Chapter 5
An Evolutionary Model of Volcanic Landscapes

Elizabeth Mazzoni and Jorge Rabassa

Abstract Taking into consideration the different situations observed in the field, this chapter proposes a model of evolution of the Patagonian volcanic landscape developed from the outcrop of basaltic flows. The different geomorphological processes that act upon the evolution of these landscapes are exposed, particularly fluvial erosion and mass movement processes, and the factors that contribute to the modification or interruption of the evolutionary sequence proposed. The term "landscape of lobes and hummocks" is proposed for the final evolutionary stage of these landscapes. The rate of relative elevation of the basaltic mesetas is also estimated.

Keywords Geomorphological cycle · Volcanic tableland landscape
Extra-Andean patagonia · Denudation rates

5.1 Introduction

The methodology applied in the preparation of the inventory of basaltic "escoriales" in the provinces of Neuquén and Santa Cruz, based upon the interpretation of satellite imagery, permitted the observation of topographic, geological, and geomorphological characteristics of more than 450 basaltic outcrops and consequently, to infer the action of past and present geomorphological agents and processes which take part in the evolution of these volcanic landscapes. All the information collected in this process, together with extensive field studies and the detailed geomorphological mapping of representative areas, allowed the characterization of diverse

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natural circumstances and to propose different evolutionary stages of the Patagonian volcanic landscapes associated to the eruption of the previously mentioned basalt lavas.

The definition of these "stages" is based upon the concept of geomorphological succession and sequences, whose aim is to determine which phases the relief follows during its evolution toward one or two states of equilibrium with the energy levels that are compatible with its dynamics (Pedraza Gilsanz 1996). This type of sequences should be understood as the normal transit toward the landscape evolution, in which geological and environmental factors are concurrent through time.

The definition of the different evolutionary stages of a certain landscape applies the methodology of comparative analysis and spatial-time correlation, which has physical and mathematical support in the "ergodic theory" (Brown 1976; Petersen 1990; Walters 2000; Anosov 2001), which states that the average for the data obtained in a sampling procedure during a certain period is interchangeable with the mean for the data obtained along a specific space and in the same temporal episode.

Based upon these concepts, evolutionary models may be proposed starting from direct observations, that is, if analysing present-times morphological associations along a due space, landform sequences or successions may be deduced for a certain area during a definite period of its geological history (Brunsden and Thornes 1977; Paine 1985; Schumm 1991; Pedraza Gilsanz 1996; Phillips 1997; Brierley 2010; Fryirs et al. 2012).

5.2 Geomorphological Evolution of the Patagonian Basaltic Landscapes

The development of the Patagonian volcanic landscapes started with different types of eruptions that occurred in the Mesozoic, perhaps even since the Triassic, with the acid volcanic activity associated with the Choyoy Group (Kay et al. 1989). Moreover, during the Middle- to Late Jurassic, huge volumes of ignimbrites were erupted in the North Patagonian and Deseado massifs (Ramos 1999). The basaltic/rhyodacitic lava eruptions started in the Late Cretaceous and persisted during the Paleocene and the Eocene, as part of the Ventana and Huitrera formations in Northern Patagonia (González Bonorino 1973; Rabassa 1974; 1975). This cycle also includes the Las Mercedes olivine basalts located in the central sector of the Deseado Massif (Panza 1982), with scarce representation, as it happens in a large portion of extra-Andean Patagonia where the basaltic volcanic activity during the end of the Mesozoic and the beginning of the Cenozoic was restricted (Haller 2002). Contrarily, the basaltic lava flows became particularly intensive during the development of a retroarc environment, starting in the Miocene, around 26 Ma ago (Ardolino et al. 1999; see Chap. 2) originating a typical morphology that occupies around 20% of the surface of the region.

The flows erupted in topographic lows in the relief, becoming later elevated portions of the landscape due to a pronounced process of "relief inversion" with, specially, deep stream bed erosion during the Pliocene and Pleistocene. The magnitude of this process in different areas depended upon the actual water availability to feed the fluvial networks. During each termination of the Quaternary glaciations, water would have been abundant, contributing to the transport of weathered materials and sediments. Nevertheless, other factors such as the geographic location of a certain "escorial" (for instance, the physical contact with a permanent stream), the thickness of the flows, and the resistance to erosion of the pre-volcanic bedrock, are also significant in the amount of erosion of the "escorial".

The consequence of this process was the subdivision of the original lava fields by downcutting of the stream valleys and the formation of elevated "mesetas", which had been valley bottoms before, with generally well-defined margins, marked by usually vertical scarps, locally known as "bardas". If the process of relief inversion has not been completed yet, the "escoriales" present transitional or mixed margins (Fig. 5.1).

Once the "mesetas" have been formed, parallel retreat of the slopes appears as the most relevant erosion evolution process. The slopes retreat toward the center of the "escorial", both under the influence of mass movement processes as by headwater erosion where the stream channels start at the margins of the flows (Fig. 5.2). In those "escoriales" composed by Tertiary lava flows these processes presently dominate the continuous areal wasting of the "mesetas".

The geomorphological term "landslide" usually refers to "the movement of a mass of rock debris or earth down a slope" (Cruden 1990; Cruden and Varnes 1996), whereas the slopes are defined as every inclined natural surface that joins other two surfaces, characterized by different gravitational potential energy (Stochalak 1974). Following Varnes (1978), the following categories can be differentiated within this type of movements: falls, topples, slides, lateral spreads, flows, and complex movements. Concerning the landslides, rotational movements (slumping) or translational movements (slides as such). The most common processes of these types that occur along the edge of the basaltic "escoriales" are slumps and debris falls.

The first type is defined as an intermittent movement of earth or rock masses, in a relatively short distance and which typically involves a mass rotation backward. Consequently, the surface of the slumped masses frequently shows a reversed slope compared with the original landform. These slumps are usually generated as small, though plentiful, landform units, which are independent from each other (Fig. 5.3). Its extraordinary long-term development originates a stepwise, lobate morphology, which is highly characteristic of these "mesetas", i.e., tableland volcanic environments. Excellent examples are observed in the Meseta Lago Buenos Aires, which have been presented in Fig. 3.23 or in the "escoriales" of Piedra del Águila (Fig. 5.2; Mazzoni and Rabassa 2007), Barda Negra, or Gobernador Gregores, among many others (Fig. 5.4). Habitually, this mass movement process initiates with the formation of cracks or fissures, basically parallel to the edge of the volcanic

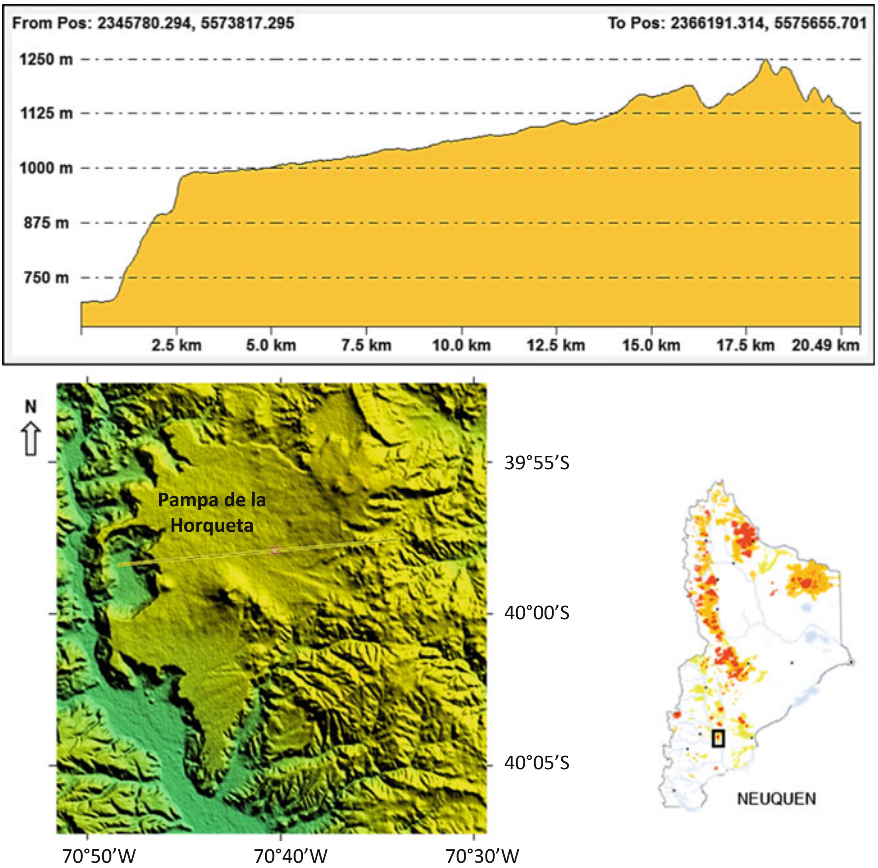

Fig. 5.1 DEM and topographic section of the La Pampa de la Horqueta "escorial", formed by Late Tertiary lavas, partially overlain by Holocene flows. This "meseta" presents scarp edges along its western and southeastern margins, excavated by the Río Collón Curá and its tributaries, whereas toward the E and NE, elevations formed by highly resistant, Triassic rocks are found (Ferrer 1982). The topographic section shows these elevations toward the right of the graph, where a gradual transition between the basalt mantle and the preexisting rocks takes place

tableland. Due to its magnitude, many of these cracks are clearly perceived in aerial photographs or satellite images of high spatial resolution (Fig. 5.5).

Slumps may affect both the surficial volcanic rocks and the underlying bedrock. Significant outcrops have been observed in the lithological sequence composed of the tuffs, ignimbrites, and sedimentary clastic rocks of the Collón Curá Formation and the basaltic flows of the so-called "Basalto I" and "Basalto II" units (Groeber 1946), or their equivalent units for other Patagonian regions. In this case, the pre-basaltic substratum is composed of fine-grained, friable sediments (mostly tuffs) which are frequently weathered, with relevant content of clay minerals that increase

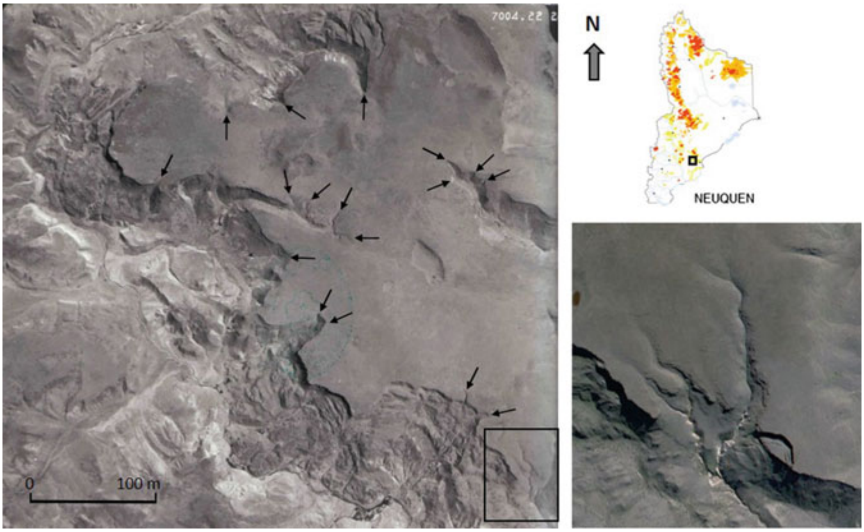

Fig. 5.2 Left: Aerial vertical photograph that shows the erosion processes that act over the slopes of a basaltic “meseta”. This photograph corresponds to the SW portion of the Piedra del Águila “escorial”, in the Province of Neuquén (40°01′S–70°15′W). Here, the action of mass movement processes, which originates the stepped topography observed along the SW and W edges of the “escorial”, is combined with the headward erosion at the rills. The most active rills have been indicated with arrows. The details to the right allow the observation of the crack that separates a basaltic block from the rest of the lava flow, thus initiating the slumping process. *Imagery* Google Earth©

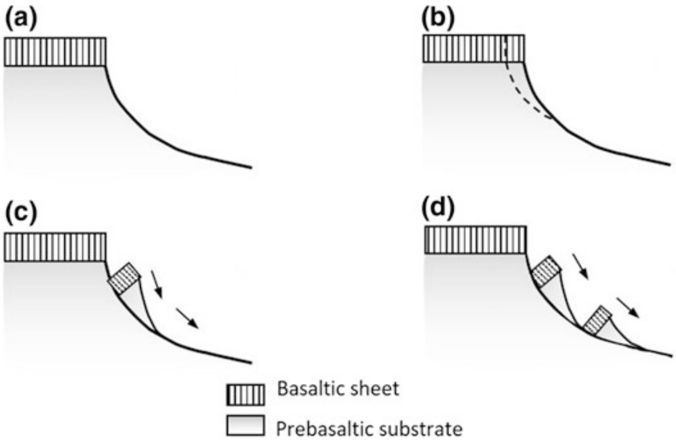

Fig. 5.3 A sketch, not to scale, of the development of rotational slumps along the edges of the basaltic “mesetas”. The arrows indicate the sense of movement

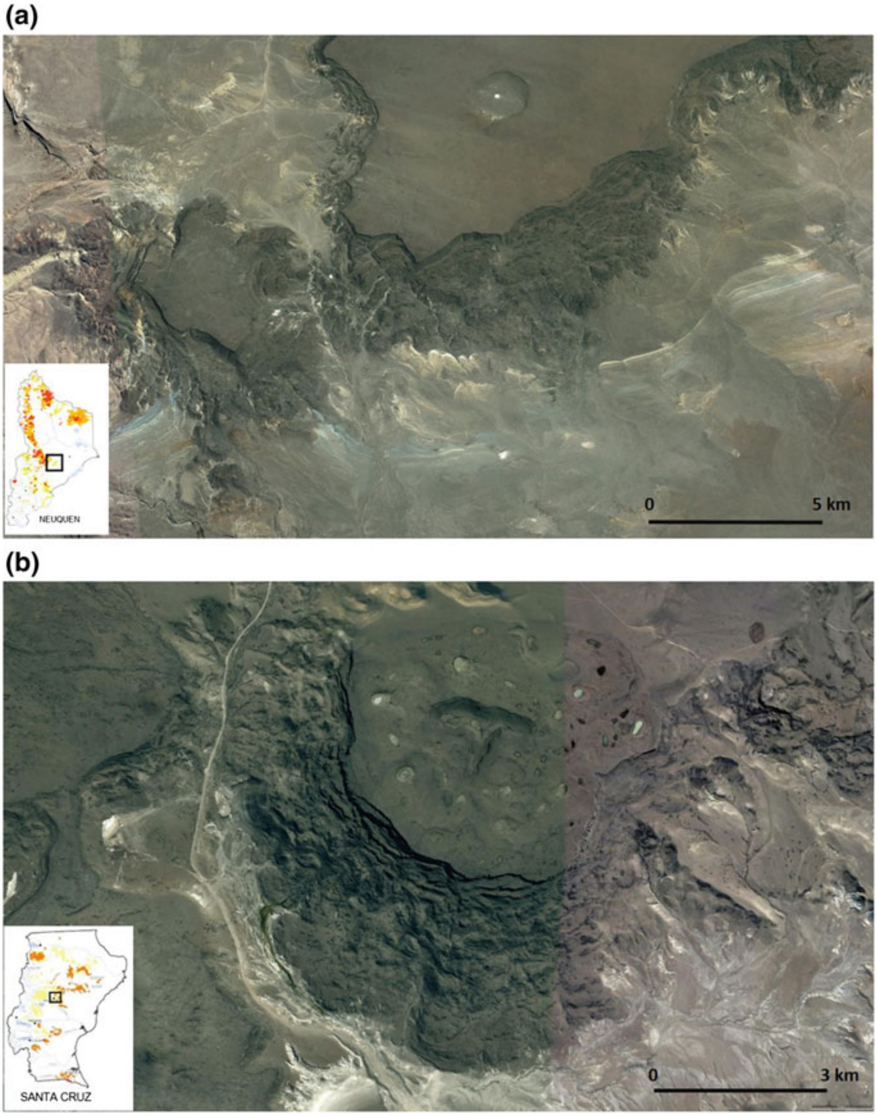

Fig. 5.4 Morphology of lobes and hummocks, modeled by mass movement processes along the edges of the basaltic “mesetas”. **a** corresponds to the southern sector of the Meseta de la Barda Negra, formed by a flow assigned to the early to middle Miocene (Ardolino et al. 1999), included in the Palaoco Formation (the so-called “Basalt I”; Groeber 1946). Based upon geological correlation, it has been assigned a radiometric age between 14 ± 1 and 10 ± 1 Ma (Linares and González 1990). In the SW end, a smaller outcrop is found, crowned by the Cerro Picún Leufú (1369 m a.s.l.), formed by Pleistocene olivine basalts (Leanza 2011). **b** shows a basaltic remnant corresponding to the Strobel Basalt, assigned to the late Miocene (Panza and Marín 1998), in whose slopes slumped deposits extend, stepped up to a distance of 3 km away from the basaltic edge. It may be observed that the blocks gradually lose their shape as the transport process continues downslope. *Imagery* Google Earth©

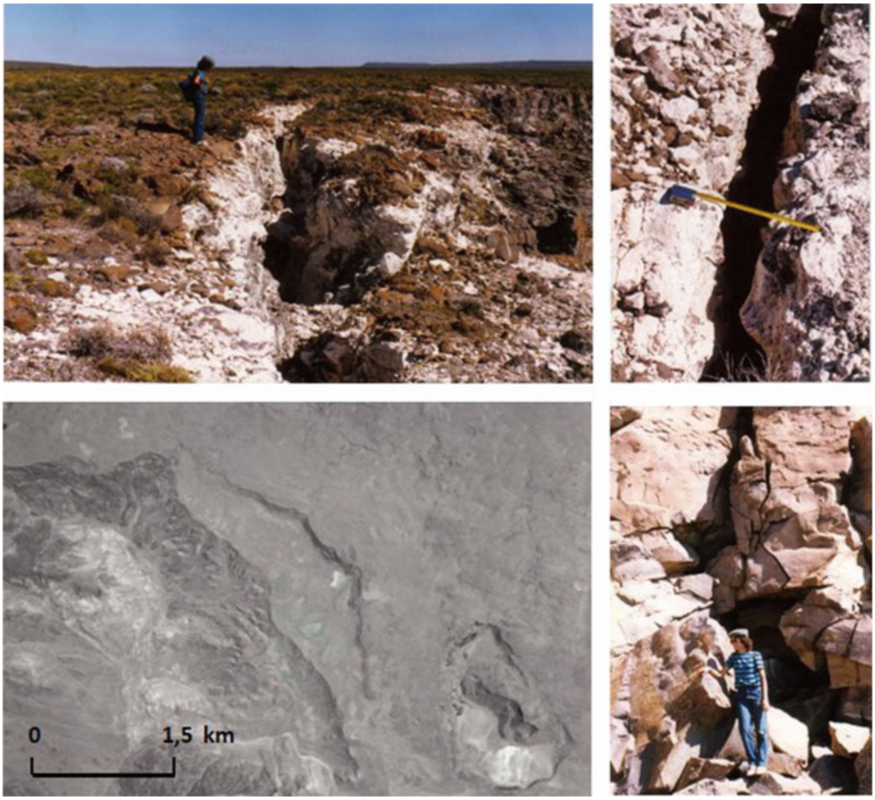

Fig. 5.5 The slumping process is produced from the generation of large cracks that cross both the volcanic mantle and the pre-basaltic substratum. Due to their magnitude, most of them are clearly visible in both aerial photographs and satellite imagery. The image presented here corresponds to the Escorial de Piedra del Aguila, Neuquén (39°49′S–70°18′W), with a full length of 7 km. *Photographs* E. Mazzoni

the erosion of these layers. This situation favors the instability of the slopes and, consequently, the development of mass movement processes.

Besides the action of gravity, the movement is favored by the presence of springs along the slopes, which contribute to generate conditions of instability as the surging water erodes the surrounding land, forcing two processes: (1) sedimentary particles removed and (2) high energy available as the water is relieved from the confining pressure within the aquifer.

The process known as "debris fall" implies the downslope movement of blocks of rock or earth and/or soil masses, which move in free fall, saltation, and rolling following very steep slopes (Cruden and Varnes 1996). The columnar jointing that the lava flows show favors the rock displacement, which collapses due to the abrupt side slopes of the "escoriales". Due to this process, original slopes become buried by the rocky blocks. In some cases, the removed materials are channeled along

Fig. 5.6 The blocks dropped from the basalt surface cover the slopes of the "escoriales". In some cases, the blocks adopt the shape of "stone rivers", when they fill up surface drainage lines. The upper photographs correspond to the Escorial de Bella Vista, in Santa Cruz province (51°51′S–70° 31′W), whereas the lower ones belong to the "La Rinconada" zone, in the Province of Neuquén (39°56′S–70°55′W). *Photographs* E. Mazzoni

drainage lines, forming true "stone rivers" (Fig. 5.6). These landforms are a peculiar feature in this relief, which has been only occasionally listed in the literature. Examples of large dimensions are found in the Malvinas/Falklands islands, where they may reach up to several km in length (Borrello 1963). However, in this archipelago, the rocks involved are mostly sandstone and quartzite, and its origin is attributed to glacial and periglacial processes. In the case of the "escoriales", the accumulation of these blocks on the slopes and discharge lines is mainly associated to mass movement processes, although it should not be ruled out the possibility of the participation of cryogenic processes once the blocks have been released, relocating them in the drainage channels.

The erosion processes that affect the slopes at the edges of the basaltic "mesetas" are developed with varying intensity, but with relevant continuity through time. When movement has taken place and the slumping lobes have been formed, they continue sliding downslope very slowly by creep (Rabassa 1978).

The landforms originated by these mechanisms present unstable conditions and are highly susceptible to perturbation. As it has been pointed by Romero (1975), any changes in the equilibrium conditions may force the reactivation of the slumps, with the movement of large rock masses. González Díaz (2003) and González Díaz et al. (2003) stated that the instability conditions may be triggered by seismic-tectonic factors.

The continuity of the erosion process through time that affects the basaltic flows allows the presentation of an evolutionary sequence in the development of these landscapes. A general model was proposed by Strahler (1979), following the ideas originally exposed by William Morris Davis about the description of his "geographical cycle" (Davis 1923).

The process starts with the lava flows that infill the topographic depressions, valleys, and hollows. In this initial state, volcanoes are in full development process and the continuous eruption of the flows cover large surfaces. When the primitive volcanoes extinguished and they started to be dismantled by erosion, the maturity stage began. The flows are separated by water and/or wind erosion from the volcanic vents. The streams erode, downcutting their valleys along the margins of the flow. When the flows form high "mesetas" the landscape is at its full maturity. The local relief of the "meseta" referred to the level of the surrounding plain increases gradually as the pre-volcanic bedrock is eroded. Mass movements model the slopes of the "mesetas", generating a peculiar topography of lobes and irregular mounds around the "escoriales", whose width is expanded as the process continues. Water outcropping along the margins of the flows collaborates with the erosion process: the small rills that are originated at the melting period in the spring evolve by headwater erosion favoring the downcutting of the channel into the lava flow. These conditions represent the initial phase of the old age, characterized by a larger area percentage occupied by the basaltic debris, over that area covered by the lava flows themselves, since the flow has been cut down in small remnants. Finally, erosion also contributes to reduce the relief from a landscape of mounds and blocks to a gentle morphology of small hills with the unique preservation of the "mesetas" or "cerros mesa" or buttes as erosion remnants. The great volcanic cones that originated the lava flows have been reduced to necks, with abundant colluvial deposits accumulated around them.

In Figs. 5.7, 5.8, 5.9, and 5.10, the diverse stages of evolution of the landscapes developed upon the mafic lavas of Patagonia is illustrated, whereas Fig. 5.11 shows the stages of slope recession of the basaltic "mesetas" until reaching the formation of "slumping hummock landscapes", a name that it is herein proposed to designate the final evolutionary stage of these environments. The original sketches herein presented were drawn during fieldwork by J. Rabassa and E. Evenson (Lehigh University, Bethlehem, Pennsylvania, USA) in 1982. In the first diagram ("A"), a compound landscape is represented by a wide "meseta" whose surface is crossed by cracks and occupied by small drainage lines. The slopes show incipient erosion, with isolated slumped blocks. In "B", the lava mantle has been cut and the ancient lava flow has been replaced by isolated "cerros mesa"; the colluvial material covers a high percentage of the surface and the topography occurs in several steps. In "C", the "mesetas" have been totally worn away and only the presence of small flat remnants prove their existence; the morphology is composed of smooth hills and irregular hummocks.

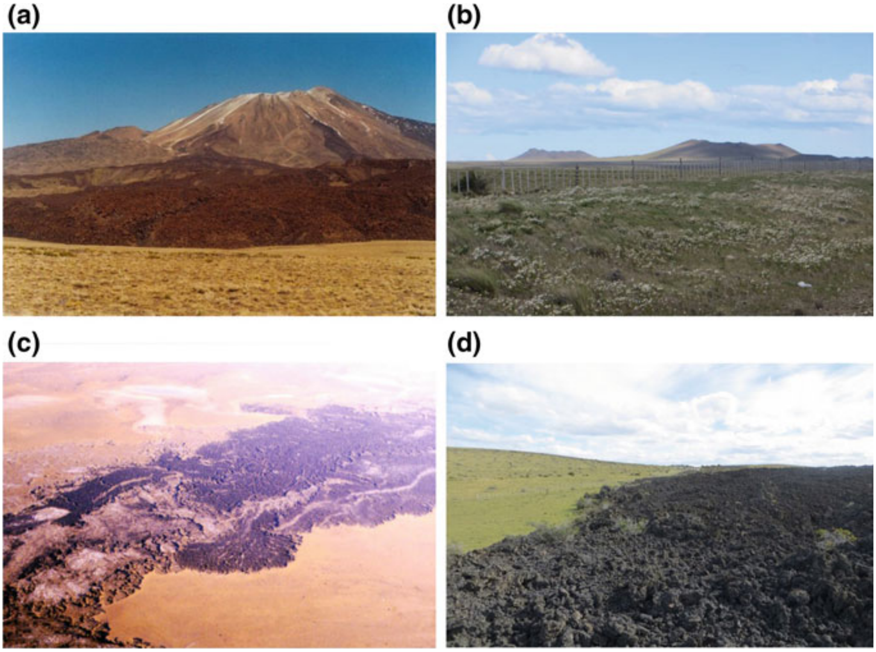

Fig. 5.7 Initial stage of the volcanic landscapes. Coming out from the volcanic vent, the lavas flowed occupying the lower parts of the landscape. **a** shows the Tromen Volcanic Complex, in the Province of Neuquén (37°11′S–70°02′W, 3978 m a.s.l.), formed by recurrent eruptions that took place from the late Pliocene until today (Llambías et al. 2011). Those more recent would have been erupted after AD 1400 (D'Elia et al. 2014), forming lava plains. **b** Small eruption centers in southern Santa Cruz province, whose elevation does not exceed 230 m a.s.l., from where the basaltic flows shown in the photographs **c** and **d**, which still preserve their original textures. *Photographs* E. Mazzoni

Considering the predominant age of the flows that comprise the set of surveyed "escoriales", most of the Patagonian volcanic landscapes are today in a stage of maturity, in various degrees of development. The fact that the "inversion of relief" process has been completed (that is, the "escorial" is forming a "meseta" with rugged edges throughout its perimeter) is one of the most important criteria followed by this evolutionary stage.

As part of the concept of landscape sequential evolution, it is implicit that there is a direct relationship with the length of time in which the geomorphological processes have been acting (Bloom 1991). However, in the evolution of the studied landscapes, special events such as Pleistocene glaciations have taken place. Likewise, it may be stated that, during this epoch, fluvial action seems to have been the main responsible in the general modeling of the volcanic "escoriales" in extra-Andean Patagonia. In present times, the volume of water is comparatively so small that its capacity to trim the "escoriales" is much lower. Nevertheless, in the heads of the rills, erosion is still active and it is exposed by the trimming of the

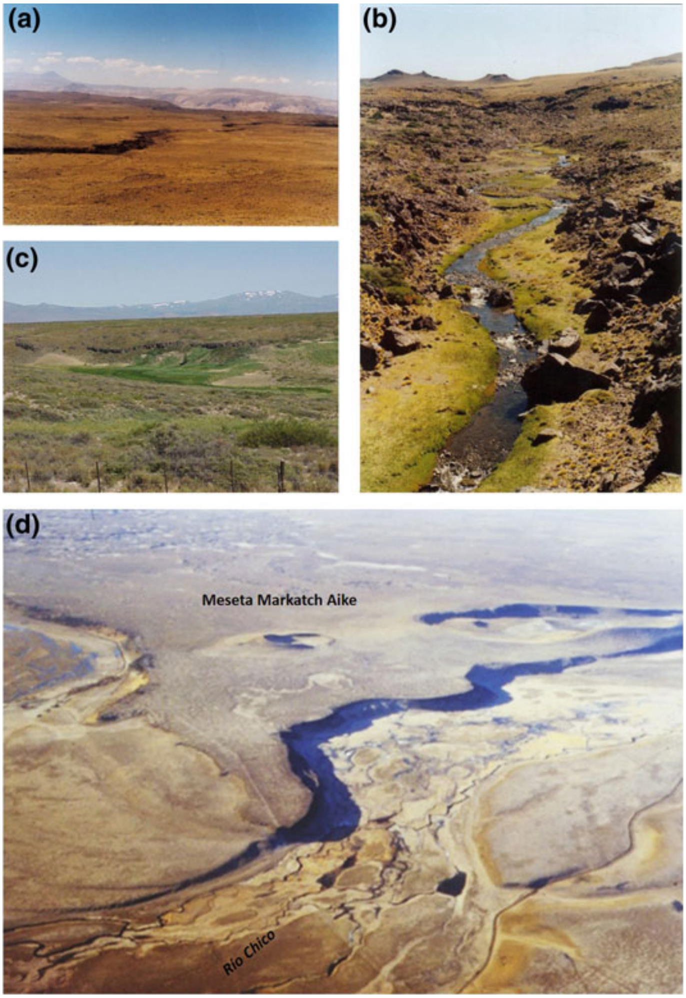

Fig. 5.8 During their youth stage, the flows start to be carved by fluvial action. The examples that are observed in these photographs correspond to the Butaco creek (36°32′S–70°13′W), which partially eroded the volcanic flows of the Tromen Complex (**a** and **b**) and the La Buitrera ranch (**c**) near the town of Las Lajas (38°33′S–70°23′W), both in the province of Neuquén. **d** shows a basaltic "meseta" in the Pali Aike Volcanic Field with a relative local relief that reaches only 15 m above the Río Chico stream bed (51°56′S–69°38′W). *Photographs* E. Mazzoni

edges of the "escoriales". This process and mass movements are those most dynamic in the modeling of the edges of the basaltic lava flows. The geomorphology of the slopes of the "escoriales" present diverse characteristics considering the different processes that have modeled them and the time when they have been active. In Fig. 5.12 some examples are shown, where simple edges lacking morphology associated to mass movement processes and slopes where the progressive

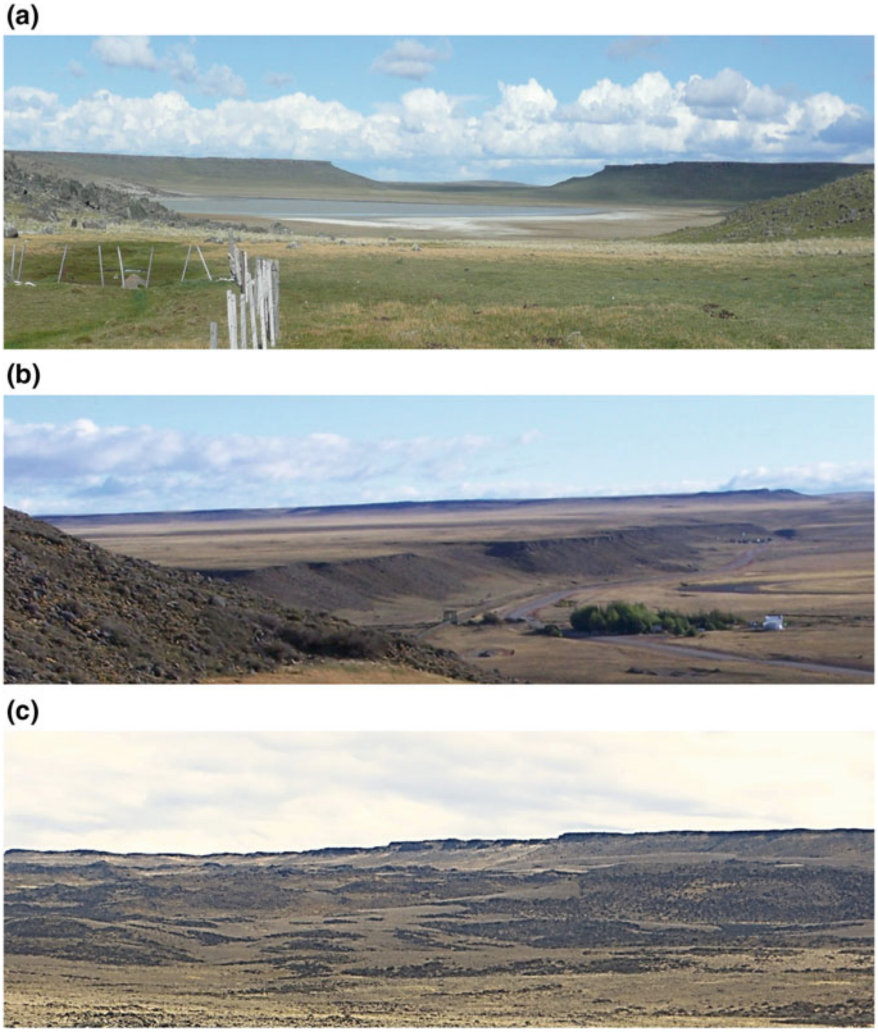

Fig. 5.9 Volcanic plateaus, “mesetas” representative of the maturity stage of this landscape. **a** and **b** show different outcrops of the Quaternary basalts of the Pali Aike Volcanic Field (Santa Cruz province) which have been carved by the Río Gallegos and its tributaries. Its maximum relative elevation does not go above 120 meters, concerning the age of the lava flows. **c** shows the western slope of the Great Central Highlands (Gran Altiplanicie Central, province of Santa Cruz) formed by the Strobel Basalt, erupted during the late Tertiary, with a local relief of 250 m and slopes intensively eroded by mass movement processes. *Photographs* E. Mazzoni

development of the rotational slumping has developed step-like relief, located aligned to basaltic edge as well as topography of lobes and hummocks. Slopes modeled by surface runoff have also been observed. It may be supposed that the extension of the surface occupied by debris is proportional to the evolution time of

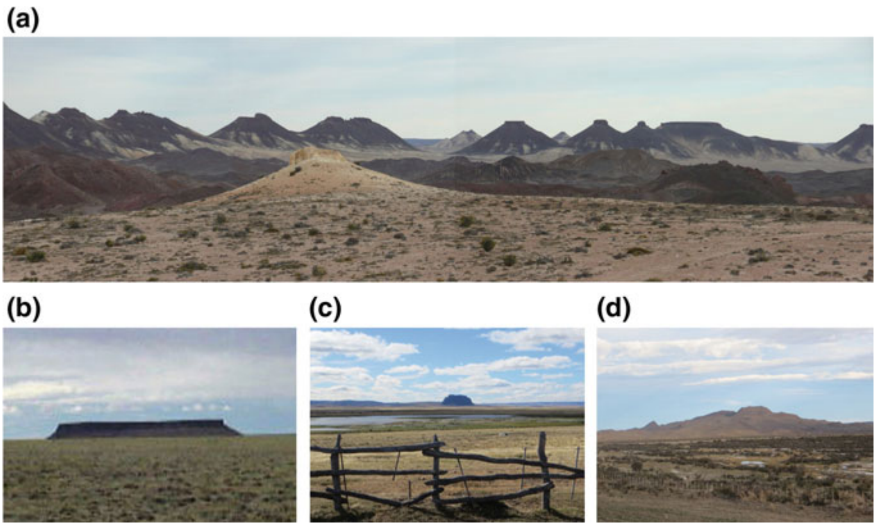

Fig. 5.10 Final stages in the evolution of basaltic landscapes. The photographs illustrate the different features that occur when these landscapes have been eroded of their "mesetas" and the volcanic vents. At a final stage, the "mesetas" are reduced to "cerros mesa" or "buttes", whereas from the volcanoes only the lava infilling the chimneys is preserved, forming "necks". Both landforms are usually surrounded by mass movement deposits. **a** Panoramic view of the numerous remnants of ancient basalts pertaining to the Deseado Massif, Santa Cruz province (47°43′S–67° 56′W). **b** "Cerro Mesa" in the Pali Aike Volcanic Field, Santa Cruz province (51°49′S–70°33′W). **c** Morro Phillippi (385 m a.s.l.), a volcanic neck located in the Río Gallegos valley, dated at 8Ma (D´Orazio et al. 2001, Meglioli 1992). **d** Cerro Las Ovejas (48°45′S–70°21′W), a remnant of an ancient volcano assigned to the Strobel Basalt (late Miocene), along the S margin of the Río Chico, whose valley is observed in the foreground. *Photographs* E. Mazzoni

these landscapes. However, there are geological and environmental factors that may stop or modify this sequence (see 6.3) and, in fact, many "escoriales" present diverse types of geomorphological features in their slopes.

Concerning the geomorphological features present in the "escoriales", the cracks in the basaltic surface appear as indicators of the continuity of the erosion process. The comparative analysis of the cracks found in two "escoriales" of the province of Neuquén (Piedra del Águila and Pampa de la Ensenada), done by means of the information produced from vertical aerial photographs toward the end of the 1960 decade and present satellite imagery, did not demonstrate significant changes in these processes (Fig. 5.13). However, it should not be ruled out that they did not act continuously, but they are triggered by instability conditions or "by pulses", from which critical points should be reached, as it has been explained before. Concerning the period studied, it may be inferred that these pulses would take place in time intervals of more than 40 years.

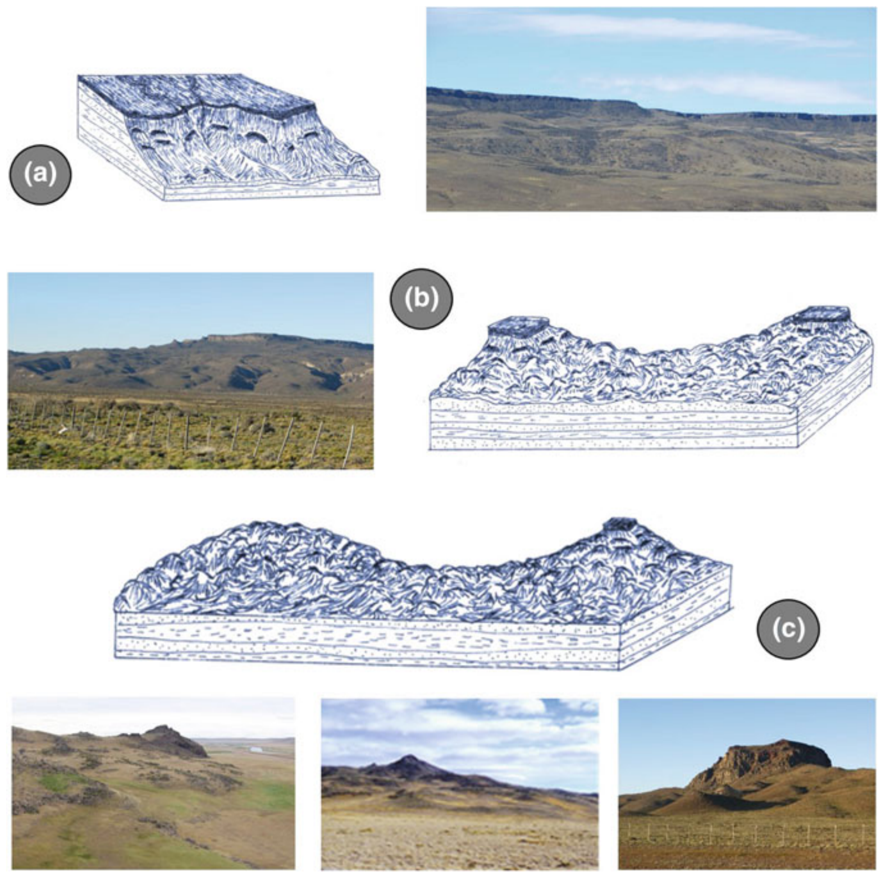

Fig. 5.11 Diagrams and field examples that show the evolution of the landscapes of basaltic "mesetas", particularly the recession of the edges of the "escoriales" and the development of landscapes of "lobes and slumped hummocks". The photographs correspond to outcrops located in the Province of Santa Cruz. **a** Gran Altiplanicie Central (Great Central Highland) near the town of Gobernador Gregores (48°33′S–70°23′W); **b** Cerro Chon Aike, SE of the previous one (49°16′S–69°43′W, 504 m); **c**. Left: a basaltic remnant at La Carlota, Pali Aike Volcanic Field (51°51′S–70° 31′W, 129 m); Center: a basaltic remnant at La Horqueta, NW of Gobernador Gregores (48°13′S–71°09′W, 950 m); right: Cerro Redondo (49°7′S–70°8′W, 508 m), volcanic neck near the Cerro Chon Aike. *Original drawings* J. Rabassa. *Photographs* E. Mazzoni

5.3 Alterations of the Evolutionary Model: "Landscape Rejuvenation"

The evolutionary model that has been described in the previous section refers to those cases in which the volcanic "escorial" was formed from one single eruption and its development has not been altered by new volcanic cycles. However, some of these plateaus were originated from repeated eruptions. One of the more spectacular

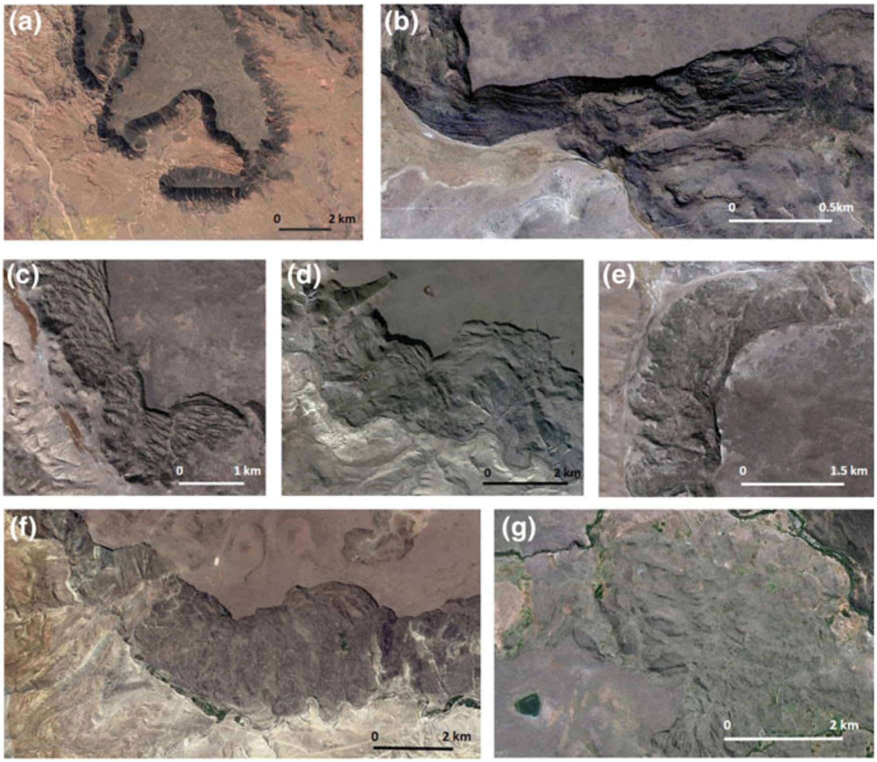

Fig. 5.12 Geomorphological features of the slopes of the "escoriales". **a** Slope which has not been modified by slumping processes (South margin of the Volcán Auca Mahuida, Neuquén, 37° 58′S–68°44′W); **b, c, d,** and **e** Margins of the Escorial de Piedra del Águila, Neuquén (39°51′S–70°13′W). In the first three, the stepped landforms dominate, with large slumped blocks, whereas the last one presents a smoother topography, where the volcanic rocks are mixed with volcanic rocks of the pre-basaltic bedrock. Possibly, the thickness of the lava flow is smaller in this sector than in the other examples. **f** South margin of the Escorial de Laguna Blanca, Neuquén (39°10′S–70°14′W). Toward the left of the image, the slope is modified by the activity of the surficial runoff; to the right, the slope is covered by fallen blocks. Only at the base of the basaltic scarp some slumps may be observed. **g** shows a typical morphology of lobes and hummocks which extends for more than 2.5 km from the margin of the Escorial de Pampa del Mallín Largo, Neuquén, whose location may be observed in the next figure, sector 1. *Imagery* Google Earth©

cases is the "Meseta Lago Buenos Aires", which is composed of basalts which were erupted during several lava pulses that took place between the Early Miocene and the Middle Pleistocene (Ton-That et al. 1999; Singer et al. 2004), and which has a local relief of 800 m with respect to the surrounding topography. Each new eruption produces alterations in the proposed model and means a rejuvenation in the evolutionary cycle of these landscapes, following, in this case, the Davisian terminology.

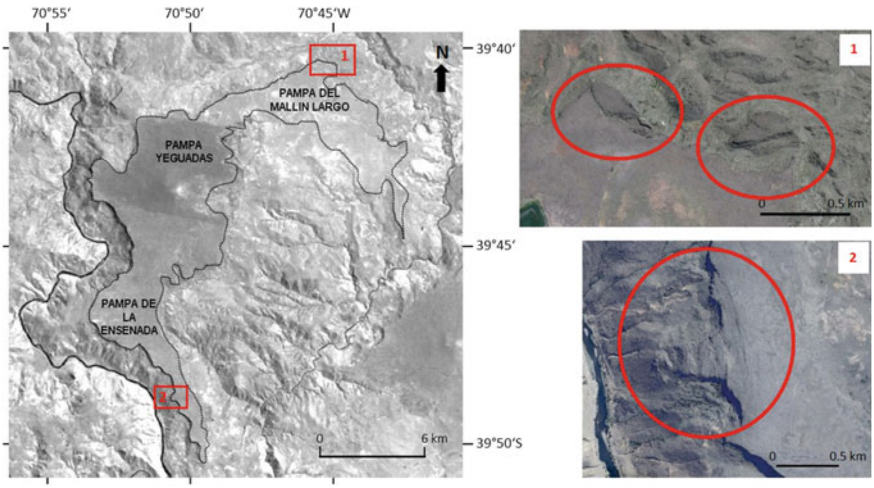

Fig. 5.13 Cracks in a diverse stage of development along the margins of the Pampa de la Ensenada—Pampa del Mallín Largo. The different tonalities of lava flows can be associated to different thickness or eruptive cycles (Mazzoni 2007)

The most common case, however, is the formation of small modern cones of Quaternary age on top of ancient flows. If the lava flows that accompany these vents extend up to the margins of the ancient "escorial", they may modify the abrupt scarp of the edges, as it happens, for instance, in the "Escorial Laguna Blanca" in the province of Neuquén, as it is shown in Fig. 3.25. This implies a retreat in the process of geomorphological evolution of these landscapes.

Another set of "escoriales" have been altered by processes which are not considered within the so-called "normal" evolutionary model proposed. This is the case of past and present glacial and periglacial processes, which have affected the volcanic landscapes located in the western sector of Patagonia and some of them as well, which are localized in more eastern positions in the southern portion of the continent. Several volcanic "mesetas" show features of glacial erosion both in the overlying cones and their slopes, as well as moraine deposits on their surfaces. Two examples, whose western slopes exhibit many glacial cirques, are the "Escorial of Loncopué", province of Neuquén (Mazzoni 2007, 2011), and the Meseta de las Vizcachas in Santa Cruz province. Imagery of these "escoriales" may be observed in Chap. 3 (Figs. 3.31, 3.32, 3.33, and 3.34). Mount Zeballos, an eruption center located in the Meseta Lago Buenos Aires, preserves small cirque and slope glaciers on its surface (47°02′S–71°42′W, Fig. 5.14).

Finally, the impact of meteorites has contributed to the evolutionary process of the basaltic plateaus, since a few of the surveyed "escoriales" show depressions that could be assigned to this origin due to morphological features. Among them, the following may be cited: the "Meseta Barda Negra" in the province of Neuquén (Fig. 3.35, Ocampo et al. 2005), the "Escorial of Bajada del Diablo" in the province

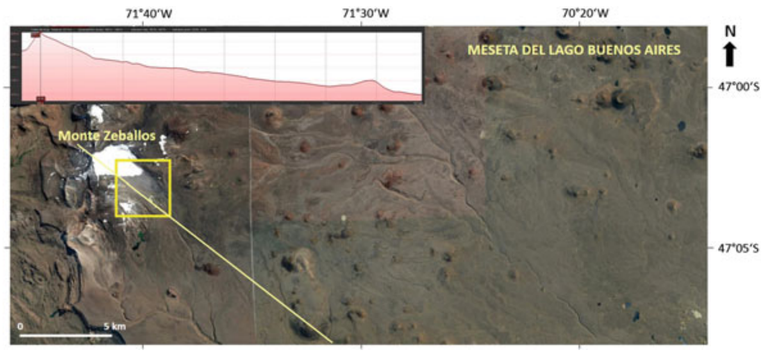

Fig. 5.14 Image of Monte Zeballos, an eruption center located in the western sector of the Meseta Lago Buenos Aires, in NW Santa Cruz province. Its summit is modeled by glacial processes, with sharp crests and cirques. The presently surviving glacier is undergoing a clear recession. Within the detailed image at the right, lateral and frontal moraines may be clearly observed and linear erosion features and striations are carved in the basalts, which have been exposed recently. In the sedimentary accumulations at the snout of the glacier many lakes are preserved. The topographic profile permitted to observe the topographic characteristics of the summit of the main volcano and the smaller eruption vents that crown the whole "meseta" surface. *Image* Google Earth©

of Chubut (Acevedo et al. 2009; see also a summary of the impact craters in South America, Acevedo et al. 2015, among other papers); several outcrops belonging to the Strobel Basalt, near the town of Gobernador Gregores in the province of Santa Cruz and the "Escorial Bella Vista" in the southernmost portion of the latter province, among other possible examples. In this last case, such depression has been interpreted by Coronato et al. (2013) as a maar (a phreatic-volcanic eruption; Figs. 3.39 c, g, h, j, and 5.15).

5.4 Relative Elevation Rate

The existing local relief between the edge of the "escorial" and the base of the scarp represents a clear evidence of the downwasting of the surrounding relief, consequently to the action of the geomorphic agents. If the age of the initial surface is known, the elevation of the "escorial" above the surrounding valleys and wadis may be correlated with the time since the starting of the erosion process until today, thus a local "denudation rate" may be obtained, which is presented through the relationship between the difference in elevation (expressed in length units) and the elapsed time (in time units, hundred thousand to millions of years). Nevertheless, it should be considered that the denudation rates thus obtained are a result of the dynamic interaction between the uplifting processes (being them of orogenic, tectonic, or neotectonic origin) and the erosion processes that tend to waste the landscape down.

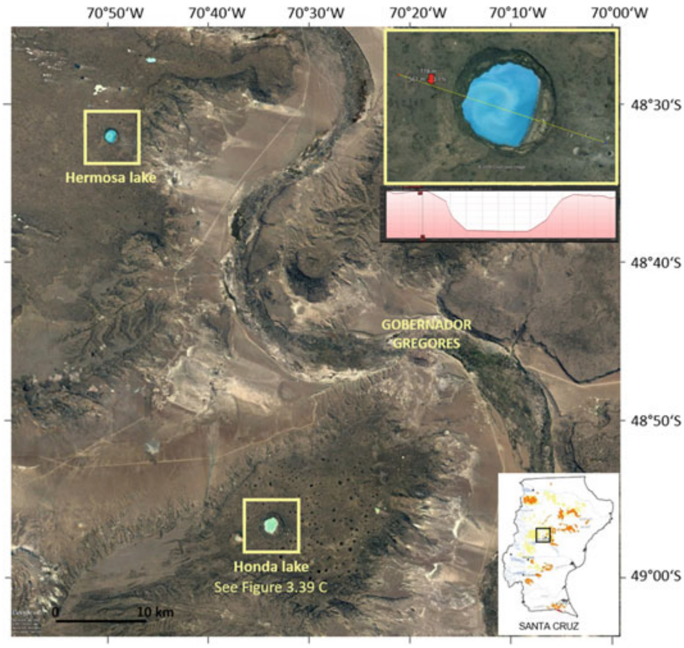

Fig. 5.15 In this satellite image, two deep, circular depressions (the Honda and Hermosa lakes) are observed on the "escoriales" formed by the Strobel Basalt, of Miocene age, close to the town of Gobernador Gregores (province of Santa Cruz). The enlargement in the box on the right makes it possible to observe the morphological characteristics of the first one, which allow us to suppose a possible origin of impact. *Imagery* Google Earth©

Several authors have estimated the surface denudation rates using the measurement of the sediment discharge of major streams. The obtained results differ in relation to the climatic regions in which each basin is located and concerning to the diverse lithology types involved, which are crossed and eroded by fluvial networks. Thus, for instance, calculations have provided values of 100 cm in depth per thousand years for the Yellow river (China), 53 cm/1000 years for the Ganges river (India), 4 cm/1000 years for the Mississippi river (U.S.A.), and 2 cm/1000 years for the Amazon river in Brazil (Judson and Ritter 1964). For different regions of the U.S.A., an average denudation rate of 6 cm/1000 years has been estimated (Bloom 1991). In the calculation of these results, many factors are involved, among which lithology, climate, terrain slope, and vegetation cover are some of the most relevant.

Concerning the volcanic "meseta" landscapes in extra-Andean Patagonia, the rate of denudation was calculated taking into consideration four "escoriales" located under similar climatic conditions (Table 5.1). The relationship between the mean relief existing between the edge of the "escorial" and the base of the scarp and the absolute radiometric age of the lava flow was calculated. The obtained values are 0.02 and 0.05 mm/year, or 2 and 5 cm/1000 years. That is, the average denudation of the areas surrounding "escoriales" belonging to extra-Andean environments is

Table 5.1 Denudation rates and relative elevation of the “escoriales”

Parameters	Barda Negra (39°07′S 69°48′W)	Piedra del Aguila (39°48′S 70°15′W)	Meseta Molinari (48°53′S 70°30′W)	Cerro Tejedor (48°10′S 69°57′W)
Absolute age (Ma)	14 to 10	5	8 to 6	5.5 to 4
Mean age considered for the calculation	12 Ma	5 Ma	7 Ma	5 Ma
Local relief (meters)	250	250	375	100
Denudation rate (mm/year)	0.02	0.05	0.05	0.02

probably close to 3.5 cm every 1000 years. As it has already been mentioned, the past and present fluvial action have special relevance in the denudation process; the aeolian processes should also be considered. No direct glacial action took place in most of these plateaus. In semiarid environments of California, denudation rates in basaltic landscapes have yielded an average of 1–3 cm/1000 years (Marchand 1971).

Considering the process of relief inversion that affects the volcanic zones under study and that allows the transformation of the lava plains in elevated areas of the landscape, the denudation rates obtained for the extra-volcanic sectors may be also indirectly interpreted as relative elevation rates of the “mesetas”.

5.5 Final Remarks

The concept of landscape sequential evolution has a high didactic interest, since it permits the full understanding of the ways and manners in which a landscape reached its present morphology. This evolutionary sequence is particularly visible in those landscapes developed on volcanic flow outcrops, because these flows have, in all cases, occupied the lowest positions of the landscapes when moving as fluids emerging from a vent. Starting from this principle, most of the landscapes formed by basaltic flows in Patagonia depict features that allow to classify them, as an analogue to the classical, Davisian fluvial landscape cycle, as “mature landscapes”, because they have completed the process of “relief inversion” and they rise several tens of hundreds of meters above the surrounding landscape. The denudation rate, estimated from only a few cases, permitted to estimate a mean erosion speed of 3.5 m/1000 years for these landscapes in Extra-Andean Patagonia. Certainly, this is not a constant value, since it is highly influenced by the nature, texture, and structure of the local rocks and the geological-environmental history of the region, particularly the glaciation/deglaciation events that have provided the supply of erosion energy to the regional streams, needed for the denudation of the landscape.

Finally, the frequent eruptions that have taken place in Patagonia during the entire Cenozoic have played the role of rejuvenation of the preexisting volcanic landscapes of lowland Patagonia, as they have contributed to the increase of local relief and thus, augmenting the available potential energy, without temporal relationship with tectonic events of either orogenic or epeirogenic nature.

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