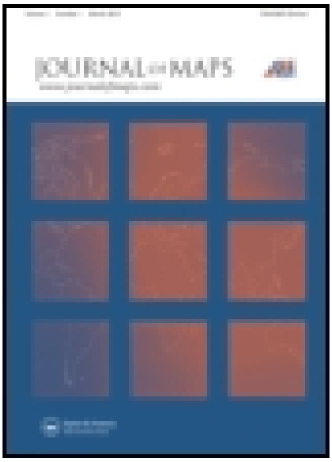

Journal of Maps
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tjom20

Geomorphology map of the marine and transitional terraces and raised shorelines of the Península Juan Mazía, Tierra Del Fuego. Straits of Magellan - Chile

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Published online: 31 Oct 2014.

Journal of Maps, 2014
http://dx.doi.org/10.1080/17445647.2014.970592

SCIENCE

Geomorphology map of the marine and transitional terraces and raised shorelines of the Península Juan Mazía, Tierra Del Fuego. Straits of Magellan – Chile

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(*Received 18 March 2014; resubmitted 23 September 2014; accepted 25 September 2014*)

This manuscript presents a detailed map (1:50,000) of the geomorphology of the marine and transitional terraces and raised shorelines linked to Holocene-Pleistocene (?) glacio-eustatic variations in Península Juan Mazía situated on the Segunda Angostura in the western area of the Straits of Magellan. The Main Map, centered on approximately 52° 40’ and 52°60’, was compiled through geomorphological survey in the field integrated with interpretation of aerial photographs and remote-sensing imagery. The survey has allowed mapping of a regular sequence of terraces and raised shorelines represented mainly by marine, and partially by transitional terraced deposits, located in four orders at the respective elevations of 18 ÷ 25 m, 6 ÷ 11 m, 3 ÷ 5 m and 1 ÷ 2 m above mean sea level. The Main Map also provides other features such as landforms and deposits, due to littoral, running water, glacial and wind processes.

1. Introduction

The purpose of this paper is to illustrate the geomorphology related to the marine and transitional terraced sequences surveyed in Península Juan Mazía, situated on the Segunda Angostura of the Straits of Magellan facing the Atlantic Ocean. The Main Map illustrates the distribution of the most recent marine terraces, with the aim of contributing toward the reconstruction of the Holocene palaeography of the vast coastal area of the Straits of Magellan. The evolution of the marine terraces had not been studied until the published work of De Muro and Brambati (1993 to 2004); up to that point the terraces had only been studied as individual features (Porter, Stuiver, & Heusser, 1984). The present work continues mapping of this vast area from a regional perspective, using digital cartography for the first time.

The Main Map results from previous studies carried out within the project ‘Coastal geological and geomorphological cartography of Quaternary deposits in the Straits of Magellan (Chile)’, with the financial support of the Regione Autonoma della Sardegna – Paesi in Via di Sviluppo (RAS-PVS). This project was part of a wider research program on the recent evolution of the

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Straits of Magellan which began in 1991, with the 'Programma Nazionale di Ricerche in Antartide' (PNRA). Moreover, the study also included the IGCP 367 project 'Late Quaternary Coastal Records of Rapid Change'.

The PNRA project was mainly focused on geomorphological and sedimentological research (Brambati, Colizza et al., 1993; Brambati, De Muro, & Di Grande, 1993; Brambati, De Muro, Di Grande et al., 1993) on the sea bottom and coastal belt of the eastern section of the Atlantic Opening of the Straits. Similar wide ranging research was also carried out, by sea vessel, on the coastal belt of the western section of the Straits (Pacific Opening), since the area is inaccessible by land due to the sheer fjord cliffs. The first geomorphological coastal studies were carried out together with sedimentological studies of the sea bottom (Brambati, Fontolan, & Simeoni, 1991), but were limited to research on the source and transport of the sediments as well as a regional definition of morphostructural units (Bartole, Colizza, De Muro, & Colautti, 2000; Bartole et al. 2001; Bartole, De Muro, Morelli, & Tosoratti, 2008). Subsequent research along the coastal belt was carried out in greater detail with mapping of the geomorphological units. During this second phase, greater attention was given to the study of raised shorelines and different terrace orders of marine and transitional origin (De Muro, Di Grande, & Brambati, 1995; Brambati, De Muro, & Di Grande, 1995; Di Grande, De Muro, & Brambati, 1995). The aim of this second phase of research was to fully map the post-Last Glacial Maximum (LGM) geomorphological evolutionary scenarios and to better understand the stages of Holocene marine transgression in the area of the Eastern Straits of Magellan. As noted in the literature (Feruglio, 1933; Porter et al., 1984; Porter, Clapperton, & Sudgen, 1992; Rabassa et al., 1992) marine terrace deposits at various heights had been located previously, but only as individual features; before 1993 a comprehensive map had never been produced of all the coastal terraces genetically linked to the complex transitional phases between the LGM and the subsequent Holocene marine ingression in the Straits. The new geomorphological map, presented in this study, includes terraces clearly linked to marine littoral dynamics, and also terraces of mixed origin (glacial, lacustrine, littoral and marine) defined as transitional. The transitional terraces have nearly flat erosion surfaces terminating with a steep palaeo-cliff at both ends. They were produced by processes ranging from glacial and lacustrine to clearly littoral (marine), typically related to glacial-interglacial phases. (Darvill, Stokes, Bentley, & Lovell, 2014; Lovell, Stokes, & Bentley, 2011).

2. Geographical setting and quaternary evolution of the area

Península Juan Mazía is situated on the Segunda Angostura of the Straits of Magellan (Figures 1 and 2). Ice caps have periodically covered the Patagonian Andes since the late Miocene, and approximately 43,000 years ago the Magellan Glacier covered the Segunda Angostura (Figure 4). Studies carried out by Clapperton (1992) have identified three distinct morainic limits (Figure 4) attributed to the last glaciation, called Otway-Magellan, Juan Mazía and lsla Dawson from the oldest to the most recent.

Clapperton (1992) placed the last phase of expansion of the Magellan Glacier north-eastwards between 29,000 and 24,000 years B.P. Subsequently, as the Magellan Glacier withdrew southwards, numerous proglacial lakes formed between the brow of the Glacier and the Atlantic side. Glaciers did not disappear from this region, withdrawing into the Darwin Cordillera, until around 13,000–12,000 years B.P. (Clapperton, 1992, Porter et al., 1992), with the Holocene Sea forming later than 10,000–9000 years B.P. (Di Grande, De Muro, & Brambati, 1996a; Di Grande, De Muro, & Brambati, 1996b). In addition, a detailed evolution of the flooding of the Straits of Magellan has been given by Brambati (2000). Previously, Caldenius (1932), Raedeke (1978) and Prieto & Winslow (1992) described the outcrops relating to the last glaciation of the Eastern Magellan area, particularly the internal and intermediate morains of the Segunda

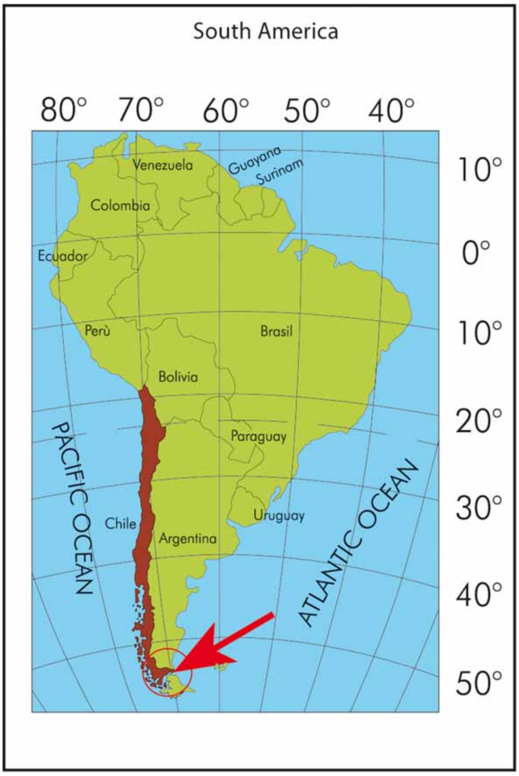

Figure 1. Location of the study area.

Angostura; they noted the presence of ancient marginal and ablation channels, and classified alluvial and fluvio-glacial deposits as previously being outwash plains.

With reference to recent research, Glasser and Jansson (2008) published a map of the glacial geomorphology of the southern part of South America, showing the main geomorphological features, the extension of the ice fields and glaciers present, and other topographic features. Lovell et al. (2011) and Darvill et al. (2014) produced glacial geomorphological maps at a scale of 1:250,000 of the Seno Skyring-Seno Otway-Straits of Magellan, in southern Patagonia, with the aim of reconstructing the pre- LGM glacial dynamics of the region. Considering the scale difference, the above mentioned studies, concur with the data presented on the different maps shown by Brambati, De Muro, & Di Grande (1998) and De Muro, Brambati, & Di Grande (2004).

Since the early Holocene, Península Juan Mazía has been an important littoral morphodynamic unit in the evolutionary history of the shoreline of the Straits of Magellan (De Muro et al., 1996b, 1996c). Its evolution from the early-to-late Holocene can be inferred upon examination of the geomorphological Main Map, and following the borders of the four terraces, which define the palaeo-coastlines planimetrically (Figure 5).

3. Methods

This Main Map was prepared using data acquired through geological and geomorphological field surveying of the deposits and landforms of the Quaternary and marine Holocene processes at a

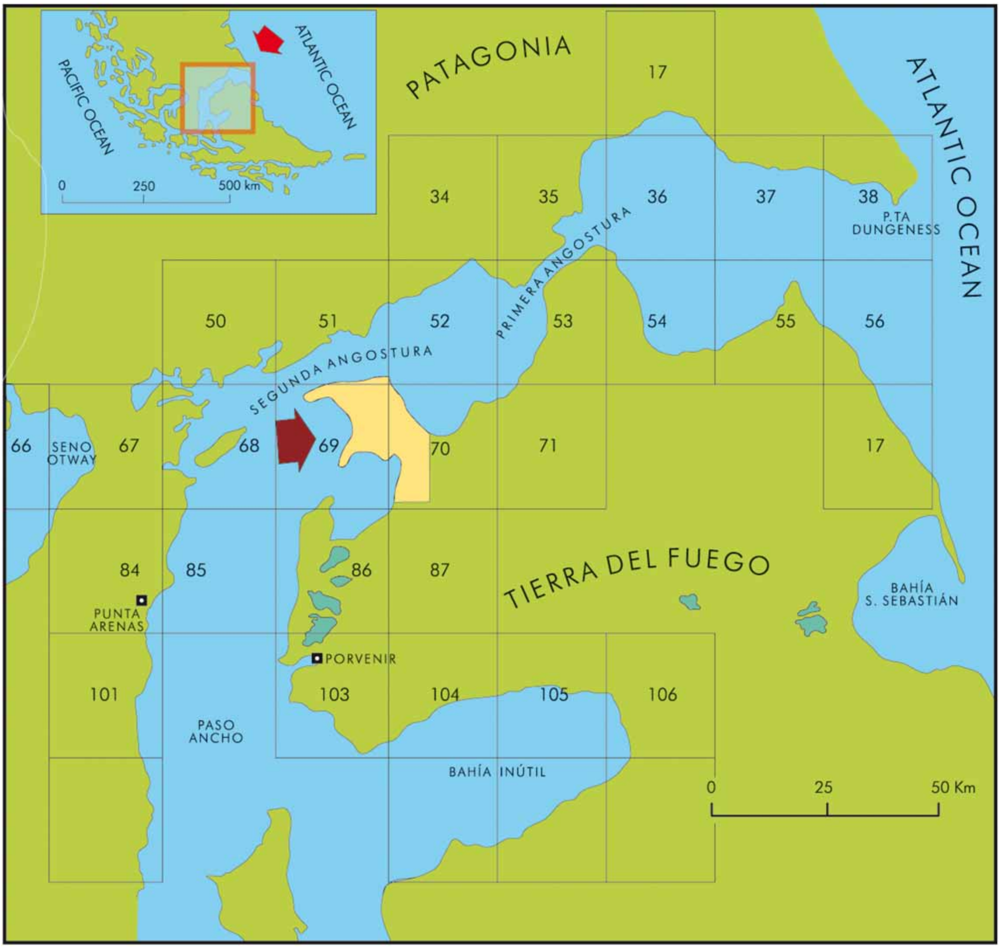

Figure 2. Study area and position of the map at a scale of 1:50,000 illustrated in yellow. Sheets No. 69, No. 70 and No. 51 of Section L - Chilean I.G.M. at the same scale as the map.

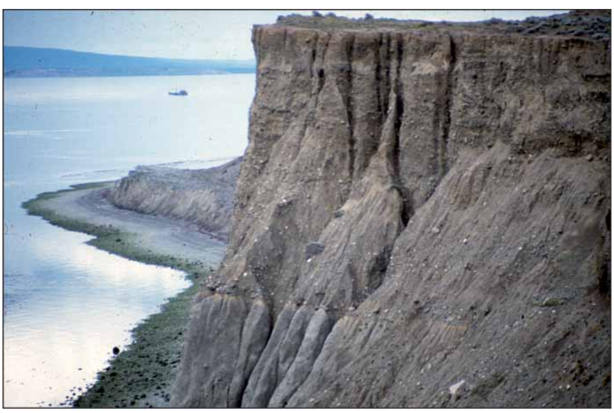

Figure 3. Cabo San Vincente (Segunda Angostura): morainic deposits forming cliff face.

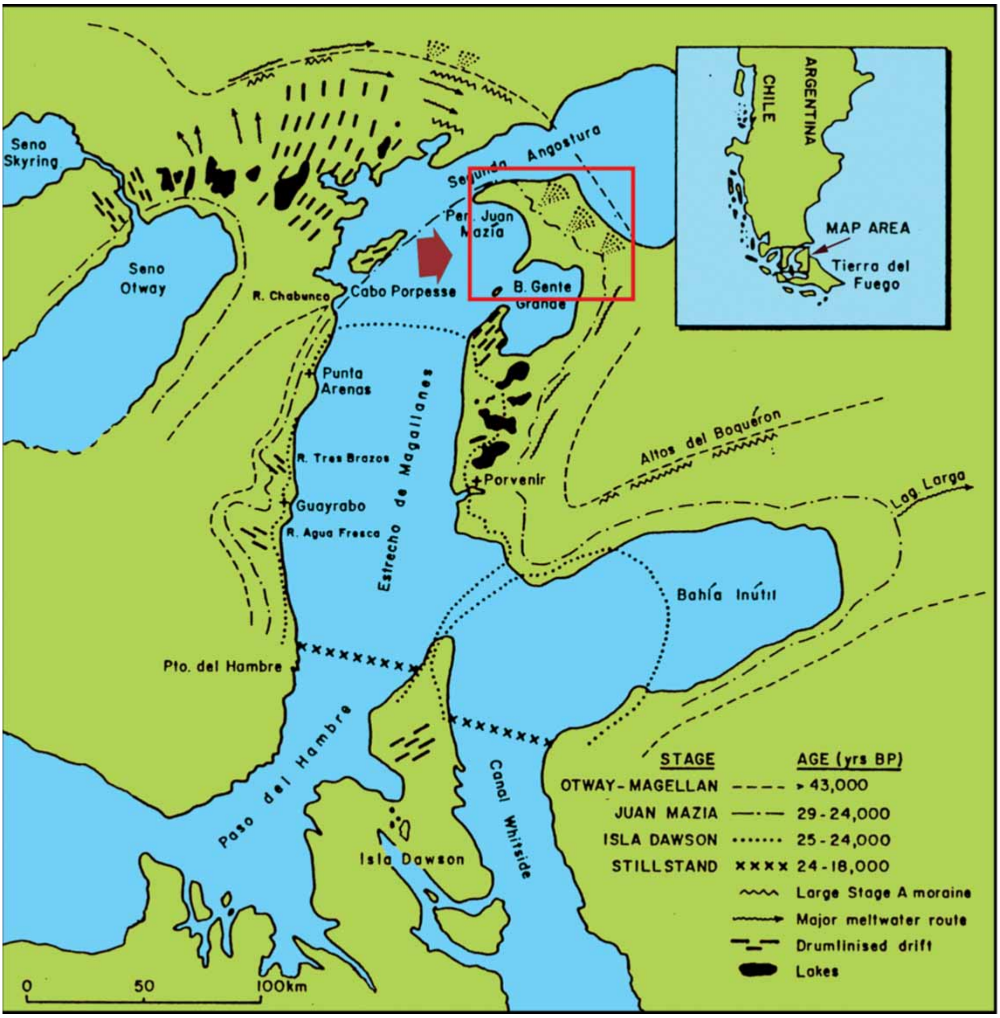

Figure 4. Expanding fronts of Magellanic Glaciers covering Segunda Angostura during the late phase of the last glaciation according to Clapperton (1992), (modified). The red arrow indicates the location of the study area.

large scale. Samples collected during fieldwork (1991, 1994, 1995, 2003) were used for sedimentological, paleontological and geochemical analysis.

Furthermore, the data collected from field surveys around the edges of outcrops and morphological features, were checked and interpreted using aerial photographs (Servicio Aerofotogrammetrico Fuerza Aerea de Chile; SAF) at an approximate scale of 1:60,000, Landsat Thematic Mapper and Multi-Spectral Scanner imagery and geological maps of E.N.A.P. (1978) and S.N.G.M. (1982).

Subsequently the first draft map was produced using a 1:50,000 scale topographic map from the Instituto Geografico Militar Chileno, sheets No. 69, No. 70 and No. 51 of Section L (Figure 2).

Land surveys of the terraces were carried out and the data positioned on the map, tracing the edges of outcrops from sea level and proceeding upwards to the higher terraces. The accuracy of the positioning is estimated at 25–50 m planimetrically and 2–3 m vertically.

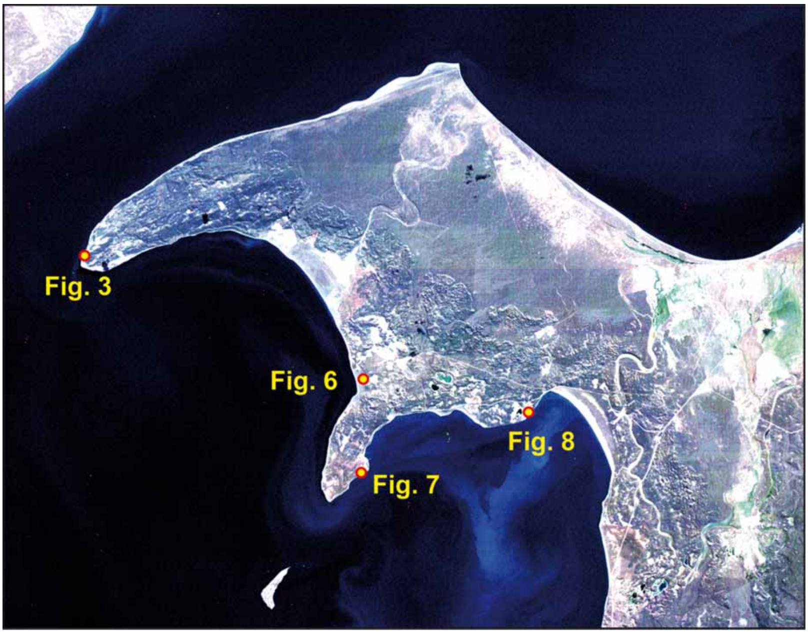

Figure 5. Península Juan Mazía, positions from which the photographs were taken located on a false color composite Landsat TM image.

Initially the entire peninsula coastline was surveyed, carrying out topographic, geomorphological and stratigraphic line transects at a spacing of 1000 m, starting from average sea level and continuing upwards to the level of the first-order terraces (about +25 m). A theodolite and a handheld global positioning system (GPS) receiver were used for the topographical survey and to measure elevation.

The land surveying ultimately aimed to define and delimit the borders of the progressively higher and older terraces; the age was defined using ^{14}C radiometric analysis (respectively from the fourth to the third toward the second and the first order, where present).

Stratigraphic continuity (type of sediment and possible fossiliferous content) was verified by digging trenches near the concave and convex nick points (palaeo wave-cut scarp – palaeo cliffs). Sedimentological, palaeontological and geochemical analyses were carried out on the samples (^{14}C on significant samples) and facies analyses were carried out on the mapped sediments.

Information regarding the other environments (glacial, lacustrine and fluvial) was acquired firstly using aerial-photogrammetric analyses, followed by both geomorphological and sedimentological verification on land.

The second draft of the Main Map was completed in an aerial photogrammetric laboratory, redrawing and refining the limits of the outcrops using an OMI stereo facet plotter (Petrie, 1992); the data from both the land surveying and aerial photographs were used to validate the final mapping.

The final stage involved the digitalization of the geomorphological paper map, which was scanned to create a digital map using Adobe Illustrator CS3.

3.1. *Organization of the map legend*

The Main Map focuses on the distribution of the marine and transitional terraces and on the raised shoreline and relative morphology, with the aim of contributing toward reconstructing the

Holocene palaeogeography of the coast along the entire Atlantic sector of the Straits of Magellan. The legend is made up of 46 items, divided into seven main blocks. This is shown in the first block.

The second, third, fourth and fifth blocks describe lacustrine, glacial, aeolian and fluvial deposits, landforms and processes, respectively. The sixth block shows the present dynamics of the coast and the seventh outlines additional information including topographic and bathymetric features, tidal range, elements linked to human activity and fossiliferous deposits. Active and inactive deposits, landforms and processes are distinguished.

The seven main blocks are:

(1) Marine and transitional deposits and landforms
Information relating to the four orders of sequenced terrace deposits; deposits and morphology of emerged and submerged present beach and raised shoreline; cliffs and abrasion platforms; tidal environment forms and deposits
(2) Lacustrine deposits, landforms and processes
Surfaces made up of lacustrine deposits, of lakes and their present dynamics
(3) Glacial deposits and landforms
Inactive deposits and forms linked to glacialiation (Quaternary)
(4) Aeolian deposits and landforms
Deposits of aeolian origin (dunes) and deflation surfaces
(5) Fluvial deposits, landforms and processes
Both active and inactive deposits, landforms and processes, some of which are genetically linked to ancient fluvial-glacial environments (outwash plain, stream channel, braided stream, eroded scarp). Others linked to the present action of running water (e.g. erosional scarp, gully, regressive erosion, rill wash)
(6) Present dynamics of the coast
Information relating to evidence of littoral transport deduced from aerial photogrammetric comparisons and subsequent land surveys.
(7) Additional information
Cartographic elements relating to the topography (contour lines, roads, path-tracks) and marine areas (isobaths, mean tidal range).

4. Coastal terraces and marine raised shorelines

The marine coastal terraces and the raised palaeo-shorelines are generally arranged in a succession of steps, and are mapped starting from the most ancient, at $18 \div 25$ m (first order), $6 \div 11$ m (second order), $3 \div 5$ m (third order) to the most recent at $1 \div 2$ m (fourth order) above mean sea level (De Muro et al., 1996a, 1996b, 1996c), as per other studies of the Straits (De Muro, 1996; De Muro, Di Grande, Brambati, & Marini, 1997; Di Grande, De Muro, Brambati, & Marini, 1997; De Muro, Di Grande, & Brambati, 2000; De Muro, Di Grande, Fontolan, & Brambati, 2000). The distribution of the different orders of terraces is consistent with the evolution of the coastline, indicating continuity (Figure 6).

The terrace succession contains mainly marine deposits and littoral forms such as paleo-marine abrasion platforms, paleo-shorelines, beach ridges, spits, cuspate forelands and other geomorphological littoral features. In some cases the coastal terraces contain both littoral deposits and forms allowing them to be classified as raised shorelines. The evolution of these terraced sequences mainly starts with a palaeo-abrasion platform of marine origin (Figure 7) as the wave cut into till, with sandy gravely beach deposits of high fossiliferous content on top; on terraces further inland, there are often sequences of beach ridges.

Figure 6. Bahía Lee, approx. 15 km south east of Cabo S. Vincente: first (I) and second (II) order terraces.

The order of terraces is numbered chronologically and stratigraphically. Following the surveying carried out De Muro et al. (1996c), number 1 was assigned to the most ancient deposit surveyed in the Atlantic sector of the Straits with marine coastal features (sedimentology, fossil content, planimetric distribution of the outcrops following the coastline, palaeo-littoral forms such as beach ridges, palaeo-abrasion platforms, structures interpreted as palaeo-spits, cuspate forelands, or other forms and deposits linked to marine-coastal environments such as marshlands and palaeo-cliffs, etc.). The fossiliferous content of the deposit was dated using radiocarbon analysis. The second, third and fourth orders are respectively more recent and lower in elevation according to the present sea level.

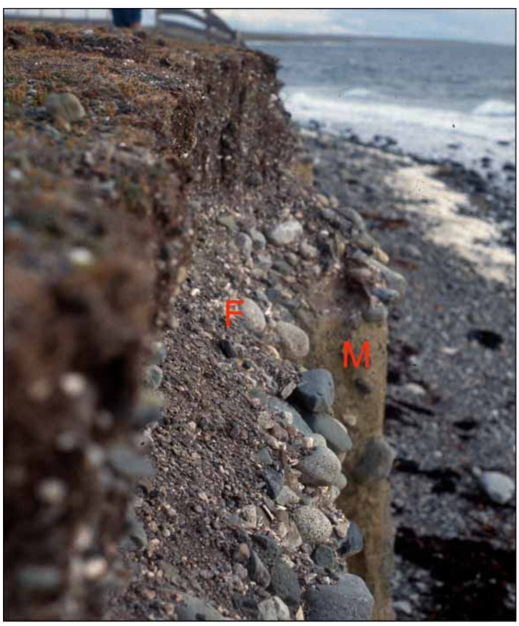

Figura 7. Site 5 km north of Punta Zegers: (F) fossiliferous gravel of the second-order terrace overlying (M) glacial deposits (till).

Figure 8. Puerto Percy: fossiliferous gravel of the second-order terrace.

The second (6 ÷ 11 m above mean sea level - 7000 ÷ 6000 years B.P.), third (3 ÷ 5 m above mean sea level - 5000 ÷ 4000 years B.P.) and fourth (1 ÷ 2 m above mean sea level - 2500 ÷ 1200 years B.P.) orders of coastal terraces and their raised shorelines, almost always contain marine fauna (Figure 8); all three are therefore of marine origin.

On the other hand, the adjective 'transitional' was chosen and used to better describe the first-order terrace (10000 ÷ 8000 years B.P.), as the layout of these terraces (18 ÷ 25 m) along the coast infers the evolution of the environment from continental to marine formation after the LGM. This transition zone in the stratigraphic sequence can sometimes be seen from the passage of sediments from fluvial-glacial (outwash plain), lacustrine (proglacial) to littoral marine.

On both the western and eastern sides of Península Juan Mazía the first-order terrace is morphologically well-defined, but its internal composition (stratigraphy and sedimentology) varies from W to E of the peninsula according to the various environments with which it came into contact during its formation (from fluvial-glacial, lacustrine to marine respectively).

5. Conclusion

The results of this geomorphological study are part of a large project which has made possible the mapping, at a 1:50,000 scale, of the coastline between the Atlantic opening of the Straits of Magellan and Punta Arenas (Chile). The results nine scientific expeditions, both on land and at sea, carried out for three different research projects in Patagonia and Tierra del Fuego form the basis for an Atlas composed of seven geomorphological maps. These are the first digital maps of the Atlas which is currently in production. The area illustrated on this first Main Map, at a 1.50,000 scale, is located in the Segunda Angostura sector, between Bahìa Felipe and Bahìa Gente Grande, on Península Juan Mazía.

The main aim of this Main Map is to depict the distribution of Holocene marine terraces for the entire eastern sector of the Straits of Magellan. The marine terraces and raised shorelines had already been located, but only described in individual locations; the evolutionary aspect is presented here from a regional perspective.

The Main Map highlights the distribution of the four orders of terraces genetically linked to Holocene marine activity. The terraces were generated, and are chronologically arranged, from the end of the LGM to the present day.

Three orders of these terraces (those closest to the present sea level) are clearly of coastal marine environmental origin, while the first (most ancient and highest above present m.s.l.) is of mixed environmental origin and has been classified as transitional. The first order is linked to the transition from the phase of glacial withdrawal to the first marine ingression of the Holocene Sea into the Atlantic opening of the Straits, as far as Paso Ancho. This marine ingression has also been described by others (Clapperton, 1990, 1992; Porter et al., 1992; Glasser & Jansson, 2008; Lovell et al., 2011; Darvill et al., 2014) and, in particular, on the basis of detailed sedimentological studies (Brambati, 2000). The evolution of this peninsular area since the LGM, as observed in the remaining eastern area of the Straits (De Muro, Brambati, & Di Grande, 2004; De Muro, Di Grande, & Brambati, 2004; De Muro & Brambati, 2004; Clapperton, 1990, 1992; Porter et al., 1992), is illustrated by the distribution of the deposits and landforms on the Main Map, and may be summarized as follows:

(1) Retreat of the ice front of the glacier and beginning of deglaciation with formation of environments such as outwash plains, proglacial lakes, etc. Progressive advance of Atlantic sea water had already taken place after previous glaciations (Auer, 1970; Feruglio, 1933; Rabassa et al., 1992). Sea water penetrated the lakes and/or flat areas and created the formations and deposits of the first-order terrace sequences now referred to as first order (10000 ÷ 8000 years B.P.) (Brambati, 2000; Brambati & De Muro, 2004)
(2) First phase of glacial isostatic rebound (which probably began in phase 1)
(3) Creation of landforms and deposits of second-order terraces (7000 ÷ 6000 years B.P.) (Palaeo-abrasion platforms, deposition of sediments and organisms in shallow water and beach, dominance of coastal hydrodynamic processes, etc.)
(4) Second phase of glacial isostatic rebound
(5) Creation of third-order terrace sequences (5000 ÷ 4000 years B.P.)
(6) Third phase of glacial isostatic rebound
(7) Modelling of fourth-order terrace sequences (2500 ÷ 1200 years B.P.)
(8) Contemporary landscape

This evolution is obviously connected to an articulated history of the area after the last glaciation during which the combination of isostatic and eustatic components must be taken into consideration; however, effects linked to recent tectonic activity (Clapperton, 1990; Winslow & Prieto, 1991), cannot be excluded (De Muro, Kalb, Brambilla, & Ibba, 2012; De Muro & Brambati, 2012).

The Main Map also illustrates landforms, deposits and processes relating to the Quaternary glacial environment. Information is also shown regarding lacustrine, glacial, aeolian and fluvial deposits, landforms and processes, and the present dynamics of the coast. The Main Map could also be used as support for coastal zone management.

Software

The Main Map was produced from geomorphological and geological field surveys of Quaternary and Holocene deposits, with the support of aerial photographs and remote-sensing interpretation. These maps were subsequently produced using Adobe Illustrator CS3.

Acknowledgements

We are grateful to Dr Ximena Prieto from the Università de Magallanes and to Dr Gino Casassa Rogazinski from the Centro Austral Antartico di Punta Arenas (Chile).

This work was funded by: Programma Nazionale Ricerche in Antartide (PNRA), 'Late Quaternary Climatic Evolution in the Magellan-Fuegine area (southern South America)' and 'Seismostratigraphy and sedimentology of the South Chile margin'. Supervisor: Antonio Brambati.

Regione Autonoma della Sardegna (RAS) – Paesi in Via di Sviluppo (PVS) Project: 'Geological and Geomorphological Map of the Coast of the Straits of Magellan'. Supervisor: Sandro De Muro.

University of Cagliari Research Project 'Evolution, dynamics, and processes of the coasts and continental shelf in Mediterranean areas compared to other areas of the Planet'. Supervisor: Sandro De Muro.

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GEOMORPHOLOGY MAP OF THE MARINE AND TRANSITIONAL TERRACES AND RAISED SHORELINES OF THE PENÍNSULA JUAN MAZÍA, TIERRA DEL FUEGO STRAITS OF MAGELLAN - CHILE

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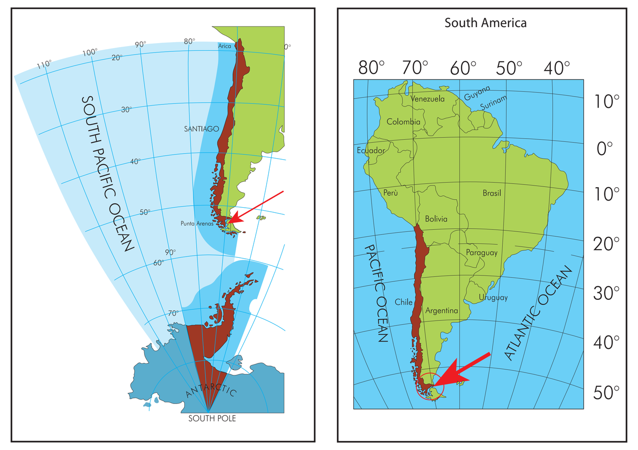
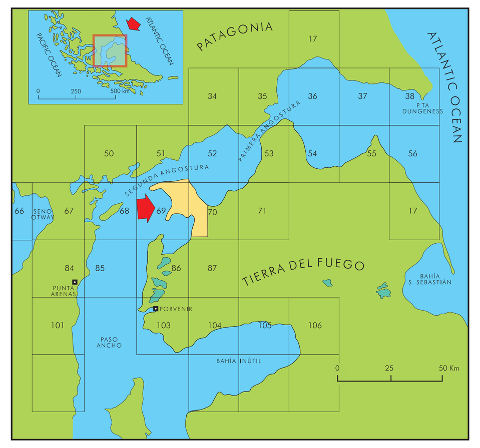


Position maps



Studied area and position maps of the 1:50,000 scale section

The map was produced by Sandro DeMuro and Angelo Di Grande 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.

The locational accuracy is estimated to be within 25 m ÷ 50 m in planimetry and 2 m ÷ 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 "Instituto 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 Aerofotogrammetrico Fuerza Aerea de Chile" (SAF) and images from TM and MSS Landsat satellites. Universal Transverse Mercator cartographic projection (UTM). Altimetrical data are referred to present mean sea level.

This work was funded by:

Programma Nazionale Ricerche in Antartide (PNRA), "Late Quaternary Climatic Evolution in Magellan-Fuegine area (southern South America)"and "Seismostratigraphy and sedimentology of the South Chile margin". Supervisor: Antonio Brambati.

Regione Autonoma della Sardegna (RAS) – Paesi in Via di Sviluppo (PVS) Project "Geological and Geomorphological Map of the Coast of the Magellan Strait". Supervisor: Sandro De Muro.

University of Cagliari Research Project "Evolution, dynamics, and processes of the coasts and continental platform in Mediterranean areas compared to other areas on the planet". Supervisor: Sandro De Muro.

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Scale 1:50.000

0 1000 2000 3000 4000

metres

LEGEND

MARINE AND TRANSITIONAL DEPOSITS AND LANDFORMS

Active / Inactive

Deposits — Terraced sequences:

- Fourth Order Terrace made up of pelites, sands and gravels (often fossiliferous), or relative paleo-abrasion platforms mainly situated between 1 and 2 metres.
- Third Order Terrace made up of pelites, sands and gravels (often fossiliferous), or relative paleo-abrasion platforms mainly situated between 3 and 5 metres.
- Second Order Terrace made up of pelites, sands and gravels (often fossiliferous), or relative paleo-abrasion platforms mainly situated between 6 and 11 metres.
- First Order Terrace made up of pelites, sands and gravels lacustrine environment and transitional environment and relative erosion surfaces mainly situated between 18 and 25 metres.
- Sandy, gravelly and pebbly beach
- Tidal bank (gravel - sand)

Landforms:

- Spit, cusp
- Beach landforms (berm, spit, ridge)
- Cliff (active: h>5m)
- Abrasion platform
- Tidal channel
- Tidal flat
- Salt marsh

LACUSTRINE DEPOSITS, LANDFORMS AND PROCESSES

Active / Inactive

- Lacustrine deposit
- Lacustrine terrace
- Lake and pond drift due to deflation
- Lake

GLACIAL DEPOSITS AND LANDFORMS

Active / Inactive

- Undifferentiated glacial and fluvioglacial deposits and landforms (moraine, esker, kame, marginal stream etc.)
- Kettle hole
- Glacial striae, glacial drift direction

AEOLIAN DEPOSITS AND LANDFORMS

Active / Inactive

- Dunes
- Deflation surface

FLUVIAL DEPOSITS, LANDFORMS AND PROCESSES

Active / Inactive

- Alluvial deposits

mainly due to fluvioglacial processes:

- Outwash plain
- Stream channel
- Braided stream
- Erosional scarp
- Gully
- Regressive erosion
- Rill wash

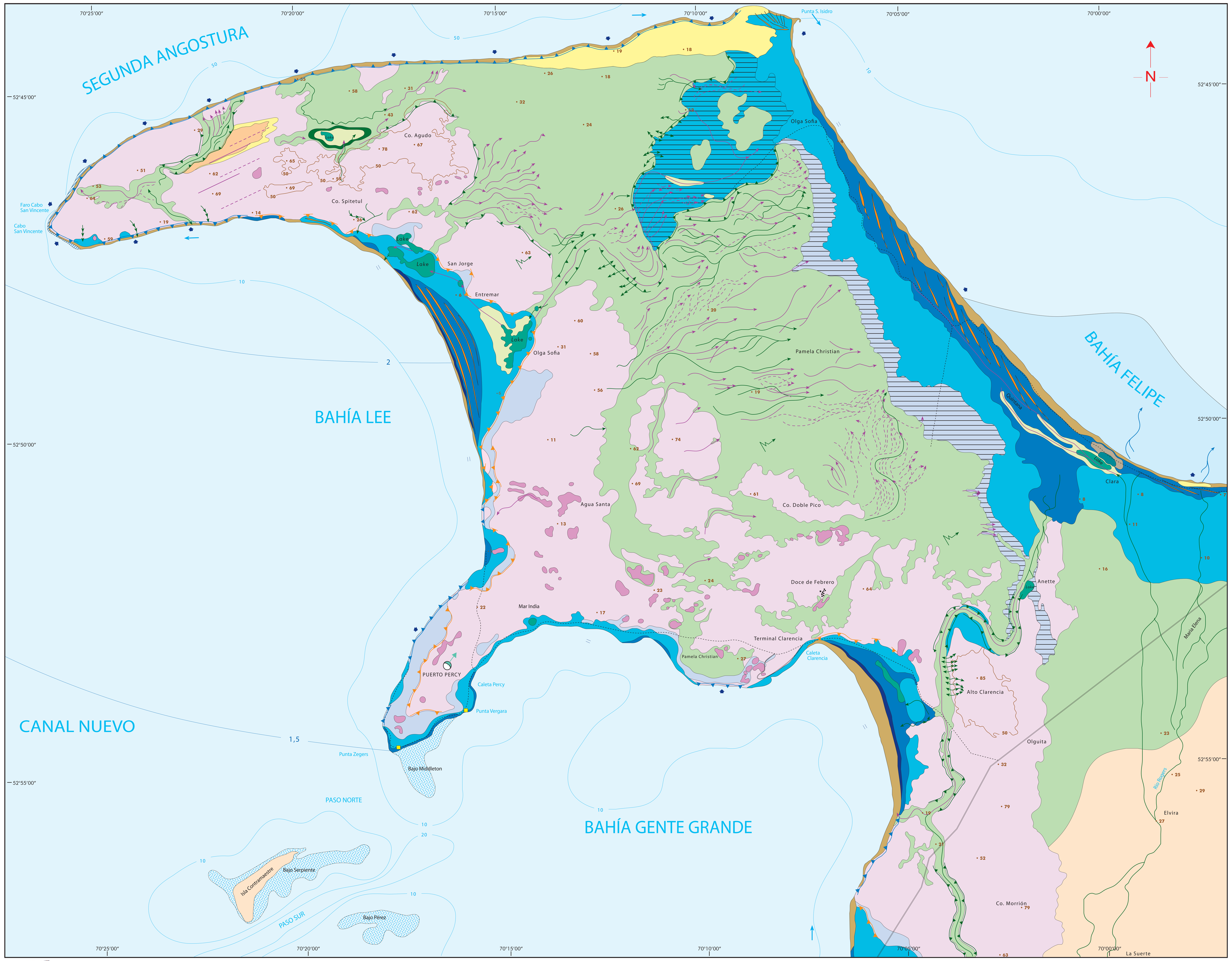
PRESENT DYNAMICS OF THE COAST

- Main littoral drift direction
- Prograding shoreline
- Stable shoreline
- Retreating shoreline

ADDITIONAL INFORMATION

Terrestrial / Marine

- Road
- Path-track
- Contour line
- Survey uncertain
- Fossiliferous deposit
- Area not studied
- Isobath (10)
- Mean tidal range (m)



section L n.69 <-> section L n.70