusser *et al.* 1999); (c) Alkenone sea-surface temperature (SST) at Ocean Drilling Project Site 1233, offshore northern Chiloé (41°S) (Kaiser *et al.* 2005); (d) Vostok deuterium record for the last glaciation (Petit *et al.* 1999). LGM: local last glacial maximum; MIS: Marine Isotope Stage.

Glacial history

The main Llanquihue glacial pulse probably occurred during the MIS 4 (Fig. 10), as inferred from the preservation of the landforms and the limited weathering of the sediments, particularly when these deposits are compared with those thought to be penultimate glaciation in age (Santa María Glaciation; Porter 1981), scattered throughout the study area. Support for this interpretation come from indirect dating and pollen records obtained from Taiquemó Mire (Heusser *et al.* 1999) and from previous work in the CLD (Mercer 1976, 1983; Porter 1981; Laugénie 1982; Denton *et al.* 1999). The record at the base of the Taiquemó Mire (>50 000 ^{14}C yr; Heusser *et al.* 1999; Fig. 10), which is located inboard from the Early Llanquihue moraines, shows stadial climate conditions as inferred from Gramineae maxima and a prominent magnetic susceptibility peak. In addition, sea surface temperatures offshore of northern Chiloé describe the coldest glacial conditions in the ocean during MIS 4 (Fig. 10; Kaiser *et al.* 2005). Glacial advances of this age have been documented in New Zealand (Preusser *et al.* 2005; Sutherland *et al.* 2007; McCarthy *et al.* 2008).

The inner moraines comprise advances of the last glaciation, dated to the LGM (e.g. Castro-Dalcahue area; Denton *et al*. 1999). The inner belts of Pupetra-Piruquina moraines, Dalcahue-Pidpid/Alto Muro moraines, and the moraines along the eastern margin of Isla Grande de Chiloé (Fig. 3) correspond therefore to the LGM advances. LGM moraine ridges have been dated directly and indirectly at different sites to the north of the island (e.g. Dalcahue Site, Pupetra Site, Tehuaco Site; Denton *et al*. 1999, Fig. 3) and in central Chiloé (e.g. Las Lajas Site, this work; Laguna Tahui, Abarzúa *et al*. 2004; Laguna Mayol, Villagrán 1988b; Heusser *et al*. 1999, Fig. 3). These ponds and mires occur in inter-morainic depressions in eastern Chiloé and their basal ages provide minimum ages for moraine deposition and deglaciation of the area.

The deposition of the lower till at Las Lajas Site (Figs 2 and 7) occurred during a glacial advance at or before 29 000 cal yr BP, reaching an unknown position, after which the ice retreated and organic deposition began at the site. As the ice approached the site again (at 26 000 cal yr BP) organic sedimentation stopped and the basin filled first with a shallow lake, and then with glaciofluvial sand as the ice came closer. This glacial advance responded to a climate cooling documented in regional pollen records (Heusser *et al*. 1999) and built the moraine in which Las Lajas Site is exposed. This is based on the diamicton capping the Las Lajas sequence, which resembles a flow till deposited from the ice margin. After the deposition of this glacial unit, the site persisted ice free, therefore the ice forming this moraine must have been the glacial advance at 26 000 cal yr BP. The Ahoni Site (Fig. 8), which is within the same moraine system, also comprises debris flow deposits from the glacier snout, interrupted laterally by glaciolacustrine rhythmites occupying a small basin. The whole section is interrupted upwards by a thick massive lodgement till unit, interpreted as a local glacier advance over the sequence. The debris flow units occurring in the upper part were deposited from the ice edge. There are no prominent moraines to the west of this point, except for the double ice-contact slope on the Cordillera de La Costa, suggesting that the advance that produced the upper till units at the Las Lajas and Ahoni Sites terminated at the inner moraine at 26 000 cal yr BP.

There is an overall excellent agreement between the paleoecological and sediment records from sites in northern (i.e. Taiquemó) and central Chiloé (i.e. Dalcahue) (Heusser *et al*. 1999) and glacial activity as inferred from Las Lajas Site. Gramineae maxima and *Nothofagus* minima (Heusser *et al*. 1999) show that glacial advances documented at Las Lajas Site before 29 000 and at 26 000 cal yr BP occurred during peak cold stadial conditions, when the temperature reached its lowest LGM level (i.e. mean summer temperature depression equal to ~8°C relative to present day; Heusser *et al*. 1999; Fig. 10). The subtle recovery in local climate between these two glacial advances (Fig. 10) was recorded in Las Lajas Site as mostly continued organic deposition and therefore glacial retreat from the site. Moreover, maxima of magnetic susceptibility at 26 000 cal yr BP (Heusser *et al*. 1999) provide more evidence that this time was probably the coldest in the region.

In summary, temporal fluctuations of the Golfo de Corcovado Lobe as inferred from previous research (Denton *et al*. 1999) and this work reveal at least five distinct glacier advances into Isla Grande de Chiloé during the Llanquihue Glaciation. These occurred possibly during the MIS 4, as inferred from the record at the Taiquemó Mire (Heusser *et al*. 1999), before 29 000 cal yr BP, as inferred from the Dalcahue (Denton *et al*. 1999) and Las Lajas Sites, and at about 26 800, 26 000, and 18 000 cal yr BP, as revealed by close-maximum ages from the Tehuaco, Las Lajas and Dalcahue Sites, respectively (Denton *et al*. 1999; this work) (Fig. 10).

Glacial environments

Llanquihue piedmont glaciers descending from the Andes south of 41°S merged to form an ice sheet with prominent lobes (Golfo de Ancud Lobe and Golfo de Corcovado Lobe; Denton *et al*. 1999) that flowed west and overrode Isla Grande de Chiloé after crossing ~80 km of present-day marine embayment. The ice flowing into Chiloé was mostly unconstrained by topography and during the Early Llanquihue glacial phase (MIS 4?) it mantled the central, and presumably the southern part of the island east of the Cordillera de La Costa (Fig. 9). Despite the fact that the outer moraine ridges and ice-contact slopes may appear breached and discontinuous, it is possible to infer an extensive, uninterrupted (e.g. ≥60 km) ice front during the early glaciation (Fig. 9). In the central region of Chiloé, the ice snout buttressed against the Cordillera de La Costa and sent meltwaters exploiting the lowlands of the mountain. Some of the big depressions present in central Chiloé, such as Lago Tarahuin, Ahoni-Estero Paildad, Lago Pio Pio and Lago Natri depressions (Fig. 3), may have initially formed as subglacial troughs during the MIS 4(?). Subglacial activity is also evident from the drumlinoid landforms and fluting. During the Early Llanquihue, central Chiloé may have attained most of its present shaping, such as the smooth and hilly relief combined with the set of depressions present to the south of the study area, and the scattered pond basins scoured in the sediment bed together with fluting landforms (Fig. 5).

During the LGM, there was local reshaping of the glacial landscape in central Chiloé; most of the ice activity was limited to the eastern margin of the island and outwash terraces and meltwater channels incised the older Llanquihue relief to the west (Fig. 9). Nonetheless, during the LGM, as in the early Llanquihue phase, the ice front formed an uninterrupted ice margin along the eastern part of the Isla Grande de Chiloé. The existence of lateral and frontal moraines in some of the big depressions mentioned above (e.g. Natri, Estero Paildad-Ahoni; Fig. 3) is potential evidence for ice occupation and landform reworking during the LGM and is indicative of sub-aerial ice deposition. The exact timing of this latter occupation remains an open question.

Style of glaciation

The glacial geomorphology inherited from the last glacial cycle in central Chiloé is a complex suit of subglacial and subaerial landforms, such as fluting, drumlinoid features, glacially scoured lake basins, and moraine ridges and outwash plains, respectively, which appear spatially intercalated. The glacial landscape then resembles a type of *active temperate glacier margin landsystem* (Evans 2005) that combines former subglacial and subaerial environments and associated deposits (Fig. 3). The existence of flutes eroded in glacial sediments and drumlinoid landforms suggest active, fast-flowing warm-based temperate ice and provide evidence for local glacial temperate thermal regime (Glasser and Hambrey 2001). These landforms have been related to subglacial deforming layers in active temperate glaciers (Evans 2005, and references therein). The presence of fluting both in central and northern Chiloé expose the generalize absence of widespread supraglacial deposits, which expose the active character of the temperate Chilotan ice sheet, both during advance and retreat phases (Evans 2005). In this sense, the hummocky moraines depicted in the geomorphologic map (Fig. 3) refer to the morphologic rather than to the genetic property of the term (e.g. Benn and Evans 2010). However, supraglacial sediments can be several meters thick in some locations (e.g. Petanes Alto), where they could be linked with melt-out of a former medial moraine or debris-rich ice margins (Evans 2005).

North of Chiloé, in the CLD, a typical Alpine type of glaciation occurred, where discrete piedmont glaciers were constrained by mountains and eroded deep elongated lake basins (Laugénie 1982; Andersen *et al*. 1999). The model that better characterizes this landscape is therefore the *glaciated valley landsystem* (Benn *et al*. 2005), which incorporates the important role played by mountain relief on glacier morphology, which today is well represented by east–west elongated, deep lake bodies and arc-shaped moraine ridges. The CLD includes nearly all the distinctive elements or units that better characterize the *glaciated valley landsystem*: cirques, well developed lateral and end moraine sets, ice-contact kame terraces, moraine-dammed lakes, meltwater channels and spillways, main and subsidiary outwash plains, among others (e.g. Andersen *et al*. 1999). Although ice in the CLD can also be associated with an active, temperate glacial regime (e.g. wet-based ice capable of erode and plough deep basins), a significant distinction with the Chilotan ice, in addition to glacier extent, includes the greater ice-surface gradient determined by the steeper mountain relief at the CLD (Oerlemans 1989; Barrows *et al*. 2001). This resulted in relatively smaller ablation zones at the latter area and spatially limited ice fluctuations. Therefore, ice bodies in the CLD were restricted to glacial valleys showing a well developed linear axis. Concentric moraine arcs infringing present lake bodies are a good example of this Alpine pattern of glaciation. However, the morphological attributes of central Chiloé are indicative of a continuous ice blanket (i.e. Golfo de Corcovado Ice Lobe) that occupied most of the island during the last glacial period. This ice sheet produced a distinct subglacial morphology and an extensive, wide-open moraine arc that resembles its maximum extent. For instance, the intricate pattern of subglacial channels/basins (Figs 3 and 9) suggests a drainage network eroded at the glacier sole. This channel pattern, together with the number and distribution of glacially scoured lake basins, become more prominent to the south of the Isla Grande de Chiloé (e.g. Lago Chaiguata).

This observation may suggest that ice covering southern locations was progressively thicker, capable of eroding deeper basins. The region known as *Los Canales Patagónicos* occurs south of the Archipiélago de Chiloé, all along west Patagonia (i.e. Patagonia Occidental) and exposes a complex network of marine basins excavated subglacially under thick, warm-based ice. For instance, the channels in the Archipiélago de Los Chonos, south of Chiloé, cut small mountain reliefs and expose glacially eroded basins today inundated by the sea. Despite that glacial erosion mostly exploits tectonic faults in west Patagonia, particularly south of the Triple Junction (46 °S, 75 °W; Charrier *et al*. 2007), this channelized pattern seems to represent a continuum of that present in the Isla Grande de Chiloé, affected by larger, thicker and more active ice than that to the north.

Conclusions

During the Early Llanquihue (MIS 4?) the distal zone of the Golfo de Corcovado Lobe covered much of central Isla Grande de Chiloé and smaller isles to the east. The glacier flow found a physical obstacle in the Cordillera de La Costa and left the west Chilotan coast ice-free. This lobe probably extended north to the Taiquemó Mire as inferred from moraine geometry and the direction of fluting. During the LGM, the Golfo de Corcovado Lobe advanced into eastern Isla Grande de Chiloé before 29 000 cal yr BP, and at about 26 800 cal yr BP, 26 000 cal yr BP, and 18 000 cal yr BP (e.g. Denton *et al*. 1999). During these glacial pulses, ice may have occupied the Pio Pio, Ahoni-Estero Paildad and Natri depressions.

The glacial geomorphology at the central region of the Archipiélago de Chiloé resulted from a mostly warm-based ice sheet, typical of an *active glacial temperate landsystem* that in central Chiloé combines deposits and landforms units originated in subglacial and subaerial environments. Based on the geomorphological and sedimentological studies by this and previous work (Laugénie 1982; Andersen *et al*. 1999; Denton *et al*. 1999), this finding suggests that the Alpine glaciation that characterized the northern PIS (i.e. at the CLD), became an ice-sheet glaciation at Chiloé and south of this location (i.e. Patagonia Occidental). This geographical break in glaciation style of the PIS at the latitude of Chiloé likely responded to local colder and wetter conditions than those at the CLD, and to a higher and more prominent Andean mountain relief in front of Chiloé than at the CLD. These two important geographical conditions determined a lower ELA in the Andean glacial catchments at the latitude of the Archipiélago de Chiloé than at the Lake District.

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Juan L. García, Instituto de Geografía, Facultad de Historia, Geografía y Ciencia Política, Pontificia Universidad Católica de Chile, Campus San Joaquín, Av. Vicuña Mackenna 4860, comuna Macul, Santiago 782-0436, Chile
E-mail: jgarciab@uc.cl

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