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Geomorphology of marine and glacio-lacustrine terraces and raised shorelines in the northern sector of Península Brunswick, Patagonia, Straits of Magellan, Chile

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ABSTRACT

This paper illustrates a detailed geomorphological map (scale 1:50,000) of the marine and transitional terraces (glacio-lacustrine to marine) and raised shorelines linked to Holocene glacio-eustasy and neo-tectonics in the northern area of the Brunswick Peninsula (Chilean region of the Strait of Magellan). The mapped area is located in Tierra del Fuego between the Segunda Angostura and Seno Otway. This map is the result of geomorphological field survey data integrated with the interpretation of aerial photographs and remote sensing imagery. The survey has allowed the mapping of a sequence of terraces and raised shorelines to be completed. The sequence mainly consists of four orders of marine and glacio-lacustrine terraced deposits, with elevations ranging from 25 to 1 m above mean sea level. The map also presents other landforms and deposits, with their formation linked to littoral, fluvial, glacial and aeolian processes.

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Coastal geomorphology; marine and transitional terraces; sedimentology; Holocene; Magellan Strait

1. Introduction

Coastal Patagonia hosts a series of raised marine shorelines with different elevations and consisting of fossiliferous coastal deposits known as ‘Marine Terraces’ (Feruglio, 1933). The formation of these terraces is typically related to the alternation of glacial–interglacial phases. Marine and transitional terrace deposits at various heights were recognized previously by several authors (Aguirre, Richiano, & Sirch, 2006; Bentley & McCulloch, 2005; Bentley, Sugden, Hulton, & McCulloch, 2005; Clapperton, Sugden, Kaufman, & McCulloch, 1995; Feruglio, 1933; McCulloch & Bentley, 1998; McCulloch, Fogwill, Sugden, Bentley, & Kubik, 2005; Porter, Clapperton, & Sudgen, 1992; Porter, Stuiver, & Heusser, 1984; Rabassa et al., 1992), but only as individual outcrops.

Understanding the distribution of the most recent glacio-lacustrine to marine terraces can be useful for the reconstruction of Holocene palaeography of an extensive coastal area of the Strait of Magellan. The sedimentary sequences of coastal terraces were mainly deposited in marine and littoral palaeo-environments. The oldest terraces have a basal glacio-lacustrine sequence developed on an erosive surface and overlaid by an upper littoral-marine sequence. Due to the mixture of erosive and depositional processes linked to different environments (from glacio-lacustrine to clearly littoral-marine), these terraces are defined as

‘transitional’ (De Muro, Di Grande, Brambati, & Ibba, 2015).

The aim of this paper is to present a study of the distribution of Pleistocene–Holocene, glacio-lacustrine and marine terrace sequences and other shoreline features found around the Strait of Magellan region (Chile). The study area is located in the northern sector of Península Brunswick, between the Segunda Angostura of the Strait of Magellan facing the Atlantic Ocean and Seno Otway facing the Pacific Ocean (Figure 1).

This map is part of a more extensive study aiming to provide a large cartographic archive of the coastal geomorphology of the Strait of Magellan (De Muro et al., 2015; De Muro, Brambati, Tecchiato, Porta, & Ibba, 2017). The Main Map presented in this paper is the third cartographic outcome of a digital mapping effort focused on the production of a detailed map of marine and transitional terraces at a scale of 1:50,000. The overall cartography, focused on the geomorphological mapping of coastal terraces formed within the complex transitional phases between the Last Glacial Maximum (LGM; ca. 26.5–19 ka, Clark et al., 2009) and the subsequent Holocene marine ingression in the straits of Magellan that was developed as part of the project ‘Programma Nazionale di Ricerche in Antartide’ (PNRA), started in 1993 (Brambati, Colizza, et al., 1993; Brambati,

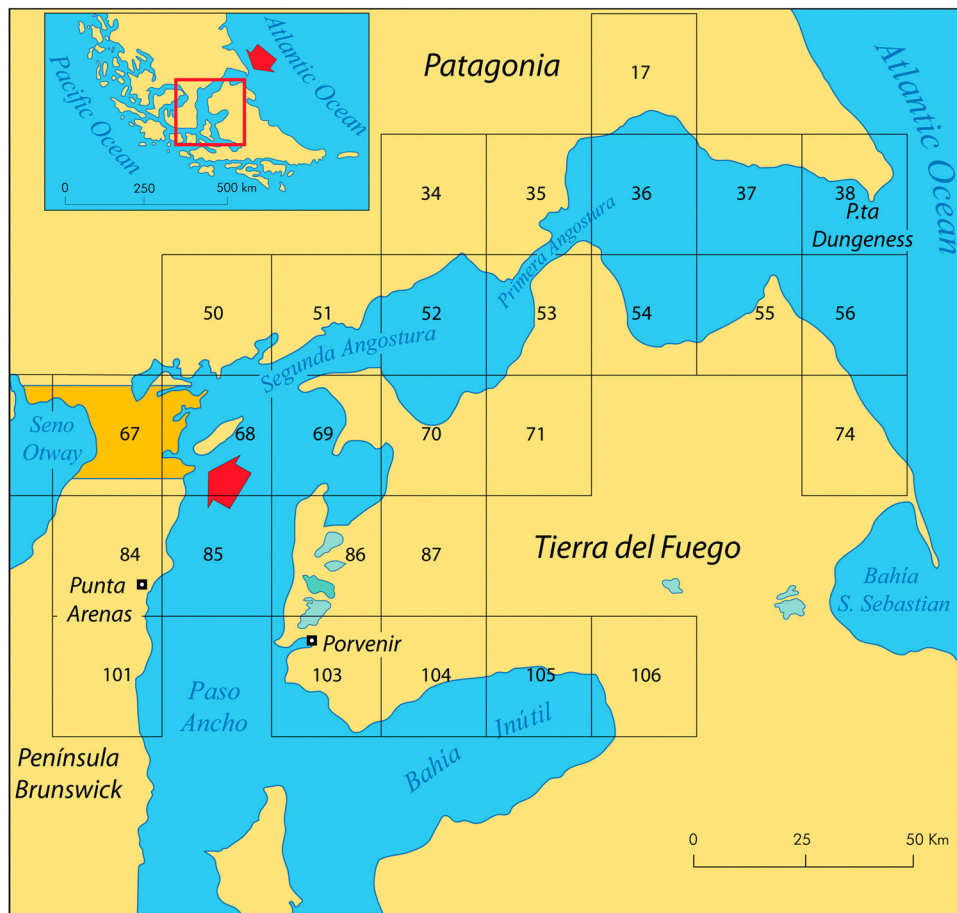


Figure 1. The orange area highlights the study area and map location. The black squares indicate the location of topographic maps published by the Chilean I.G.M. at a scale of 1:50,000. The geomorphological map published herein also has a scale of 1:50,000 and falls within Sheets No. 66, 67 and 68 of Section L of the Chilean I.G.M. cartography.

De Muro, & Di Grande, 1993, 1995). Initial regional studies on coastal geomorphology were also undertaken as part of these investigations (Brambati, Fontolan, & Simeoni, 1991), but were limited to research on sediment sources and transport mechanisms as well as to the definition of morphostructural units at a regional scale (Bartole, Colizza, De Muro, & Colautti, 2000; Bartole, De Muro, Morelli, & Tosoratti, 2008; Bartole et al., 2001).

A second phase of coastal research focused on the study of raised shorelines and the identification and mapping of terrace orders of marine and transitional origins (Brambati, De Muro, & Di Grande, 1995; De Muro, Di Grande, & Brambati, 1995; Di Grande, De Muro, & Brambati, 1995). The aim of this phase was to describe the geomorphological evolution of the area following post-LGM and to develop an understanding of the Holocene marine transgression stages in the eastern section of the Strait of Magellan.

2. Regional settings

Península Brunswick is situated on the eastern side of the Andes Mountains, to the west of the Strait of Magellan in the physiographic unit of Southern Patagonia (Figure 1).

The geology of this area is of particular interest for the reconstruction of glacial history and ice-dynamics of the region, which have been investigated in detail since the pioneering work of Caldenius (1932) and Feruglio (1933). Several glacial geomorphological maps have been published to investigate the nature and chronology of past glacier fluctuations e.g. Benn and Clapperton (2000); Bentley et al. (2005); Clapperton et al. (1995); Darvill, Stokes, Bentley, Evans, and Lovell (2017); Darvill, Stokes, Bentley, and Lovell (2014); Glasser and Jansson (2008); Lovell, Stokes, and Bentley (2011); Lovell, Stokes, Bentley, and Benn (2012); McCulloch and Bentley (1998); Rabassa, Coronato, and Martinez (2011).

The geological substrate of this region mainly consists of Cretaceous and Tertiary sedimentary rocks. The southern parts also include argillaceous deposits, silicic volcanic and volcanoclastic rocks of the Jurassic. A pre-late Jurassic crystalline basement outcrops in the southernmost part of the peninsula (Bentley & McCulloch, 2005; E.N.A.P., 1978). Several NW-SE oriented thrust faults were found on land (Bentley & McCulloch, 2005 and references therein). Glaciers in this region are today situated south and west of the study area in the high Cordillera Darwin (Bentley et al., 2005). In this area of South America, a combination

of plate tectonics, volcanism, isostasy and eustatic sea-level change is significantly active (Cande & Leslie, 1986; Clapperton, 1990; Dott, Winn, & Smith, 1982; Lodolo et al., 2003).

The coastal geomorphology of the Península Brunswick is mainly due to two main Quaternary glacier lobes: Seno Otway and Magellan (Clapperton, 1992; Coronato, Martínez, & Rabassa, 2004; Feruglio, 1933; Glasser & Jansson, 2008; Lovell et al., 2011) and glacial processes associated to Glacial stage A (>40 ka B.P.) and Glacial stage B (25.2–23.1 ka B.P.; age from McCulloch, Bentley, Tipping, & Clapperton, 2005). In particular, in the northern sector of the Brunswick Península drumlin direction and lateral-terminal moraine systems indicate that the Seno Otway lobe joined the glacier of the Strait of Magellan adjacent to Segunda Angostura during Glacial Stage A (Darvill et al., 2017; Kilian et al., 2013; Lovell et al., 2011). The LGM moraines (Glacial stage B) were found along the northeastern coast of Seno Otway (Figure 2). The moraine system associated to Glacial stage C is not preserved or yet detected along the shore of Seno Otway, whereas the moraines of Glacial stage D formed closer to the Andes in the south-western area of Seno Otway (Kilian et al., 2007). On the western coast of the Strait of Magellan, moraine ridges of Glacial stages B, C and D are deposited near Puntas Arenas and are linked across the Strait on the eastern side. They also correspond to submarine ridges which link the moraine of Península Juan Mazia with the limit just south of Punta Arenas (Bentley et al., 2005; Figure 2). During Glacial stages B and C, the glacial lobes retreated reaching the western shore of Seno Otway and Seno Skiring after 19 ka (Darvill et al., 2017; Kilian et al., 2013; Lovell et al., 2011; McCulloch, Bentley, et al., 2005). During the ice margin retreat from the distinct lobate positions, ice and topography would have blocked the lower ground contained within the former Skyring and Otway lobes, impeding drainage and damming proglacial lakes (Lovell et al., 2012). Consequently, proglacial lakes would have formed in front of both Skyring and Otway lobes likely draining initially through northern spillways towards the Atlantic. But as lake levels dropped, drainage likely switched to north-westward into Skyring proglacial lake and the Pacific Ocean (Darvill et al., 2017; Kilian et al., 2013; McCulloch, Bentley, et al., 2005). Deglaciation and ice-free conditions in Seno Otway have been dated at 14.7 ka (Kilian et al., 2013). The retreat of the Magellan lobe occurred at least 14–15 ka ago (Clapperton et al., 1995; Darvill et al., 2017; McCulloch & Bentley, 1998; McCulloch, Fogwill, et al., 2005; Porter et al., 1992).

3. Methods

The geomorphological map compiled in this study was prepared using data acquired in 1991, 1994, 1995 and

2003 through geological and geomorphological field surveys of marine Quaternary deposits and landforms. Several research phases led to the development of the mapping output described in this paper. An extensive series of geomorphological and geological maps were developed both at regional and landform scale in a large area of the Strait of Magellan (Brambati, Colizza, et al., 1993; Brambati, De Muro, et al., 1993, 1995; De Muro et al., 1995; De Muro, Di Grande, & Brambati, 1996a, 1996b, 1996c; De Muro, Di Grande, Brambati, & Marini, 1997; De Muro, Di Grande, & Brambati, 1997a, 1997b; De Muro, Di Grande, Fontolan, & Brambati, 2000; 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, a series of nine maps presented at the 32nd International Geological Congress Committee (Brambati & De Muro, 2004; De Muro, Di Grande, & Brambati, 2004). Further improvements were made to the described datasets using additional geochemical data (Brambati, 2000; De Muro, Kalb, Brambilla, & Ibba, 2012).

For each marine terrace, several markers were measured and/or estimated: shoreline angle, inner and outer edge, width of the treads, elevation range, fossiliferous deposits, presence and distribution of beach-ridges and palaeo-abrasion platforms and associated palaeo-cliff. Marine terraces were initially mapped in the field tracing the deposit edges and outlining erosional morphologies. Mapping practices were developed from sea level moving to higher elevations with a position accuracy of 25–50 m for horizontal distance and 2–3 m for vertical elevation. This accuracy has to be considered in the context of map scale (1 mm = 50 m), graphic error and complexity and variability of the geological feature. The coastline was investigated through topographic, geomorphological and stratigraphic transects approximately 1000 m apart alongshore. Information along transect was recorded from present average sea level moving inland and reaching the first-order terraces (about +25 m). Some transects were investigated repetitively and for those position accuracy was improved using both theodolite and hand-held global positioning system (GPS) receiver. The age of marine terraces was defined using ¹⁴C radiometric analysis. Facies analyses were carried out on stratigraphic sections (the type of sediment and possible fossiliferous content) by digging trenches near the concave and convex nick points (palaeo wave-cut scarp – palaeo-cliffs).

Marine terrace markers mapped in the field were successively interpreted using aerial photographs at an approximate scale of 1:60,000 followed by ad-hoc geomorphological and sedimentological land surveys. Aerial photography was provided by the ‘Servicio Aerofotogramétrico Fuerza Aerea de Chile’ (SAF)



Figure 2. Glacier fluctuations in the Strait of Magellan according to Kilian et al. (2013, modified). Limits of glacial stages B (25.2–23.1 ka B.P.), D (17.7–17.6 ka B.P.) and E (15.5–11.7 ka B.P.); ages from McCulloch, Bentley, et al., 2005) are indicated in this figure. According to Kilian et al. (2007) the moraine system of Glacial stage C is not preserved or yet detected along the shore of Seno Otway. Red and green dots indicate the location points of Figures 3 and 4, respectively.

and images from TM and MSS Landsat satellites were also analysed.

A preliminary geomorphological map was produced using a 1:50,000 Chilean I.G.M. (Instituto Geografico Militar, Chilen Government) topographic map as a base layer.

The second draft of the map was completed in aerial photogrammetric laboratories integrating information on other environments (glacial, lacustrine and fluvial), redrawing and refining the limits of the terraces using an OMI stereo facet plotter (Petrie, 1992). Data from field surveys and interpretation of aerial photography was incorporated to validate the final mapping outcome.

The third and final mapping stage was the digitalization of the geomorphological map using Autodesk Map 3D.

4. Results

In the study area, four orders of marine and transitional terraces were recognized and mapped. In the *Main Map* marine coastal terraces and raised palaeo-shorelines are mapped from most ancient to most recent, from an elevation of 18–25 m above mean sea level (first order), to 6–11 m (second order), and

3–5 m (third order) to 1–2 m (fourth order) (De Muro, et al., 1996a, 1996b, 1996c). These features show a staircase distribution. Each terrace shows a set of features, such as paleo-abrasion platforms, beach deposits, relict foredunes and beach-ridges locally associated with paleo-cliffs.

Additional geomorphological features described on the *Main Map* refer to glacial or periglacial processes.

The distribution of the four terrace orders corresponds to narrow belts parallel to the coast and is controlled by the alternation of both littoral deposits and erosional features. The combination of these landforms and deposits can be classified as raised shorelines. In some sections, the identification of raised shorelines is very clear because the basal feature of these sequences corresponds to a palaeo-abrasion platform of marine origin generated by wave abrasion into the till, and is overlaid by sandy gravely beach deposits containing marine shell and shell fragments. In other sections, the base of raised shoreline sequences is not evident as an erosional surface is visible on top of the till and deposits with marine shell fragments are not common. The width of the treads measured in a transversal direction to the shoreline is generally larger in inlets (up to 4 km) and narrower in marine cliff and scarp areas (about 5–10 m).



Figure 3. Second-order terrace: (F) fossiliferous gravel (6500 years BP; Brambati et al., 1998; De Muro et al., 2012) overlying glacial deposits (T – till). The position point is shown in Figure 2 (red dot).

The first and second-order terraces are locally lying on the top of a pre-existing glacial erosion platform and evolve towards a marine domain. In other locations, terraces lie on the top of glacial landforms deriving from the reworking of proglacial lake deposits.

The first order terrace (18–25 m a.s.l.) is the most ancient on the Atlantic sector of the Straits. This terrace began to form at the end of LGM (Brambati, De Muro, & Di Grande, 1998; Di Grande, De Muro, & Brambati, 1996) and the deposition of terrace sequences continued with the formation of second, third and fourth-order terrace until present day (De Muro et al., 2015; Figure 3).

The first order terrace documents the transition from glacio-fluvial-lacustrine conditions to clearly littoral-marine environments. In fact, sand and silt deposits of fluvio-lacustrine to marine conditions prevail in these terraces that have been classified as transitional (De Muro et al., 2015).

Second, third and fourth-order terraces are found at lower elevations and consist of sedimentary sequences of coastal marine origin generally overlying basal unconformities (palaeo-abrasion platforms). The second-order terrace (6–11 m a.s.l.) consists of gravel and sand deposits, locally showing a high fossiliferous content (Figure 4). This terrace order is distributed regularly and continuously throughout the coastal stretch of the studied area. Radiocarbon dating shows an age between 6000–7000 years BP for this terrace (Brambati et al., 1998).

The third-order terrace (3–5 m a.s.l.) consists of pelites, sands and gravels (often fossiliferous) of marine origins and formed between 4000 and 5000 years BP (Brambati et al., 1998). This terrace order was found in a rather narrow belt, oriented parallel to the present coast. Its distribution is almost identical to that of present shoreline leading to the interpretation of this terrace being the result of a brief depositional phase.

The fourth-order terraces (1–2 m a.s.l.) are composed of sediment of marine origin and their distribution is discontinuous along the coastline.

5. Discussion

The present work contributes to the reconstruction of Holocene palaeogeography of a vast coastal area of the

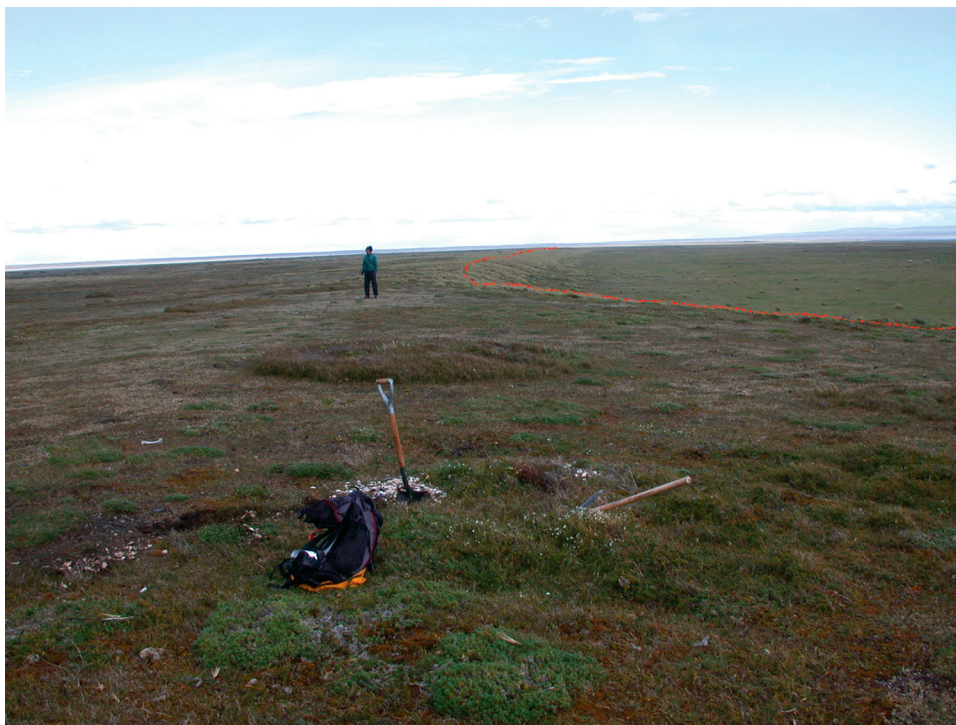


Figure 4. Seno Otway site 19.5 km to the south-east of Fitzroy Channel: view of the second-order terrace. Dashed red line indicates the outer edge. The position point is shown in Figure 2 (green dot).

Straits of Magellan, where marine terraces had previously been studied as individual features (Porter et al., 1984). The *Main Map* allows the mapping of marine terrace sequences to be extended towards the western side of the Straits of Magellan. In fact, these features show a staircase morphology which is consistent in the surrounding area of the Straits of Magellan (De Muro, 1996; De Muro, Di Grande, et al., 1997; De Muro et al., 2000; De Muro et al., 2015, 1996a, 1996b, 1996c; De Muro et al., 2017; Di Grande et al., 1997). Similar terrace sequences had already been observed by Kilian et al. (2013) on the eastern shores of Seno Otway with altitudes of 25–30 m at around 14 ky BP. These features formed during the last glacial retreat and are comparable with first-order terrace sequences described herein.

The marine terraces represent various stages of formation linked to the marine ingression following deglaciation in the western region of the Straits of Magellan and their formation stages are linked to the history of the area. The first terrace order corresponds to stages of marine ingression and their interaction with the lasting longstanding of deglaciation. In fact, post-glacial uplift is linked to a complex dynamic and alternation of combined isostatic rebound, eustatic movements and recent tectonic activity (Clapperton, 1990; De Muro et al., 2012; De Muro et al., 2015; Winslow & Prieto, 1991). The present tectonic setting of the Tierra del Fuego region is the result of the relative movements and interactions between three main plates: Antarctica, South America and Scotia (Burns, Rickard, Belbin, & Chamalaun, 1980; Cunningham, Klepeis, Gose, & Dalziel, 1991; Dalziel, Kligfield, Lowrie, & Opdyke, 1973; Lodolo, Menichetti, Tassone, & Sterzai, 2002; Menichetti, Lodolo, & Tassone, 2008). Evidence of recent tectonic activity was reported especially on the Pacific side of the Strait of Magellan (Bartole et al., 2000) and strike-slip faults are known to be linked to the complex dynamics of the collisional margin of the Southern Chilean plate (Lodolo et al., 2003). However, the south-eastern coast of Patagonia and the northeastern 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 rearrangement, with subsequent mild tectonic activity resulting from deglaciation (De Muro et al., 2012; Rabassa et al., 1992; Winslow & Prieto, 1991). As previously observed (Schellmann & Radtke, 2010), the relative marine ingression that produced terraced sequences is likely to be linked to uplift of the coastal system and inland following final deglaciation of the region. Isostatic rebound probably occurred in synchronicity with sea-level changes or 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 et al., 1998). Further studies are required to understand this process more fully.

6. Conclusions

This paper presents a geomorphological map (1:50,000 scale) focused on Holocene marine and transitional terraces of the northern sector of Peninsula Brunswick, extended between Seno Otway and Segunda Angostura of the Strait of Magellan in southernmost Patagonia. The morphological features illustrated in this map provide an overview of four orders of marine and transitional terraces mapped along the coast. These terraces formed from the end of the LGM to present day and their formation is the result of a complex combination of deglaciation, Holocene marine processes, local tectonic activity and uplift events linked to glacial isostatic rebound. The first terrace is the most ancient and was found at higher elevation than the second, third and fourth terraces. The origin of the first order terrace is linked to the development of proglacial lakes formed during a phase of glacial withdrawal and subsequent marine ingression. Second, third and fourth orders of terraces are clearly of coastal marine origin however they locally inherit and rework both pre-existing topography and deposits of glacial origin.

The distribution of Holocene marine terraces illustrated in this map provides useful information for the reconstruction of palaeogeography and post-glacial evolution of a geologically complex area such as Patagonia and Tierra del Fuego.

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. This map was subsequently digitalized using Autodesk Map 3D and refined in Adobe Illustrator CS5.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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