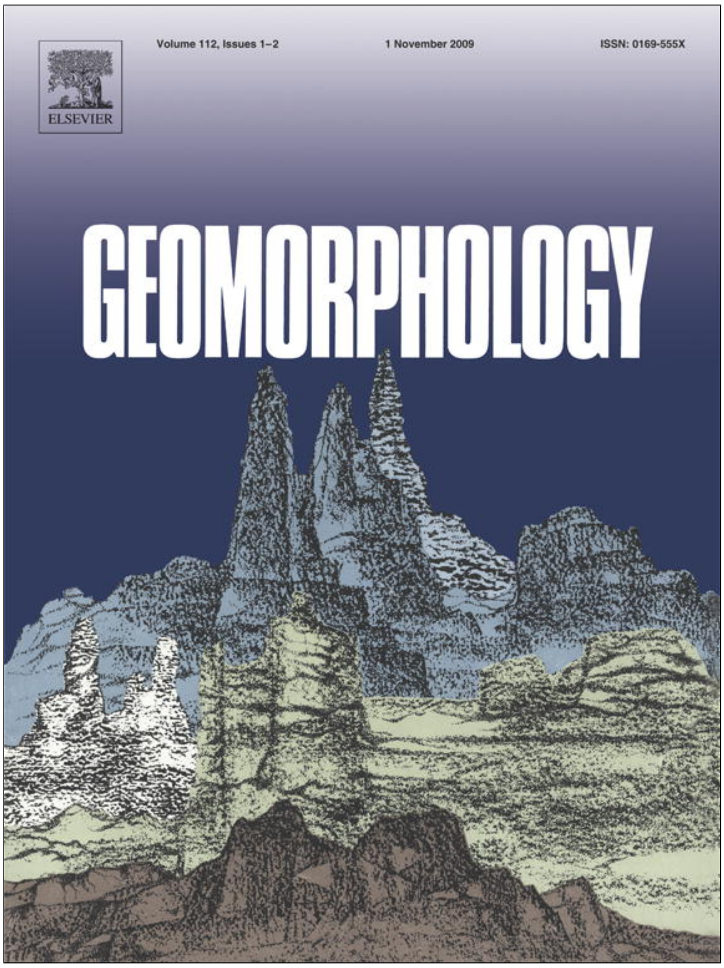
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Glacial geomorphology of the Pleistocene Lake Fagnano ice lobe, Tierra del Fuego, southern South America

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ABSTRACT

A regional geomorphological study is presented of the southern and eastern coast of Lake Fagnano, one of the most extensive glacial areas of Tierra del Fuego Island, at the southernmost tip of South America. A palaeoglacial reconstruction is made, based on the location of erosional and depositional glacial landforms. The outlet glacier flowing eastwards from the Darwin Cordillera (Fuegian Andes, Chile) had more than 50 tributary glaciers. An alpine-type landscape, including arêtes, cirques, truncated spurs and hanging valleys developed in the western region of the present lake, whereas a piedmont-type landscape including lateral moraines, glaciofluvial and glaciolacustrine terraces and an ice-disintegration landscape developed in the eastern region. The glacier spread over the low ranges and lowlands through three different lobes, and was drained by four main outwash basins, directly into the Atlantic Ocean. The ice-covered area is estimated at 4000 km^2; the maximum length of the main lobe at 132 km, and the general slope at 8°. Four terminal positions of the glacier were recognized and related to the Inútil Bay and Beagle Channel glacial areas, located to the north and south, respectively. ^{14}C dates from basal peats show that most of the area, especially the easternmost part and the southern coast, were free of ice by 12,300 years B.P. Fossil peat contained in the lower basal till deposits yield ^{14}C dates of 31,000–48,200 years B.P., indicating that a glacial advance occurred in the area prior to the Last Glacial Maximum (ca. 25,000–23,000 cal. years B.P.).

1. Introduction

Lake Fagnano (named as Lago Kami by the native inhabitants), located in the centre of the Tierra del Fuego Island (54°26′–54°37′S, 66°42′–68°35′W; 26 m a.s.l.; Fig. 1A), is one of the most important glacial areas of southernmost South America, because of the extensive glaciated surfaces and a large volume of ice contained by the glacier network that covered the region. The lake basin, which is more than 110 km long in mountainous relief, formed a fjord-like environment due to the former glacier advance from the west. The width of Lake Fagnano varies from 2.8 to 9.8 km. The total area of the lake is 609 km^2. Its maximum depth (200 m) is located very close to the northern coast near the eastern end of the lake. The shallow areas, about 30 m deep, are located in the centre of the lake and near the eastern shore. The geological structures of the Fuegian Andes controlled the formation of glaciers of varied size and thickness which developed an extensive ice network. This ice body, based upon its morphology, could be defined as an outlet glacier, fed by smaller alpine glaciers in its upper and middle reaches, and taking on the appearance of a piedmont glacier in its lower portion. This differential behaviour of the ice in the various sections forced the initiation of a mixed glacial landscape, of both mountain and lowland environments; an unusual occurrence in the Fuegian Archipelago.

The description and mapping of the glacial landforms is used in this paper as a tool for understanding the glacial events. This landscape, located in the southernmost continental region of the Southern Hemisphere outside Antarctica, was modeled by a palaeoglacier coming from the southernmost present ice-field in the Andes Cordillera. This study should improve the knowledge of ancient glacier systems which were located in subantarctic environments. These glacial environments should be quite different from those of the Northern Hemisphere due to the influence of maritime climates, controlled by the South Pacific high pressure systems and the Polar depression. The environments should also be different from those in both sides of the Patagonian Andes which flowed from the present North and South Patagonian icefields, due to differences in mountain altitude, humidity content, and catabatic winds effects. This paper presents the first detailed model of a large palaeoglacier system located in a subantarctic latitude belt, which is unique in South America and preserves continental palaeoclimatic information.

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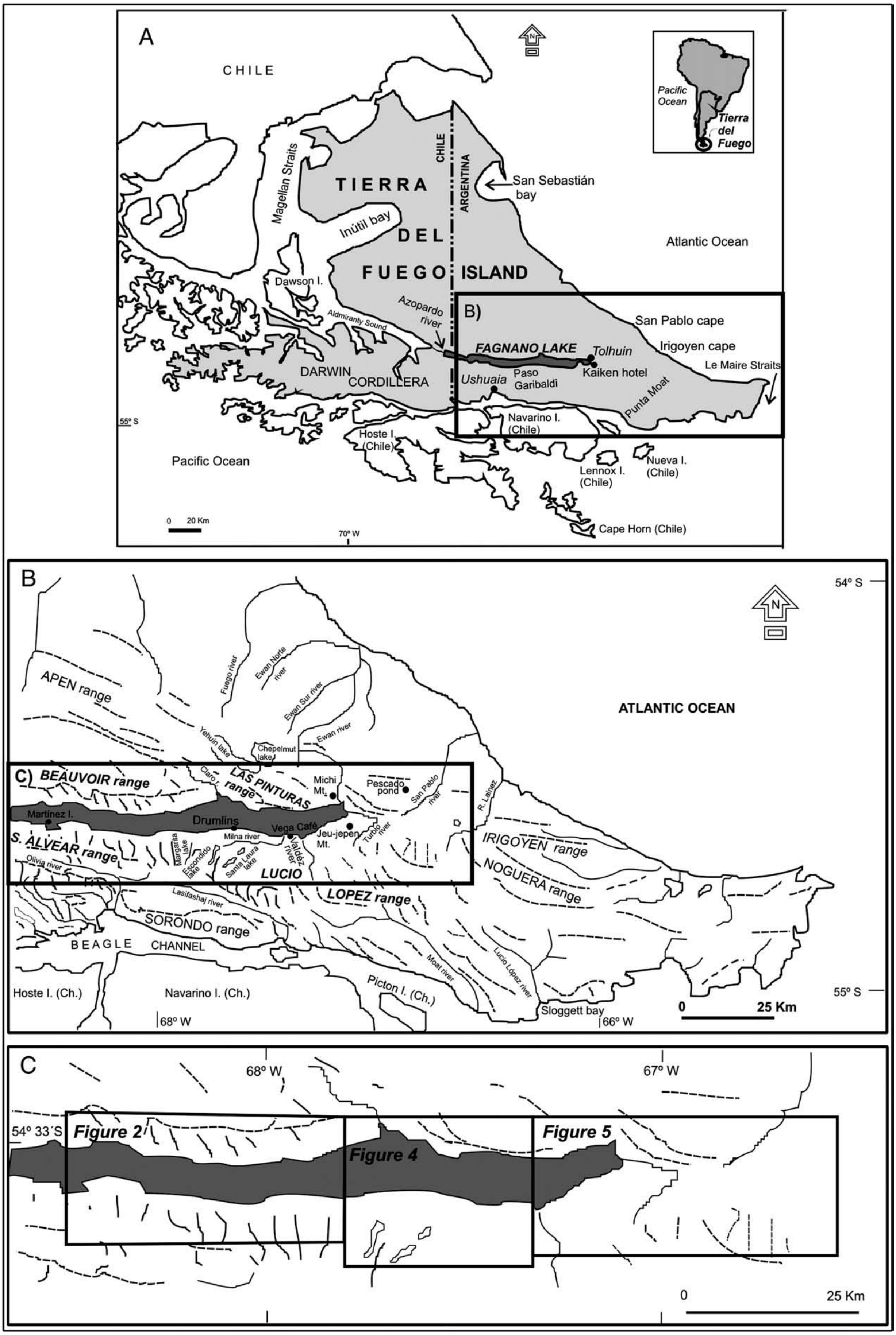

A
CHILE
Pacific Ocean
Tierra del Fuego
Magellan Straits
TIERRA
DEL
FUEGO
ISLAND
CHILE
ARGENTINA
San Sebastián bay
Inútil bay
Atlantic Ocean
Dawson I.
Azopardo river
B)
San Pablo cape
Irigoyen cape
Aldmiranty Sound
FAGNANO LAKE
Tolhuin
Kaiken hotel
Le Maire Straits
DARWIN
CORDILLERA
Ushuaia
Paso Garibaldi
Punta Moat
55º S
Navarino I. (Chile)
Hoste I. (Chile)
Pacific Ocean
Lennox I. (Chile)
Nueva I. (Chile)
0 20 Km
70º W
Cape Horn (Chile)
B
54º S
APEN range
ATLANTIC OCEAN
Fuego river
Ewan Norte river
Ewan Sur river
Ewan river
Yehuin lake
Chepelmut lake
C)
BEAUVOIR range
LAS PINTURAS range
Michi Mt.
Pescado pond
San Pablo river
R. Lainez
Martínez I.
Drumlins
Vega Café
Jeu-jepen Mt.
Turbo river
S. ALVEAR range
Milna river
Valdéz river
IRIGOYEN range
NOGUERA range
LUCIO
LOPEZ range
Olivia river
Lasifashaj river
SORONDO range
BEAGLE CHANNEL
Moat river
Lucio López river
Hoste I. (Ch.)
Navarino I. (Ch.)
Picton I. (Ch.)
Sloggett bay
55º S
0 25 Km
68º W
66º W
C
68º W
67º W
54º 33´S
Figure 2
Figure 4
Figure 5
0 25 Km

2. Regional setting

2.1. Geology

Lake Fagnano is located along one of the main tectonic features of the east–west oriented and transforming boundary between the South American and Scotian plates (Fuenzalida, 1972; Dalziel, 1989). Both tectonic plates are being displaced laterally at a relative velocity of 4 mm year^{-1} (Olivero and Martinioni, 2001). In 1949 an earthquake with the epicentre in the lake and a magnitude of 7.8 (Richter scale) occurred, and probably created a seiche. The bedrock of the Alvear and Lucio López ranges (with maximum elevations of 1300 and 1490 m a.s.l., respectively, Fig. 1B) is composed of rhyolitic and dacitic lava and tuffs, frequently of ignimbrite type, with tuffaceous, sandy and sometimes, conglomeritic inter-bedding (Caminos et al., 1981), corresponding to the Lemaire Formation of the Late Jurassic (Borrello, 1969). The rocks located along the northern shore (Beauvoir range, with a maximum elevation of 1050 m a.s.l.) and eastwards from the lake belong to the Beauvoir Formation (Camacho, 1967; Fig. 1B), of Albian–Cenomanian age. They are mainly composed of dark mudstones, shales and tuffs, with rhythmite sections of fine sandstones and layers of marl (Olivero and Martinioni, 2001). The Las Pinturas range (Fig. 1B, maximum elevation 660 m a.s.l.) is composed of yellowish brown to greenish grey, fine to very fine sandstones, with fine intercalations of shelly limestones, mudstones and conglomerates, of Danian–Palaeocene age (Río Claro Formation; Camacho, 1967; Martinioni et al., 1999).

Most of the local rocks are easily weathered and eroded, and have produced much debris to be moved by slope processes, and, formerly, glaciers. This means that glacial striations have been preserved only under stable till covers and are, at present, difficult to find.

Granitic boulders are scattered in the landscape like erratics, as a consequence of glacial transport. Granitic rocks are found to the west, in the central and southern Darwin Cordillera, Chile (Fig. 1A). They are mainly composed of biotites, granites, granodiorites and tonalities and are intruded by amphibolite dikes.

2.2. Climate and vegetation

According to the classification of Köppen (1936), the Lake Fagnano region has a humid temperate (Cfc) climate in its eastern areas and tundra climate (ET) in the western sector, both with oceanic influence. The dominant winds come from the western sector. The climatic conditions permit the development of small cirques or wall glaciers and permanent snow patches between 900 and 1300 m a.s.l. in the summit areas. Due to the present equilibrium line altitude (ELA) of ca. 1100 m a.s.l., most of the cirque glaciers are receding rapidly.

The area is included in the Subantarctic phytogeographic province, represented by the Deciduous Magellanic Forest (Pisano, 1977). The dominant vegetation type is *Nothofagus* forest, with *N. pumilio* and *N. antarctica* species. In poorly drained, lowland areas, peatlands and grasslands, together with shrubby formations, are found. South and east of Lake Fagnano, *Sphagnum magellanica* forms mires.

3. Previous work

Glacial landforms or deposits located in the surrounding areas have been described in part by several authors, especially along the eastern shore of the lake. However, the northern and southern shores, as well as the surrounding glacial valleys and lowlands, have never been studied in detail. Nordenskjöld (1899), Quensel (1912) and Bonarelli (1917) mapped terminal moraines surrounding Lake Fagnano. They interpreted these to indicate that the glacial lobe was bifurcated, one towards the northeast by the present San Pablo River and another towards the southeast, in the direction of Sloggett Bay and the Beagle Channel (Fig. 1B). Later, Caldenius (1932) mapped four glacial limits, named as the “Finiglacial”, “Daniglacial”, “Gotiglacial” and “InitioGlacial” from youngest to oldest. The first of these was recognized in the morainic ridges that surround the heads of Lake Fagnano and 20 km to the east, close to the Pescado pond (Fig. 1B); the other three were located between the Lucio López, Noguera, and Irigoyen ranges, close to the present Atlantic Ocean coast (Fig. 1B).

More recently, Meglioli (1992) identified different drift units around the lake. Along the northern shore, he postulated the diffluence of a glacial lobe flowing northwards. Three morainic arcs, named as Tills 5, 4 and 3, were identified and interpreted as OIS 2, 6 and 10 glacial events, respectively. Till 5 was also recognized further east from the lake heads, coinciding with the location of the Caldenius limits. Till 3 was mapped even farther east, in the San Pablo valley (Meglioli, 1992, Fig. 1B), and it is thought that the moraines of the three older glaciations proposed by Caldenius (1932) represented the same phase. To the south, at the mouth of the Valdéz River (Fig. 1B), Meglioli (1992) identified Till 3 outcrops, based on weathering rinds of the basaltic glacial boulders and soil development. It is accepted that the Fuego and San Pablo valleys were the drainage channels of meltwaters during the different glacial and deglaciation stages of the ice bodies of the present Lake Fagnano basin (Caldenius, 1932; Meglioli, 1992). Moreover, Quensel (1912) mapped another drainage path towards the southeast and south, at the foot of the Lucio López Range, reaching the Sloggett Bay (Fig. 1B).

Bujalesky et al. (1997) described the glaciofluvial and glaciolacustrine sequence of a proglacial deltaic environment located near the Kaiken hotel (Fig. 1A). Radiocarbon dating of fossil peat interbedded in lacustrine layers, overlying the delta beds and underlying the uppermost till unit, has yielded ages between 39,500 and >58,000 years B.P. This demonstrates that the delta deposition would have taken place during an ice advance prior to the Last Glacial Maximum (LGM). Coronato et al. (2002) mapped the glacial landforms of the eastern region of the lake heads, and suggested the presence of basal moraines to the east of Pescado pond, thus challenging Caldenius' (1932) ideas about the maximum expansion of the ice to the east. Palynological studies performed in the region show that the glacial valleys of Yehuin Lake (100 m a.s.l.; Fig. 1B) and Paso Garibaldi (400 m a.s.l.; Fig. 1A) were free of ice by ca. 12,500 years B.P. and 10,700 years B.P., respectively (Markgraf, 1983, 1993).

The knowledge that glaciation occurred both north and south of Lake Fagnano is quite important for comparisons with other ancient glacial lobes and chronological interpretations. The glacial deposits located along the Magellan Straits and from Inútil Bay to San Sebastián Bay (Fig. 1A), in northern Tierra del Fuego, suggest the occurrence of at least five glaciations between 1 Ma and 23 ka B.P. (Meglioli, 1992; Porter et al., 1992; Clapperton et al., 1995; Bentley et al., 2005; McCulloch et al., 2005; Kaplan et al., 2007). During Late Glacial times, at least three stages of ice stabilization would have occurred between 19,000 and 10,200 uncalibrated ^{14}C years (McCulloch et al., 2005). In the south, the Beagle Channel and its tributary valleys along the north coast were fully glaciated during the LGM (Rabassa et al., 1986, 1988, 1990a, 1996, 2000; Coronato, 1990, 1993, 1995). Basal radiocarbon ages in coastal and lowland peatlands indicate a minimum ice recession date of between 14,600 and 10,000 years B.P. (Heusser, 2003). A cold climatic reversal during the Younger Dryas along the Beagle Channel was postulated by Heusser and Rabassa (1987) based on pollen analyses. The palaeoenvironmental conditions have also been studied by Borromei (1995), Heusser (1998, 2003) and Borromei et al. (2007).

Fig. 1. Study area. A) Tierra del Fuego Island in the southern tip of South America, close to the Cape Horn where the Atlantic and Pacific Oceans meet. B) Places mentioned in the text. C) Locations of Figs. 2, 4 and 5.

4. Materials and methods

Due to the lack of detailed topographic maps and aerial photographs, satellite image maps of the Instituto Geográfico Militar (IGM), at a scale of 1:100,000, SPOT satellite images taken in 1995 and free-access NASA SRTM-3 images were used. Several drafting and digital cartography programs were employed to create maps and topographic sections, based upon NASA digital elevation models with a resolution of 60 m. The terrain elevations were taken with barometric altimeter and controlled by the SRTM-3 digital elevation model. Depth data in the lake were obtained from a bathymetric study by Lippai et al. (2004). The unpopulated mountain zone, difficult to access due to the lack of roads, was surveyed from a small plane by several especially prepared flights. Oblique photographic surveying was performed for the reconnaissance of those areas that contained the landforms of greatest interest, such as moraines, roches moutonnées, and rock thresholds.

Field work included the usual techniques of regional mapping using some accessible roads, which were mostly forestry trails. Special attention was paid to erratic rocks and their distribution. The southern coastal area was observed from zodiac boats, kindly provided by Prefectura Naval Argentina. Locations of field observations were recorded by means of a GPS with barometric altimeter.

Sedimentary profiles were described, and organic and inorganic sediments were sampled. Peat coring was carried out in order to obtain basal peat material for radiocarbon dating. These dating assays were made at the NSF Arizona AMS Facility, Arizona University (Tucson, U.S.A.).

5. Glacial landforms and deposits

Landforms of glacial origin due to Pleistocene ice activity are dominant in the area studied around Lake Fagnano. Due to its extent, the area is divided in three sections, as shown in Fig. 1C.

5.1. Western mountainous area

Hanging glacial troughs, developed in volcano-sedimentary rocks, are frequent with arêtes interposed at elevations between 840 and 1100 m a.s.l. (Fig. 2). The troughs have a mean local relief of 730 m, while the mean elevation of their thresholds above the main glacial valley is 300 m a.s.l. Most of the hanging valleys result from erosion due to the merging of two or more glaciers descending from independent cirques. A few valleys were created only by one cirque glacier with short ice tongues. The mean length of these high valleys is 2.5 km, with the largest ones having a mean length of 5.8 km. Erosional glacial landforms prevail. The slopes show rocky outcrops with roches moutonnées and glacial abrasion. The troughs are developed in steps, which contain lakes and ponds, in some cases forming a lake-chain. The morphological evidence indicates that this area was under the palaeoglacier accumulation zone. Also, the Grande Bay (Fig. 2) is an evidence of glacial erosion controlled by bedrock structure. The topographic cross-section (Fig. 3A) shows the sculpture of hanging valleys on both sides of the main valley, which are occupied by the lake at present. Till deposits, located over 100 m a.s.l., and the glacial boulders on Martínez Island (Fig. 4A) indicate that the ice has been positioned in this area during its general recession.

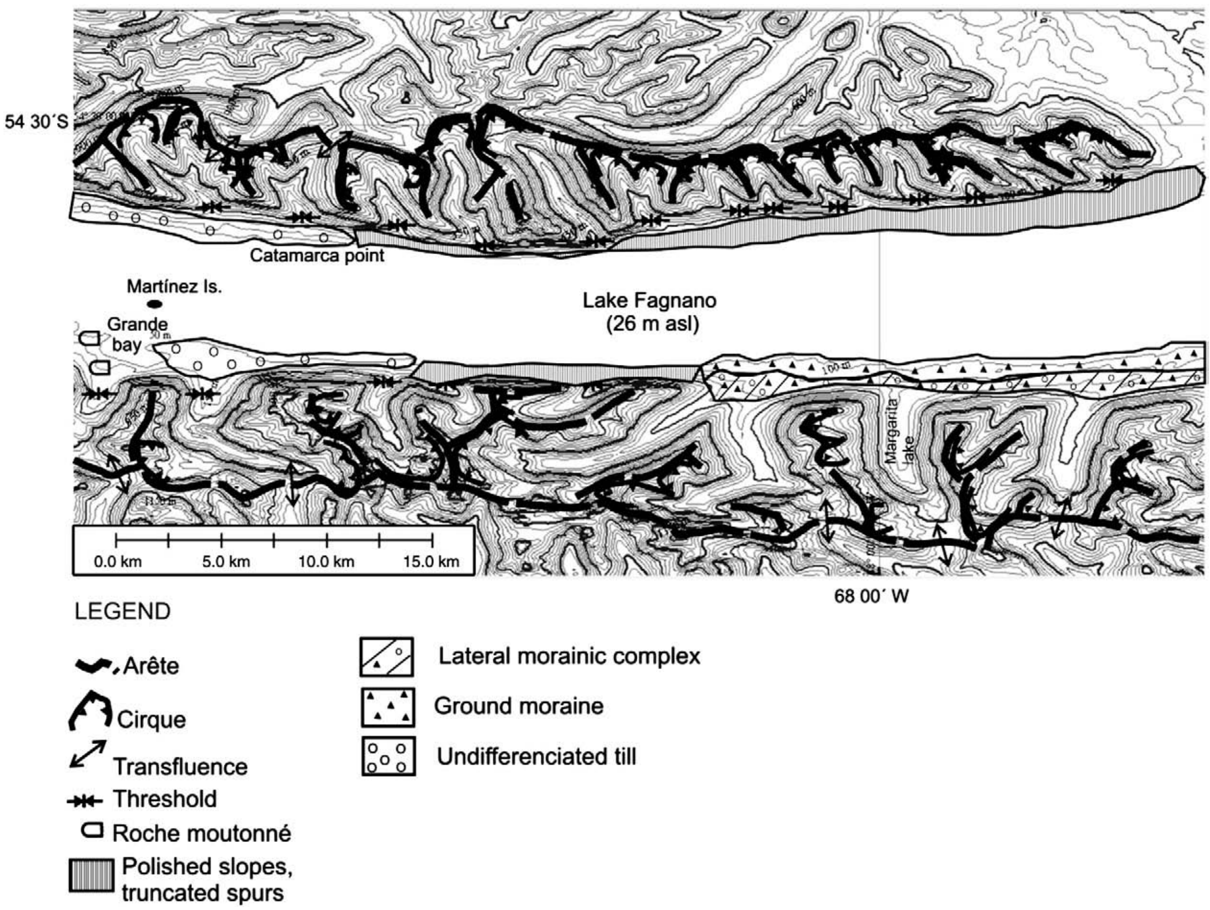


Fig. 2. Glacial landforms located between 67°46′W and 68°35′W, in the western mountainous area of Lake Fagnano. Note that the mapped area corresponds to the Argentinean sector of the lake. Field work and detailed mapping around the Argentina–Chile border were impossible.

From 68°03′W to the east (Fig. 2), lateral moraines are found along the lake shore. They block the tributary troughs. In the contact zone between the tributary valley Margarita (Figs. 2 and 4B) and the Fagnano Lake shore, ablation till has been recognized. It includes meltwater structures oriented in a northward direction, indicating the presence of contact between the tributary glaciers and the Fagnano palaeoglacier.

Frontal moraines, which may have closed the tributary valleys, are not clearly observed. Instead, elongated hills of west–east orientation, located between 60 and 130 m a.s.l. are evident. The large erratic boulders of granitoid lithology, and the parallel channels developed in between the hills suggest that these hills are lateral moraines of the Fagnano palaeoglacier, which obstructed the tributary glaciers flowed from the Margarita and Alvear valleys in the Alvear range (Figs. 1B and 2). Till can be observed between 100 and 700 m a.s.l. on the slopes of tributary valleys, indicating an ice thickness of at least 600 m within these troughs.

On the lake shore (26 m a.s.l.), there are ground moraines, slightly convex in shape, composed of 20-m-thick basal till (Figs. 2 and 4E). The till is affected by oxidation in the upper 10 m, but no evidence of unconformities between till layers was found. Clast shape, boulder striation and a large silty–clayey matrix indicate a subglacial origin. The till presents erosion features typical of superficial runoff.

5.2. Central hilly area

From the tributary valley of Lake Escondido to the east (67°48′W, Fig. 5), the glacial landforms are widespread, forming a lowland landscape, very different from the mountain glacial landscape located in the western troughs. Fig. 3B shows tributary valleys which have formed depositional landforms, presently besides the ground moraines deposited by the Fagnano palaeoglacier. They form the lake shore-cliffs, with a local relief of 30 m above the lake. In many sections of the cliffs, the basal till includes dipping gravel layers. Similar glaciofluvial structures were found forming the proglacial delta found near Hotel Kaikén (Figs. 1 and 4G; Bujalesky et al., 1997).

At 67°36′W, the subglacial deposits exhibit the morphology of drumlins and fluted moraines (Fig. 5). A small drumlin field has developed along the lake shore, at 60–90 m a.s.l. with long axes oriented in the direction of 107°–117° (Coronato et al., 2006). The scattered erratic boulders on the surface of the drumlins indicate that the till was deposited by the Fagnano palaeoglacier. On the northern shore of the lake, a till outcrop is found. According to the topographic map, it is an undulating surface of drumlin type, suggesting that the drumlin field may be partially submerged, if not totally eroded by wave action. These subglacial features are developed outside the confined area of the Fagnano trough, down ice from the merging point of the tributary Escondido palaeoglacier, thus increasing the total ice mass and, therefore, the erosive capacity of its own deposits. The drumlins are located down ice from a bedrock threshold shown by the lake bathymetry near the Claro River mouth (Fig. 1B).

Topographic irregularities cause obstacles to the ice-flow, generating subglacial cavities in the lee of the irregularities (Lliboutry, 1968; Aario, 1977; Seppälä, 1986; Glückert, 1987) and favoring stream-lined landforms as drumlins. To the east, beyond the mouth of the Milna River, moraine spurs and basal till outcrops continuously occur.

5.3. Eastern lowland area

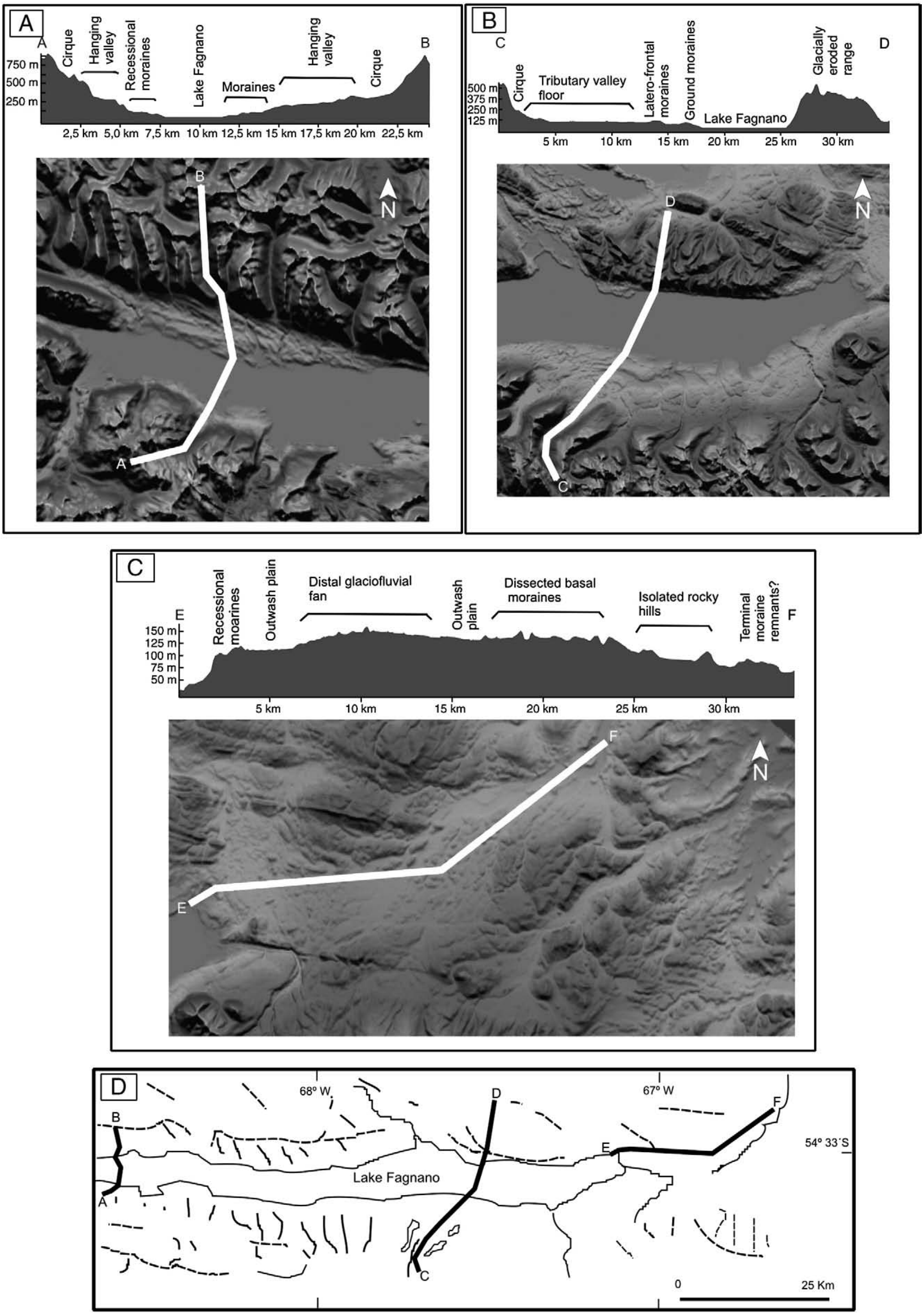
At 54°33′55″S and 67°17′24″W, basal till developed up to 2 m thick, presenting iron oxide cementation layers and highly weathered clasts (FFP in Fig. 6). Above these units, there is a 1 m thick bed of rounded gravels, which progrades towards the east and ends in a horizontal topset layer of 3 m thick. Lenses of diatomite are found over the gravels and three layers of fossil peat, around 2 cm thick each, are found within the till beds (Fig. 7). The sequence ends with basal till at the top. The radiocarbon ages of these materials (localities LF2 1bis, LF2 6 and LF2 7) are presented in Table 1. They indicate that the till bearing these peat layers is older than the Last Glacial Maximum, and most likely, even older than OIS 4. Similar sedimentary structures located at Hotel Kaikén (Bujalesky et al., 1997; Figs. 4G and 6) are thought to be formed before the Last Glacial (Lago Fagnano—Section 6 in Table 1 and HKFP in Fig. 6).

The basal moraines extend up to 2.5 km from the shore, with elevations of 120 m a.s.l. Based upon the dip and strike of the sandy beds at the foot of Jeu Jepen Mountain (Fig. 1B), Coronato et al. (2002) have interpreted the top of them as meltwater stream deposits coming from the mountain palaeoglaciers, probably in contact with the Fagnano palaeoglacier during its recession. Several hills form an arc close to the lake coast, west of the Valdéz River mouth (67°18′W). The bathymetry of the lake in this area shows shallower depths and the development of submerged crests. These could be partly the continuation of the moraine ridges under the lake water, or landslides deposits generated from the exposed moraines. Rhythmic lacustrine sediments of 3 m thick, grading laterally into a fluvioglacial sequence, occur near the lake shore. These deposits are interpreted as a marginal environment between the Fagnano palaeoglacier and its tributary along the Valdéz valley.

The occurrence of till only up to 350 m a.s.l. on the southwest-oriented slopes of Jeu Jepen Mountain indicates that the ice did not overtop the entire mountain. In addition, the cirque development at ca. 640 m a.s.l. indicates that glacial ice accumulated and subsequent erosion independent of the Fagnano palaeoglacier activity occurred; whereas, on higher slopes, a very intense cryoclastic weathering would have occurred. On the northeast-oriented slopes of this mountain, three moraine levels appear at elevations of 145, 175 and 200 m a.s.l. (Fig. 6). They have low gradient and consist of silty–clayey till with a large content of rounded to sub-rounded gravels and striated boulders. On the opposite side of the valley, on the Michi Mountain slopes (400 m a.s.l., Fig. 1B), till and erratic boulders are also found. Downslope, a lateral frontal moraine ridge descends from 170 to 120 m a.s.l. to the foot of the lower hills. This has already been described by Coronato et al. (2002) as the “Tolhuin lateral frontal moraine complex” (“Recessional moraines” in Fig. 3C), reflecting its dissection by the present Turbio river valley. Accordingly, this paper suggests that the moraine steps of Jeu Jepen Mountain must be understood as the continuation of the Tolhuin moraine. Northeastwards, a glacial disintegration landscape developed (Fig. 6), formed by glaciofluvial gravel hills, 6 m higher than the surrounding depressions, many of them of circular shape.

Terraces interrupt the glaciofluvial plain detached from the Tolhuin moraine. They have been described as a glaciofluvial fan (later dissected) generated by meltwater streams coming from tributary mountain glaciers (Coronato et al., 2002; Fig. 3C). The lowest terraces are intercalated with irregularly shaped mounds composed of gravels and an upper thin till layer. These depositional landforms may have resulted from till accumulation during the disintegration of heavily sediment-loaded ice, carrying fine sediments supplied from the Las Pinturas range underlain by marine sandstones and siltstones. Similar landforms are also present to the north, in between hills (250 m a.s.l.), suggesting that an ice-disintegration process also took place there.

To the east of the Pescado pond (Figs. 1B and 6), the glaciofluvial plain continues at 130 m a.s.l. and narrows close to a set of ground moraines heavily dissected by palaeochannels. The moraines occur between 150 and 175 m a.s.l. and have a flat shape. Although there are no outcrops, striated erratic boulders are scattered on their surface confirming the glacial genesis. These moraines are thought to be deposited by the Fagnano palaeoglacier when it was most expanded. The existence of frontal moraines in this zone is not clear, although ridges are present at the narrowest point of the valley (Fig. 3C). There is a succession of lateral till deposits of almost flat shape, which occurs stepwise towards the interior of the valley and separates the San Pablo River basin from the Lainez River basin (Fig. 1B). They are composed of



A
A
B
Cirque
Hanging valley
Recessional moraines
Lake Fagnano
Moraines
Hanging valley
Cirque
750 m
500 m
250 m
2,5 km 5,0 km 7,5 km 10 km 12,5 km 15 km 17,5 km 20 km 22,5 km
N
B
C
D
Cirque
Tributary valley floor
Latero-frontal moraines
Ground moraines
Lake Fagnano
Glacially eroded range
500 m
375 m
250 m
125 m
5 km 10 km 15 km 20 km 25 km 30 km
N
C
E
F
Recessional moraines
Outwash plain
Distal glaciofluvial fan
Outwash plain
Dissected basal moraines
Isolated rocky hills
Terminal moraine remnants?
150 m
125 m
100 m
75 m
50 m
5 km 10 km 15 km 20 km 25 km 30 km
N
D
68° W
67° W
54° 33´S
Lake Fagnano
0
25 Km

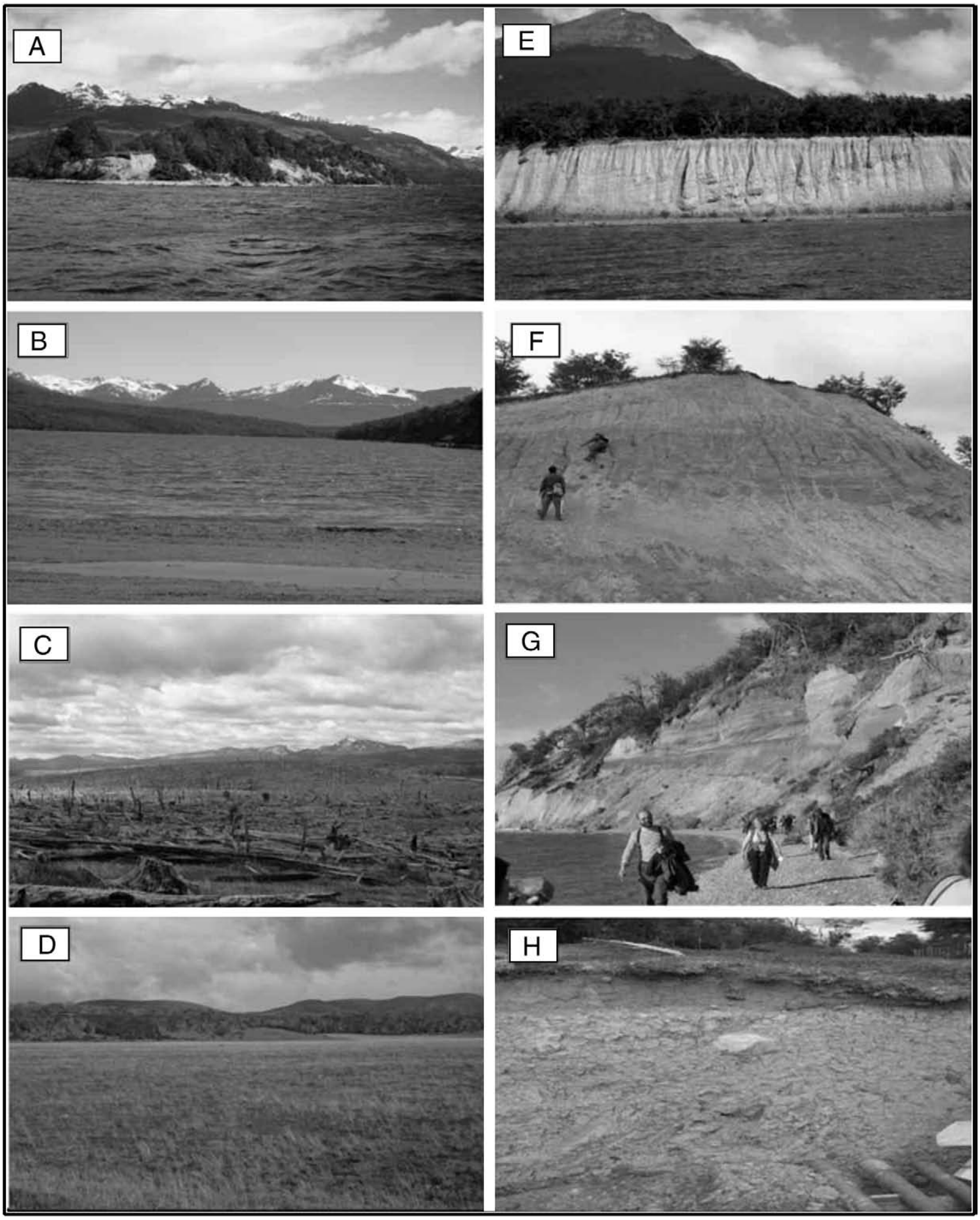


Fig. 4. Glacial landforms and deposits around the Fagnano Lake basin. A) Martínez Island, a recessional moraine in the western region of the Fagnano Lake. The Alvear Range Mountains is at the back. B) Margarita glacial lake, seen from N, and moraines closing its basin. The glaciated Beauvoir range in the northern side of the Fagnano basin at the back. C) Drumlins in the southern coast of Lake Fagnano. The glaciated Lucio Lopez range at the back. D) The Yehuin moraine deposited by the Fuego river ice lobe closing Lake Yehuin. A glaciofluvial plain at the front. The Las Pinturas range at the back. E) Basal till overlaid by gravel strata dipping eastwards, forming gently convex moraines in the south coast of the Fagnano Lake. Its surface is finely dissected by rills. F) Glacial deposits forming cliffs at the mouth of Vega Cafe Creek, in the southern coast of the Fagnano Lake. They are composed of basal till overlying gravel layers and glaciolacustrine silty clays, including dropstones. G) Glaciodeltaic deposits at the Kaikén Hotel forming coastal cliffs. Their age is pre-LGM according to Bujalesky et al. (1997). H) Till deposit in the Yehuin moraine. The granitic erratic boulder has the Darwin Cordillera lithology, confirming the depositional action of an ice lobe flowing along the Fagnano Lake. See Fig. 1A for locations of the sites.

Fig. 3. Topographic sections showing the morphology of the Fagnano glacial valley. A) A–B across the western mountainous area; B) C–D across the central hilly area; C) E–F across the eastern lowlands; D) location of the topographic sections in the region. Free-access NASA SRTM 3 images were used: S55W069 in A), S55W068 in B), S55W068-S55W067 in C).

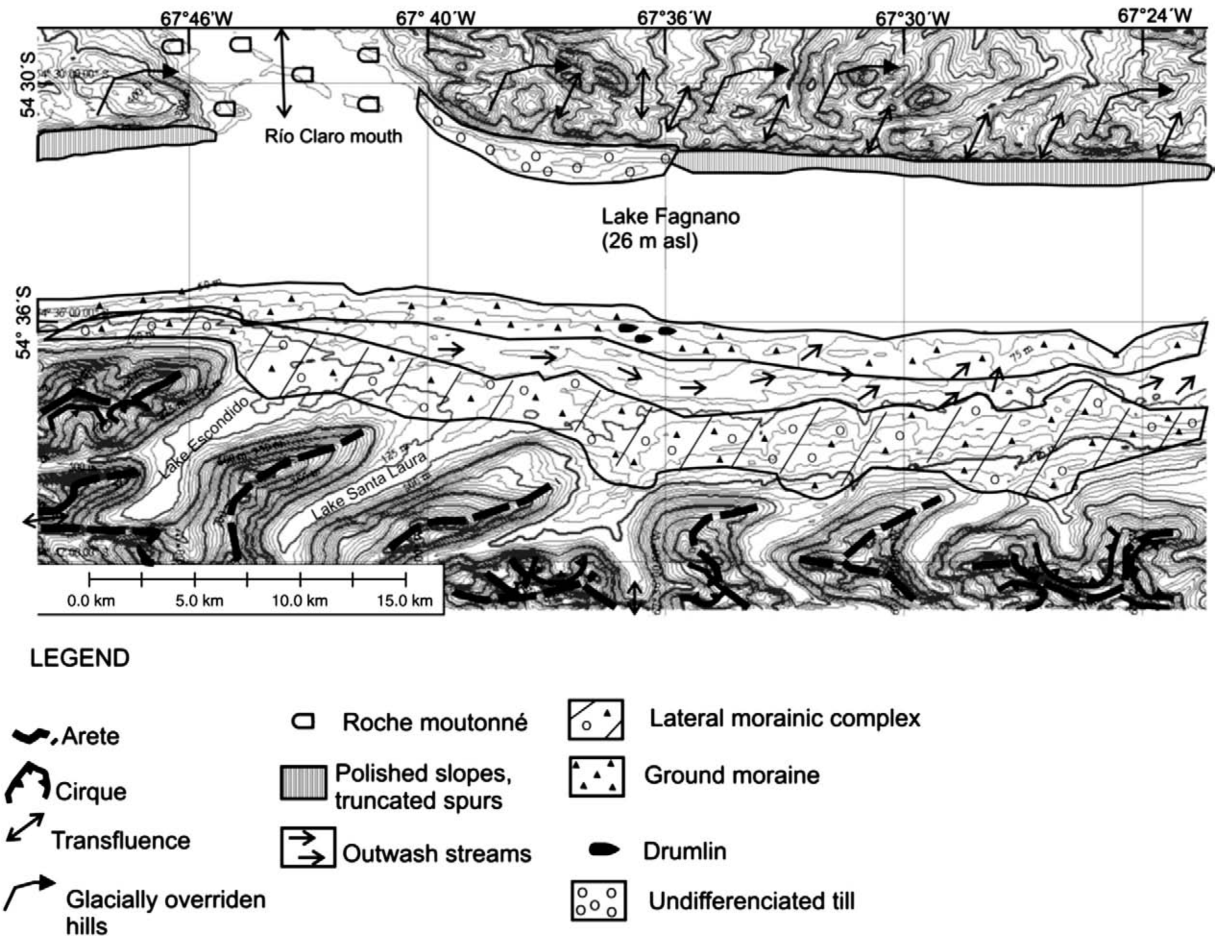


Fig. 5. Glacial landforms located between 67°46′W and 67°24′W, in the central hilly area. Erosional features prevail in the north coast, whereas basal and lateral moraines occur in the south coast. The latter seem to have blocked the mouth of the tributary glacial valleys eroded in the mountains. Glaciological and geomorphological relationships between the Fagnano palaeoglacier and the mountain palaeoglaciers have not been established.

mixed glaciofluvial materials and some ablation till. The grouping of large size erratic boulders along the margins of the straight sections of the San Pablo River, downstream from the hypothetical frontal zone, is the sole evidence of coarse till remnants. The original till deposits would have been dissected by meltwater streams coming from the Lucio López Range palaeoglaciers. Although no evidence of a clear frontal moraine arc at the bottom of the trough has yet been recognized, the resulting landforms of the ice-disintegration landscape, located down ice from the Tolhuin–Jeu Jepen frontal moraine arc, indicate that the terminal ice front was located 30 km east of the Tolhuin moraine. High lateral moraines (100–250 m a.s.l.), with material plucked from the hilly rocks, extend northeastwards (Fig. 6) to the boulder concentration and isolated till-mounds area, beside the San Pablo River.

6. The Fagnano palaeoglacier

The extent, shape and flow direction of the Fagnano palaeoglacier was reconstructed based on the following geomorphological criteria: 1) elevations of cirques, arêtes, thresholds, truncated spurs, hanging valleys' floors, and trough steps and 2) type of the depositional landforms. Fig. 8 shows the area affected by the palaeoglacier, its tributaries and inferred ice sources.

Frontal moraines, not only located around the head lake but also closing the Fuego, Ewan and San Pablo valleys (Fig. 1B) indicate that several ice tongues were formed by the main body of the Fagnano palaeoglacier. Accordingly, the western half of the present lake seems to have been the accumulation zone of these three ice tongues, which spread out over a hilly landscape northwards and northeastwards.

Based on the present geomorphological features, it could be said that the Fuego ice lobe was also supplied by western mountain valley glaciers. On the other hand, the Ewan and San Pablo valleys do not show any apparent connection to other palaeoice supply sources than the palaeo-Fagnano glacier main trunk. The influence of the Fagnano palaeoglacier over these three surroundings valleys has been proposed by Caldenius (1932), Meglioli (1992) and Coronato et al. (2002).

The Fagnano palaeoglacier was flowing from west to east as a discharge glacier coming from the Fuegian mountain ice-sheet which occupied the western portion of the Darwin Cordillera (Chile, Figs. 1A and 8). Once out of the mountain ice-sheet, alpine glaciers joined it, enlarging its volume and size, and the former discharge glacier became a large valley glacier. The place in which the ice discharge occurred cannot be determined precisely, although the morphology suggests that it was located west of the present Azopardo River (Chile, Figs. 1A and 8). From here, the ice mass diverged both westwards and eastwards, forming the beginning of the ice lobe of the Magellan Straits (Figs. 1A and 8).

From the edge of the mountains north of the lake, 27 alpine glaciers flowed down the slopes to merge with the Fagnano palaeoglacier. From the elevation of the highest glacial erosive landforms and their relief above the trough floor, the ice thickness is estimated at 300–500 m within the cirques and 150–300 m in the terminal sections. The surface inclination of the tributary glaciers is estimated at 1–2°. The tributary glacier supply mainly occurred in the upstream area of the present Claro River valley (Fig. 1B). The threshold elevation of the present hanging valleys suggests that the merging of the tributary glaciers and the Fagnano palaeoglacier took place between 170 and 380 m a.s.l. Arêtes and troughs are not clearly developed east of the Claro River

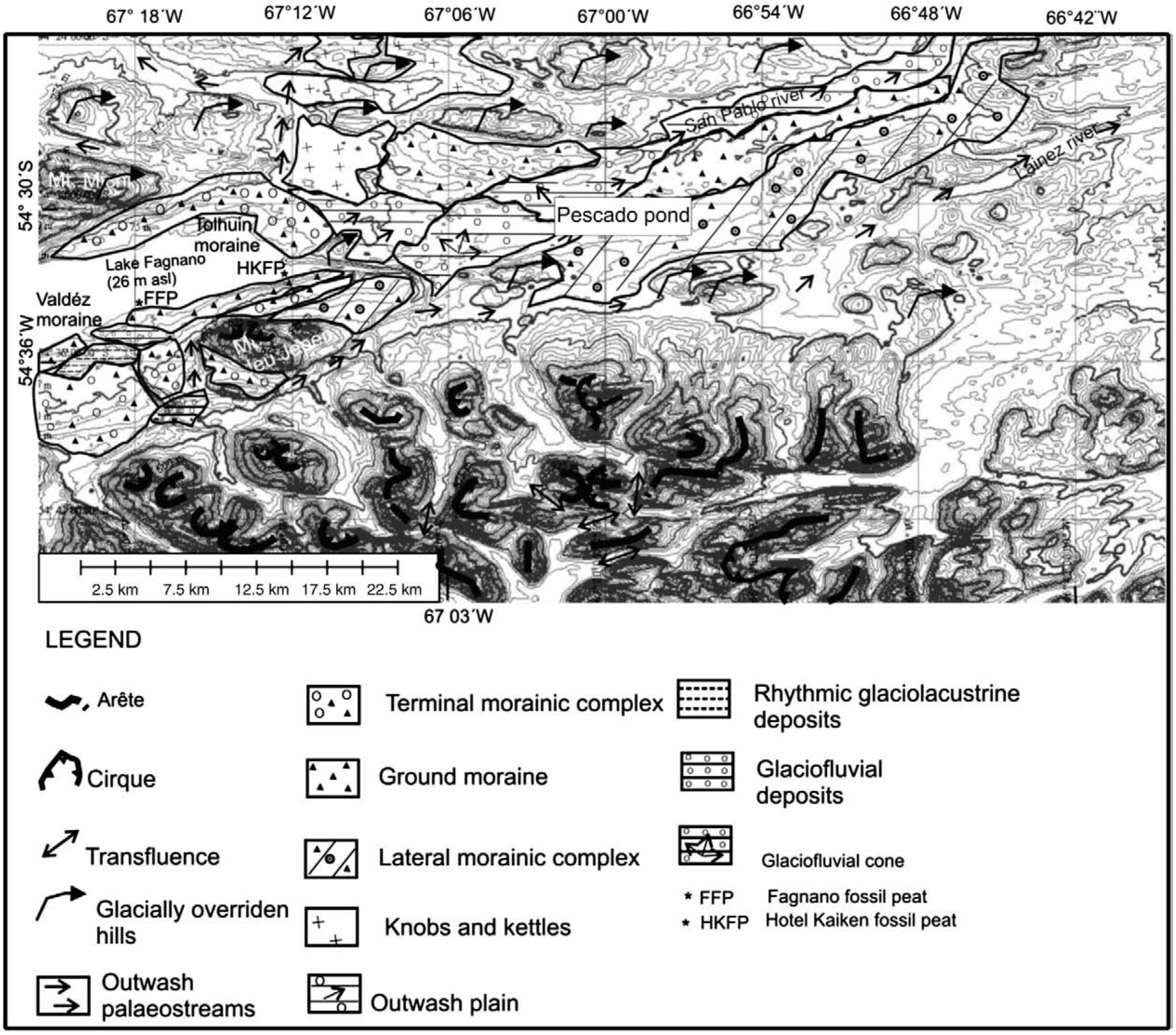


Fig. 6. Glacial landforms located between 67°24′W and 66°42′W in the eastern lowlands. Rocky hills overridden by the ice occur in the northern side. Dissected basal moraines occupy the bottom of the valley, whereas lateral moraines extend at higher altitudes towards the east. No clear terminal moraines are found. If they had been deposited, they would have been eroded by meltwater streams flowing not only from the Fagnano palaeoglacier but also from the mountains. By this time the Tolhuin Moraine Complex must have been formed. It shows the position of the first recessional stage of the Fagnano palaeoglacier. While the palaeoglacier deposited the Tolhuin Moraine, an outwash plain was forming eastwards. Sometime later, meltwater streams flowing from the southern mountains deposited gravel and sand forming a glaciofluvial fan over the outwash plain.

mouth; by contrast the rounded summits and the strong drainage incision near them indicate that the ice overtopped these hills, with elevations varying between 450 and 220 m a.s.l.

From the edge of the mountains south of the lake, 32 alpine glaciers merged with the trunk glacier, several of them formed by two small bodies coming from independent, isolated local cirques. The ice thickness in the cirques is estimated at 300 to 600 m, whereas in the troughs at 190 to 500 m, with inclination ranging from 1.5° to 4°. The two largest tributary glaciers were located in the westernmost sector of the Alvear Range. The easternmost portion of the Darwin Cordillera mountain ice-sheet was located in this area, from which other glaciers, such as the Lasifashaj and the Beagle palaeoglaciers with W–E direction (Fig. 1B), flowed out.

The quantity, extent and thickness of the tributary glaciers merging into the Fagnano palaeoglacier from the southern mountains were greater than those from the northern ranges. Undoubtedly, the proximity to the mountain ice-sheet and the higher precipitation values in this zone contributed to the formation of larger glaciers. This network of alpine glaciers fed the Fagnano palaeoglacier as far as 68°46′W. The mean dip of the surface of the Fagnano palaeoglacier is estimated at 3°.

Based on lake depth and altitude of the erosional glacial features along the valley slopes, a maximum ice thickness for the palaeoglacier was crudely estimated at 1000 m. Bathymetric studies (Lippai et al., 2004) indicate the existence of a topographic threshold at 67°45′W, in front of the mouth of the Claro River. Consequently, the depth of the lake is only 30 m there. Although it has not yet been possible to study its lithological composition, the threshold is likely a rocky outcrop, a remnant of glacial erosion. This hypothesis is sustained by the fact that the relative height difference between the greatest known depth (200 m) and this submerged knob seems to be too large to correspond it to a moraine, and there is no evidence of coastal processes. Ongoing seismic studies will certainly help to confirm or discard this hypothesis. It is from this area that the palaeoglacier left the trough behind to expand over a low rocky hilly landscape. It was fed by valley glaciers coming from the local mountain front forming an ice mass like a piedmont glacier along its southern margin. By contrast, the ice overtopped the hills along the northern side, forming new ice lobes. The frontal moraine arcs in the Fuego valley, 40 km north of Lake Fagnano, point to a diffluent ice lobe flowing northwards (Caldenius, 1932; Meglioli, 1992). Moreover, the existence of till within the valleys or plastered to the hills in the upper Ewan River basin (Fig. 1B) suggests the presence of the Ewan ice lobe, which flowed towards northeast, forming extensive and wide meltwater channels (Fig. 8).

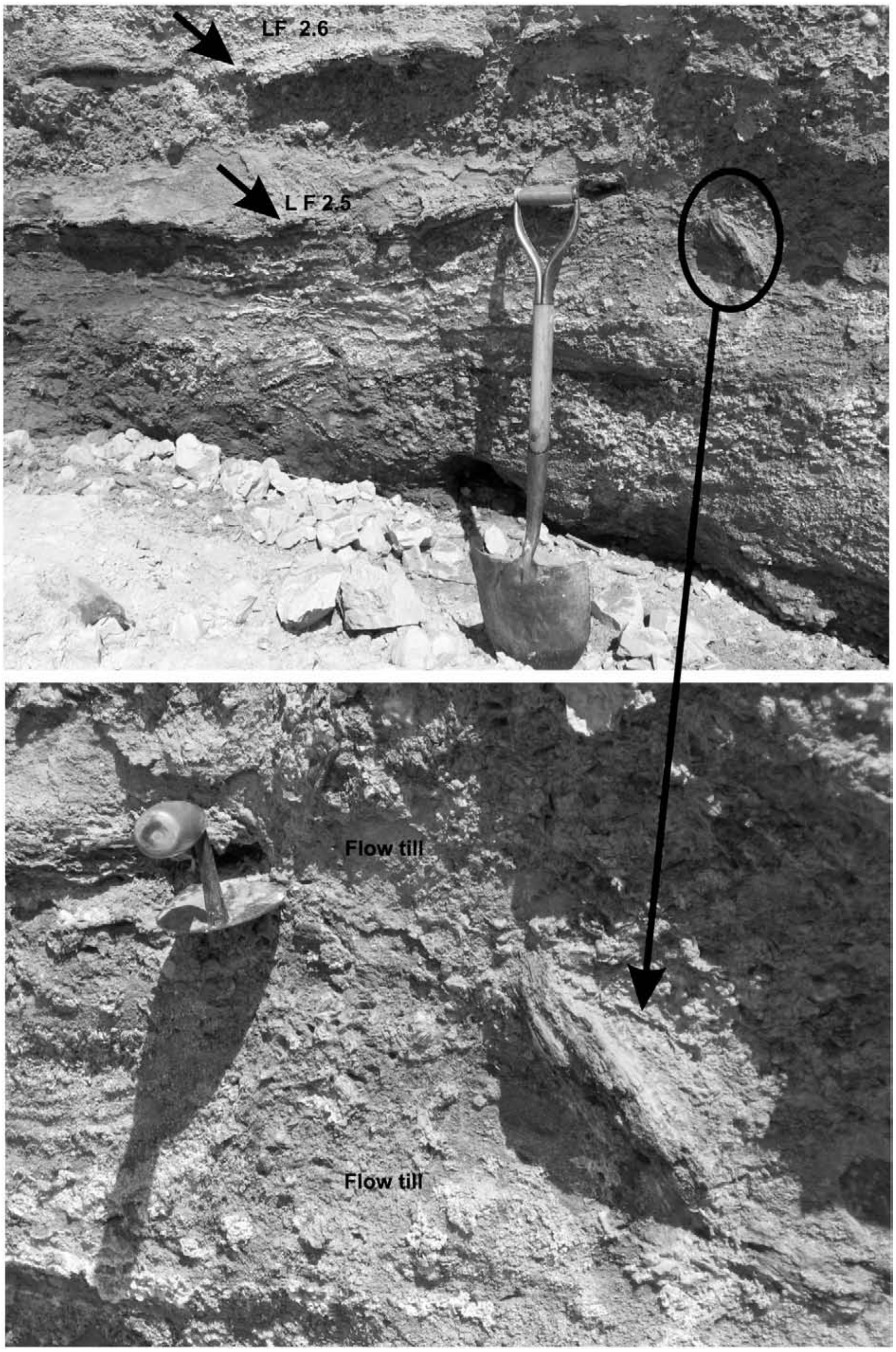


Fig. 7. Fossil peat levels in a till matrix at a basal section of glacial and glaciolacustrine deposits. The arrows show the upper and intermediate fossil peat beds where LF 2.6 and LF 2.5 samples were collected for ^{14}C dating. Radiocarbon results (Table 1) indicate that the peat was taken into the till by the advancing glacier sometime before the LGM.

From 67°30′W to the east, the elevation of the Las Pinturas Range lowers progressively from 600 to 300 m a.s.l (Figs. 1B and 5). At 450 m a.s.l., drainage lines with a strong incision on the slopes, which seem to be oversized for present runoff conditions, have been observed. These features are interpreted as subglacial drainage channels in which meltwater flowed at high speed and pressure, thus providing a minimum ice elevation estimate in this area. The presence of till up to 400 m a.s.l. and scattered erratic boulders, along with the rounded topography of the summits and the knob and kettle landscape, suggests that the low and parallel ranges were overtopped by the ice during the maximum ice-stage (Fig. 9).

To the south, in the Escondido valley, the Fagnano palaeoglacier was fed by longer alpine glaciers (with a mean length of 10 km), flowing from the Lucio López Range (TGA or tributary glaciers area in Fig. 8). During the LGM, these glaciers formed a group of subparallel ice lobes, with northeastward orientation that surrounded the Jeu Jepen Mountain, at least up to 350 m a.s.l., according to the maximum elevation of till on its slopes. The largest of these valleys is currently occupied by the Escondido, Santa Laura and San Ricardo lakes, and by the Valdéz River. The ice thickness in the cirques would have been at least 500 m and between 200 and 500 m in the troughs (Fig. 3C). At the commencement of deglaciation, when ice became thinner and uncovered the hills at 300 m a.s.l., the terminal section of the Fagnano palaeoglacier would have separated from the main trunk body, becoming dissected. Huge chunks of dead ice may have been trapped between the low ranges located in the northeast. The occurrence of

Table 1
^{14}C ages of fossil peat from basal till along the southern coast of Lake Fagnano.

Locality	^{14}C age (years B.P.)	Calibrated age (years B.P.)	Calibrated age range (cal B.P., p: 95%)	Lab. code	Source
Lago Fagnano, Section 6, 14 m a.s.l.	39,560 ± 3980	43,840 ± 3650	51,140 − 36,540	AECV 482C	Bujalesky et al. (1997)
Lago Fagnano, Section 6, 16 m a.s.l.	>58,000	Infinite	–	GRN 16240	Bujalesky et al. (1997)
Lago Fagnano LF2-1bis	31,080 ± 510	36,170 ± 460	37,090–35,250	AA 68977	This paper
Lago Fagnano LF2-5	>44,800	Infinite	–	AA 68978	This paper
Lago Fagnano LF2-6	48,200 ± 3300	51,580 ± 3430	58,580–44,580	AA 68979	This paper
Lago Fagnano LF2-7	44,800 ± 2300	48,380 ± 2450	53,280 − 43,480	AA 68980	This paper

Reported calibrated ages are shown with a 95.4% (2σ) confidence interval and rounded to the nearest 10 years. Calibration was made using the Cologne Radiocarbon Calibration and Palaeoclimate Research Package (Cal Pal_A 2007) online version (Weninger and Jöris, 2004). The calibration curve used was Calpal 2005 SFCP. Lago Fagnano Section 6 location is shown as HKFP in Fig. 6. LF2 location is shown as FFP in Fig. 6.

granitic boulders at 200 m a.s.l. and the knob and kettle landscapes is evidence of dead ice in this area. In all probability, such thinning of the ice would have forced the separation of the ice mass over the topographic threshold located at 67°46′W, becoming progressively disconnected from the northern diffluent ice lobe, which followed the present Fuego valley, but joining the ice mass of the larger tributary glaciers coming from the Lucio López Range.

Based on the surface morphology, at least one stabilization stage seems to have taken place in the Isla Martínez area (Fig. 1B) before the final retreat of the ice, although the existence of submerged recessional moraines is under consideration.

7. Late Pleistocene glaciations

From the location of landforms resulting from glacial erosion and accumulation, the sediment types of which they are comprised, and the radiocarbon dating of organic deposits (Table 2), it is interpreted that the glacial expansion of the Lago Fagnano region took place in several stages (Table 3, Fig. 10).

7.1. The maximum extent (Last Glacial Maximum)

The Fagnano palaeoglacier reached its maximum frontal position at 66°45′W, making a total length of 132 km of ice from the source area. The minimum elevation in the accumulation area is estimated at 800 m a.s.l., and 200 m a.s.l. at the ice snout. The ice mass would have occupied an approximate surface area of 4000 km^2, which is equivalent to 30% of the surface of the Southern Patagonian Icefield, located 48°15′ S–51°35′S in the Southern Patagonian Andes. The main drainage courses of the Fagnano palaeoglacier seem to have been the present valleys of the Fuego, Ewan, San Pablo and Lainez rivers. The existence of a discharge drainage line towards the southeast reaching Sloggett Bay (Bonarelli, 1917; Caldenius, 1932) is rejected. These authors were probably confused by local ice lobes draining from the Lucio López Range slopes.

According to the altitude of the higher lateral moraines located east of the Jeu Jepen Mountain (Figs. 1B and 7), the ELA position during this stage is estimated at ca. 250 m a.s.l., meaning that it has dropped by 950 m to its present position. During this phase, the basal moraines in the southern shore of the lake and the easternmost part of the region would have been deposited. No evidence has been found that could provide a firm, absolute, age of the LGM in this region. However, the radiocarbon ages of the fossil peat found in the basal till of the southern coast of Lake Fagnano indicate maximum limiting age between 53.2–43.4 and 37.0–35.2 cal. years B.P. (Table 1) for the last ice advance. Ongoing palynological studies performed by F. Ponce on this fossil peat, indicate a pre-LGM cold steppe environment.

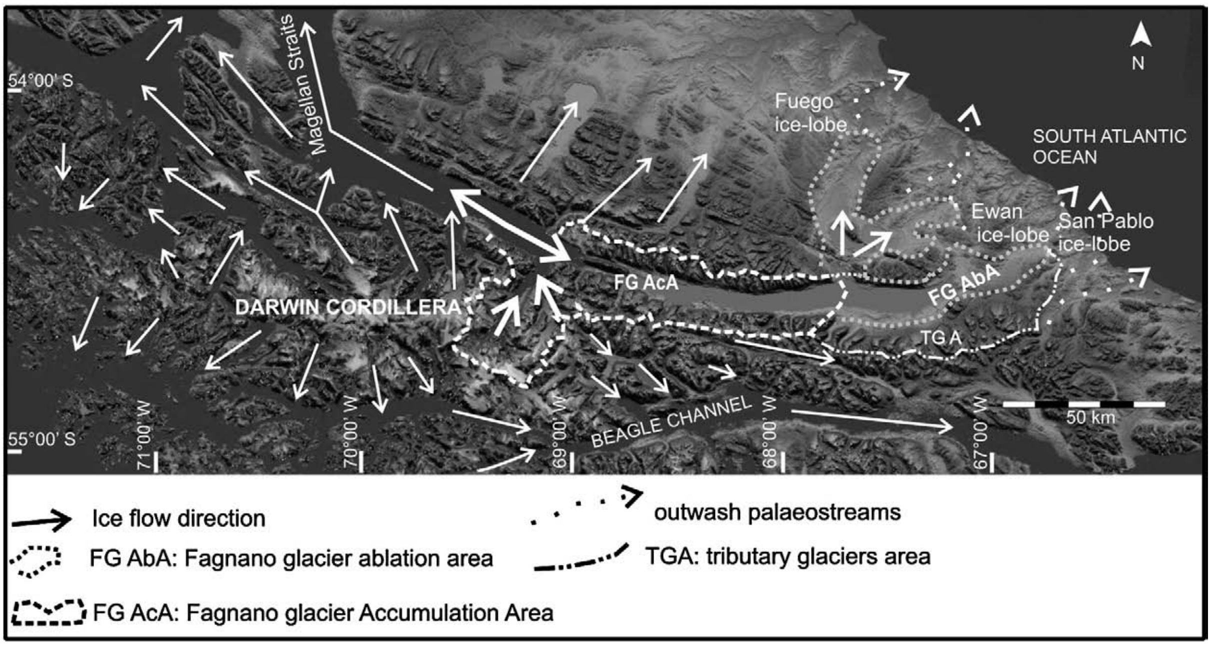


Fig. 8. Fagnano palaeoglacier accumulation (FG AcA) and ablation (FG AbA) areas. The main ice tongue flowed eastwards from the Cordillera Darwin ice-sheet, but several minor alpine-type glaciers merged it from both sides during the LGM. The hanging valley floors indicate merging altitudes between l70 and 380 m a.s.l. In the ablation area, the palaeoglacier jointed laterally to tributary glaciers flowing from the southern mountains (TGA). From the Cordillera Darwin ice-sheet, several outlet glaciers spread in several directions forming the present intricate fjords and marine-channel net. DTM: SRTM S55W067 to S55W072.

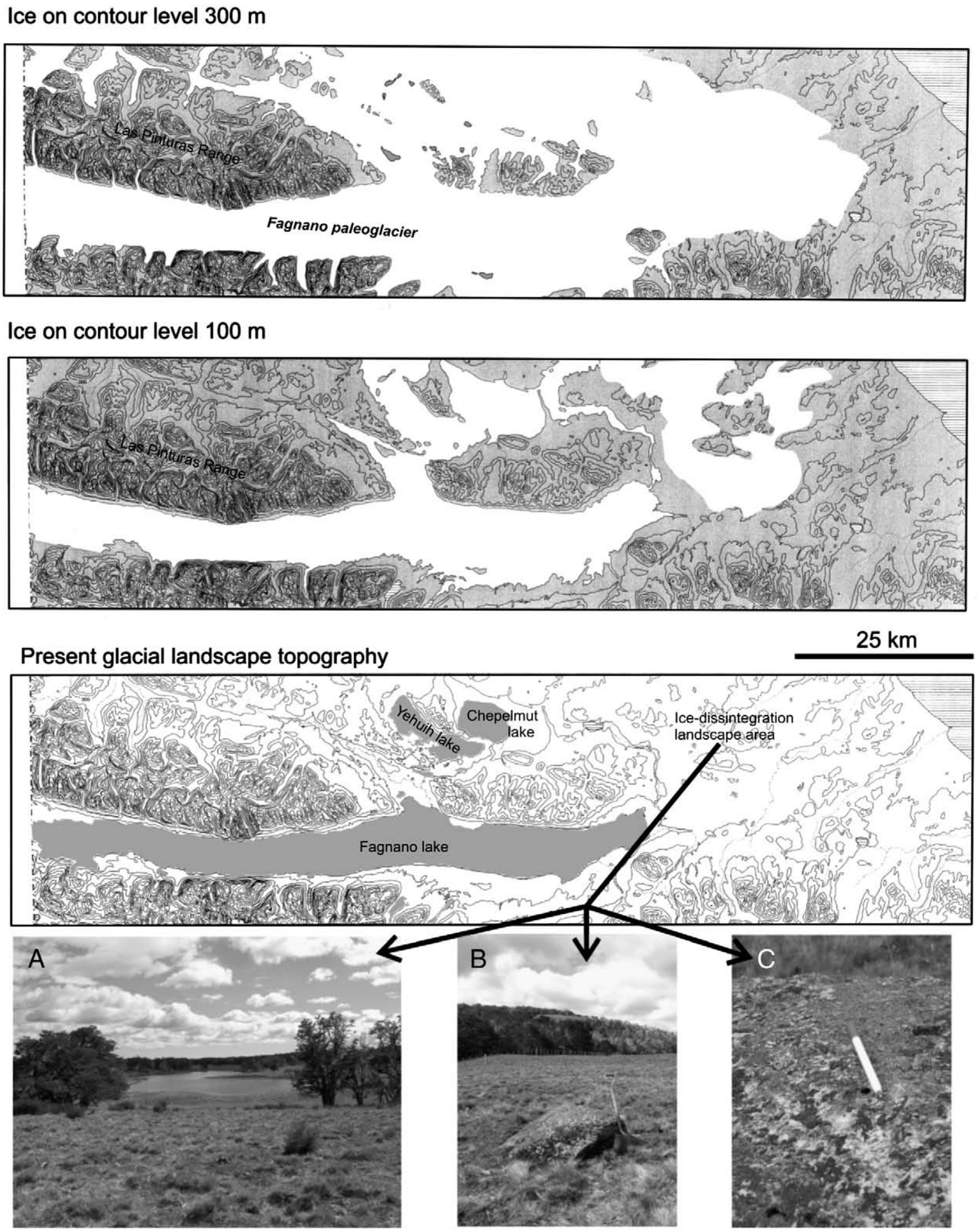


Fig. 9. Ice-covered recession model at 300 m and 100 m a.s.l. in between the Las Pinturas range (600–400 m a.s.l) and its northeastern-most extensions. Dead-ice was generated once the ice covered the surface below the present 100 m a.s.l. contour line. The thinness of the Fagnano palaeoglacier in a hilly landscape generated a hummocky landscape where depressions became ponds and small lakes, eastwards the Tolhuin Moraine Complex (see Fig. 10 for location).

Based upon the currently established chronology in the Magellan Straits and Inútil Bay areas, the LGM is considered to have taken place during "Stage B", between 25.2 and 23.1 cal. ka B.P. (McCulloch et al., 2005). No precise chronological data for the deglaciation are yet available for the area studied. However, the basal ages of the peat bogs San Pablo 1 and La Correntina (Table 2, Fig. 10), indicate a minimum age range for the ice recession between 14.4 and 13.4 cal. ka B.P.

7.2. Recessional phase 1 (Earliest Late Glacial)

This phase is represented by the Tolhuin–Jeu Jepen moraine and the ice-disintegration landscape. Once the critical thickness of 300 m a.s.l. was reached, the Fagnano palaeoglacier would have separated from the main ice body, whose front was then forming the Tolhuin–Jeu Jepen moraine, and from where meltwater was provided to

Table 2
^{14}C ages of basal peat around the Lake Fagnano glacial valley.

Locality	^{14}C age (years B.P.)	95.4% (2σ) cal age range	Laboratory code	Source
TSP San Pablo 1	12,210±80	13,830–14,400	CSIR 8516	Coronato et al. (2005)
TLC La Correntina	11,830±120	13,410–13,940	CSIR 8521	Coronato et al. (2005)
TF Lago Fagnano	8920±70	9860–10,230	CSIR 8515	Coronato et al. (2005)
LF Lago Fagnano	10,800±70	12,710–12,900	Beta 52683	Heusser (2003)
TA Australis	12,366±80	14,050–14,820	AA 65161	This paper
T C Cervetti	12,138±77	13,810–14,160	AA 65171	This paper
TRT Río Turbio	8186±63	8990–9300	AA 65172	This paper
TH Harberton	14,640±260	16,840–18,580	QL-527980	Heusser (1989a)
TCR Caleta Róbalo	12,730±90	14,650–15,360	QL-1685	Heusser (1989b)
TU2 Ushuaia 2	12,430±80	14,130–14,900	Beta 55681	Heusser (1998)
TL Lapataia	10,080±250	11,070–12,660	RL 2001	Rabassa et al. (1990b)

Calibration was made using the Calib 5.0.1 software (Stuiver and Reimer, 1993) and the Intcal 04 curve (Reimer et al., 2004). Reported calibrated ages are shown with a 95.4% (2σ) confidence interval and rounded to the nearest 10 years. Localities are shown in Fig. 10.

generate the main glaciofluvial plain. The basal ages of the peat bogs located in this area (Turbio River and Fagnano Lake peat bogs; Table 2, Fig. 10) indicate an early Holocene age for the beginning of peat accumulation; consequently, these ages do not indicate the minimum absolute age of the ice recession in this area. If the deglaciation process in the Fagnano basin was similar to the Magellan Straits–Inútil Bay model (McCulloch et al., 2005), this phase would be comparable to "Stage C", when glaciers advanced less extensively or receded before 21,700–20,400 cal. years B.P. Ice would have remained as, in all probability, debris-covered, huge dead ice chunks, thus delaying the formation of peat in the depressions for many thousands of years.

7.3. Recessional phase 2 (Late Glacial)

This event is characterized by the Valdéz Moraine (Figs. 5 and 10). The tributary lobes coming from the Lucio López Range, i.e. the Escondido, Santa Laura and Valdéz palaeoglaciers, would have generated the moraine arc which ends at the present lake shore, with a northeastward orientation. This is the narrowest part of the lake and, according to bathymetric information, a submerged hill extends towards the northern margin. In this zone, ice-marginal lakes and meltwater streams existed, which separated the Fagnano palaeoglacier deposits from those of the Valdéz tributary valley. The basal ages of the Terra Australis, Cervetti and Fagnano peat bogs (Table 2, Fig. 10) show that the area was finally free of ice between 14.8 and 12.7 cal. ka. B.P., which coincides with the evidence from the easternmost portion of the study area. In the Beagle Channel, a minimum age between 18.5 and 16.8 cal. ka B.P. (14,640±260 years B.P. according to Heusser, 1989a, 2003) is given by the basal age of the Harberton peat bog (54°52′S; 67°13′W, 25 m a.s.l., Fig. 10). This was considered as a minimum age for the beginning of deglaciation in that glacial area (Rabassa et al., 2000).

Although it is not yet possible to provide absolute dates for ice recession, the basal peat radiocarbon dates (Table 2) allow us to postulate that this area was free of ice during the Late Glacial (12–10 ka B.P.). This phase would be comparable with the third major glacial advance ("Stage D") of the Inútil Bay model (McCulloch et al., 2005), which occurred sometime before 17,500–16,600 cal. years B.P., and has been correlated with a cold event pointed out in the Vostok core (Blunier and Brook, 2001), named as the "Antarctic Cold Reversal" (or ACR, McCulloch et al., 2005), and also recognized farther north along the Andes, in the Chilean Lake District region (Denton et al., 1999).

7.4. Recessional phase 3 (Latest Late Glacial)

This episode is represented by the Martínez moraine. Small moraine remnants along the south coast, located 51 km west of the phase 2 moraine, indicate a fast and sustained recession of the Fagnano palaeoglacier in a westward direction. Although the existence of submerged frontal moraines located eastwards has been inferred from seismic studies (Waldmann et al., 2007), it is uncertain if other glacial recessional phases have been occurred before the Martínez moraine stage. The Fagnano palaeoglacier would have been disconnected from its tributaries because it receded towards their higher valleys. Moreover, the hypothesis of a calving ice front in a proglacial lake may be supported by establishment of the ice, west of the topographic threshold at the Claro River mouth (67°45′W). This threshold would have blocked the meltwater drainage, promoting the formation of a proto-proglacial lake which accelerated the ice front recession towards the west due to calving and wave erosion. To the west, the smaller Martínez and Chilena moraines (the latter, located in the Chilean area) suggest the last depositional stage of the Fagnano palaeoglacier before its definitive recession, once its edge reached the present Azopardo river threshold. There are no absolute ages which permit establishment of this phase in a chronological framework. Following the Inútil Bay scheme (McCulloch et al., 2005), this recessional stage may be assumed as "Stage E", which has a tentative minimum age between 12.5 and 11.7 ka (calibrated

Table 3
Glacial landscape evolution of the lake Fagnano basin.

Palaeoglacier evolution	Geomorphological and sedimentary evidence	Limiting ages (cal. ka B.P.)	Stages	Comparison with Bahía Inútil glacial model (after McCulloch et al. (2005))
Maximum extent	Basal moraines at the lake coast and in San Pablo valley. Till remnants over the San Pablo valley. Lateral moraines eastwards Jeu Jepen Mt. Fagnano fossil peat layers, San Pablo peat bog (TSP).	<36.1>13.9	Last Glacial Maximum	Stage B (ca. 25–23 cal.^{14}C ka B.P.)
Recessional phase 1	Tolhuin–Jeu Jepen moraine. Ice-disintegration landscape area, glaciofluvial plain. Fagnano fossil peat layers, San Pablo peat bog (TSP).	<36.1>13.8	Earliest Late Glacial	Stage C (ca. 21.7–20.4 cal ^{14}C ka B.P.)
Recessional phase 2	Valdéz Moraine Complex (lake bathymetry; till, glaciolacustrine and glaciofluvial deposits). Cervetti peat bog (TC).	>13.8	Late Glacial (Antarctic Cold Reversal?)	Stage D (ca. 17–16.5 cal ^{14}C ka B.P.)
Recessional phase 3	Martínez and Chilena moraines. Submerged moraines?	Not available	Latest Late Glacial (Younger Dryas equivalent?)	Stage C (ca. 12.5–11.7 cal ^{14}C ka B.P.?)

Minimum ages for ice recession are from basal peat radiocarbon ages (see Table 2).

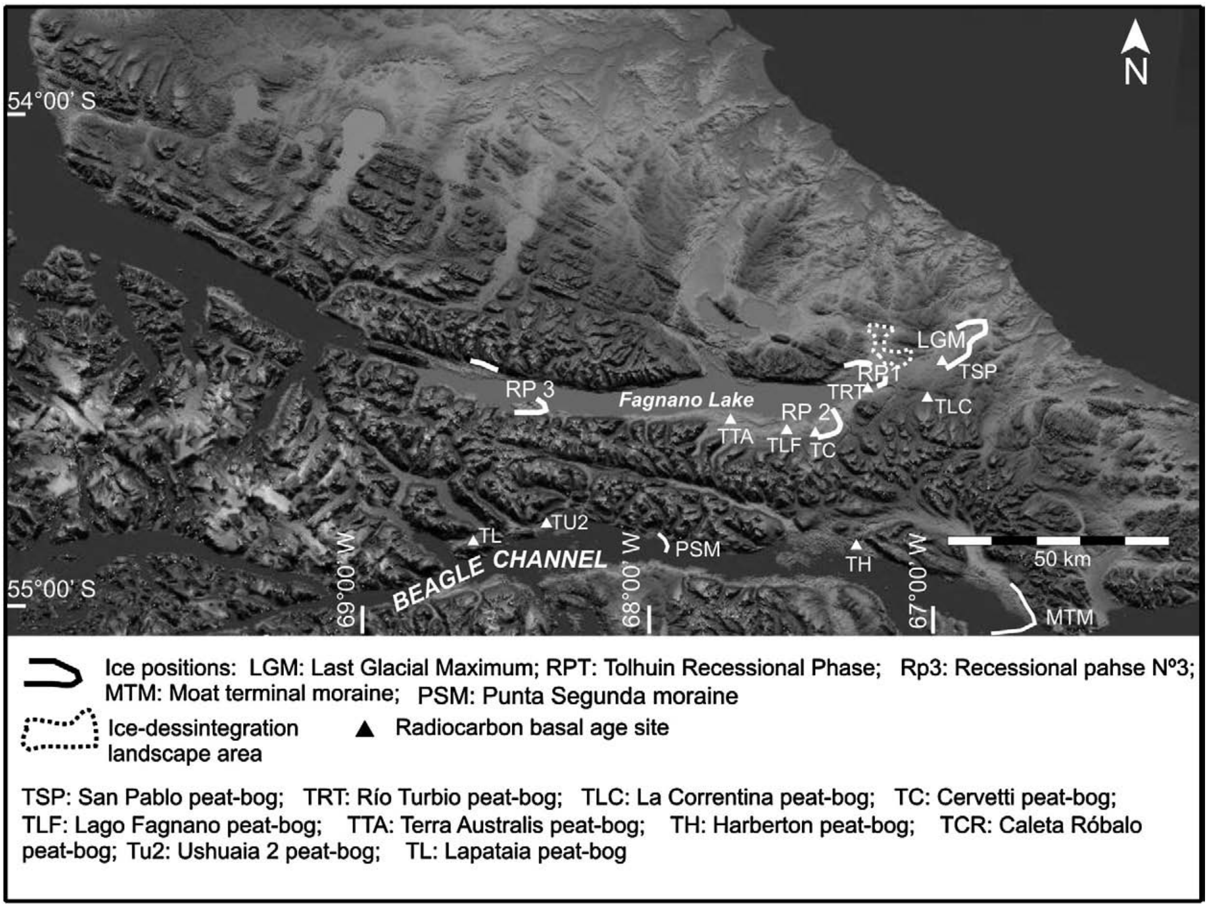


Fig. 10. Ice limits in the Fagnano Lake basin compared with the Beagle Channel palaeoglacier, during the Last Glaciation and ice recession times. Locations of ^{14}C dates of the basal peat shown in Table 2 are indicated. See text for definition of recessional phases 1 to 3. D.T.M SRTM S55W067 to S55W072.

radiocarbon years). This stage represents a short cooling episode, possibly equivalent to the Northern Hemisphere Younger Dryas event.

8. Conclusions

A glacial/deglaciation model during the Upper Pleistocene along the entire Fagnano Lake basin is proposed. New insights into past glacial processes in the region are suggested as follows:

– A glacially-covered surface area of ca. 4000 km^2 and a length of 132 km were calculated for the LGM. This maximum expansion of the ice reached further east than postulated by previous studies. The Fuego, Ewan and San Pablo–Lainez ice lobes spread from the main palaeoglacier towards the north and east. The drainage systems followed the Fuego, Ewan San Pablo and Lainez rivers, all of them ending at the Atlantic coast. A 950 m fall in the ELA during the LGM is estimated.
– The palaeoglacier could be defined as a discharge-type glacier along both sides of Lake Fagnano, from the west to the Las Pinturas Range at the north coast and the Escondido valley at the south coast, and as a piedmont-type glacier joining with the ice lobes coming from valleys to the south. Consequently, an alpine-type landscape was developed in the upper course of the glacier in the west, and a lowland glacial landscape in the lower course in the eastern part of the lake basin.
– Basal till deposits, sometimes including deltaic sequences and forming drumlins or flat ground moraines are located all around the southern and eastern coasts of the lake. Fossil peat layers, included in basal till exposures, suggest an ice advance sometime between 48.3 and 36.1 cal. ka B.P., before the LGM. This could be related to the “Stage A” of the Inútil Bay model (McCulloch et al., 2005).
– Several glacial terminal positions have been recognized along the Fagnano basin. The easternmost one corresponds to the LGM and the others to recessional stages that occurred during the general ice retreat (recessional phases 1 to 3). The knob and kettle landscape between the terminal positions of the LGM and the recessional phase 1 is evidence for an eastern terminal position.
– The absence of surficial frontal moraines along a length of 50 km suggests a rapid ice retreat towards the west, by calving in a proglacial lake or the confinement of the ice lobe into the deep basin, forming moraines which should be presently submerged.
– Although available dating is not abundant, comparisons with other regional models (McCulloch et al., 2005) may provide a tentative framework of glacial chronology in the study area.

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