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Geomorphological Characterization of the Coastal and Marine Area between Primera and Segunda Angostura, Strait of Magellan (Chile)

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ABSTRACT

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A detailed geomorphological study of the Chilean coastal area of the Strait of Magellan aimed at the determination and description of different coastal environments and related processes. The survey data have been compiled in a map that outlines the influence of glacial history in the coastal landscape development. Sea-bed characteristics such as bathymetry and sedimentology, together with information on tides, direction and magnitude of currents are also presented in the map. A subdivision of the coastal area was carried out dividing the coastline into 40 homogeneous segments, each described by 15 representative morphological and physical variables. By means of multivariate analyses of the data matrix six coastal groups subdivision was obtained. Groups were reviewed and re-interpreted in order to highlight relationships between coastal landforms and variables. Three factors fully describe the main coastal types and constraints. First factor groups the inherited coastal landforms, that are cliffs developed where ancient morainal deposits heighten. Second factor represents the wind-enhanced coastal landforms, where the combined action of tide and wind permits the development of the highest coastal form variability. Third factor groups the tide-controlled coastal landforms, that are well-specialized landforms, mainly tidal flats and marshes. The Factor I-II-III path defines increasing coastal stability.

Additional Index Words: Geomorphology, coastal zone, littoral dynamics, statistical analysis, Strait of Magellan.

INTRODUCTION

Despite the great extension of the coastal area of the Strait of Magellan a review of coastal environments and related processes is still lacking. The major interest in this remote area was devoted to oil-spill hazard, and a very preliminary coastal subdivision related to environmental susceptibility was attempted by HAYES *et al.* (1976). In 1991 a detailed geomorphological study of the eastern coastal area of the Strait of Magellan was performed, both along the Patagonian and Fuegian coasts. The results of field surveying and interpretation of aerial photographs are summarized in a morphological map (Appendix). In order to understand the meaning of the present littoral area and its evolution, onshore landscapes were described in relation to offshore morphologies. The map describes only Quaternary morphologies, with a focus on the present landscape of the coastal area. The studied coastline shows a high variety of morphologies and processes and a detailed classification is quite difficult. The purpose of this paper is to furnish a simplified scheme of littoral and marine morphologies and features of the eastern sector of the Strait, together with a coastal zoning based on similarity quantitative criteria among coastal stretches described by selected coastal-marine forms and forcings as variables.

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STUDY AREA

The Strait of Magellan is located at the southernmost part of South America, between 52° and 54° latitude south. It extends for about 500 km, connecting the Pacific and Atlantic oceans and separating Patagonia from Tierra del Fuego. The eastern part of the Strait (Fig. 1; map in Appendix) has an entrance 27 km wide, delimited by Punta Dungeness in the north, and Punta Catalina in the south. Westwards, the Strait consists of a series of wide basins connected by two narrows (Primera and Segunda Angostura). The sea-bottom morphology shows an eastern inlet oriented NW–SE, due to the accretion of an elongated sand bank, which is connected to Punta Dungeness. On the Fuegian side, Punta Catalina represents the eastern limit of Bahia Lomas, which is the widest tidal flat in the Strait of Magellan.

Climate

The climate of the eastern Strait is a modified middle-latitude steppe type, with low rainfall, ranging from 250 to 350 mm/y in the Patagonia Pampa region (ROMERO, 1985). The

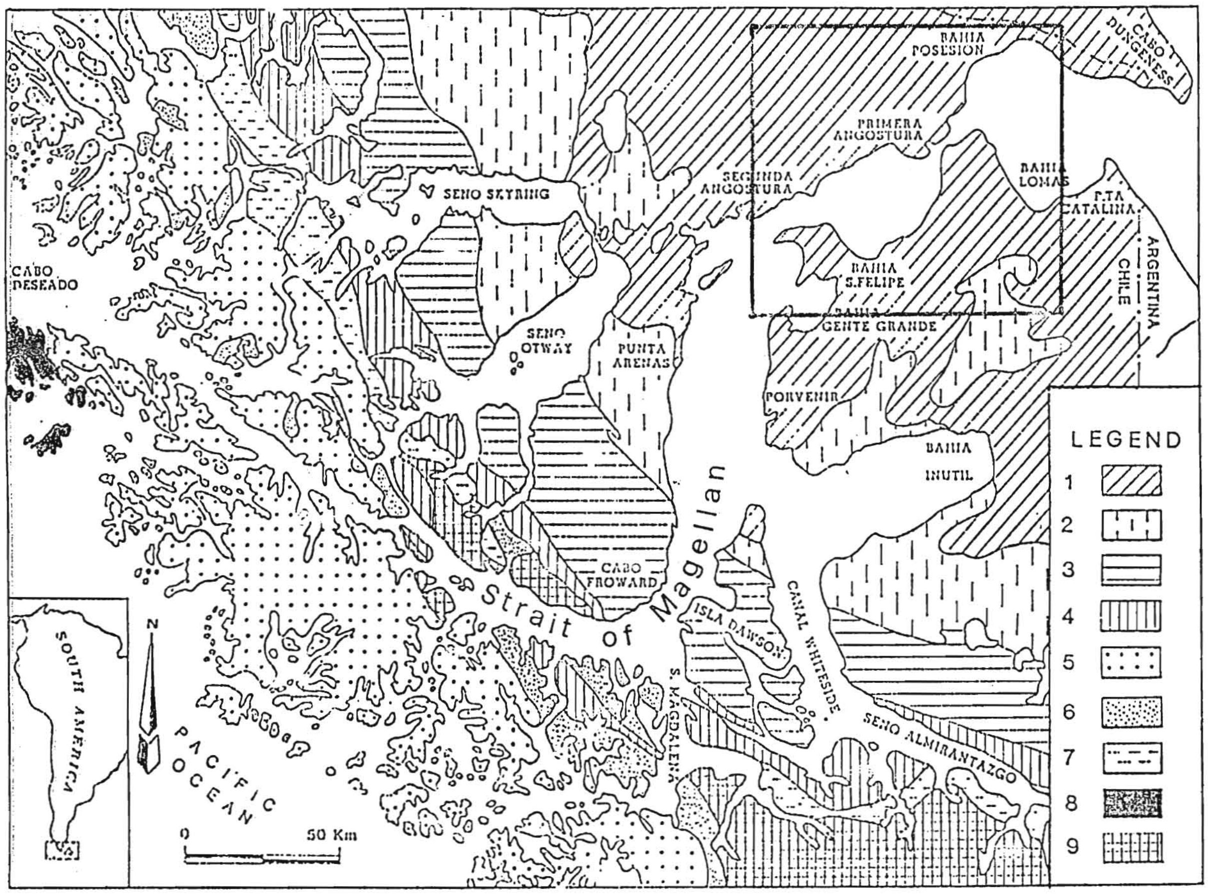

Figure 1. Location of the study area (square) inside the schematic geological map of the southernmost Chile (after S.N.G.M., 1982, modified). (1) Glacio-fluvial and glacial sediments (Quaternary); (2) Marine and continental deposits (Tertiary); (3) Marine sedimentary rocks (Late Cretaceous); (4) Marine sedimentary rocks (Early Cretaceous); (5) Andean Batholith (Late Jurassic-Early Tertiary); (6) Basaltic sequences (Late Jurassic-Early Cretaceous); (7) Volcanic sequences (Jurassic); (8) Sedimentary and volcanic rocks (Late Paleozoic-Early Mesozoic); (9) Metamorphic basement (Paleozoic).

mean annual temperature is 6–7° C (HUBER, 1977a, 1977b). Temperature varies from 8° to 11° C in summer (December–February), and from 2° to 3° C in winter (June–August). Winds in the region are particularly strong, blowing from the west 60% of the year, and from NW and SW 20% of the year. Their average speed is 7 m/s, but they can often exceed 25 m/s, particularly during winter and spring, when the Antarctic cold air masses flow northward (ZAMORA and SANTANA, 1981). The eastern side of the Strait of Magellan is dominated by semi-diurnal tides. A macrotidal regime affects the first bay (see Appendix) westward of the Atlantic entrance, with a mean tidal range of 7.1 m and a spring range reaching up to 9 m (MEDEIROS and KJERFVE, 1988). These values become larger in the Bahia Posesion, at times exceeding 10 m in range and decreasing down to 4–5 m in the bay enclosed between the two narrows and to 2 m in the Paso Ancho basin (MEDEIROS and KJERFVE, 1988). Currents are very strong, with maximum superficial values measured in the Angosturas. They can reach 2.5 m/s in the Atlantic entrance, and increase up to 4.5 m/s and 3 m/s in the Primera and Segunda Angostura respectively (MEDEIROS and KJERFVE, 1988). Shallow water depths and strong currents are the main features of the eastern part of the Strait; these induce erosion and re-suspension in the coastal and offshore sediment (BRAMBATI *et al.,* 1991; FONTOLAN and PANELLA, 1991).

Geologic Setting and Quaternary Evolution

The Strait of Magellan crosses the four major physiographic units (Archipelago, Cordillera, pre-Cordillera, Patagonian Pampa) defined by OLEA and DAVIS (1977), roughly corresponding to the morphotectonic zones of MILNES (1987). A geological scheme of the area is reported in Figure 1. The study area crosses only the Patagonian Pampa, which is entirely covered by Quaternary glacial and glacio-fluvial sediments (unit 1 of Figure 1).

Quaternary geology of the southern Patagonia and Tierra del Fuego is well documented in literature. A brief description is herein reported, mostly based on the meticulous reviewing of CLAPPERTON (1993).

The maximum ice advance, responsible for the most of the Patagonian moraine deposits, occurred during the early

Pleistocene about 1.0–1.2 Ma BP (MERCER, 1976). During this period, glaciers advanced along wide and deep valleys up to 200 km east of the Cordillera, reaching the Atlantic continental shelf. These valleys correspond to the present Strait of Magellan, and embayments (Bahia Inutil, Bahia S. Sebastian), lakes (*i.e.* Fagnano Lake) and channels (*i.e.* Beagle channel) in Tierra del Fuego (CALDENIUS, 1932; RAEDEKE, 1978; ISLA *et al.*, 1991).

In the middle Pleistocene a prolonged interglacial stage occurred, interrupted only by a strong impulse of isostatic uplift which gave rise to the formation of canyons typical of the present landscape. The last glaciation is testified by three main advances, at about 70 ka BP, between 18–20 ka BP (late glacial maximum) and between 10–15 ka BP (late glacial), each one probably containing minor fluctuations (RABASSA *et al.*, 1990).

The insular condition of Tierra del Fuego, with the final opening of the Strait of Magellan, was completed about 7.9 ka BP (PORTER *et al.*, 1984; RABASSA *et al.*, 1990). Relative sea level reached its maximum (ca. + 3.5 m above present m.s.l.) at about 5.5–6.0 ka BP (PORTER *et al.*, 1984).

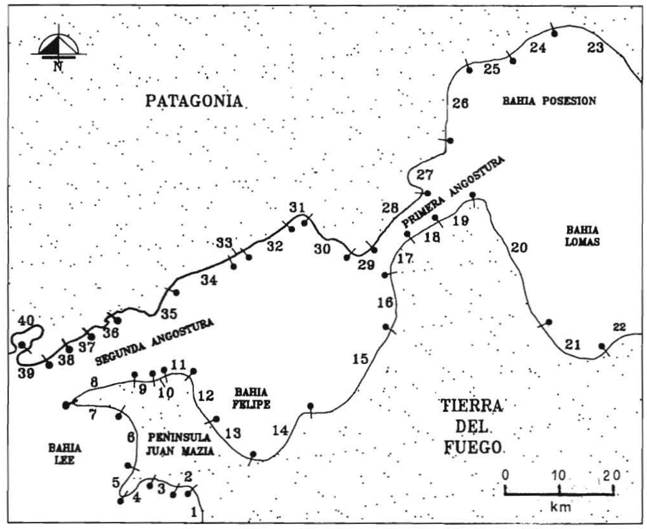

Figure 2. Coastal tracts location map.

GEOMORPHOLOGY

A morphological scheme of the coastal and marine area between Primera and Segunda Angostura is reported in the map (Appendix). The topographic base is given by nautical charts n. 1160 (Primera Angostura a Punta Dungeness) and n. 1144 (Bahia Gente Grande a Primera Angostura) published by the Instituto Hidrografico de la Armada de Chile (Santiago) at a scale of 1:100,000. Data are schematically presented following three main subdivisions: continental, coastal and marine areas.

Continental Area

Most of the continental morphologies are related to glacial molding occurred during the last glaciation. One of the clearest evidence of glacial action is given by the marginal moraine deposits of the Magellanic Pampa, previously described by MARANGUNIC (1974). A good example is given by the highest ridges (Cumbres de S. Gregorio), which are located immediately northwards of the area between the two Angosturas. They reach a maximum altitude of 400 m, and correspond to MARANGUNIC's (1974) 'Posesion' morainal lobe.

Several glacio-fluvial morphologies were observed in the study area, mostly in the Fuegian side, related to the glacial retreat occurred about 18 ka BP (CLAPPERTON, 1993). Outwash processes produced several meltwater channels that later evolved into the canyons currently present in the area. Within outwash deposits and forms many kettle-holes are easily recognised in aerial photos. Some of these depressions have become small ponds or lakes, either because of patterns in local drainage or because fed by small rivers. The high evaporation due to the dominant westerly winds often causes the ponds to dry out (RAEDEKE, 1978), leaving evidence of wind-driven drift.

Landforms generated by down-slope processes are found mainly in the coastal areas with active cliffs. Slope failures produce detachment surfaces on sub-vertical cliff faces and masses of detritus at the foot of the slope. In some areas the failure is more gradual, mainly as debris flows, and the erosion process produces runoff incisions on the surface of the slope. Although this last phenomenon is very common, it was not mapped in detail. However, such morphologies are easily identified on the map, using criteria such the as the presence of suitable cliffs, their height, slope angle and coastal dynamics.

Aeolian landscapes are predominant in the whole of southern Patagonia due to strong, almost unidirectional westerly winds blowing throughout the year. Wind action is particularly evident as either dunes and sand sheets or deflation surfaces, furrows and hollows. These forms are particularly frequent in the eastern part of the coast of Bahia Felipe and Bahia Santiago since these low-lying areas are most exposed to dominant winds. The vegetation distribution is also conditioned by winds with predominance of small shrubs and plants oriented eastwards (BALDUZZI, 1991).

Coastal Area

The rugged coastline is the result of interaction among postglacial, eolian and marine processes. About 45.5% of the surveyed 391 km of coast is cliffed, while the remaining coastline consists of beaches. Cliffs are cut into fine-grained till (URIBE and ZAMORA, 1981; ISLA *et al.*, 1991; RAEDEKE, 1978) and lie at the edge of marginal moraines, deposited during different glacial advances. They were classified according to height (between 2–10 m, 10–50 m, >50 m), slope angle (<30°, between 30–60°, >60°) and location with reference to the shoreline (on the shoreface or behind beaches with width between 50–100 meters).

The highest and steepest (sub-vertical) cliffs predominate where the action of tidal currents is stronger, such along the two Angosturas and Bahia Posesion. Active cliff are normally bordered by a small, narrow pebble and cobble beach. A notch is deeply cut at the base of active cliffs, because of the strong

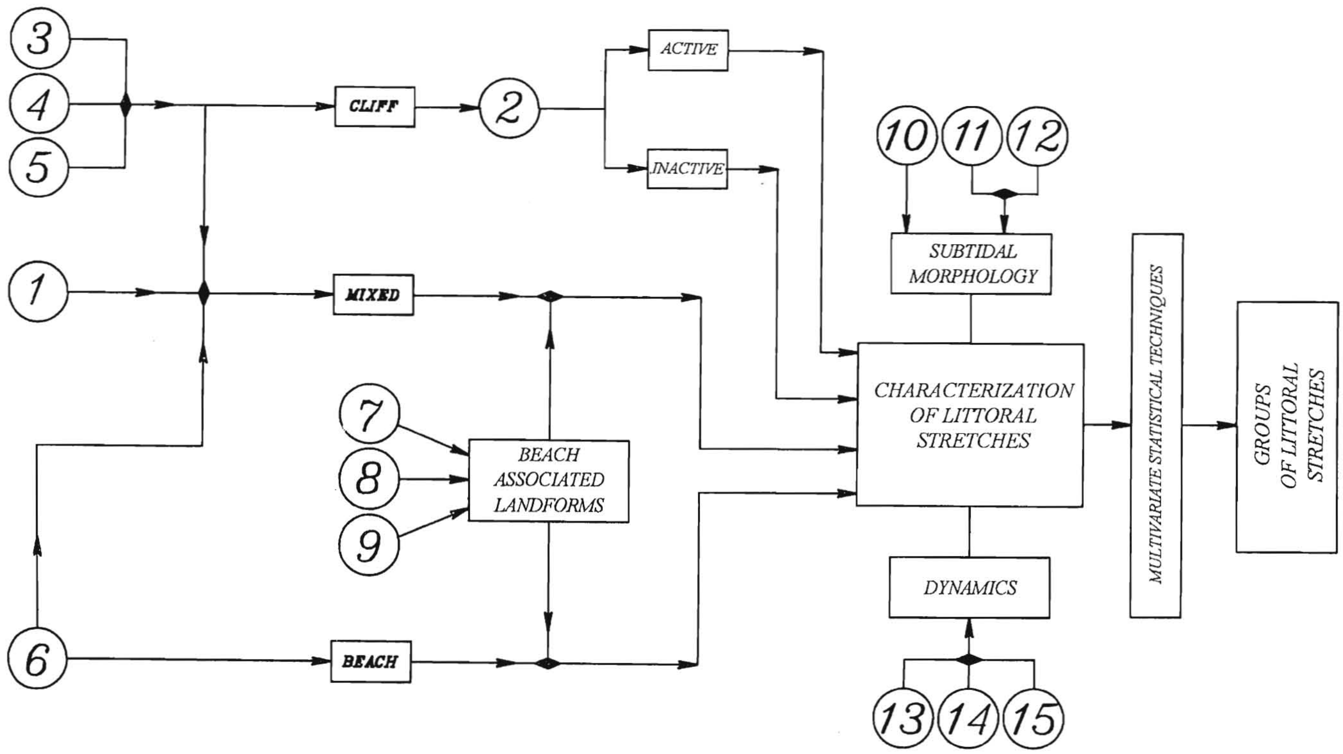

Figure 3. Flow chart of decision scheme. Numbers refer to the variables (see text for details).

erosive action of current during high tides, that may cause small slumps and detachment crowns in the poorly consolidated material. All these features indicate a high erosion rate. Relict cliffs are located behind large pebble beaches having a width of 50–100 m. Cliff material has low strength and the slope surface is covered by rills and gullies, thus involving a slower erosion process. The transition between cliffs and low-lying coastal landscapes is marked by a small erosive scarp with a maximum height of 2 m, located on or slightly behind the shoreline. In the first case the shoreface is subvertical and tends to migrate backward, while in the second case it is less pronounced and more stable, mainly where a large tidal flat extends seawards.

Low-lying coastal landscapes are generally shingle beaches of varying width, normally with sediments finer than those of the cliff-facing beaches. In areas with a large tidal range the inner foreshore is characterized by well developed berms, with heights up to one meter and sometimes in groups of three. The backshore inner limit can be marked by a small erosive scarp, by beach ridges or foredunes. Foredunes are well developed along the most wind-exposed parts of the coastline, and their crest orientation is perpendicular to the predominant wind directions (N–S e NE–SW). Beaches border also some saltmarsh landwards, in areas where large tidal flats have been developed, such as in Bahia Lomas, Bahia Gregorio, Bahia Felipe and Bahia Posesion. These isolated beaches remember chenier-like forms, and their presence testifies the strong macrotidal regime affecting the eastern Strait of Magellan. Sediments are mainly sand- and sandy-mud-sized (FISCHER and HAYES, 1977), although localised coarse lag deposit of glacial origin (cobbles and pebbles) are easily found.

The dynamics of the studied sector is mainly controlled by tidal and wave-driven currents. Longshore currents in areas with high longshore drift can form large cuspate spits on both sides of the eastern entrance of the Strait such as Punta Dungeness and Punta Catalina. These accretionary forms can provide clues on nearshore transport and coastal change driven by climate changes occurred during Pleistocene and Holocene (URIBE and ZAMORA, 1981; FONTOLAN and SIMEONI, in prep.). Other evidences of Quaternary sea-level change are given by marine terraces, briefly summarized by BRAMBATI *et al.* (1993) and mapped by BRAMBATI *et al.* (1995) and DE MURO *et al.* (1995). In the map only the youngest, ca. 3 m high terrace is reported, featuring a large amount of bivalve and gastropod shells. At times this terrace corresponds to the wave-cut beach scarp.

Marine Area

The information on sea-bed sediments that is presented in the map has been compiled from data of BRAMBATI *et al.* (1991). Water depths are referred to the datum of nautical charts (lowest astronomical tide). The type of sediment and transport are related to the tidal regime, described on the map by co-tidal lines (MEDEIROS and KJERFVE, 1988). There

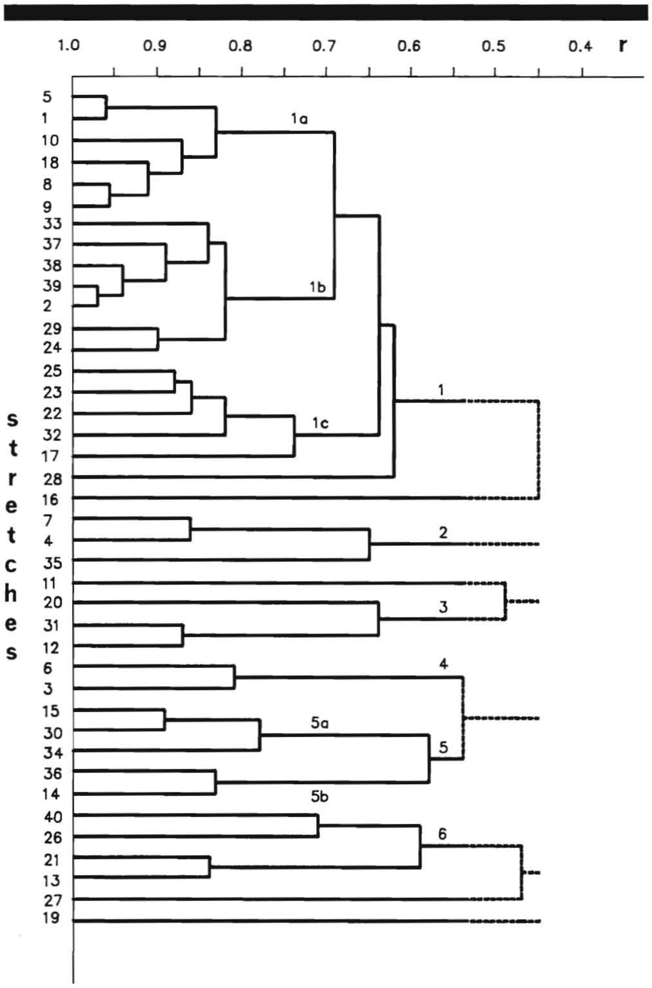

Figure 4. Dendrogram resulting from cluster analysis of 40 coastal stretches debribed by 15 normalized variables (see Figure 2 for coastal stretches identification). Coastal groups and sub-groups are defined by numbers inside the diagram.

is an overall predominance of sand westward of Primera Angostura and gravel between the two Angosturas.

Hard substratum outcrops all along, or immediately close to both narrows' sea-bed, because of strong scouring action by tidal currents. Fine sediments, mainly muddy sands, are confined to the inner part of Bahia Gente Grande. As it was already mentioned in the section describing the coastal area, large sand banks are present westward of Cabo S. Gregorio and Bahia Posesion (Banco Plumper).

Marine dynamics is described using the main sediment transport direction, as shown by sediment patterns and orientation of tidal currents as indicated on nautical charts.

Littoral drift is interpreted using the orientation of coastal landforms, and the main wave direction as it was observed during the surveys.

COASTAL ZONING METHODOLOGY

The proposed methodology of classification is based on the work of Hayes *et al.* (1976), Gornitz and Kanciruk (1989), Sunamura (1992), Dal Cin and Simeoni (1994).

Coastline sectors are grouped into the following classes: (1) rocky coastlines with cliffs; (2) low-lying coastlines with beaches; (3) mixed coastlines, where the morphologies of classes 1 and 2 alternate with each other. On the basis of these considerations 40 homogeneous coastal segments were identified (Figure 2), having a length between 2.5 (segment n. 10) and 25.5 km (segment n. 20). Each segment was then described using fifteen variables, with four describing the morphology (variables 1-2-3-4), two the prevalent lithology of the coastline (5-6), three the presence of peculiar littoral environments (7-8-9), three the nearshore sea-bed morphology (10-11-12), one the tidal range (13), one the orientation of the coastline in relation to predominant winds (14), and one the evolutionary trend of the shoreline (15).

The considered variables are: (1) Presence of small scarps with a maximum height of 2 m; (2) Location of cliffs in relation to the shoreface; (3) Cliff height; (4) Cliff slope; (5) Cliff lithology; (6) Beach grain-size; (7) Presence of dunes; (8) Presence of spits and deltas; (9) Presence of coastal lagoons, saltmarshes and tidal flats; (10) Presence of nearshore banks; (11) Width of the intertidal area; (12) Distance between the shoreline and the −10 m contourline (DS-10); (13) Tidal range; (14) Orientation of the coast with reference to predominant winds; (15) Evolutionary trend of the coastal sectors.

The numeric or alpha-numeric codes referred to variables were then standardised within a range of values between 1 and 8, which correspond to minimum and maximum (as value, presence, exposition, or accretionary trend), respectively. Whenever some variables lost significance (i.e. absence of the form) a zero value was assigned.

During the quantification process a compulsory algorithm-path must be followed (Fig. 3). Cliffed coastlines imply a selection of the variables 3-4-5 and 2; the selection of the latter permits to identify two sub-groups within a main typology: active cliff (on the shoreface) or inactive cliff (protected by a narrow beach). If the cliff belongs to the second sub-group, an answer to variable 6 is also implicit.

Beaches follow a different path. Variables 2-3-4-5 loose significance (zero value is assigned to them), and the starting point will be variable 6, that needs variables 7-8-9-10-11 to fully describe particular environments.

The third type of coast, mixed-coastlines, requires a response to all the variables used to characterise the other two types of coasts (starting point: variable 1). The data were collated to produce a matrix of 600 elements (40 coastal sectors x 15 variables), that was analysed using cluster analysis. The matrix was then analyzed by Q-mode factor analysis, to outline more clearly the relationships between groups of coastal stretches and considered variables. The factor analysis was used to determine the minimum number of independent variables needed to account for most of the information in the table of similarity coefficients (Rummel, 1967; Davis, 1973; Joreskog *et al.*, 1976; Temple, 1978). While cluster analysis permits the identification of the relationships between different coastal sectors, factor analysis outline those between groups and variables.

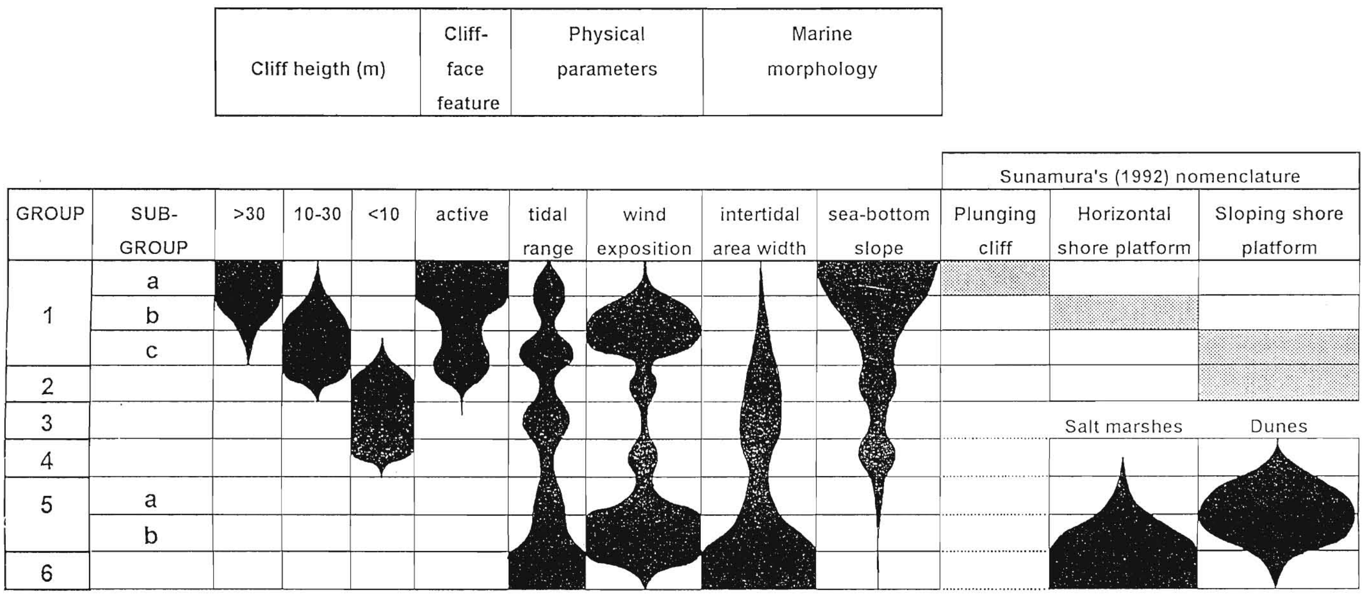

Figure 5. Type and frequency of littoral characteristics related to coastal groups and subgroups, resulting from cluster analysis.

RESULTS AND DISCUSSIONS

Coastal Groups and Characterization

Figure 4 reports the dendrogram produced by cluster analysis of the matrix. Considering 38 degrees of freedom (n) and a probability level (p) of 0.999, the correlation coefficient (r) is significant for values higher than 0.52. This limit permits the coastal tracts to be grouped into six categories. The sectors 11-16-19-27 (about 11 % of the studied coastal length) cannot be included in any group because of their r absolute values lower than 0.52.

Cliffed coastlines fall within the groups 1 and 2, that correspond to about 42.3 % (165.5 km) of the total length of the studied coastline. Because of some simplification in the classification process about 5 km of mixed coastlines are associated to these groups.

The coastlines of these two groups are located either in high-energy environments, with tidal currents reaching speeds of 4–5 m/sec (sectors 8-9-10-17-18-28-29-37-38-39), or in areas with a large tidal range and having steep sea-bed slopes (23-24-25) (Figure 5).

Group 1 (137.5 km) can be divided into three sub-groups. The sub-group 1a includes sectors 1-5-8-9-10-18 (34.5 km) and describes active cliffs higher than 30 m and with steep slopes; a well developed wave-cut notch is often present at the cliff base. The cliff is retreating rapidly and a large amount of pebbles and cobbles, produced by detachment from the cliff face is deposited at its base. The sectors are normally protected by winds, have a narrow intertidal areas, and mean DS-10 of ca. 200 m. According to the classification proposed by SUNAMURA (1992), these can be classified as plunging cliffs.

The subgroups 1b (sectors 2-24-29-33-37-38-39) and 1c (sectors 17-22-23-25-32) cover a total length of 91 km and describe active cliffs, with heights between 10 and 30 m, generally erosional. The two sub-groups are differentiated according to marine characteristics. The sub-group 1b (37.5 km) has steep sloping sea-bed (DS-10 m is 1.3 km instead of 5–6 km of the sub-group 1c), low tidal range (about 2 m instead of 8 m) and subsequent narrow intertidal areas. The sectors belonging to sub-group 1b are also exposed to the predominant winds, which enhance the deflation action on cliff-top. According to SUNAMURA (1992) the coasts of sub-group 1b can be classified as horizontal shore platforms, while those of sub-group 1c as sloping shore platforms. Sector 28 has a lower similarity with all subgroups (r = 0.62), due to the fact that this cliffed coastal stretch includes 2.5 km of small pocket beaches.

Group 2 includes the sectors 4-7-35 and represents 28 km of cliffs cut into poorly consolidated material, with a maximum height of 10 m. The cliff is easily eroded because of the low strength of the material and small gravel beaches with isolated boulders lie at the base. Tidal flats are narrow (100 m) due to both the low (2–3 m) tidal range and the steep slope of the nearshore sea-bed. This group is similar to sub-group 1c and can be classified as sloping shore platform.

Groups 3 and 4 (Figure 5) correspond to 14.1 % of the studied coastline and include short lengths of cliffs alternated with small beaches (mixed coast) or shorelines with a wave-cut beach scarp (variable 1). Group 3 includes sectors 12-20-31, all roughly protected to wind action, that correspond to 39 km of coastline. The coast consists of sandy and pebbly beaches and is generally either stable or slightly eroding. Several small spits were observed. Tidal range is about 4 m and the intertidal area is narrow, with a maximum width of 200 m. The sea-bed has a gentle slope (DS-10 m is between 2 and 7 km).

Sectors 3–6 were included in group 4 and correspond to 16 km of coastline. The beach has a width of 25–100 m, and is generally pebbly or sandy. Small dune fields sometimes develops landwards. Small bays features some tracts of the total coastal length of the group.

Groups 5 e 6 (Figure 5) were classified as low-lying coastlines. Group 5 corresponds to 66.5 km of coastline and can be divided into two sub-groups. The first one, 5a, includes sectors 15-30-34 (47.5 km), that are stable and located between the two Angosturas. The sandy-pebbly beach is 50 m wide and is delimited by well developed coastal dunes. The intertidal area is wide (on average 500 m) and consists of sand and gravel. Small gravel spits develops at times. The sea-bed has a gentle slope (DS-10 m is about 3 km) and tidal range is 4–5 m . Sub-group 5b includes only two sectors (14, 36) that correspond to 19 km of coastlines. Their exposition to winds and the wide sand- and silty sand-sized backshore support the foredunes nourishment. The beach is stable or slightly accretionary and consists mainly of gravel. The most sheltered areas often feature large sand spits and saltmarshes. Tidal flats reach 600 m width (tidal range is 3 m) and nearshore slope is gentle but highly variable (DS-10 m between 1.5 and 6 km).

Group 6 (sectors 13-21-26-40) corresponds to 61.5 km of coastline and includes beaches made of sand or gravelly sand, generally accretionary. Among the coastal forms, marshes and tidal flats prevail. Tidal flats have widths between 0.8 and 8 km and sea-bed slopes show large variability: DS-10 m is on average 9 km, but at times is as close as 1 km. Tidal range is between 2 and 7 m and coastline orientation is parallel or slightly oblique to the predominant wind direction.

Coastal Processes and Landform Constraints

The normalized varimax factor components (3 Factors: total variance of 85.4%) of the 40 coastal stretches calculated using Q-mode factor analysis are presented in Table 1, and plotted inside a triangular diagram in Figure 6a. The similarity between groups that was already outlined by cluster analysis is present once again. However, cluster analysis was not able to describe sectors 11-16-19-27, that are instead included in the Q-mode factor analysis.

Cliffed coastlines are plotted close to Factor I, whereas beaches along the Factor II-III axis. The decrease in importance of Factor I in favour of Factor II indicates presence of lower and lower active cliffs, with subsequent decreasing in slope (Figure 6c). The opposite axis (Factor I-III) represents the relict cliffs protected by small beaches. Mixed coastlines of groups 3 and 4 have a weight of Factor I between 0.10 and 0.45.

Considering the relationship between the distribution of coastal sectors and single variables (Figure 6b), the closer the sectors to the vertex of Factor III, the larger the tidal range (macro- and mesotidal), and the wider the tidal flat are. Moving away from Factor III, sea-bed slopes become steeper and coastal stretches more exposed to predominant winds. Dunes and aeolian landforms are well developed in sectors characterized by a large weight of Factor II, with a Factor I loading < 0.5 and Factor III < 0.6. Saltmarshes and tidal flats are related to large loadings of Factor III and II. They are developed in areas with macro- and mesotidal range and where sand banks are connected to stable coastlines. This is in agreement with the works of HAYES (1979) and PETHICK (1984). Tidal landforms (saltmarshes and tidal flats) develop mainly with tidal ranges larger than 3–4 m. These landforms are not influenced by waves even in the Strait, despite the strong winds, since the point of wave action continuously shifts due to the change in tidal elevation.

Table 1. *Communalities and normalized varimax factor loadings resulting from Q-mode factor analysis of the coastal stretches data.*

Stretches	Comm.	Factors I	Factors II	Factors III
1	0.88	0.85	0.14	0.01
2	0.96	0.93	0.03	0.04
3	0.71	0.25	0.65	0.10
4	0.82	0.86	0.03	0.11
5	0.92	0.85	0.15	0.00
6	0.86	0.15	0.80	0.05
7	0.87	0.88	0.05	0.07
8	0.94	0.93	0.07	0.00
9	0.94	0.97	0.03	0.00
10	0.90	0.87	0.13	0.00
11	0.72	0.26	0.52	0.22
12	0.71	0.11	0.35	0.54
13	0.83	0.02	0.51	0.47
14	0.84	0.07	0.86	0.07
15	0.92	0.08	0.90	0.02
16	0.82	0.59	0.30	0.11
17	0.93	0.67	0.30	0.03
18	0.96	0.93	0.06	0.01
19	0.75	0.35	0.34	0.31
20	0.87	0.16	0.27	0.57
21	0.82	0.05	0.41	0.54
22	0.92	0.46	0.37	0.17
23	0.94	0.64	0.26	0.10
24	0.93	0.81	0.08	0.11
25	0.90	0.62	0.22	0.16
26	0.87	0.03	0.07	0.90
27	0.79	0.24	0.17	0.59
28	0.83	0.94	0.04	0.02
29	0.93	0.82	0.10	0.08
30	0.94	0.06	0.84	0.10
31	0.76	0.12	0.40	0.48
32	0.93	0.58	0.29	0.13
33	0.94	0.77	0.06	0.17
34	0.79	0.04	0.72	0.24
35	0.75	0.81	0.00	0.19
36	0.72	0.04	0.75	0.21
37	0.91	0.86	0.05	0.09
38	0.95	0.91	0.05	0.04
39	0.98	0.96	0.02	0.02
40	0.84	0.00	0.09	0.91
Variance		45.8	23.6	16.0

Therefore, the main relationships between coastal landforms and forcings, can be summarized as follows:

(1) *Factor I* represents cliffed coasts, along narrow and steep intertidal areas. Their distribution is independent from the tidal range, whereas their face features are now conditioned by hydrodynamic condition. Primary control of these coastal morphologies is exercised by moraine outcrop. We can call them 'inherited coastal landforms', that means: controlled by geological (glacial) setting, or better,

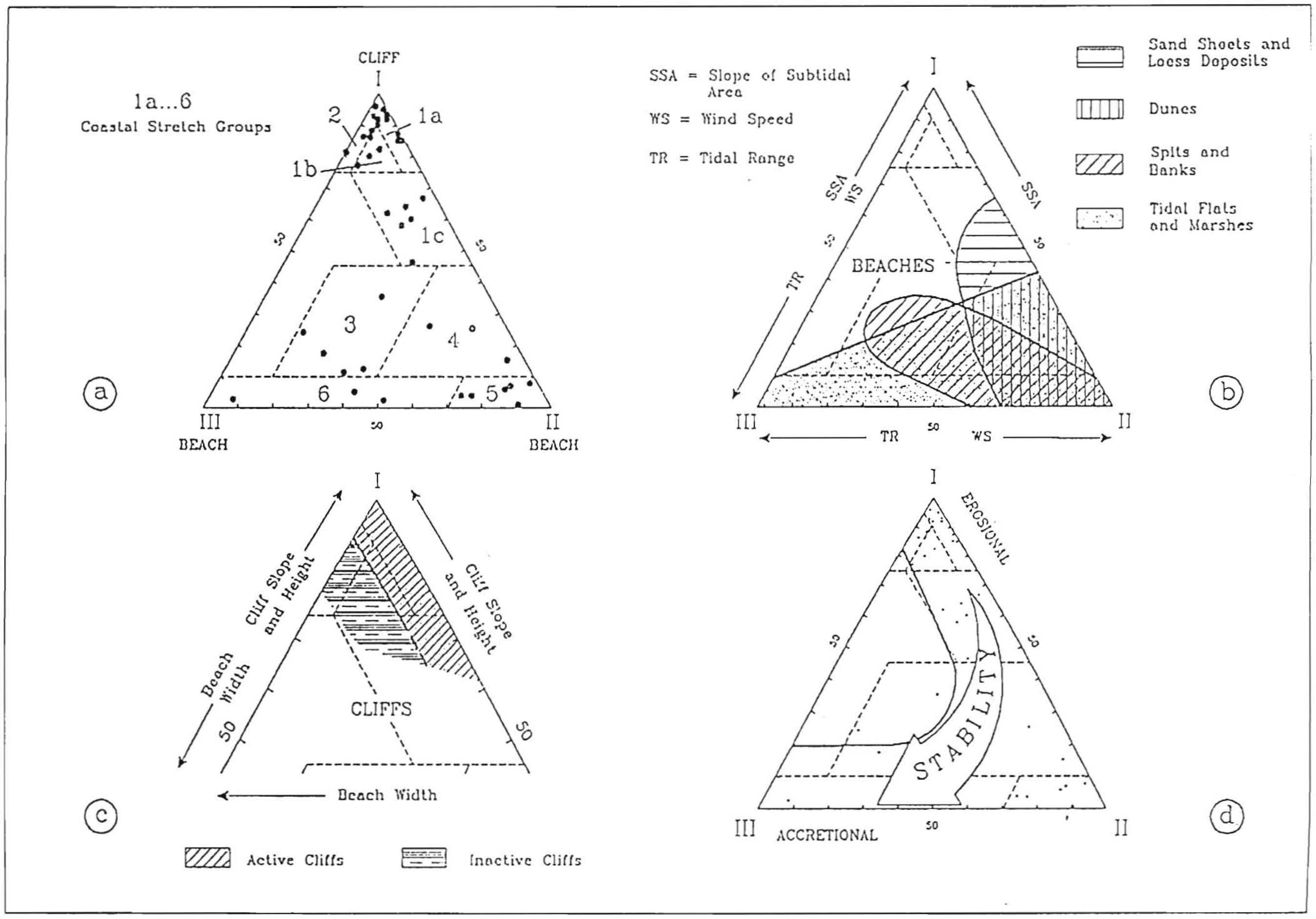

Figure 6. Coastal grouping and characterization resulting from Q-mode factor analysis: (a) occurrence of coastal groups; (b) devopment of low-lying coastal landforms as function of physical constraints; (c) occurence and some features of active and inactive cliffs; (d) trend of coastal stability. Arrows indicate increasing values of the phenomena.

developed and modelled during submergence of ancient marginal moraine ridges.

(2) *Factor II* represents mixed coast and beaches *s.s.*, with an high variety of coastal landforms (*i.e.* dune fields, sand-sheets, tidal flats, marshes, spits and banks). Major forcing is given by wind, enhanced by tidal action, which exercises maximum deflation activity on wide intertidal surfaces. Wind-driven currents and tidal currents enhance sediment transport. Therefore we can define this group as 'Wind-enhanced coastal landforms'.

(3) *Factor III* groups low-lying, well-specialized landforms, mainly tidal flats and marshes in macrotidal and wind-protected environment, thus permitting to define it as 'tide-controlled coastal landforms'.

Beach stability (Figure 6d) increases progressively along the path Factor I-II-III. Factor I-II side represents the coastal erosion to stability path, while Factor II-III the coastal stability to accretionary path.

SUMMARY AND CONCLUSIONS

The geomorphological study of the eastern coastal area of the Strait of Magellan, integrated with dataset on sea-bed morphology, sediment texture, wind and marine dynamics permitted to:

(1) Draw a coastal-marine geomorphological map of a complex and less known area;
(2) Propose and test a method of coastal zoning, based on multivariate statistical analyses of almost uniform coastal sectors described by means of morphology and physical parameters. Despite its simplicity, the method permitted to evidenziate how apparently different coastal tracts in term of few descriptive parameters can be grouped into a same typology, when considering the whole of parameters that describe them.
(3) Highlight the relationships between physical and geological variables, and landform development. Three main factors control coastal morphologies: geological setting,

wind and tides. First factor controls the development of cliffed coast, which formed during the Holocene submergence of the Strait of Magellan mainly along the most heightened coastal tracts, owing to the presence of ancient morainal ridges. Second factor permits, directly or indirectly, the rapid development of a great variety of coastal and marine forms. Where the wind action can be considered negligible, tidal effects become more selective and enhances the development of accretionary systems, like tidal flats and marshes.

Therefore, apart from the inherited coastal landforms, we confirm the strong influence of tides and wind in coastal modelling of the Strait of Magellan, where the combined action of both parameters produce complex and highly mutable morphologies.

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