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Coastal geomorphology and evolution of Tierra del Fuego (Southern Argentina)

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ABSTRACT

The northeastern Atlantic coast and the Beagle Channel are significant geomorphological areas of Tierra del Fuego (Southern Argentina). The northeastern Atlantic coast is located at the extra Andean lowlands (South-American Plate Domain). This coast line undergoes a macrotidal regime and is exposed to high energy waves and intense westerly winds. Extensive and wide beaches and littoral forms are composed of gravel and coarse sand. This zone was a free-ice area since 1,8 Ma B.P. Glacigenic deposits were re-worked by litoral processes that formed gravel beaches during sea level highstands of the. During the Holocene (i.e. approximately 5,000 years B.P.) gravel barriers plugged the inner estuaries of the palaeoembayments These barriers suggest a relative sea level fall of 0.214 m each 1,000 years, but a portion of this gradient could be due to wave dynamics since greater set-up of the storm waves enters the embayments. The growth of the northern gravel beach ridge plains and spits at the seaward flank of the embayments took place under limited sediment supply. The elongation of these littoral forms was triggered by erosion and sediment recycling at the seaward side (cannibalism), resulting in a significant landward retreat. Southward the gravel beach ridge plains underwent a regressive trend during the Holocene. They do not reveal either erosion, or sediment recycling, or significant landward retreat. The Beagle Channel connects the Pacific and Atlantic oceans. It is a 300 m depth basin separated from the Atlantic Ocean by a 30 m depth shallow sill. The Beagle Channel is located at the active seismotectonic setting of the Fuegian Andes (Scotia Plate Domain). It is a 5 km wide tectonic valley that was completely covered by ice during the Last Glaciation. After this period, glaciofluvial and glaciolacustrine environments developed in the basin. The Beagle valley was rapidly flooded by the sea immediately after the Younger Dryas, 11,000 year B.P. It undergoes a micro tidal range regime and shows a rugged, 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 years B.P. The estimated average tectonic uplift for this period is 1.5 to 2.0 mm/year.

KEYWORDS **Tierra del Fuego. Holocene. Coastal evolution. Sea-level. Gravel beaches.**

INTRODUCTION

The Argentine sector of the Isla Grande de la Tierra del Fuego is located between latitude 52°40'S-55°7'S and longitude 65°05'W-68°40'W (Fig. 1). The eastern Atlantic coast extends for 330 km along, affected by a NW-SE trend. It undergoes a macrotidal range (up to 10 m) and is exposed to high energy Atlantic waves and strong and intense westerly winds. Extensive and wide beaches and littoral forms are composed of gravel and coarse sand. Pleistocene glacigenic deposits gave rise to highs and cliffs at its northern section. These and other submerged glacial deposits have supplied the sediments for beach generation.

The southernmost coasts of Tierra del Fuego (northern Beagle Channel coast and southern Atlantic coast) extend for 220 km after a WE trend. It presents a rugged, rocky shoreline, where pocket gravel beaches develop in the embayments. The Beagle Channel occupies a drowned glacial valley and connects the Atlantic and Pacific oceans at this latitude. This channel is 5 km wide, its average depth ranges between 100 and 450 m and it undergoes a microtidal range. Holocene raised beaches occur in many places along the southern coast of Tierra del Fuego and their elevations vary considerably.

Considering the above mentioned features, the analysis of the geomorphology and evolution of the Fuegian coast must consider the dissimilar characteristics between the northern and southern parts of Tierra del Fuego, regarding tectonic uplift, glacio-isostatic rebound, wave and tide climate, availability of sediments and local hydrodynamic conditions. This paper deals withy summarizing and comparing the geomorphological characteristics of the northern and southern zones of Tierra del

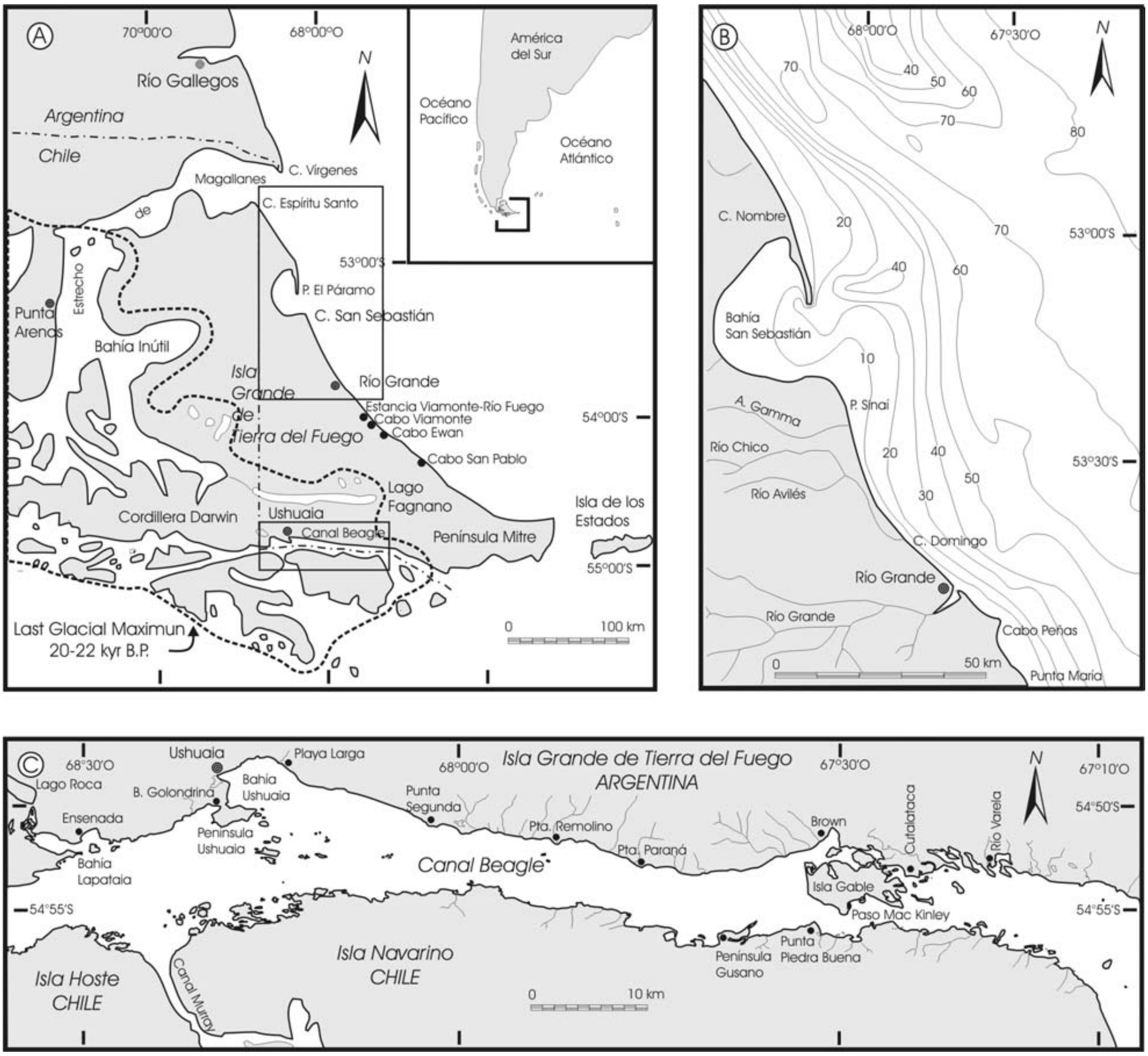

FIGURE 1 | **Location maps. A) Isla Grande de Tierra del Fuego. B) Northern Atlantic coast of Tierra del Fuego, depths in meters referred to spring low tide level (SLTL). C) Beagle Channel.**

Fuego, emphasizing their diverse evolutionary trends and the origin of the observed differences.

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 WE trend as a result of a transform motion between the South American, Antarctic and Scotia plates (Menichetti et al., in press; Tassone et al., in press). 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. 2). Recent fault scarps, sag ponds and landslides along this alignment indicate significant tectonic activity (Dalziel, 1989). The basement is composed of pre-Jurassic highly deformed metamorphic rocks (Borrello, 1969), covered by late Jurassic to Early Cretaceous volcanic pyroclastics and by Early Cretaceous mildly metamorphosed marine in origin rocks (Borrello, 1969; Kranck, 1932). These Mesozoic rocks are overlain unconformably by Palaeocene marine beds and continental deposits (Caminos et al., 1981; Buatois and Camacho, 1993; Olivero and Martinioni, 1998; Olivero and Malumián, in press). Several tectonic deformation stages (i.e. late Palaeozoic-early Mesozoic Gondwanic; Cretaceous Patagonidic; and Eocene-Miocene Andic phases) affected the sedimentary sequence (Caminos et al., 1981). The northern Atlantic coast of Península Mitre is located at the foot-hill belt (southern boundary of Magallanes or Austral Basin) and is made up by early to late Cretaceous marine siliciclastic sequences and by early Tertiary marine limestones, siltstones and sandstones (Camacho, 1948, 1967; Petersen, 1949; Furque, 1966; Olivero et al., 1999; Furque and Camacho 1949; Olivero and Malumián, 1999; Olivero and Martinioni, 1999), which were deformed during the middle Tertiary (Caminos, 1980; Winslow, 1982).

The northern part of Tierra del Fuego lies on a more stable setting. The Atlantic lowlands developed on a stable

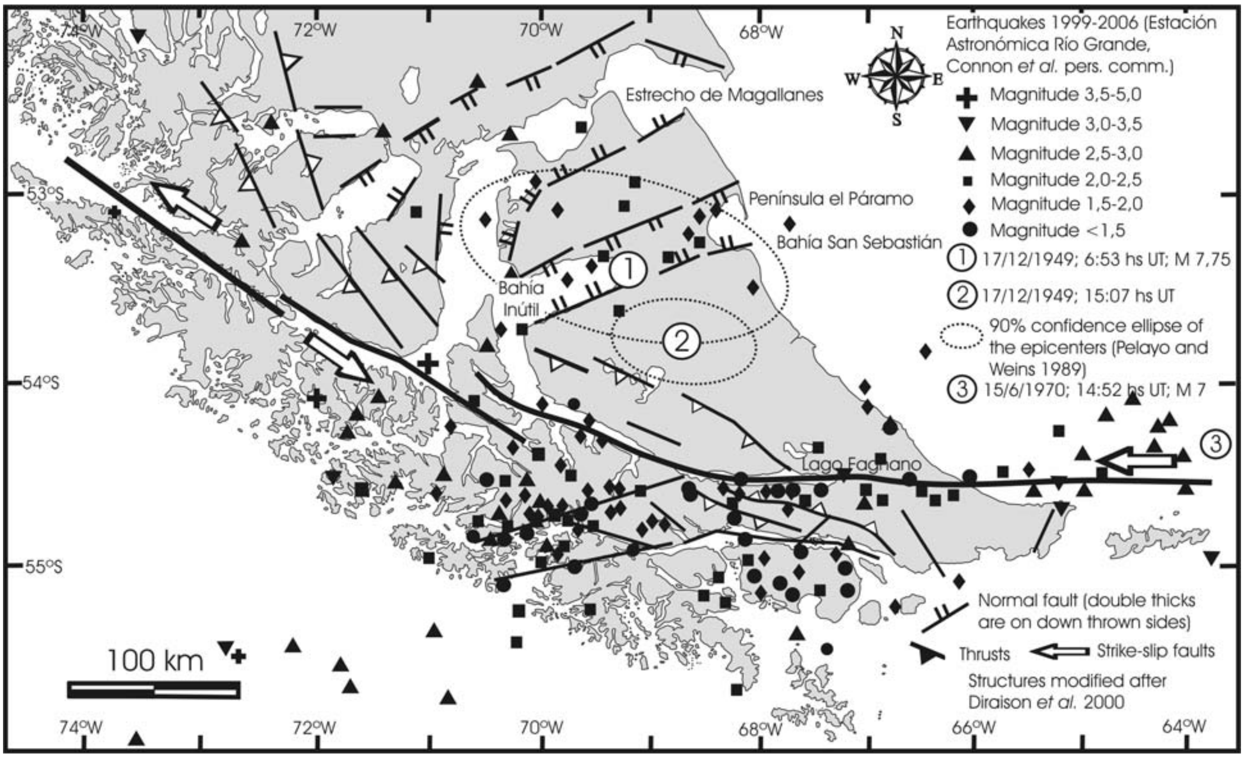

FIGURE 2 **Plate tectonic setting, major fault lineaments and seismicity of Tierra del Fuego (after Pelayo and Wiens, 1989; Diraisson et al., 2000; Connon pers. comm., 2006). The list of the most significant seismic episodes related to the tectonic structures is provided here and the location of some of them is shown in this Figure: a) the earthquake of February 1, 1879, (5:00 hs LT) reported by the Rev. Thomas Bridges (1879), resident in Ushuaia: "we had a succession of shocks, sufficiently strong to wake almost everybody and to make walking somewhat difficult. It split largely the milk in the pans, and was felt all over the country"; b) the earthquake of December 17, 1949 (6:53 hs UT), when sinking movements occurred on certain shores of Lago Fagnano, (7.75 degrees in Richter's scale), location of the epicenter according to Castano (1977) 54°06' S-70°30'; relocated at 53°24' S-69°13'12" W (Pelayo and Wiens, 1989); c) the earthquake of December 17, 1949 (15:07 hs. UT), epicenter at 53°59'24" S-68°46'12" W (Pelayo and Wiens, 1989); d) the earthquake of June 15, 1970 (14:52 hs UT), with a magnitude of 7.0, epicenter located northwards of Isla de los Estados (54°18' S-63°36' W) at a focal depth of 6 km (Unesco, 1972; Pelayo and Wiens, 1989); e) the earthquake of December 29, 1975, magnitude of 6.5, epicenter located in the Drake Passage (56°48' S-68°30' W) at focal depths of 11 km (Unesco, 1979; Pelayo and Wiens, 1989); f) the earthquake of November 30, 1997 (23:17 hs UT), with a magnitude of 3.8 and epicenter located at 54°48'57"S-68°04'20"W (February, 1997).**

platform, composed of non-deformed Late Jurassic-Early Cretaceous rocks (Thomas, 1949). The oldest exposed sediments are continental or marine in origin Tertiary rocks (Codignotto and Malumián, 1981). Plio-Pleistocene glacial deposits overlie the Tertiary rocks. Recent 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). This is consistent with the displacement of the stratigraphic contacts for the last 34 Ma that is in the order of about 1 mm/year (Olivero and Martinioni, 1998, 1999; Del Cogliano et al., 2000). The seismicity of the Scotia Arc is well reported by Castano (1977), Pelayo and Wiens (1989). Several significant episodes were reported from 1879 to 2006 (see Fig. 2).

GLACIATIONS

The Pliocene-Quaternary glaciations in Tierra del Fuego have been studied by many researchers (Nordenskjöld, 1898; Bonarelli, 1917; Caldenius, 1932; Feruglio, 1950; Auer, 1956; Codignotto and Malumian 1981; Rabassa et al., 1988, 1989, 1990, 1992, 2000; Rabassa and Clapperton, 1990; Porter, 1989; Meglioli et al., 1990; Meglioli, 1992; Coronato, 1990, 1993, 1995a, b; Clapperton, 1993). Nordenskjöld (1898), Bonarelli (1917) and Codignotto and Malumián (1981) thought that none of the oldest glaciations totally covered the island. Caldenius (1932) and Auer (1956) considered that the pre-Wisconsinan glaciations extended over the whole of Tierra del Fuego and the glaciers flew northwards and eastwards from the Cordillera Darwin along deep valleys or corridors (Estrecho de Magallanes, Bahía Inútil Bahía San Sebastián, Lago Fagnano and Beagle Channel) reaching the Atlantic Shelf. Meglioli et al. (1990) and Meglioli (1992) 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 with the exception of an area located between Río Grande and Bahía San Sebastián. This hypothesis is supported by the evidence of highly weathered till deposits and erratic boulders located 9 km westwards of the city of Río Grande. The absence of other till deposits in the drainage basin of the Río Grande is explained considering its geographic position where the melting channels of the major ices lobes flew. Meanwhile, the area northwards of Bahía San Sebastián was located in a higher interlobated position and it was almost undissected by rivers (Meglioli, 1992, 1994). The last glaciation (older than 16 and younger than 47 kyr B.P., Late Wisconsin) 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 (Wisconsinan and Illinoian in age, or older) were recognized along the Beagle Channel, reaching approximately 1,400-1,500 m thick during Late Wisconsinan times (Rabassa et al., 1990). The Last Glacial Maximum was attained around 20-22 kyr B.P. and the ice recession started before 14.7 kyr B.P. (Fig. 1; Rabassa et al., 1990).

PRESENT CLIMATE

The climate of Tierra del Fuego Island lacks marked continental influences and is determined by its upper mid-latitude location within the belt of prevailing westerlies (latitude 40° to 60°S), in the path of eastward moving cyclones and not far from the Antarctic ice (Tuhkanen 1992). The Andean Cordillera causes a steep climatic gradient from west to east and from south to north. The mean annual temperature in Ushuaia and Río Grande is around 5 to 6°C, the rainfall is 499 mm/yr in Ushuaia and 340 mm/year in Río Grande (Servicio Meteorológico Nacional, 1986). The most frequent winds have a west to northwest direction in the Magellanic region, a west direction in Río Grande (annual frequency: 39.3%, average velocity: 33 km/h), but in Ushuaia the relief causes deviations and southwest is the prevailing direction there (23.6%, 31 km/h).

The winds are more persistent and stronger in spring and summer than in winter. Köppen (1936) identified three climatic types for Argentine Tierra del Fuego: steppe climate (BSk, north of Bahía San Sebastián), humid temperate climate (Cfc, Bahía San Sebastián and Río Chico area, Ushuaia and eastern margin of Lago Fagnano area), and tundra climate (ETC, Río Grande drainage basin and Península Mitre). According to the system of 'seasonal climates' of Troll and Paffen (1964) the southern part of the island presents an oceanic climate (III.2.) and the northern part displays a dry steppe climate with mild winters (III.10.a.). Walter (1976) considered that almost the whole of Tierra del Fuego belongs to the Antarctic zone (oceanic variant).

OCEAN HYDRODYNAMIC CONDITIONS

The water masses that surround Tierra del Fuego are the result of intense mixture processes because of vertical convective currents between the Pacific and Atlantic ocean waters that develop at the Drake Passage, northwards of the Antarctic convergence and in region that extends between the Islas Malvinas and the eastern Tierra del Fuego coast (Capurro, 1981; Boltovskoy, 1981). Northwards of lat. 44°00'S, the Malvinas Current mixes with tropical waters (Brazilian Current). This oceanographic environment between the Antarctic and the Subtropical convergences is named Subantartic.

The Atlantic coast of Tierra del Fuego undergoes a macrotidal range with a semi-diurnal regime. The mean tidal range at the Atlantic coast increases from south to north (Bahía Thetis: 2.5 m; Cabo San Pablo: 4.6 m; Río Grande: 5.2 m; Bahía San Sebastián: 6.6 m). The flood and ebb currents reach a velocity of 2 knots in NW-SE directions, respectively. The Beagle Channel has 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, 2006).

The wave climate is relatively benign at the Atlantic coast due to the dominance of strong winds from the west. IMCOS Marine Limited (1978) reports data from ship's observations obtained from the British Meteorological Office, covering the sea area from the coast to long. 65° W and between lat. 50° S and 55° S (1949-1968). These data reports that: a) the frequency of wave heights higher than 3.5 m was very low; b) around 20% of waves were less than 1 m in height on average throughout the year; c) the long period waves have low frequency, and wave periods higher than 10 seconds come from the east to northeast; d) gales of 41-47 knots from any direction between N and ESE (with a return period of 50 years) were estimated to generate an extreme wave of height of 12 m and a period 11.5 seconds in a depth of 50 m (referred to spring tide level); and e) this estimated extreme wave would break in a water depth of 15 m (chart depth + tidal height above chart datum + storm surge), and would be near breaking point in 10 m depth even at spring high water.

A one year record at the Cullen area (lat. 52°49'19,1"S - long. 68°13'52,3"W, 110 km northwards of the city of Río Grande) gave the following results: a) a maximum wave height of 5.86 m (Compagnie de Recherches et d'Etudes Oceanographiques and Geomatter 1985); b) a maximum significant wave height of 3.43 m; c) an average significant wave height of 1.02 m; d) a maximum period of 17.5 seconds; d) a maximum significant period of 12.9 seconds; e) an average significant period of 5.5 seconds; f) the waves higher than 3 m corresponded to periods of 7 to 9 seconds; g) the longer periods were associated to wave heights of 1.25 m; h) the stronger swell were associate to north-norteastern winds; and i) the estimated extreme wave height would be of 5.8 m for NE to E winds and of 7 m for winds from the north considering a return period of 50 years.

The Beagle Channel offers 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. The southern Atlantic coast of Península Mitre receive strong open ocean swell from the south but unfortunately there are no available records.

GEOMORPHOLOGY OF THE ATLANTIC COAST OF TIERRA DEL FUEGO

The Atlantic coast of Tierra del Fuego includes several geomorphological systems that will be described and analyzed to provide a general, integrated view: the Pliocene-Pleistocene raised beaches, the Northern cliffs, Bahía San Sebastián, Peninsula el Páramo, the paleoembayments of Rio Chico Basin (i.e. Punta Sinaí to Cabo Domingo) and of Rio Grande Basin (i.e. Cabo Domingo to Cabo Peñas), and the Ensenada of La Colonia beach ridge plain and Río Fuego Spit (i.e. Cabo Peñas to Cabo Auricosta).

Plio-Pleistocene raised beaches

The southernmost Pliocene and Pleistocene beaches of the world occur in the northeastern atlantic coast Tierra del Fuego Island, along 100 km between Punta Sinaí (53º24'21"S-68º04'38"W) and Cabo Ewan (54º06'53"S-67º09'35"W). The oldest raised mixed sand and gravel beach is located on the top of La Arcillosa hill (53º 34'50"S-68º01'59"W, 30 km northwards Río Grande). It corresponds to an ancient storm berm deposit (10 m thick), at 79 m above the present counterpart, with abundant fragments of the bivalve *Cyclocardia velutina*, (Smith, 1881). It was considered that this unit corresponds to the Middle Pliocene, between the transition of oxygen isotope stages M2/M1 and G19/G18 (3.29 Ma to 2.97 Ma B.P.; Shackleton, 1995) in the middle part of the Gauss Normal Polarity Chron (Bujalesky and Isla, 2005). It is estimated that during this period of relatively warm and stable climate, the reduction of the ice volume in Earth planet caused a sea-level rise of 25 m referred to the present one and an increase in the sea-water surface temperature at high latitudes (Dowsett et al., 1999). This beach deposit would probably correlate with the 131-138 m a.m.s.l. marine terrace at Cabo Buen Tiempo, northern margin of Río Gallegos inlet, which have yielded a record of extinguished mollusk remains (Feruglio, 1950).

On the other hand, six levels of Pleistocene mixed sand and gravel beaches were recognized in the area. Taking into account their relative altitudes, the diverse absolute dating carried out on mollusk valves (Uranium Series Analysis; aminoacid racemization; Rutter et. al., 1989) and the comparison with their counterparts in the Atlantic coast of Patagonia (Feruglio, 1950; Schellmann, 1998; Schellmann and Radtke, 2003) these gravel beaches have been assigned to several ^{18}O isotope stages (Table 1; Bujalesky et al., 2001; Bujalesky and Isla, 2005). The fossil mollusk faunas in these ancient beaches are relatively poor and they do not allow inferring environmental conditions different from the present ones.

Northern cliffs

These cliffs extend along 40 km from Cabo Espíritu Santo (90 m high) to Cabo Nombre (10 m high) at the northern part of Tierra del Fuego. They are composed of glacial deposits (Drift Tapera Sur sensu Codignotto and Malumián, 1981) older than Illinoian (older than 400 kyr BP; Pampa de Beta Drift, Río Cullen Drift and Serranías de San Sebastián Drift, sensu Meglioli et al., 1990; Meglioli, 1992, 1994). There are also Tertiary continental silty-sandy deposits (Cullen Formation, Petersen and Methol, 1948; Codignotto and Malumián, 1981). These cliffs are affected by rapid erosion. At Cabo Nombre the cliffs had not retreated between February 1987 and February 1988, but after that, strong swells at spring high tide level (on February 20, 1988, breaker height was greater than 3 m with periods of 9 to 12 seconds) caused a retreat of 3.7 m (Bujalesky, 1990). The effective cliff retreat would be produced by these episodic events although there is also a continuous percolation, freezing and melting action on these weak deposits. These cliffs supplied part of the gravels that have formed the El Páramo spit.

Bahía San Sebastián

This semicircular embayment (55 km x 40 km) occupies a wide, low-relief valley formed by glaciers during the Pleistocene and reshaped by the sea during the Holocene transgression (Fig. 3). It shows different environments including marshes, gravel ridges, cheniers, tidal flats and tidal channels.

Fossil marsh

This is an inactive marsh located landwards of the National Route 3 (Fig. 3; Ferrero et al., 1987; Vilas et al., 1987a, b, 2000; Ferrero and Vilas, 1988, 1989; Isla et al., 1991). A flat surface, formerly drowned seasonally by the sea, was subject to strong deflation after the road construction. Very shallow ponds developed and the roots of small shrubs have been deflated by the westerlies causing their death. Erosion continues and erosive scarp recedes. When the water table emerges, erosion ceases, but the pond continues enlarging towards the east. The cycle closes when the pond or lagoon is naturally silted up by wind-blown material. Blown silt and fine sand are minimum during the winter season, when snow and ice cover the entire area. Blow-outs from this fossil marsh are the principal source of sediment for the marsh and mudflat.

Upper marsh

It is controlled by deflation processes. Circular clumps 1-2 m across, dominated by *Salicornia*, are scattered over the mudflat and evolving in the wind direction: *Salicornia* is progressively buried on the windward sides; *Lepidophyllum* shrubs colonize the top, whereas grass grows downwind (eastern sides).

Gravel ridges

Waves entering the bay are strong enough to transport gravels along its southern coast. They also approach obliquely, causing a gravel beach drift towards the northwest (Fig. 4). The Río San Martín inlet forms the northern limit of these gravel and sand deposits. At the southern coast of the bay, occasional large waves move pebbles up to 20 cm in diameter across the tidal berm. Fossil ridges were constructed during the regressive phase of the sea-level fluctuation. Attached to a palaeocliff sculptured into the Carmen Silva Formation (Miocene siliciclastic deltaic deposits; Codignotto and Malumián, 1981), older ridges span in at least 3 stages, separated by northerly oriented depressions.

Cheniers

North of the Río San Martín, littoral processes have reworked shells and sands and constructed cheniers over the mudflat (Fig. 4). Bivalve, gastropod and equinoid remains are reworked from the subtidal zone to the coast during easterly storms. There are three chenier lineations. The oldest is continuous, and stretches farther north than the others. The most recent consist of 0.8-1 m high ridges separated every 400 m by washover channels (Bujalesky, 1997a). Both, gravel ridges and cheniers, resulted from storms in the bay, and differ due to the fact that the Río San Martín limits the gravel longshore transport.

Tidal flats

Tides move clockwise within the bay, and grain size progressively decreases in the same direction. This northward transition from sand to mudflats reverses in the tidal flat slope, where sand increases to the lower portions with persistent wave action. The sand flat extends in front of the gravel ridges and constitutes a monotonous, barren of channels rippled or flat surface. The mixed flat, extending from the village San Sebastián to the Río San Martín inlet, is characterized by flaser, wavy and lenticular bedding. The mudflat occupies the widest area (10 km) of the tidal flat. It comprises an upper zone, very

TABLE 1 **Quaternary stratigraphy of the notheastern region of Tierra del Fuego island (after Bujalesky et al., 2001; Bujalesky and Isla, 2005). Glacial stratigraphy after Meglioli, 1992. ^{18}O isotope stages referred to Shackleton (1995). Altitude m a.s.b.: meters above present storm berm.**

Stratigraphic name: Regional	Stratigraphic name: Local	Latitud (S) Longitude(W)	Fossil content	Absolute ages	Altitude m a.s.b.	^{18}O isotope stage	Ages
Holocene Transgression	San Sebastián Formation (Codignotto, 1979)	53°33'29" 68°03'30"		5918 +/- 44 ka 14C AA65166	1,31	1	Holocene
Segunda Angostura Glaciation (Meglioli, 1992)	Bahía Inútil Glaciation (Meglioli, 1992)			> 16 ka 14C		2	Upper Plesitocene
Interglacial	La Sara Formation (Codignotto, 1979)	53°30°12" 68°05'46"	*Eurhomalea exalbida, Pitar rostrata*	82 U ka	6-8	5	
Primera Angostura Glaciation (Meglioli, 1992)	Lagunas Secas Glaciation					6	Middle Pleistocene
Interglacial	Shaiwaal Formation (Bujalesky and Isla, 2005)	54°04'47" 68°15'38"			12	7	
Punta Delgada Glaciation (Meglioli, 1992)	San Sebastián Glaciation (Meglioli, 1992)					8	
Interglacial	Las Vueltas Formation (Bujalesky et. al., 2001)	53°34'19" 68°02'59"	*Eurhomalea exalbida*	300? U ka	19	9	
Cabo Vírgenes Glaciation (Meglioli, 1992)	Río Cullen Glaciation (Meglioli, 1992)			<1.07 Ma Ar/Ar		10	
Interglacial	Laguna Arcillosa Formtion (Bujalesky et al., 2001)	53°34'26" 68°02'37"	*Eurhomalea exalbida Mytilus edulis chilensis, Trophon geversianus, Adelomelon ancilla*	400-600? U ka	23	11?	Lower Pleistocene
Sierra de los Frailes Glaciation (Meglioli, 1992)	Pampa de Beta Glaciation (Meglioli, 1992)			<1.04? Ma Ar/Ar		12	
Interglacial	Viamonte Formation (Bujalesky and Isla, 2005)	54°02'40" 67°19'32"			38	13-15	
Glaciation						16-22?	
Interglacial	Najmishk Formation (Bujalesky and Isla, 2005)	54°03'21" 67°17'43"			53	25 –31	
Río Grande Glaciation	Río Grande Glaciation			>1.86 <2.05? Ma K/Ar		¿64-74?	Pliocene
	Cullen Formation (Petersen and Methol, 1948)		*Nothofagus* sp.	2.2 Ma			Middle Pliocene
Interglacial	Raised gravel beach of Cerro La Arcillosa	53°34'50" 68°01'59"	*Cyclocardia velutina*	3-4 Ma	79	¿K1-G15?	

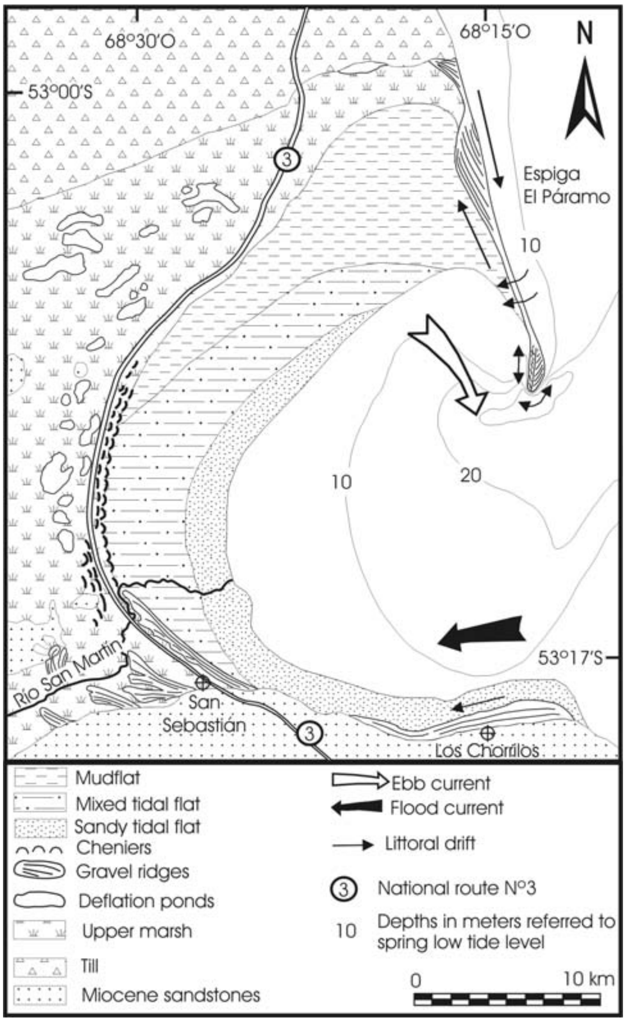

FIGURE 3 | **Morphology, sedimentology and dominant processes in Bahía San Sebastián (modified after Isla et al., 1991). See location in Figure 1.**

flat and uniform, and a lower zone, where meandering tidal channels are more frequent.

Tidal channels

The mudflat has drainage of meandering tidal channels reaching sizes over 3 m depth and 50 m width. Within the channels, there is a rapid evolution of point bars, and slumping. Sediment transport in these channels increases significantly during spring tides, and during winter, when cold water and ice are able to carry higher sediment loads and larger particles (fine sand).

Península el Páramo

Península El Páramo is a 20 km long gravel spit barrier that closes partially the San Sebastián Bay by the east and ends at a 36 m deep channel (Fig. 5). El Páramo Spit not only has grown longitudinally southward but receded to the west and encroached the tidal flat, and so evolving as a transgressive spit. The northern part of Península El Páramo shows a beach ridge plain, where the oldest ridges are parallel to a palaeocliff with a west-east orientation and the younger ones developed a concave shoreline in plan view. Another beach plain of over 200 ridges (1,200 m wide, 8 km long) develops to the south showing a north south alignment and a landward convex shoreline.

The northeastern trending, coarse gravel beach ridges are the oldest ones and are cut by marine erosion. At the Bay Shore, the ridges are growing northward and represent an episodic onshore progradation of gravel over the tidal flat. These two beach-ridge complexes represent different stages of the spit growth under progressive wave

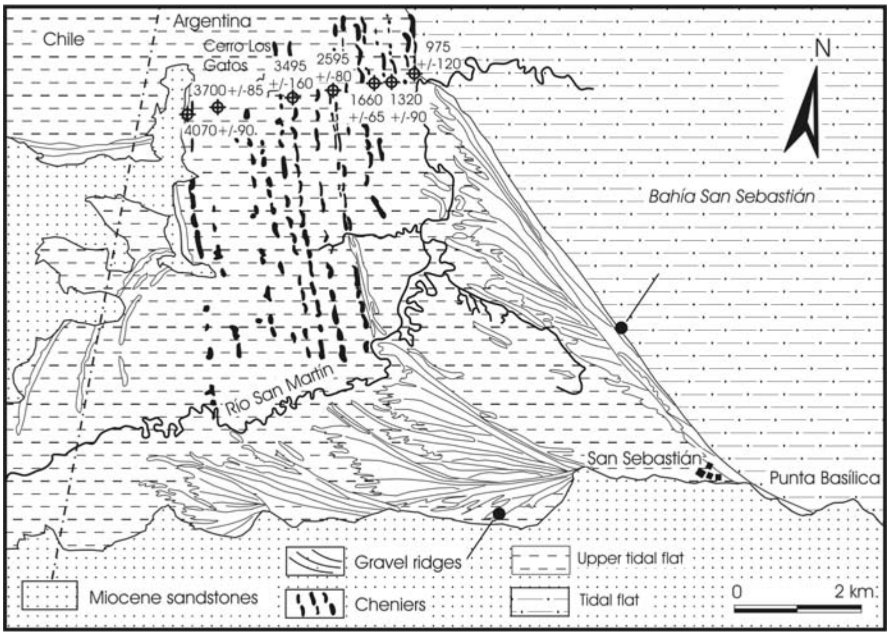

FIGURE 4 | **Within the San Sebastián Bay there is a gravel beach drift towards the Río San Martín. The Río San Martín gravel beach plain evolved previously to 4,000 years B.P. and continued to 975 years B.P. North of this inlet, there is no drift of sediment and storms reworked the mudflats to accumulate episodically shelly cheniers (modified after Vilas et al., 2000). See location in Figure 3.**

energy diminishing to the bay side as consequence of the tidal flat progradation.

The central sector (7 km long) presents parallel shorelines and is 50 m wide at high tide and 200 m wide at low tide. In this sector washover channels occur sloping towards the bay. They are active during sea storms or during spring tides with strong Atlantic swells. Overwash contributes to the lateral spit migration over the tidal flat.

The southern sector has a triangular shape. Its maximum width is 900 m and its length is 2 km. The western side comprises 60 coarse gravel beach ridges. The youngest ones are asymptotic to the present shoreline while the oldest ones have been eroded. On the eastern side, there are an equivalent number of beach ridges that are cut by erosion in its northern section. The beach ridges on both sides imbricate along a central line that is almost parallel to the present western shoreline. The shape of the southern sector is controlled by the relief of the abrasion platform. The channel that bounds the spit has probably a glacial-fluvial origin. The gravel thickness in this sector is estimated in 20 m.

The Atlantic beach is formed by boulders, gravel and sand. The difference in elevation between the beach crest and the toe of the beach is 9.5 m to the north increasing gently to the south because of the topography of the abrasion platform. Five zones can be differentiated in this beach (Bujalesky, 1988, 1990): storm berm (width 15 m, gradient 3.5°), storm swash terrace (width 25 m, gradient 2°), tidal berm (width 10 m), high intertidal (width 50 m, gradient 7°, reflective beach), low intertidal (width 70 m, subhorizontal, dissipative beach).

The bay beach is 100 m wide to the south with 10 m of difference of elevation and 50 m wide at 10 km to the north of the spit point with a difference of elevation of 7 m. It consists mainly of gravel. Four zones are differentiated: storm ridge, tidal ridge, intertidal (gradient: 4-6°) and gravel pavement.

Paleoembayment of the Río Chico basin (Punta Sinaí to Cabo Domingo)

Diverse Pleistocene and Holocene coastal environments can be recognized in the Río Chico area (Fig. 6). The Río Chico basin was affected by processes related to the Quaternary glaciations and transgressions. The basin occupies a relative higher topographic position than the contiguous areas (Bahía San Sebastián northwards and Río Grande southwards) and it was free of ice during the last four or five glaciations, approximately since 1.8 Ma B.P. (Meglioli, 1992, 1994). Even though, melt water streams generated gravel alluvial fans. During marine interglacial stages, these sediments were re-worked by littoral processes that formed gravel beach-ridge plains. The interlobe position of the area during modern glaciations contributed to the preservation of glacio-fluvial bedforms

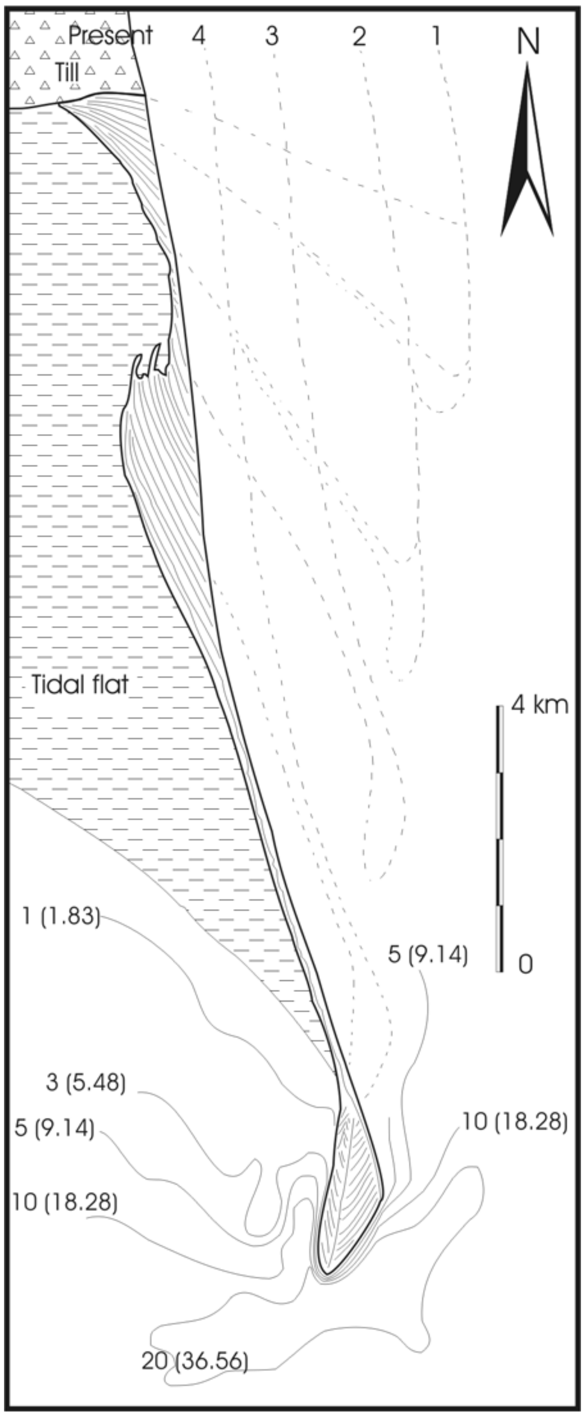

FIGURE 5 | **Morphologic features and sedimentary evolution of El Páramo spit (Bujalesky, 1990). 1, 2, 3, 4: successive stages of growing of El Páramo spit as from an initial cuspate foreland (1). 1(1.83): depths in fathoms and meters, respectively, referred to SLTL. See location in Figure 3.**

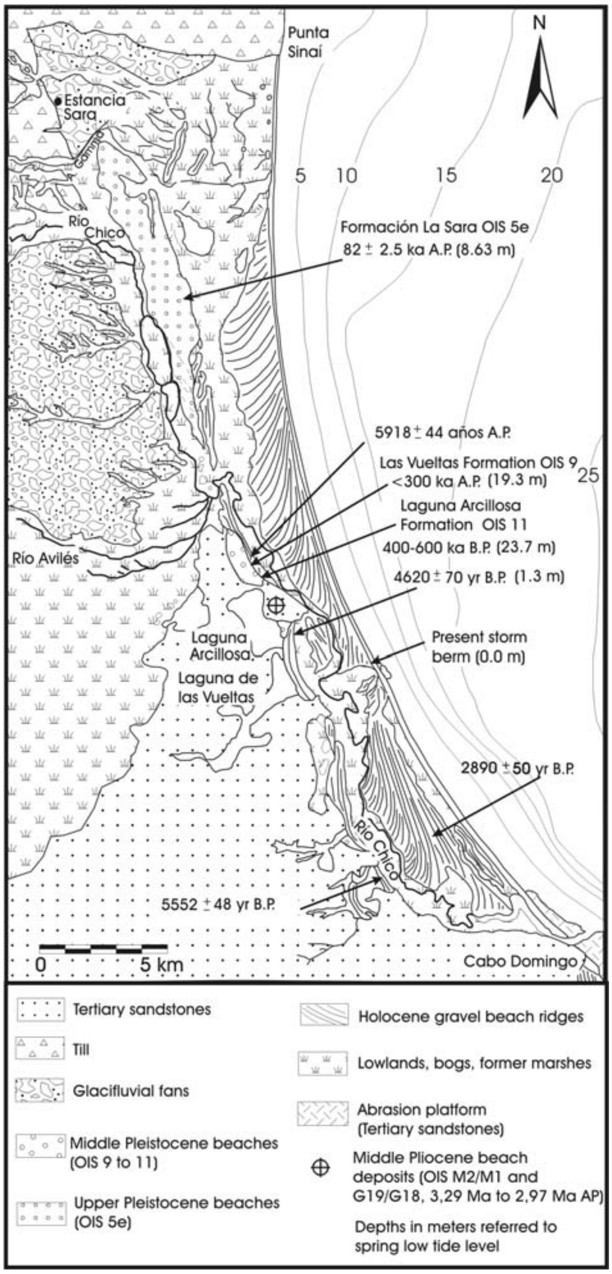

FIGURE 6 | **Morphology, and Pleistocene and Holocene sedimentary environments in the Río Chico area. See table 1 for altitudes of absolute dated units. Depths in m referred to the spring low tide level. See location in Figure 1.**

that were only affected by minor, local glacifluvial processes and littoral erosion at their eastern flank and by littoral interglacial deposits.

Low grade seaward sloping wet lowlands and seasonal ponds develop in between Tertiary highlands, westward of Río Chico (Fig. 5). Other reduced Pleistocene raised beaches occur following the eastern Tertiary highland boundary, also westward of Río Chico. Holocene small gravel beaches, barriers and spits developed attached to the base of this line and at the base of the eastern margin of the main exposure of the Upper Pleistocene littoral deposits. One of these gravel barriers plugged the tidal inlets of the La Arcillosa and de las Vueltas lagoons (53°35'19"S-68°1'27"W). Radiocarbon dating performed on valves of *Mytilus* sp of this fossil barrier was dated on 4620 ± 70 ^{14}C years B.P. (LP-1011). This fossil barrier reach an altitude 1.31 m higher than the present storm berm and it would indicate a relative sea level fall of 0.214 m/ka. Radiocarbon dating performed on mollusk valves from another older gravel beaches provided ages of 5,918 ± 44 ^{14}C years B.P. (AA65166; 53º33'30"S-68º03'30"W) and 5,552 ± 48 ^{14}C years B.P. (AA65167; 53º40'06"S-67º57'30"W; Fig. 6).

The shape of some of these former Holocene features suggests a northward growth, meanwhile others, located in more restricted embayments, do not show a prevailing longshore transport direction, appearing as swash-aligned beaches.

An extensive beach-ridge plain develops eastward of the Río Chico enclosing Holocene estuarine facies. The beach ridges represent successive stages of growth to the south and have caused the Río Chico inlet migration in that direction (Bujalesky, 1998). The oldest beach ridges were totally eroded; the northern ones are cut by erosion and the southern and younger ones tend to be asymptotic to the present shoreline. A radiocarbon dating of one of these distal fossil beach ridges, located 2 km landward from the present shoreline, indicated an age of 2890 ± 50 ^{14}C years B.P. (LP-1073; Isla and Bujalesky, 2000; Fig. 6). The younger and distal beach ridges were eroded and the growing of a later flying spit caused a lagoon formation. This process would indicate discontinuous pulses of sediment supply and a relatively scarcity of sediment supply to maintain beach stability under strong longshore drift conditions. The development of the beach ridge plain has followed the palaeorelief of the erosion platform of relatively uniform depth, all along the NS direction of progradation.

Paleoembayment of the Río Grande basin (Cabo Domingo to Cabo Peñas)

A narrow Holocene gravelly beach ridge plain (250 m wide) develops between Cabo Domingo and the Río Grande inlet, attached to the base of an Upper Pleistocene marine terrace (Oxygen isotope stage 5e, 18 m a.m.s.l.). This terrace represents a former delta of the Río Grande (Halle, 1910). The Holocene beach ridges have grown to the southeast drifting long 5 km of the La Misión rivulet mouth and growing towards inside the Río Grande estuary (Fig. 7).

At the present alluvial plain of Arroyo La Misión (10 km north of the city of Río Grande, Fig. 7), a former Pleistocene

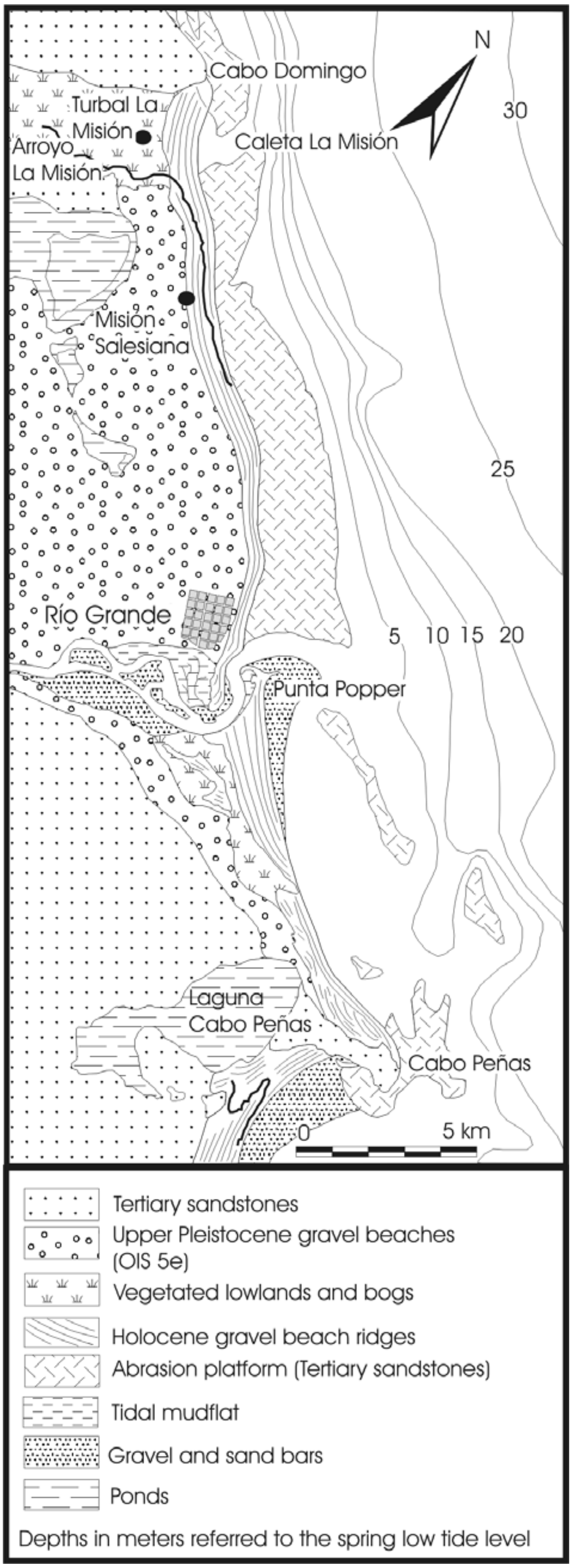

FIGURE 7 | **Morphology of Holocene beach ridges between Cabo Domingo and Cabo Peñas. Depths in metres referred to SLTL. See location in Figure 1.**

glaciofluvial valley carved on Tertiary rocks was filled with sediments of changing origins. The uppermost portion of the sequence recorded the Holocene transgression (Auer, 1959, 1974; 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 9,000 ^{14}C years B.P. and a tidal flat developed at an altitude of 0.9 m a.h.t.l. at 4,000 to 2,000 ^{14}C years B.P. (Mörner, 1991).

A wide abrasion platform (up to 3 km wide) carved on Tertiary sandstones develops seawards of the shoreline. A narrowing beach ridge plain develops southward of the Río Grande inlet, showing a northward grow direction and erosion of its oldest and southern components. An interlacing beach ridge complex is attached to the northern base of Cabo Peñas cliff.

Río Grande inlet and Punta Popper spit

The Río Grande inlet is controlled by macrotides and high-energy waves, where processes and littoral forms related to both domains can be recognize depending u pon the state that the system is recording. A gravel spit barrier (Punta Popper) is located at the downdrift side of the inlet (Fig. 8).

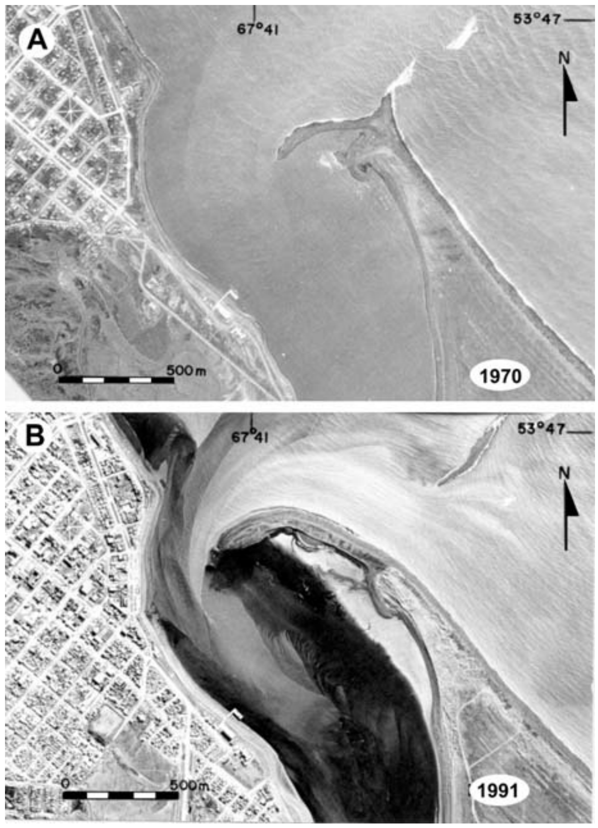

FIGURE 8 | **Río Grande inlet and Punta Popper spit in 1970 (A), and 1991 (B) (tidal levels of 7 and 5 m, respectively). Note the urban advance over the tidal flat and the storm beach since 1970 (Bujalesky, 1997b). See location in Figure 7.**

Punta Popper spit has grown in a direction opposite to the regional drift. This behaviour is generated by the interaction between strong ebb tidal currents and the refraction of northeastern waves on a broad abrasion platform. Under these conditions, a clockwise sediment circulation cell operates seaward from the inlet (Fig. 9).

The historical evolution of the spit involves 10 to 13 years cycles of longshore growth, landward retreat and breakdown (Fig. 10; Bujalesky, 1997b). Longshore growth is mainly due to sediment transport and erosion of the backbarrier beach by ebb tidal currents. Wind waves develop in the estuary waters at high tide and favor the initiation of sediment motion. Littoral drift on the seaward side of the spit has a secondary role. Sluicing overwash provides sediment to the backbarrier beach and causes a landward migration. When the spit reaches its maximum possible length, overwashing sediment supply is insufficient to compensate the eroded volume at the backbarrier. Then the landward migration rate of the shoreface might be faster than the backbarrier. The throat of the inlet is anchored in bedrock; it does not migrate significantly, becoming unstable with its minimum flow area reduction (Fig. 9). These facts cause the breakdown of the spit barrier. A transverse bar fixed to the shoreface of the spit forms as consequence of the reduction of the minimum flow area, where stronger ebb tidal currents meet the waves. After the spit barrier breakdown, minimum flow area increases, ebb tidal currents velocities diminish and waves recycle the transverse bar sediments.

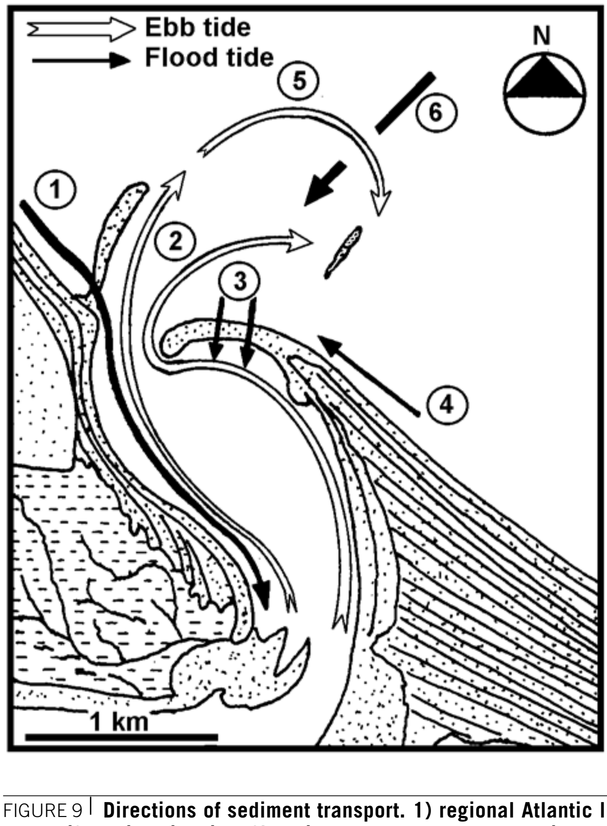

FIGURE 9 | **Directions of sediment transport. 1) regional Atlantic littoral drift, during high tide; 2) sediment transport due to ebb tidal currents; 3) overwashing due to Atlantic swells at spring tide; 4) local littoral drift due to wave refraction; 5) interaction between ebb tidal currents with Atlantic waves; 6) landward migration of subtidal bars (Bujalesky, 1997b). See location in Figures 3 and 7.**

Cabo Peñas and Punta Popper beach-ridge plains

The Cabo Peñas and Punta Popper beach-ridge plains evolved in an area of wave refraction induced by the Gusano and Exterior rocky platforms (called Banks). Waves coming from the NNE to the E suffer divergence of orthogonals (Bujalesky, 1997b). The Cabo Peñas Holocene beach-ridge plain is at the foot of a palaeocliff carved on Upper Pleistocene coastal deposits (La Sara Formation, OIS 5e) and underlying Tertiary sandstones. This Sangamonian terrace encloses a coastal lagoon (Cabo Peñas Lagoon) formed behind a tombolo (Cape Peñas tombolo). The offset of the beach ridges shows a supply of gravels from the north, with periods of littoral reworking. The southern ridges are attached to the cape, and indicate a drift towards the southeast (Fig. 11). On the northern extreme of the plain, the Punta Popper Spit is a set of beach ridges that are today growing northward, next to the Río Grande inlet In a quarry south of Punta Popper, the Holocene beach-ridge plain is composed of more than 4 m of sandy gravels that dip to the northeast.

The Cabo Peñas lagoon have not ever been connected northeastwards to the sea during the Holocene (it was limited by the Sangamonian Terrace). However, the southern gravel beach-ridge plain was formed during the Holocene, and therefore the lagoon was connected to the sea at the south.

The Cabo Peñas beach is locally reworked by wind action. A narrow foredune (up to 1.5 m high) today indicates places where sand availability exceed that of gravel and therefore permits the formation of foredunes (fixed by vegetation). This aeolian activity is more pronounced at Ensenada de la Colonia beach (south of Cabo Peñas), where littoral dunes are fixed by grass.

Ensenada de la Colonia beach ridge plain and Río Fuego spit (Cabo Peñas to Cabo Auricosta)

Ensenada de la Colonia is a shallow embayment where a wide abrasion platform develops carved on Tertiary silty sandstones (Cabo Peñas Formation, De Ferrariis, in Fossa Mancini et al., 1938; Codignotto and Malumián, 1981). The subtidal topography of the abrasion platform shows the existence of former glaciofluvial valleys (Fig. 12; Bujalesky and Isla, 2005). A gravel beach ridge plain (1,100 m wide) develops at this embayment. Three sets of

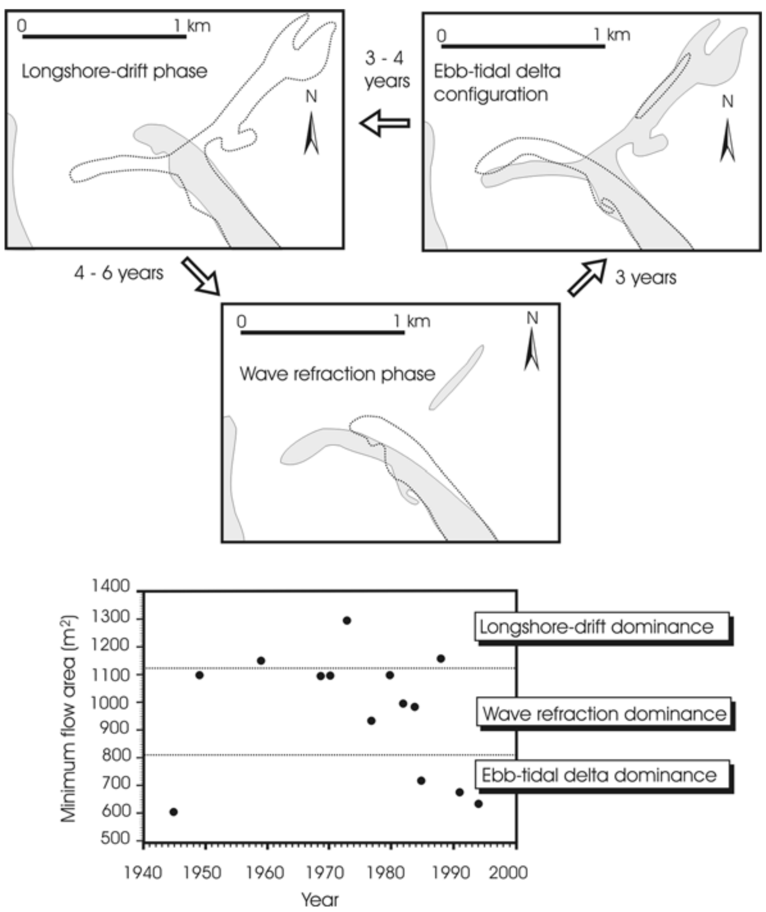

FIGURE 10 | **Evolutionary cycle of Punta Popper spit and minimum flow areas of Rio Grande tidal inlet (areas below the mean tide level obtained after soundings performed by the Servicio de Hidrografía Naval, 1994). See location in Figure 7.**

gravel beach ridges can be distinguished taking into account their altitude referred to the present storm berm. The oldest set is at 2.9 m a.s.b, the intermediate set is at 2.25 m a.s.b. and the youngest set is at 1 m a.s.b. Lowlands develop between the beach ridge plain and smooth hills composed of Tertiary sandstones. These vegetated and saturated lowlands correspond to former marshes, nowadays inactive because of the seaward connection closure during Holocene times.

An Upper Pleistocene gravel beach ridge plain was recognized at the central part of Ensenada de la Colonia. This deposit corresponds to the last interglacial stage (Oxygen Isotope Substage 5e, La Sara Formation). It reaches a difference of level of 6.15 m to the present storm berm. Its eastern margin develops a former erosive scarp carved during the Holocene transgression. A small relict of a Middle Pleistocene gravel beach (0.6 m thick) is exposed on the top of a scarp carved on Tertiary sandstones at the southern margin of Cabo Peñas pond (Fig. 12). Its top is 11.85 m high referred to the present storm berm crest. This fossil beach probably corresponds to the Oxygen Isotope Stage 7. On the other hand, the bed of Cabo Peñas pond is 1.5 m below the present storm berm indicating that this area was a huge lagoon during the Holocene transgression.

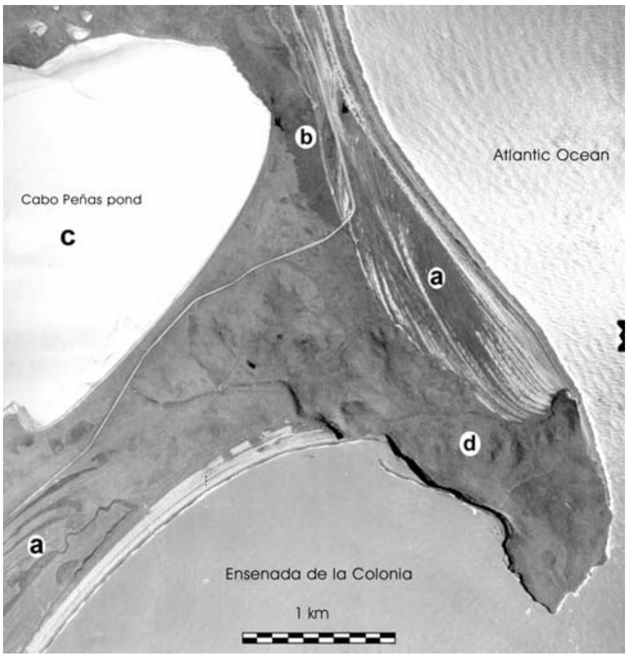

FIGURE 11 | **Aerial photograph of the Holocene beach-ridge plain (a) and the Upper Pleistocene coastal terrace (b) from Cabo Peñas. The Cabo Peñas coastal lagoon (c) is located to the west. Both coastal systems are formed as a tombolo constructed from the Cabo Peñas tertiary deposits (d). See location in Figure 7.**

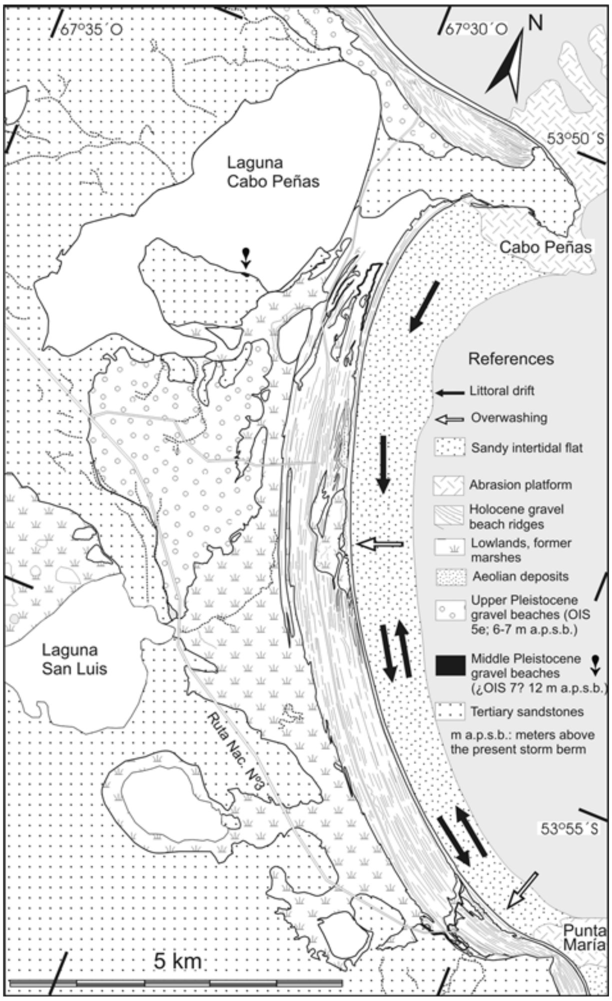

FIGURE 12 | **Geomorphology and Quaternary littoral deposits of Ensenada de la Colonia. See location in relation to Cabo Peñas in Figure 7.**

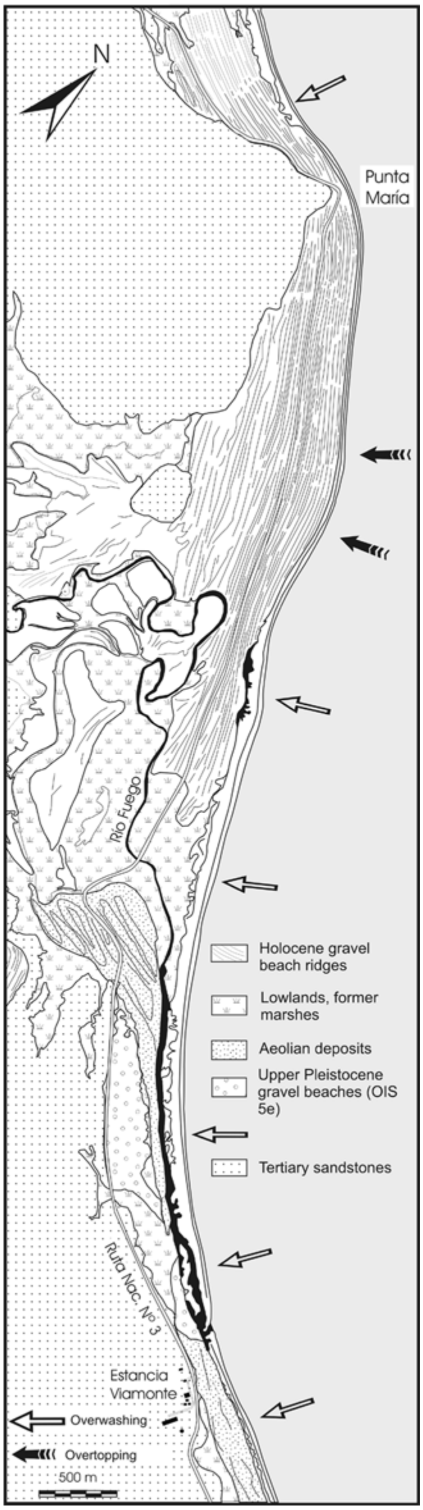

FIGURE 13 | **Geomorphology and Quaternary littoral deposits of Río Fuego region. See location in Figure 1.**

Another Holocene shallow embayment (3.7 km wide) develops southwards Ensenada de la Colonia (Fig. 13; Bujalesky and Isla, 2005). Nowadays, this embayment is mainly filled by littoral in origin gravel and coarse sand and in less proportion by fluvial sediments. Fuego River flows in this environment drifting southward along 5 km because of gravel beach ridges growth. The altitude of the oldest and the youngest beach ridges is relatively uniform in this area. The youngest beach ridges are connected with the youngest ones of Ensenada de la Colonia. Punta María did not work anymore as a cape in a relatively recent past and was over passed by the southward downdrift growth of gravel beach ridges of Ensenada de la Colonia. The modern beach ridges developed an incipient cuspate foreland 2 km southward Punta María. A 4 km long solitary beach ridge develops to the south drifting the Fuego River inlet. The inner flank of this unit presents numerous washover fans and the inlet of Fuego River may be plugged by a gravel and sand deposition. The inlet of Fuego River migrated 400 m to the south during the last 30 years (13 m/year). Figure 13 was drawn after 1970 aerial photographs. At present the Fuego River inlet is located in front of the main building of Estancia Viamonte.

Discussion. Holocene Sea Level Changes and evolutionary trends in the Atlantic Coast of Tierra del Fuego

At the present alluvial plain of Arroyo La Misión (Fig. 7) a Holocene lake (at a present level of 5.7 m below high tide level) was flooded by the marine transgression about 9,000 ^{14}C years B.P. and a tidal flat developed at an altitude of 0.9 m a.h.t.l. at 4,000 to 2,000 ^{14}C years B.P. (Mörner, 1991).

At Bahía San Sebastian (Figs. 1 and 3), the Holocene sedimentation took place after the sea-level rise and a later stillstand. The initiation of this sequence is not precisely dated but a radiocarbon date indicates a minimum age of 5270 ± 190 yrs B.P. (Vilas et al., 1987b; Ferrero et al., 1989; Isla et al., 1991; Vilas et al., 2000). The 8 km wide sequence of cheniers (Fig. 4) developed between 5,270 and 1,080 ^{14}C years B.P., suggests a sea-level fall of 1.8 m (0.363 m/1000 year). Each of these chenier alignments originated every 300-400 year (Ferrero et al., 1989). The San Sebastián bay is partly closed by El Páramo gravel spit (22 km long; Fig. 5). The growth of El Páramo Spit took place at least in the past 5,000 years. Sediment supply was provided from coastal or submerged glacial deposits. Initially, a cuspate foreland developed in the north. Gradually, the spit extended from the tip of the cuspate foreland due to sediment input from the Atlantic shoreline. This detritus formed the fossil beach ridges facing toward the bay in the northern part of the spit. As the spit grew along shore, sediment feeding to the northern shore of the bay diminished. The Atlantic shore was eroded and gravel from the fossil ridges was recycled (Bujalesky, 1990; González Bonorino and Bujalesky, 1990; Bujalesky and González Bonorino, 1991; Isla and Bujalesky, 1995). The leveling across the older beach ridges originated at the bay flank of the spit suggests that relative sea level fell slightly, or was stable, during its growth. The approximately 1 m-altitude decrease from the oldest (eastern) beach ridge to the youngest (western) can be explained by a fetch shortening and a decrease in wave energy within the bay as consequence of the tidal flat progradation. The development of wave-cut platforms off Bahía San Sebastián and the continued spit transgression support the conclusion of a relative stable sea level during the last 5,000 years (Bujalesky, 1990; Bujalesky and González Bonorino, 1990, 1991). At San Sebastián tidal flat, the seaward gradient of the supratidal high-energy wave formed deposits would be partially the result of diminishing in wave height within the bay in response to spit growth and progressive protection from Atlantic swells (Bujalesky, 1990; Bujalesky and González Bonorino, 1990).

The fossil gravel barrier that plugged de las Vueltas lagoon (Río Chico area; Fig. 6) indicates a relative sea level fall of 0.214 m/ka, significantly less than the observed at Bahía San Sebastián, even though part of this gradient could be attributed to wave dynamics processes, such as a higher storm wave set-up.

The geomorphology and evolutionary trend differences between Bahía San Sebastián Bay (Figs. 3 to 5) and the Río Chico palaeoembayment (Fig. 6) essentially arise from the underlying palaeorelief carved during Pleistocene glaciations on Tertiary rocks. The palaeoembayment of Río Chico developed in an interlobate position and it was relatively little disturbed by fluvial or glacifluvial discharge during the Middle Pleistocene. The low gradient palaeorelief of the extensive and shallow subtidal platform allowed the formation of regressive gravel beaches and marsh environments in wave-protected areas. These facts favoured the preservation of fossil beach relicts. During the Pleistocene transgressions, the area located at the present confluence of Chico and Avilés rivers, worked as a tidal inlet, allowing the development of estuarine facies up to 16 km landward, reaching the proximity of Grande, de la Suerte and O'Connor ponds (Fig. 14). During the Holocene and at the Atlantic flank, an extended beach ridge plain grew from the northern margin of the embayment diminishing the wave attack. Its back-barrier side was stabilized by a gradual estuarine infilling. Growth of this beach ridge plain took place under limited sediment input conditions as in Península El Páramo. The progressive elongation was maintained by erosion and sediment recycling (cannibalization), resulting in a significant landward retreat. The downdrift extreme of the beach ridge plain evidences a pulse of sediment scarcity where a lagoon developed between a beach ridge plain and the outer beach ridge (Fig. 15). This fact shows a senile stage of the system where recycled sediments result scarce to support downdrift growth under a significant longshore currents.

Ensenada de la Colonia and Fuego River basin show regressive facies. The gravel beach ridges have developed on a shallow and abrasion platform under a balanced condition of sediment supply and transport. The continuity of the gravel beach ridges between Ensenada de la Colonia and Fuego River embayments at Punta María paleocape indicates a sediment overflow and a very mature stage of the littoral system (Bujalesky and Isla, 2005).

At Ensenada de la Colonia, the oldest beach ridges are slightly higher than their counter parts in the northern paleoembayments. This fact could be due to differential tectonic uplift. Moreover, this could be attributed to wave dynamics dissimilarities (higher storm wave set-up) because of the orientation of the embayment and a complex subtidal topography of the abrasion platform. The

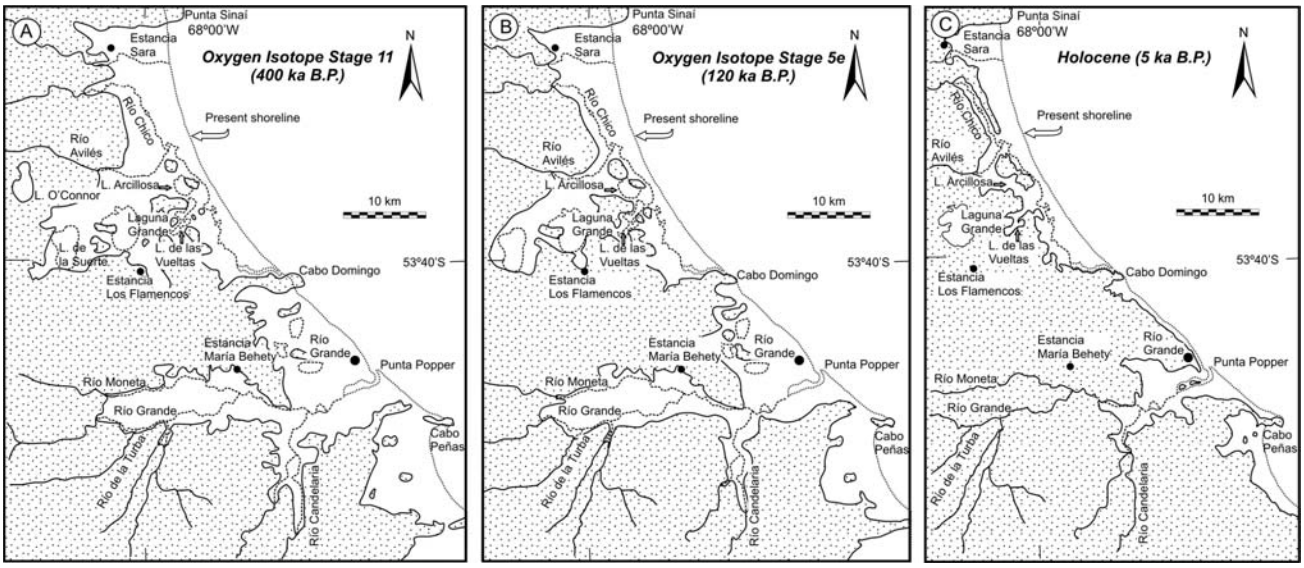

FIGURE 14 | **Oxygen Isotope Stages 11 (A), 5 (B), and 1 (C) transgression boundaries at Río Chico and Río Grande drainage basins. See location in Figure 1.**

existence of former glaciofluvial valleys carved on Tertiary sandstones conditions the wave refraction pattern causing a wave energy concentration in the central part of the embayment (Bujalesky and Isla, 2005).

THE BEAGLE CHANNEL

The Beagle Channel is a 180 km long, 300 m deep and 5 km wide basin. Its eastern section is separated from the Atlantic and Pacific oceans by shallow (40 m deep) and narrows sills (Paso Mackinlay and Murray Channel, respectively; Fig. 16). The Beagle Channel is a tectonic valley that was completely covered by ice during the Last Glaciation. The paleontological evidence of raised littoral deposits indicates that the marine environment was fully established along the channel at least by 7,900 ^{14}C years B.P., reaching a maximum sea-level between 6,000 and 5,000 years B.P. (Rabassa et al., 1986; Gordillo et al., 1992).

The Beagle Channel shows 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 (Fig. 17). 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.

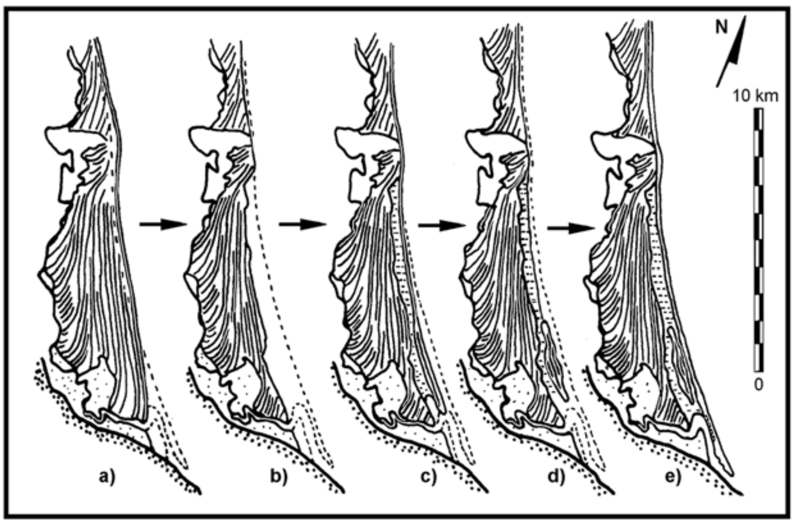

FIGURE 15 | **Recent evolutionary trend of the distal extreme of the Río Chico beach ridge plain (Bujalesky, 1998). a) Development of beach ridge plain under appropriate sediment supply. b) Erosive stage due to insufficient sediment supply under strong southward longshore transport. c) Increase in sediment supply (pulse) as a consequence of cannibalisation of the northern beach ridges. Development of a flying spit and a backbarrier marsh. d) Erosive stage due to scarcity of sediment supply. e) New pulse of sediment supply and present spit formation. See location in Figure 6.**

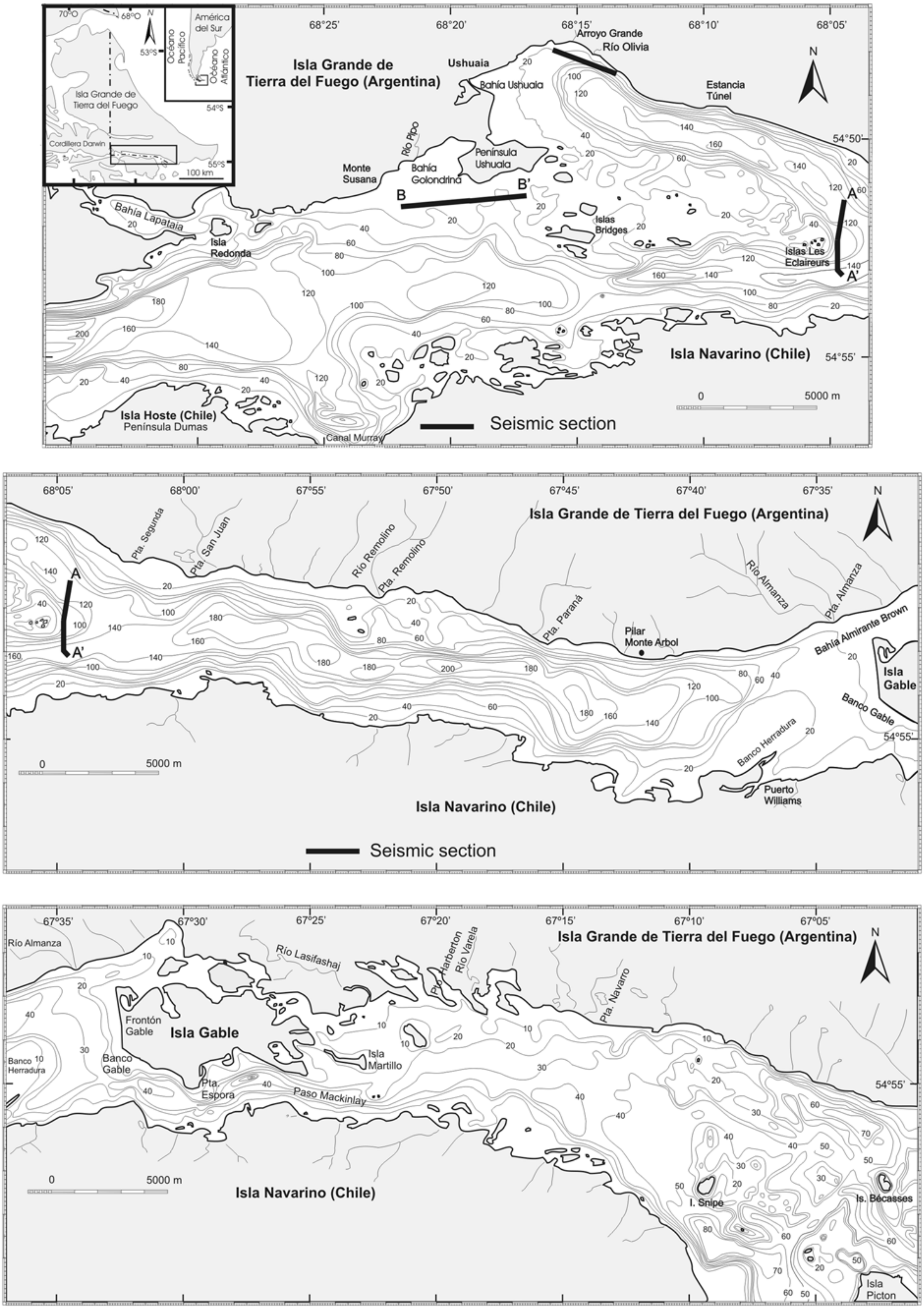

FIGURE 16 | **Beagle Channel bathymetry after Carta H-477, Servicio de Hidrografía Naval, 1969 (depths in metres).**

Mean tidal range is of 1.1 m at Ushuaia and the tidal wave moves from west to east (Servicio de Hidrografía Naval, 1981, 2006). The narrowing (sill) of Isla Gable not only conditions morphologically the fjord dynamics, but also limits 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 offers 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.

A geophysical survey (side scan sonar and 3.5 kHz profiler) carried out in the channel to analyze the surface and sub-bottom sedimentary facies 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 (Fig. 18; Punta Segunda to Faro Les Eclaireurs seismic section). Paleovalleys and submerged fluvial sequences transgressed by marine deposits have been also observed (Fig. 19; Bahía Golondrina, Bujalesky et al., 2004). Submerged deposits with high gas concentration near Isla Gable reveal the development of postglacial peat bogs (Bujalesky et al., 2004).

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. The distinctive features that can be recognized along the Beagle Channel coast are Holocene raised beaches reaching up to 10 m a.m.s.l. and attached to metamorphic rocks or glacial deposits (Table 2). 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 often capped by anthropogenic shell midden deposits.

Playa Larga (‘Long Beach’, Fig. 20, Table 2) 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 years B.P.), 3.8 m (3095±60 ^{14}C year B.P.), 5.2 m (4335±60 ^{14}C years B.P.), 7.5 m (5615±60 ^{14}C year B.P.) and 10 m a.m.s.l. (still undated).

Bahía Lapataia-Lago Roca palaeofjord

The Bahía Lapataia-Lago Roca valley (20 km west of Ushuaia) is a palaeofjord that was occupied by a lateral

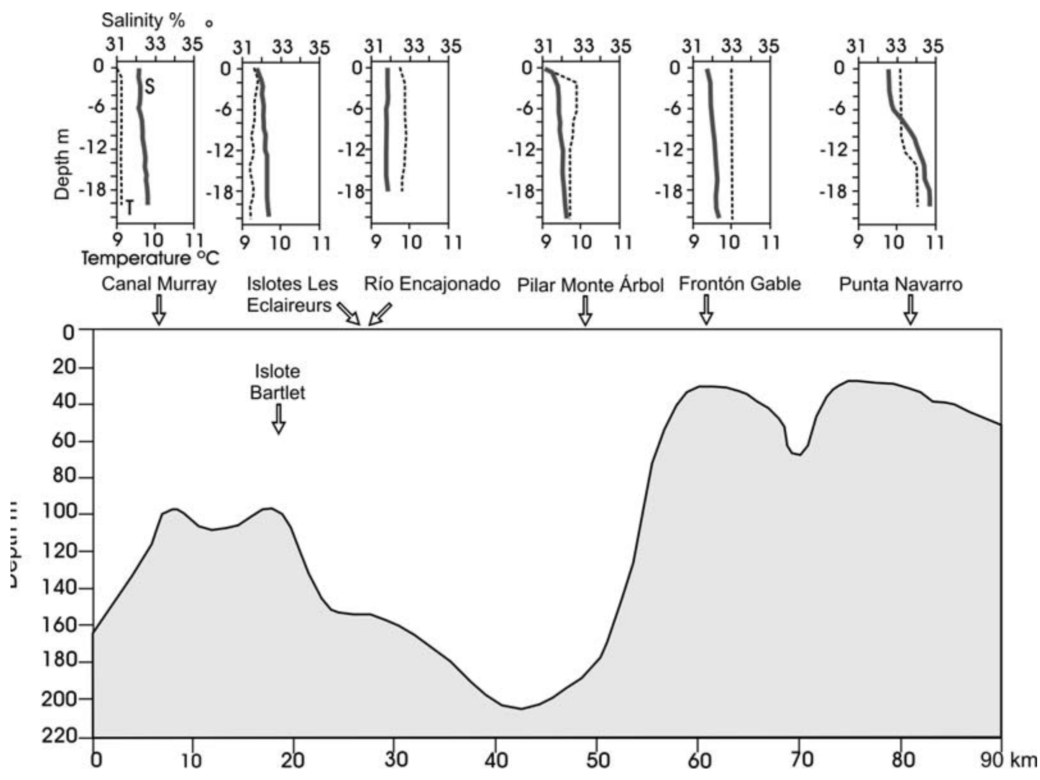

FIGURE 17 | **Salinity and temperature soundings along the Beagle Channel performed in February 1998 (Isla et al., 1999).**

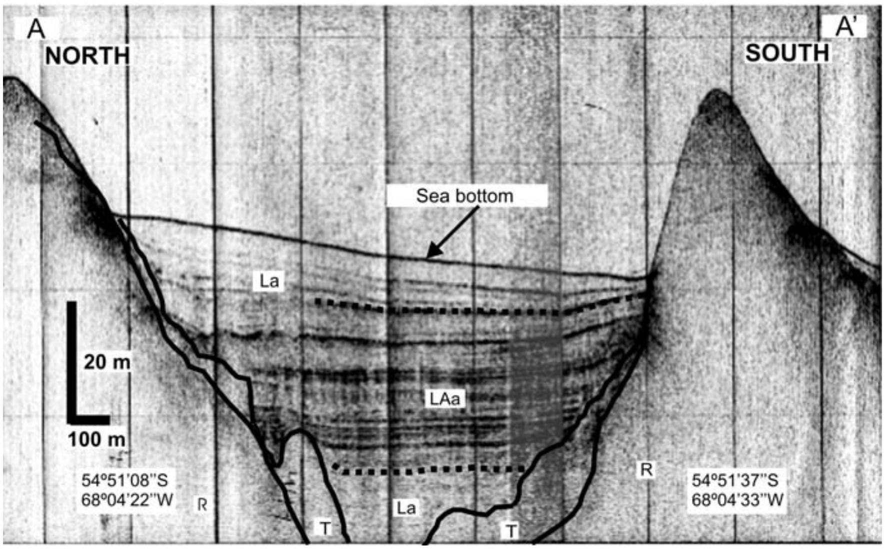

FIGURE 18 **N-S subbottom seismic section of the Beagle Channel from Punta Segunda to Les Eclaireurs Islands performed with a 3.5 kHz profiler. R: Mesozoic metamorphic rocks; T: till; A: gravelly sands; LAa: silty sands; La: sandy silts (Bujalesky et al., 2004). See location in Figure 16.**

and tributary valley-glacier system during the last glacial maximum (18-20 ^{14}C kyr B.P.; Gordillo et al., 1993). Well-rounded glacially formed rocky hills, 'roches moutonnées', lateral moraines and 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 Roca, overlying glacial landforms and reaching a maximum altitude of at least 8.4 m a.s.l. (Fig. 21, Table 2; Gordillo et al., 1993). The cold and shallow-water mollusk assemblages associated to the Beagle Channel raised beaches have not shown significant climatic changes during the Holocene (Gordillo, 1991, 1992, 1993; Gordillo et al., 1992, 1993).

Holocene sea level changes and evolution in the Beagle Channel. Discussion.

Porter et al. (1984) considered that the Holocene relative sea level along the Estrecho de Magallanes and the Beagle Channel reached a maximum altitude of at least 3.5 m above the present sea level about 5,000-6,000 ^{14}C years B.P. and then fell progressively to its present level. These authors proposed a glacioisostatic and hydroisostatic warping as the cause of this sea level behaviour. It is worth mentioning that Porter et al. (1984) records of Puerto Hambre are located at the mainland opposite to Dawson Island and more than 100 km behind the outer limit of the last glaciation. This site presents two raised beaches: a) at 2.05 ± 0.5 m height about 7,980 ± 50 ^{14}C years B.P., and b) at 3.5 ± 0.5 m height about 3,970 ± 70 ^{14}C years B.P. Porter et al. (1984) considered these data as 'apparently anomalous', and interpreted that this area may reflect isostatic response to deglaciation. These authors did not take into account the tectonic setting of the area and that Puerto Hambre is located next to the Magellan Fault alignment. To the North and in an area not affected by tectonic uplift other data were reported: Bahía Gente Grande (3.36 ± 0.15 m, 5,860 ± 40 ^{14}C years B.P.) and Bahía San Gregorio (3.0 ± 0.2 m, 3,860 ± 40 ^{14}C years B.P.; Porter et al., 1984).

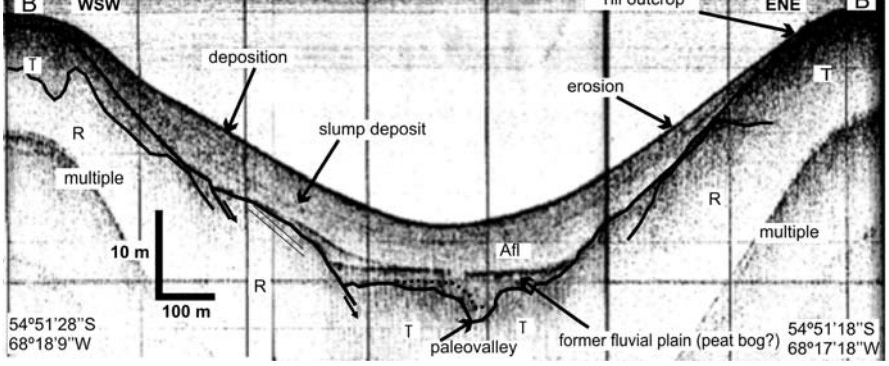

FIGURE 19 **WE subbottom seismic section along Golondrina Bay (Beagle Channel) performed with a 3.5 kHz profiler. R: Mesozoic metamorphic rocks; T: till (Bujalesky et al., 2004). See location in Figure 16.**

TABLE 2 **Radiometric dates from Holocene littoral deposits along the Beagle Channel (refer to Figure 1C for locations).**

Locality	Altitude (m a.s.l.)	Age ^{14}C (BP)	Laboratory Nº	Source
Bahía Lapataia	1.65	8240±60	SI-6737	Rabassa et al. 1986
Bahía Lapataia	1.80	7260±70	SI-6738	Rabassa et al. 1986
Bahía Lapataia	1.95	5800±65	SI-6739	Rabassa et al. 1986
Lago Roca	8.4	5920±90	AC-1060	Rabassa et al. 1986
Lago Roca	3.95	7518±58	NZ-7730	Gordillo et al. 1993
Isla El Salmón	4.30	3860±75	SI-6734	Rabassa et al. 1986
Alakush	5.00	4400±120	AC-0937	Figuerero and Mengoni 1986
Nacientes Río Ovando		4160±45	Pta-7573	Coronato et al. 1999
Río Ovando	3.10	4425±55	SI-6735	Rabassa et al. 1986
Río Ovando Camping		7500±80	Pta-7691	Coronato et al. 1999
Bahía Ensenada	2.20	2120±45	Pa-1012	Gordillo et al. 1992
Bahía Golondrina	10.00	5460±110	AECV-877C	Gordillo 1990
Punta Pingüinos	8.50	5430±270	L-1016C	Urien 1966
Punta Pingüinos	2.50	1400±300	L-1016B	Urien 1966
Ushuaia	8.00	5160±130	AECV-876C	Gordillo 1990
Playa Larga	1.60	405±55	Pa-1017	Gordillo et al. 1992
Playa Larga	3.80	3095±60	Pa-1016	Gordillo et al. 1992
Playa Larga	5.70	4335±60	Pa-1015	Gordillo et al. 1992
Playa Larga	8.00	5615±120	Pa-1018	Gordillo et al. 1992
Punta Paraná	6.00	4370±70	Pta-7686	Coronato et al. 1999
Bahía Brown	1.80	985±135	Pa-1011	Gordillo et al. 1992
Bahía Brown	3.30	2970±70	Pa-1010	Gordillo et al. 1992
Cutalátaca	2.30	2770±50	Pa-1009	Gordillo et al. 1992
Río Varela	-1.26	6290±70	Pta-7581	Coronato et al. 1999
Punta Piedra Buena (Isla Navarino-Chile)	0.65	1470±30	QL-1653	Porter et al. 1984
Península Gusano (Isla Navarino-Chile)	3.55	4600±30	QL-1652	Porter et al. 1984

Rabassa et al. (1986) considered that the present Beagle Channel was occupied by a glacial lake at about 9,400 ^{14}C years B.P., with a level up to 30 m above the present sea level, and the lake water was replaced by seawater before 8,200 ^{14}C years B.P. The marine environment was fully established along the channel at least by 7,900 ^{14}C years B.P. But a 3.5 kHz seismic section showed submerged paleovalleys and fluvial sequences 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 two 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 overpassing Mackinlay and Murray sills, immediately after the Younger Dryas, 11,000 years B.P.

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 years B.P. (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 to 2.0 mm/year for the last 6,000 years (Rabassa et al., 1986; Rabassa, 1987) and it increased up to 2.9 mm/year for the last 1,000 years (Gordillo et al., 1993). The youngest terraces at Playa Larga (405 ± 55 ^{14}C years B.P. at 1.7 m above the present counterpart) and Bahía Brown (985 ± 135 ^{14}C year B.P. 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 Holocene raised beaches are the result of tectonic uplift.

Mörner (1987, 1991) pointed out that the Estrecho de Magallanes (Magellan Straits) and Beagle Channel coasts underwent different uplifting 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 years B.P. to a level only slightly above the pre-

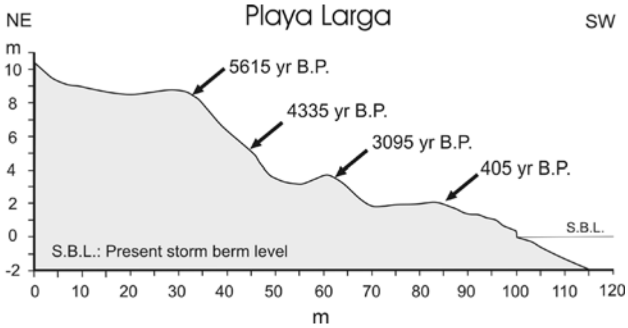

FIGURE 20 | **Profile from Playa Larga site showing location of stratigraphic sections and detailed stratigraphy (Gordillo et al., 1992). See location in Figure 16.**

sent (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 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 m, 4-6 m and 1.5-3 m (Gordillo et al., 1992).

Taking into account the hydrodynamic setting and the morphology at the Beagle Channel, it would be difficult that

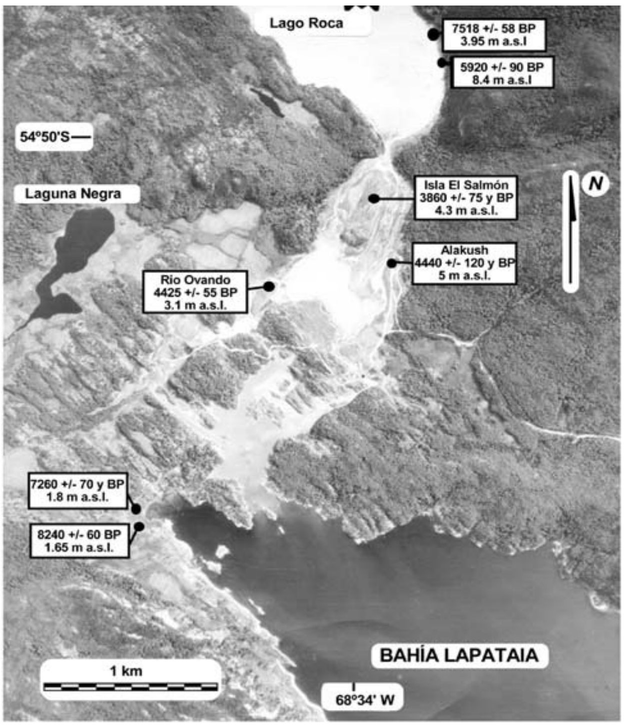

FIGURE 21 | **Lago Roca-Bahía Lapataia palaeofjord. Radiocarbon dating and altitudes of raised beaches after Gordillo et al. (1993). Aerial photograph from the Servicio de Hidrografía Naval, 1970, Buenos Aires. See location in Figure 16.**

the highest wind waves or storm surges entering form the Atlantic side would have been able to build beach ridges 2 m higher than present wave conditions. Earthquake-generated standing waves would have left beach deposits of the same age but different elevations, depending on the shoreline configuration. This fact has not been observed.

The comparison of the Holocene raised beaches between the northern Atlantic coast of Tierra del Fuego (La Misión: Auer, 1974 and Mörner, 1991; Bahía San Sebastián: Ferrero et al., 1989) and the northwestern coast of Beagle Channel (Punta Pingüinos: Auer 1974; Bahía Golondrina: Gordillo, 1990; Playa Larga: Gordillo et al., 1992) indicate differential tectonic uplifting rates of 1.2 ± 0.2 mm/year for the last 7,760 ^{14}C years B.P., 1.3 ± 0.3 mm/year for the last 5,400 ^{14}C years B.P. and 1.2 ± 1 mm/year for the period comprised between 7, 760 and 5,400 ^{14}C years B.P., respectively.

CONCLUDING REMARKS

The study of the geomorphological features in the NE Atlantic coast of Tierra del Fuego results in some outstanding conclusive remarks:

1. In northern Tierra del Fuego occur the southernmost Pliocene and Pleistocene beaches recorded in the world. The Pleistocene littoral deposits were recognized at levels of 53, 38, 23, 19, 12 and 8 m a.s.b. and would probably correspond to the Oxygen Isotope Stage 25-31, 13-15, 11, 9, 7 and 5, respectively.

2. The interlobate position of the area located between San Sebastián Bay (NE Atlantic coast) and Lago Fagnano glacial valleys, the semiarid climate conditions and the limited fluvial erosion during the later glaciations contributed to the preservation of these Pleistocene littoral deposits.

3. Glacial-fluvial deposits were the main sediment supply source for the formation of gravel beaches along the Atlantic coast of Tierra del Fuego; these gravels were recycled many times by littoral processes during the Quaternary interglacial episodes.

4. The littoral deposits along the northeastern Atlantic coast show noticeable dissimilarities in their geomorphological and evolutionary trends. These dissimilarities mainly arise from the influence of the underlying palaeorelief that dips northwards and was carved during the older Pleistocene glaciations.

5. The distinctive characteristic of the Holocene littoral deposits at the northern Atlantic coast of Tierra del

Fuego is the presence of regressive-like sequences at protected areas, meanwhile transgressive-like beach facies have developed at exposed areas.

6. In the northern Atlantic coast, several evidences indicate a very mature evolutionary stage: infilled shallow palaeoembayments (Río Chico), progressive spit thinnings (El Páramo), spit cannibalizations (El Páramo, Río Chico), overpassed headlands resulting from bay infilling (Punta María-Ensenada de la Colonia). During the Holocene, the growth of the northernmost and exposed gravel beach-ridge plains of the Atlantic coast took place under limited sediment supply. The progressive elongation was sustained by erosion and sediment recycling (cannibalization) at the seaward flank, resulting in a significant landward retreat. The younger and distal beach ridges show evidence of sediment starvation pulses.

7. The extensive and gentle supratidal gradient of chenier alignments of San Sebastián Bay (1.8 m for the last 5,270 ^{14}C years; Ferrero et al., 1989) would be partly due to progressive diminishing wave set-up, as a consequence of spit growth operating like a natural jetty. Littoral forms have developed under relatively stable eustatic conditions since 5,000 years B.P.

8. The inner estuaries of the Río Chico palaeoembayment (northern Atlantic coast) were plugged approximately 5,000 years B.P. in coincidence with the highest Holocene sea level. The altitude of the fossil barrier that plugged former lagoons indicates a relative sea level fall of 0.214 m/ka. Part of this gradient could be also attributed to wave dynamics processes, such as a higher storm wave set-up.

Moreover, the following conclusions may be remarked in relation to the evolution of the Beagle Channel zone:

9. The tectonic uplift during the last 8,000 years was maximum at the western Beagle Channel (approx. 1.2 ± 0.2 mm/year) and diminished northwards and eastwards. It seems to be negligible at the northeastern Atlantic coast of Tierra del Fuego. The glacial isostatic rebound at Beagle Channel seems to have operated during deglaciation or in a 1-2 milennia after the final ice recession.

10. Different ancient sedimentary environments were recognized in subbottom sections of the Beagle Channel: basal moraines, glacial retreat fining upward sequences (glacial-fluvial to glacial-lacustrine facies), submarine slump deposits and submerged peat bogs and glacial-fluvial valleys covered by marine sediments. The morphology of the basin and the post-glacial sedimentary sequences suggest that the Beagle valley was rapidly flooded by the sea overpassing Mackinlay and Murray sills, immediately after the Younger Dryas, 11,000 years B.P.

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