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Volcanic Landscapes and Associated Wetlands of Lowland Patagonia

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Editors
Elizabeth Mazzoni
Unidad Académica Río Gallegos
Universidad Nacional de la Patagonia Austral (UARG – UNPA)
Río Gallegos
Argentina

Jorge Rabassa
Laboratorio de Geomorfología
CADIC-CONICET and Universidad Nacional de Tierra del Fuego
Ushuaia
Argentina

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Contents

Chapter 1
Introduction: Patagonia Basalt Tablelands ("Escoriales") and Their Significance in the Genesis of Wetlands

Elizabeth Mazzoni and Jorge Rabassa

Abstract This chapter presents the problems discussed in this book and the methodology used for their study, based upon a wide use of remote sensing techniques. The spatial relationships established between the two major and typical elements of the Patagonian landscapes, the basaltic plateaus and the wet meadows, known in this region as "escoriales" and "mallines", respectively, are analyzed. The characteristics of both landscape components are described and a classification system is proposed, based upon a six-digit system which synthetizes the geological, geomorphological, and hydrological characteristics of each "escorial". The full structure of the book, organized in 10 chapters, is herein presented.

Keywords Patagonia · Cenozoic volcanic landscapes · Volcanic tablelands "Escoriales" · Wetlands · Wet meadows · "Mallines"

1.1 Introduction

Patagonia is the southernmost region of the South American continent, with an approximate surface of 1,000,000 km^2. It comprises two large natural regions (Coronato et al. 2008): "Andean Patagonia", composed of large mountain ridges, included in the Andean Ranges, a result of intense plutonic and volcanic activity and of tectonic folding and faulting that took place mostly during the Late Tertiary, which extends along the western side from latitude 39° S until the southernmost end of the continent in the archipelago of Tierra del Fuego, at 56° S latitude, with

E. Mazzoni (✉)
Unidad Académica Río Gallegos, Universidad Nacional de la Patagonia Austral (UARG – UNPA), Río Gallegos, Argentina
e-mail: elimazzoni@yahoo.com.ar

J. Rabassa
Laboratorio de Geomorfología, CADIC-CONICET and Universidad Nacional de Tierra del Fuego, Ushuaia, Argentina
e-mail: jrabassa@gmail.com

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conditions of humid-cool climate and dense vegetation, mostly covered by the *Nothofagus* Patagonian forest, and "Lowland Patagonia", extending over most of the region east from the Andean ranges, with a tableland relief, forming numerous landscape steps from the Andean piedmont to the Atlantic Ocean coast, with a variable width from N to S, roughly between 600 and 200 km. This is the result of the sedimentary and volcanic in-filling of tectonic blocks of the ancient basement, which occurred between the Early Mesozoic and the Cenozoic. This large area, that represents more than 60% of the total region, has arid to semiarid climate conditions, and a plant cover related to open shrubby and grassy steppes (Figs. 1.1 and 1.2).

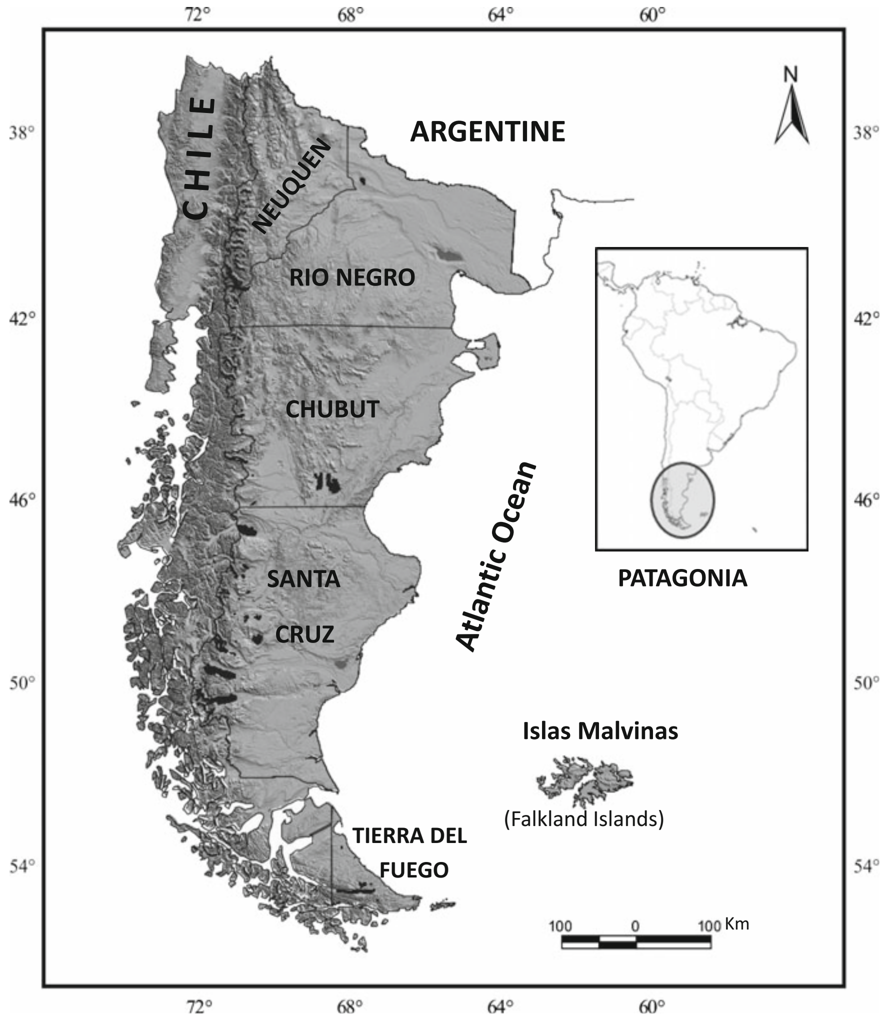


Fig. 1.1 Localization of the Patagonian region and the administrative districts which are forming it ("provincias")

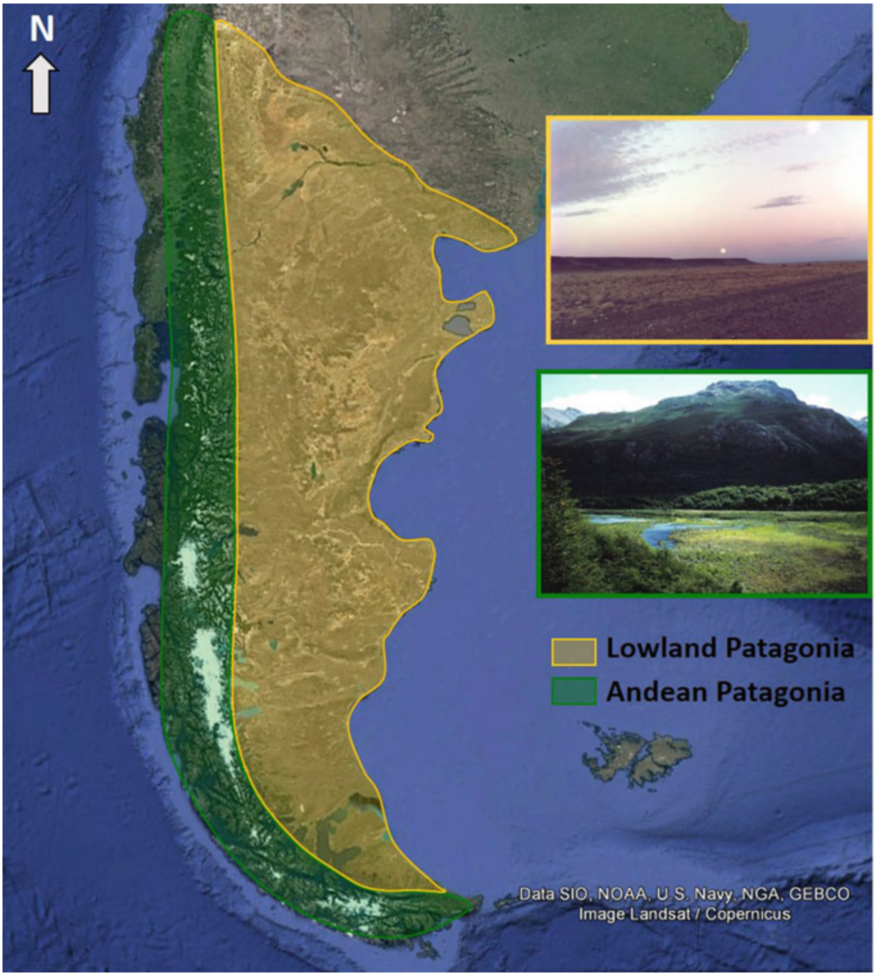


Fig. 1.2 Natural Patagonian environments: to the left, Andean Patagonia, with mountain relief modeled by fluvial and glacial action and wet climate that allows a dense forest cover. To the right, the "meseta" environment may be observed, with almost horizontal relief covered by shrubby and grassy steppes

In these environments, water availability appears as one of the natural limiting factors acting upon the distribution of living beings. It has also conditioned the aboriginal and European peopling processes and the development of economic activities based upon the use of the available renewable natural resources. Along the ample sectors where permanent regime streams are absent, the population settlement has always depended upon the availability of underground water of good quality.

Many aquifers are associated to a peculiar feature of the Patagonian relief: the volcanic tablelands or "mesetas", also known as "escoriales", due to the frequent presence of volcanic scoria layers which, due to their lithological, topographic and geomorphological features, act as water reservoirs. The genesis of these landforms is related to volcanic eruptions of the fissure type, which emitted basaltic lava flows during different eruptive periods mostly during the Middle and Late Tertiary times. According to its age, the morphology of the lava mantles has been modified by different erosion processes. The oldest lava flows are now at higher elevations than the younger ones, a few hundreds of meters, due to "relief inversion" processes. This circumstance provides them particular hydrological dynamics that allow them to intercept the scarce precipitation available in the region, providing reliable water resources for the neighboring lowlands, supplied from springs or sources that are localized along their slopes, in the contact zone between the basaltic mantle and the underlying rocks (Figs. 1.3 and 1.4).

The extra supply of water in the system of the Patagonian tablelands favors the development of wet grasslands, commonly known as "vegas" or "mallines" (Boelcke 1957; Cabrera 1976; Movia 1984; Roig 1998; among others). These are

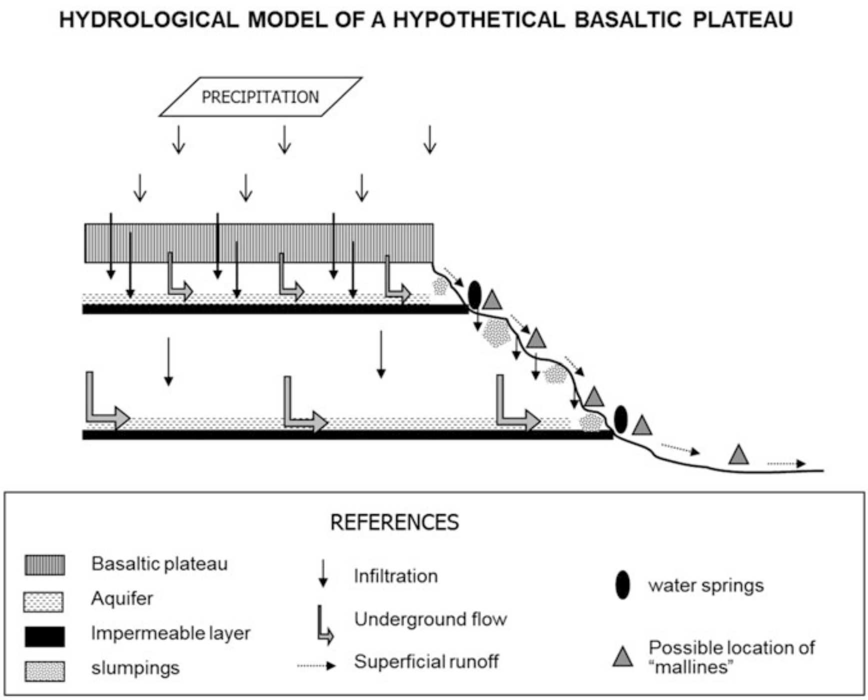


Fig. 1.3 Hydro-geomorphological model of a hypothetical basaltic plateau area (basaltic "meseta"), where the localization of the "mallin" ecosystems may be observed. *Source* E. Mazzoni (2007)

Fig. 1.4 Water springs at the locality "Piedras Meonas" (37°03′S–70°46′W), Northern Province of Neuquén. *Photographs* E. Mazzoni

ecosystems composed of rushes and hydrophyte grasses, with high plant cover, which impact positively in the region, becoming places of water supply and food for the rural population, wildlife, sheep, and cattle. For its particular characteristics, in contrast with the xerophyte vegetation of the surroundings, they comprise a natural resource of extreme high economic, ecological, and scenic value (Fig. 1.5), but of significant fragility if inadequate management practices are applied (Bonvissuto et al. 1992; Del Valle 1993; Raffaele 1999; Mazzoni 2007; Mazzoni and Vázquez 2009; Mazzoni and Rabassa 2013).

This book analyzes the spatial relationships that have been established between the diverse basaltic tablelands and the wet meadows along the various extra-Cordilleran environments of Patagonia. For this purpose, the distribution of "escoriales" or volcanic tablelands throughout the regional space is studied (Chap. 2) and their peculiar geomorphological and morphometric characteristics are considered (Chaps. 3 and 4) after proposing a classification system which is presented in this chapter. Based upon the analyzed case studies, an evolutionary model of the Patagonian volcanic landscapes is proposed, with images that illustrate the different evolution stages (Chap. 5). In the following chapters, this book is focused on the study of "mallines" or Patagonian wet meadows. Chapter 6 exposes the remote sensing techniques that were used for the identification of these ecosystems in the extra-Andean Patagonian environment. Chapters 7 and 8 analyze the aspects related to the spatial distribution of wet meadows on the slopes of the basaltic plateaus as well as their morphometry and typology. Chapter 9 examines the hydro-eco-geomorphological aspects of these wetlands and analyzes their internal variability from a case study. Finally, Chap. 10 explains the importance of volcanic

Fig. 1.5 View of a "mallín" (wet meadows) emplaced in the Patagonian "meseta" environment. Their characteristic green are contrasting with the zonal biome seen in the foreground. The photograph corresponds to the volcanic field located W of the town of Zapala, in the province of Neuquén (38°52′S–70°27′W). *Photographs* E. Mazzoni

landscapes and their associated "mallines" in the Patagonian region, as well as aspects related to the state of conservation and degradation of these wetlands.

The mechanism of water interception in the basaltic tablelands of Patagonia has been frequently cited and described in numerous previous works. Perhaps the first time this happened was in the work of Charles Darwin, who visited Patagonia between 1833 and 1834. In his book "*A Naturalist's Voyage Round the World*", he indicated that "along the line in which the igneous and sedimentary formations merge, several small springs occur, an uncommon fact in Patagonia, which may be distinguished, even from long distances, for the presence of small patches of intense green" (Darwin 1997).

In the reports of the Geological Sheets prepared by the Servicio Geológico Minero Argentino (the Argentine Geological and Mining Survey; SEGEMAR) for those areas with volcanic materials, reference has been made explicitly to the very high secondary permeability of the basalt flows and their reservoir function. Among others, the works of Feruglio (1949), Suero (1951), Galli (1969), Leanza and Leanza (1970), Turner (1976), Panza et al. (2005) and Cobos et al. (2009) are relevant sources for the area. Similar comments appeared in the explicative text of the Hydrogeological Map of Argentina (1963) and in the publications reported in the geological congresses, when they had taken place in any of the Patagonian provinces (Rolleri 1978; Ramos 1984; Haller 2002; Leanza et al. 2011).

Analogue references exist also in the classical publications of a geographical nature, such as the "La Suma de Geografía" (Difrieri 1958, Fig. 1.6), "El país de los Argentinos" (Chiozza 1974) and the "Atlas Total de la República Argentina" (Chiozza and Figueira 1981). Likewise, Reboratti (1982) exposed the importance of the outcropping of underground water in the process of occupation of the regional space.

In papers developed as a by-product of consulting studies, such as those related to hydroelectrical dams or regional development projects, this hydrological behavior of the volcanic tablelands has been cited; see, for instance, Romero (1975) and Rabassa (1978). These authors have also made explicit reference to the mechanisms of water interception in the "escoriales" (see also, Rabassa 1974).

The study in a greater detail was steered by Hernández (2000) in his work about the Geohydrology of the Cerro Rubio-Cerro Vanguardia, where it was suggested that the intervening factors in the role of the volcanic tablelands as water reservoirs are the following: (a) the net water volume supplied to the plateau, which is the product of the surface of the volcanic fields times the water recharge (net vertical supply); and (b) the morphology of the lava body. In this latter aspect, Hernández (2000) concluded that the semicircular shape of the plateaux favors the concentration of the phreatic runoff and thus, the occurrence of water springs. The dipping of the beds that underlie the volcanic flow is also essential information. If both factors are coincident, the occurrence of the discharge is explained through the presence of these springs (Hernández 2000).

With relation to the study of the Patagonian "mallines", although traditionally their importance as highly productive ecosystems has been stated, only in the last years research activities pointing to learn diverse aspects related to their spatial distribution, physiographic and ecological features, management criteria, etc., have been developed mostly by institutions involved in problems of regional development, such as the Instituto Nacional de Tecnología Agropecuaria (Argentine Institute of Agricultural Technology, INTA). In general, since these are azonal ecosystems, of small surficial extent and irregular spatial distribution, they have not been described in detail in general studies about soils and/or vegetation of the Extra-Andean Cordillera. Notwithstanding, some of their characteristics have been cited and described by Soriano (1956), Boelcke (1957), Boelcke et al. (1985) and Roig (1998), among others. In several articles about the Patagonian vegetation, Movia (1984) and Movia et al. (1982, 1987) noted the existence of "mallines" and provided bases for their classification, considering their physiographic aspects and their position in the landscape. The delimitation of homogeneous units within the larger "mallines" appeared in the work of Speck et al. (1982), on physiographic systems along the southern portion of the Province of Río Negro, which was published by INTA. The criteria applied by both cited authors provide significant methodological advances about the study of these ecosystems and they are used here for the analysis of the spatial variability and the heterogenic physiographic conditions of these wetlands.

Highly focused thematic studies have been done in some "mallines", especially those located in glacial and fluvial environments, since these are those with larger

Fig. 1.6 Basaltic outcrops of Patagonia. Modified from Difrieri (1958)

surface extent. Among them, the studies by Laya (1969), Marcolín (1973, 1975), Lanciotti (1980, 1983), Lanciotti et al. (1998), Gandullo and Schmid (2001), San Martino (2003), Utrilla et al. (2005), Horne (2010), Gaitán et al. (2011), Gandullo et al. (2011), Enriquez et al. (2014, 2015), etc., should be mentioned. These authors studied aspects related with their edaphic and vegetational, fertility, and productivity. The smaller wetlands associated to the volcanic environments have not been studied in depth, with the exception of the work of Mazzoni (1983, 2007) whose results have been exposed in several articles (Mazzoni 1987a, 1987b, 2002, 2005, 2008; Mazzoni and Rabassa 2010, 2013).

In spite of the great regional significance that the "mallines" ecosystems have, the total surface that they occupy in Patagonia and their spatial distribution is only partially known. This is due to the fact that, in general, they are rather small and heterogeneously distributed in diverse geomorphological environments.

Some estimations provide values ranging between 1 and 4% for the volcanic tableland environments and between 4 and 7% for the Andean mountain range environment (Iriondo 1989; Bran 2004; Mazzoni and Vázquez 2004). Bran (2004) stated that the total "mallín" area would be about 1,000,000 and 2,000,000 hectares, depending upon if "mallines" are considered in a strict sense, i.e., including those which are presently dry and/or degraded. For western Neuquén province (Northwestern Patagonia), Ferrer and Mazzoni (2014) prepared a detailed inventory at a 1:100,000 scale, identifying a total of 6539 "mallines", which covered 155,885 ha, equivalent to the 3.68% of the surveyed surface. Its localization depends upon local factors that favor the water retaining in the soil, as it has been already stated. In this sense, the appropriate environments for their genesis are the glacial plains, the alluvial plains, and the slopes of the volcanic tablelands. This last environment is analyzed in this work, using case studies of two Patagonian provinces, Neuquén and Santa Cruz, located in the northern and southern portions of Patagonia, respectively (Fig. 1.1).

1.2 Meaning of the Terms "Escorial" and "Mallín"

The terms "escorial" and "mallín" are frequently used by the Patagonia inhabitants, mostly the rural dwellers, and they have been incorporated regularly to the scientific literature. In this paragraph, the meaning and characteristics for both landscape elements are specified, considering that they form the central axis of the present contribution.

1.2.1 "Escorial"

This term refers to the group of volcanic landforms mainly composed of basic lavas, mostly basalts, which comprise volcanic fields of rugged texture, which makes it very difficult to walk on them. They may take the shape of plains, "mesetas" and/or cones (Figs. 1.7 and 1.8).

This texture is generated in the cooling process of these lavas, characterized by their low silica content, low viscosity, and low gas content, which favor the high fluidal nature and slow-down of the cooling process (Tarbuck and Lutgens 1999). Consequently, the consolidation of the lava flow takes place first along the surface and then, slowly, in its interior. The inner flux does not continue while the superficial layer becomes solidified, generating superficial tensions that end with the deformation and/or break up of the lava flow. Frequently, tensional stress generates columnar jointing within the lava flow (Fig. 1.9), whereas in the surface these volcanic fields show very irregular and rugose substrate, which are known as "escoriales" in the Extra-Cordilleran Patagonian environment.

According to the factors that control the consolidation of the lava flow (chemical composition, substratum slope, flow velocity, atmospheric conditions, etc.), sheet flows can exhibit a variety of surface textures, such as "pahoehoe" lavas, or "aa" lavas, in the Hawaiian denomination (Harrington 1944). The first ones present a surface of smooth and glassy aspect with structures similar to ropes. The second ones exhibit a rugged, irregular surface, with blocks of decimeter or metric size, shapeless, and with angular sides. If these blocks are larger than a meter, they are named as "block lavas". There are also a variety of textures in between these extreme ends, such as lobate, linear, and jumbled textures. In subaqueous environments, "pillow lavas" are generated. Other frequent surficial features are tunnels and "hornitos". The first ones allow the flux of lavas over large distances, whereas the second ones are small

Fig. 1.7 Detail of an "escorial" formed by very young basaltic lavas, which still preserve their original textures. At the background, aligned volcanoes. These outcrops are part of a volcanic field located in the southernmost end of Patagonia, province of Santa Cruz (52°03′S–69°35′W). *Photographs* E. Mazzoni

Fig. 1.8 A volcanic plateau near the town of Gobernador Gregores in Santa Cruz province (48° 41′S–70°33′W). At the foreground, in greenish tones, a small "mallín" appears, which is being used for cattle and sheep pastures. At the intermediate plane, the irregular morphology of the "escorial" slopes may be observed, with a local relief of 340 m. *Photographs* E. Mazzoni

cones of welded scoria, of a few meters of local relief, formed by explosive events within a lava flow due to the release of gases contained in it (Fig. 1.10). Shallow supra-basaltic depressions appear commonly as well, which are originated when the consolidated material falls into the interior of the still viscose lava (Fig. 1.11).

1.2.2 "Mallín"

This term refers to "prairies and very dense and green grasses directly associated to water presence within or nearby the soil surface" (Movia 1984). "Mallín" or "malliñ" is a Mapuche term whose meaning refers to a grassy and herby soil located in the mountain slopes or in the flatter areas, with the presence of surficial or underground water. This term includes the typical herbs that grow within these wetlands (Vuletín 1979). This author indicated that these features are dangerous for the transit circulation, since they are a sort of flooded soils. The Spanish-Mapuche dictionary, published under the direction of E. Wilhelm de Moesbach (1980) provides this term with the meaning of "watery swamps, wet depressions and mountain range meadows".

A term with similar meaning is the word of Spanish origin: "vega". The city of Las Vegas, in Nevada, U.S.A., was named following this concept, the presence of wetlands amidst the desert. In the Patagonian tablelands, both terms are referred, according to Reboratti (1982) to "very localized areas, with different moisture and vegetation characteristics due to the presence of smaller streams, generally surging". In the Andean zone, the term "mallines" is given to the wetlands located in flat

◂**Fig. 1.9** Columnar jointing in basalts. These columns are produced by the contraction and fracture resulting from the cooling of a lava flow. In decreasing order, the photos show basalt flows located in the surroundings of Lago Moquehue (Neuquén, 38°55′S–71°23′W); to lava flows nearby the site of Varvarco (Neuquén, 36°50′S–70°45′W) and to a volcanic neck which is localized in the surroundings of the town of Gobernador Gregores (Santa Cruz province, 49°04′S–70°07′W). *Photographs* E. Mazzoni

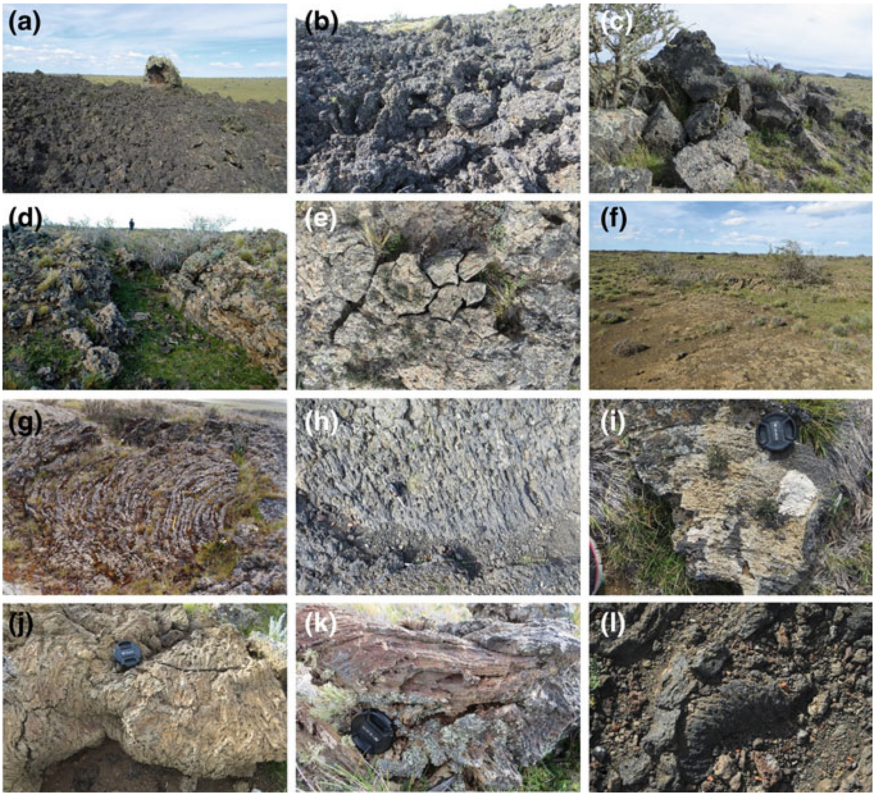


Fig. 1.10 Superficial textures in the “escoriales”. The photographs show diverse features and surficial textures of basaltic flows seen in the Pali Aike Volcanic Field of Santa Cruz province (52°00′S–69°40′W). **a**, **b** and **c** show lavas of the “aa” type, with various block sizes. The larger ones are bigger than 1 m. In A, a “hornito” is also seen, a structure formed by explosion of the gas bubbles inside the lava flow. Its height is close to 2 m. In **d**, a lava flow channel is observed, whose roof has collapsed. **e** shows the columnar jointing of the volcanic rocks. **f**–**l** illustrate about the smoother surface of the “pahoehoe” lavas and their different structures. In **g**, the “rope pattern” is clearly appreciated. *Photographs* **a**, **b**, **c**, **e**, **f**, **g**, **h**, **i**, **j** and **k**: E. Mazzoni. *Photographs* **d** and **l**: M. E. Palacios

Fig. 1.11 Supra-basaltic depressions in the Piedra del Águila plateau, Neuquén (39°58′S and 70° 09′W). *Photograph* E. Mazzoni

reliefs, particularly the bottom of the valleys, whereas the term “vega” is reserved for the dipping areas. In both cases, reference is made to the availability of water and the herbal and prairies vegetation that provides the “mallín” a wet grassland character, recognized for having, at least partially, badly drained soils and hydrophilic vegetation. In fact, the common name of “pasto mallín” applies to some species of rushes (*Juncus balticus* and *J. lesueurii*), very frequent in these ecosystems, particularly the first one (Figs. 1.12 and 1.13).

“Mallines” comprise a particular type of “wetland”, taking into consideration the definition of the term prepared by the “Convention related to wetlands of international significance”, as signed in the city of Ramsar, Iran, in 1971: “These are extensions of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters” (Ramsar Convention 1971).

These areas correspond, consequently, to sites in which water is the primary factor that controls the environment as well as the plant and animal life associated with it. They occur where the layer of water is located at or near the ground surface or where the ground is covered by shallow waters (Cintrón-Molero and Schaeffer-Novelli 2004). Its presence is determined by the geomorphological emplacement (Brinson and Malvárez 2002).

Cowardin et al. (1979) and Mitsch and Gosselink (2000) defined wetland as the ecosystem that fulfills the following conditions: (a) periodic presence of shallow waters or wet soils, (b) hydromorphic soils that are different from the soils of

Fig. 1.12 Panoramic views of wet meadows, "mallines", localized in the volcanic environments. It may be observed that in most cases, they have become settlement places for rural dwellers. The location of the rural dwellers is inferred by the presence of trees, which act as windbreakers. Many "mallines" occur as if they were "hanging" along the slopes, associated to the position of the water springs and they continue downslope following small drainage lines. In descending order, the examples correspond to the "escorial" of Piedra del Águila (40°03′S–70°06′W) and to the La Rinconada site (39°58′S–70°48′W), both in the province of Neuquén, and the Bella Vista plateau (51°51′S–70°31′W) in Santa Cruz province. *Photographs* E. Mazzoni

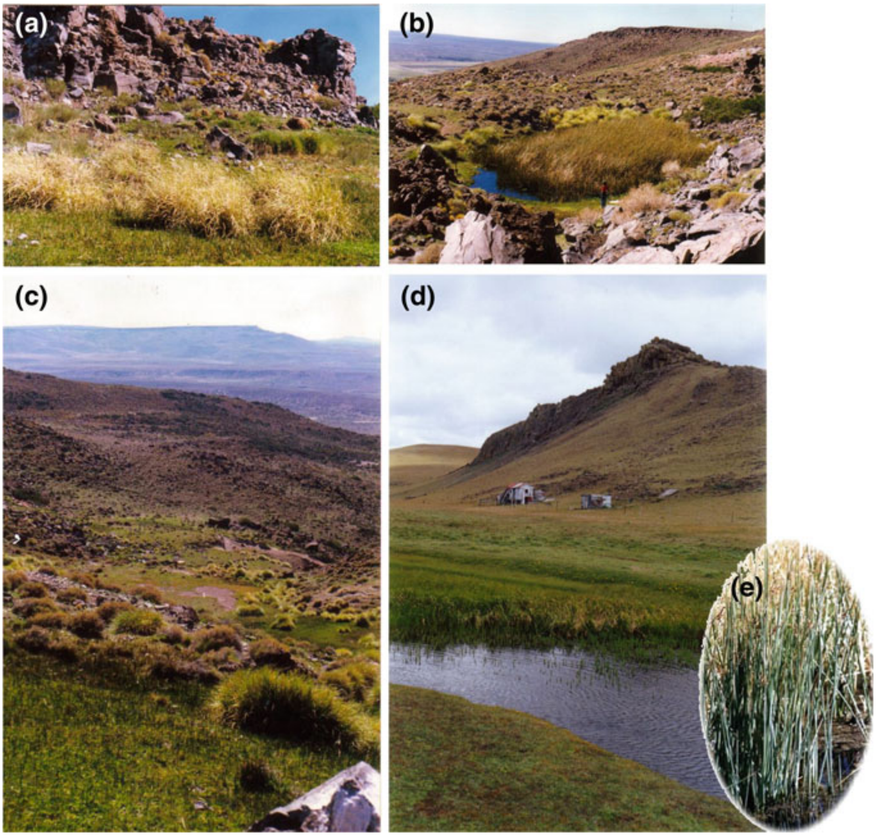


Fig. 1.13 The "mallines" possess a varied physiognomy, as well as high heterogeneity of their internal characteristics, basically depending upon their water supply and their dynamics and landscape position. This group of photographs illustrates about these conditions. **a** shows a "mallín" located at the foot of the basaltic scarp, with grasses and herbs of different height; **b** shows a lake system, with large size rushes; **c** illustrates about a "mallín" developed along the slope and **d** does so about another one located in the lower part of the slope, following a drainage line. **a**, **b**, and **c** are situated in the Piedra del Águila "escorial", Neuquén, and **d** is so in the Pali Aike volcanic field, province of Santa Cruz. **e** shows a detail of one of the species characteristic of these wetlands, *Juncus balticus*, popularly known as "pasto mallín". *Photographs* E. Mazzoni

surrounding sectors, and whose biochemical features are influenced by the anaerobic conditions of flooded soils, and (c) presence of plant species adapted to direct contact with water (hydrophytes). The "mallín" ecosystems also fulfill these conditions.

Among the more outstanding characteristics of these landforms, Brinson (2004a) emphasizes the fact that, in wetlands, "patterns and processes are more variable than in terrestrial ecosystems". Accordingly, the range of variation in wetland habitats is greater than that in terrestrial habitats situated in the same geographical region.

Another important factor is that they may occur in different biomes with similar patterns (Brinson 2004a).

Wetlands may be classified according to the origin of the hydrological source and the destination of the water. From this hydrological point of view, three categories are distinguished (Brinson 1993, 2004b):

- Wetland that receives water only from precipitation and it gives it up downstream or to underground water.
- Wetland that receives mostly discharge water from the subsoil and loses water by superficial flow.
- Wetland that is dominated by the superficial flow and it is frequently able to move sediments due to the high water kinetic energy.

"Mallines" whose genesis is related to the presence of volcanic tablelands or "escoriales" are included in this second category.

1.3 Methodological Aspects

With the purpose of knowing in detail the geomorphological characteristics and quantifying the importance of the basaltic "escoriales" in the "mallín" genesis, two work areas were selected, respectively located in northern and southern Patagonia: the provinces of Neuquén and Santa Cruz, which both have a combined area of almost 350,000 km^2, that is, roughly the size of Great Britain. Notwithstanding, the Cenozoic basaltic expressions are distributed throughout the entire Patagonian region, with the only exception of the archipelago of Tierra del Fuego, where they are not represented.

The survey of the "escoriales" in both provinces was done on the basis of detailed visual interpretation of satellite images Landsat 5 and 7 (sensors TM and ETM+) in digital format, geo-referred to the coordinate system Transverse Mercator, ellipsoidal reference and datum WGS84. Each image was individually processed with the aim of improving its visual quality and integrated into a GIS Framework in which each "escorial" was digitalized and a set of obtained data was organized for each of them. In those cases in which the boundaries of the lava flows were of difficult identification (transitional margins between the lava flow and its surroundings), various techniques were applied with the objective of enhancing the photographic texture of the image and filters to highlight the margins (Figs. 1.14 and 1.15). Due to the spatial resolution of the available imagery and the objectives of the present work, only the "escoriales" with a surface equal or larger than 1 km^2 were considered.

As each lava sheet was digitalized at the screen (Fig. 1.16), data tables associated to each polygon were simultaneously created (Table 1.1), with the following information:

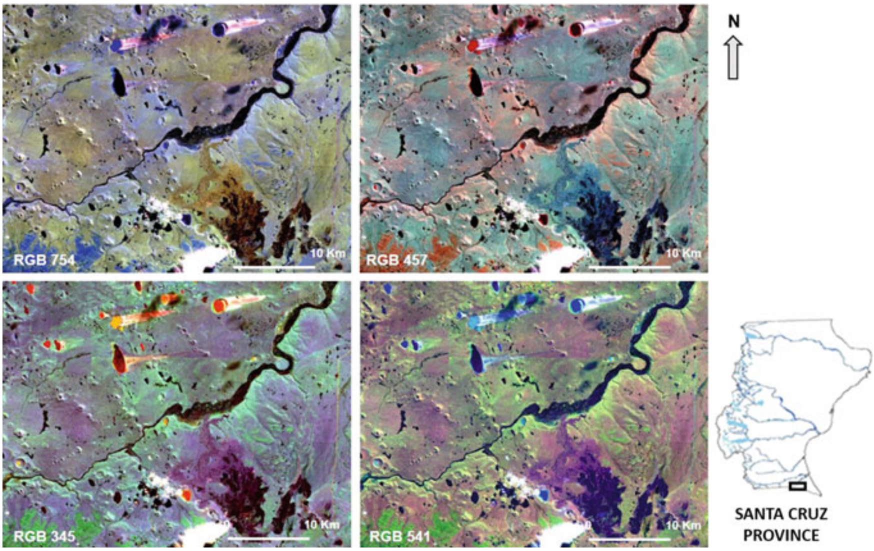


Fig. 1.14 Examples of different combinations of bands used for the identification and digitalization of the "escoriales" in the screen. A portion of the Pali Aike Volcanic Field may be observed in the image, in southern Santa Cruz province (51º59′S–69º48′W). In the lower right sector of the image, a Holocene lava flow occurs in dark tones. Other, older lava flows are shown in several places of the image

1. Geographical location (coordinates of the center of the polygon);
2. Location according to the corresponding climatic belt (precipitation);
3. Surface of the "escorial";
4. Altitudinal position (maximum elevation, mean elevation of the margin of the flow and mean relief with the extra-basaltic environment);
5. Age of the basalt;
6. Geomorphological features at the margins and surface of the flow;
7. Presence of "mallines" along the margins of the "escorial".

The geographical position and the surface of each "escorial" are obtained automatically when each polygon is digitalized. The climatic information was obtained from the statistics published by the Servicio Meteorológico Nacional (Meteorological Survey of Argentina) and the NOAA network (www.ncdc.noaa.gov/pub/data/). The topographic data were extracted from the topographic maps at 1:100,000 scale, published by the Instituto Geográfico Militar (Militar Geographic Institute: presently National Geographical Institute, IGN). The geological information was taken from maps and charts elaborated by the Servicio Nacional Minero Geológico (SEGEMAR; the Geological and Mining National Survey of Argentina). The geomorphological information for each "escorial" and the data about

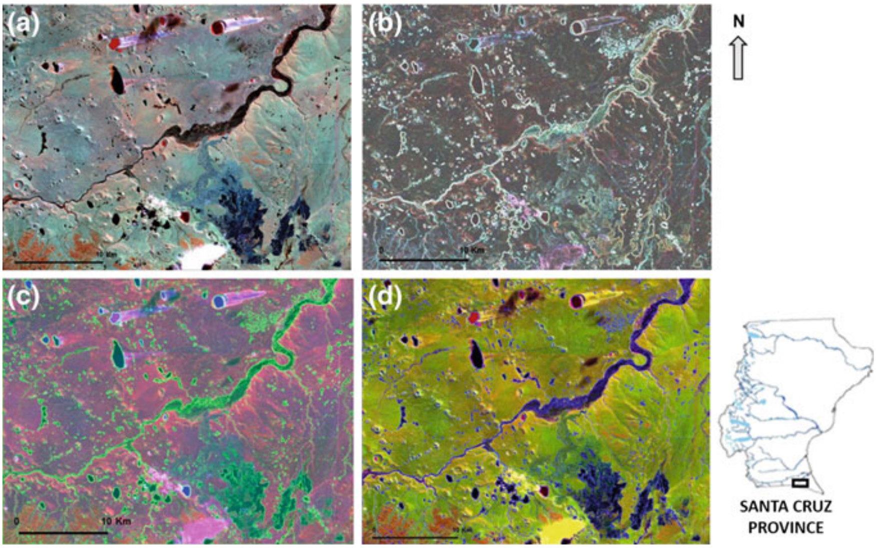


Fig. 1.15 Examples of different techniques applied to highlight the textures and edges in a Landsat 7 image: **a**. Results of the application of a spectral filter of high pass (3×3 matrix) which highlights the textures of the image and provides better definition; **b**. Bands 4,5,7 in which spatial enhancement techniques were applied (TEXTURE command, 3×3 matrix, software Erdas Imagine). Note that the edges of the different landscape forms are "drawn"; **c**. Combination of two original bands with a band processed with the TEXTURE command (RGB 4, 5 textured and 1). This type of combinations allows to highlight the margins without losing information of the inner part of each cover. **d**. Results of the application of the two previous techniques (spectral and spatial enhancement) on the image. The final coloration obtained in each case is the result of the used bands and the order in which these bands are displayed in the RGB visualization system. In this case, a 3×3 edge enhancement filter was applied on the image composed by the 4, 5 and 5 textured bands

availability of "mallines" was obtained from the visual interpretation of the satellite images.

With the data presented in the items 3, 5, 6, and 7, a classification of "escoriales" was prepared, composed of six digits that synthetizes, for each of them, their principal geological, geomorphological, and hydrological characteristics, this latter aspect is evaluated from the presence of "mallines" nearby the "escorial" (Table 1.2).

All the data was statistically analyzed so as to describe the behavior of each variable and their relationship with the others. Descriptive techniques were applied together with a test of adjustment of the distributions to theoretical models and the analysis of correlation.

The results allowed to characterize to the set of "escoriales" present in each provincial space, information that is presented in Chap. 4.

In addition to the information obtained for all the basaltic outcrops, several case studies were selected in which the geomorphological aspects were analyzed in

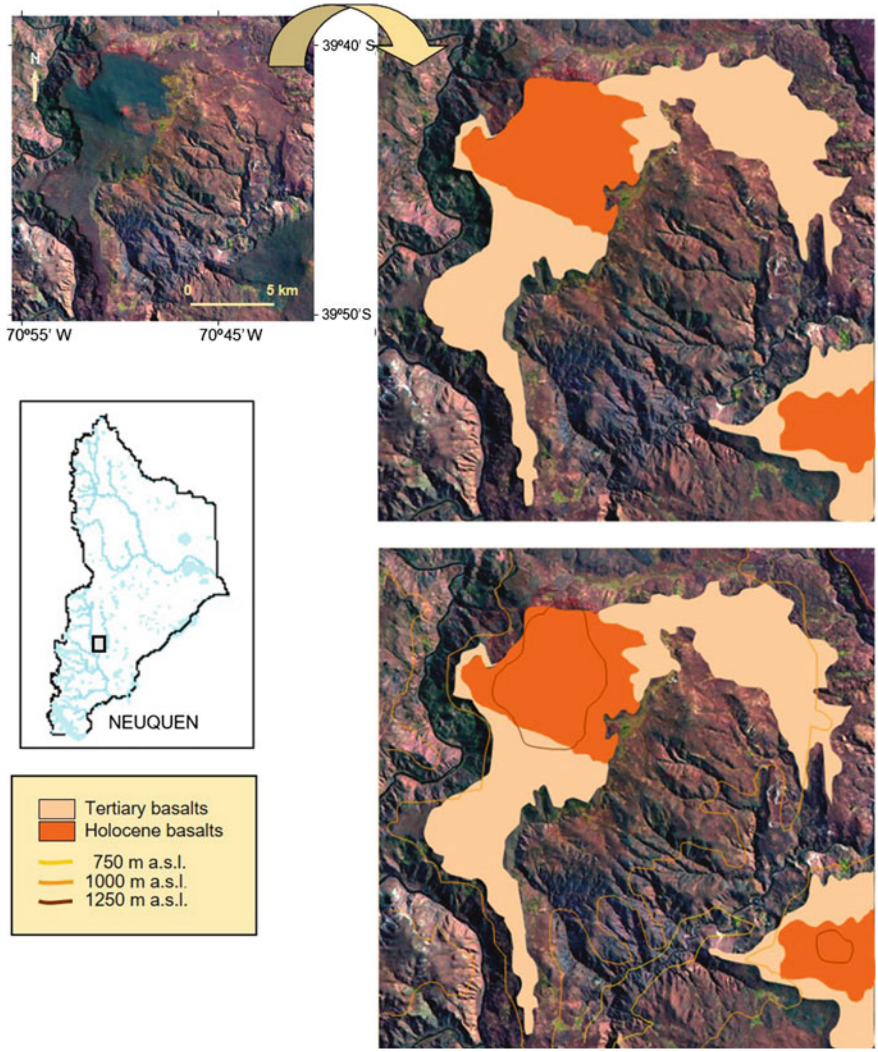


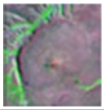
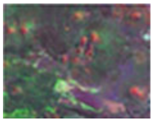
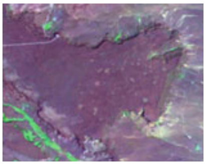
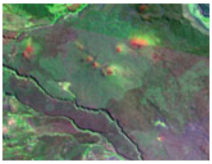
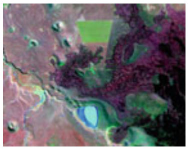
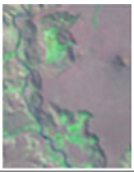
Fig. 1.16 An example of digitalization of basalt "escoriales", differentiated according to the age of the lava flows. In the lower image, the contour lines have been superposed. The image corresponds to the Pampa de la Ensenada tableland in the Province of Neuquén (39º43′S–70º50′W). Geological information taken from Turner (1973)

detail, as well as the relationship between the characteristics of the volcanic mantle showing the presence of wetlands nearby. A geomorphological cartography was developed at a 1:100,000 scale, identifying different landscape modeling processes and each of the "mallines" found at the slopes of the "escoriales" were labeled. The geomorphological map of the "Escorial de Loncopué", in the Province of Neuquén, is presented in Chap. 3.

Table 1.1 Table of attributes of the "Escoriales"

Number (ID)	Mean annual precipitation (mm per year)	Surface (km^2)	Maximum elevation (m)	Mean elevation of the margin (m)	Mean elevation of the foot of the slope (m)	Local relief (m)	Age of the basalt	Classification
3	800	9,1	2800	2200	2100	100	Pleistocene	1 1 1 1 2 2
32	500	56,5	1500	1100	1000	100	Pleistocene/Holocene	1 1 4 3 4 1
42	800	6,9	2200	1800	1800	0	Holocene	2 2 3 1 1 1
53	130	512,3	1800	1100	800	300	Tertiary	1 1 1 5 3 2
55	130	3,6	950	950	900	50	Tertiary	1 1 1 1 3 3
78	200	1441	1100	1100	1100	0	Tertiary/Pleistocene/ Holocene	1 3 7 5 4 1
100	300	256,4	1320	1100	800	300	Tertiary/Holocene	1 1 7 4 4 1

Table 1.2 Classification of the Basaltic “Escoriales” and examples of their visualization in Landsat 8 images, bands 7, 5 and 3

First digit: type of “escorial” 1. Plain or meseta 2. Cone	 (1)	 (2)
Second digit: type of margin 1. Scarp 2. Transitional 3. Mixed	 (1)	 (2)
Third digit: surficial geomorphology **Simple “escoriales”:** 1. Basaltic tableland whose surface does not show specific features 2. Surface with depressions generated by differential cooling phenomena 3. Isolated volcanic cone **Complex “escoriales”:** 4. Stepped surface due to superposition of different lava flows 5. “Meseta” with volcanic cones at its surface 6. “Meseta” with fluvial channels at the surface 7. “Meseta” with complex geomorphology (combination of the 4, 5 y/o 6 types or other type of landforms) 8. Complex volcanic cone	 	
Fourth digit: size of the “escorial” 1. Up to 10 km^2 2. 10–50 km^2 3. 50–100 km^2 4. 100–1000 km^2 5. More than 1000 km^2		
Fifth digit: age of the “escorial” 1. Holocene basalts 2. Pleistocene basalts 3. Middle and late Tertiary basalts 4. Combination of Tertiary and Quaternary basalts		
Sixth digit: presence of “mallines” nearby the “escorial” 1. Abundant “mallines”, clearly identifiable in aerial photographs or satellite imagery 2. Rare “mallines” 3. No “mallines”	 (1)	 (3)