Chapter 4
Landscapes and Geology of Patagonia: An Introduction to the Land of Reptiles

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Abstract The purpose of this chapter is to summarize the geological-geomorphological regions of Patagonia with a general characterization of the main geomorphological units. A review of studies on geology, stratigraphic, main geologic landmarks, geological history, and geological resources will be briefly described. This review was performed on the base of geological province concept, including a stratigraphic-morphostructural criteria and a description of major endogenous and exogenous processes responsible for the formation of landscape units. In this chapter these geological-geomorphological regions include Chile and Argentina and were grouped as: (1) Coastal Cordillera and Central Valley (Chile), (2) Southern Andes Cordillera, (3) Mountain Sector of the Neuquén Embayment, (4) Northern Patagonian Tablelands, (5) The North Patagonian Broken Foreland and Somún Curá Massif, (6) Central Patagonian Tablelands, (7) Deseado Massif, (8) Southern Patagonian Tableland, and (9) Islas Malvinas Plateau.

Keywords Patagonian Andes · Extra-Andean Patagonia · Geological provinces · Geomorphological processes

4.1 Introduction

The region considered in this chapter occupies more than 1,000,000 km^2 and is the only continental landmass emerging along the midlatitudes in the Southern Hemisphere (Fig. 4.1). The region involves two different countries, Chile to the

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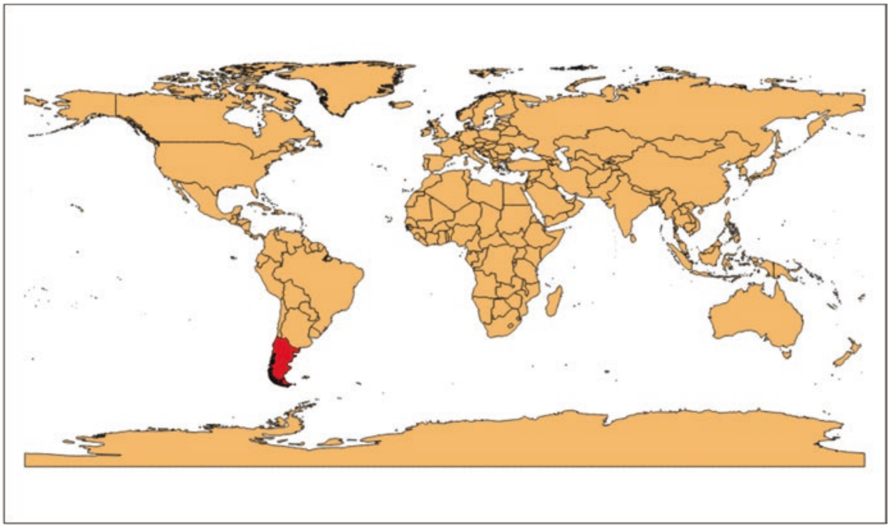

Fig. 4.1 Patagonian region emerging along the midlatitudes in the Southern Hemisphere

west and Argentina to the east. Its natural boundaries are from the north of the Barrancas and the Colorado Rivers in Argentina (Provinces of Mendoza and La Pampa and the southern portion of Buenos Aires) and by the Maule River in Chile. To the south, the natural boundaries are the Cabo de Hornos (Cape Horn), the Canal de Beagle, and the Navarino Island archipelago (Fig. 4.2).

While it is generally accepted that the beginning of the Andean margin configuration is determined by the start of the subduction at the western margin of the South American plate at around 190 Ma (D'Elia et al. 2012), the main configuration and development of the Andes and Andean Foreland was developed during the Neogene (18 Ma; Folguera and Ramos 2011; Bilmes et al. 2013, 2017a). At this time a renewed episode of orogenic grow started and shifted toward the foreland during the lower to upper middle Miocene (19–10 Ma; Guillaume et al. 2009; Bilmes et al. 2013). In addition, since the Late Miocene-Pliocene the foreland region is characterized by a regional uplift, a process that is still observed today (Guillaume et al. 2009; Pedoja et al. 2011; Folguera et al. 2015). As a consequence of this foreland uplift several Late Miocene-Pliocene fluvial terraces were tilted and all Pleistocene Atlantic shorelines were remarkably elevated, in some cases more than 100 m with respect to present-day sea level (Pedoja et al. 2011).

At the western side of the Patagonian Andes, the wet west winds produced a rain shadow; therefore the western slope of the Patagonian Andes was subjected to an extreme erosional gradient producing asymmetric erosion with respect to the eastern slope. The end of early Miocene period is marked by an increased aridity of the eastern side of Patagonian Andes (Bellosi 1999; Blisniuk et al. 2005; Palazzesi et al. 2014; Bucher et al. 2018). Due to this change on climatic conditions, from the physiographic point of view, two contrasting sectors can be distinguished: (1) the

Fig. 4.2 Patagonian geological-geomorphological regions (Modified from Ramos 1999; Coronato et al. 2008) and major geological structure features

Patagonian Andes (North and South Patagonian Cordillera and Fueguian Andes; Ramos 1999) and (2) the Extra-Andean Patagonia, which extends eastward up to the Atlantic Ocean.

Glaciation processes mainly modeled the landscape in Patagonian Andes. The mountain range was covered by a continuous mountain ice sheet (continental and alpine-type glaciations), from 37° S to 56° S (Cape Horn), during at least five major glaciations over the last million years, beginning with the Great Patagonian Glaciation (GPG) (Fig. 4.3; Rabassa and Clapperton 1990; Rabassa 2008; Caldenius 1932; Bendle et al. 2017; Griffing 2018). The landscape of the Extra-Andean Patagonia region is modeled by severe aridity conditions (low rainfall rate and

Fig. 4.3 Late Glacial Maximum (LGM) and Great Patagonia Glaciation (GPG) in Patagonia (Modified from Caldenius 1932; Bendle et al. 2017; Griffing 2018). NPI North Patagonian Icefield, SPI South Patagonian Icefield, CDI Cordillera Darwin Icefield

sparse vegetation cover) with major influence in the operation and development of landforms (Thomas 1997).

Although wind is an important geomorphological agent that has deeply modified the arid regional landscapes, water erosion due to short- and high-intensity rainfalls is the most active exogenous geomorphic process, either as raindrop splash, as surface runoff, or as concentrated flow erosion, in the form of rills and gullies. Many of these landforms exhibit large patches of bare soils (desert pavements and surface soil crusts) and thus they are exposed to wind erosion, raindrop impact, and surface runoff (Bouza et al. 1993; Bouza and del Valle 1997; Rostagno and Degorgue 2011; Chartier et al. 2013).

The main feature of Extra-Andean Patagonia is the presence of extensive plains of different origins and ages, placed at different levels. This relief is occasionally interrupted by the appearance of rocky cliffs, lava plains (plateaus), and low mountain hills. In the southern sector the major landforms are of glacial origin: great moraines produced during several glaciations, mainly during the Last Glacial Maximum (LGM, ca. 24 ka; Fig. 4.3).

From a geologic point of view, Patagonia can be divided into geological provinces. The term geological province refers to a region characterized by a certain stratigraphic succession, its own structural style, and peculiar geomorphological features, being the whole expression of a particular geological history (Rolleri 1976; Ramos 1999). This morphostructural criterion is useful to describe the landscape units associated to the main endogenous and exogenous processes.

In this chapter, nine geological-geomorphological regions are described to characterize the general Patagonian landscape. The definition and delimitation of the units adopted in this work follows, with some modifications, the proposal of Ramos (1999) and Coronato et al. (2008) (Fig. 4.2).

4.2 Coastal Cordillera and Central Valley

The Costal Cordillera and the Central Valley are two geological regions completely developed in Chile (Fig. 4.2). The Coastal Cordillera is a coastal batholith (between 18° and 42° S) directly on the Pacific shoreline formed by predominately Late Paleozoic and Mesozoic igneous rocks, with parallel belts of Paleozoic metamorphic rocks outcropping out south of 34° S. It is the oldest and westernmost remnant of a magmatic arc formed during the birth of the modern Andes (195–130 Ma). With a moderate height, about 1000–2000 m a.s.l., it disappears completely in Northern Chile near Arica (Pankhurst and Hervé 2007; Casanova et al. 2013). Only the southern extremity of this range concerns the study region.

In the Patagonia region, this geological province is mainly represented by the Bahía Mansa Metamorphic Complex of Carboniferous and Permian-Triassic ages, outcropping between 39° 30′ and 42° 00′ S. This Metamorphic Complex corresponds to a heterogeneous group of metamorphic rocks, with mainly pelitic to semipelitic schists, which are well exposed in the coastal cliffs (e.g., Valdivia; Fig. 4.4a, b). Further south, in the island of Chiloé, Paleogene volcano and sedimentary rocks are outcropped (Duhart et al. 2001).

The Central Valley is located between the Andes to the east and the Coastal Cordillera to the west and thus it runs along a north-to-south axis adjacent to the southeastern Pacific shoreline (Fig. 4.2). The area includes the Chilean Lake District and the Chilotan archipelago, most noteworthy Isla Grande de Chiloé (between 40°

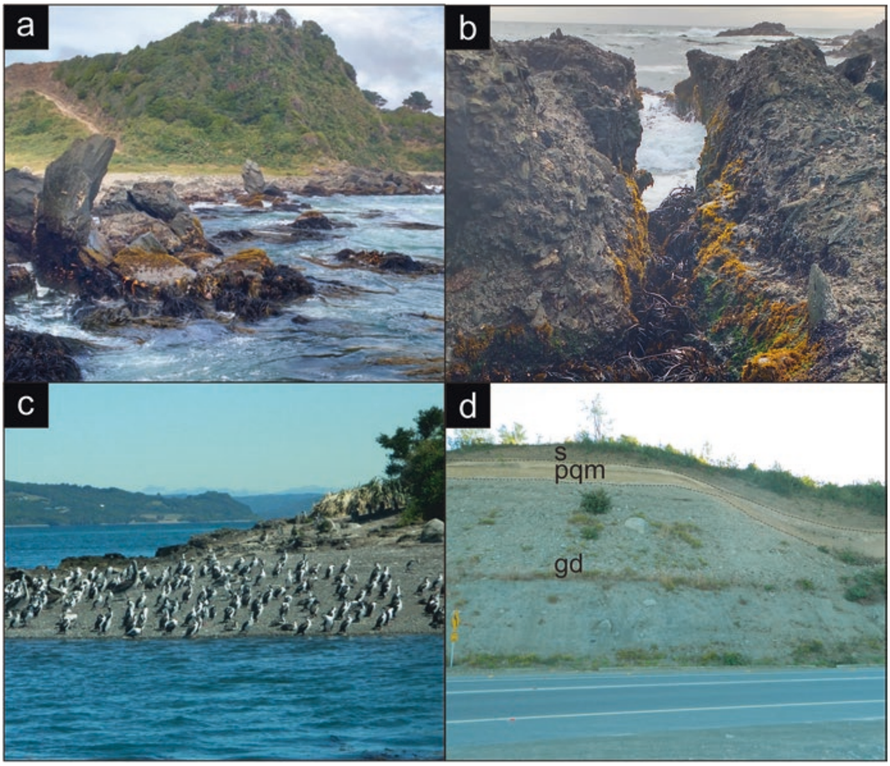

Fig. 4.4 Coastal Cordillera and Central Valley; (**a**, **b**) metamorphic rocks in coastal cliff (**c**) Chilotan archipelago; (**d**) LGM Llanquihue glaciation, gd glacial deposit, pqm pyroclastic Quaternary materials, s soil

and 44° S; Fig. 4.4c). The valley floor features large lakes and marine water bodies that were filled during the Last Glacial Maximum (LGM, Llanquihue glaciation) by Andean piedmont ice lobes. The rest of the valley floor is covered with moraine belts and outwash plains deposited by those lobes during both the LGM and earlier glacial expansions (Andersen et al. 1999; Moreno et al. 2015). In sectors, the glacial substrate was covered by pyroclastic materials, derived from Quaternary volcanoes, on which soil developed (Fig. 4.4d; Casanova et al. 2013).

4.3 Southern Andes Cordillera

This region includes four geological provinces defined by Ramos (1999): (1) the southern portion of the Cordillera Principal (between 34° and 39° S), (2) the Cordillera Patagónica Septentrional, (3) the Cordillera Patagónica Austral, and (4) the Cordillera Fueguina (Fig. 4.2).

These geological provinces have been considered as a whole because of the common mountainous and glacial landscape and similar physiographic features. The mountainous landscape of Southern Andes Cordillera is distinguished according to the type of endogenous geological processes produced northward or southward from the triple junction tectonic plates (Fig. 4.2). The associated geomorphic elements to volcanoes in Patagonian Andes are volcanic scum, lava tunnels, lava flows, and volcanic boiler calderas.

The southern part of the Cordillera Principal and the Cordillera Patagónica Septentrional (Ramos 1999) are characterized by mountain peaks associated with igneous rocks of the Patagonian Batholith (González Díaz 1982; Rapela et al. 1987) and with Neogene-Quaternary stratovolcanoes; some of them are active or potentially active, which indicates the Southern Volcanic Zone (SVZ, 33–46° S). The SVZ includes at least 60 volcanoes in Chile and Argentina, as well as three caldera systems and numerous minor eruptive centers (Stern 2004; Moreno et al. 2015) (Fig. 4.5a, b; e.g., Lanín, Osorno, Villarrica, Cordon Caulle-Puyehue, Hudson, and Quizapú, among others), being some of them very active in the past decade (e.g., Cerro Hudson eruption in August 1991, Volcán Chaiten eruption in February 2009, Cordón Caulle-Puyehue eruption in June 2011, Volcán Copahue eruption in December 2012, Volcán Calbuco eruption in April 2015) Petrinovic and D'Elia 2018.

The Cordillera Patagónica Austral (Leanza 1972) is characterized by two sectors: (1) a gap of inactive volcanism that occurs between 46° and 49° S and (2) another volcanic area that appears southward of the Austral Volcanic Zone (AVZ; 49–55° S). The Cordillera Patagónica Austral (mostly within the gap of inactive volcanism) includes peaks composed of isolated plutons of the Patagonian Batholith, like Cerro San Valentín, Cerro San Lorenzo, Cerro Fitz Roy (Chaltén; Fig. 4.5c), Cerro Poincenot, Cerro Torre, and Torres del Paine granitic intrusions of Early Miocene age (Skarmeta and Castelli 1997; Ramos and Ghiglione 2008). These peaks do not correspond to volcanic bodies and with the exception of Cerro San Lorenzo, these igneous intrusives (stocks) were emplaced on Cretaceous marine sedimentary rocks belonging to the Austral (or Magallanes) Basin. The Cerro San Valentín (4070 m a.s.l.) is the highest peak in the Patagonian Andes and is just south of the Chile Ridge. This significant change in elevation north and south of 46°30′ S latitude coincides with the collision of the Chile Ridge (Ramos and Ghiglione 2008). The Austral Volcanic Zone (AVZ; 49–55°S) consists of five stratovolcanoes and a small complex of Holocene domes and flows on the Cook Island, the southernmost volcanic center in the Andes south of the Magallanes fault zone and therefore on the Scotia Plate (Fig. 4.2).

The Cordillera Fueguina (Borrello 1972) is represented by a mountain range located in the southern sector of the Isla Grande de Tierra del Fuego. This is the only Andean segment that extends in a W-E direction, from the Magellan fault, in the South Pacific Ocean, to the Isla de Los Estados (Staten Island), in the South Atlantic Ocean. It includes the lowest Andean summits of Patagonia: in Chile region, the Monte Sarmiento in Darwin Cordillera reaches 2488 m a.s.l., while in Argentina, the Monte Olivia and the Monte Cornú do not exceed 1500 m a.s.l. According to Coronato et al. (2008), Cordillera Fueguina is characterized by three areas: (a) the Fueguian Archipelago, in the western and southern Chilean sector, formed by plutonic rocks resulting from several intrusions during the Cretaceous and the Cenozoic,

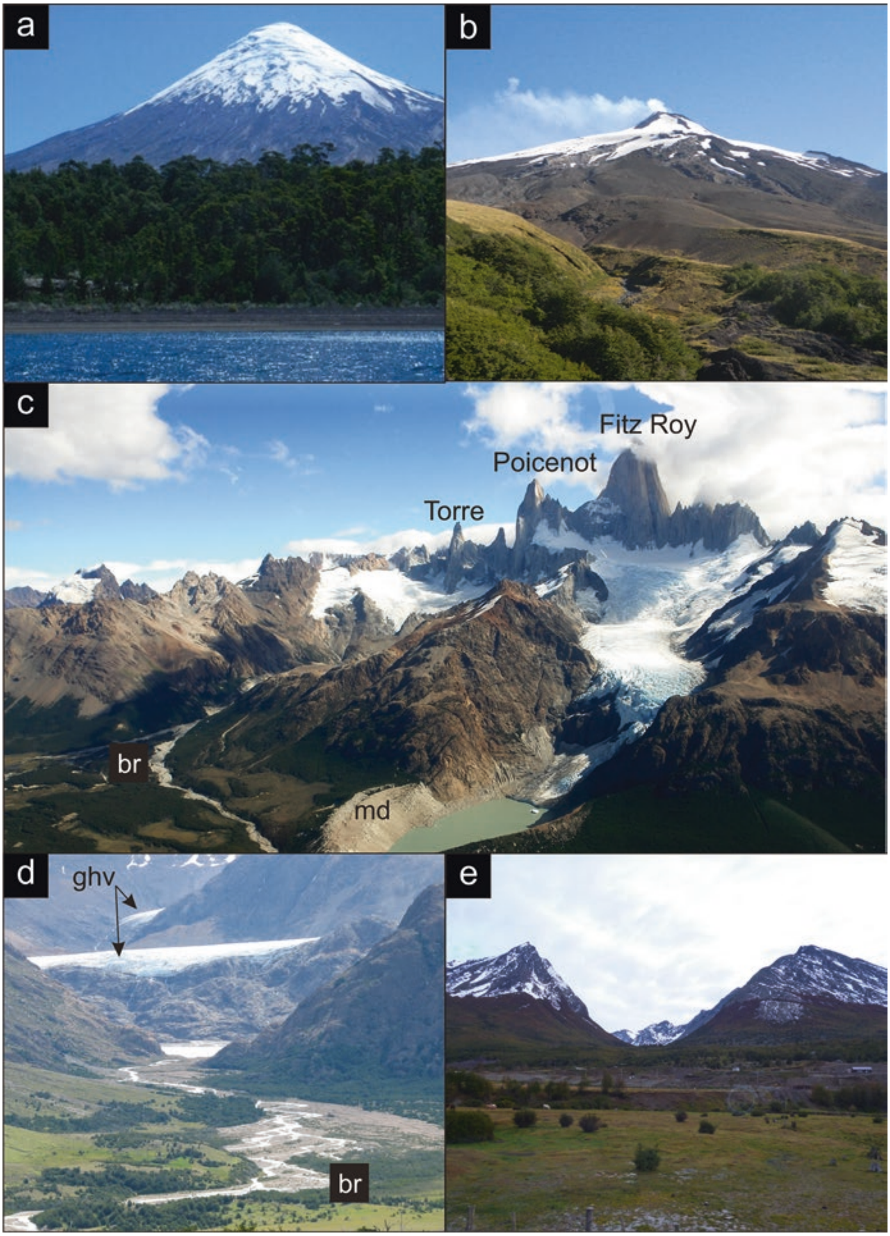

Fig. 4.5 Southern Andes Cordillera; (**a**, **b**) Southern Volcanic Zone, Osorno and Villarrica volcanoes, respectively; (**c**) gap of inactive volcanism, Cerro Fitz Roy, Cerro Poincenot, Cerro Torre (courtesy of photographer Daniel Rivademar), moraine deposits (md) from LIA (glacial retreat), braided rivers (br); (**d**) valley of glacial origin (Río Tunel, Chalten), in the background, a hanging glacier is observed (ghv, Tunel Inferior Glacier); (**e**) U-shaped valleys (Ushuaia, Tierra del Fuego)

(b) the Fueguian Cordillera, and (c) the foothills of the Fueguian Cordillera, north of Lago Fagnano, up to 53° 30′ S, approximately.

Since the Late Miocene (ca. 6 Ma), glaciations were the main geomorphic processes that modeled the landscape of the Southern Andes Cordillera (Fig. 4.3). The present drainage network was developed after the Last Glacial Maximum (LGM) since ca. 21 ka BP. Figure 4.3 shows the maximum advance of the GPG and the LGM, respectively. Presently, tree icefield relicts are recognized: North Patagonian Icefield, South Patagonian Icefield (Hielo Continental Patagónico, Norte y Sur, respectively), and Cordillera Darwin Icefield.

The landscape in the Southern Andes Cordillera is mainly characterized by abrasion action during glacier advances. The resulting erosional landforms include striations, cirques, arêtes, nunataks, glacial horns, U-shaped valleys, and hanging valleys (Fig. 4.5c, d, e). Nunataks are mountainous peaks resulting from the residual relief that resisted the alpine glacial erosion, emerging as a relief in the form of islands, similar to inselbergs or witness hills. These landforms concern hypothetical glacial refuges during glacial periods. For example, Fitz Roy (or Cerro Chaltén, 3405 m a.s.l.), Poincenot, Torre, Cerro Catedral, and Torres del Paine, among others, are considered a combination of arêtes and horns and nunataks (Fig. 4.5c). Small depositional glacial landform is mainly constituted by moraine deposits associated to the Little Ice Age (LIA, AD 1400–1750, Fig. 4.5c). Based on dendrochronological analysis of the trees colonizing the successive moraine ridges, the LIA extended between middle seventeenth and middle nineteenth centuries, indicating two neoglacial advances (Rabassa et al. 1984).

The fluvial action of this region is represented by braided rivers forming both from the thaw of glaciers and snow accumulation during winter. In the Argentinean side streams converge in main allochthonous rivers (e.g., Negro, Colorado, Chubut, and Santa Cruz) that cross the Extra-Andean Patagonia and flow into the South Atlantic Ocean. They have extensive fluvial valleys (disproportionate valleys) with successive terraces produced during the past glaciations. The mass wasting landforms in Southern Andes Cordillera (and in general in the entire Andes) are mostly produced by freeze-thaw activity (frost action) that causes physical weathering entailing the talus cone formation, the pipkrake process (frost heaving by ice needle growth) and gelifluction.

4.4 Mountain Sector of the Neuquén Embayment

The Mountain Sector of the Neuquén Embayment (Bracaccini 1970) includes the Cordillera del Viento and the Sierra de Chachil, two range systems with N-S orientation situated to the east near the Cordillera Principal, but in the Andean foreland (Fig. 4.2). The Cordillera del Viento includes a volcanic landscape whose summits are Cerro Butalón (2986 m a.s.l.) and Cerro La Corona (2991 m a.s.l.). The cordillera del Viento is flanked by the Tromen volcano to the south (Fig. 4.6a; 3978 m a.s.l.) and by the Domuyo volcano to the north (Fig. 4.6b; 4709 m a.s.l), and these are the

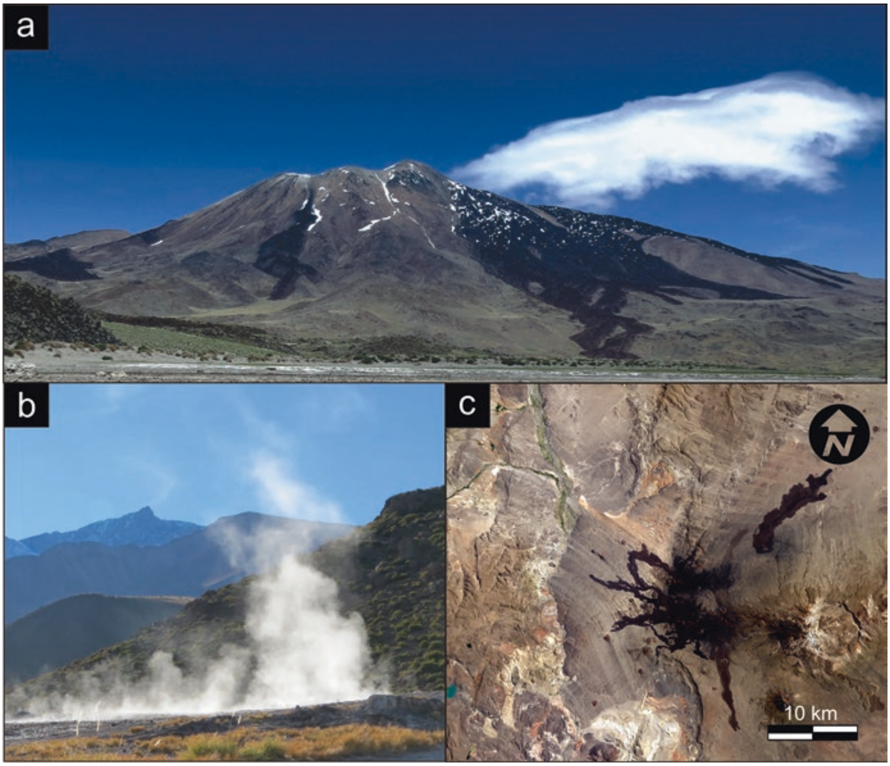

Fig. 4.6 Mountain Sector of the Neuquén Embayment, (**a**) Tromen volcano, (**b**) Domuyo volcano (foreground hydrothermal activity) (Tromen and Domuyo photographs courtesy of Dr. Leandro D'Elia), (**c**) Payún Matru volcanic field

largest mountain peaks of this region. The Sierra de Chachil (Cerro Chachil 2839 m a.s.l.) is situated 115 km west Neuquén city. The cordillera del Viento and Chachil Mountain ranges constitute blocks tectonically elevated that expose Paleozoic-Mesozoic rocks. In these outcrops, granitic, tonalithic, and granodioritic igneous bodies as well as rhyolitic dykes are recognized. Surrounding these outcrops, pyroclastic and sedimentary rocks from the continental origin of Mesozoic age also appear (Limarino et al. 1999). The volcanic landscape is constituted by calderas, volcanoes, and lava flows of Pleistocene-Holocene age, which represent basaltic distensive volcanism of retroarc type (chain of volcanoes formed above a subducting plate), as the Payún Matru volcanic field (Fig. 4.6c). Basic and acid to mesosilicic volcanic and pyroclastic rocks of Neogene age occur as outcrops forming discontinuous mountain ranges with an approximately north-south distribution. The Cerro Nevado (3773 m a.s.l.) is a volcanic massif situated to the east of Malargüe city, composed of volcanic and pyroclastic rocks of Neogene-Pleistocene age.

4.5 Northern Patagonian Tablelands

The Northern Patagonian Tablelands is a geological province defined in this chapter to refer to the developed plains of different origin located east and southeast of the Mountain Sector of the Neuquén Embayment (Fig. 4.2).

The main tableland landforms are composed of (1) isolated remnants of the Pleistocene basalt plains (plateau), (2) stabilized aeolian fields and active dune fields, and (3) Piedmont levels of Neogene age (bajadas) located to the south of Buenos Aires Province and to the north of Río Negro Province (Fig. 4.7a).

The Plio-Pleistocene basalt plain includes the Sierra de Auca Mahuida (2253 m a.s.l.), a volcanic complex that includes more than 100 minor vents that provided basaltic flows that overlie the pre-Pliocene to Quaternary sedimentary deposits (Kay et al. 2007).

Stabilized aeolian fields are composed of sandy mantles and dune fields of Late Pleistocene age; they extend across the southern most part of Buenos Aires, southern La Pampa, and northern Río Negro. In this geomorphological unit, linear, parabolic, barchanoid, and crescentic dunes are recognized (Fig. 4.7b, c) (Szelagowski et al. 2004; Zárate and Tripaldi 2012). These landforms are stabilized mainly with *Hyalis argentea* (olivillo). The active dune field is located in northeastern Río Negro Province on Golfo San Matías coast (east San Antonio Oeste); it has an eastward migration, mainly of transverse sand ridges.

Coalescing alluvial fans (bajadas) of Neogene-Quaternary period were developed in the eastern piedmont of the Mountain sector of the Neuquén Basin. These landscapes have eastern-southeastern distribution and their deposits are constituted of gravel and sand. Embedded into these old coalescing alluvial fans, fluvial terrace levels of the Colorado and Negro Rivers were developed.

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 mainly *Spartina* genus. The representative salt marshes are located in the estuarine sector of the Negro River (El Cóndor beach), Caleta Los Loros, and San Antonio Oeste (Fig. 4.7d, e).

4.6 The North Patagonian Broken Foreland and Somún Curá Massif

The Patagonian Broken Foreland region defined in this work as part of the Patagonian broken foreland (Fig. 4.8a, sensu Bilmes et al. 2013), bounded to the north by the Río Limay and to the south by the southern end of the Sierra de San Bernardo (Figs. 4.2 and 4.8a). This region includes three geological provinces described by Ramos (1999): (a) the Precordillera Patagónica to the northwest, (b) the Bernárdides to the southeast, and (c) the western sector of the Meseta Patagónica Norte where there are outcrops of Mesozoic rocks from the Cañadón Asfalto Basin (Fig. 4.2).

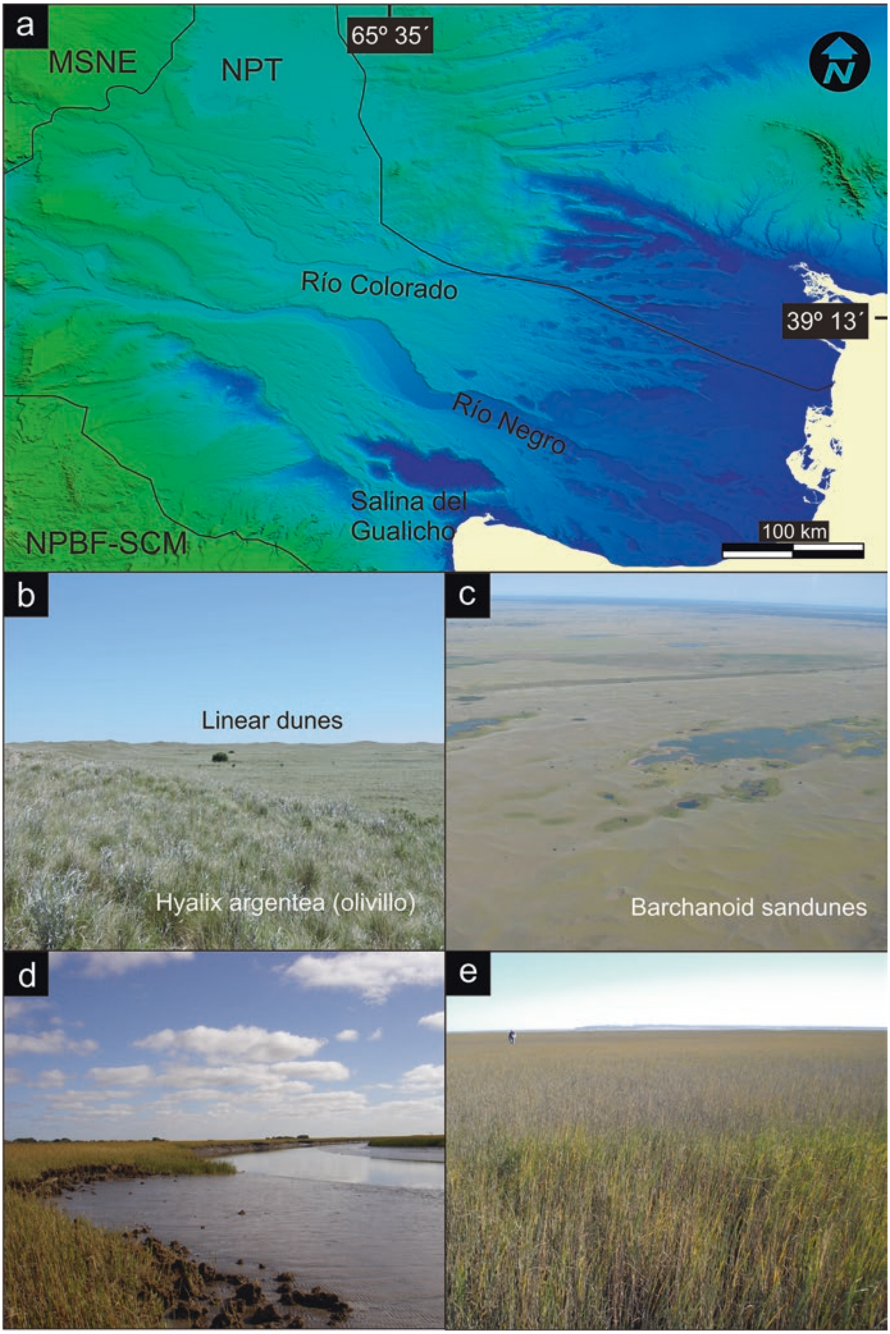

Fig. 4.7 (**a**) DEM showing the Northern Patagonian Tablelands region (NPT); MSNE Mountain Sector of the Neuquén Embayment, NPBF-SCM Patagonian Broken Foreland and Somún Curá Massif; (**b**) stabilized aeolian fields are composed of sandy mantles and dune field complex (linear, parabolic, crescentic dunes); (**c**) barchanoid sand dunes (**b** and **c** photographs courtesy of Dra. Adriana Mehl); (**d**) El Cóndor salt marsh (Negro River estuary, muddy intertidal); (**e**) Caleta Los Loros salt marsh (sandy intertidal) (salt marshes photographs courtesy of Dr. Alejandro Bortolus)

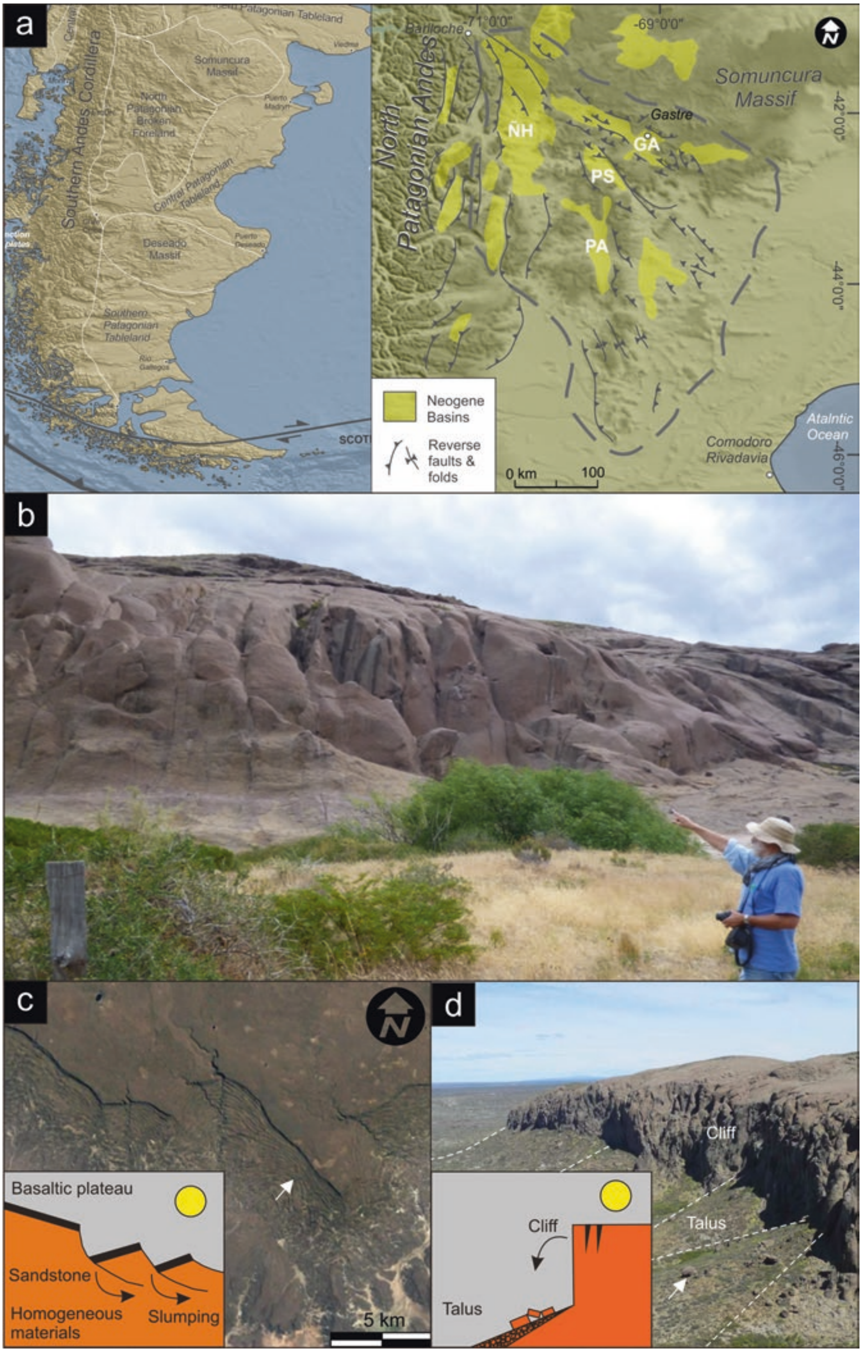

Fig. 4.8 (**a**) The Patagonian Broken foreland and Somún Curá Massif, (**b**) exhumed planation surfaces (Marifil Formation), (**c**) slumping in basaltic plateaus, (**d**) rockfall

This region is characterized by Neogene-Quaternary intermontane basins (e.g., Gastre Basin, Paso del Sapo Basin, Agnia Basin, Ñirihuau Basin) surrounded by fault block mountain ranges constituted by a Paleozoic-Triassic crystalline basement, uplifted Jurassic-Cretaceous sedimentary and volcanic deposits, and volcanic Paleogene rocks (Cazau et al. 1989; Bilmes 2013; Bucher et al. 2018; Fig. 4.8a). The Quaternary record of the intermontane basins includes fluvial-alluvial deposits, playa lakes, and lakes (*salinas*) and lava flows (Massaferro et al. 2006; Bilmes et al. 2017b).

The Somún Curá Massif received its denomination due to Precambrian features of their basement (Ramos 1999) and forms a complex landscape composed of exhumed planation surfaces and extended basaltic plateaus. Between these dominant features, other aggradational and erosional units developed as pediment association levels, fluvial terraces and alluvial fan levels (moderns and relicts), alluvial plains, wetlands (*mallines*), and endorheic basins. Exhumed planation surfaces correspond to Gondwana paleosurfaces and are the result of deep chemical weathering and/or pedimentation processes, occurred in very stable tectonic environments and mostly under hypertropical climates, extremely wet, or seasonally changing (Rabassa et al. 2010, 2014). In the Somún Curá Massif, the exhumed planation surfaces are easily recognized by their rounded hills and include Permian to Jurassic volcanic and plutonic rocks (Fig. 4.8b). The processes responsible for landscape modeling are due to a combination of spheroidal, chemical, and physical weathering. Physical weathering is reinforced by the displacive effect of the aeolian influx and subsequent pedogenesis (e.g., calcretization; Bouza et al. 2017b) between expansion joints.

One of the most important features of the Somún Curá Massif is the presence of basaltic plains constituting the actual positive relief, so constituting a dominant plateau landscape. This plateau landscape is composed of mafic lava flows and smaller volumes of silicic volcanic rocks associated with large shield volcanoes of late Oligocene to Early Miocene age (Ardolino and Franchini 1993; Kay et al. 2007). The exogenous geomorphic processes dominant in basaltic plateaus are mass wasting (gravitational), mainly by rotational movement or slumping and rockfall (Fig. 4.8c, d).

4.7 Central Patagonian Tablelands

The Central Patagonian Tablelands defined in this section comprises the plateaus of the central region of Chubut and north of Santa Cruz, between Somún Curá and Deseado Massifs, and to the east of the Patagonian Broken Foreland (Fig. 4.2). The landscape of this geological province is composed of erosional and aggradational geomorphic surfaces (surfaces defined in space and time terms) and by basaltic plateaus.

The erosional geomorphic surfaces are represented by badlands and pediment associations developed on sedimentary rocks. A pediment 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) and a lower plain where active aggradation dominates (i.e., *bajadas* or coalescent alluvial fans; Dohrenwend and Parsons 2009). In the Central Patagonian Tablelands, the erosional landscape is developed on continental sedimentary rocks, mainly of the Chubut Group (Jurassic-Lower Cretaceous) in the central Chubut Province (Fig. 4.9a, b), and on continental and marine sedimentary rocks of the Paleogene and Neogene period (e.g., Sarmiento, Gaiman, and Puerto Madryn formations) eastward. The pediment associations are highly dissected and present several levels caused by local changes in base level (Bouza et al. 2017a, b).

The aggradational geomorphic surfaces include coarse sediments that build alluvial/fluvial fans/*bajadas* that connect the pediment to either playa lakes in endorheic basins or gravel/sand beaches in the Atlantic coastal zone. The great endorheic basins are characterized by a typical centripetal drainage network (Fig. 4.9c, d). The main great endorheic basins in Patagonia are the Gran Bajo de San Julián (−105 m a.s.l.) in Santa Cruz Province, Bajo del Gualicho (−72 m a.s.l.), Bajo de la Tierra Colorada (60 m a.s.l.), Salina Grande (−43 m a.s.l.), Salina Chica (−19 m a.s.l.), Gran Salitral (0 m a.s.l.), and Bajo del Diablo (38 m a.s.l.) in Chubut Province. There are many controversies about the geomorphologic processes that originated these landforms. Whereas wind erosion was proposed to explain the formation of the endorheic basins, for example, in the Península Valdés region (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). Although wind erosion could have been important, tectonic activity related to fault blocks probably triggered the formation of the great endorheic basins (Bouza et al. 2017b). This 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 which are straight and in many cases match with subsurface faults (see Kostadinof 1992), and (3) post-Miocene faults which were observed in the region (Haller et al. 2000; Haller 2017).

The aggradational geomorphic surfaces are represented by old fluvial and marine terraces of Neogene-Quaternary period. The fluvial terrace relicts correspond mainly to the informal geological unit named Rodados Patagónicos (Plio-Pleistocene; Fidalgo and Riggi 1970). The genesis of this unit is related to old pluviofluvial and glaciofluvial plains widely distributed in the region, formed during the Neogene-Quaternary glaciations and deposited in an arid periglacial environment (Mercer 1976). On the Atlantic coast, these plains are composed of several terrace levels that descend in steps from southwest to northeast, with altitudes from 750 m a.s.l. (Pampa del Castillo) to 90 m a.s.l. around Puerto Madryn (Fig. 4.9d). The youngest plains generally present a braided type of paleo-drainage that is highlighted by a shrub vegetation pattern. In the Peninsula Valdés the Rodados Patagónicos extend widely at 50 m a.s.l, whereas only some relict surfaces reach 90 m a.s.l. (Bouza 2012).

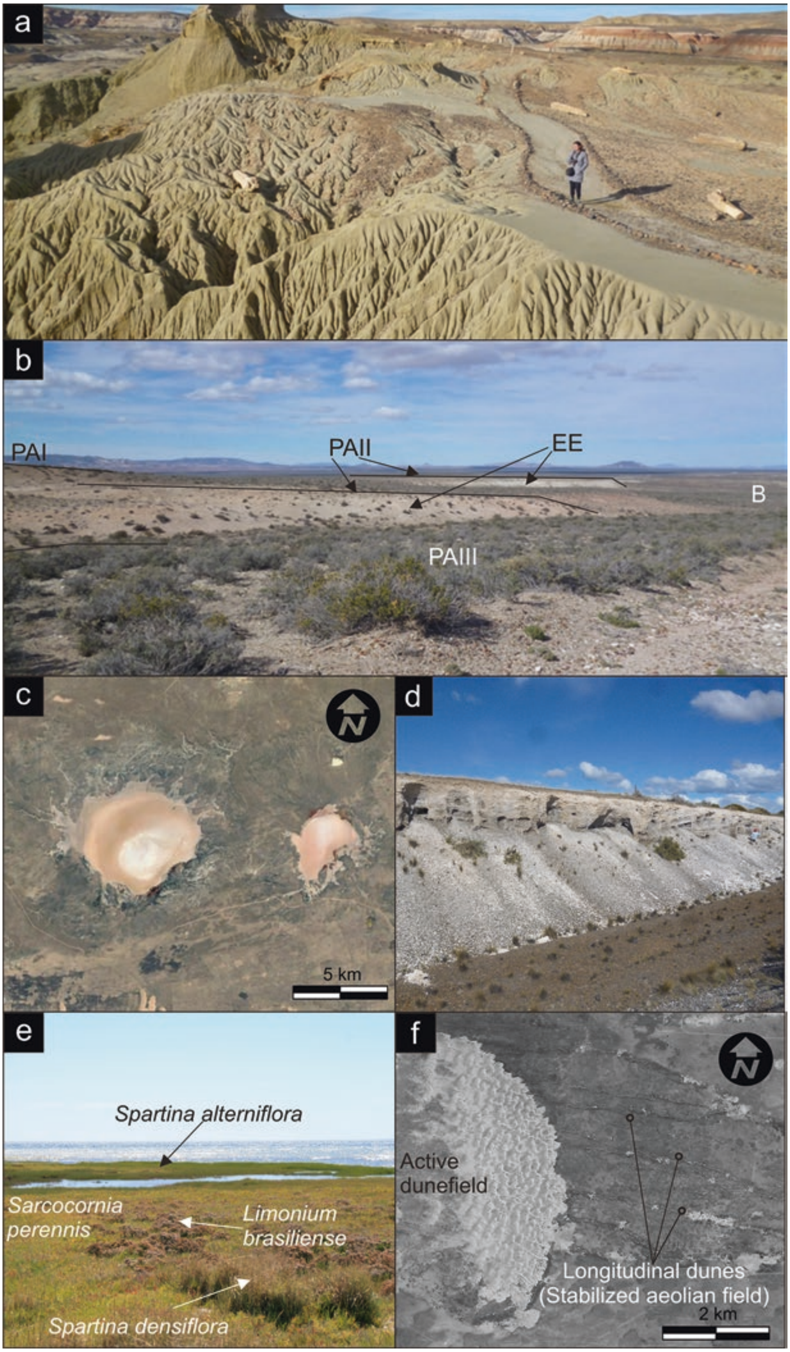

Fig. 4.9 Central Patagonian Tablelands; (**a**) Badlands, Sarmiento Petrified Forest; (**b**) pediment association levels (PA I-III); EE erosion scarp on sedimentary rocks (Chubut Group); bajada (B) (taken with modifications from Bouza et al. 2017b); (**c**) great endorheic basins in Península Valdés, centripetal drainage network; (**d**) detail of sedimentary structure of a Rodados Patagónicos terrace level; (**e**) *Sarcocornia* marsh, Fracasso beach, Golfo San José, Península Valdés; (**f**) stabilized aeolian fields and active dune field, Península Valdés

The current alluvial plains are present either linked to the allochthonous rivers (e.g., Chubut, Chico, and Deseado Rivers) or to ephemeral creeks, tributary streams, and bajadas of endorheic basins. Wetlands, locally named *mallines*, are located in restrained areas where the underground water discharge at the thalweg sectors of the channels.

Ancient marine terraces are distributed discontinuously along the Atlantic coast and were used to reconstruct changes in sea level that occurred during the Neogene-Quaternary through morpho-stratigraphic studies (Feruglio 1949–1950; Codignotto et al. 1992; Rostami et al. 2000; Pedoja et al. 2011). The malacological analysis of bivalves and gastropods housed in these deposits constituted the basis for the paleoclimatic reconstruction of the sea surface during the interglacial periods (Aguirre et al. 2008). Also, studies of paleosols developed on these terraces contributed to estimate the paleoenvironmental changes in continental environments (Schellmann and Radtke 2000; Bouza 2014).

The coastal landforms along the Atlantic shoreline in this sector are characterized by an alternation of headlands and bays, which due to the process of water wave diffraction erosion predominates on cliffs and wave-cut platforms and accretion on the beaches. The current accretional landforms are sandy and gravelly pocket beaches, formed between headlands of sedimentary rocks. Due to a combination of littoral drift and diffraction waves, accretional spits are formed (e.g., Caleta Valdés in Chubut). In sectors, the marine erosion is more prominent, reaching rectification of the coastline. Cliffs are developed on marine sedimentary rocks, mainly of Miocene age, when wave breakers impacted on the coast destabilizing the slope and promoting rockfall (mass wasting processes). This produces the cliff retreat and generates the wave-cut platform. On the other hand, when the Marifil Formation outcrops along shoreline, it is irregular due to resistance to marine erosion that offers these igneous rocks. The accretional landforms are sandy and gravelly pocket beaches, formed by wave diffraction between these outcrops of igneous rocks that emerged in the shoreline.

Spartina marshes are more common and larger in the northern part of Patagonia (latitudes lower than 42°S), while *Sarcocornia* marshes at latitudes higher than 42° S (Fig. 4.9e), and these two marsh physiognomies overlap between 42° S and 43° S (Bortolus et al. 2009).

The aeolian environment is noticeable mainly on the Atlantic coast landscape and in the southern sector of the Península Valdés, where two sub-geomorphology units are recognized: stabilized aeolian fields and active dune fields (Fig. 4.9f).

Stabilized aeolian fields have a well-developed vegetation cover of grasses (mainly *Sporobolus rigens*) and shrubs (principally *Hyalis argentea*). This unit stretches from the west to the east coast (i.e., from the Golfo Nuevo to the open Atlantic coast). In turn, the stabilized aeolian landforms are represented by a 0.4–2-m-thick sandy layer (Fig. 4.9f). In the aeolian field, the general orientation of the dunes is in agreement with the prevailing regional wind flow from the west-north-west. The sources of windblown sediment are the extensive sandy beaches located on the western coast of Golfo Nuevo, where a continued supply of loose, sand-sized sediment is available to be transported inland by the prevailing westerly winds. There is an eastward migration of the active dune fields to an average speed of 9.1 ± 2.7 m year^{-1} (annual rate 1969–2002; del Valle et al. 2008).

The basaltic plateaus (lava flows and volcanic necks) of Late Eocene to Pleistocene age extend east of the Patagonides and north of the Muster-Colihue Huapi lakes (Bruni et al. 2008).

4.8 Deseado Massif

The Deseado Massif has been considered as an ancient massif independent from the Somún Curá Massif already described (Fig. 4.2). It is a geological province located between the Deseado and the Chico Rivers in the Santa Cruz Province, characterized by its tectonic stability, for which it is considered a nesocraton, due to its stable and sub-positive relief during the Paleozoic (Ramos 1999).

The basement of the Deseado Massif is characterized by a sequence of metamorphic rocks of Upper Proterozoic-Lower Cambrian age. Granitoids and subvolcanic rocks of Silurian age intrude into these metamorphic rocks. Continental sequences of Permian and Triassic ages deposited on this basement were intruded by acid rocks of Upper Triassic-Lower Jurassic age.

These last intrusions correspond to a generalized extension linked to the opening of the Atlantic Ocean, followed by a clastic continental sequence, interdigitated with the rhyolitic volcanism of the Chon Aike Formation (Late to Middle Jurassic). These rhyolites and pyroclastic flows constitute an extensive plateau that in general constitutes, as the Somún Curá Massif, a wide exhumed planation surface.

The irregular coastal landforms along Atlantic shoreline in Deseado Massif have the same characteristics of coastal zone in Somún Curá Massif, with igneous rocks from Chon Aike Formation outcrop on the shoreline.

4.9 Southern Patagonian Tableland

The Southern Patagonian Tableland is located south of the Deseado Massif and east of the Southern Patagonian Andes (Fig. 4.2). The substratum of these plains is constituted by Mesozoic and Cenozoic deposits of the Austral-Magellan basin.

The northern sector of the plateau is formed by extensive alkaline basaltic casts of Miocene to late Pliocene (Camusú Aike Volcanic Field, tablelands on the north side of the Santa Cruz River valley, Meseta del Viento, Meseta de la Muerte, and Meseta Strobel); toward the south, the basalts form smaller plateaus and are replaced by large plateaus of Rodados Patagónicos (Miocene-Pleistocene age). These gravel terraces are dissected by wide valleys with glacial and fluvioglacial deposits.

At the central part of the Southern Patagonian Tableland is the Pali-Aike volcanic field (late Pliocene-Quaternary), where three postglacial volcanic cycles have been distinguished (Fig. 4.10). The oldest event originated *maars* while the last two episodes formed cones and lavas that cover most of the region (Skewes 1978). Based on archaeological and geomorphological evidence, it is presumed that the last volcanic event, which resulted in the formation of Cerro Diablo, occurred within the last 15 ka. The area covered by cones and lavas of Campo Pali-Aike exceeds 3000 km^2 across Chilean-Argentine border. The *maars*, originated by the first volcanic event, are formed by very violent volcanic explosions when the rising magma reacts violently with the water table (Fig. 4.10a). The intermediate volcanic episode gave rise to slag cones and lava flows that cover a large part of the Pali-Aike volcanic field and often appear covered by soils of aeolian origin (oldest lava flows). The most recent volcanic event originated the Cerro Diablo, which constitutes a pyroclastic cone. The lavas of the Cerro Diablo present few signs of erosion and soil development (Fig. 4.10b–d).

This geological province continues southward, beyond the Straits of Magellan, in the Extra-Andean region of Tierra del Fuego, with similar characteristics, although there are no basalt flows as in the Santa Cruz Province.

The dominant landform in the Extra-Andean region of Tierra del Fuego is composed of an erosion surface from marine sedimentary rocks of Paleogene to Neogene age (Fig. 4.10e). These surfaces were dissected and filled by morainic and fluvioglacial deposits, terraced fluvial deposits of Pleistocene epoch, and alluvial and colluvial deposits of Holocene epoch. A notable geomorphological feature in this region is the presence of numerous deflation hollows or pans (atmospheric dust sources), which become bodies of water or temporary lagoons of importance for migratory birds (Fig. 4.10f; Coronato et al. 2017).

The piedmont areas from the Southern Andes Cordillera were extensively glaciated, mainly by giant outlet glaciers coming from Patagonian Ice Sheets (Rabassa et al. 2011; Fig. 4.3). Andean lakes, U-shaped valleys, and marine channels (e.g., Estrecho de Magallanes and Canal de Beagle) evidence the advance of paleo-ice lobes. In addition to glacial moraines, other types of glacial drift deposits are named drumlins. These are located next to the Estancia Harberton (Harberton drumlin field) and were formed in the direction of the paleo-Beagle glacier flow. These landforms are elongate and streamlined hills composed largely of glacial deposits.

4.10 Islas Malvinas Plateau (Plateau de Las Islas Malvinas)

This region was described in the pioneering work of Darwin (1846), Thomson (1877), and Halle (1912). The Islas Malvinas are two islands, Isla Gran Malvina and Isla Soledad, located within the Argentine continental platform in the Malvinas Plateau, 500 km east of the Patagonian coast (Fig. 4.2). The geology of the area is dominated by outcrops of Paleozoic age intruded by Jurassic dykes that are partially

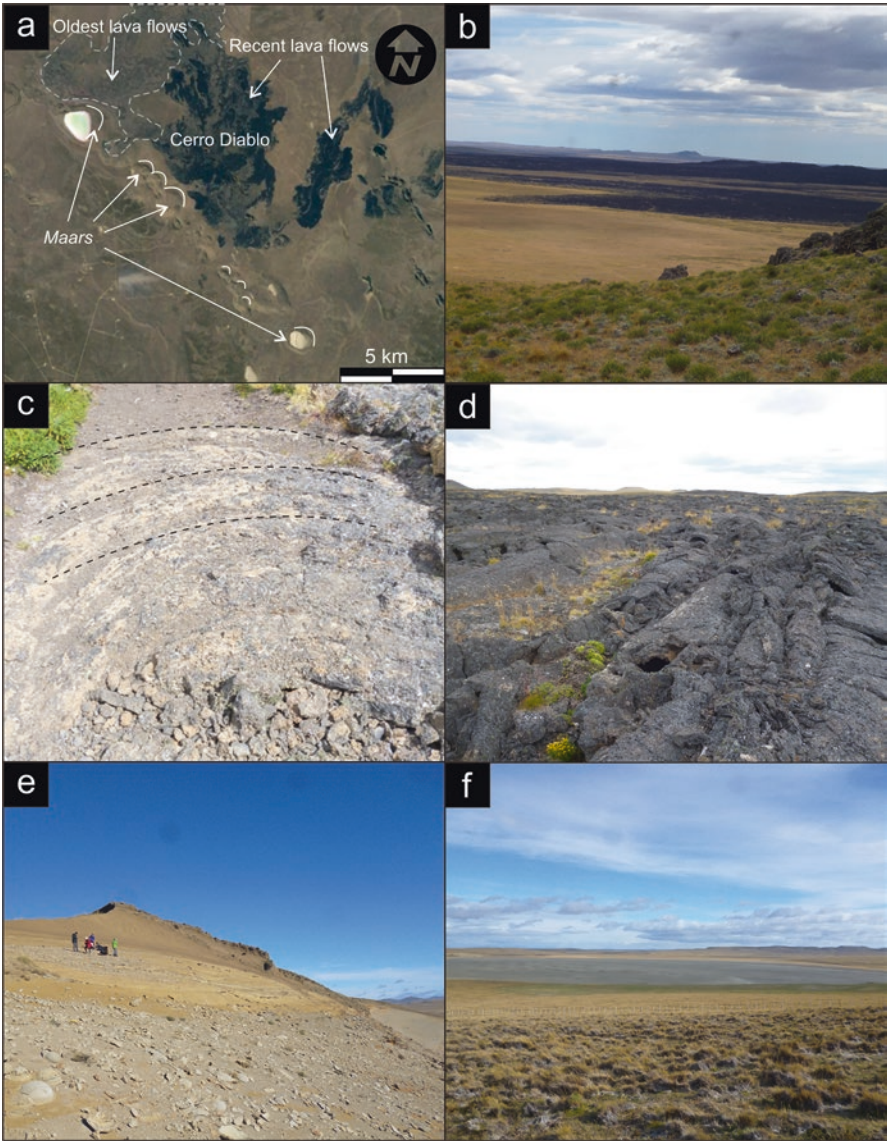

Fig. 4.10 Southern Patagonian Tableland, (**a**) Pali-Aike volcanic field, (**b**) lavas of the Cerro Diablo, (**c**) corded lavas or pahoehoe type, (**d**) structures of lava tunnels, (**e**) erosional landscape on marine sedimentary rocks of Paleogene and Neogene period in Tierra del Fuego, (**f**) deflation hollows or pans

or completely covered by Quaternary deposits. This region is part of a Gondwana paleosurface, conforming a landscape dominated by rounded hills (Fig. 4.11a–c). The Quaternary deposits include the amazing deposits of the classic stone runs (Fig. 4.10a, d), marine clays and sands, windblown sand, alluvium, and an extensive

Fig. 4.11 Malvinas Plateau (Plateau de Las Islas Malvinas); (**a**–**c**) landscape characterized by rounded hills; (**d**) stone runs (Malvinas photographs courtesy of Dr. Fernando Coronato)

cover of blanket peat (Stone 1999). In the highest ground, a few small cirque glaciers exist (Clapperton and Sugden 1976), but for the most part the conditions were of deep-frozen tundra indicating that the islands never experienced any substantial ice cover. The "stone runs" (Fig. 4.11d) are peculiar stone rivers developed on such a large scale that their extensions can only really be appreciated from the air (Stone 1999). Their origin is controversial, while some agree that their formation is related to periglacial activity (Bellosi and Jalfin 1984; Rosenbaum 1996; Hansom et al. 2008), others consider a complex polygenetic origin associated with subtropical weathering (André et al. 2008).

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