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## Geomorphology of marine and transitional terraces and raised shorelines between Punta Paulo and Porvenir, Tierra del Fuego, Straits of Magellan – Chile

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### ABSTRACT

This paper presents a coastal geomorphology map of some of the Chilean region of the Straits of Magellan, and is based on a combined geomorphological and sedimentological approach applicable to a larger section of the coast. The mapped area is located in Tierra del Fuego between the Segunda Angostura of the Straits of Magellan and Bahía Inútil. A detailed geomorphological map was compiled at a scale of 1:50,000, describing a sequence of 4 marine and transitional (glacio-lacustrine to marine) terrace orders and raised marine shorelines found between 0 and +20 m. These features are mainly linked to glacio-eustasy and secondarily to Holocene neo-tectonics. This research derives from the interpretation of aerial photographs and remote sensing imagery along with geomorphological-stratigraphic field surveys and geochemical data. The **Main Map** illustrates an area with dominant palaeoglacial and glacio-lacustrine morphology with extensive lacustrine deposits and well-developed lake systems characterising the Porvenir region.

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### 1. Introduction

Understanding the distribution of Pleistocene–Holocene marine terraces and raised shorelines is a fundamental tool for the reconstruction of palaeogeography and glacio-isostatic/neo-tectonic evolution of a geologically complex area (Patagonia and Tierra del Fuego). In fact, the present tectonic setting of the Tierra del Fuego region describes the relative movements and interactions between three main plates: Antarctica, South America and Scotia (Burns, Rickard, Belbin, & Chama-laun, 1980; Cunningham, Klepeis, Gose, & Dalziel, 1991; Dalziel, Kligfield, Lowrie, & Opdyke, 1973; Lodolo, Menichetti, Tassone, & Sterzai, 2002; Menichetti, Lodolo, & Tassone, 2008). Other authors (Bujalesky, Coronato, & Rabassa, 2004) noted that the coasts of the Magellan Straits and Beagle Channel have been affected by different types of uplift (tectonic uplift and glacio-isostatic rebound). Evidence of recent tectonic activity is also documented in the literature, especially on the Pacific side of the Strait of Magellan (Bartole, Colizza, De Muro, & Colautti, 2000). Strike slip faults linked to the complex dynamics of the collisional margin of the Southern Chilean plate are well known, but extensional (Pull Apart basins) phenomena are also linked to these settings (Lodolo et al., 2003). However, the south-eastern coast of Patagonia and the north eastern coast of Tierra del Fuego are considered mostly tectonically stable during the Holocene

(Schellmann & Radtke, 2010) and the Holocene palaeogeography of the area is deemed to be mainly controlled by glacio-isostatic readjustment, with subsequent mild tectonic activity resulting from deglaciation (De Muro, Kalb, Brambilla, & Ibba, 2012; Rabassa et al., 1992; Winslow & Prieto, 1991). Little evidence of this activity is visible on land (De Muro, Di Grande, Brambati, & Ibba, 2015). As previously observed (Schellmann & Radtke, 2010), the relative marine ingression that produced terraced sequences along the coast and inland is likely to be linked to uplift of the coastal system following final deglaciation of the region. Isostatic rebound probably occurred rather late compared to post-glacial transgression, and this uplift is superimposed on to the local geological setting in a complex manner that is currently not entirely understood (Brambati, De Muro, & Di Grande, 1998), and further studies are required in order to understand this process more fully.

In the Patagonia Fuegian region, marine terrace deposits have historically attracted the attention of many researchers (Aguirre, Richiano, & Sirch, 2006; Andersson, 1906; Auer, 1974; Bentley & McCulloch, 2005; Bujalesky, & Gonzales Bonorino, 1990; Codignotto, 1984; Feruglio, 1933; Gordillo, Coronato, & Rabassa, 1990; Halle, 1910; Markgraf, 1980; Mörner, 1987; Porter, Clapperton, & Sudgen, 1992; Porter, Stuiver, & Heusser, 1984; Rabassa et al. 1992; Rabassa, Serrat, Marti, & Coronato, 1988; Urien, 1966), however, the geomorphology of

the area described in this paper is still largely unknown, particularly when discussing the contiguous spatial distribution of four orders of Holocene terraces of marine and transitional origin. Most of the previous studies described, sometimes with great accuracy, the glacial evolution of this region and associated geomorphological features (Benn & Clapperton, 2000; Bentley, Sugden, Hulton, & McCulloch, 2005; Darvill, Stokes, Bentley, & Lovell, 2014; Darvill, Stokes, Bentley, Evans, & Lovell, 2016; Glasser & Jansson, 2008; Lovell, Stokes, & Bentley, 2011; Lovell, Stokes, Bentley, & Benn, 2012; McCulloch & Davies, 2001) with some reference to Holocene paleo shoreline and other coastal landforms (Isla & Bujalesky, 2008; Rostami, Peltier, & Mangini, 2000). However, the previous literature did not complete coastal geomorphological mapping of the area discussed herein but focused on single outcrops relevant to the interpretation of regional glacial evolution (Benn & Clapperton, 2000; Schellmann & Radtke, 2003). Other geological–geomorphological regional studies carried out in the Straits of Magellan (Brambati, Fontolan, & Simeoni, 1991) allowed morphostructural units (Bartole et al., 2001; Bartole, De Muro, Morelli, & Tosoratti, 2008), seafloor and littoral sediment dynamics to be identified over large areas covering both the Atlantic and Pacific openings of the Straits (Bartole et al., 2000).

This paper aims to further describe the coastal geomorphological features which occur in the eastern arm of Straits of Magellan. In particular, it focuses on the area surrounding the town of Porvenir located in Tierra del Fuego between the Segunda Angostura of the Straits of Magellan and Bahía Inútil (Figure 1). The mapping presented herein provides new data on modern littoral sediment dynamics and support the interpretation of Holocene palaeogeography on the basis of the distribution of marine terraces distributed between 0 and 20 m above mean-sea level along the coast of the Patagonian Fuegian region.

## 2. Regional settings

The study area is situated in the southernmost tip of Chile at the border with Argentina and is centred on the ‘Caletta Hobbs’ and ‘Porvenir’ Sheets of the Chilean Army Geographic Institute I.G.M. (Section L – No 86/530000-700730 and 103/531500-700730).

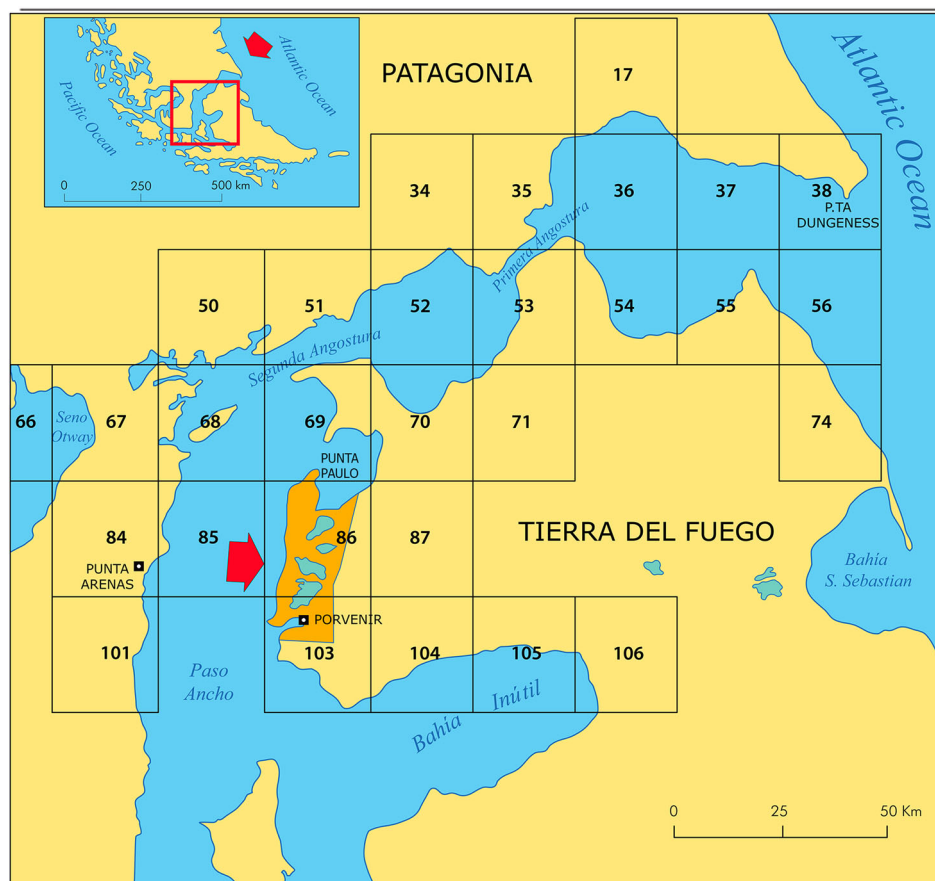
McCulloch, Fogwill, Sugden, Bentley, and Kubik (2005) published an integrated chronology of glacier fluctuations in the Strait of Magellan with specific reference to the study area (Figure 2) and suggest that the Last Glacial Maximum (LGM) began after 31,250 yrs BP and culminated approximately 25,200–23,100 yrs BP (stage B). The glacier retreated before 21,700–20,400 yrs BP, when a slightly less extensive advance (stage C) than the previous LGM occurred. A third major glacier advance was also found before 17,500–16,620 yrs BP (stage D) with evidence that

glaciers continued to occupy the southern Strait for a further 1000 year. A detailed evolution of the flooding of the Strait of Magellan has been given by Brambati (2000). As in other areas of Patagonia-Tierra del Fuego (Schellmann & Radtke, 2010) the glacial evolution of the area has added to the contemporaneous and subsequent morphogenesis of a littoral and marine environment, which is particularly active in depressed areas due to glacio-isostasy.

The most commonly outcropping ground in the region between Punta Paulo and Porvenir consists of glacial deposits almost exclusively from the last glaciation (Clapperton, Sugden, Kaufman, & McCulloch, 1995). Probable exceptions are the deposits found on the relief of Altos de Boqueron representing an older glaciation. In the Porvenir-Paso Ancho area remains of the largest fronts of three glaciations can be recognised (Clapperton, 1992; Darvill et al., 2016; Kaplan et al., 2008; McCulloch, Fogwill et al., 2005; Figure 2). Clapperton et al. (1995) indicate an age of 13,920, 14,990 and 17,710 years B.P. for the deposits in the neighbourhood of Porvenir associated with these glacier fronts. Large moraines were also identified in the study area by Bentley et al. (2005).

## 3. Methods

The geomorphological map compiled in this study was prepared using geological and geomorphological data acquired through field surveys of Holocene glacio-eustatic and marine deposits and landforms. Sedimentological and palaeontological samples were collected during field surveys in 1991, 1994, 1995 and 2003 as part of the Italian National Programme for Research in Antarctica (PNRA) and subprojects: ‘Late Quaternary Climatic Evolution of the Magellan-Fuegine area (southern South America)’ and ‘Seismostratigraphy and sedimentology of the Southern Chilean margin’. Several studies were carried out as part of these two projects; however, the latest phase of coastal research continued from previous geomorphological mapping of the coast of the Strait of Magellan and focused on the study of raised shorelines and terraces of marine and transitional origins formed during the most recent Post-Glacial Maximum. This research led to the publication of two geomorphological maps at a scale of 1:100,000 (Brambati, Colizza, et al., 1993; Brambati, De Muro, & Di Grande, 1993) and three geomorphological maps at a scale of 1:200,000 (Brambati, De Muro, & Di Grande, 1995, 1997; Di Grande, De Muro, & Brambati, 1995). More detailed studies were also undertaken with cartographic production at a scale of 1:50,000 (De Muro, Di Grande, & Brambati, 1996a, 1996b, 1996c; De Muro, Di Grande, & Brambati, 2000; De Muro, Di Grande, Brambati, & Marini, 1997; De Muro, Di Grande, Fontolan, & Brambati, 2000; Di Grande, De Muro, &



**Figure 1.** The orange area highlights the study area and map location. The black squares indicate the location of topographic maps published by the Chilean I.G.M. at a scale of 1:50,000. The geomorphological map published herein has a scale of 1:50,000 and falls within Sheets No. 86, 69 and 103 of Section L of the Chilean I.G.M. cartography.

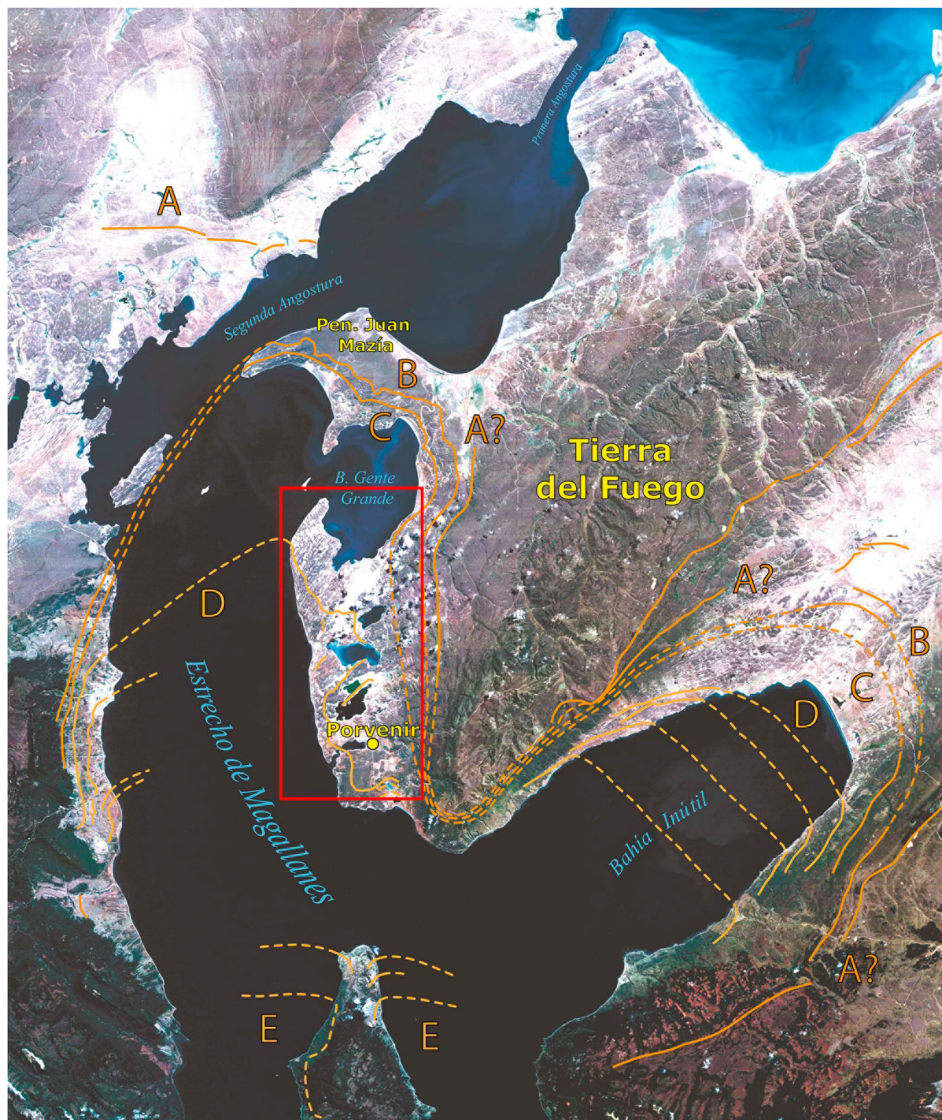
Brambati, 1996a, 1996b; Di Grande, De Muro, Brambati, & Marini, 1997). These studies represent the starting dataset for the development of the Geomorphological Atlas of the Coasts of the Straits of Magellan focused on the mapping of marine and transitional terraces. The Atlas consists of nine maps edited and printed for distribution as part of a dedicated booklet presented at the 32nd IGCC (Brambati & De Muro, 2004; De Muro, Di Grande, & Brambati, 2004). Newer studies (De Muro et al., 2012; De Muro & Brambati, 2012) focused on the fossiliferous content of the identified coastal terraces formed within the complex transitional phases between the LGM and the subsequent Holocene marine ingression in the Straits. As part of this research, the mapping outputs changed from hard copy to digital cartography compiled at a detailed scale of 1:50,000 (De Muro et al., 2015), with further details added to the identification of coastal terraces and raised shorelines and data on present littoral dynamics.

The **Main Map** presented in this paper is the second cartographic outcome compiled as part of this latest digital mapping effort focused on the production of a detailed map at a scale of 1:50,000. This cartographic series allowed the visualisation of raised shorelines to be made continuously throughout the investigated region. It is part of a new surveying and mapping

phase (De Muro, Ibba, & Kalb, 2016) which is testing the usage of new map keys (De Muro, Pusceddu, Buosi, & Ibba, 2017) applicable worldwide to a variety of environmental and managerial topics (De Muro, Porta, Passarella, & Ibba, 2017; Pennetta et al., 2016).

The **Main Map** presented in this paper includes terraces formed as a result of marine littoral sediment dynamics, and also terraces of mixed origin which were defined as transitional in De Muro et al. (2015). This map also focuses on raised shorelines providing important clues for the reconstruction of the Holocene palaeogeography of the study area. Transitional terrace successions have nearly flat erosion surfaces terminating with a step palaeo cliff at both ends. They were generated by processes ranging from glacial and lacustrine to clearly littoral (marine), typically related to glacial–interglacial phases (Darvill et al., 2014; Lovell et al., 2011).

Outcrop field data corresponding to geological boundaries and geomorphological features were checked and interpreted using aerial photographs at an approximate scale of 1:60,000. Aerial photography was provided by the ‘Servicio Aerofotogrammetrico Fuerza Aerea de Chile’ (SAF). These analyses led to the generation of a preliminary geomorphological map using a 1:50,000 I.G.M. topographic map as a base layer.



**Figure 2.** Glacier fluctuations in the Strait of Magellan according to McCulloch, Fogwil et al. (2005, modified). The red rectangle indicates the location of the study area. Limits of glacial stages A, B, C, D and E are indicated in this figure.

The spatial distribution of marine terraces was subsequently surveyed in the field tracing by generating a topographic transect grid. Transects were oriented both perpendicular and parallel to the shoreline, with distance among consecutive transects dependent on beach and survey site access. Position accuracy was 25–50 m for horizontal distance and 2–3 m for vertical elevation and was achieved using both theodolite and a hand-held global positioning system (GPS) receiver.

The second draft of the map was completed in aerial photogrammetric laboratories, redrawing and refining the limits of the outcrops using an OMI stereo facet plotter (Petrie, 1992). Data from field surveys and observation of aerial photography were incorporated to validate the final mapping outcome. The third and final mapping stages were the digitization of the geomorphological map, which was scanned and processed using Autodesk-Map-3D. The final digital map was created using Adobe Illustrator CS5.

#### 4. Results

The following morphogenetic units can be outlined in the study area: (1) Altos de Boqueron ridge, in the easternmost zone, includes the highest area and is made up of glacial deposits. (2) Porvenir-Paso Ancho ridge, is characterized by drumlin fields and related lakes. (3) Terraced coastal belt and (4) Central peri-lacustrine belt. The overall geomorphology is mainly characterised by the presence of low relief (prevalently hills) and flat areas in both the coastal and peri-lacustrine regions.

According to Benn and Clapperton (2000), the distribution and internal architecture of moraine belts such as the Porvenir-Paso Ancho ridge suggest that the formation of Bahía Gente Grande can be attributed to glacial morphogenesis as an effect of an eroding glacier front. The research carried out as part of this study confirms that the area is characterised by a high frequency of drumlins, at times eroded, rigorously

NE–SW oriented, also outlined by Darvill et al. (2016). Among the features associated with surface runoff, kettle hole-type forms are also present, also associated with drumlins and outlined by Benn and Clapperton (2000).

Geomorphological and palaeogeographic data presented in this paper are in line with studies by Benn and Clapperton (2000), Bentley et al. (2005), Clapperton (1992), Clapperton et al. (1995), Glasser and Jansson (2008) and Meglioli (1992) on the glacial environment of the Magellan area. These studies focus on glacial landforms and provide baseline information for mapping glacial geomorphological features. However, the most prominent features of the map presented herein are Holocene coastal terraces of marine and transitional origin. Raised shorelines are also common morpho-sedimentological features.

#### 4.1. Marine and transitional features

Mainly Holocene raised shorelines, consisting of marine and transitional features, were identified in a large coastal area of the Straits of Magellan extending for ~1000 km and including the study area. They are mainly represented by gravel, sand and silt deposits, or rarely only by simple erosion surfaces. In the majority of the analysed outcrops, terrace sequences start with an evident unconformity eroded in the till, with sandy gravel beach deposits rich in modern marine fauna at the top (Brambati et al., 1998). The terrace

succession contains mainly marine and littoral deposits and other complex sedimentary features of medium- and small-scale, such as beach ridges, sand bars, cusped forelands and other marine littoral features.

Four main orders of terraced sequences were identified. The first and oldest terrace shows a regular distribution between 18 and 25 m above present sea level (Figures 3 and 4). Sand and silt deposits of a transitional depositional environment from glacio-lacustrine to marine prevail in this terrace. Because of its stratigraphic position and through radiocarbon dating presented in De Muro and Brambati (2012) and De Muro et al. (2015), the first-order terrace was attributed to the Early Holocene.

The second-order terrace is distributed between 6 and 11 m above present sea level, and is mainly represented by fossiliferous gravel deposits, sands and silts (Figures 3, 5–7). It regularly outcrops along the coast showing a large coastal extent, but is also visible in the main fluvial valley further inland. Complex sedimentary structures such as palaeo beach ridges and sand bars are occasionally observed within this terrace representing the remains of previous beach environments of the Magellan Straits. 14C data from Brambati et al. (1998) suggest that this terrace formed between approximately 6000 and 7000 years B.P.

The third-order terrace follows the morphology of the present beach environment at an elevation of 3–5 m above sea level, immediately below the second-order terrace. This terrace consists of fossiliferous gravels and sands of marine origin. 14C analysis of samples taken discontinuously along this landform provided ages between 4000 and 5000 years B.P. for the oldest marine deposits in the terrace. Dating of the upper part of the sequence showed ages up to 3000–2500 B.P. (Brambati et al., 1998; De Muro et al., 2012).

The fourth order terrace was identified at 1–2 m above mean-sea level and is discontinuous along the coastline.

#### 4.2. Lacustrine features

The main lakes in the study area are elongated in the prevalent direction of drumlins and other glacial forms. According to Clapperton (1992), McCulloch, Bentley, Tipping, and Clapperton (2005) and Darvill et al. (2016), these are glacial remnants related to various stages of the last glaciation. The central and northern lakes visible on the Main Map could represent marine ingressions areas for the Late-Holocene post-glacial phase with subsequent deposition of terrace sequences. Present lacustrine depressions and surrounding terraces are found at elevations compatible with that of the second order of coastal terraces; however, the lack of marine invertebrates does not allow the correlation between lacustrine and coastal terraces to be made. For this reason, the area surrounding Laguna

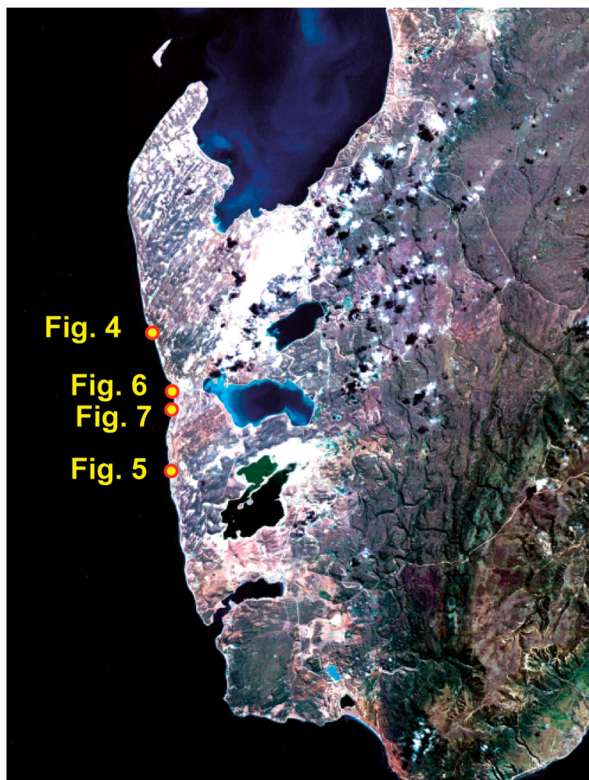


Figure 3. Locations of Figures 4–8.



**Figure 4.** North of Porvenir: view of first-order terraces and relative palaeo cliffs.

Verde is mapped with the same colour as the second-order terrace but is described as ‘uncertain attribution to marine/transitional environments’ in the [Main Map](#) legend.



**Figure 5.** South of Punta Gente: view of second-order terraces and relative palaeo cliffs.

#### **4.3. Aeolian features**

Wind activity is extremely intense and continuous along the entire coastal belt and the most evident effect is the leeward migration of lakes. The distribution of small lakes is strongly conditioned by glacial residual morphology, particularly drumlins. The lake’s water surface is exposed to wind blowing prevalently from west to east all year round, thus favouring lake and pond drift due to the deflation.

Small dunes are found along the coast especially in areas characterised by a large tidal range, such as Bahia Gente Grande ([Main Map](#)). In this region, wind erosion of fine beach sediment generates extensive lag deposits and dunes. The south-eastern quadrant of Bahia Gente Grande is characterised by west–east alternations of deflation surfaces and longitudinal dunes.

#### **4.4. Features linked to surface runoff**

Streams characterising the coastal belt show a discontinuous water flux, sometimes generating rills. At higher elevations and away from the coast, features most likely related to glaciation or receding outwash during glacial times dominate in the form of braided surfaces (meandering branches), associated with paleo-outwash channels. These features are clearly visible on satellite images of the central-eastern sector of the study area. These meandering torrents evolved to meandering systems in Holocene times and are occasionally fed by snow from Altos de Boqueron ridge. Flood plains are characterised by alluvial deposits that in the mouth area, according to a glacial interpretation, become outwash plains.



**Figure 6.** North of Porvenir: fossiliferous gravel of the second-order terrace overlying glacial sediments (till) and present beach environment.

## 5. Conclusions

The geomorphological map presented in this paper provides an overview of the marine and transitional terraces occurring in the coastal belt between Punta Paulo and Porvenir. These features deposited following LGM in a chronological succession till present. Coastal terrace sequences are mostly developed above glacial features showing clear angular discordance and sharp

erosive truncation. These features were produced by processes ranging from glacial and lacustrine to littoral (marine), typically related to glacial–interglacial phases (Benn & Clapperton, 2000; Darvill et al., 2014, 2016; Lovell et al., 2011, 2012; McCulloch & Davies, 2001).

The mapped terraces represent various stages of formation linked to the highest marine ingression following deglaciation in the eastern region of the Straits of Magellan. The first-order (18 and 25 m) terrace is



**Figure 7.** Detail of fossiliferous gravel of Figure 6 showing the transition to present soil.



highly eroded at present and is likely to have formed in the initial deglaciation phase (following stage E of McCulloch, Fogwill et al., 2005). The deposition of this terrace occurred in a transitional environment from glacio-lacustrine to marine, stratigraphically evolving to a tidal marine environment. The second-order terrace (6000–7000 years B.P.) was mapped between 6 and 11 m and is deemed to show the previous coastal morphology of the Magellan Straits. The third-order terrace (4000–5000 years B.P.) was found at elevations between 3 and 5 m and faithfully reproduces the present course of the Strait as evidence of a slow-down reaching eustatic equilibrium and renewed isostasy. The second, third and fourth (1–2 m above mean-sea level –2500–1200 years B.P.) order of coastal terraces and their raised shorelines, almost always contain marine fauna; all three are therefore of marine origin. Whilst the first-order terrace is linked to the transition from glacial withdrawal to the first marine ingressions of the Holocene Sea, the remaining three terrace orders found a net marine dominance interrupted by several uplift events linked to glacial isostatic rebound.

The remaining geomorphological features mapped in the study area have lacustrine, aeolian and surface runoff origins. Whilst deglaciation processes resulted in the formation of several lacustrine (i.e. proglacial lakes) and surface runoff features (i.e. outwash plains) in the Porvenir region, intense wind activity is responsible for the formation of coastal sand dunes and deflation surfaces in the Bahía Gente Grande area.

### Software

The map was produced manually on the basis of geomorphological and geological field surveys of Holocene deposits, with the support of aerial photographs and remote sensing interpretation. The map was drafted using Autodesk-Map-3D. Final map layout was performed using Adobe Illustrator CS5 TM.

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No potential conflict of interest was reported by the authors.

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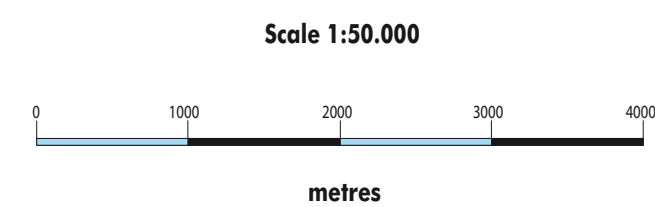
# GEOMORPHOLOGICAL MAP OF THE MARINE AND TRANSITIONAL TERRACES AND RAISED SHORELINES BETWEEN PUNTA PAULO E PORVENIR, TIERRA DEL FUEGO STRAITS OF MAGELLAN - CHILE

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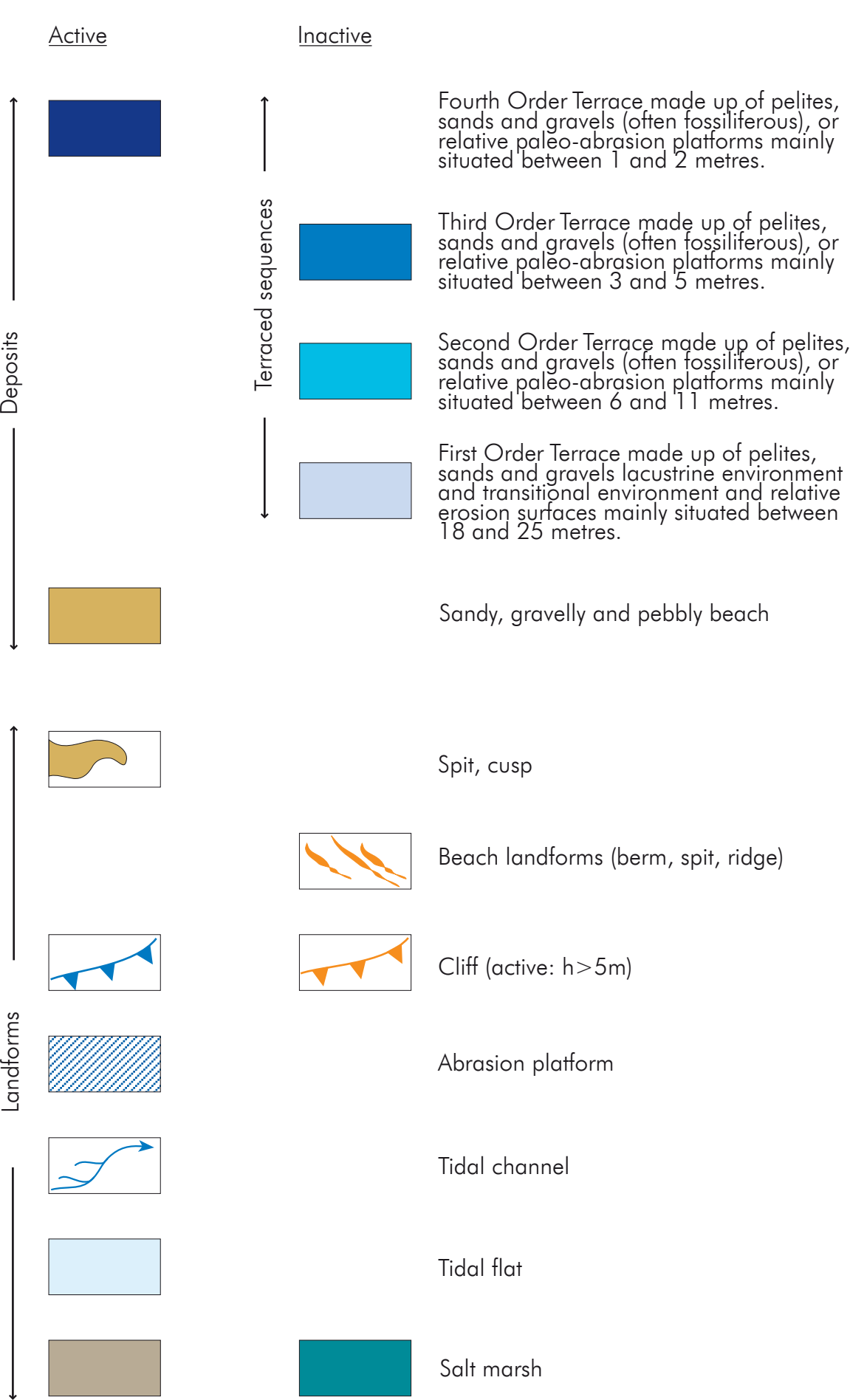
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The map was produced by Sandra DeMuro, Angelo Di Grande and Antonio Brambati from geomorphological and geological field survey of Quaternary deposits and with the support of aerial photographs and remote sensing interpretation. The map was subsequently improved with new geomorphological observations derived from aerial photographs and remote sensing interpretation by Angelo Ibba, Marco Porta and Sira Tecchiato. The locational accuracy is estimated to be within 25 m  $\pm$  50 m in planimetry and 2 m  $\pm$  3 m in elevation (the latter refers to mean sea level). The map was produced using a 1:50,000 scale topographic base of the "Istituto Geografico Militar Chileno" on the basis of geodetical data related to the 1969 south American ellipsoid. Outcropping limits were checked by means of aerial photographs on an approximate scale of 1:60,000, from the "Servicio Aerofotogrametrico Fuerza Aerea de Chile" (SAF) and images from TM and MSS Landsat satellites. Universal Transverse Mercator cartographic projection (UTM). Altimetric data are referred to present mean sea level.

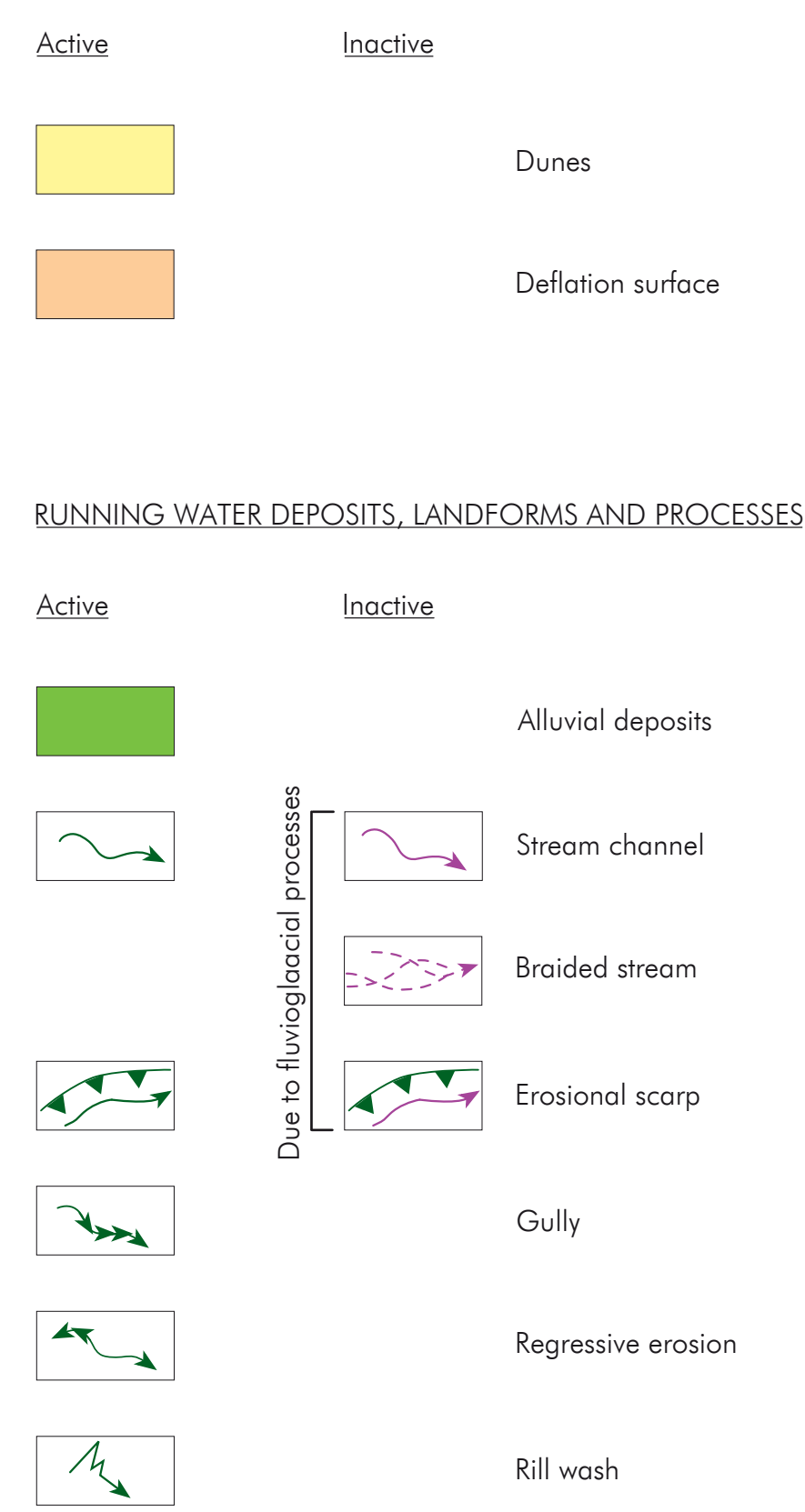
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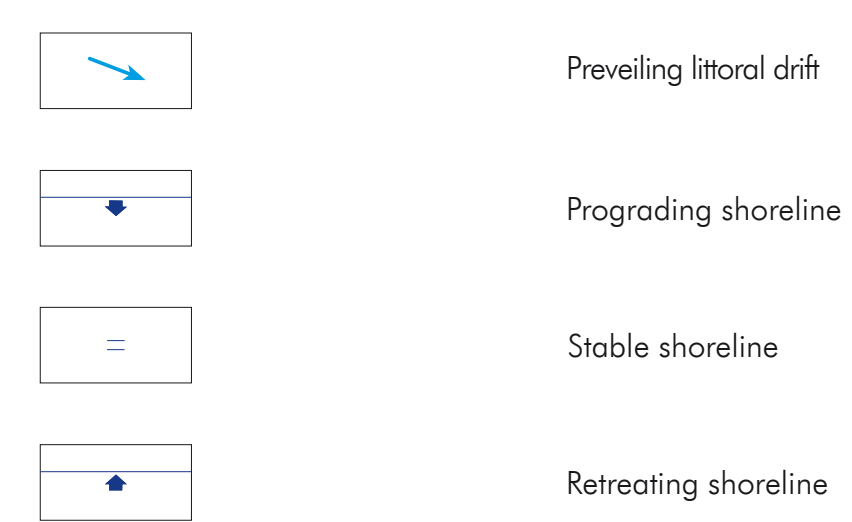
## MARINE AND TRANSITIONAL DEPOSITS AND LANDEFORMS



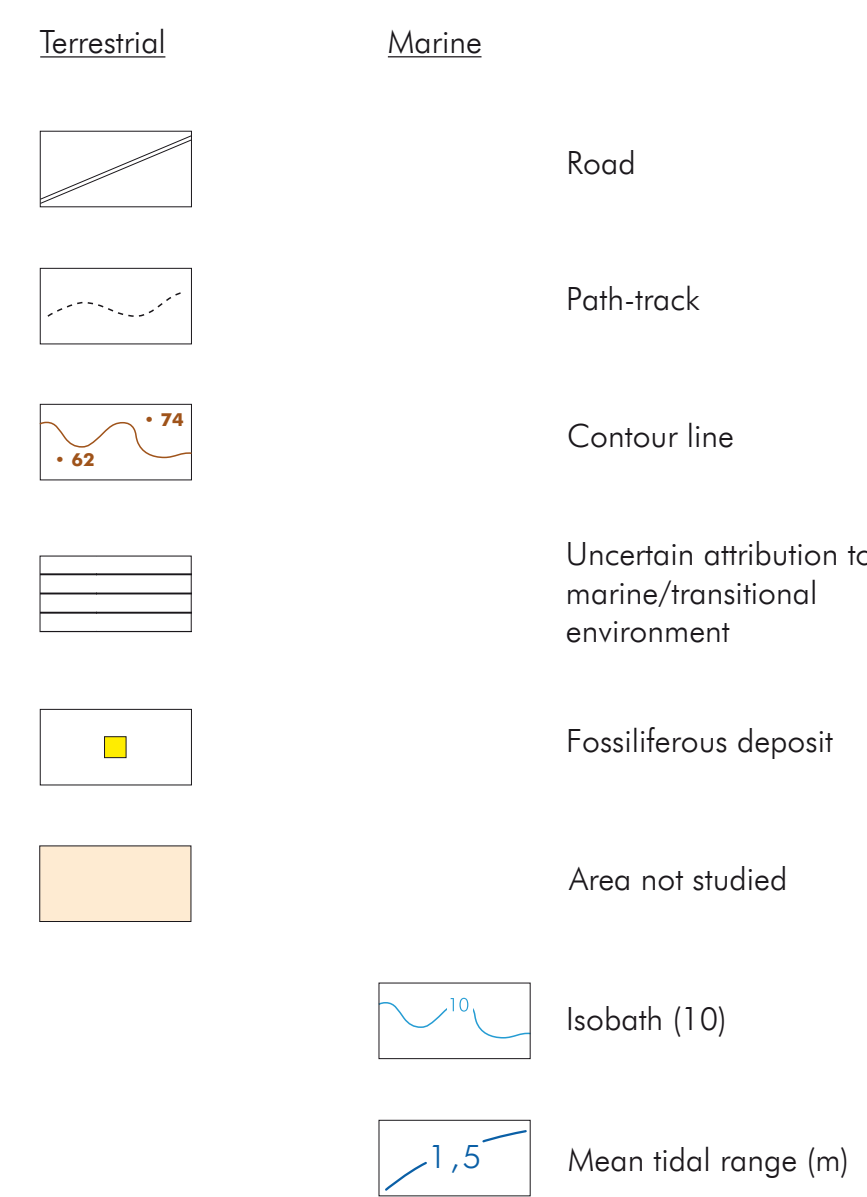
## AEOLIAN DEPOSITS AND LANDEFORMS



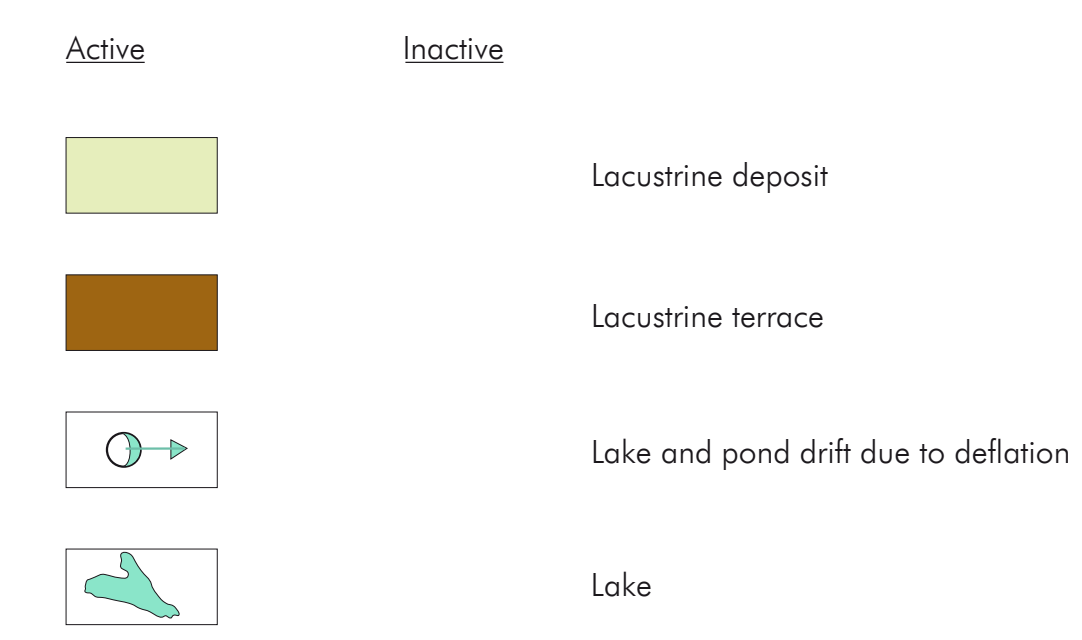
## PRESENT COASTAL DYNAMICS



## ADDITIONAL INFORMATION



## LACUSTRINE DEPOSITS, LANDEFORMS AND PROCESSES



## GLACIAL DEPOSITS AND LANDEFORMS

