THE FLOOD OF THE BEAGLE VALLEY (11,000 YR B.P.), TIERRA DEL FUEGO

LA INUNDACIÓN DEL VALLE BEAGLE (11.000 AÑOS A.P.), TIERRA DEL FUEGO

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RESUMEN

El canal Beagle conecta los océanos Pacífico y Atlántico. Es una cuenca profunda, de hasta 200 m de profundidad, separada de estos océanos por sillas topográficas someras, de 30 m de profundidad. El canal se encuentra en el ambiente sismotectónico de los Andes Fueguinos (placa de Scotia). Es un valle tectónico, de 5 km de ancho, que fue completamente cubierto el hielo durante la última glaciación. Presenta una amplitud micromareal y una costa rocosa, donde se desarrollan playas de grava de bolsillo en las entrantes costeras. A lo largo del canal, se observan playas elevadas del Holoceno. Sus elevaciones varían, alcanzando las paleoplayas de 6.000 años A.P. 10 m por encima de la contraparte actual, indicando un levantamiento tectónico de 1,3 mm/año.

Luego de la última glaciación, en la cuenca se desarrollaron ambientes glacifluviales, glacilacustres y turbales. Inmediatamente después del Dryas temprano (11.000 años A.P.), el valle Beagle fue rápidamente inundado por el mar, cuando la transgresión sobrepasó las sillas topográficas del paso Mackinlay (hacia el este), del canal Murray (hacia el sur) y de los brazos sudoeste y noroeste del canal, que conformaban divisorias de aguas y los límites de la cuenca (actualmente a 30 m de profundidad).

Palabras clave**:** Tierra del Fuego, canal Beagle, Holoceno, evolución costera, nivel del mar.

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ABSTRACT

The Beagle Channel connects the Pacific and Atlantic oceans. It is a deep basin (up to 200 m depth) separated from the Atlantic and Pacific oceans by shallow sills (30 m depth). The Beagle Channel is located at the active seismotectonic setting of the Fuegian Andes (Scotia Plate Domain). It is a tectonic valley (5 km wide) that was completely covered by ice during the Last Glaciation. It has a microtidal range and an indented rocky shoreline, where pocket gravel beaches develop in the embayments. Holocene raised beaches can be recognized in many places along the channel and their elevations vary considerably, reaching maximum elevations of 10 m above the present counterpart at ages of 6,000 yr B.P. The estimated average tectonic uplift is 1.3 mm/yr for this period.

After the Last Glaciation, glaciofluvial, glaciolacustrine and peat bog environments developed in the basin. The Beagle valley was rapidly flooded by the sea immediately after the Younger Dryas, 11,000 yr B.P. when the sea level transgressed the water divides and boundaries of the basin of Paso Mackinlay (eastward), Murray Channel (southward), Beagle Channel northwestern and southwestern branches. Nowadays, these topographic sills are approximately 30 m deep.

Key words: Tierra del Fuego, Beagle Channel, Holocene, coastal evolution, sea-level.

INTRODUCTION

The Argentine sector of the Isla Grande de Tierra del Fuego is located between latitude 52°40'S-55°7'S and longitude 65°05'W-68°40'W (Fig. 1). The southernmost coasts of Tierra del Fuego (northern Beagle Channel coast and southern Atlantic coast) extend for 220 km in a west-east trend. It presents an indented rocky shoreline, where pocket gravel beaches develop in the embayments. The main Beagle Channel basin extends between Punta Divide (Chile) and Isla Gable (Argentina), is 105 km long, 200 m deep, 5 km wide and connects the Atlantic and Pacific oceans at this latitude. It presents a microtidal range. Its eastern section is separated from the Atlantic ocean by shallow (about 30 m deep) and narrow topographic sills (Paso Mackinlay and Murray Channel, respectively, Fig. 2). Meanwhile, the western section is connected with the Pacific Ocean through the northwestern and eastern branches of the channel which also have 30 m deep topographic sills.

The Beagle Channel is a former tectonic valley that was completely covered by ice during the last glaciation. After glacier melting, this glacial valley had a terrestrial environment with lake basins, peat bogs and fluvial valleys. Then the valley was drowned by the sea. Holocene raised beaches can be recognized in many places along the southern coast of Tierra del Fuego and their elevations vary considerably.

The objective of this paper is the analysis of the evolution of the glacial Beagle valley to a terrestrial enclosed basin where fluvial, lacustrine and peat bog environments developed until sea level rise over-passed rapidly the topographic sills (water divides) and created a marine environment.

Geological and tectonic setting

The southern part of Tierra del Fuego Island is located within the Andean Cordillera tectonic environment. The Fuegian Andes present a W-E trend as a result of a transform motion between the South American, Antarctic and Scotia plates. The alignment formed by the western end of the Estrecho de Magallanes, Seno Almirantazgo and Lago Fagnano marks the South American-Scotia plates boundary and the northern limit of the left lateral transpressional transform motion (Fig. 1). Recent fault scarps, sag ponds and landslides along this alignment indicate an important tectonic activity (Dalziel 1989[1]). The basement is composed of pre-Jurassic metamorphic rocks, covered by Jurassic acidic volcanic and pyroclastic rocks and Early Cretaceous marine shales, with low-grade metamorphism (Borrello 1969, Kranck 1932). The

[1] Dalziel, I., 1989. Tectonics of the Scotia Arc, Antarctica. Field Trip Guidebook T. 180, 28th International Geological Congress, 206 pp.

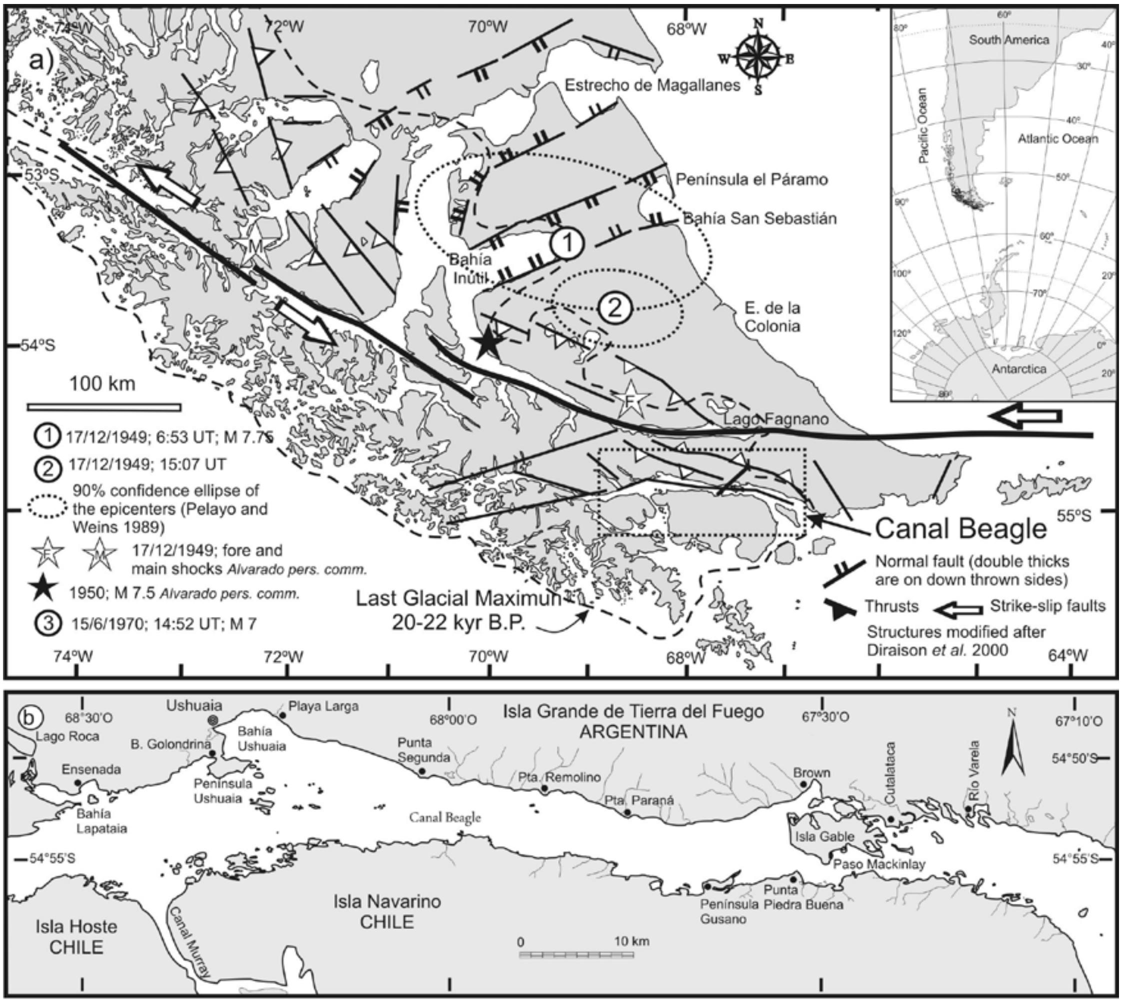

Fig. 1. Location maps. a) Isla Grande de Tierra del Fuego major fault lineaments (Diraisson *et al.* 2000), 1949 earthquake location (after Pelayo and Wiens, 1989; Alvarado *pers. comm.,* 2009) and position of the Last Glacial Maximun. b) Beagle Channel.

Mesozoic rocks are overlain by Paleocene marine beds and continental deposits (Caminos *et al.* 1981[2], Olivero[3] & Martinioni 1998, Olivero & Malumián 1999). Several deformation phases related to Mesozoic and Eocene-Miocene movements affected the sedimentary sequence (Caminos *et al.* 1981). GPS measurements, taken since 1993 to 1999 and located northward and southward the left lateral strike-slip Magallanes-Fagnano fault system, showed that the Scotia plate is moving eastward at about 5 mm/year with respect to the South America plate (Del Cogliano *et al.* 2000[4]).

[2] Caminos, R., M. Haller, O. Lapido, A. Lizuain, R. Page, V. Ramos 1981. Reconocimiento geológico de los Andes Fueguinos, Territorio Nacional de Tierra del Fuego. VIII Congreso Geológico Argentino, Actas 3, 759-786. San Luis. Argentina.

[3] Olivero, E., & D. Martinioni 1998. A review of the Mesozoic-Paleogene geology of the Marginal-Austral Basin of Tierra del Fuego. IGCP Project 381 South Atlantic Mesozoic Correlations Third Annual Conference, Comodoro Rivadavia, Argentina, Field Trip 3:1-13.

[4] Del Cogliano, D., R. Perdomo, J. Hormaechea, E. Olivero, J. Strelin, D. Martinioni 2000. GPS detection of movements between SCO and SAM plates in the Argentinean part of Tierra del Fuego Island. 31st International Geological Congress, Río de Janeiro, Brazil, Abstracts.

The historic seismicity of the Scotia Arc is reported by Pelayo & Wiens (1989) and the current seismicity is monitored by Estación Astronómica Río Grande (Sabbione *et al.,* 2007 a[5], b). It is worth mentioning the strongest earthquake of December 17, 1949, when sinking movements occurred on certain shores of Lago Fagnano. It reached a magnitude of 7.75 in Richter's scale (Fig. 1, Castano 1977, Pelayo & Wiens 1989, Alvarado *pers. comm.*).

Glaciations

Meglioli *et al.* (1990)[6] and Meglioli (1992[7], 1994) recognized several Plio-Pleistocene glaciations in northern Tierra del Fuego and the oldest one (older than 1.9 Ma B.P., Late Pliocene-Nebraskan?) covered almost the entire island. The last glaciation (older than 16 and younger than 47 kyr B.P., Late Wisconsinan) in northern Tierra del Fuego was restricted to the western Estrecho de Magallanes and Bahía Inútil, in the Chilean territory (Porter 1989, Meglioli *et al.* 1990, Meglioli, 1992). The last two quaternary glaciations were recognized along the Beagle Channel, reaching approximately 1400 m thick during Late Wisconsinan times (Rabassa & Clapperton 1990, Rabassa *et al.* 1990[8]). The glacial history and the deglaciation of the Beagle Channel were recognized from research of basal peat chronostratigraphic data (Rabassa *et al.,* 2006). The Last Glacial Maximum was attained around 20-22 kyr B.P. reaching the area of Punta Moat (100 km eastwards Ushuaia) where terminal moraines of this episode can be observed. The ice recession started before 14.7 kyr B.P. (Fig. 1). The first event of deglaciation was found in Harberton peat bog basal layers radiocarbon dated at 14,680 ± 100 years B.P. Basal peat bog layers of Bahía Lapataia (20 km westwards Ushuaia) show ^{14}C ages of 10,080 years B.P. indicating the definitive glacial retreat of this area (Rabassa *et al.* 2006).

Bathymetry and basin morphology

The depth contours of the Beagle Channel suggest that three or four main lake basins developed in this former glacial valley, with water surface levels placed at different altitudes. The Beagle basin is divided in two secondary 200 m deep depressions separated by a 60 m deep topographic sill developed in the area of Peninsula Ushuaia and Islas Bridges (Figs. 2 and 3). The origin of this sill is probably related to oblique fault lineaments to the major west-east faulting. The bathymetric analysis suggests the development of two former lake basins westwards Peninsula Ushuaia. The higher and subsidiary basin is 120 m deep and is placed in front of Bahía Golondrina. Probably the former surface of the lake was positioned next to the present 100 m isobath. The main western basin is 240 m deep and is located in front of Bahía Lapataia (Argentina) and Bahía Yendegaia (Chile). The former lake surface probably was placed about the present 160 m deep countour. Another elongated basin developed between Bahía Ushuaia and Islas Les Eclaireuers with maximum depths at the present contour of -160 m.

The depth contours shape between Islas Les Eclaireurs and Isla Gable suggest the development of a lake basin with a former surface about -160 m and maximum depths at the present -200 m isobath, in the area of Punta Remolino and Punta Paraná (Fig. 2). The contours of the eastern flank of the basin (immediately westward Isla Gable) are "V" shaped suggesting the action of fluvial erosion from east to west to its deepest section. A shallow submerged fluvial plain extends eastward Isla Gable with depths of 20 m to 40 m. The deeper "V" shaped contours are nearer of the northern coast of Isla Navarino (Chile).

Taking into account the Murray Channel, the depth contours indicate a former and small lacustrine basin at its northern end, with maximum present depth of 140 m (Fig.4). Probably its former surface was positioned at the present -100 m isobath. This

[5] Sabbione, N., G. Connon, C. Bufón & J. Hormaechea 2007a. Tierra del Fuego reference standard earthquake catalogue. Geosur 2007, Congreso Internacional sobre Geología y Geofísica del Hemisferio Sur, Santiago de Chile, 143.

[6] Meglioli, A., E. Evenson, P. Zeitler & J. Rabassa 1990. Cronología relativa absoluta de los depósitos glaciarios de Tierra del Fuego, Argentina y Chile. XI Congreso Geológico Argentino, Actas 2:457-460. San Juan.

[7] Meglioli, A. 1992. Glacial geology and chronology of Southernmost Patagonia and Tierra del Fuego, Argentina and Chile. Ph.D. Dissertation, Lehigh University, Bethlehem, U.S.A., 216 pp. Unpublished.

[8] Rabassa, J., D. Serrat, C. Marti & A. Coronato 1990. El Tardiglacial en el Canal Beagle, Tierra del Fuego, Argentina. XI Congreso Geológico Argentino, Actas 1:290-293. San Juan.

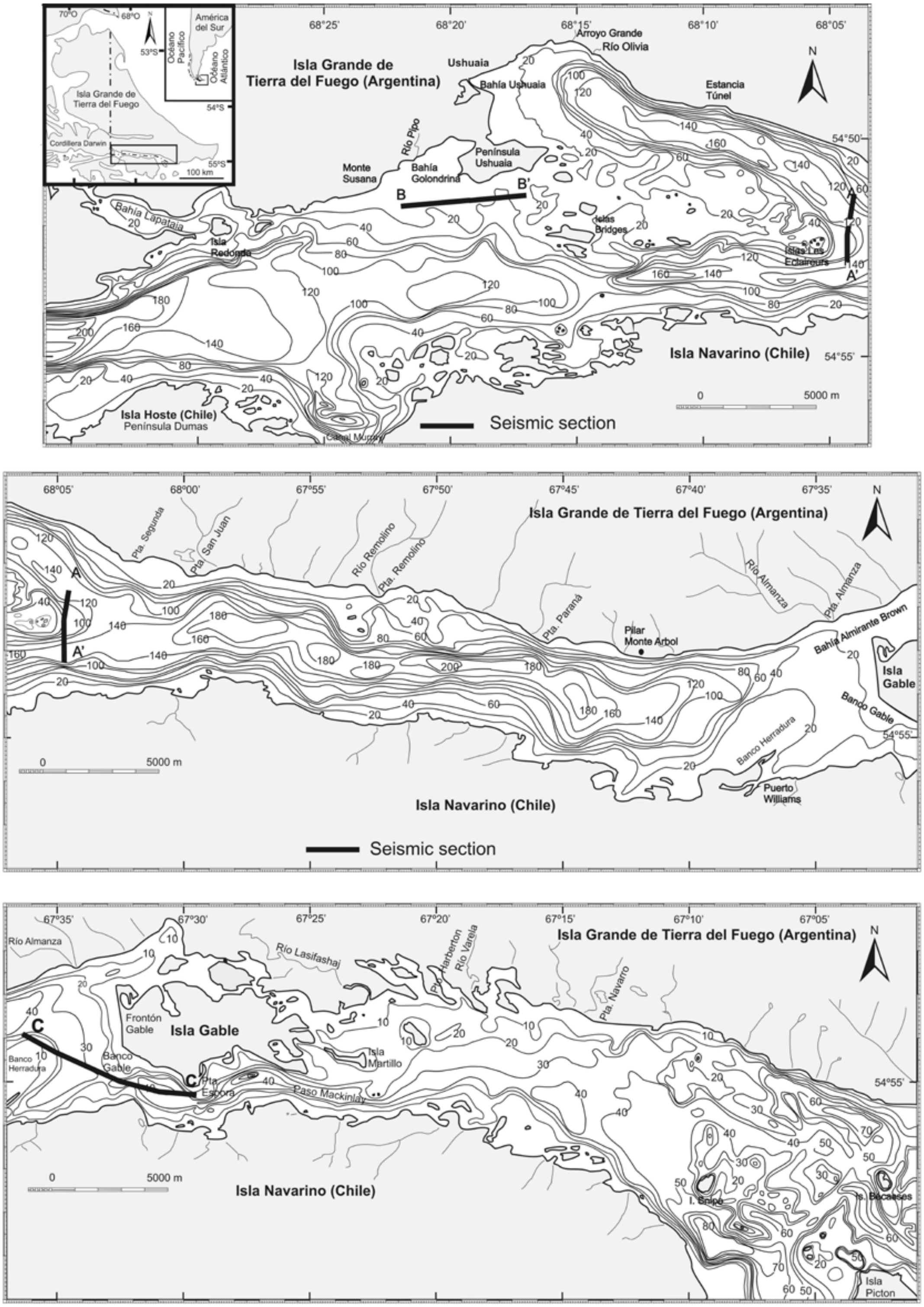

Fig. 2. Beagle Channel bathymetry after Carta H-477, Servicio de Hidrografía Naval, 1969 (depths in metres) and 3.5 kHz seismic section locations.

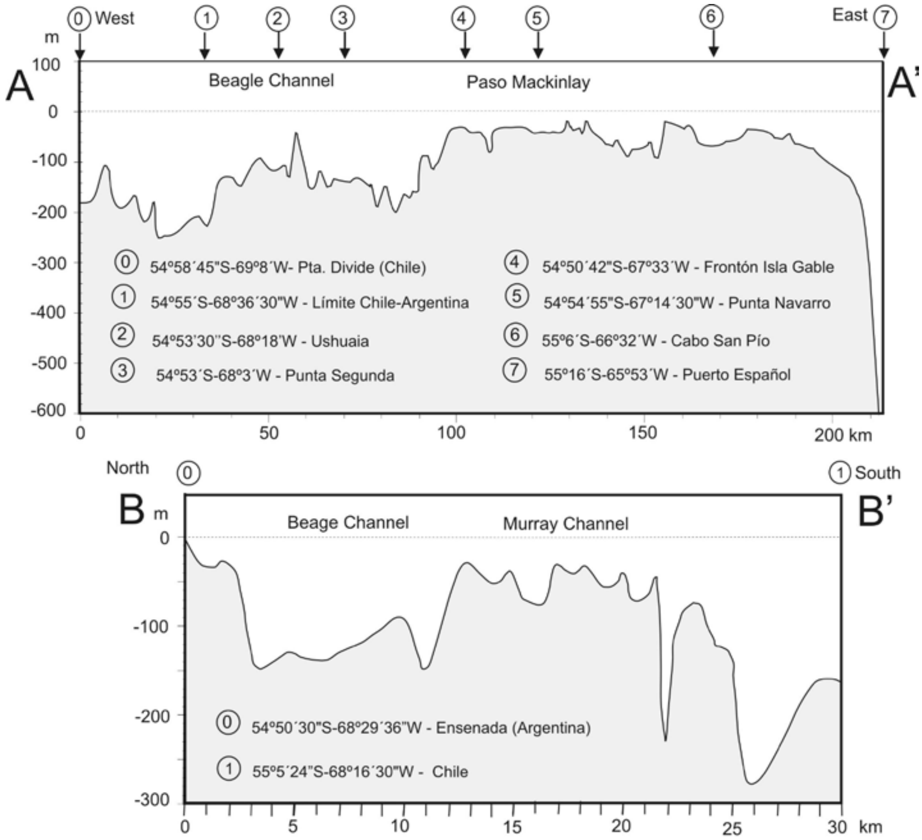

Fig. 3. Beagle Channel bathymetric section showing the 250 m deep basin and the topographic sills of Murray Channel and Paso Mackinlay.

small basin would have discharged to the deepest basin located in front of Bahía Lapataia. The Angostura Murray (Murray narrowing) is 1 km wide and shows a maximum depth of about 30 m. This section of the channel conform a topographic sills and had worked as a water divide in the past. Southward Angostura Murray the contours show a significant slope and indicate the development of a prominent glaciofluvial valley.

The western boundary of the Beagle Channel basin correspond with the topographic sills of the northwestern (Punta Divide-Isla Diablo sill) and southwestern (Bahía Fleuriais sill) branches (Fig. 5; 27 m and 31 deep, respectively). At this places the depths change abruptly from 200 m to 31 m. The northern branch separates Isla Grande from Isla Gordon and the southern branch divides the later form Isla Hoste.

Hydrodynamic conditions

The Beagle Channel presents an estuarine (fjord) dynamics controlled by significant and seasonal pluvial sources, and by tidal flow from both the east (Atlantic) and the west (Pacific; Isla *et al.* 1999). Two layers of different salinity and temperature develop in the water column during summer eastwards Gable Island. Lower salinities and temperatures and no water stratification (up to a depth of 22 m) were observed westwards Gable Island during summer due to the increment of fresh water input to the Beagle Channel. The channel shows a microtidal range and a semi-diurnal regime with diurnal inequalities. Mean tidal range is of 1.1 m at Ushuaia and the tidal wave moves from west to east (Servicio de Hidrografía Naval 1981, 2009). The narrowings (topographic sills) of Isla Gable, Murray Channel and

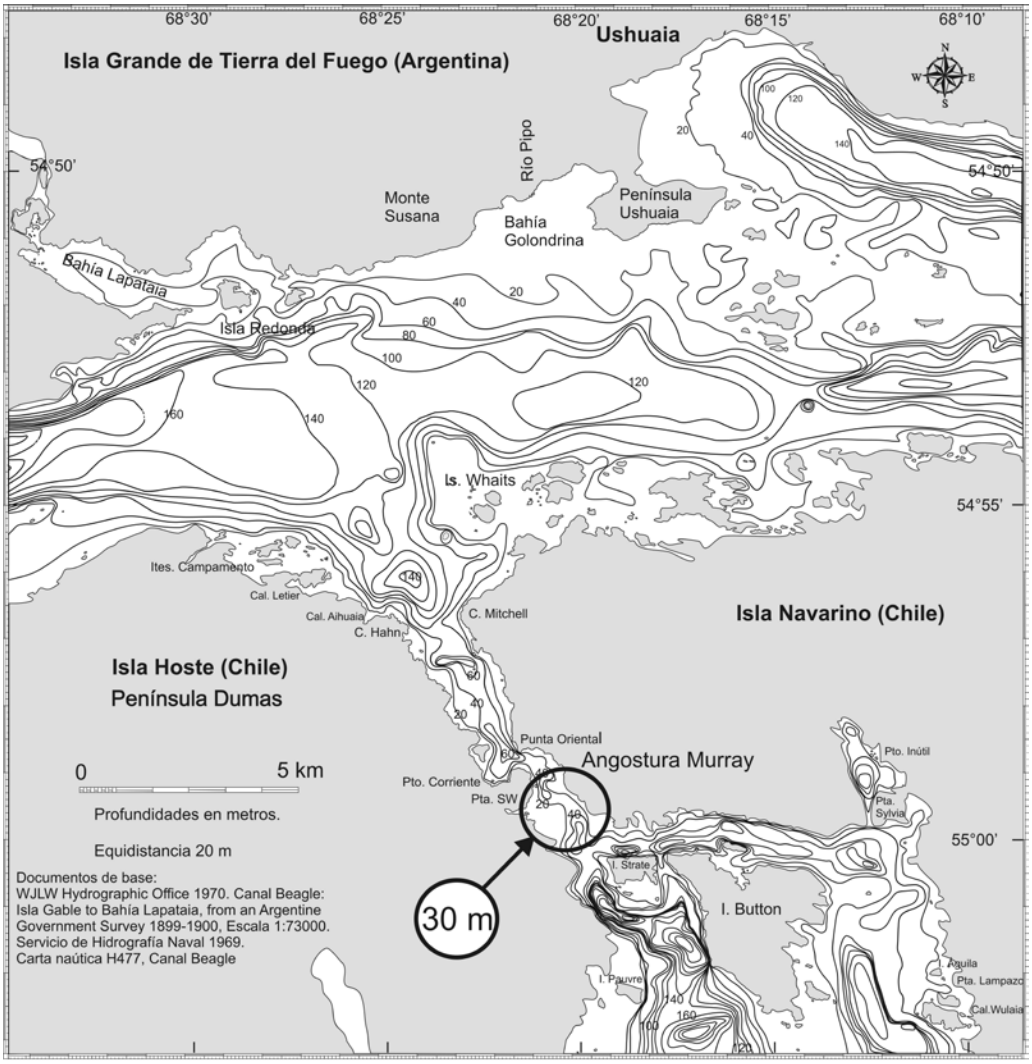

Fig. 4. Murray Channel bathymetry (depths in metres) showing the 30 m deep topographic sill. Modified after WJLW Hydrographic Office 1970, Canal Beagle: Isla Gable to Bahía Lapataia, from an Argentine Government Survey 1899-1900, scale:73000 and Carta naútica H477, Canal Beagle, Servicio de Hidrografía Naval 1969.

northwestern and southwestern Beagle Channel branches not only condition morphologically the fjord dynamics, but also limit the relative effects of the eastern and western flowing tidal currents, and the gravity waves which originate from the west (D´Onofrio *et al.* 1989). The Beagle Channel has a short fetch to the main southwestern winds and the waves are choppy with periods of 1 to 3 seconds. High wind velocities yield small plunging breakers with heights of up to 0.5 m.

Sub-bottom facies

A geophysical survey (side scan sonar and 3.5 kHz profiler) was carried out in the channel in order to analyze the surface and sub-bottom sedimentary facies. A west-east sub- bottom seismic section performed along Paso Mackinlay with a 3.5 kHz profiler (Fig. 6; Bujalesky *et al.* 2004) showed a basement of metamorphic rocks is overlaid by glacigenic deposits (till and ice retreat moraines). Sandy muds of

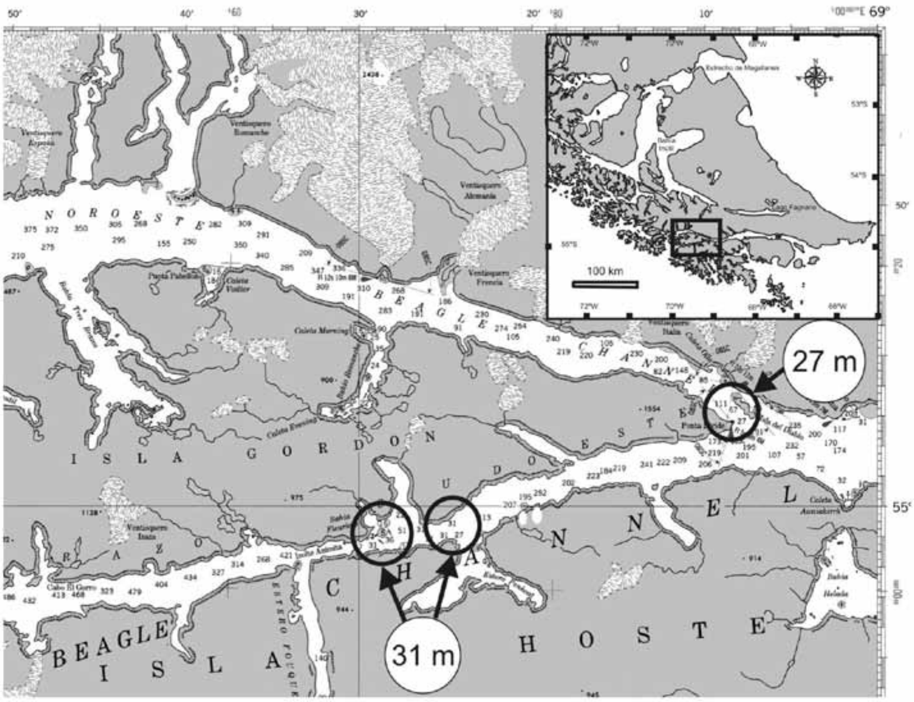

Fig. 5. Beagle Channel bathymetry from a Chilean chart of 1954 (1st edition 1989) Bahía Desolada to Punta Yamana (depths in metres). Topographic sills of the northwestern and southwestern branches of Beagle Channel are about 30 m deep.

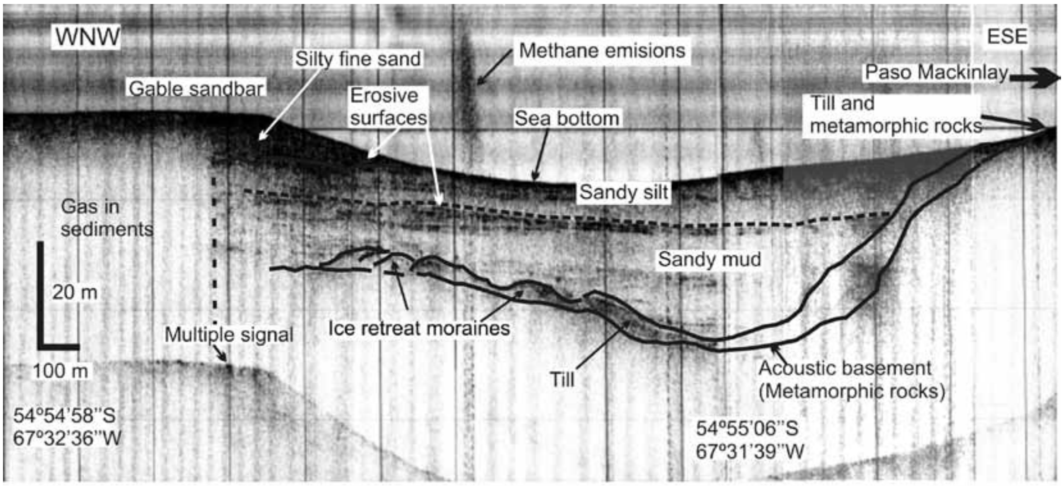

Fig. 6. W-E subbottom seismic section of Paso Mackinlay carried out with a 3.5 kHz profiler (Bujalesky *et al.*, 2004). The basement is overlying by glacigenic deposits (till and ice retreat moraines). Sandy muds of possible glaciolacustrine origin cover the restricted bowl shaped basin. Marine sandy silts develop over an erosive surface. Transparent areas of the 3.5 kHz profiler signal indicate the presence of gas in sediments. The darker plume in the water column shows methane emissions. The existence of methane is probably related to submerged peat bogs.

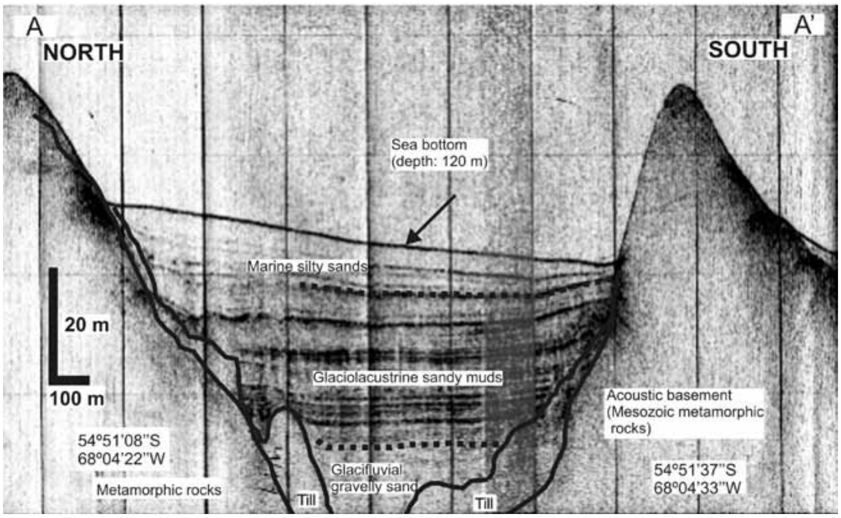

Fig. 7. N-S subbottom seismic section of the Beagle Channel from Punta Segunda to Les Eclaireurs Islands performed with a 3.5 kHz profiler (Bujalesky *et al.*, 2004). It is possible to observe a sequence of glaciofluvial deposits, glaciolacustrine layers and a cover of marine sediments. No significant erosive contact is observed between the marine deposits and the glacilacustrine sandy muds.

possible glaciolacustrine origin cover a local basin. Marine sandy silts develop over an erosive surface. Transparent areas of the 3.5 kHz record indicate the existence of gas in sediments. The darker plume in the water column shows methane emissions. The later facts are probably related to the existence of submerged peat bogs.

A north-south sub-bottom seismic section of the channel from Punta Segunda to Les Eclaireurs Islands showed Mesozoic rocks overlain by glacial deposits (till 20 m thick) and fining upwards sequences. These sequences represent different stages of the glacial retreat, showing in their upper parts proglacial lacustrine facies. On-lap stratified Holocene marine deposits overlie the glacigenic deposits indicating a sediment provenance from the northern coast of the channel. No significant erosive contact is observed between the marine deposits and the glacilacustrine sandy muds (Fig. 7; Bujalesky *et al.* 2004).

A paleovalley and submerged fluvial sequences transgressed by marine deposits have been also recorded southwards of Peninsula Ushuaia. A west-east subbottom seismic section showed a submerged sequence of fluvial facies covered by a prominent peat bog layer and overlaid by marine sediments (Fig. 8; Bujalesky *et al.* 2004). Non erosive contact is observed between the marine facies and the former a peat bog layer. The depth of the sea bottom is 36 m referred to the present sea level and the top of the peat bog layer is about 41 m deep (5 to 6 m below the Murray Channel and Paso Mackinlay minimum depths).

Holocene raised beaches and tectonic uplift

The embayments of the indented rocky shoreline of the Beagle Channel have their origin in tectonic lineaments affected by the successive glacial modeling action. They present a restricted hydrodynamic environment where small pocket gravel beaches develop. Holocene raised beaches were recognized along the northern Beagle Channel coast reaching maximum elevations of nearly 10 m a.s.l. with ages of approximately 6,000 ^{14}C yr B.P. (Lago Acigami –Roca–, Bahía Golondrina, Playa Larga; Rabassa *et al.* 1986, Rabassa 1987[9], Gordillo *et al.* 1992[10], 1993; Bujalesky 1998, Bujalesky, 2007).

9 Rabassa, J. 1987. Lago Roca, Tierra del Fuego: the highest Holocene marine beach in Argentina, IGCP Project 200, Late Quaternary Sea-Level Correlations and Applications, Abstracts 21, Dalhousie University-NATO Advanced Study Institutes Programme, Halifax.

10 Gordillo, S. 1992. Tafonomía y paleoecología de moluscos bivalvos del Holoceno del Canal Beagle, Tierra del Fuego. Ph.D. Dissertation, Universidad Nacional de Córdoba. Unpublished.

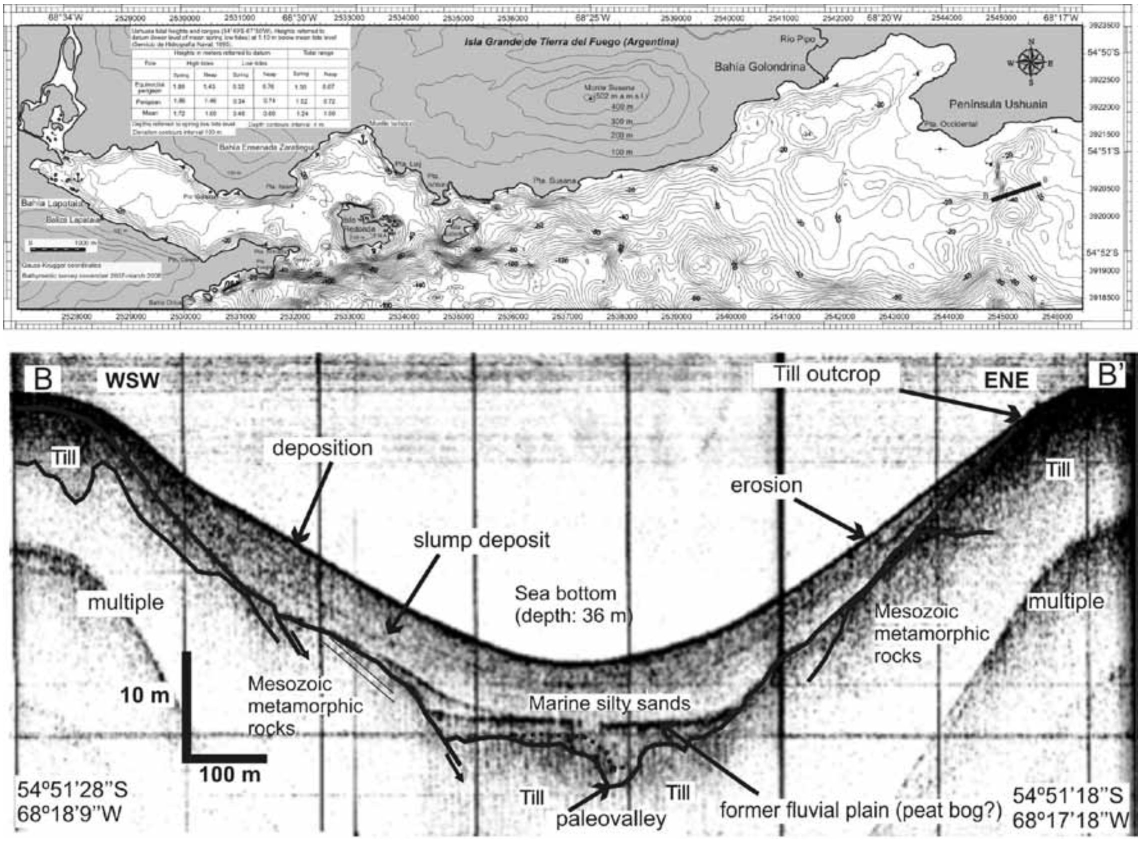

Fig. 8. a) Detailed bathymetric survey from Lapataia Bay to Peninsula Ushuaia where is possible to recognize lake and delta shaped features in Golondrina Bay and a fluvial valley in front of Peninsula Ushuaia. b) W-E subbottom seismic section showing a submerged sequence of fluvial valley deposits, a peat bog layer and marine sediments in front of Peninsula Ushuaia (Beagle Channel) performed with a 3.5 kHz profiler (Bujalesky *et al.* 2004). The sea bottom is 36 m deep referred to the present sea level and the non erosive contact between the marine deposits and the former fluvial plain (probably a peat bog) is about 41 m (5 to 6 m below the Murray Channel and Paso Mackinlay minimum depths).

Mörner (1987, 1991) pointed out that the Estrecho de Magallanes (Magellan Straits) and Beagle Channel coasts were under different uplifting behaviors 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 9,000 to 4,000 ^{14}C yr B.P. to a level only slightly above the present (ranging from 0.0 m 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.

At least three levels of terrace systems have been established along the northern coast of the channel at 8-10 m, 4-6 m and 1.5-3 m (Gordillo *et al.* 1992). These Holocene raised beaches are commonly capped by anthropogenic shell midden deposits. Playa Larga represents a good example of well-developed terraces, located a few hundred meters east of the Río Olivia inlet, near the eastern boundary of Ushuaia city (Gordillo *et al.* 1992). This site presents a sequence of five superimposed raised beaches developed at 1.6 m (405±55 ^{14}C yr B.P.), 3.8 m (3,095±60 ^{14}C yr B.P.), 5.2 m (4,335±60 ^{14}C yr B.P.), 7.5 m (5,615±60 ^{14}C yr B.P.) and 10 m a.m.s.l. (recognized as a gravel beach but still undated).

The Bahía Lapataia-Lago Acigami (Roca) valley (20 km west of Ushuaia) is a palaeofjord that was occupied by a lateral and tributary valley-glacier system during the last glacial maximum (Fig. 9; 18-20 ^{14}C kyr B.P.; Gordillo *et al.* 1993). Well-rounded glacially formed rocky hills, lateral moraines and

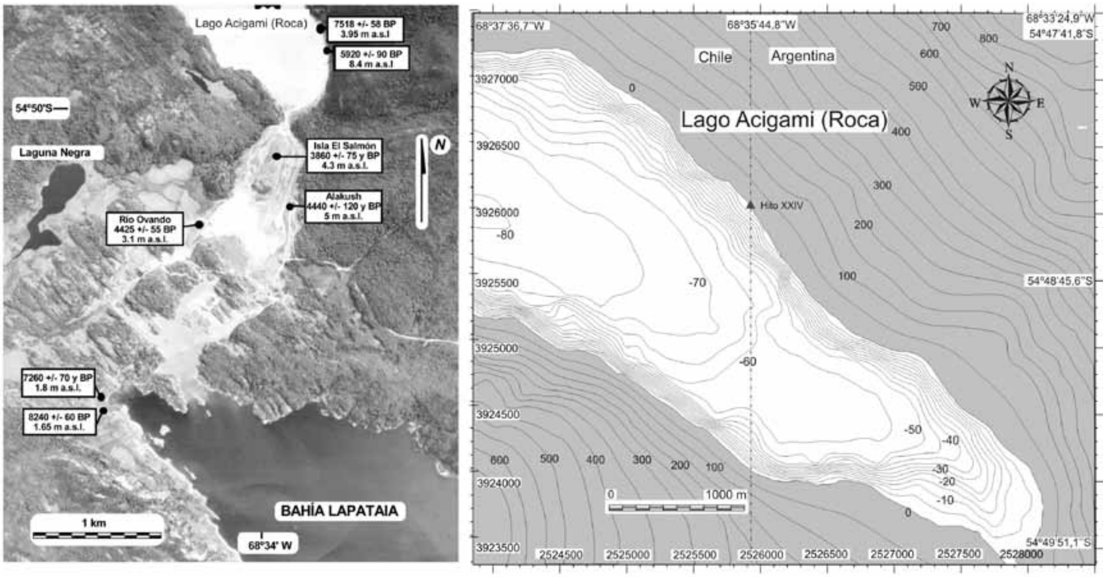

Fig. 9. Lago Acigami (Roca)-Bahía Lapataia palaeofjord. Radiocarbon dating and altitudes of raised beaches after Gordillo *et al.* (1993). Aerial photograph from the Servicio de Hidrografía Naval 1970, Buenos Aires. Bathymetry carried out in march 2009 (depths in meters), topography after: Hoja Ushuaia 5569-17-1, Gobierno de Tierra del Fuego 2003, Gauss-Krugger coordinates (contour altitudes in meters above lake level). "V" shaped contours of the southeastern section of Lago Acigami indicate a drainage flow to the northwest where the deepest area of the basin develops.

kame landforms are present in this area and *Sphagnum* peat bogs develop at the lowlands. Holocene marine deposits are scattered along Bahía Lapataia, Archipiélago Cormoranes, Río Ovando, Río Lapataia and the eastern shoreline of Lago Acigami (Roca), overlying glacial landforms and reaching a maximum altitude of at least 8.4 m a.s.l. (Gordillo *et al.* 1993). The cold and shallow-water mollusk assemblages associated with the Beagle Channel raised beaches have not shown significant climatic changes during the Holocene (Gordillo 1991, 1992, 1993, Gordillo *et al.* 1992, 1993).

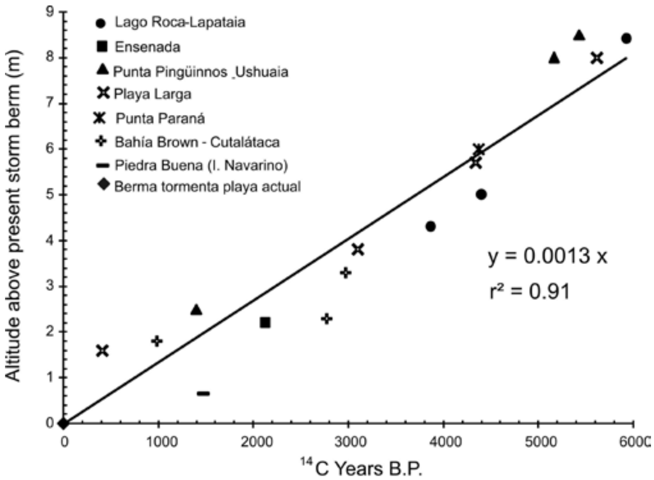

Fig. 10. Altitude of raised beaches of the Beagle Channel referred the present storm berm versus age in ^{14}C years before present (data after table 2, Bujalesky, 2007). An average tectonic uplift of 1.3 mm/year was estimated for the last 6,000 years (refer to Fig 1.b. for locations).

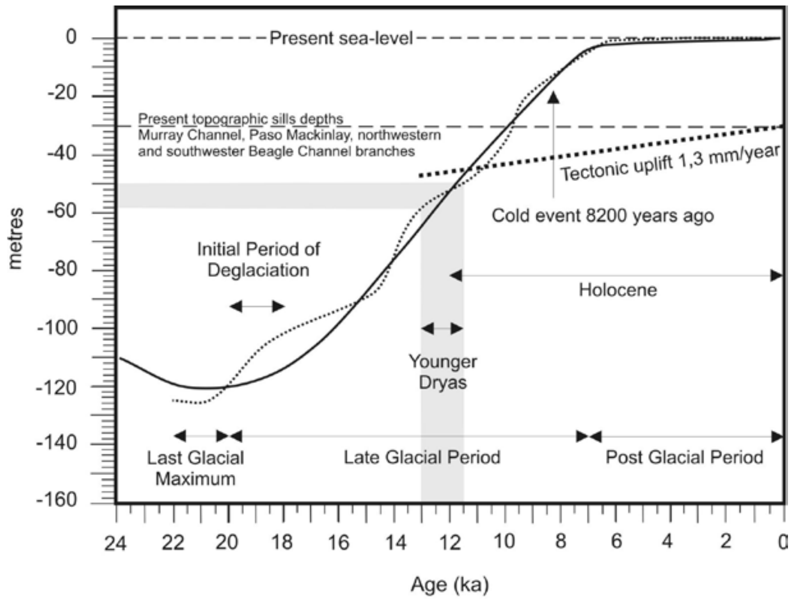

Fig. 11. Estimated eustatic sea-level curves from the Last Glacial Maximum to the present day after Fleming *et al.*, 1998 (solid line represents the nominal eustatic curve and the fine dotted line indicates a modified curve showing minimal variations in the rate of sea level change). The estimated eustatic sea-level rise from 18,000 to 6,000 years B.P. is about 10 mm/year. The coarse dashed line indicates the present depths of the Murray Channel, Paso Mackinlay, northwestern and southeastern Beagle Channel branches topographic sills. The coarse dotted line represents the extrapolation to the past of the estimated tectonic uplift of the Beagle Channel area. It cuts the eustatic sea-level curves about 11,000 to 11,500 years B.P. immediately after the Younger Dryas period. It is inferred that as from this moment the sea water overpassed the topographic sills and the flood process rapidly begun to fill the continental environment of the former Beagle Valley.

The altitude of fossil storm berms of the Holocene raised beaches of the Beagle Channel referred the present storm berm were correlated to their ages in ^{14}C years before present (Fig. 10; data after table 2, Bujalesky 2007). An average tectonic uplift of 1.3 mm/year was estimated for the last 6,000 years. The extrapolation to the past of mean tectonic uplift trend of the Beagle Channel form the present depth of the Murray Channel, Paso Mackinlay, northwestern and southeastern branches topographic sills intersect the eustatic sea-level curves (Fleming *et al.* 1998) about 11,000 to 11,500 years B.P. immediately after the Younger Dryas period (Fig. 11). This fact let infer that as from this moment the sea water overpassed the topographic sills and the flood rapidly begun to fill the continental and lacustrine environment of the former Beagle Valley.

DISCUSSION

An evolutional model of a former continental basin flooded by the sea during the maximum Holocene transgression was described for the Black Sea by Ryan *et al.* (1997) and Ryan & Pitman (1999). Ryan *et al.* (1997) carried out seismic profiles across the continental shelf in the Black Sea. They showed an erosional unconformity above the -150 m isobath which truncated an underlying glacial-age alluvial and delta deposit. A rapid transgression, occurred 7,150 ± 100 yr B.P., left the erosion surface intact as shown by the burial of a former river channel. Ryan *et al.* (1997) and Ryan & Pitman (1999) considered that during last glaciation, the Black Sea became a freshwater lake. The surface of this lake drew down 100 m below its outlet (-150 m bellow the present sea level) by evaporation and reduced river input. When the Mediterranean rose to the Bosphorous sill at 7,150 years B.P., saltwater poured through this spillway to refill the lake and submerge 100,000 km^2. Ryan & Pitman (1999) inferred the infilling of the lake at a rate of 15 cm/day, taking 2 years the total flood of the basin.

Ballard *et al.* (2000) located an exposed paleoshoreline on the continental shelf of the Black Sea at a depth of 155 m. Radiocarbon dating of shells of this ancient beach revealed that the marine flooding took place between 7,460 and 6,820 years ^{14}C B.P. Ryan (2003) refined the water level variation curve for the Euxinian Lake-Black Sea basin and considered that since 14,000 years B.P. to 11,000 years B.P. the lake level was at -120 m referred to the present sea level. Then the lake level rose up to -30 m at 10,000 years B.P. Since that moment up to 8,500 years B.P. the lake level felt to -95 m. Later, the sea over-passed the topographic sill of the Bosphorous Strait. Turney & Brown (2007) considered that the marine flooding of the Black Sea basin took place at the same time that the main rise in global sea level, between 8,350 and 8,230 calendar years B.P., lasting 34 years and submerging 72,700 km^2.

Yanko-Hombach *et al.* (2007) recognized that the Black Sea was a semi-fresh to brackish lake of Neoeuxinian age with a level that never dropped below the -50 m isobath after 9.8 ky B.P. The brackish lake changed into a semi-marine basin by a process that occurred in an oscillating manner. The first immigration of Mediterranean organisms occurred at 9.5 ky B.P. The re-colonization became well-defined by 7.2 ky B.P., reaching its culmination between 6.0 and 2.8 ky B.P. The water level in the Black Sea rose gradually, during the last 10,000 years, with a rate of 3 cm/100 years.

Ryan (2007) considered that the oldest unconformity recognized up to -140 m in the Black Sea shelf separates deposits of late glacial age (with evidence of subaerial exposure) from overlying Neoeuxinian sediment containing fresh to brackish fauna.
The Neoeuxinian cover represents a transgression leading to a highstand at –20 m below present's sea surface, which was reached by 10,000 B.P. Sediments with marine fauna lie above the Neoeuxinian. Dunes between –65 and –80 m and wave-truncated terraces with beach berms up to –100 m hold shell material dated between 9,500 and 8,500 B.P., suggesting that the youngest unconformity represents a post-Younger Dryas regression that took the surface of the Black Sea's lake below the level of the global ocean. The first arrival of saltwater was at 8,400 B.P.

Giosan *et al.* (2009) carried out a chronostratigraphic analysis of the Danube delta. In the early Holocene (9,800–9,500 years B.P. or 8,660 ^{14}C years B.P.), before the Black Sea reconnection to the ocean at 9,400 years B.P. (8,400 ^{14}C years B.P.), the Danube was building a ramp delta lobe that needed the contemporaneous level of the enclosed Black Sea to be above 40 m b.s.l. Morphology of the lacustrine–marine contact from Danube delta aided by radiocarbon ages of mollusks restrict the level in the Black Sea before the marine reconnection to 30 m below the present sea level. Giosan *et al.* (2009) considered that the increase of the Black Sea level was smaller than 50 m.

Taking into account the Beagle Channel, Rabassa *et al.* (1986) considered that the glacial valley was occupied by a glacial lake at about 9,400 ^{14}C yr B.P., and the lake water was replaced by seawater before 8,200 ^{14}C yr B.P. The paleontological evidence of raised littoral deposits (positioned about the present sea level) indicates that the marine environment was fully established along the channel at least by 7,900 ^{14}C yr B.P., reaching a maximum sea-level between 6,000 and 5,000 yr B.P. (Rabassa *et al.* 1986, Gordillo *et al.* 1992, Bujalesky 1998, Bujalesky 2007).

But 3.5 kHz seismic sections showed submerged paleovalleys and fluvial sequences and peat bogs transgressed by marine deposits. This fact indicates that after the deglaciation, glaciofluvial and glaciolacustrine environments developed in the Beagle basin followed by a rapid flood. The shallow depths of the four channels that connect this deep basin with the Atlantic and the Pacific oceans and the balance between eustatic sea-level trend (Fleming *et al.* 1998) and the tectonic uplift during the Holocene suggest that the Beagle valley was rapidly flooded by the sea over-passing Mackinlay and Murray sills, immediately after the Younger Dryas, 11,000 yr B.P. (Fig. 12, modified after Bujalesky *et al.* 2008). Probably, the sea level rise deceleration during the Younger Dryas made possible that the sea waves had eroded slowly and even out the water divides (topographic sills) surfaces of the main basin.

The non erosive contact (41 m deep, 5 to 6 m below the Murray Channel and Paso Mackinlay depths) observed between the marine facies and former well preserved a peat bog layer developed in the submerged paleovalley located southwards of Peninsula Ushuaia suggests a rapid transgression. The layout of these facies indicates that the sea-level rise was so fast that the waves had no time to erode the exposed deposits at that moment.

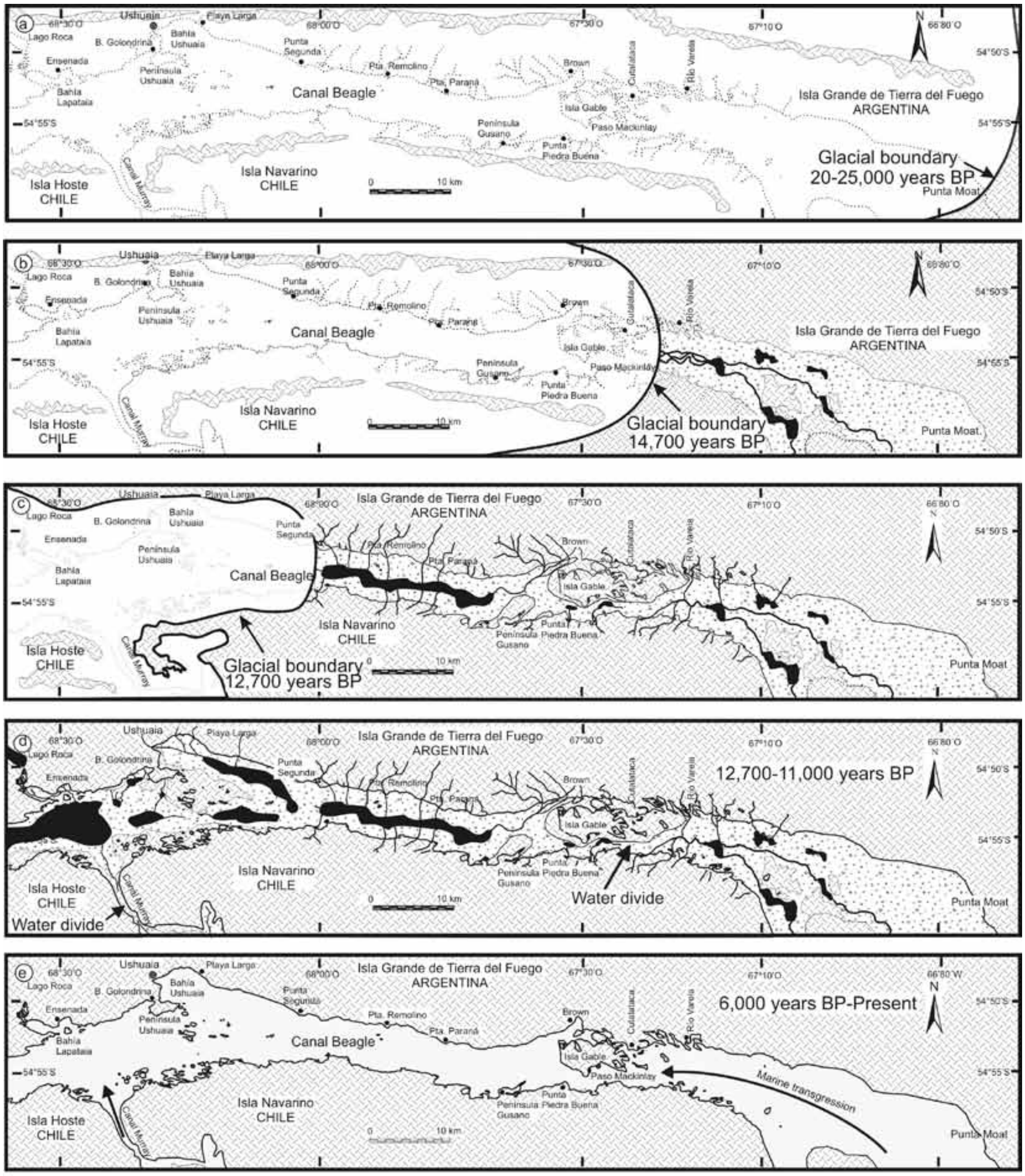

Fig. 12. Evolution model of the Beagle Channel for the last 25,000 years (modified after Bujalesky *et al*., 2008). a) Last glacial maximum, 20-25,000 years B.P., the glacier reached Punta Moat, it was 200 km long, 10 km wide and 1.2 km thick. Only the highest mountains outcropped the glacier as nunataks (Martial, Olivia and Cinco Hermanos mountains). b) 14,700 years B.P., glacier position at Gable Island. An eastward free of ice valley developed on the eroded plains with some remaining hills as Picton, Snipe and Becasses Islands). Lakes, ponds and rivers flowed eastwards to the Atlantic Ocean. The first peat bogs began to develop. c) 12,700 years B.P., Punta Segunda terminal moraines indicate glacial retreat detention. Melting water supplied an elongated lake located in the deeper area of the valley bounded eastward by the topographic sill of Gable Island. Modern peat bogs began to develop. d) 12,700 to 11,000 years B.P., Beagle Channel coasts were free of ice from Gable Island to Ushuaia. Melting water developed proglacial lakes in the deeper areas of the basin. Gable Island, Murray Channel and the shallow areas of the northwestern and southwestern branches of the Beagle Channels were topographic sills that worked as water divides. e) 11,000 years B.P., the glacial valley was rapidly flooded by the sea. The terrestrial and lacustrine environments were replaced by the marine setting. The sea level reached the highest level 6,000 years B.P. The sea water entered simultaneously through the Murray (south), the Paso Mackinlay (east), and northwestern and southwestern branches of the Beagle Channel.

CONCLUSIONS

The depth contours of the 200 m deep Beagle Channel basin that extends between Punta Divide (Chile) and Isla Gable (Argentina) suggest that three or four main lake basins developed in this former glacial valley, with water surface levels placed at different altitudes. The basin is connected with the Atlantic and the Pacific oceans by four shallow (30 m deep) and narrows topographic sills (Paso Mackinlay, Murray Channel, the northwestern and eastern branches of the channel).

Different sedimentary environments were recognized in sub-bottom sections of the Beagle Channel: basal moraines, glacial retreat fining upward sequences (glacufluival to glacilacustrine facies), submarine slump deposits and submerged peat bogs and glaciofluvial valleys covered by marine sediments without the development of significant erosive surfaces. This would point out a rapid flood process of the sea waters.

The morphology of the basin and the postglacial sedimentary sequences suggest that the Beagle valley was rapidly flooded by the sea overpassing Mackinlay, Murray Channel and northwestern and southeastern branches topographic sills, immediately after the Younger Dryas, 11,000 yr B.P. This process was similar to the Black Sea flood through the Bosphorous Strait or the Izmit Bay, Sapanca Lake, and the Sakarya River route.

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