# Late Cenozoic Landforms and Landscape Evolution of Península Valdés

**Pablo Bouza, Andrés Bilmes, Héctor del Valle and César Mario Rostagno**

**Abstract** The present landscape of the Península Valdés is the result of a complex interrelation between climatic (aeolian deposition, windblown processes, glacial and interglacial cycles, pluvial and fluvial processes), tectonic, and *eustatic controls* that had work in the Andean foreland during the late Cenozoic. Based on a geomorphological approach, which includes new descriptions, interpretations, and hierarchically classification of the main landforms of this region, together with previous geomorphological surveys, the Península Valdés area was grouped in three major geomorphologic systems: Uplands and Plains, Great Endorheic Basins, and Coastal Zone. Based on the interrelationship among these three geomorphological systems the landscape evolution of the late Cenozoic of Península Valdés could be summarized in five main stages: (1) development of fluvial and alluvial systems during the Pliocene early Pleistocene; (2) closed basin formation associated to tectonic processes during the early middle Plesitocene; (3) first marine transgressions during the late Pleistocene; (4) flooding of the gulfs and construction of the peninsula in the late Plesitocene–Holocene; (5) final flooding in the region during the middle Holocene.

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## 1 Introduction

The landscape of Península Valdés, as well as the Extra-Andean Patagonia region (Fig. 1), is characterized by arid-semiarid conditions. Low rainfall and sparse vegetation cover are typical features of this region and are of considerable importance for the operation and development of landforms (Thomas 1997). Many of these landforms have large patches of bare soils and so are exposed to wind erosion, raindrop impact, and surface runoff.

Although wind is an important geomorphological agent that has deeply modified the Península Valdés landscape, water erosion is the most severe geomorphic process, either as *raindrop-splash* and *laminar runoff* (interril) or as concentrated flow erosion, in the form of rills or gullies. In addition, as the Península Valdés is bounded by the Atlantic Ocean and the Nuevo and San José Gulfs (Golfo Nuevo and Golfo San José), distinctive characteristics related to coastal processes also imprint the landscape of this region. Previous studies in the Península Valdés region based on different geomorphological approaches (aeolian, physiographical and coastal) were performed by Rostagno (1981), Beltramone (1983), Codignotto and Kokot (1988) and del Valle et al. (2008).

The objective of this chapter is to perform an updated characterization of the main geomorphological units of Península Valdés by describing, interpreting, and hierarchically classifying the main landforms of the study area.

The result of this work expects to develop a useful tool in Península Valdés to better understand the Neogene–Quaternary landscape evolution, soil genesis and soil distribution, hydrogeological characteristics, distribution patterns of vegetation, geoecological functions and processes, and distribution of archaeological material.

The present chapter follows a hierarchically classification adapted from Peterson (1981), Iriondo and Ramonell (1993) and Súnico (1996) that uses the geographic scales, genetic relationships and shapes of the topographic forms. Following this scheme, the Península Valdés region (defined in the hierarchy classification of this work as a *super system*) was grouped in three major *systems* (Fig. 2). These systems are then successively divided into smaller and genetically more homogeneous classes defined as *units* that could be subdivided, respectively, into *landforms elements*. In a descending order these categories are as follows:

*Super system*: the geological dimension (space-time insight). It takes into account the regional geology from a geodynamic evolution viewpoint (see Chapter "Climatic, Tectonic, Eustatic, and Volcanic Controls on the Stratigraphic Record of Península Valdés"). Plains and basins in a continental-marine setting are named to as distinctive landscapes affected by a relative rise of the land followed by the formation of closed depressions, surrounded by a marine environment.

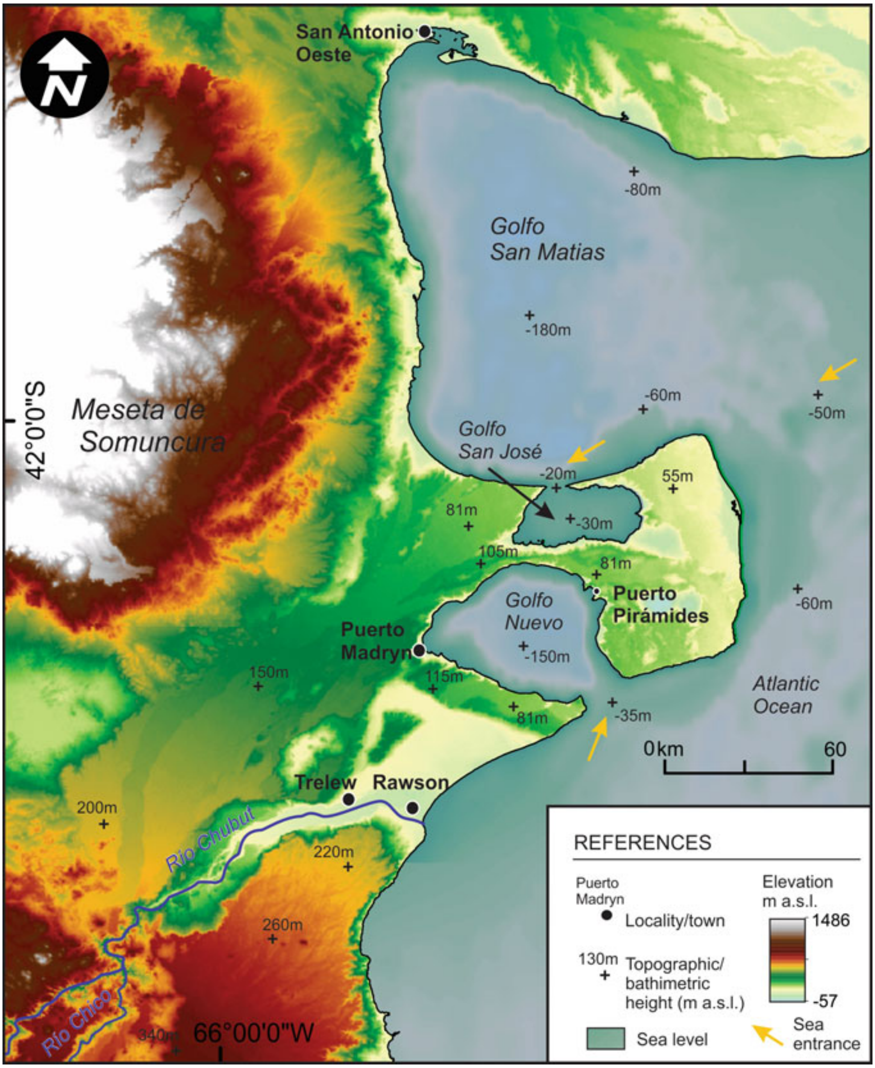


**Fig. 1** Digital elevation model (DEM) of northeastern Chubut province

*System*: Uplands and Plains, Great Endorheic Basins, and Coastal Zone landforms are the main geomorphological settings based on the dominant landform processes within the system.
*Unit*: is the minor geomorphological landform defined by morphogenetic criteria and space-time relationships. In this category, relict landforms are included (e.g., fluvial terrace levels and beach ridges sequences), especially to define remaining parts of a same geomorphic surface which has been otherwise degraded by erosion. An erosional relict must be older than the destructive erosion cycle. Recognition of relict

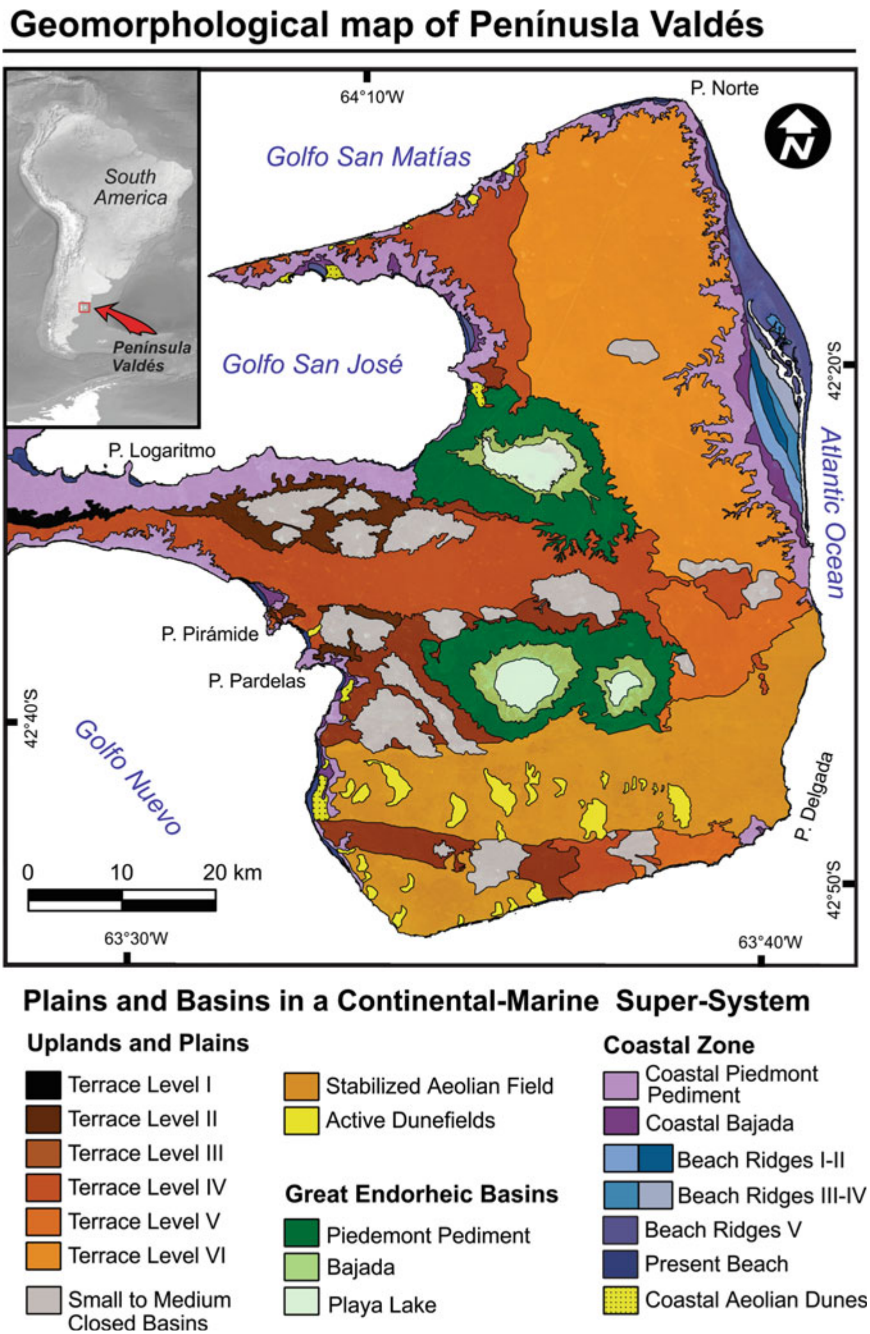


**Fig. 2** Geomorphological sketch of the Península Valdés

land surfaces is the basic tool for establishing relative ages of the different surfaces (Peterson 1981). Some examples of this category are relict fluvial Terrace Levels and Stabilized Aeolian Field, Small to Medium Closed Basins and Beach Ridges I–IV. *Landform elements*: This description level is used on some geomorphological units to separate different geomorphic processes observed within a Unit (e.g., shallow *pans* by deflation, discontinuous patches of sandy aeolian mantles, *nebkas*, gullies, *desert pavement* patches). Landform elements are normally not represented in regional maps mapped only at high scale surveys.

## 2 System A: Uplands and Plains

This system corresponds to a landscape consisting of wide plateau-like plains make up of Pliocene–Pleistocene fluvial terraces of the *Rodados Patagónicos lithostratigraphic unit* (see Chapter "Geology of Península Valdés"). Other geomorphological units (e.g., small to medium closed basins, stabilized aeolian fields and active dunefields) are superimposed the regional landscape.

### *2.1 Terrace Levels I–VI*

The six Terrace Level units are included in the Plio-Pleistocene *Rodados Patagónicos* lithoestratigraphic unit of Plio-Pleistocene age (Fidalgo and Riggi 1970), also known in other Patagonian areas as the Patagonian Shingle Formation (Darwin 1846). The term "Rodados Patagónicos" is used in different parts of the Patagonian foreland and includes terraces of gravel deposits of varied genesis and age (Martínez et al. 2009). In all the cases, the terrace levels were affected by different geomorphic processes and are highly strongly interacting with the other geomorphological units of this system. The terrace levels are dissected by centripetal drainage networks and the retreat and coalescence of erosion scarps of small/medium closed basins; many of them (i.e., Terrace Levels III, IV, and V) are discontinuously covered by Stabilized Aeolian Fields and the Active Dunefields Units (del Valle et al. 2008) (Fig. 3d).

In the study area, terrace level deposits are 1–6 m thick, composed of sandy gravel sediments with a maximum clast size of 6 cm (pebble-size clasts). Rhyolites are the main component of the gravel size fraction, and in smaller proportion andesites and basalts. The accumulation of these deposits, related to fluvial plains generated during Neogene and Pleistocene glaciations, occurred in an arid periglacial environment (Mercer 1976). While all the terrace levels could be seen as a whole unit (i.e., *Rodados Patagónicos*; see Chapter "Geology of Península Valdés") some diagnostic properties of each terrace level allow to differentiate six mayor units (i.e., Terrace Levels I–VI). Each terrace level was identified by a Roman numeral according to the descending order of relative age. The terrace levels were separated

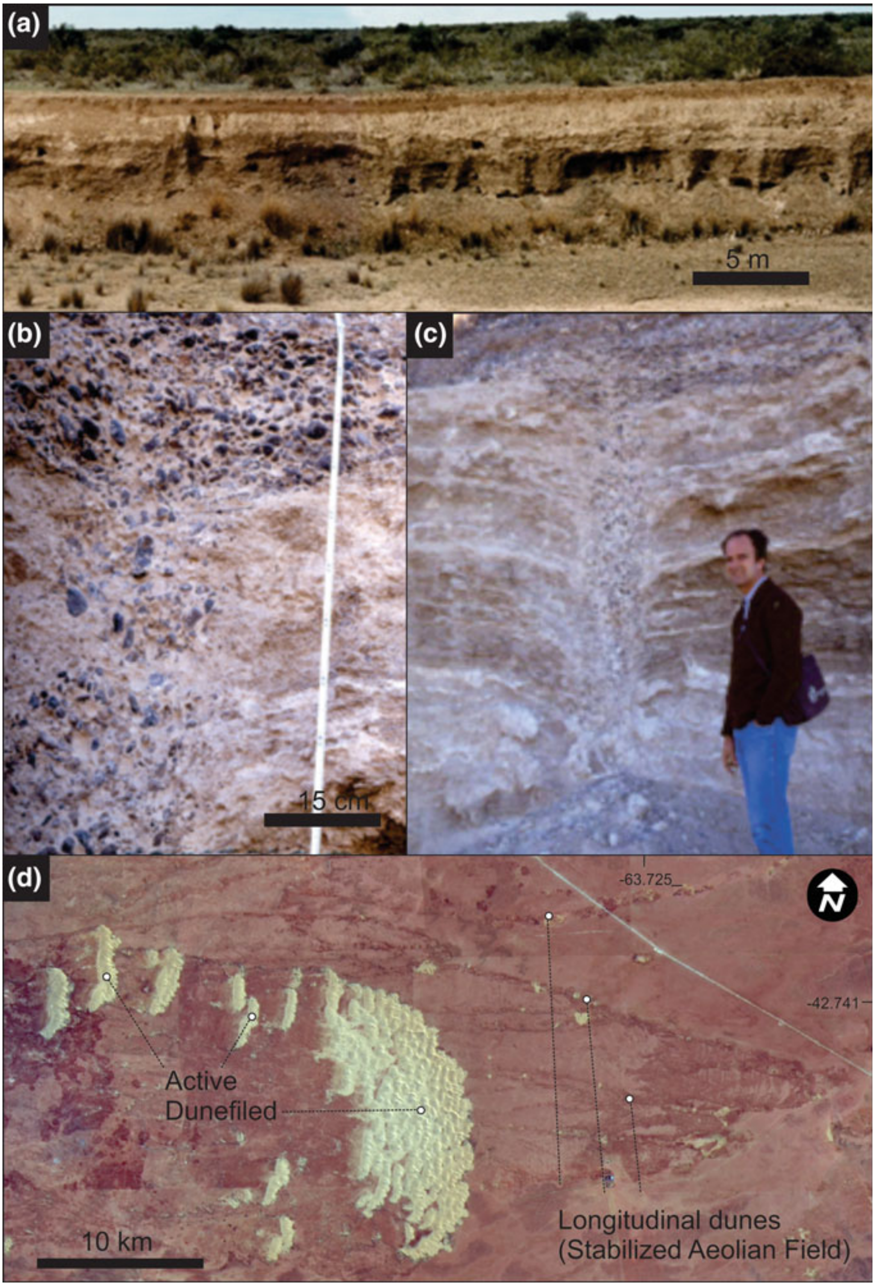


**Fig. 3** **a** Outcrop of the Rodados Patagónicos (Terrace Level VI), Calcrete zone (CZ); cryogenic morphologies: columns (C) and windows (W), bar scale = 2 m. **b** and **c** Epigenetic fossil ice-wedge casts in RP deposit (Terrace Level I), the marine sedimentites of Puerto Madryn Formation (Miocene) affected by cryogenic processes is observed. **d** Active dunefield, complex dome-shaped dunes and transverse ridges and

on the basis of two relative age parameters: morphostratigraphic position and soil profile development (e.g., carbonate accumulation rate; see Chapter "Soil–Geomorphology Relationships and Pedogenic Processes in Península Valdés").

The morphostratigraphic position parameter includes topographic heights and surface area of the terraces. Generally, the older are the terrace levels, the higher are their heights, and smaller are their surface areas. In the study region maximum heights of the terrace levels range between 104 and 50 m a.s.l. having topographic heights differences of more than 5 m among them (Table 1). The altitude of the terrace levels progressively increases to the south of the study area, reaching the 700 m a.s.l., 400 km SW from Península Valdés. The surface area of the different units are directly related to the degree of dissection and consequently with their age. Older terraces, as Terrace Level I and II, are highly dissected and exhibits several gullies and ravines developed by fluvial and hillslope processes. With the exception of Terrace Level V, the smaller is the terrace level surface, the higher is the degree of dissection and oldest is the terrace (Table 1, Fig. 2).

**Table 1** Topographic heights measured using SRTM data

| Supersystem | Area ($km^2$) | Max. height (m) | Min. height (m) | Avg. height (m) |
|---|---|---|---|---|
| System A: uplands and plains | | | | |
| Terrace Level I | 67.07 | 104 | 91 | 99 |
| Terrace Level II | 82.24 | 99 | 75 | 91 |
| Terrace Level III | 232.08 | 89 | 69 | 81 |
| Terrace Level IV | 595.08 | 84 | 57 | 71 |
| Terrace Level V | 151.71 | 60 | 45 | 55 |
| Terrace Level VI | 838.05 | 59 | 38 | 51 |
| Small to middle closed basins | 313.95 | 96 | 22 | 67 |
| Stabilized Aeolian field | 644.77 | 86 | 38 | 66 |
| Active Dunefields | 66.83 | 90 | 53 | 73 |
| System B: great endhoreic basins | | | | |
| Piedemont Pediment | 344.37 | 83 | −23 | 36 |
| Bajada | 90.74 | 18 | −40 | −8 |
| Playa lake | 70.07 | Salina grande (−43 m) | | |
| | | Salina Chica (−19 m) | | |
| | | Gran Salitral (0 m) | | |
| System C: coastal zone | | | | |
| Coastal Piedmont Pediment | 491.17 | 92 | 3 | 38 |
| Coastal Bajada | 48.91 | 22 | 0 | 13 |
| Beach Ridges I–IV | 54.32 | 20 | 2 | 12 |
| Beach Ridges V | 67.45 | 12 | 0 | 7 |
| Present Beach | 25.71 | 2 | 0 | 1 |
| Coastal Aeolian Dunes | 14.65 | 84 | 3 | 28 |

Soil profiles on terraces allows terrace levels differentiation. As soil evolution involves time-depending properties (Gile et al. 1966; Bachman and Machette 1977; Machette 1985; Bouza et al. 2007; Bouza 2012), the rate and depth of pedogenic carbonate accumulation, the occurrence of *argillic horizons*, and clay-minerals transformation and neoformation could be used as tool for correlation of soils and unconsolidated deposits (Table 1, see Chapter "Soil–Geomorphology Relationships and Pedogenic Processes in Península Valdés"). The soils developed on Terrace Levels I and II correspond to a Haplocalcids–Petrocalcids complex, while on the younger terrace levels, a Haplocalcids–Natrargids–Natrigypsids complex occurs.

Finally, *ice-wedge casts* and cryoturbations structures allow to differentiate terrace levels affected by persistent arid periglacial conditions in the Península Valdés region. During Greatest Patagonian Glaciation (Rabassa and Clapperton 1990), that occurred ca 1.0–1.16 Ma (Ton-That et al. 1999), the older deposits were affected by cryogenic processes, which are registered by fossil ice-wedge casts and a three-dimensional reticulate structure (network system) resembling columns (carbonate cements) and windows (sediments without cements) (Trombotto 1998, 2008). Examples of Late Cenozoic deposits affected by cryogenic processes are the Miocene marine sediments of the Puerto Madryn Formation (see Chaps. "Geology of Península Valdés" and "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity") and Terrace Level I, where fossil ice-wedge casts are prominent (Fig. 3b, c), while on younger terrace levels only columns and windows structure are observed (Fig. 3a). The columns and windows structure is apparently associated with cryogenic conditions when it is observed transversally to the net-like structure revealing a classical polygonal pattern (Trombotto 1996).

The tread of these geomorphic surfaces are gently sloping, mostly descending to the east. The surface treads are linked through vegetated surface risers, which generally at the junction with younger terrace treads, a series of small to medium closed basins are commonly observed (see Sect. 2.2).

Small pans at the bottom of the closed basins generated by deflation are randomly distributed on these geomorphic surfaces. In other cases, the pans have a distribution following a paleo-channels pattern of Rodados Patagónicos surfaces.

## 2.2 Small to Medium Closed Basins

This geomorphological unit corresponds to closed basins with a surface area below 100 $km^2$ with complex genesis, consisting of a combination of water and wind erosion and hillslope (raindrop impact and surface water runoff) and *mass wasting processes*. As it is explained for the genesis of the Great Endorheic Basins System (see Sect. 3) a geodynamic factor might have contributed.

Both small and medium closed basins develop both, on and between levels of terraces (Fig. 2). In Península Valdés region they occupy 315 $km^2$, reaching with a maximum diameter of 10 km and depths up to 25 m. The evolutions of these closed basins produce a dissection of the terrace levels by the retreat and coalescence of erosion scarps.

## 2.3 Stabilized Aeolian Field

This geomorphological unit is represented by relict landforms that are no longer active. Two areas with stabilized aeolian landforms are distinguishable, both located in the southern part of the Península Valdés. The largest one is located in the central area forming a corridor that stretches from the west to the east coast (i.e., from the Golfo Nuevo to the open Atlantic coast), and the smaller one is a fringe-like dunefield in the southwest corner of the Peninsula (Fig. 2). The two stabilized aeolian fields cover an area of approximately 645 km$^2$, where a well-developed vegetation cover of grasses (mainly *Sporobolus rigens*) and shrubs (principally *Hyalis argentea*) occurs on the inactive dunes. The stabilized aeolian landforms are represented by a 0.4–2 m thick sandy layer. Local relief shows an undulating appearance with some depressed areas that may reach the substratum (Miocene marine sedimentites or terrace level deposits).

Many stabilized linear (longitudinal) forms are distinguishable. The linear forms develop as the marginal sand dunes of the advancing the active dunefield unit. They are observed in the northern and eastern sectors (Fig. 3d), and are bounded by an homogeneous sand mantle toward both sides as northern and southern winds redistribute part of the eastward transported sand. These recently deposited sand layers change the original Xeric Haplargids soils into Arenic Haplargids (see Chapter "Soil–Geomorphology Relationships and Pedogenic Processes in Península Valdés"). *Blowouts* are common in the linear dunes and new and smaller sand dune fields in the stabilized sand mantles. Longitudinal dunes exhibits parallel to subparallel crests, west–east oriented with a variable thick, in function of the degree of degradation. Dune crest heights range between 0.6–1.5 m thick and 10–15 km in length. Separations between longitudinal dunes are irregular and go from 60 to 150 m in the west part of the Península Valdés to more than 1000 m in the east part (Súnico 1996). While longitudinal dunes are strongly modified by present aeolian erosion (blow-out formation) and superimposed by the younger active dunefield unit, it is possible to distinguish that they converge to "Y" shaped junctions (Fig. 3d). The west–east orientation of the stabilized longitudinal dunes suggests that they were formed by predominant winds from the west quadrant. However, to establish the relationship between landform, vegetation, aeolian materials and the frequency and intensity of the winds, a detailed study is needed (Súnico 1996).

## 2.4 Active Dunefields

These landforms are developed in the west coast of Península Valdés and moves westward mostly above the stabilized aeolian lanform units.

The general orientation of the dunefields in Península Valdés is in agreement with the prevailing regional wind flow from the WNW, and active dunes show a coincident trend. Notwithstanding active dunes present a variety of forms which reflect local variations in the wind flow. In the area of this study, mesoscale wind circulation is strongly influenced by the shape of the coastline of Golfo Nuevo. The sources of windblow sediment are the extensive sandy beach located on south-western coast of Península Valdés, where a continued supply of loose, sand-sized sediment is available transported inland by the prevailing westerly winds (Haller et al. 2000). Sand is also derived from aeolian erosion of friable marine sediments of Puerto Madryn Formation (see Chapter "Geology of Península Valdés") exposed at the cliffs along the shoreline (Súnico 1996; del Valle et al. 2008).

Trend of the displacement of the dunes is W–NW with a migration rate of 8–10 m/a (Annual rate 1969–2002; del Valle et al. 2008). Active dunefields is the smallest unit of the upland and plains system and occupy a total area of 67 km$^2$, covering 7% of the southern portion of the Península Valdés. Three areas with active dunefield are observed. A smaller one in the central west of the Península Valdés, a larger one in the south-central area and a medium one in the southwest corner of the Peninsula (Fig. 2). Active dunefields observed in the coastal zone system (i.e., coastal aeolian dunes) are considered in another unit and will be described later in the Sect. 4.6.

The dune types of the Península Valdés are far from showing a simple pattern, regardless of the sector in which they are located. Two main types of active sand dune are distinguished: (1) compound dome-shaped dunes, and (2) complex dome-shaped dunes (del Valle et al. 2008). Besides these dominant forms, a few scattered parabolic dunes, barchans, sand sheets, and shrub dunes (*nebkas*) are also present in the area. Compound dome-shaped dunes (2–20 m high) occur in a wide area mainly in the south-central and southwest areas (Fig. 3d). Transverse sand ridges are locally superimposed on the domes and may modify them greatly; the resulting dune form is transverse domal-ridge (row of connected domes).

Complex dome-shaped dunes (4–20 m high) are located exclusively in the south-central area. Transverse ridges and star dunes coalesce or grow together. Network dunes consist of NW–SE trending main ridges and nearly vertical secondary ridges (NE–SW orientation).

There have been no final conclusions for the period when the dunes and their morphology developed as the age of the Península Valdés has not been studied systematically.

## 3 System B: Great Endorheic Basins

This system corresponds to landforms developed over the uplands and plain system. Although many landforms and processes are similar to those described in small–medium closed basins units (Fig. 2) the intensity of the different geomorphic processes is more accentuated in this system, allowing to clearly distinguishing three geomorphologic units: *Piedmont Pediment, Bajada, and Playa lake*.

The Great Endorheic Basin System is characterized by a typical centripetal drainage network. This drainage dissects the piedmont *pediments units*, give rise to alluvial–fluvial fans that form the *bajada unit*, and ends at the bottom of the basin in the *playa lake unit*. In the Península Valdés this system represent more than 20% of the entire area, and includes the Gran Salitral, the Salina Grande, and the Salina Chica basins (Fig. 2). Salina Grande and Salina Chica are located in two different basins, though both share the same 25 km W–E elongated depression occupying 250 km$^2$. They are separated by an interfluve (5 m a.s.l.) of tertiary and quaternary sediments 50 m below the surrounding terrace level units. The Salina Grande lies at 43 m below sea level, one of the lowest areas of Patagonia. The playa lake of Salina Chica is at 19 m below sea level. In the Salina Grande and Salina Chica, differences of elevation between the playa lakes and the upper surrounding terrace levels are around 120 and 100 m, respectively. The Gran Salitral, a closed basin adjacent to the Golfo San José, extends in a W–E direction 15 km N of the Salina Grande and Salina Chica depressions. It is shallower (0 m a.s.l.) and presents a rectangular shape with almost straight W, S, and N borders; to the E, an extended drainage network has enlarged the basin in what seems to be the capture of a pre-existent closed basin.

In order to analyze the Great Endorheic Basin System a description of the main geomorphological units will be presented.

## *3.1 Piedmont Pediment*

The Piedmont Pediment unit (also defined in the literature as flank pediments, Fidalgo and Riggi 1970) is defined by a gently and short slope transport surfaces of bedrock, covered by a thin alluvium, developed between an upland area where erosion dominates (i.e., the erosion scarps of Terrace levels) and a lower plain where active aggradation dominates (i.e., *Bajadas*) (Fig. 4a, b). Dohrenwend and Parsons (2009) defined this sequence of landforms and processes on hillslope as pediment association.

In the Piedmont Pediment unit pediments are the dominant landforms that develop in the large closed basins. Changes in base level throughout the genesis of the large depressions that contains the closed basins of the Salina Grande, Salina Chica, and Gran Salitral gave rise to different pediment surfaces developed in ancient *bajadas* (Súnico 1996; Alvarez et al. 2008).

Piedmont pediment-surfaces are carved on marine sandstone of Puerto Madryn Formation and are densely incised by the drainage network that locally is reactivated by the lowering of the base level that accelerates the erosion process (Súnico 1996). In the three Great Endorheic Basins of the study area, there is more than one pediment level, which reflects variations at the base level (Súnico1996; Alvarez et al. 2012).

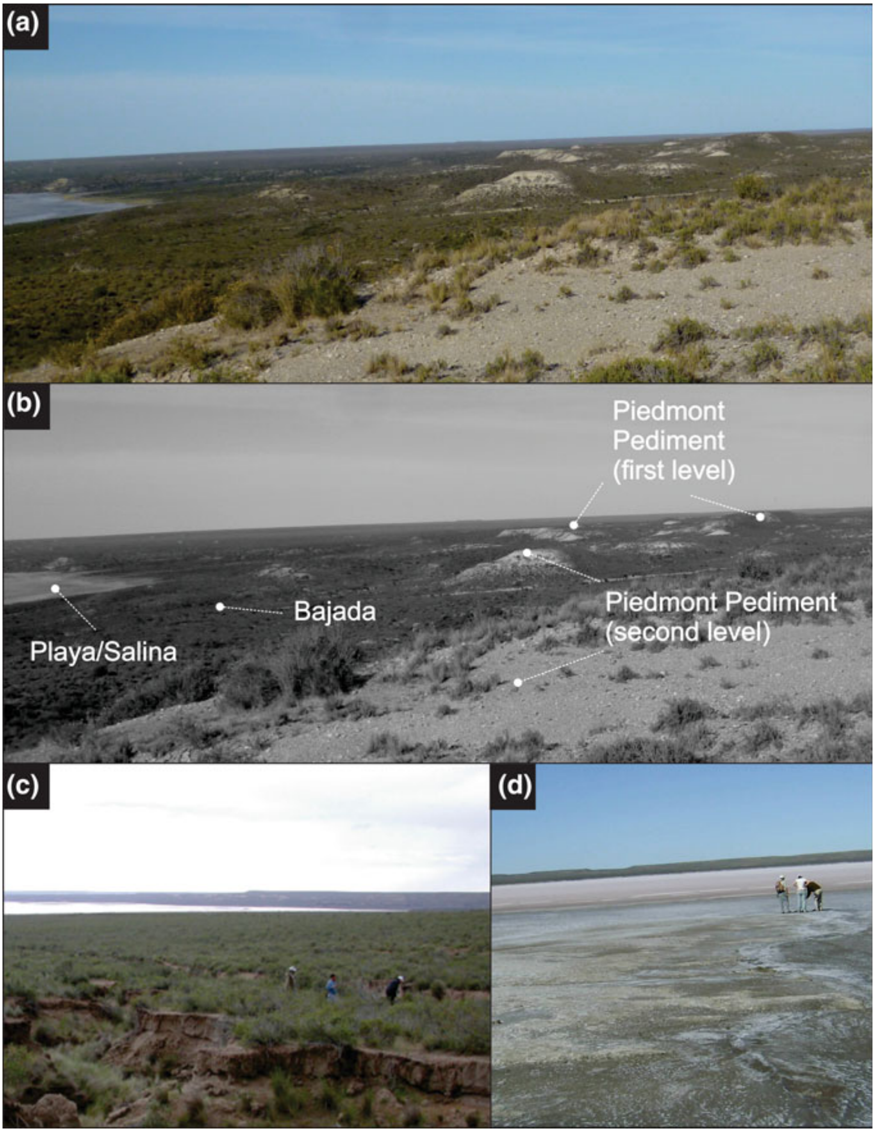


**Fig. 4** Great Endorheic Basin System; **a** and **b** geomorphological sequence on hillslope setting: erosion escarps, piedmont pediment levels, *bajada* (pediment association) and playa Lake; **c** and **d** details of *bajada* and playa lake units, respectively

The springs of the Salina Grande and Salina Chica basins give rise to wetlands in otherwise dry landscapes. Spring waters flows from the southern scarps of the Salina Grande and Salina Chica basins. These springs originate in the sand dune areas that cover part of the southern Península Valdés (Alvarez et al. 2008) where water recharge occurs. The soils developed on Piedmon Pediment Unit correspond to

Natrargids, Calciargids, complex (Bouza et al. 2008; Blanco et al. 2010, see Chapter "Soil–Geomorphology Relationships and Pedogenic Processes in Península Valdés").

## 3.2 Bajadas

In the different pediment levels, sheet erosion dominates, although a network of gullies has developed and, in the lower portion of the piedmont pediments units, they deposit most of the sediment charge and form a gentle sloping depositional surface.

The coarse sediments are first deposited and build the alluvial fan that connects the pediment to the playa lake; the finer sediments are deposited at the playa. This aggradational landform is named *bajada* and consists of a series of coalescing alluvial fans. This unit is linked to drainage systems that incise the piedmont pediment and is represented by sandy gravel deposits. In the Great Endorheic Basins system, the *bajadas* occupy a small portion adjacent to the playa (90.74 $km^2$; Table 1). The soils developed on *bajadas* correspond to Torriorthents (Blanco et al. 2010, see Chapter "Soil–Geomorphology Relationships and Pedogenic Processes in Península Valdés").

## 3.3 Playa Lakes

The playa lake unit represents the base level of the Great Endorheic Basin Systems (Fig. 4d). They are uniform flat areas (slope $<0.01°$) were the water table is generally near the surface. Due to the influence of the water table near the surface, the soils correspond to suborder Aquents. The vegetation is developed on the perimeter the playa lake and consists predominantly of the genus *Distichli*s and *Sarcocornia.*

In the Penísnula Valdés, the playa lake units constitute shallow ephemeral lakes or salinas of a few $km^2$ in extent up to 70 $km^2$ (i.e., Salina Chica, Salina Grande and Gran Salitral). These units are composed of laminated clays and silts, interbedded with fine- to medium-grained sands that form a network of cracks during dry conditions. In the Salina Grande and Salina Chica, where water is continuously flowing from springs located in the upper pediments, important salt accumulation occurs at the bottom of the basin (see Chapter "Geology of Península Valdés").

# 4 System C: Coastal Zone

The Coastal Zone of Península Valdés includes the littoral region of Golfo Nuevo and Golfo San José and the eastern coastline of the Atlantic Ocean. The coastal landform in the mentioned gulfs is characterized by an alternation of headlands and bays, where due to the process of water wave diffraction erosion predominates on cliffs and wave-cut platforms and accretion on the beaches. Whereas that on the Atlantic coast, except in the Caleta Valdés area, the marine erosion is more prominent, reaching rectification of the coastline.

As in the case of the Great Endorheic Basins System, on the coastal area of the Golfo Nuevo and Golfo San José, there are two levels of pediments caused by local changes in base level developed when these gulfs were also formed as Great Endorheic Basins, presumably during early middle Pleistocene. During the late Glacial transgression, approximately between 15 and 10 ka BP (Mouzo et al. 1978; Ponce et al. 2011) Great Endorheic Basins were flooded by the sea. Changes of base level caused by sea level rise are recorded by oldest shorelines mainly represented by beach ridges of the middle Holocene (San Miguel Formation) and some relics of wave-cut platforms.

On the Atlantic coast, there is also a sequence of beach ridges corresponding to the Caleta Valdés Formation, representing the sea level during late Pleistocene (see Chapter "Geology of Península Valdés" and Sect. 5).

## *4.1 Coastal Piedmont Pediment*

The coastal slopes of the Golfo Nuevo and Golfo San José has the same geomorphological units and genesis than Great Endorheic Basins System: the erosion scarp, two levels of ancient pediments and *bajadas*. The integration of these geomorphological units with the coastline gives an irregular shape, where levels of ancient pediments culminate abruptly in cliffs and associated wave-cut platforms (coastal erosion), whereas, accretion prevails in the distal areas of *bajadas* (beaches and salt marshes; Fig. 5b). Dominant soils are Natrargids, Calciargids, Torriorthens complex with a shrub steppe vegetation community. Holocene stream valleys dissected coastal pediments on the eastern slopes of Península Valdés region. These valley were filled with aeolian sandy sediments where the soils correspond to Haplocalcids with a grassland vegetation community (see Chapter "Vegetation of Península Valdés: Priority Sites for Conservation").

## *4.2 Coastal Bajada*

This unit connect the coastal piedmont pediment with the Pleistocene and Holocene beach ridges. Geomorphic properties, vegetation patterns, and soil development have the same characteristics that those observed in Great Endorheic Basin System (see Sect. 3.2).

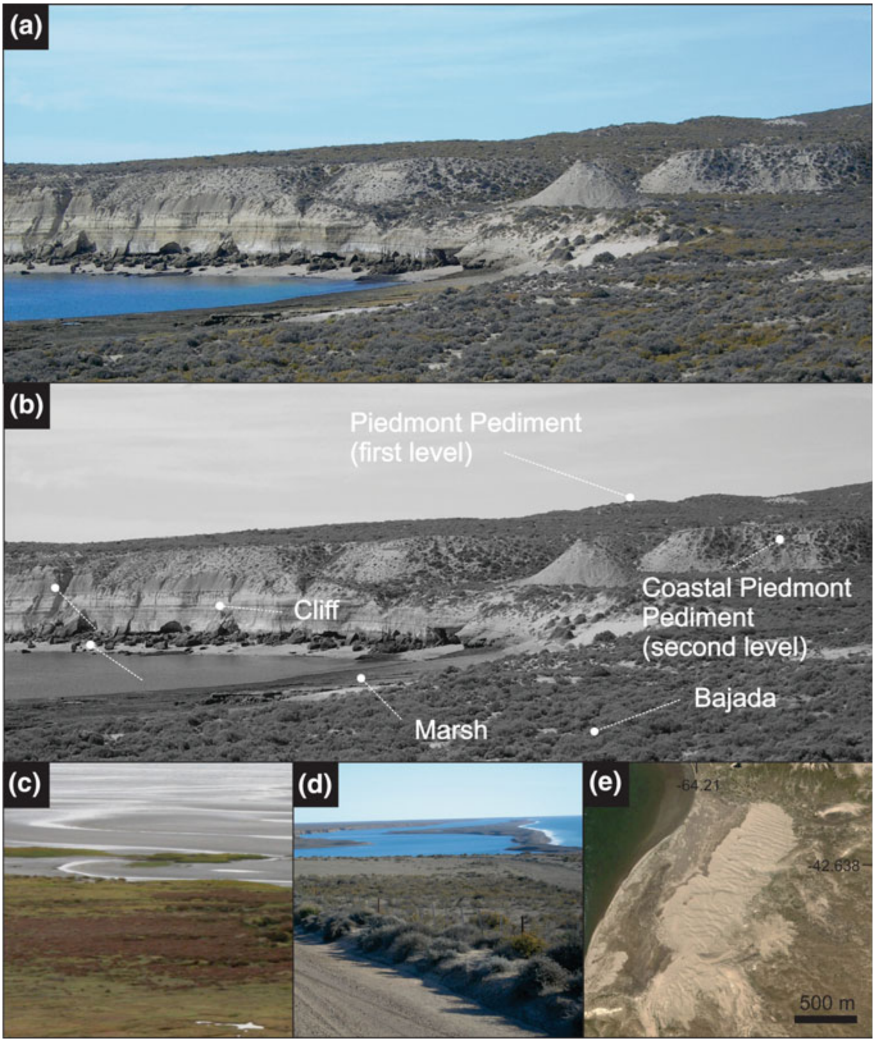


**Fig. 5** Coastal zone system; **a** and **b** geomorphological sequence on littoral hillslope setting: erosion escarps, cliff (and wave-cut platforms associated), coastal piedmont pediment levels, *bajada* (pediment association), and present beaches (with salt marshes associated); **c** details of present beach and salt marsh; **d** coastal lagoon of Caleta Valdés site, BR I–IV Pleistocene Beach ridges (Caleta Valdés Formation), CS cuspate spit, BR V Holocene beach ridge (spit, San Miguel Formation)

## *4.3 Beach Ridges I–IV*

On the easternmost side of the Península, in Caleta Valdés, a Pleistocene beach ridge sequence has long been recognized and described (Feruglio 1949–1950;

Fasano et al. 1983; Codignotto and Kokot 1988; Rutter et al. 1989; Súnico 1996; Rostami et al. 2000; Brückner et al. 2007; Pedoja et al. 2011; Bouza 2014) (Fig. 2). These deposits correspond to Caleta Valdés Formation (Haller et al. 2000; see Chapter "Geology of Península Valdés") and are composed of pebbly conglomerates with sandy matrix and few banks of calcareous skeletal remains of fossil mollusk. Nonevidences of Pleistocene shorelines are observed in other parts of Península Valdés (Fig. 2).

The beach ridge sequence has four paleoshorelines informally named with Roman number (i.e., I–IV) in descending order of elevation (Fig. 2). The highest marine terrace, beach ridge I, reach over 20 m a.s.l. dropping to about 14 m a.s.l. seaward, which is about the same reaches as beach ridges II, III, and IV. Although identification is tenuous because the four shorelines have roughly the same level elevation, they are separated on the basis of elongated paleo-coastal lagoons, vegetation patterns, soil development, and minor elevation differences.

Numerical ages obtained using $^{14}$C, U/Th, ESR, and amino acid racemization give a middle to later Plesitocene age for this deposits (Rutter et al. 1989; Rostami et al. 2000; Schellmann and Radtke 2000; Brückner et al. 2007). These ages in addition to stratigraphic correlations with other beach ridges of the Atlantic Patagonian coast allow correlating them with specific Marine Isotope Stages (MIS). Formation of shorelines II, III, and IV are correlated to the interglacial period of the MIS 5 (80–130 ka), whereas shoreline I could be correlated to both the MIS 5 or even to the MIS 7 interglacial (230–190 ka).

As sea levels during MIS 5 and MIS 7 were around to ±4 m a.s.l. (e.g., Hearty and Kindler 1995; Schellmann and Radtke 2000; Pedoja et al. 2011) the higher elevations of beach ridges I–IV were used to demonstrate that the Atlantic Patagonian coast had a large-scale uplift during the Quaternary (Rostami et al. 2000; Pedoja et al. 2011). The hypothesis concerning this uplift is that it was and is still being generated by the subduction of the Chile ridge and the associated dynamic uplift (Guillaume et al. 2009; Pedoja et al. 2011; see Chapter "Climatic, Tectonic, Eustatic, and Volcanic Controls on the Stratigraphic Record of Península Valdés").

## 4.4 *Beach Ridges V*

This geomorphological unit is the youngest raised beach located between 5 and 10 m a.s.l. (Fig. 2). It is a barrier spit formed by Holocene beach ridges composed of coarse and very coarse gravel with a small sandy matrix and shells. The unit is included in the San Miguel Formation (Haller 1981) and has long been studied in previous works (Feruglio 1949–1950; Codignotto and Kokot 1988; Rutter et al. 1989; Codignotto et al. 1992; Súnico 1996; Monti 1997; Rostami et al. 2000; Kokot et al. 2005; Brückner et al. 2007, Schellmann and Radtke 2010; Pedoja et al. 2011). This geomorphological unit is developed in the Caleta Valdés area, to the east of the Pleistocene shorelines and also as pocket beaches in the Golfo San José and in the

Golfo Nuevo (Fig. 2). Due to the soil parent materials of beach ridge deposit is relatively young, the soils have a weak development, presumable corresponding to Torriorthens.

Absolute ages are based on $^{14}C$ ages and give a Holocene age, between 6500 (at the uppermost beach ridges) to 2.2 ka $^{14}C$ yr BP (at the lowest beach ridges) (Codignotto and Kokot 1988; Rutter et al. 1989; Codignotto et al. 1992; Monti 1997; Rostami et al. 2000; Brückner et al. 2007). Thus, beach ridge IV formation is correlated to the MIS 1 and more specifically to the end of the Holocene Climatic Optimum or the mid-Holocene Thermal Maximum (5–6 ka BP, *sensu* Briner et al. 2006).Therefore, it can be assumed that the uppermost beach ridges, which are 6.5–5.2 ka BP, were deposited during the maximum Holocene transgression when relative sea level was higher than present. Sea level later declined, reaching the present beach level as early as 2.2 ka BP. As south Patagonian Atlantic coast did not undergo significant uplift during the Holocene (Schellmann and Radtke 2010; Pedoja et al. 2011), surface elevations of these beach ridges have been strongly dominated by eustatic sea level variations (see Chapter "Climatic, Tectonic, Eustatic, and Volcanic Controls on the Stratigraphic Record of Península Valdés").

## *4.5 Present Beach*

In the same way than the San Miguel Formation the present beaches are sandy and gravelly pocket beaches, formed between headlands of rocky (Miocene sedimentites) shorelines.

In Caleta Valdés site, the San Miguel Formation (beach ridge V) is constituted by a set of gravel beach ridges of middle Holocene age. Longshore drift has been predominantly north to south for the last 4–5 ka BP (Codignotto et al. 1992; Rostami et al. 2000). Evolution of the area has been monitored by Kokot et al. (2005). In this period, the northern spit has been growing southward, and its rate has increased 25 m/a (1971–87), 89 m/a (1987–96), and 167 m/a (1996–1999). These beach ridges form the V system proposed by Fasano et al. (1983, Fig. 5d). In the coastal lagoon of Caleta Valdés, barrier islands, tidal plains, salt marshes, and cuspate spit are observed (Codignotto and Kokot 1988).

The barrier island genesis is probably due to the segmentation from a previous spit by channels generated by the action of the sea. The origin of cuspate spit is due to longshore drift operating on a coastline from two different directions as occurs in tidal currents.

On some intertidal areas, small coastal salt marshes occur. These landforms develop in the intertidal zone where a generally muddy substrate supports varied and normally dense stands of halophytic plants (Allen and Pye 1992). The main salt marshes in Península Valdés area develop in Golfo San José. Riacho San José marsh (see Chapter "Vegetation of Península Valdés: Priority Sites for Conservation") is located to the west of the Istmo Carlos Ameghino. This wetland is classified as salt-restricted-entrance embayment salt marsh, characterized by a sandy-loam sediment gain-size, and protected from the wave action by sandy and/or gravel spits (Bouza et al. 2008). Dominant plant species in Riacho marsh is the genus *Spartina*, where S. *alterniflora* installs at the lowest marsh level and *S. densiflora*, accompanied by *Limonium brasiliense*, *Sarcocornia perennis*, and *Atriplex sp*., extends at the highest marsh level. Fracasso marsh is located to the northeast of Istmo Carlos Ameghino and was classified as an open coast salt marsh with a predominantly silty grain size at the highest marsh level and sandy at the lowest marsh level due to the marine influence. Dominant plant species in Fracasso marsh is *Sarcocornia perennis*, accompanied by patches of *Limonium brasiliense* (installed on the marsh levees of the tidal creeks) and isolated plants of *Spartina densiflora*. *Spartina alterniflora* extends over a thin patch parallel to the coastline at lowest marsh level and on the point bars of the tidal creeks (Idaszkin et al. 2014; see Chapter "Vegetation of Península Valdés: Priority Sites for Conservation"). The soils are Aquents, where in the lowest marsh levels, sulfidic material occurred, being these soils classified as Sulfaquents (see Chapter "Soil–Geomorphology Relationships and Pedogenic Processes in Península Valdés").

In some erosional coasts in both Golfo Nuevo, as in the Gofo San José, rocky marshes are developed on top of wave-cut platforms, being specially dominated by *Spartina alterniflora* (Bortolus et al. 2009).

### *4.6 Coastal Aeolian Dunes*

Sand dunes on the coast of Península Valdés are the typical small ridges of sand found at the top of the sand beaches, and above the usual maximum reach of the waves, in the transition area with coastal *bajada* (i.e., foreshore zone). In preferential deposition sites as small low areas, coastal dunes can be installed on coastal pediments. In these cases, the great coastal aeolian landforms of Península Valdés are located in Golfo San José and Golfo Nuevo on windward coast, where both compound linear and transverse dunes were identified (Fig. 5e).

Compound linear dunes (7–13 m high) are located at the NW coastal dunefield. Most linear dunes along the escarpment adopt a compound form owing to the NNE winds, attached to the cliff headland. A linear dune characteristic is that adjoining ridges often branch or merge at a "Y" junction. In the study area, junctions are most common where the ridge deflection occurs.

## 5 Landscape Evolution of the Late Cenozoic of Península Valdés

The present landscape of the Penísnula Valdés is the result of a complex interrelation between climatic, tectonic, volcanic, and eustatic controls that had work in the Andean foreland during the late Cenozoic. (See Chapter "Climatic, Tectonic, Eustatic, and Volcanic Controls on the Stratigraphic Record of Península Valdés”). These interrelations had induced base level changes that favored the erosion of many geomorphological units (e.g., Terraces Levels I–VI) but that also the development of many others (e.g., *bajada*). Based on the interrelationship among the geomorphological units of the Upland and Plains System, the Great Endorheic Basin System and the Coastal Zone System, the landscape evolution of the late Cenozoic of Península Valdés could be reconstructed.

During the Pliocene to early Pleistocene ($\sim$5 to $\sim$1 Ma) the sea coast was 100 km far east from the present coast line (Fig. 6a). At that moment, the landscape of the Penínusla Valdés region was quite different, characterized by fluvial systems (i.e., *Rodados Patagónicos*) developed from the SW to the NE (Cortés 1981; González Díaz and Di Tommaso 2011) and alluvial and fluvial system connected to the Meseta de Somuncura (Fig. 1). Terrace Levels I–VI were deposited in that period, indicating that at least six important base level variations has caused fluvial system modifications.

Later, in a period not clearly defined, closed basins start to developed (Fig. 6b). These depressions were not flooded by the sea and include both, the major depressions and the gulfs of Península Valdés (e.g., Golfo Nuevo, Salina Grande depressions). The period of closed basin formation could be roughly estimated based on the stratigraphic position of the Great Endorheic Basins System units. Geomorphological units of this system are developed over terraces I–VI, thus an age younger than 1 Ma is proposed for this period (youngest age of the *Rodados Patagónicos*). On the other hand as pediments of the Great Endorheic Basins are correlated with coastal pediments which are older than the Beach ridges I–VI, the closed basin formation period would have been not older than 230 ka (maximum age of the MIS 7 obtained in beach ridge I). This indicates that during the lower (i.e., Calabrian stage) to middle Pleistocene the Golfo Nuevo, Golfo San José, Gran Salitral, Salina Chica, and Salina Grande depressions started to develop. Regarding the causes and trigger mechanisms involved in the closed basin formation, there are many controversies. Whereas, wind erosion was proposed to explain the close basins formation (Mouzo et al. 1978; González Díaz and Di Tommaso 2011); tectonics was also proposed (Roveretto 1921; Kostadinoff 1992; Isla 2013) and a combination of both processes was also suggested (Kostadinoff 1992; Haller et al. 2000). In this chapter, we arrive to the conclusion that while wind erosion could have been important, tectonic activity related to fault blocks was probably the trigger mechanism for the formation of the great closed basins. This idea is supported by (1) the occurrence of closed basins formed on pebble gravel deposits that cannot be removed by deflation, (2) borders of the major depressions are straight and in many cases match with subsurface faults (see Kostadinof 1992), (3) post Miocene faults were observed in the region (Haller et al. 2000, Chapter “Geology of Península Valdés”). Further work is needed to bring some light to this issue.

During the late Pleistocene in the Penísnula Valdés region a landscape similar than today’s start to configure. At that time, sea level raised during many interglacial periods, some of them remarkably registered in Península Valdés (MIS5/7). However, nonevidence of Pleistocene marine ingressions (Beach ridges I–IV) is

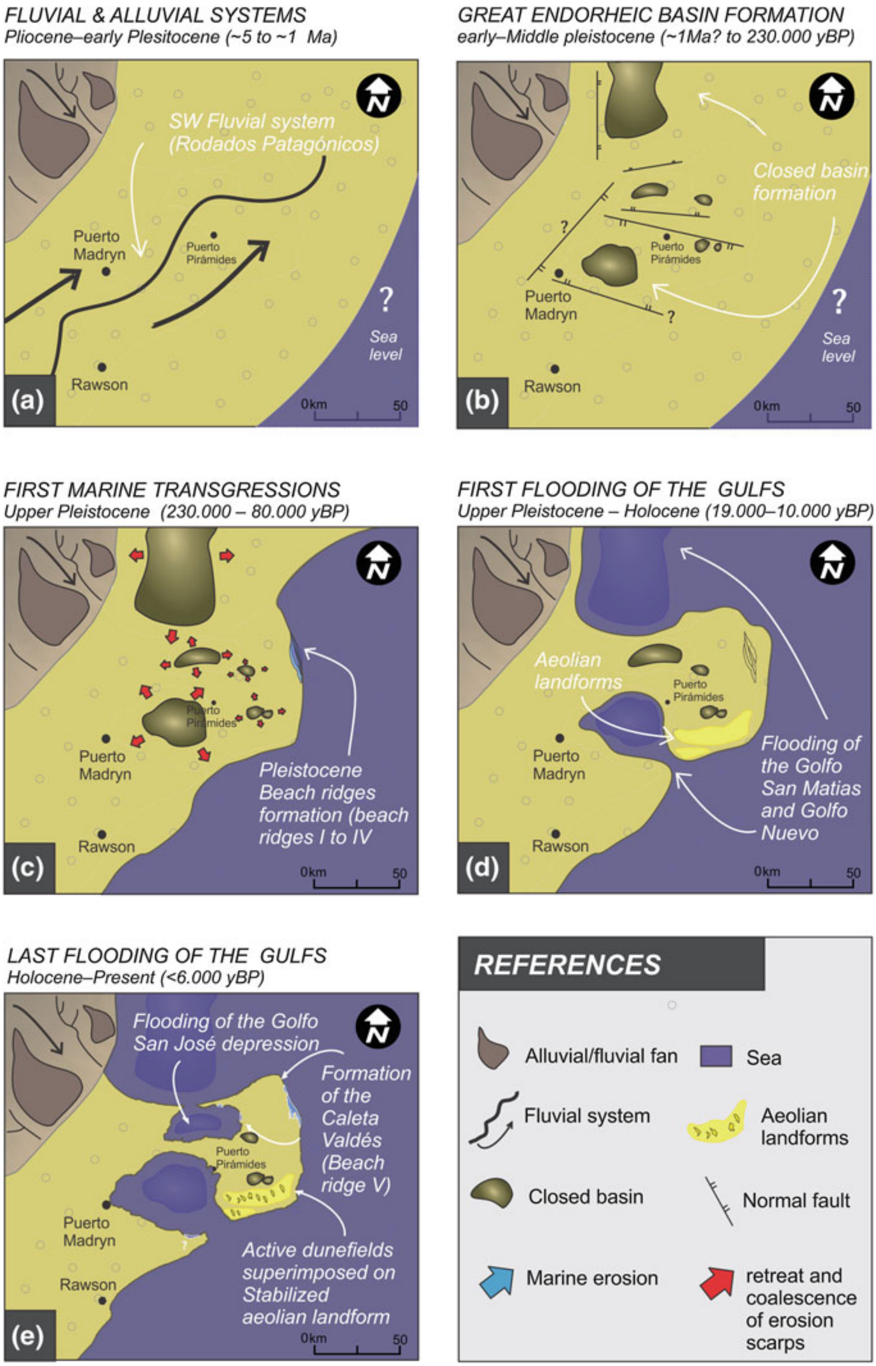


**Fig. 6** Landscape evolution of the Península Valdés area

registered inside the Golfo Nuevo and the Golfo San José, indicating that gulf flooding did not occur in the Pleistocene (at least the final part of the MIS5 ~80 ka), but probably during the Mid-Holocene Thermal Maximum (5–6 ka BP). Topographic/bathymetric data of the Golfo San Matías and Golfo Nuevo indicate depression borders much deeper than the topographic borders of the Golfo San José (−55, −35 and −20 m a.s.l., respectively). Thus, Golfo San Matías and Golfo Nuevo would have been flooded before the Golfo San José (Fig. 6c, d), as previous studies suggested (i.e., 10–19 ka BP; Codignotto 2008; Ponce et al. 2011; Isla 2013). Finally, during the last millennium, sand dunes formation in the upland and plain system and present beach/marsh formation in the coastal zone system took place, resulting in the current landscape of The Península Valdés (Fig. 6e).

As a final remark, it is possible to suggest that, despite many authors had contributed to the knowledge of this region, important uncertainties related to the landscape evolution of the Península Valdés still exist. Understanding the formation of the closed depressions, to determine the timing of sea ingressions in the gulfs or to comprehend the trigger mechanisms of relative sea level changes are far from being clear and offer significant potential for further studies.

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## Glossary

| | |
|---|---|
| Bajada | Alluvial plain formed at by the coalescing of several alluvial fans |
| Barchan dunes | Barchan or barkhan dune is a crescent-shaped dune. Barchans face the wind, appearing convex and are produced by wind action predominately from one direction |
| Blowouts | Depressions or hollows formed by wind erosion on a preexisting sand deposit, generally in vegetation-stabilized dune fields |
| Closed basin | A basin draining to some depression or pond within its area, from which water is lost only by evaporation or percolation. A basin without a surface outlet |
| Complex dunes | Complex dunes consist of two or more different types of simple dunes which have coalesced or are superimposed, usually of barchanoid or linear shapes |
| Compound dunes | Compound dunes consist of two or more dunes of the same type which have coalesced or are superimposed |

| | |
|---|---|
| Desert pavement | A stony surface generally composed of a layer of angular or subrounded gravels one or two stones thick developed on a mantle of finer stone free material |
| Dome-shaped dunes | Dome dunes are the rarest type of dune. They are circular and do not have a slipface. The wind can blow material onto the dune from any side |
| Ice-wedge casts | The filling of sand or other materials that replaces former ice wedges |
| Linear dunes | Linear dunes form straight or nearly straight lines. Some linear dunes are shaped like a wiggling snake, with regular curves. Linear dunes develop where wind pressures are nearly equal on both sides of a dune |
| Mass wasting processes | The failure and movement by gravity of a volume of soil or rock to a downslope site |
| Nebkas | A small landform that forms mainly around shrubs, built, and shaped by the action of wind |
| Parabolic dunes | If strong winds erode a section of the vegetated sand (commonly referred to as a blowout), a parabolic dune may form |
| Pediments | A gently sloping erosional surface developed on bedrock or older uncosolidated deposits subaerially exposed or covered by a discontinuous to continuous veneer of alluvial deposits |
| Playa lake | A near level area at the bottom of a closed basin, sometimes temporarily covered with water |
| Salt marshes | A flat or gently sloping vegetated wetland in the upper intertidal zone on sheltered parts of the coast (estuaries, inlets, lagoon shores) |
| Simple sand dunes | Simple dunes consist of individual dune forms which are spatially separate from nearby dunes. These sand dunes are small in most cases, with wavelengths (shortest distance from one dune crest to the other) of 10–500 m |
| Star dunes | Star dunes have pointed ridges and slip faces on at least three sides. Star dunes develop where winds come from many different directions |
| Transverse dunes | A large, strongly asymmetrical, elongated dune lying at right angles to the prevailing wind direction |
| Wave-cut platforms | A flat to gently sloping surface at the base of a cliff, formed by erosion by waves. It develops as a result of wave abrasion and is also called abrasion platform |

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