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Quaternary of Tierra del Fuego, Southernmost South America: an updated review

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Abstract

The Quaternary of Tierra del Fuego is represented by glacial, glaciofluvial, glaciolacustrine, marine and aeolian deposits. Six drift units have been described, the oldest dating from the Late Pliocene: these are, starting from the oldest, the Río Grande, Sierra de los Frailes, Cabo Vírgenes, Punta Delgada, Primera Angostura and Segunda Angostura Drifts. Neoglacial and "Little Ice Age" events are represented in cirques and higher mountain valleys. Marine deposits and raised beaches were formed during Middle Pleistocene, Late Pleistocene and Holocene interglacial stages. After the definitive ice-retreat (10 ka ago) vegetation changed from tundra and cold steppe to subantarctic forest environments. Marine deposits reflect also colder conditions than the present ones. Aeolian processes prevailed in northern Tierra del Fuego, where semiarid conditions and the frequent westerlies favoured the retransportation of finer materials coming from pre-existing deposits. Before the opening of the Magellan Straits, earliest human colonization occurred in northern Tierra del Fuego ca. 11 ka BP, in tundra-like environmental conditions. Pedestrian hunters of camelids and foxes co-existed with Pleistocene fauna that became extinct during Late Glacial–Earliest Holocene times. The steppe area (inland and Atlantic coast) was successively occupied since then until recent times. On the other hand, the Beagle Channel coasts were occupied since 6 ka BP by hunter–gatherer groups adapted to maritime littoral conditions. Finally, the easternmost area of the island was inhabited at least since 1.5 ka BP. The human settlements in these latter areas occurred under environmental conditions similar to the present ones, when the Fuegian forest was definitively established.

1. Introduction

As we did in 1992 when saluting the work of Professor Jan Lundqvist (Stockholm University) in Quaternary studies (Robertsson et al., 1992), we would like to offer in this opportunity the state of advance of our knowledge of the Quaternary of Southernmost South America honoring Professor Nat Rutter, who has distinguished us in the past with his interest in the regional Quaternary problems and who has done important contributions on the interpretation of sea level variations in Tierra del Fuego and Patagonia, among other topics.

This paper updates a previous version (Rabassa et al., 1992) and it includes the results obtained by our research group since such publication until today.

The Quaternary Geology of Tierra del Fuego reveals the development of geological processes that took place at the regional and global scale. Ice ages, ash-fall deposition, lacustrine sedimentation, peat accumulation and relative sea-level variations should be taken into consideration among them. On the other hand, human colonization and consolidation in the use of the space should be analysed, as well as the past climates and palaeoenvironments through the palynological, dendrochronological and malacological data.

Although the first observations on the Fuegian Quaternary were made by Charles Darwin in 1833, when he visited South America on board of the "H.M.S. Beagle",

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the most relevant scientific contributions were published in the first half of this century by Carl Caldenius and Väinö Auer.

Later, several works have been published by many different authors. Since 1986, our research group has studied various problems such as Pleistocene and Holocene geomorphology and glacial stratigraphy, palaeoclimatology, sea-level oscillations, peat-bog and marine sediment palynology, environmental geomorphology and dendrochronology. Radiometric data have contributed to solve when these different processes took place; a summary of radiocarbon datings is shown in Table 1.

2. Geographical setting

The Isla Grande de Tierra del Fuego is the largest of the Fuegian Archipelago islands, located at the southernmost extreme of South America, between lat. 53–55° S and long. 66–74° W (Fig. 1).

Geologically, the island is formed by two tectonic plates separated by the Magellan Fault, where tectonic activity has been widely registered. The South American Plate carries on Middle and Late Tertiary marine sedimentary rocks which extend as high plains, isolated hills and low ranges. On the Scotia Plate the Fuegian Andes occur as an intrusive core, acid lavas and Mesozoic

Table 1
Radiocarbon dating performed by the authors and mentioned in this paper. Localities are cited from west to east along the Beagle Channel and from south to north inland

Localities	Laboratory no.	^{14}C age	Sample
Lapataia Bog	RL-2001	10,080 ± 250	Wood
Lapataia 1	SI-6737	8240 ± 60	Marine shells
Lapataia 2	SI-6738	7260 ± 70	Marine shells
Lapataia 3	SI-6739	5800 ± 65	Marine shells
Lapataia	AECV 397C	7700 ± 130	Peaty sediments
Lago Roca 1	AC-1060	5920 ± 90	Marine shells
Lago Roca 2	NZ-7730	7518 ± 58	Marine shells
Alakush	AC-0937	4440 ± 120	Marine shells
Nacientes Río Ovando	Pta 7573	4160 ± 45	Marine shells
Río Ovando	SI-6735	4425 ± 55	Marine shells
Río Ovando Camping	Pta 7691	7500 ± 80	Marine shells
Bahía Ensenada	Pa-1012	2120 ± 45	Marine shells
Bahía Golondrina	AECV 877 Cc	5460 ± 110	Marine shells
San Salvador	QL-4162	12,100 ± 50	Wood
Punta Pingüinos	RL-1998	10,080 ± 280	Fossil peat
Punta Pingüinos 1	L-1016C	5430 ± 270	Marine shells
Punta Pingüinos 2	L-1016B	1400 ± 300	Marine shells
Monte Gallinero 04	β-72531	1490 ± 90	Wood
Monte Gallinero 21	β-72532	2780 ± 70	Wood
Ushuaia	AECV 876 Cc	5160 ± 130	Marine shells
Pista de Ski	QL-4232	11,750 ± 50	Wood
Break Point	Beta-55681	12,430 ± 80	Wood
Valle Carbajal 41	β-71801	260 ± 60	Wood
Valle Carbajal 34	β-71799	3770 ± 60	Wood
Playa Larga 1	Pa-1017	405 ± 55	Marine shells
Playa Larga 2	Pa-1016	3095 ± 60	Marine shells
Playa Larga 3	Pa-1015	4190 ± 60	Marine shells
Lago Fagnano	AECV 482C	39,560 ± 3980	Fossil peat
Lago Fagnano	GRN-16240	> 58,000	Fossil peat
Punta Paraná	Pta. 7686	4370 ± 70	Marine shells
Bahía Brown	Pa-1011	985 ± 135	Marine shells
Bahía Brown	Pa-1010	2970 ± 70	Marine shells
Cutalataca	Pa-1009	2770 ± 50	Marine shells
Puerto Harberton	QL-4279-80	14,640 ± 260	Wood
Isla Gable	AECV 648 Cc	4790 ± 100	Marine shells
Río Varela	Pta 7581	6290 ± 70	Marine shells
Bahía Aguirre	UTC-5402	10,920 ± 70	Peat
Laguna Arcillosa 1	CSIR-7685	5410 ± 70	Marine shells
Laguna Arcillosa 2	LP-994	4440 ± 60	Marine shells
	CSIR-7682	3690 ± 70	
Chacra Pafoy	LP-1069	320 ± 60	Marine shells
Cabo Domingo	LP-1033	Moderno	Marine shells
Cabo Peñas	CSIR-7684	620 ± 45	Marine shells

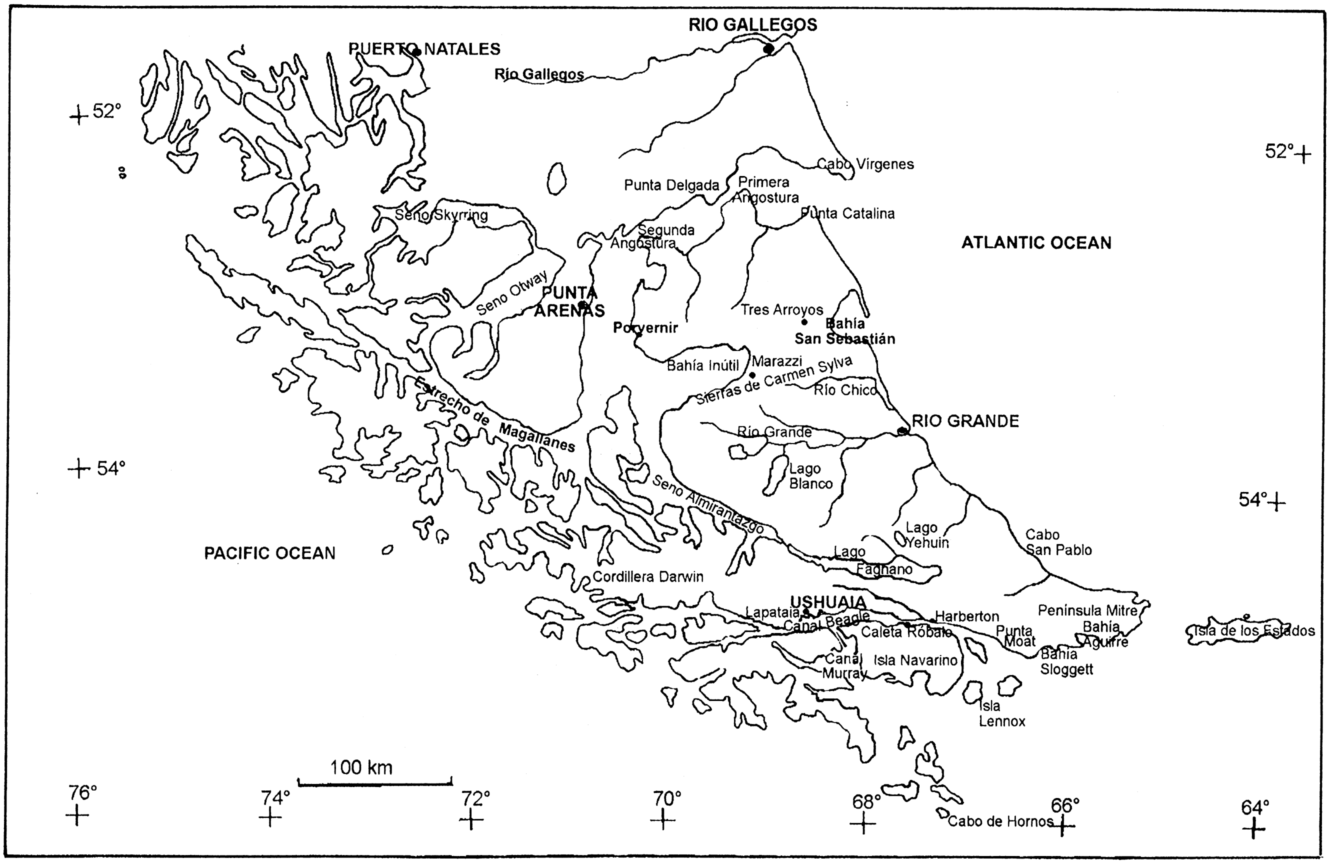


Fig. 1. Location map.

low-grade metamorphic schists. These rocks correspond to the Late Paleozoic to Early–Middle Cretaceous. The southern mountainous region has been intensively eroded by Late Cenozoic glaciers developing deep valleys and rugged mountains. In the summits exposed to the southwestern humid winds, cirque glaciers and snow fields persist, though the western (Chilean) portion of the Fuegian Andes is still covered by an extensive mountain ice sheet, with large outlet glaciers that reach down to sea level.

The regional climate is cold-temperate in the south and temperate-oceanic in the north, with a mean annual temperature of 5°C. Precipitation is of the orographic type, provided by the most frequent winds, coming from the south and southwest. Rainfall show a strong gradient from the southwest, with 550 mm/yr, to the northeast, with less than 300 mm/yr. A west–east precipation gradient is also evident.

The present vegetation corresponds to the Subantarctic Deciduous Forest dominion from sea level to 700 m a.s.l. Above this altitude, the High Andean Desert (Roig, 1998) develops. The presence of moss and grass peat bogs is frequent in all different plant communities.

3. Plio-Pleistocene Ice Ages

Glacier fluctuations seem to reflect climatic changes of the Southern Ocean and Antarctica since Plio-Pleistocene times. Although many authors have been working in the extent of glaciations in Southernmost South America, the unique complete studies were made by Carl C:Zon Caldenius more than six decades ago (Caldenius, 1932). Later studies have intensified the investigation in different areas located along the Patagonian Andes, but none has covered its entire length.

In the Patagonian Andes and also, in the west–east trending Fuegian Andes, a very extensive mountain ice cap was developed during the Late Cenozoic Ice Ages (Rabassa and Clapperton, 1990). According to the morphological and chronostratigraphic evidence of the till deposits, the Patagonian Andes and Fuegian Andes ice sheet would have had a different extent and thickness in each of the known glacier advances, reaching the Andean piedmont zone and the Patagonian tablelands in several opportunities, receding to the summits and high lands during the interglacial periods.

The absolute number of glacier advances that took place in Southernmost South America is still a matter of debate. North of the Magellan Straits at least six major glacier advances have been described based on terminal moraines, whereas in Tierra del Fuego the morphological evidence points to two to five advances, from south to north. Note that the seven drifts (= glaciations) of Cerro del Fraile (Ton-That et al., in press) and other Late Pliocene glacial deposits of the Province of Santa Cruz are not considered in this listing. Table 2 shows the regional chronostratigraphy, as established according to the drift sequences of the Magellan Straits (Meglioli, 1992).

Caldenius (1932) mapped four major glacial episodes, that he named as Initioglacial (the oldest glaciation), Daniglacial, Gotiglacial and Finiglacial, indicating also Post-Finiglacial deposits in various localities. This author recognized the extension of four glacial events in the northern side of the Magellan Straits and only three in the southern coast. He located the eastern limit of the two oldest glaciations beyond the coast, into the present Atlantic submarine platform. According to his interpretation, both glaciations covered the entire island. His field mapping was extremely detailed; unfortunately, his glacial chronology relating them to recessional phases of the Last Glaciation ice-sheet, following a Scandinavian model, was totally inaccurate. Later, Mercer (1976) obtained absolute, radiometric dates that showed that the first Patagonian glaciation took place in the Latest Miocene, extensive glaciation started around 3.5 Ma ago (Middle Pliocene) and various events continued during the Late Pliocene. The Plio-Pleistocene glaciation in Tierra del Fuego was widely extended. Large outlet glaciers of the Cordillera Darwin (2000 m a.s.l.; lat. 55° S–long. 69° W) ice cap flowed north and eastwards to reach the present Atlantic submarine platform (Porter, 1990; Meglioli et al., 1990; Isla and Schnack, 1995), along large, deep valleys known today as the Magellan Straits, Bahía Inútil-Bahía San Sebastián Depression, Lake Fagnano, Carbajal–Tierra Mayor Valley and the Beagle Channel. Several glaciations have been recognized in the northern part of the island (Meglioli et al., 1990) and at least two of them along the Beagle Channel (Rabassa et al., 1990a). The last glaciation is equivalent to the Llanquihue Glaciation of Chile (Porter, 1981; Clapperton, 1993, Wisconsinan of North America, ^{18}O Isotope Stages 2–4).

Although precise ^{14}C dating is still lacking, the Last Glacial Maximum (LGM) in Tierra del Fuego was probably attained between 18 and 20 ka, but ice recession from its maximum position had already started before 14.7 ka (Rabassa et al., 1990b).

Fig. 2 shows the position achieved by the main ice lobes in the different ice expansion times.

3.1. The Magellan Strait lobe

The Magellan Strait lobe was the largest and most impressive glacier which covered this region. It was originated in the Darwin Cordillera (western Tierra del Fuego) and flowed to the north and east towards the Atlantic Ocean. Several disfluent tongues came out in several directions.

At least five glacial advances may be described in both margins of the Magellan Straits, though we will refer only to those of the southern margin, that belongs to the northern extreme of the Isla Grande de Tierra del Fuego (Fig. 2).

The oldest drift in this area (Sierra de los Frailes Glaciation), which is also the most laterally distant of the glacierization axis, extends over the Pampa de Beta high plains (100 m a.s.l.). This is a wide flat surface, with poor fluvial drainage, but which underwent an intense deflation. Although the superficial morphology does not show clear glacial landforms in this area, the till, as seen along the marine cliffs, forms the sedimentary core of the high plains. On this surface, large volcanic clasts show a similar weathering degree as those of the corresponding till unit in the northern coast of the straits. This drift unit occurs as remnants between the Magellan Straits and Bahía Inútil-Bahía San Sebastián Depression lobes, probably representing a piedmont-type glaciation which would have covered the southern end of the continent and a large portion of the Isla Grande de Tierra del Fuego.

The following glacial advance (the Cabo Vírgenes Glaciation) is represented by well-defined morainic arcs, though with subdued, planated summits (100 m a.s.l.) that reach this cape where the drift is defined. The moraines are represented in both margins; the terminal position is not visible, though it is inferred that it may be submerged in the present Atlantic platform, in the eastern entrance of the Straits, or that its moraines have been eroded by the fluvioglacial streams of later glaciations.

An inner morainic belt is developed in both margins of the Magellan Straits until Bahía Posesión (northern margin) and Punta Catalina (southern margin, Fig. 1). These moraines have been interpreted as another glacial advance (Punta Delgada Glaciation), independent of the Cabo Vírgenes Drift, due to the differences in morphology, soil development, periglacial features and weathering rinds of the clasts incorporated in the till.

Towards the west, at Primera Angostura, isolated moraines of eroded summits occur, generally covered by fluvioglacial deposits that extend over the two margins of the straits, representing the glaciation of such name.

The innermost morainic arc is located at the Segunda Angostura, representing the youngest glaciation. Its moraines present little erosion, angular ridges, non-filled depressions, and abundant, slightly weathered metamorphic clasts. Soils have very poor development.

The chronostratigraphic sequence, adjusted to the regional glaciation model as proposed by Meglioli (1992), is presented in Tables 2 and 3.

Clapperton et al. (1995) mapped inner morainic arcs (in relation to the Segunda Angostura moraines)

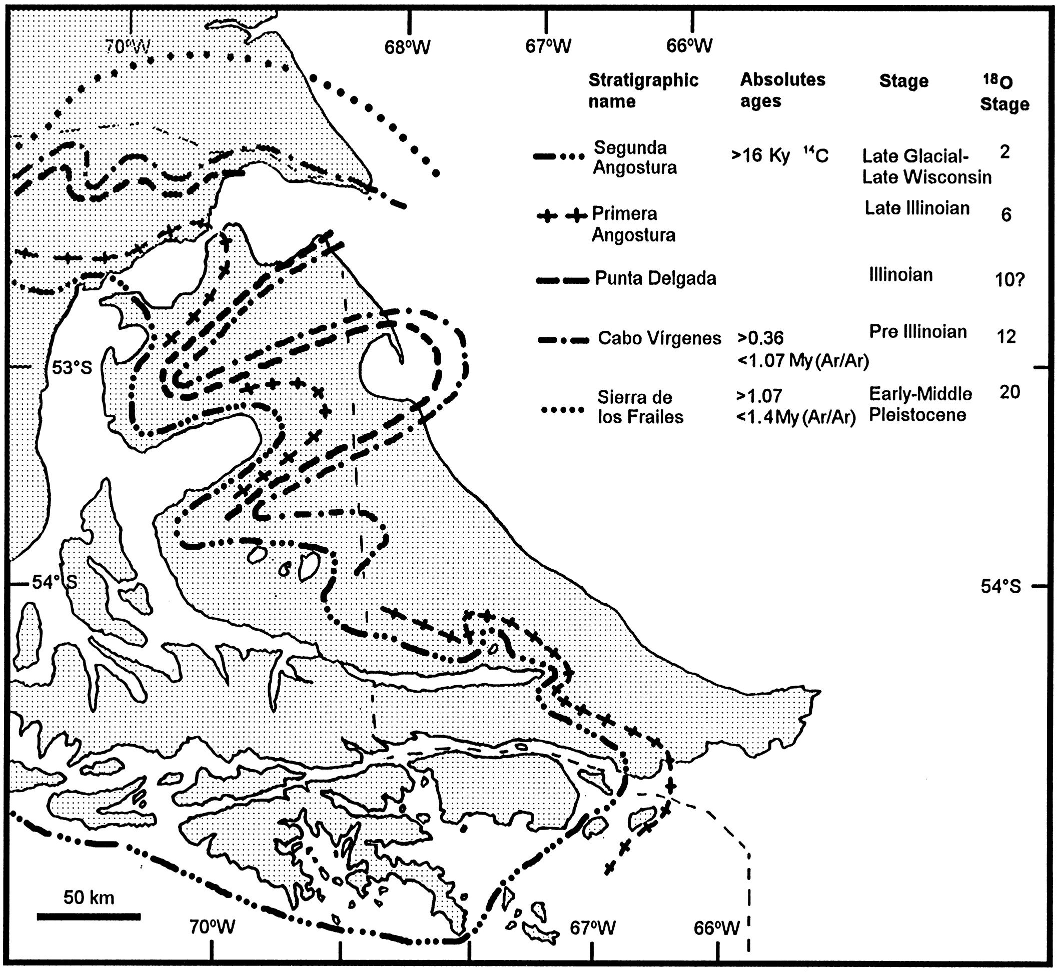


Fig. 2. Extent and chronology of the main glacier lobes in Tierra del Fuego, during the Quaternary.

Table 2
Chrono-stratigraphic chart of ice ages and sea levels in Tierra del Fuego, during the Quarternary[a]

Period		Stage	Stratigraphic name	Absolute ages	^{18}O Stage	Magnetic polarity
Holocene	❄	Little Ice Age (XVII–XIX centuries)	Martial moraines	Not available		
	❄	Middle to Late Holocene	Vinciguerra I, II, III	Not available		
		Early to Late Holocene	Beagle Fm.	405 ± 55 to 8.240 ± 60 ka (^{14}C)		
Latest Pleistocene	❄	Younger Dryas	Caleta Róbalo peat bog	11.8–10.2 ka (^{14}C)		
	❄	Late Glacial	Pista de Ski–Punta Segunda Complex	14,640 ± 260 to 11,780 ± 110 ka (^{14}C)		
Late Pleistocene	❄	Late Wisconsin	Segunda Angostura Drift	> 16 Ka (^{14}C)	2	
Middle Pleistocene		Sangamon	La Sara Fm.	0.36 Ma AAR	5e	
	❄	Late Illinois	Primera Angostura Drift	Not available	6	
	❄	Illinois	Punta Delgada Drift	Not available	10?	
		Marine interglacial	North of Río Grande	Not available	11	
	❄	Pre-Illinois?	Cabo Vírgenes Drift	> 0.36 < 1.07 Ma (Ar/Ar)	12	
Early Pleistocene	❄	Pre-Illinois	Sierra de los Frailes Drift	> 1.07 < 1.4 Ma (Ar/Ar)	20?	
Late Pliocene	❄		Río Grande Drift	> 1.86 < 2.05? Ma (K/Ar)		

[a] ❄: glacial event, ▨: Brunhes, ▧: Matuyama.

between Isla Santa Isabel and Península Juan Mazía. The five mapped morainic arcs have been interpreted as glacial advances that took place during the Last Glacial cycle and the Late Glacial events. A similar model has been suggested by these authors for Bahía Inútil (Fig. 2).

3.2. The Bahía Inútil–Bahía San Sebastián Depression Lobe

This lobe, coming from the main body of the Magellan Straits Glacier and the northern slope of the Darwin Cordillera, reached the Atlantic Ocean Platform and the interior of the Isla Grande de Tierra del Fuego in various opportunities (Fig. 2). The oldest till has been eroded from the flat and high surfaces that form the Pampa de Beta. The type locality of this Drift is located in the marine cliff between Río Cullen and Cabo Espíritu Santo, where it may be observed that the till integrates the high plains and mesetas. This drift correlates with similar units north of the Magellan Straits, but, it is absent south of the Depression instead, although towards the west its existence is inferred by the occurrence of striated clasts and weathered till remnants.

A later glacial advance is evident in both margins of the depression by the Río Cullen moraines, with SW–NE orientation, conforming a wide, ample relief of planated summits and continuous landscape. In the southern margin, the Río Cullen Drift covers the slopes and high plains of the Sierras de Carmen Sylva (350 m a.s.l.), extending towards the Atlantic Ocean in the shape of a flat moraine, with elongated ridges formed by glaciofluvial deposits and an extensive erratic boulder field at Punta Sinaí (Fig. 3). The terminal position of the morainic arc is located 40 km into the sea (Isla and Schnack, 1995).

Towards the interior of the depression and at both of its margins, the San Sebastián moraines are located, forming the core of the mountain ranges of this name in the northern margin, at 60 m a.s.l. Its kettle hole topography represents disintegration ice stages along the highest plains. The type locality is Cabo Nombre, on the Atlantic coast, where a grey, compact till, with abundant fragments of fossil shells coming from the pre-existing sedimentary rocks, has been identified. The frontal position of this moraine is located below the present sea level, at approximately 20 km into the sea (Isla and Schnack, 1995).

In the northern margin and the centre of the Bahía Inútil-San Sebastián Depression, at an elevation of 180 m a.s.l., the moraines that form the Lagunas Secas Drift occur. They are deeply dissected morainic arcs, with small E–W elongated lakes, probably ancient outwash channels, strongly eroded and deepened by deflation.

The heads of the bay and its margins are surrounded by the moraines forming the Bahía Inútil Drift. They are composed of a clayey–silty till, with scarce clast content, glaciolacustrine structures and abundant, large erratic boulders, aligned over the surface.

The presented drift units would correspond to different glacial events, correlated on both sides of the Magellan Straits, based upon the morphological, stratigraphic and chronological distribution.

Table 3 shows the tentative chronostratigraphic location of the different drift units identified along this glaciation lobe.

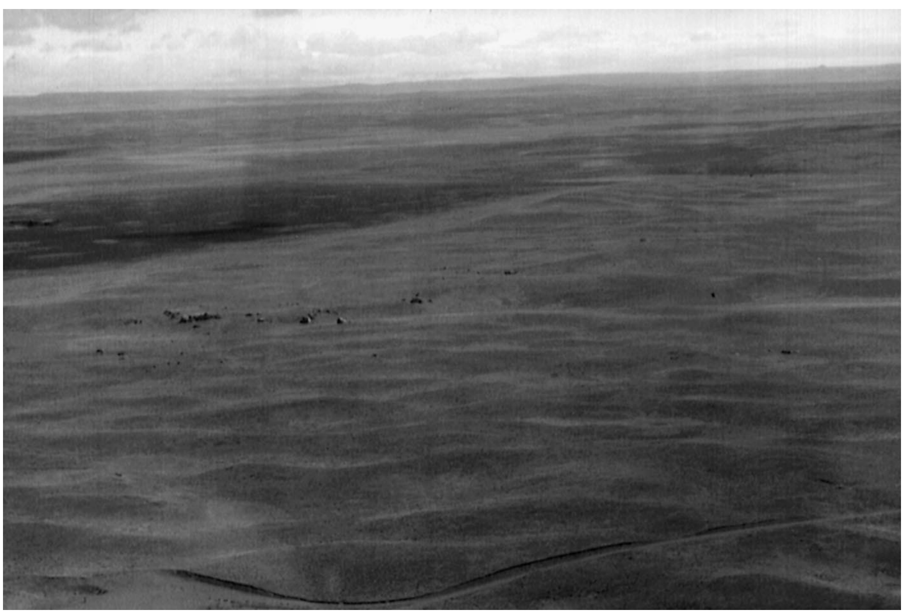


Fig. 3. Flat topography of the Rio Cullen moraine with glaciofluvial elongated ridges (SW–NE) and scattered erratic boulders (view to the NW).

Table 3
Pleistocene glaciations and drift units in Magellan Strait and Tierra del Fuego

Regional model (Magellan Strait lobe)	Bahía Inútil lobe	Lago Fagnano lobe	Beagle Channel lobe
Segunda Angostura Drift	Bahía Inútil Drift	Lago Cami Drift	Moat Drift
Primera Angostura Drift	Lagunas Secas Drift	Lago Chepelmut Drift	Sloggett Drift
Punta Delgada Drift	Sierras de San Sebastián Drift	Río Valdez Drift	—
Cabo Vírgenes Drift	Río Cullen Drift	—	—
Sierra De Los Frailes Drift	Pampa de Beta Drift	—	—
Rio Grande Drift	Río Grande Drift	—	—

3.3. The Lago Fagnano lobe

The Lago Fagnano lobe was built by many different glaciers merging to form a large, outlet valley glacier in the present Seno Almirantazgo, a branch of the Magellan Straits (Fig. 2). An ice thickness of more than 1200 m favoured its eastward spreading, with additional ice supply from local glaciers at Sierra de Beauvoir and Sierra Alvear. Bonarelli (1917), Caldenius (1932), Auer (1956) and Meglioli (1992) suggested that the eastern limit of the ice lies between the Irigoyen and Noguera Ranges, or even along the Atlantic coast. Between the Atlantic shore and the eastern end of the lake, a morainic belt is found, in which Laguna del Pescado (20 km east of the Lago Fagnano) and a number of peat bogs are situated. The belt was mapped by Caldenius (1932) as the outermost extent of the ice in this area, corresponding to the "Gotiglacial" glaciation. The moraines at the eastern end of Lago Fagnano are thought to correspond to glacier oscillations within the lake basin, possibly during the "Finiglacial" glaciation. According to this interpretation, the glacial deposits of Illinoian and Wisconsinan age would be recognized within the Lago Fagnano valley. Later, Meglioli (1992) identified two drift units predating the last glaciation: (i) the Río Valdez drift, along the southern coast of Lake Fagnano, believed to be of Illionian or pre-Illinoian age; and (ii), the Lago Chepelmut drift, along the northern lake coast, which is referred to late Illinoian glaciation. The Lago Cami drift, of Wisconsinan age, is represented by the moraines at the easternmost end of Lago Fagnano.

A proglacial deltaic sequence develops along the eastern lake margin, next to Hostería Kaikén (Bujalesky et al., 1992, 1997). The gravel and lacustrine sequence overlies glacial deposits of the outer morainic belt of Laguna Pescado and underlies a till related to the frontal moraines at the eastern margin of Lago Fagnano. Two peat beds, dated at 39,000 ^{14}C yr BP and $>53,000$ ^{14}C yr BP (Rabassa et al., 1998), interbedded in the upper lacustrine levels, suggest that the delta was formed by deglaciation processes during an Early or Pre-Wisconsinan interstadial, when climate was colder and drier than today. Further studies are underway in order to establish the latest glacial stades and glaciolacustrine sequences of the Lago Fagnano basin, which extend towards the Atlantic coast along the valleys of the San Pablo, Lainez and Irigoyen rivers.

Table 3 shows the tentative chronostratigraphic position of the drift units recognized for the glacial lobe.

3.4. The Beagle Channel lobe

The Beagle Channel is a drowned glacial valley, formerly occupied by a large outlet glacier from the Darwin Cordillera, the Beagle Glacier (Fig. 2). This valley was repeatedly glaciated, at least in two major episodes. Caldenius (1932) described glacial deposits in the Beagle Channel and in the Nueva, Lennox and Navarino islands (Fig. 1). These are the oldest known glacial deposits in the Southern Fuegian Andes: the so-called Lennox Glaciation. Evidence from previous glaciations was certainly eroded by the Beagle Glacier during successive events.

During the oldest recognizable glaciation (Sloggett Glaciation, Illinoian age, ^{18}O Isotopic Stage 6 or older), the ice occupied the entire channel basin, as far east as Bahía Sloggett, depositing the Punta Jesse and Punta Argentina moraines (Rabassa et al., 1996), located to the East of the Last Glaciation moraines or Moat Glaciation (Moat Glaciation, see below). A thick sequence of glaciofluvial gravels along the bay head would represent ice melting episodes of pre-Moat and Moat age. Inner moraines, closer to the mountain front, would represent the maximum development of a local glaciation of Moat age, with local cirque and valley glaciers. Field work has established the existence of a drumlin field beyond the Moat moraines. Whether these drumlins were formed during ^{18}O Isotope Stage 4 or 6 is still a task of future research.

The Last Glaciation is represented by a complex system of terminal moraines at Punta Moat (Fig. 1). This event has been named the Moat Glaciation (Wisconsinan; Rabassa et al., 1990b). In Fig. 4, the position and extent of the mountain ice field during the last glacial maximum is presented.

At least five morainic arcs have been recognized, with very fresh morphology, extending between sea-level and 150–200 m a.s.l. A striking feature is the development of

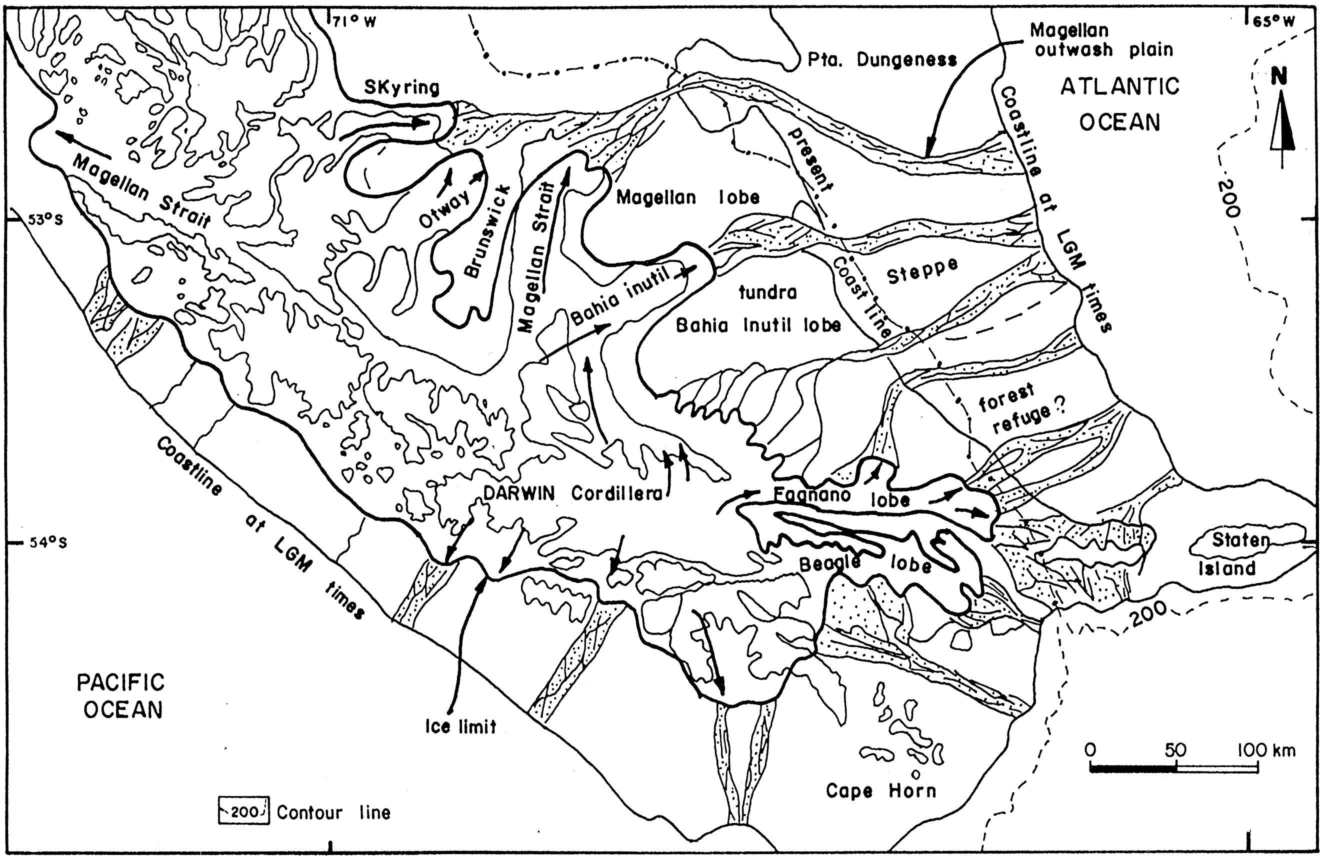


Fig. 4. Extent and position of the mountain ice sheet of southernmost South America during the LGM (after Coronato et al., 1999).

a drumlin field at Isla Gable (Fig. 5; Rabassa et al., 1988, 1990c). Drumlins at Isla Gable are part of a larger field which extends along the Beagle Channel from Estancia Harberton to Bahía Brown, and at Puerto Williams (Chile). Caldenius (1932) and Kranck (1932) misinterpreted these landforms as terminal moraines, but Halle (1910) had already suggested that these landforms could be drumlins or drumlinoid features. The sedimentary structures reveal that these landforms would have been formed during the final phases of the Moat Glaciation. No absolute dating has yet been obtained for the LGM in this area. A minimum radiocarbon age of 14,640 ± 260 yr BP for the glacier retreat from the Punta Moat moraines is given by such a basal ^{14}C date at the Puerto Harberton peat-bog (Heusser, 1989a, b; Rabassa et al., 1990c). The lateral complexes that extend to Estancia Moat, 100–150 m a.s.l., are considered to correspond to the LGM (Caldenius, 1932). At the same time, the upper surface of the Beagle Glacier at Ushuaia (110 km W of Punta Moat, Fig. 1) reached over 1200 m a.s.l., as shown by glacially eroded surfaces and the occurrence of erratics inside the major cirques.

During the Late Glacial (between 16 and 10 ka BP) glacial advances — as the Younger Dryas event between 11 and 10 ka BP — or stabilization periods would have taken place.

A first ice retreat phase probably took place before 14.6 ka BP. A model of a calving glacier front, either in the adjacent sea or a proglacial lake, is favoured. A stabilization phase of 1–2 ka could have occurred when the ice front reached the Isla Gable rise. This is suggested by the basal ^{14}C age of the Caleta Róbalo peat-bog (12,700 ± 90 yr BP), a minimum age for the ice retreat from Isla Gable. During the initial recession period, the glacier thickness decreased at Ushuaia by a minimum of 550 m. Then, the main Beagle Glacier receded from the cirques, allowing their glaciers to expand downslope. Radiocarbon dating of basal peat of 12,060 ± 60 yr BP at Pista de Ski Moraine (300 m a.s.l.) suggests that this retreat phase probably peaked ca. 12 ka, when a relative maximum of arboreal pollen is reached at 11,780 ± 110 yr BP eastwards, at Puerto Harberton (Rabassa et al., 1990b).

Morphological evidence of stabilization occurs also between Punta Segunda (35 km W of Isla Gable) and Arroyo Fernández, building up a 4-stage frontal moraine complex that extends into the Beagle Channel, below present sea level (Fig. 6; Vermeijden, 1997). These moraines develop from 100 m a.s.l. at the mountain sides, in a discontinuous shape, as till pockets packed against erosional bedrock remnants or as low moraines (<75 m a.s.l.) in the city of Ushuaia. Notwithstanding,

Fig. 5. Morphology and sedimentological profile of drumlins from Isla Gable in the Beagle Channel. Intermediate dark sediments correspond to glaciofluvial and glaciolacustrine deposits interbedded between infra and supra basal till units. The landforms are being eroded by runoff and wave action.

Fig. 6. At Punta Segunda locality, northern coast of Beagle Channel, frontal morainic complex develops besides the coast, representing a stabilization phase during the general Beagle Glacier retreat. A succession of Holocene raised beaches is shown at the front.

the basal radiocarbon ages of the Break Point (80 m a.s.l.; 12,430 $\pm$ 80 yr BP) and San Salvador (10 m a.s.l.; 12,100 $\pm$ 50 yr BP) peat bogs in Ushuaia, show that the ice would have already disappeared from these sites allowing the formation of lacustrine environments (Heusser, 1998). The similarity of the peat bog basal ages between 300 and 10 m a.s.l. in Ushuaia suggests that the ice recession from Isla Gable to Ushuaia had taken place in a single phase. Although the pollen profiles show evidence of cooling between 11 and 10 ka and subsequent vegetation changes (McCulloch et al., 1997), perhaps the climatic conditions had been not rigorous enough so as to alter the Beagle Glacier dynamics and to allow the ice stabilization and interrupt the general headward recession. This leads to the redefinition of the chronostratigraphy of the lowest morainic arcs in Ushuaia, previously defined as Ushuaia Drift by Rabassa et al. (1990b). Radiocarbon ages of the terminal moraine complex at Punta Segunda are still needed to adjust the chronology in this region.

The 10 ka glacial retreat was definitive: basal peat layers of Punta Pingüinos in Ushuaia (20 m a.s.l.) and Lapataia (20 km westwards, 18 m a.s.l.) show ages of 10,080 yr BP (Rabassa et al., 1986; Heusser, 1987), a condition observed also for the glaciers that were tributaries to the glaciation axis located in the eastern end — long. 66°W, Bahía Aguirre — where the basal ages of fossil peats reach 10,920 $\pm$ 70 yr BP (UTC-5402).

Table 3 shows the tentative chronostratigraphic position of those drift units identified for this glacial lobe.

3.5. Tributary lobes in the inner valleys

A glacierization model in mountain valleys (Andorra, Cañadón del Toro, Pipo, Olivia and Carbajal-Tierra Mayor), tributaries to the main one (the Beagle Channel) in the Fuegian Andes was proposed (Coronato, 1995a, b; Coronato and Roig, 1999). The transversal and longitudinal valleys of the Fuegian Andes show the effect of Pleistocene glacier erosion. The tributary valleys were occupied by multiple valley glaciers, ranging from 20 to 30 km in length, with smaller, single valley glaciers.

These valleys probably underwent the same sequence of glacial events as the rest of Tierra del Fuego, but such episodes are not represented in the existing geological record. This is probably due to erosion during the Last Glacial Maximum. Moreover, the entire study area was mostly ice covered and well above the equilibrium line altitude (ELA), impeding the formation of lateral moraines. As in all interdependent ice system, the glacial activity in the tributary valleys was controlled by the glaciological behaviour of the main ice stream and regional climatic variations. Several phases which took place between the late Pleistocene and the early Holocene in the Andean valley glaciers have been established: (i) the "Glacial Maximum", (20–18 ka BP), (ii) "Individualization" at decaying of the Moat Glaciation (18–14 ka BP), (iii) "Stabilization" when the ice bodies took their maximum positions during Late Glacial times (14–12 ka. BP), and (iv) "Deglaciation" (10–9 ka BP) when glaciolacustrine environments were dominant into the valley mountains.

The erosive landforms are recognizable in the rocky aretes in which glacial peaks, horns and cirques abound, some of them still bearing ice bodies of significant magnitude. Slopes and rock uprisings of the valley bottoms show evidence of glacier abrasion as roche-moutonnée, lateral and subglacial channels and minor erosion features such as striae. The glacial accumulation landforms are rare, although some depositional features have been modelled in subglacial, supraglacial and marginal ice-environments. The presence of latero-frontal morainic arcs, basal moraines, kame terraces, glacial plains and *Sphagnum* peat bogs has been clearly defined and mapped in the valleys involved, as well as the remains of glacio-lacustrine bodies (Coronato, 1990, 1995a, b). The frontal morainic arcs of the Andorra and Cañadón del Toro valleys are separated by glaciolacustrine deposits that are also present in the Pipo valley, although they have an older age. In that valley, ice-marginal landforms related to the general glacier recession prevail (Coronato, 1993).

The Carbajal–Tierra Mayor Valley is another important glaciation axis in the Fuegian Andes, tributary of the Beagle Channel at Bahía Brown, 50 km east of Ushuaia. During the maximum of the Last Glaciation a trunk glacier established here, flowing from W to E along the tectonic alignment Carbajal–Tierra Mayor–Lasiparshak and minor transversal glaciers, coming from lateral cirques. Due to glacial diffluence, an overflowing ice tongue would have displaced southwards along the Río Olivia Valley down to its confluence with the Beagle Glacier, E of Ushuaia (Coronato and Roig, 1999). The Late Glacial–Early Holocene depositional sequence is presently under study concerning the palynological and palaeoclimatic aspects.

The geomorphological evidence found in the Fuegian Andes indicate that the definitive deglaciation process would have started after 10 ka BP. In the inner valleys, a lacustrine phase has been characterized, shown in lake sedimentary sequences or at the base of the present peat bogs (Coronato, 1991, 1995a, b; Gordillo et al., 1993). The existence of palaeolakes in different relative positions in between confluent glaciers has been dated ca. 10–9 ka BP (Coronato, 1993).

4. Holocene Ice Ages

After 10 ka, ice persisted only as cirque glaciers and small valley glaciers in the Eastern Fuegian Andes, and as remnants of a mountain ice sheet in the Darwin Cordillera (McCulloch et al., 1997; Rabassa et al., 1992).

In the Andorra and Cañadón del Toro valleys, the cirques are dominantly oriented towards the S, SE and SW. The ice occurrence/orientation relationship shows concordant aspects with the hemispheric insolation and the regional climatic conditions, because ice relicts are still present facing towards the SE (45.1%) in the Andorra Valley, to the S (18.5%) in the Cañadón del Toro, to the SW (16.1 and 33.3%) in the Andorra Valley and Cañadón del Toro, respectively (Coronato, 1996).

Recession followed the Late-Glacial maxima and evidence for several Neoglacial readvances are observed in the cirques. Three morainic arcs have been mapped at the Vinciguerra Glacier. The oldest moraines reach 600–650 m a.s.l. and have been largely colonized by the

Fuegian forest. The youngest one lies well above timberline. This moraine was apparently formed during the Little Ice Age; older readvances are represented by complex moraine systems, but all of them remain undated.

The occurrence of ice bodies within the glaciated valleys is also restricted to a minimum elevation of 700–800 m a.s.l. The topography of the glacier valleys shows clearly the events that occurred during the Holocene. These were defined as: Vinciguerra I phase (8.5–5.0 ka) when the glacier receded continuously without evidence of stabilization. The Vinciguerra II phase (5.0 ka) represents the stabilization of the glacier, generating lateral morainic deposits located at 500–540 m a.s.l., and the erosional landforms on the first threshold at 480–600 m a.s.l. The last phase, Vinciguerra III (Little Ice Age, LIA), corresponds to a second stabilization event with two well-developed pulsations, depicted by moraines formed within the present glacial environment (Rabassa et al., 1992).

In the Martial Glacier cirque, at least two morainic levels of Late Glacial age are developed on both valley sides and Late Holocene and Little Ice Age moraines (XVIth to XIXth centuries) occur next to the ice front, the latter still lacking plant colonization.

5. Sea level variations

The analysis of the evolutionary trends along the Fuegian coast during the Quaternary should take into consideration the following aspects:

(a) The Beagle Channel coast is located in the seismotectonically active area of the Fuegian Andes (Scotia Plate domain), but the northeastern Atlantic coast is located in a more stable, extra-Andean environment, developed over an undeformed Mesozoic rocks platform (South American Plate domain).
(b) The Last Maximum Glaciation covered the entire Beagle Channel, whereas the Atlantic coast was ice-free during this epoch.
(c) The Beagle Channel, 5 km wide, presents a microtidal regime and wind waves of short period and low height; it shows an indented rocky coast with development of gravel beaches in bays.
(d) The Atlantic Coast is macrotidal in regime, and exhibits large cliffs carved in glacigenic deposits and Tertiary sediments and extensive gravel beaches. It is affected by long-period swells or significant strong storm waves. The distinctive characteristic of the Holocene coastal deposits at the northeastern Tierra del Fuego (Bahía San Sebastián and Río Chico area) is the presence of regressive-like sequences at protected areas, meanwhile transgressive-like beach facies have developed at exposed areas. The dissimilarities in geomorphological and evolutionary trends of the littoral deposits of the northeastern Atlantic coast mainly arise from the underlying palaeorelief, dipping northwards and carved during the Pleistocene glaciations. The growth of spits and beach ridge plains took place under limited sediment supply. The progressive elongation was sustained by erosion and sediment recycling at the seaward flank, resulting in a significant landward transport. Shallow palaeoembayments infilled (Río Chico), progressive thinning of spits (El Páramo), and cannibalization of spits (El Páramo, Río Chico) indicate a senile stage of evolution.

Pleistocene beaches have not been preserved in the Beagle Channel area due to the erosive effect of the last glaciation. Pleistocene beaches are exposed in the northeastern region of Tierra del Fuego island, from Cabo San Sebastián to Cabo Peñas. Codignotto and Malumián (1981) and Codignotto (1983, 1984) reported radiocarbon dates from shells of La Sara Formation (Codignotto, 1969; lat. 53°30′ S–long. 68°5′ W) as older than 43,000 yr BP. Radiocarbon dating on shells from the 18 m height marine terrace located at Río Grande indicated an age of 29,650 $\pm$ 1450 ^{14}C yr BP (Isla and Selivanov, 1993). Aminoacid racemization techniques applied to shells of La Sara Formation reported D/L ratio of aspartic acid of 0.36 (Rutter et al., 1989). It was considered that this deposit is older than the last glaciation, i.e. the last interglacial stage (Sangamon, Oxygen Isotope Substage 5e; Rutter et al., 1989). Rutter and Meglioli (in Meglioli, 1992) carried out new aminoacid racemization analysis on other valves collected from this formation and concluded that this raised beach is probably Oxygen Isotope Substage 5e. The sediment supply for the formation of these beaches came from the wave reworking of the glaciofluvial deposits of the Chico and Avilés rivers. At the Río Chico-Río Avilés palaeoembayment the inner landward boundary of the maximum Sangamonan transgression would have reached areas located 20 km landwards from the present shoreline, where estuarine facies developed.

Taking into account the Holocene littoral deposits in the northeastern Atlantic coast, at the present alluvial plain of Arroyo La Misión (10 km north of the city of Río Grande), a former Pleistocene glaciofluvial valley carved on Tertiary rocks was filled with sediments of varied origins. The uppermost portion of the sequence recorded the Holocene transgression (Auer, 1959, 1974; Deevey et al., 1959; Markgraf, 1980; Porter et al., 1984). A Holocene lake (at a present level of 5.7 m below high tide level) was flooded by the marine transgression about 9000 ^{14}C yr BP and a tidal flat developed at an altitude of 0.9 m a.h.t.l. at 4000–2000 ^{14}C yr BP (Mörner, 1991).

At Bahía San Sebastián, the Holocene sedimentation took place after the sea-level rise and later stillstand. The initiation of this sequence is not precisely dated but a radiocarbon date indicates a minimum age of 5270 ± 190 yr BP (Vilas et al., 1987; Ferrero et al., 1989; Isla et al., 1991). The 8 km wide sequence of cheniers developed between 5270 and 1080 ^{14}C yr BP, suggests a sea-level fall of 1.8 m (0.363 m/1000 yr; Ferrero et al., 1989; Isla, 1994). This gentle supratidal gradient of Bahía San Sebastián Bay would be partly due to progressive diminishing wave set-up, as a consequence of El Páramo spit growth operating like a natural jetty. Littoral forms have developed under relatively stable eustatic conditions since 5000 yr BP (Bujalesky, 1990, 1998; Bujalesky and González Bonorino, 1990, 1991).

The present Beagle Channel was occupied by a glacial lake at about 9400 ^{14}C yr BP, with a level up to 30 m above the present sea level. The Beagle Channel opened before 8200 ^{14}C yr BP and the lake water was replaced by seawater. The marine environment was fully established along the channel at least by 7900 ^{14}C yr BP (Rabassa et al., 1986). Holocene raised beaches were recognized along the northern Beagle Channel coast (Fig. 6) reaching maximum elevations of nearly 10 m a.s.l with ages of approximately 6000 ^{14}C yr BP (Lago Roca, Bahía Golondrina, Playa Larga; Rabassa et al., 1986; Rabassa, 1987; Gordillo et al., 1992, 1993). The estimated uplift rate is of approximately 1.5–2.0 mm/yr for the last 6000 yr (Rabassa et al., 1986; Rabassa, 1987) and it increased up to 2.9 mm/yr for the last 1000 yr (Gordillo et al., 1993). The youngest terraces at Playa Larga (405 ± 55 ^{14}C yr BP at 1.7 m above the present counterpart) and Bahía Brown (985 ± 135 ^{14}C yr BP at 1.8 m) suggest that the last coseismic uplift movements could have been quite recent, in relation to its average return period and it would have been probably followed by a long quiescent time to allow the stress accumulation according to the prevailing long-term tectonic trend (Gordillo et al., 1992). It is considered that the oldest Holocene coastal deposits may partially be the result of isostatic recovery and the younger levels have been due to recent tectonic uplift (Rabassa et al., 1990a, b; Gordillo et al., 1992, 1993).

Mörner (1987, 1991) pointed out that the Magellan Straits and Beagle Channel coasts were under different uplifting behaviours and the area has not undergone any significant glacioisostatic warping during the Holocene. Mörner (1991) considered, for the regional Holocene eustatic changes, a sea level rise from 9000 to 4000 ^{14}C yr BP to a level only slightly above the present (ranging from 0.0 or 0.5–1.0 m up to 1–2 m), but he argued that these higher levels seems to be the effects of storm waves rather than tidal flat levels. One of the assumptions on which Mörner (1987, 1991) sustained his conclusion is the incorrect affirmation of the absence of elevated Holocene terraces and the general horizontality along the Beagle Channel. Its coast is characterized by a terrace system and at least three levels have been established at 8–10, 4–6 and 1.5–3 m (Gordillo et al., 1992). Table 4 summarizes the localities along Beagle Channel (west to east) where raised beach deposits and fauna were analysed.

The comparison of the Holocene raised beaches between the northern Atlantic coast of Tierra del Fuego (La Misión: Auer, 1959, 1974; Mörner, 1991; Bahía San Sebastián: Ferrero et al., 1989) and the northwestern coast of Beagle Channel (Punta Pingüinos: Auer, 1974; Bahía Golondrina; Playa Larga: Gordillo et al., 1992) indicate differential tectonic uplifting rates of 1.2 ± 0.2 mm/yr for the last 7760 ^{14}C yr BP, 1.3 ± 0.3 mm/yr for the last 5400 ^{14}C yr BP and 1.2 ± 1 mm/yr for the period comprised between 7760 and 5400 ^{14}C yr BP, respectively.

6. Palaeoenvironments

6.1. Terrestrial environments

6.1.1. Pollen analysis

Late Glacial climate, according to the pollen stratigraphy at Lapataia, Ushuaia, Puerto Harberton (Fig. 7), Caleta Róbalo (Heusser, 1989a) and Bahía Moat (Heusser, 1995) profiles, along the Beagle Channel, was apparently warmer between 14.6–13 ka and between 11.7–11.16 ka BP and became cooler earlier than 13 ka until 12 ka, and from around 11.16 until 10.2 ka. The last cooling indicates the development of a Younger Dryas period in this part of the Southern Hemisphere, where the estimated summer temperature was $< 3°C$ lower than the present at Ushuaia (Heusser and Rabassa, 1987; Heusser, 1998).

The formation of the *Nothofagus* woodland under the postglacial climatic amelioration started towards 10 ka BP in southern Tierra del Fuego, but it was not until 5000 yr BP that the closed forest developed, under wetter and cooler conditions (Heusser, 1989b), when the peat bogs incremented their sedimentation rate (Rabassa et al., 1989). In the northern slope of the Fuegian Andes the woodland stabilization took place around 8000 yr BP, but only after 5000 yr BP the forest established with open spaces until it reached a more recent, definitive expansion, as shown in the pollen profile of Cabo San Pablo (Fig. 7). In this contact zone between the deciduous forest and the steppe, the open forest developed towards ca. 3000 yr BP, although with permanent invasion of steppe pastures. The definitive expansion of the forest occurred towards 900 yr BP, becoming more intense after 300 yr BP due to the increasing humidity coming from the Southern Pacific and the weakening of the subtropical anticyclonic cells (Heusser and Rabassa, 1995).

6.1.2. Dendrochronology

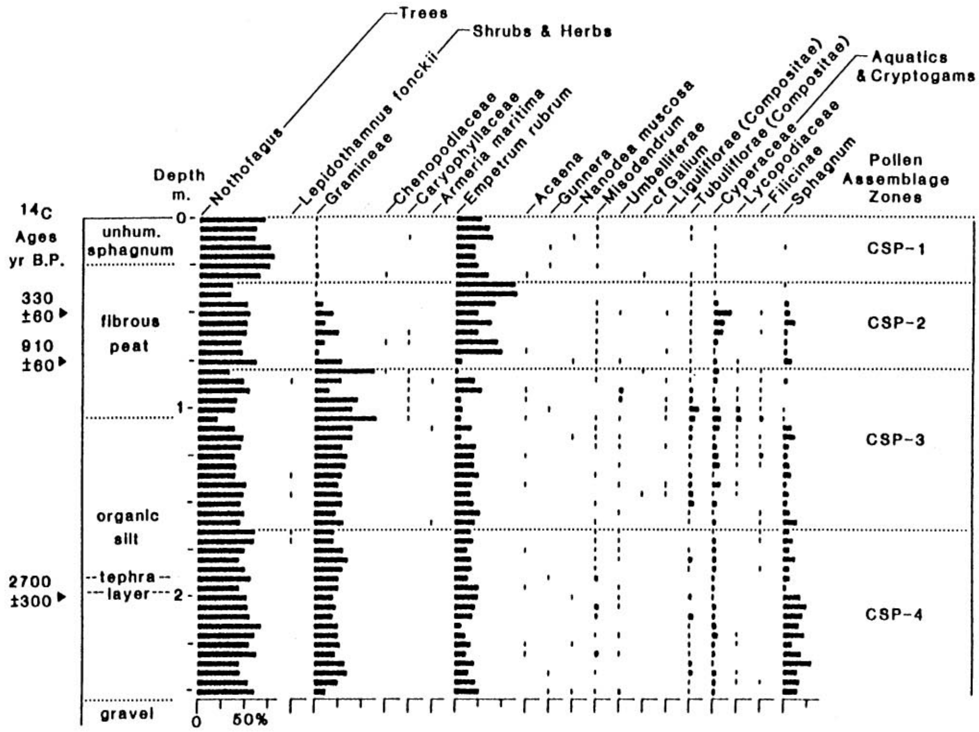
In Tierra del Fuego tree-ring chronologies have been used to determine the seasonal variation of air temperature over terrestrial and marine surfaces, precipitation and indexes of atmospheric pressure at sea level

Table 4
Radiometric dates from Holocene littoral deposits along the Beagle Channel[a]

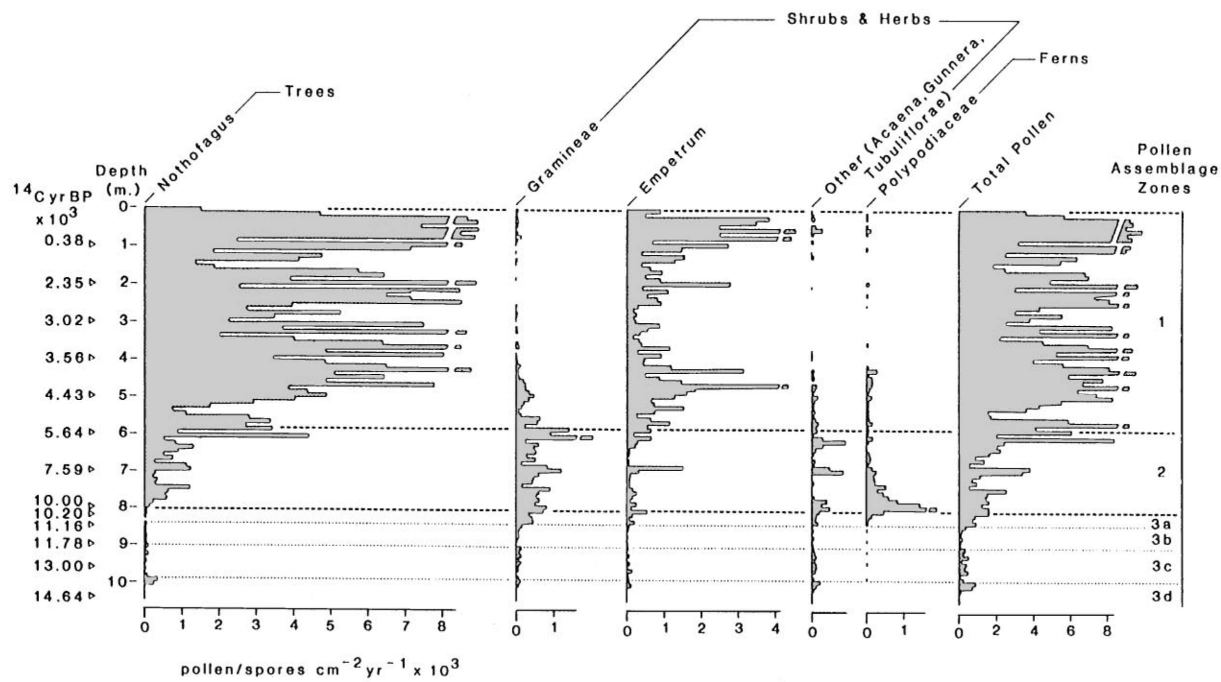
68°34′ W ← 54°53′ S → 67°17′ W

Localities / m a.s.l.	Lago Roca-Lapataia	Bahía Ensenada	B. Golondrina	Punta Pingüinos	Ushuaia	Playa Larga	Punta Paraná	Bahía Brown	Isla Gable Cutalataca	Navarino	Río Varela
10			5460 ± 110 (BG)								
9											
8	5920 ± 90 (LR1)			5430 ± 270 (PP1)	5160 ± 130 (Us)						
7											
6							4370 ± 70 (PPA1)				
5	4440 ± 120 (Ak)					4190 ± 60 (PL3)			4790 ± 100 (IG)		
4	3860 ± 75 (IS)										
3	7518 ± 58 (LR2) ~ 1425 ± 55 (RO) 7500 ± 80 (ROC) ~ 4160 ± 45 (NRO)					3095 ± 60 (PL2)		2970 ± 70 (BB1)		4600 ± 30 (PG)	
2		2120 ± 45 (BE)		1400 ± 300 (PP2)							
1	5800 ± 65 (L3) 7260 ± 70 (L2) ~ 8240 ± 60 (L1) ~					405 ± 55 (PL1)			2770 ± 50 (C)		
0										1470 ± 30 (PPB)	
− 1.26											6290 ± 70 (RV) ~

[a]Beach deposits; ~ : estuarine deposits. Lago Roca; [Abbrv.] Ak: Alakush; IS: isla Salmón; ROC: Río Ovando Camping; NRO: Nacientes Río Ovando; L: Lapatia; BE: Bahía Ensenada; BG: Bahía Golondrina; PP: Punta Pingüinos; Us: Ushuaia; PL: Playa Larga; PPA: Punta Paraná; BB: Bahía Brown; IG: Isla Gable; C: Cutalataca; PG: Punta Gusano; PPB: Punta Piedra Buena; RV: Río Verla.



Cabo San Pablo (Atlantic coast, forest - steppe transition zone)



Puerto Harberton (Beagle Channel, subantarctic deciduous forest)

Fig. 7. Palynological profiles from Cabo San Pablo and Puerto Harberton localities of northern and southern Tierra del Fuego, respectively (after Heusser, 1989a, Heusser and Rabassa, 1995). See Fig. 1 for location.

during the last centuries (Boninsegna et al., 1989; Boninsegna, 1992; D'Arrigo et al., 1996; Roig et al., 1997; Villalba et al., 1997).

The analysis of principal components on chronologies of two species of *Nothofagus*, *N. pumilio* and *N. betuloides* allowed the identification of three regions in Tierra del

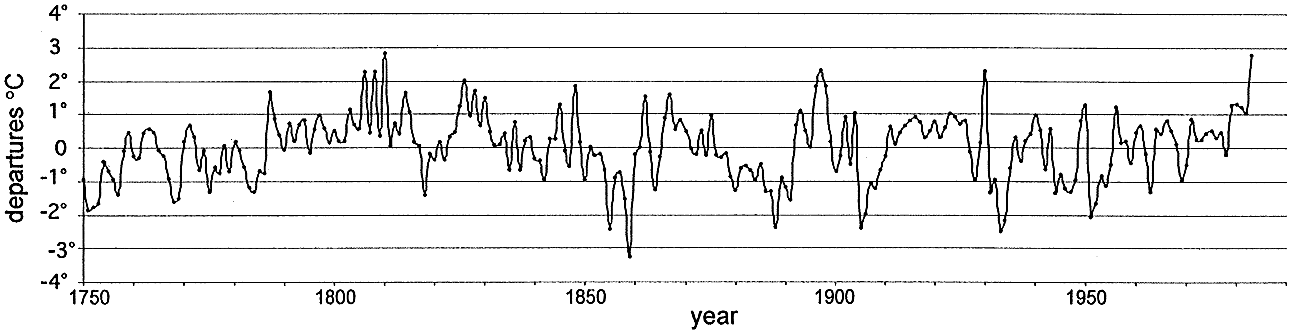


Fig. 8. Full reconstructed summer temperatures (departures) for Tierra del Fuego.

Fuego (Boninsegna et al., 1989). Regions 1 and 2 include southern Isla Grande de Tierra del Fuego and Isla de los Estados. In these regions there is a strong control of summer temperature on the tree-ring growth (Fig. 8), as evidenced by correlation and response function analyses. Third region shows the limitant effect of soil humidity north of the Fuegian Andes.

In earlier investigations, Boninsegna et al. (1989) developed a preliminary reconstruction of summer (November–February) temperatures for Ushuaia city, based on a sub-set of *Nothofagus* chronologies from Regions 1 and 2, and dating back to the middle 1700s. More recently, D'Arrigo et al. (1996) explored the relationship between Fuegian chronologies and a $5 \times 5^{\circ}$ grid of regional-scale land/marine temperatures, showing a strong correlation of temperature variability during the warm-season months (November–March) with tree growth. In this model, the tree-ring data explained 38% of the variance in warm-season (November–March) temperatures for this grid, a fact that emphasize the importance of Fuegian tree-ring data in regional-scale climatic reconstructions for southern South America and adjacent ocean areas. Fig. 9 shows the actual and estimated warm-season averaged grid temperature values for the common period from 1910 to 1984.

Villalba et al. (1997) explored the simultaneous relationship between the Fuegian and New Zealand chronologies with November–February (summer) mean sea-level pressure (MSLP) data of the South American sector of the Southern Ocean and reconstruct the dominant modes in sea-level pressure fluctuations around Antarctica for the last two centuries. The teleconnections in MSLP on opposite sides of Antarctica shows that during 1930s and after 1950 the MSLP pressure decrease, and experienced a positive trend since the mid-1960s. Other above-average MSLP periods appeared during the 1820s, 1860s and 1890s. These persistent long-term trends are in agreement with those registered in other proxy records from the subantarctic domain (Peel et al., 1996; Aristarain et al., 1990; Nicholls and Paren, 1993).

One of the most ambitious challenges in subantarctic dendroclimatology is to extend back the living chronologies several centuries to millenia. The extension of chronologies, obtained in the Southern Patagonian Forests, rarely extend over 300 yr; notwithstanding, it is possible to obtain millenary chronologies by means of wood preserved in peat bog environments, which had been quoted by Bonarelli (1917) and Auer (1965), and more recently, by Roig et al. (1995). These findings corroborate the potential of this region to develop longer chronologies by means of using these subfossil woods (Roig et al., 1996, 1997).

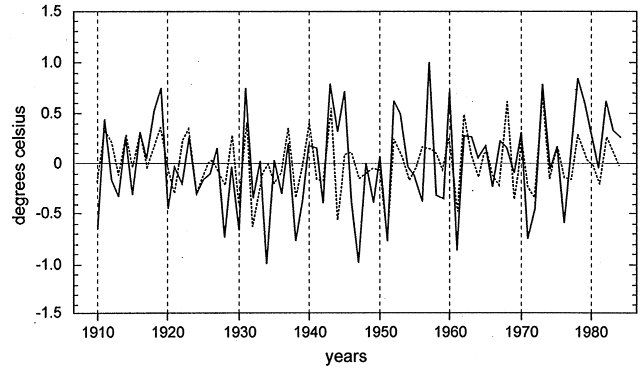


Fig. 9. Actual (solid line) and estimated (dashed line) for summer temperatures (November–March) in Tierra del Fuego, reconstructed from *Nothofagus* tree-ring width chronologies.

The obtention of buried wood from the Valle Carbajal and Monte Gallinero sites have allowed to form a collection of over 400 subfossil trunks, including some of them found in vertical position, with a range of radiocarbon ages comprised between 260 ± 60 and 3770 ± 60 yr BP and from 1490 ± 90 to 2780 ± 70 yr BP, respectively (Roig et al., 1996). The ^{14}C ages show a direct relationship with the depth at which the logs were found. The first floating chronology, built on the basis of the Valle Carbajal samples, extends, although still in a discontinuous manner, determined periods during the last 1500 calendar years (Roig et al., 1996, Fig. 10).

6.2. Marine palaeocommunities

6.2.1. Plankton and pollen analysis

Bahía Lapataia (lat. 54°50′ S, long. 68°34′ W) is a fjord-like embayment located 20 km west of Ushuaia

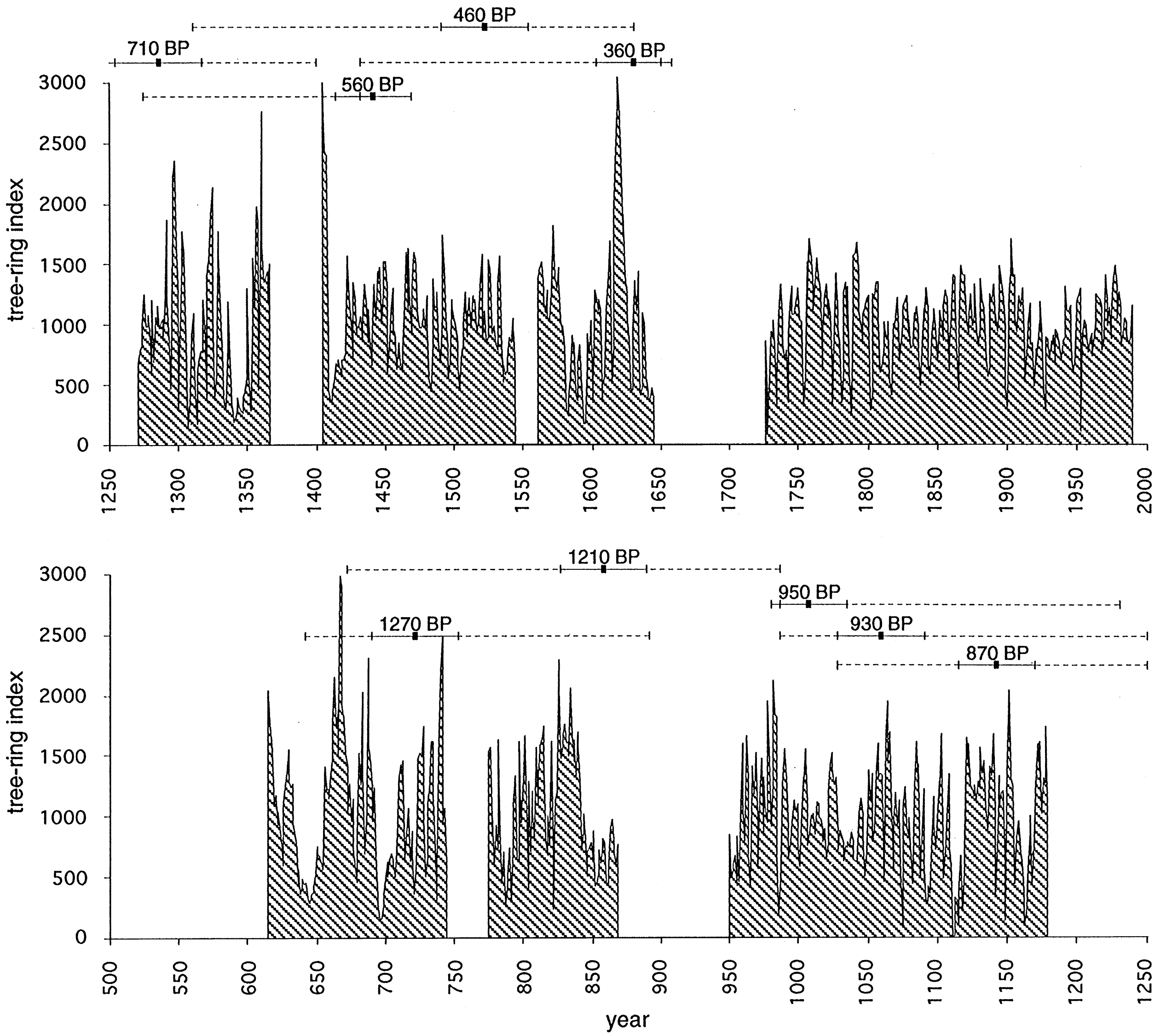


Fig. 10. Floating index tree-ring width chronology of the Carbajal Valley (Tierra del Fuego) covering almost the last 1400 years. The relative position of each record is based on the available radiocarbon ages. The solid line corresponds to ^{14}C age (yr BP $\pm$ 1δ), and the broken line corresponds to the range of age according to the Northern Hemisphere calibration curve. The portion of the curve at the right top corresponds to the modern chronology (from Roig et al., 1996).

(Fig. 11), where a fossil palynological section (1.04 m deep) was sampled from a Holocene marine terrace. A marine unit is recognized between depths of 0.71 and 0.24 m (Borromei et al., 1997).

This is a greenish sandy clay with two levels of marine shells. The lower level of marine shell has a ^{14}C age of 8240 $\pm$ 60 yr BP and the upper level of marine deposits yielded a ^{14}C age of 7260 $\pm$ 70 yr BP. The former age is slightly older than a date from underlying peaty, organic sediments (7700 $\pm$ 130 yr BP), likely due to the reservoir effect (630 ^{14}C yr according to Albero et al., 1987; a minimum of 540 ^{14}C yr according to our estimations; Rabassa et al., 1986, 1992).

The palynological analysis, mainly based on palaeomicroplankton abundance and diversity allowed to evaluate palaeoclimatic and palaeoenvironmental conditions during the Holocene marine transgression (Fig. 12). Due to the characteristics of the studied sediments under the influence of glacioeustatic factors and neotectonic movements, the palaeomicroplankton assemblages would be influenced by reworking.

The abundance of terrestrial elements (pollen and spores) over the palaeomicroplankton, and the acritarchs over the dinoflagellate cysts, would indicate nearshore environments (Batten, 1996).

Two relative higher sea level are registered in this unit. One of them, between 7700 $\pm$ 130 and 7260 $\pm$ 70 yr BP, has the greatest abundance of acritarchs, represented by *Domasiella* sp., together with abundance of gonyaulacoid dinoflagellate cysts. Stancliffe and Matsuoka (1991) have

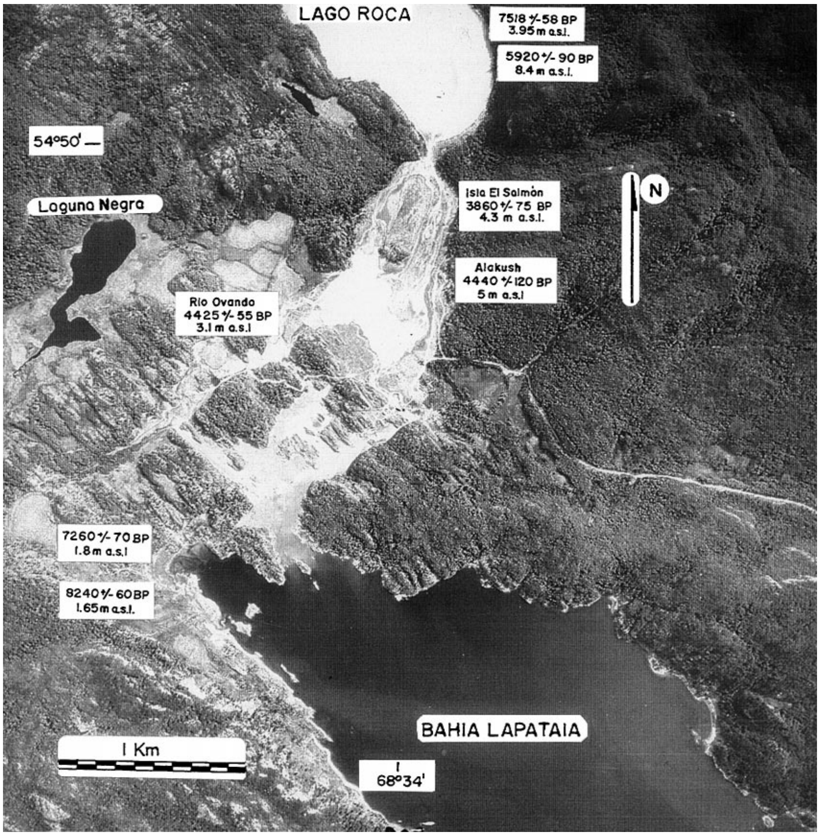


Fig. 11. Lago Roca-Lapataia palaeofjord aerial view. Phases of the Holocene marine transgression are indicated with ^{14}C dates from marine shells (after Bujalesky, 1998).

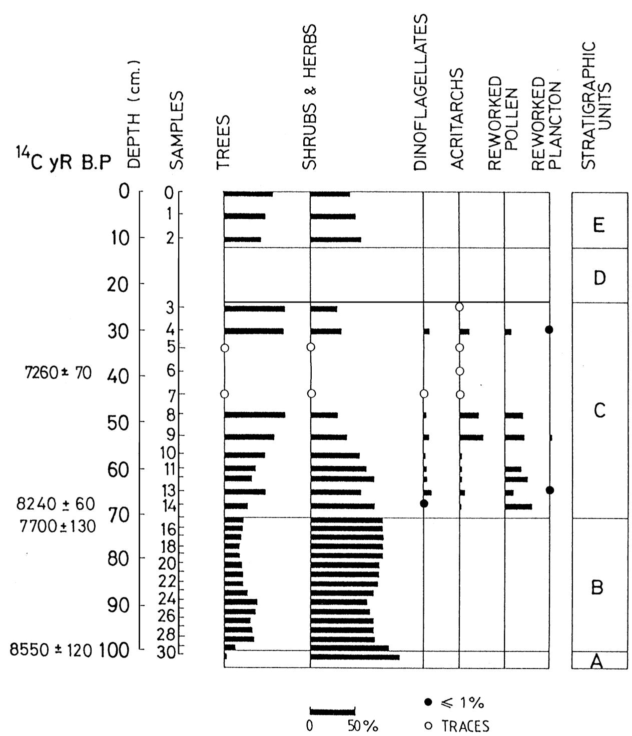


Fig. 12. Pollen and paleoplankton analyses from Lapataia marine deposits.

recorded *Domasiella* sp. in sediments of the Optimum Climatic in the middle Holocene from the northwest shore of Japan. Gonyaulacoids are usually favoured by stratified warm surface water, in contrast to peridinioids which are associated with upwelling resulting in colder, more nutrient-rich waters (Lewis et al., 1990). *Pyxidinopsis psilata* (*Pyxidinopsis* sp. in this work, resembles this species) recorded from early Holocene sediments of the Black Sea suggests low-salinity fresh-water to brackish-water sediments (Wall et al., 1973). Foraminiferal test linings abundant at this level suggest variable salinity estuarine marshes (Batten, 1996).

The palaeomicroplankton assemblage could indicate neritic conditions, cool-temperate sea temperature and low salinity to brackish waters for this marine episode.

Another relative higher sea level is registered, at an age earlier than 7260 $\pm$ 70 yr BP, with greatest abundance of *Halodinium minor*, together with gonyaulacoid dinoflagellate cysts. *Halodinium minor* have been recorded in lower Holocene and recent sediments of the Hudson Bay and the estuary and gulf of the St. Lawrence river, Quebec. *Halodinium* sp. also were reported from modern sediments in estuarines entering the Beaufort Sea and a Baffin Bay fiord (Head, 1993). This taxon, a common Quaternary acritarch that typically occurs in large number at Arctic estuaries (Mudie and Harland, 1996), suggests a strong fluvial influence (Mudie, 1992) and associations with transitional environments (Head, 1993).

The palaeomicroplankton assemblage would indicate unstable conditions, variable salinity, cooler sea-water temperature and freshwater influxes into the basin during this marine episode.

The record of continental elements (*Botryococcus*, Chlorophyceae and fungal spores) along this unit, would also indicate freshwater influxes into the basin (Batten, 1996; Mudie and Harland, 1996). The presence of probable planktonic crustacean eggs could indicate neritic environments with nutrient supply (van Waveren, 1992).

6.2.2. Malacological analysis

Quaternary marine molluscs from the Magellan region are of great interdisciplinary interest. Firstly, Late Quaternary molluscs are the most common macrofossils observed in raised marine deposits from this region (Gordillo, 1992). Secondly, their living counterparts represent a significant proportion of the benthos in the area (Arntz et al., 1996). The third reason is that this region lies between the Atlantic and the Pacific oceans, being a critical area for the interpretation of faunal distribution and palaeodistribution. The final goal focused on molluscs is the reconstruction of the evolution of the Beagle Channel faunas during the Quaternary with particular reference to palaeoecologic and palaeoclimatic analysis, in the more general context of the "global change" phenomenon.

A combination of neontological, palaeontological and sedimentological data was used here to reconstruct the palaeoecology of macrofossil assemblages, especially along the Beagle Channel. A total of 47 mollusc species were recorded. Eleven taxa are mentioned for the first time for the Quaternary of Argentina, besides 10 more taxa, first time mentioned for Tierra del Fuego (Gordillo, 1993; unpublished data). Despite the obvious bias in preservation due to taphonomic processes these assemblages retain useful information on the life habit and habitat of the paleocommunities from which they are derived. Taphonomic analysis (i.e. ratio of opposite valves, fragmentation, orientation, shell surface and size range) and comparison of the species composition of Holocene macrofaunal assemblages with modern counterparts and their habits indicate that the fossil faunas most commonly represent autochthonous and para-autochthonous assemblages which inhabited cold-temperate near-shore environments (Gordillo, 1999). Special attention was given to biotic interactions revealed by macroborings in mollusc shells collected from these deposits (Gordillo, 1994, 1998a), with complementary data obtained from modern specimens under laboratory conditions (Gordillo and Amuchástegui, 1998). Finally, morphometric analysis on *Hiatella solida* (Sow.) specimens show that the shell size of this taxa can be used with caution to estimate palaeotemperatures (Gordillo, 1995). After all, postglacial succesion of faunas is not evidenced from our data, suggesting an apparent stability of modern marine communities back through periods of several thousand years (Gordillo, 1999). This stability during the Holocene was also observed along the Argentinian and Uruguayan coast, although minor displacements of the distribution range of some taxa are produced by minor temperature fluctuations during the Holocene (Gordillo, 1998b).

7. The Peopling

The peopling of Southernmost South America occurred during the end of the Late Glacial (16 and 10 ka BP) times, as it has been demonstrated in several sites of continental Patagonia (Coronato et al., 1999; Salemme and Miotti, 1999; Borrero, 1999) and a single site in northern Tierra del Fuego. Probably, most of these environments where colonized during and after the Younger Dryas event — between 11 and 10 ka BP — probably under the progressive conditions of climatic amelioration.

From a biological viewpoint, the Fuegian population would have been the result of different groups originated in regions to the east and the west of the Andean Cordillera, farther north; then, the differentiation from this previous group, not so remote but genetically homogeneous would have succeeded in a region relatively close to Tierra del Fuego Island, and then, they evolved locally (Cocilovo and Guichón, 1985–1986).

Human colonization in Tierra del Fuego has been proved ca. 11,000 yr ago, when a group of hunters occupied the NW portion of the island, as shown by cultural and faunal remains found in the Tres Arroyos site (Massone, 1987; Massone et al., 1998, Table 5). By that time, the Isla Grande of Tierra del Fuego was yet part of the continent.

It is the only Fuegian site where some extinct species — among the associated fauna — have been identified, like the American horse (*Hippidion* sp.), ground sloth (*Mylodon* sp.), a small camelid (*Lama gracilis*) and a species of canid (*Dusicyon avus*), as well as *Lama guanicoe*. These hunters reached the island from southernmost Patagonia, before the definitive retreat of the glaciers, and became isolated from their original populations in the continent after the opening of the Magellan Straits. An open steppe-environment is indicated by the faunal species recorded as well as the Bahía Inútil profile, which shows a high proportion of steppe elements (Heusser, 1994a); this could have been the space where these colonizers moved.

Other sources proving the early peopling in Isla Grande of Tierra del Fuego seem to be the charcoal particles detected in the above-mentioned pollen profiles,

Table 5
Radiometric dates from archaeological sites of Tierra del Fuego

	^{14}C Datings	References
Northern Tierra del Fuego		
Tres Arroyos	11,880 ± 250; 10,280 ± 110; 10,580 ± 50; 10,600 ± 90	Massone (1991) and Massone et al. (1998)
Marazzi	9520 ± 210; 5570 ± 400	Laming-Emperaire et al. (1972) and Morello, R. (1998)
San Genaro I	1070 ± 80; 1479 ± 95; 1190 ± 90; 1620 ± 140; 610 ± 45	Horwitz (1995), Isla and Selivanov (1993), Favier Dubois and Borella (1999)
San Genaro II	1483 ± 80; 380 ± 70; 440 ± 70	Horwitz (1995), Favier Dubois and Borella (1999)
Cabeza de León 1	1100 ± 95 (Comp. B); 230 ± 60	Borrero (1985)
Cabeza de León 4	3700 ± 70; 1600 ± 60	Favier Dubois (1998)
Bloque Errático	785 ± 120	Borrero and Casiraghi (1980), and Borrero et al. (1985)
Lag. Arcillosa I y II	5410 ± 70; 4440 ± 60; 3690 ± 70	Salemme and Bujalesky, i.p.
Chacra Pafoy	320 ± 60	Salemme and Bujalesky, i.p.
Cabo Domingo	Moderno	Salemme and Bujalesky, i.p.
Cabo Peñas	620 ± 45	Salemme and Bujalesky, i.p.
Heads of Lago Fagnano		
Marina I	1800 ± ??	Mansur et al., i.p.
Cabeceras del Fagnano	n.d.	Borrero (1985)
Southeastern Tierra del Fuego		
Rancho Donata		Lanata (1993)
María Luisa		Lanata (1993)
Bahía Valentín	5900 ± 80; 500 ± 50	Acedo de Reinoso et al. (1988)
Northern margin of Beagle Channel		
Túnel I	6900 ± 70 to 450 ± 60	Orquera and Piana (1987)
Túnel II	1140 ± 90; 1120 ± 90	Orquera and Piana (1999)
Túnel VII	100 ± 45	Piana and Orquera (1995)
Shamakush I	1927 ± 120; 1020 ± 100 to 940 ± 110	Orquera and Piana (1997)
Shamakush X	1450 ± 100; 500 ± 100	Orquera and Piana (1999)
Lancha Packewaia	4980 ± 70 to 280 ± 85	Orquera and Piana (1995) and Orquera and Piana (1999)
Imiwaia I	6490 ± 120 to 5872 ± 147	Orquera and Piana (1998) and Orquera and Piana (1999)
Lanashuaia I	XIX th.	Piana et al. (1998)
Lomada Alta del Olivia	5600 ± 125; 5410 ± 160	Orquera and Piana (1999)
Río Pipo 17	1080 ± 85	Figuerero Torres and Mengoni Goñalons (1986)
Tolkeyen	760 ± 80; 490 ± 80	Figuerero Torres and Mengoni Goñalons (1986)
Isla El Salmón	1820 ± 120; 1765 ± 25; 1560 ± 90	Figuerero Torres (1988)

as Heusser (1994a) stated, taking into account that sea level was much lower than today, and a land connection with the continent existed in the area of Segunda Angostura.

In the way to the south of the island, the evidence close to and along the Atlantic coast seems to be younger, since recent investigations on shell middens located nearby ancient coastlines of Middle Holocene (Bujalesky, 1998) have yielded radiocarbon datings between 5400 and 3700 yr BP (Table 5; Salemme and Bujalesky, in press). Charcoal particles from pollen profiles of Onamonte (on the Chilean side) and Cabo San Pablo allow to infer the presence of hunter–gatherer groups much later, in the last millenia (Heusser, 1994a, b) as well.

Then, as far as the pollen data can be interpreted, the steppe was dominant in northern Tierra del Fuego until the *Nothofagus* forest colonization, that occurred lately during the Holocene. The palaeoenvironment from Middle to Late Holocene was characterized by a shrubby steppe with drier and probably colder climatic conditions than the present ones in the area, while the forest would have migrated to the east and south alternatively and irregularly as can be checked from Lago Fagnano profile, ca. 5000 BP (Heusser, 1994b); thus, the forest was completely settled close to Onamonte ca. 1500 BP and in Cabo San Pablo towards 1000 BP (Heusser, 1993; Heusser and Rabassa, 1995, Fig. 4).

Except for the Selk'nam (the main aboriginal group in this region) from the historical period, the previous societies are poorly known, but they can be referred to hunter–gatherer groups, living mainly on terrestrial ecosystems, but taking advantage of the marine resources, at least sporadically as complementary/occasional resources. This is shown in several archeological sites along the Atlantic coast, like mixed shell middens, rockshelters and surficial sites (Borrero, 1985; Favier Dubois and Borella, 1999; Salemme and Bujalesky, in press).

But the history of this island was different along the coasts of Beagle Channel, which was definitively opened around 8000 yr BP. Heusser (1994a) and Salemme et al. (1995) have hypothesized that people arrived at these coasts ca. 9.0 ka; however, the most reliable data up to now proceed from Túnel I and Imiwaia sites (Orquera and Piana, 1998, 1999).

The First Component at Túnel I site represents a single and short occupation, where neither the artifacts nor the archaeofaunal remains would indicate the intensive profit of the maritime littoral, though probably it was used as an ocassional resource. The open environment by 7000 BP would offer the chase of terrestrial mammals without difficulties, and the technological context indicate a better approach to the hunting of guanacos (*Lama guanicoe*) (Orquera and Piana, 1999) than that occurred during later events. This earliest occupation in Túnel I site was dated between 6980 and 6680 yr BP (Table 5).

After that time, the groups living along this northern coast of the Beagle Channel indicates a clear adaptive strategy to the marine environment. The oldest occupation that reveals the presence of maritime hunter–gatherers has been dated in ca. 6500 yr BP (Table 5). By the times of the occupational episodes that characterized this Second Component in Túnel, the *Nothofagus* forest was completely settled; the expansion of the forest took place at the end of Early Holocene (ca. 6000–5000 yr BP), under a warmer climate as it can be deduced from pollen profiles (Heusser, 1994b). A similar situation would have occurred in the northern coast of Magellan Straits, as it is reflected in the Bahía Buena and Punta Santa Ana, on the Chilean side (Orquera and Piana, 1999). After that time, though the climate became colder again, the aborigins living along the coasts of Beagle Channel were already adapted to this environment, with a simple but efficient technology and social organization.

Extended shell middens along the Beagle Channel, then, show those adaptive strategies developed since 6.5 ka BP, based on the hunting of sea mammals (*Arctocephalus australis* and *Otaria flavescens*) and birds, fishing and gathering molluscs (*Mytilus* sp., *Patinigera* sp., etc.). They were able to survive under environmental conditions even colder than today, but similar regarding the biomass that the Europeans found by the beginnings of XIXth century.

It has been formulated that the Atlantic coast, at least during the middle Holocene, would have been occupied, following a discrete pattern and probably never re-occupied, opposite to those sites in the Beagle Channel, where the geography would have conditioned or limited the availability of space and resources (Salemme and Bujalesky, in press).

The central and southeastern area of Tierra del Fuego Island is less studied, although some information has been already presented and/or published (Borrero, 1985; Lanata, 1993; Acedo de Reinoso et al., 1988; Mansur et al., in press). It adds archaeological data about hunter–gatherers living under a similar environment to the present one. The radiocarbon dates (Table 5) point out the occupational events during the late Holocene, except for the earliest occupation at Bahía Valentín ca. 5 ka BP.

Early and/or late sites from all over the island support evidence of human groups very well-adapted — harmoniously — to a rough environment; however, they soon became extinct after encountering with the first European explorers and settlers. The introduction of new economies (gold exploitation, sheep pastoralism, seal and whale slaughters for oil) altered the environment completely and the natives were unable to adapt to them successfully.

8. Final comments

Many questions are still remaining to be solved, so as to understand the natural history and the early peopling of this region of the Southern Hemisphere and its inter-hemispheric relationships.

Our present and forthcoming studies point towards several still unsolved problems, such as the genesis, chronology and extent of the tantalizing Río Grande Glaciation, the dating of morainic surfaces by cosmogenic isotopes, the location of pre-Illinoisan glaciation remnants along the Beagle Channel, the glacial chronology of the Lago Fagnano lobe, the past glacierization of the eastern portion of Isla Grande de Tierra del Fuego, Sangamon and pre-Sangamon raised marine beaches, differential tectonic behaviour along the Beagle Channel coast, detailed studies of the Late Glacial pollen sections, particularly the Younger Dryas event, and its relationship with geomorphological evidence, the Neoglacial and Little Ice Age chronology, the analysis of some taxonomic problems to better define the Magellan malacofauna and its relationship with other regions as Antarctica and New Zealand, and the preparation of a long-term dendrochronological curve which could be used in the callibration of the ^{14}C curve for the Southern Hemisphere.

These are some of the many fascinating scientific problems of the Quaternary of Tierra del Fuego which will hopefully keep us busy during the next decade.

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