Quaternary Science Reviews 71 (2013) 13–26

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Glacial, fluvial and volcanic landscape evolution in the Laguna Potrok Aike maar area, Southern Patagonia, Argentina

Andrea Coronato [a,b,*], Bettina Ercolano [c], Hugo Corbella [d], Pedro Tiberi [c]

[a] CADIC-CONICET, B. Houssay 200, 9410 Ushuaia, Argentina
[b] UNPSJB-Sede Ushuaia, Darwin y Canga, 9410 Ushuaia, Argentina
[c] UNPA-UARG, Av. Gregores y Piloto Rivera s/n, 9400 Río Gallegos, Argentina
[d] MACN-CONICET, Av. Ángel Gallardo 470, C1405 Buenos Aires, Argentina

ARTICLE INFO

Article history:
Received 20 November 2011
Received in revised form
16 June 2012
Accepted 26 June 2012
Available online 9 August 2012

Keywords:
Glaciofluvial landforms
Maar
Potrok Aike
Middle Pleistocene
South America

ABSTRACT

We describe the Pleistocene evolution of the landscape in the Laguna Potrok Aike area in southern Patagonia, Argentina, based on a geomorphological survey. Basaltic eruptions generated tablelands and scoria cones between the Late Miocene and Middle Pleistocene, and phreatomagmatic eruptions produced maars during Middle and Late Pleistocene time. The first glaciations during the Early Pleistocene generated a gently undulating to flat landscape that was affected by cryogenic processes; they are documented but not dated. Outwash surfaces indicate that the Greatest Patagonian Glaciation was multiphased. The eruption that produced Potrok Aike maar truncated terrace levels dating to a Middle Pleistocene glaciation. The abundance of maars dating to this time may be linked to large amounts of water associated with meltwater streams and permafrost. The landscape in the Potrok Aike area has changed little since the Middle Pleistocene and only minor modifications of landforms have occurred due to cryogenesis, moderate fluvial incision, mass wasting and eolian activity.

1. Introduction

This paper summarizes current knowledge of the evolution of the landscape around Laguna Potrok Aike (Fig. 1). It provides contexts for geological, ecological, archaeological and paleoenvironmental investigations that are being conducted in southern Patagonia, specifically in the Pali Aike Volcanic Field (cf. Zolitschka et al., 2013). Laguna Potrok Aike is of considerable scientific interest because of its potential to serve as a Quaternary paleoenvironmental archive for the Southern Hemisphere. The sediment infill in the maar is currently being studied within the framework of the "Potrok Aike Maar Lake Sediment Archive Drilling project" (PASADO).

Our work builds on several previous studies by other researchers. Scalabrini Ortiz et al. (1985) provide a geological and geomorphological compilation of previous research in the area. Several authors (Skewes, 1978; Corbella et al., 1996; Diraison et al., 1997; D'Orazio et al., 2000; Corbella, 2002; Corbella and Ercolano, 2002) describe the tectonic and volcanic history. Other researchers have focused on the extent of Pleistocene glaciers along the Gallegos River and southward. Meglioli (1992) identified six glacial advances in the region, although only two of them affected the study area (Fig. 2). Landforms related to the earliest of these advances, the Bella Vista Glaciation, occur along the Rio Gallegos valley. This glacier flowed from the Andes to the Atlantic coast and deposited moraines near Estancia Bella Vista (Fig. 2). Meglioli (1992) suggested that this glaciation occurred between 1.07 and 0.47 Ma; the advance was later constrained to between 1.15 and 1.05 Ma by Ton-That et al. (1999) and Singer et al. (2004a,b). It was first named the Initioglacial by Caldenius (1932) and later the Greatest Patagonian Glaciation by Mercer (1976). Another glacier lobe flowed along the Strait of Magellan and reached the southwest corner of the study area at the same time. Subsequently, during a later Mid-Pleistocene glaciation (Cabo Vírgenes glaciation), a glacier again advanced along the Strait of Magellan to its eastern end. Meglioli (1992) concluded that it occurred sometime between 1.07 and 0.45 Ma. The outermost moraines of the Cabo Vírgenes glaciation are located south of the study area. Most recently, Bockheim et al. (2009) and Kliem et al. (2013) showed that permafrost and tundra existed at several times in the Laguna Potrok Aike area during the Pleistocene.

Sediment cores collected from Laguna Potrok Aike have provided sedimentary, geochemical and paleoenvironmental data, reported by Zolitschka et al. (2006), Haberzettl et al. (2005, 2007,

* Corresponding author. CADIC-CONICET, B. Houssay 200, 9410 Ushuaia, Argentina. Tel.: +54 2901 433320; fax: +54 2901 430644.
E-mail address: acoronato@cadic-conicet.gob.ar (A. Coronato).

0277-3791/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.quascirev.2012.06.019

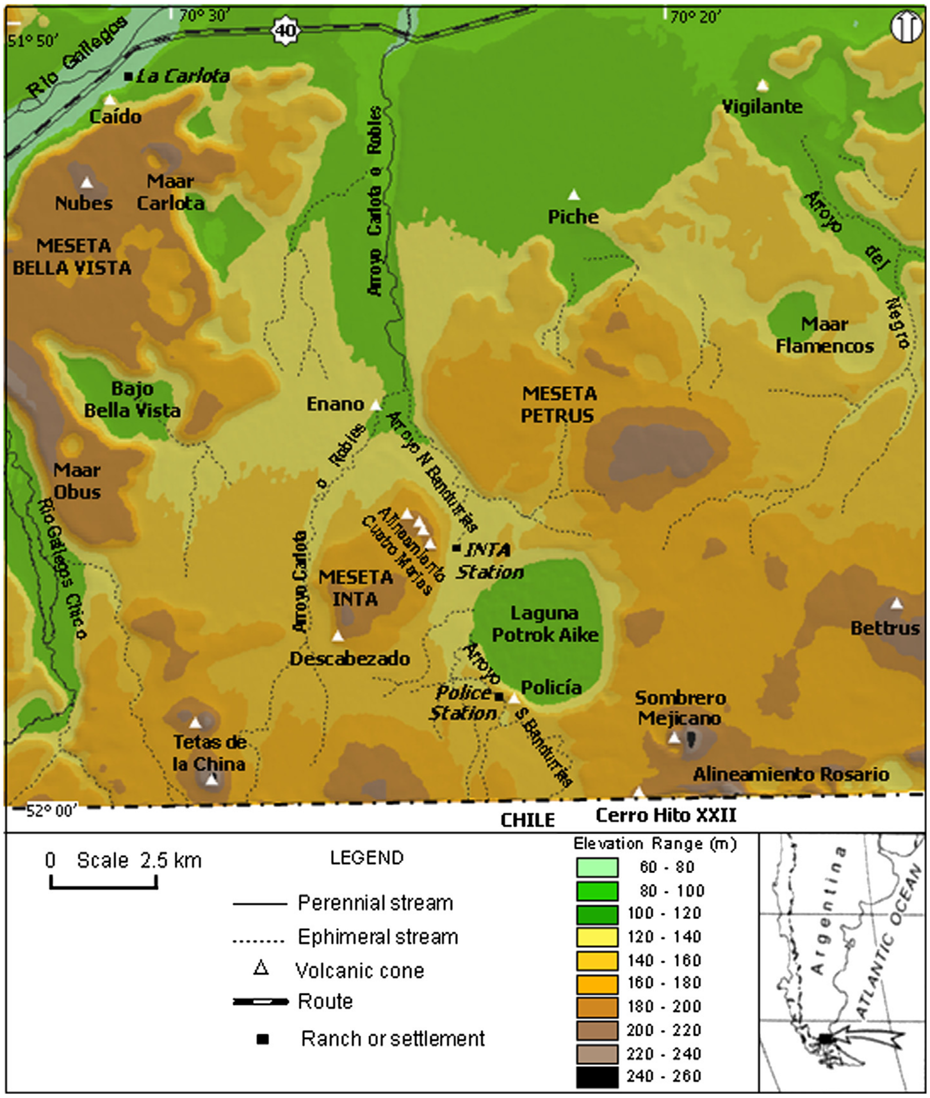

Fig. 1. Location map of the study area around Laguna Potrok Aike.

2008, 2009), Wille et al. (2007), Mayr et al. (2009), Kastner et al. (2010) and Recasens et al. (in press). The current hydrogeological conditions in the lake have been inferred from stable isotopes by Mayr et al. (2007), and seismic surveys were performed to help interpret the stratigraphy (Anselmetti et al., 2009; Gebhardt et al., 2012) and geometry (Gebhardt et al., 2011) of the lake fill. Most recently, Gogorza et al. (2011, 2012) report the results of high-resolution paleomagnetic and rock magnetic studies.

Few papers, however, refer to geomorphology. Only Mazzoni and Vázquez (2009) studied eolian activity near the Bella Vista closed basin. This study tries to fill an evident gap between volcanological and paleoenvironmental studies in the Pali Aike Volcanic Field.

2. Regional setting

The study area is located on the south side of the Río Gallegos valley near the Argentina-Chile border (Fig. 1), 300 km east of the Andean volcanic front. Laguna Potrok Aike is part of the Pali Aike Volcanic Field, within the Magellan sedimentary basin, just beyond large Early and Middle Pleistocene moraines. The stratigraphic column is dominated by continental sedimentary rocks of the Miocene Santa Cruz Formation (SCF). Also present are Mio-Pliocene basalts, local and regional pyroclastic and phreatomagmatic sediments, and Quaternary tills, glaciofluvial, fluvial, lacustrine and eolian deposits, as well as distal Andean tephra.

The SCF has been dated to between 19 and 10 Ma (Fleagle et al., 1995; Ramos, 2002). It crops out extensively throughout the study area. The formation consists of weakly lithified continental tuffaceous sandstones, micro-conglomerates and siltstones (Ameghino, 1889) that are 660 m thick in the Laguna Potrok Aike area. Fossil mammal bones and osteoderms found along the lakeshore indicate nearby outcrops of middle or upper parts of the SCF.

Polylithic gravels of Andean origins that are regionally extensive, known as “Rodados Patagonicos” (Fidalgo and Riggi, 1970) or Patagonian Gravels, unconformably overlie the SCF and locally underlie alkali basalts (Skewes, 1978).

The dominant faults that control most of the Plio-Pleistocene eruptive activity in the area strike northwest; other faults strike west and west-southwest. The northwest-striking faults coincide with an underlying Jurassic paleo-rift zone (Corbella et al., 1996) related to the separation of Africa from South America during the breakup of Gondwana (Uliana and Briddle, 1987). The west and west-southwest-striking faults were produced by northwesterly

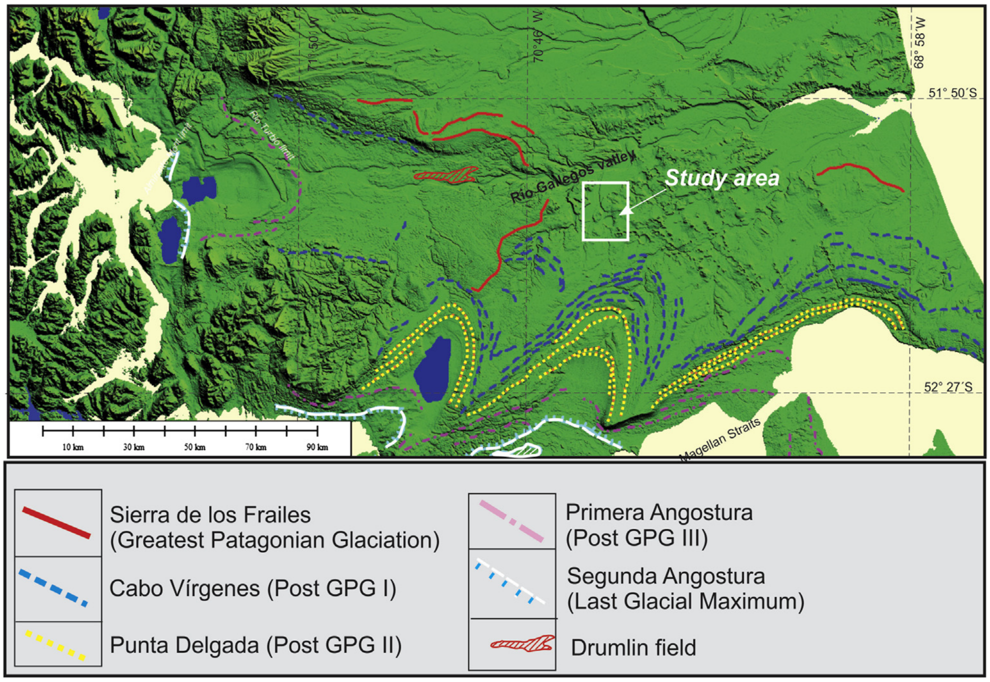

Fig. 2. Glacial limits in the Río Gallegos valley and along the north coast of the Magellan Straits. Limits were drawn on a SRTM digital terrain model following Meglioli (1992). The legend refers to the stratigraphy of Meglioli (1992) with their equivalents (in brackets) according to Coronato and Rabassa (2011).

oriented stretching related to a younger stress field along the southern flanks of the Magellan Basin (Diraison et al., 1997). Faults appear to control the paths of ancient rivers, such as the Rio Gallegos, and Pleistocene glaciers, which flowed through Skyring and Otway sounds and along the Strait of Magellan.

The climate of southern Patagonia is temperate to cold and semiarid. The mean annual temperature is 5.9 °C; the mean monthly temperatures in the study area in January and July are, respectively, −0.2 °C and 11.6 °C (Instituto Nacional de Tecnología Agropecuaria weather station data, 1999–2009; INTA Station in Fig. 1). Mean annual precipitation is 220 mm, with maximum rainfall events and amounts in the austral summer. Winds are constant during warm periods from the southwest and west-southwest. The mean wind speed is 4.6 m s^{-1}, although the maximum speed exceeds 360 m s^{-1}.

The main stream is Río Gallegos, a perennial river draining from the foot of the Andes to the Atlantic Ocean through the Patagonian tablelands (Fig. 1). Two of its southern tributaries, Río Gallegos Chico and Arroyo Carlota (also named Arroyo Robles), are ephemeral.

3. Material and methods

We defined geomorphological units covering 420 km^2 and using satellite imagery and Shuttle Radar Topography Mission (SRTM) digital elevation models (DEMs). Digital information was captured using the GIS software packages ENVI 4.3, ArcView 3.2a and Global Mapper 11. All data were projected into Gauss-Krüger, Zone 2 (WGS 84 datum). Field waypoints and tracks were determined with E-trex Vista and Magellan GPS devices. INTA provided vertical aerial photographs, taken in 1968, of the Gallegos and Carlota valleys at a scale of 1:40,000. We surveyed part of the region using vertical aerial photographs at a scale of 1:10,000 obtained by H. Corbella in 1997. A high-resolution (2 m) satellite image was captured from the Google Earth website. All images were scanned and geo-referenced using field control points obtained with a Garmin HCX Vista GPS.

We used ENVI 4.3 software to process Landsat 7 ETM (bands 1 to 7, dated 02/02/2002, 10% cloud cover) and ASTER (bands 1 to 9, dated 14/10/2006, 15% cloud) images. Bands with the best contrast were visually selected to map soil, water and vegetation coverage. Band ratios and filters were also used for image analysis.

Due to the limited relief in the study area, we used the SRTM DEM to enhance topography and create contours with different vertical spacing. Landforms were digitized from raster files to produce a geomorphological map. We checked the preliminary digital map in the field, made slope and elevation measurements, described stratigraphy and landforms, and sampled rock and sediment for petrographic, chemical and radiometric analyses.

4. Results and discussion

The results of the geomorphological survey are structured according to bedrock, volcanic, glacial, glaciofluvial and fluvial features and into other geomorphological processes and landforms (Fig. 3).

4.1. Bedrock surfaces

Nearly flat, broad surfaces that are underlain by the SCF and Patagonian gravels gently slope to the east are remnants of the Mio-Pliocene landscape. Much of these surfaces are overlain by lava flows, forming volcanic tablelands. Fig. 3 shows one of the few surfaces that are not capped by lavas east of Arroyo Carlota.

4.2. Volcanic features

Mio-Pleistocene volcanic tablelands, scoria cones, lava flows and maars are the main volcanic features in the study area (Table 1).

4.2.1. Basaltic tablelands

The Bella Vista, INTA and Petrus basaltic tablelands or “mesetas”, located north and west of the Laguna Potrok Aike, are the oldest volcanic features in the Pali Aike Volcanic Field (Fig. 4A,B). Basalt

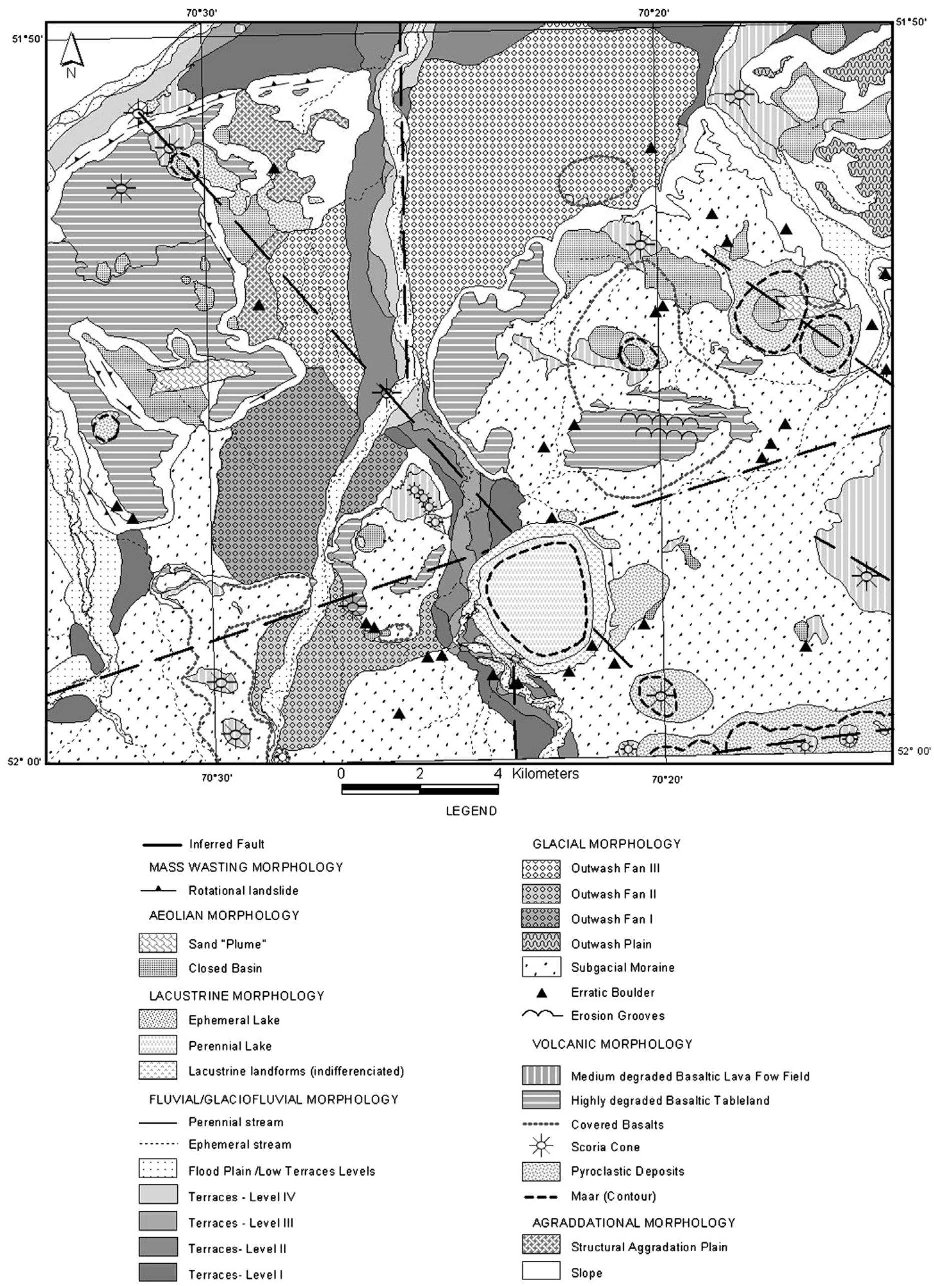

Fig. 3. Geomorphological map of the Laguna Potrok Aike area.

Table 1
^{40}Ar/^{39}Ar and K/Ar ages from volcanic rocks of the investigated area as available from the literature.

Locality	Geographical position	Age (Ma)	Source
Bella Vista	51° 51′S 70° 32′W	9.15 ± 0.08	(Mejia et al., 2004)
INTA	51° 55′S 70° 25′W	3.78 ± 0.12	(Corbella, 1999)
Puesto Negro (Cerro Piche)	51° 52′S 70° 21′W	2.15 ± 0.03	(Meglioli, 1992)
Rosario	52° S 70° 17′W	1.53 ± 0.11	(Corbella, 1999)
Bandurrias	51° 58′S 70° 24′W	1.19 ± 0.02	(Zolitschka et al., 2006)
La Carlota	51° 51′S 71° 31′W	0.85 ± 0.03	(Mejia et al., 2004)

flows more than 10 m thick overlie the SCF. Thin tuffs, microbreccias and agglomerates commonly mark the basal contact with the SCF (Fig. 4C). The basalts are dissected remnants of more extensive lava flows, forming plateaus up to 100 m above adjacent streams. They were erupted onto a plain or a series of wide valleys with little relief and gentle slopes. The lava flows have been weathered and eroded, thus their surfaces are flat and lack the roughness of recent basaltic flows. Circular or elliptic closed basins, up to hundreds of metres in diameter are present on the basaltic surfaces. These basins, which are common elsewhere on the Patagonian basaltic tablelands, are known as “bajos sin salida” (basins without outlet) and have been attributed to dissolution, settling and subsidence (Methol, 1967; Volkheimer, 1972; Dessanti, 1973; Fidalgo, 1973), erosion by strong persistent winds (Clapperton, 1993), or by cryogenic processes (Trombotto, 2002).

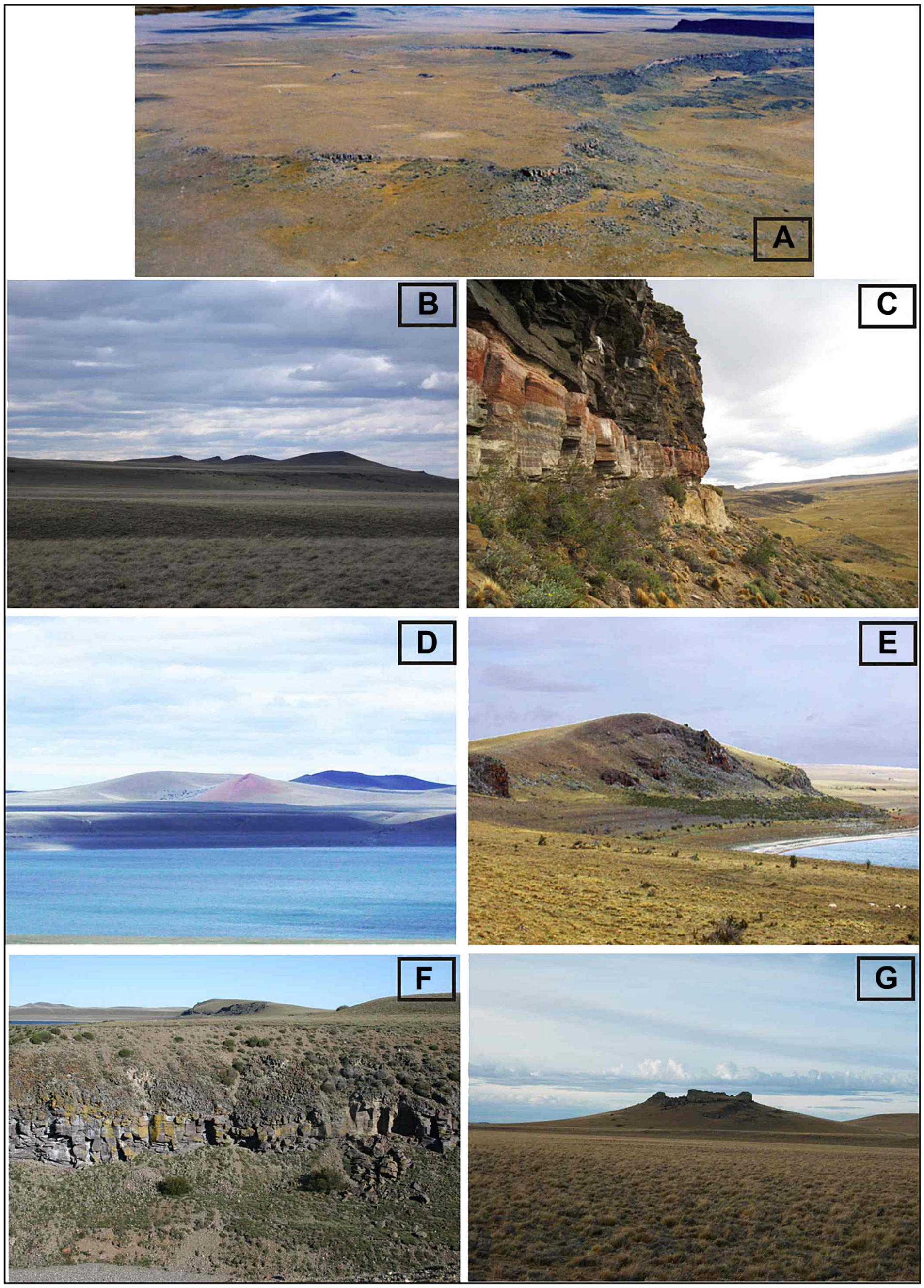

Fig. 4. Examples of positive volcanic relief (see Fig. 1 for location). A: aerial view of the Bella Vista plateau. B: Cuatro Marías alignment on the INTA basaltic tableland; this tableland is mantled by glacial deposits. C: grey to red pyroclastic deposits underlying the Bella Vista plateau along the Río Gallegos. D: Sombrero Mejicano maar and scoria cone with Laguna Potrok Aike in the foreground. E: eroded Policía scoria cone with Laguna Potrok Aike at the right. F: Bandurrias basalt flow draped by till and fluvial deposits; in the background are Policía scoria cone and Laguna Potrok Aike maar lake. G: Vigilante scoria cone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The next step in the geomorphic evolution of the study area was incision of the tablelands and inversion of topography. Topographic inversion was facilitated by the erosional resistance of the lavas with regard to the underlying SCF. The basaltic cover rocks, however, failed along the margins of the developing "mesetas", contributing to a fringe of rockfall and slumps along the flanks of the western and northern Bella Vista tableland (Figs. 3 and 5A).

Differences in the morphology of the tablelands suggest that the lavas were erupted episodically over a long period of time. These observations are verified by radiometric ages on basalt flows, which range from ca 9 Ma to ca 3.8 Ma (Table 1).

The Bella Vista basaltic plateau is the largest tableland (33 km^2). It ranges from 170 to 220 m asl with a slight slope towards the east (Fig. 4A). Volcanoes on the Bella Vista plateau have a pronounced northwest alignment, coincident with one of the main fault directions in the Pali Aike Volcanic Field. We identified and mapped three lava flow fields with different geomorphological characteristic: Carlota in the north, Nubes in the centre and Lagunitas in the south.

The Nubes field, which is the oldest lava field on the Bella Vista plateau, was sourced in vents aligned in a northwest direction. Only one severely degraded and breached scoria cone is recognisable.

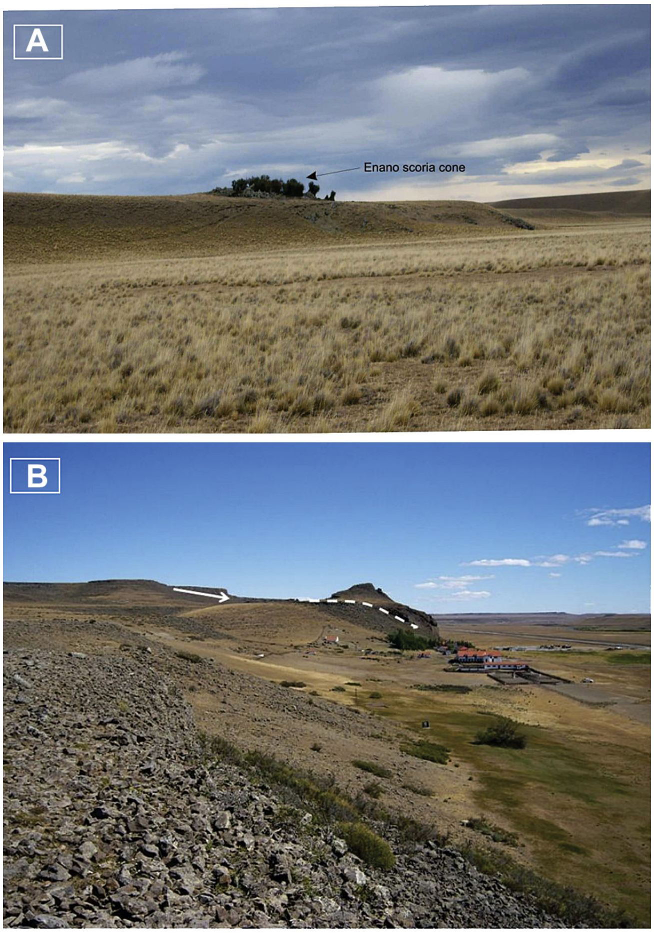

Fig. 5. A. Enano scoria cone buried by glaciofluvial deposits of Terrace Level II in Arroyo Carlota (see Fig. 1 for location). Low fluvial terrace covered by steppe vegetation in the foreground, and southwestern part of Outwash Fan III in the back right. B. The Caído scoria cone slumped from Bella Vista tableland (see Fig. 1 for location). Arrow and dashed line indicate direction of movement and sliding plane. Houses are located on the highest terrace of the Río Gallegos valley. In the foreground: Carlota lava flow field.

Other volcanoes have lost their original form, presumably due to glacial erosion. Circular or elliptical basins 300–500 m in diameter containing ephemeral lakes are located at the south side of the Nubes flow field.

The Lagunitas field has the same degraded surface as the Nubes lava flow field, but some lobate flow margins can still be recognised. Additionally, it has a less continuous cover of eolian sediments and soil, and numerous, although small, closed basins. The southwest edge of the Lagunitas field is covered by glacial sediments, including plutonic and metamorphic erratic blocks and basalt boulders of local origin.

The small Carlota field is the youngest and least degraded of the lava flow fields on the Bella Vista plateau. It was formed by eruptions on both sides of a major northwest striking structure. The eruptions produced the Carlota maar and several scoria cones.

The INTA basaltic tableland has an area of 7.5 km^2, is about 35 m above the surrounding terrain, and is partially covered by glacial deposits. A set of four degraded but aligned scoria cones, Cuatro Marías (Fig. 4B), is located on the northern margin of the INTA tableland; Cerro Descabezado, a deeply eroded vent, is located in its southwest corner.

The Petrus basaltic tableland is east and north of Laguna Potrok Aike. Its flat western edge is covered by glacial sediments, and basalts in the central area show deep grooves and other lineations resulting from glacial erosion. The central area is 50 m above the surrounding terrain. It has an oval shape that could reflect injection of a relatively young hypabyssal body of basalt (Chelotti and Trinchero, 1991). A sample of basalt form the west margin of the Petrus tableland yielded a ^{40}Ar/^{39}Ar total rock age of 3.78 ± 0.12 Ma (Corbella, 2002).

4.2.2. *Scoria cones and lava flow fields*

Plio-Pleistocene basanitic to alkali basaltic scoria cones and associated lava flow fields occur in the Laguna Potrok Aike area. Intense weathering of scoria cones has made it difficult to obtain reliable radiometric ages. The cones are nearly devoid of rill drainage patterns and have moderate to highly degraded morphologies. They are truncated or have a horseshoe-shaped morphology, with slopes of approximately 34° where fresh.

The relative ages of the scoria cones can be established from their morphology; the average slope angle decreases with increasing age due to height reduction and growth of flanking debris aprons.

Most of the cones have low cone slopes and low height to width ratios (Wood, 1980; Hasenaka and Carmichael, 1985), indicating that they have been moderately to severely degraded through cryogenesis, gravity and glacial erosion. The average slope angles of the main edifices are as follows: Nubes 7°, Vigilante 11°, Cuatro Marías 12°, Bettrus 12°, Tetas de la China 14° and Sombrero Mejicano 18° (Fig. 4D). Based on these data, the Sombrero Mejicano cone is likely the youngest in the group. This cone is located southeast of Laguna Potrok Aike inside a maar, from which scoria and lapilli were erupted and deposited over adjacent areas. Two scoria cones, Enano (Fig. 5A) and Piche (K–Ar age: 2.15 Ma, Table 1) are nearly buried; their summits emerge, respectively, above the Carlota and Gallegos valley bottoms. The Bandurrias lava flow (Figs. 1 and 4F) is located on the southwest shore of Laguna Potrok Aike near the Policía scoria cone (Fig. 4E). It was erupted 1.19 ± 0.02 Ma ago (Zolitschka et al., 2006).

4.2.3. *Maars*

The Pali Aike Volcanic Field contains about 100 maars, the most in South America. Corbella (2002) suggest a possible link between their formation and the Pleistocene periglacial environment in southern Patagonia. The maars in the Pali Aike Volcanic Field differ in size and morphology. Potrok Aike, Flamencos E and W, Rosario, Sombrero Mejicano, Carlota and Obus are shallow volcanic edifices above diatremes (Fig. 6). They are dominantly depressions in contrast to the scoria cones (White, 1991).

Gevrek and Kazanci (2000) divided maars in Turkey into three groups on the basis of their diameters: small (<500 m), medium (500–1000 m) and large (>1000 m). Using this classification, we determined that the maars around Laguna Potrok Aike surroundings are medium to large. The large maars have the following diameters: Potrok Aike 4500 m, Flamencos W and E 1960 m and 1470, respectively; Cerro Negro 1300 m; the two larger craters of the 8 km-long Rosario alignment 1100 m and 1200 m. The medium-size maar craters are Sombrero Mejicano (900 m), Carlota (650 m) and Obus (600 m). Two factors have been invoked to explain differences in diameters of maars: the hardness of the rock in which the maar formed (Lorenz, 2003) and the groundwater regime during the ascent of magma (Beget et al., 1996). The only known maars more than 4 km in diameter are the Espenberg maars on Seward Peninsula, Alaska. Their exceptional diameters have been attributed to explosive phreatomagmatic eruptions that occurred when ascending magma came into contact with water from ground ice or permafrost (Beget et al., 1996). The ratio of maar diameter to depth (D/d) is considered to be an indicator of the age of a maar (Cas and

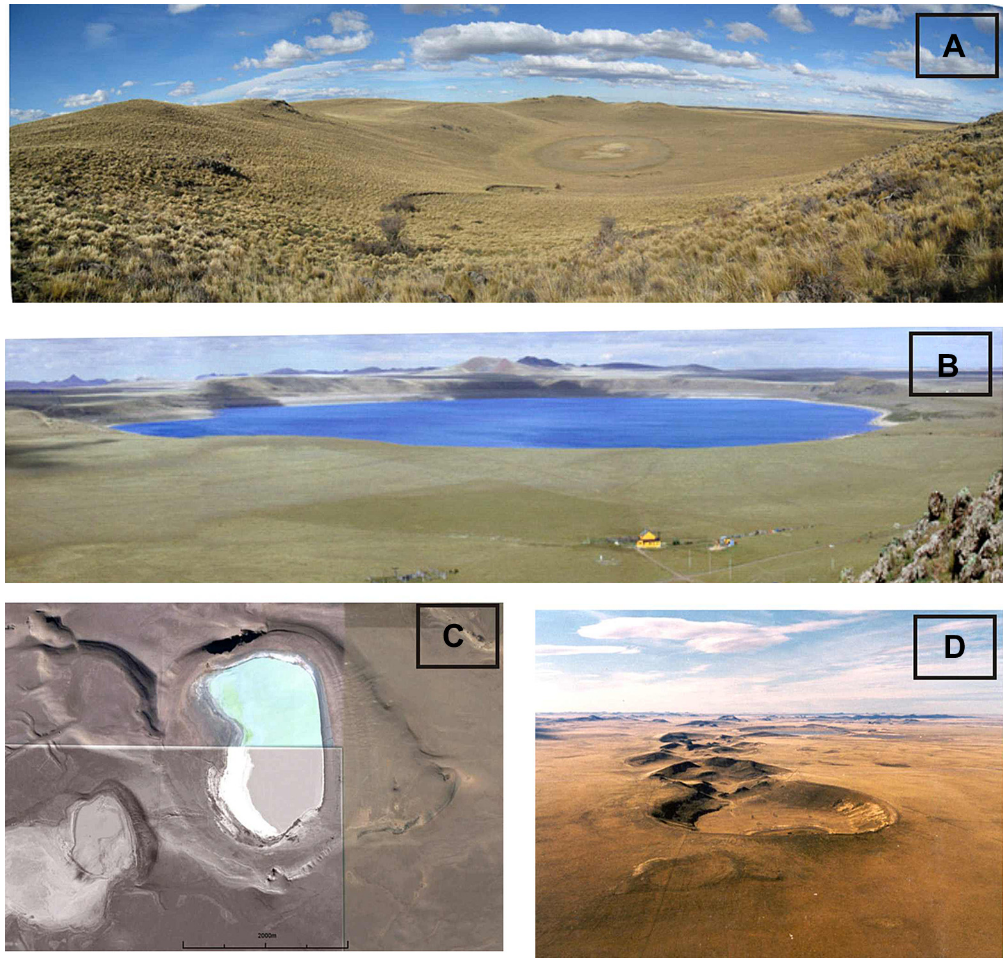

Fig. 6. Maars in different substrates. A: Carlota maar on the Bella Vista tableland. B: Laguna Potrok Aike associated with tablelands, moraines and fluvial deposits. C: Flamencos maar group. D: Rosario maar aligned with moraines.

Wright, 1987; Carn, 2000; Ross et al., 2011). Young maars have D/d ratios of 5:1. The D/d ratio increases with age as the maar is filled with sediments and erosion increases the diameter of the crater. Based on this criterion, we conclude that the youngest maars of the Laguna Potrok Aike area are Carlota and Obus, which have D/d ratios of, respectively, 15:1 and 13:1. Most of the larger maars, which are located in soft sedimentary rocks of the SCF, have higher ratios: Flamencos W and E have ratios of 39:1 and 42:1, respectively, and Potrok Aike has a ratio of >30:1. These are thought to be the oldest maars in the study area. D/d ratios may also reflect the hardness of injected rocks. When a maar forms in soft sedimentary rocks, the walls of the crater slope gently, resulting in wide craters (Smith and Lorenz, 1989; Lorenz, 2007). Carlota and Obus maars, located on competent basalts that cover the SCF, have the smallest diameters and hence D/d ratios, whereas Flamencos E and W and Potrok Aike have the largest values. Potrok Aike maar is broad ($\sim$4.5 km wide) and flat (Fig. 6B). The lake inside the maar (113 m asl and 100 m deep) is 3 km wide and has a nearly circular shape. The vertical elevation difference between the lake surface and the surrounding morainic plain is about 50 m. Topographic profiles, bathymetric maps (Zolitschka et al., 2013) and seismic surveys (Anselmetti et al., 2009; Gebhardt et al., 2011) show that the maar depression and the diatreme beneath it have a subsurface cross-section shaped like a champagne glass, which is characteristic of maars erupted into soft rocks (Lorenz, 2007). The Potrok Aike diatreme is developed in brittle sandstones and conglomerates that are capped by till and gravel. Basaltic tephra lying on top of the maar sequence yielded a $^{40}Ar/^{39}Ar$ age of 0.77 $\pm$ 0.24 Ma (Zolitschka et al., 2006). Till and overlying sediments are cut by wedge-shaped structures filled with sand, which indicate permafrost in an arid periglacial tundra environment (Kliem et al., 2013). The extraordinary size of the Potrok Aike maar can be explained by the ascent of magma when the surface was frozen (Corbella, 2002). Explosive energy and melt fragmentation are greatest for water/melt mass ratios of about 0.3 for magmas of basaltic composition. In addition, the soft bedrock favoured development of crater walls with low slopes and thus a wide crater. Once eruptive activity ended, the walls of the crater may have collapsed inside the diatreme. Erosion by lake waters may have further widened the crater.

4.3. *Glacial landforms and sediments*

Glacial sediments and landforms are widespread in the study area (Fig. 3). Rocks on the Petrus basaltic tableland have glacially polished, striated and grooved surfaces. All volcanic cones have been eroded by glaciers, for example those on the Petrus and INTA tablelands, which resemble “roches moutonnées”, and Nubes cone in the Bella Vista tableland.

Glacial depositional landforms are common on the tableland southwest of Bella Vista, on the INTA and Petrus tablelands and in the valleys (Fig. 7A,B). These landforms are generally streamlined in a westerly direction and have a low relief. Boulders up to 6 m long,

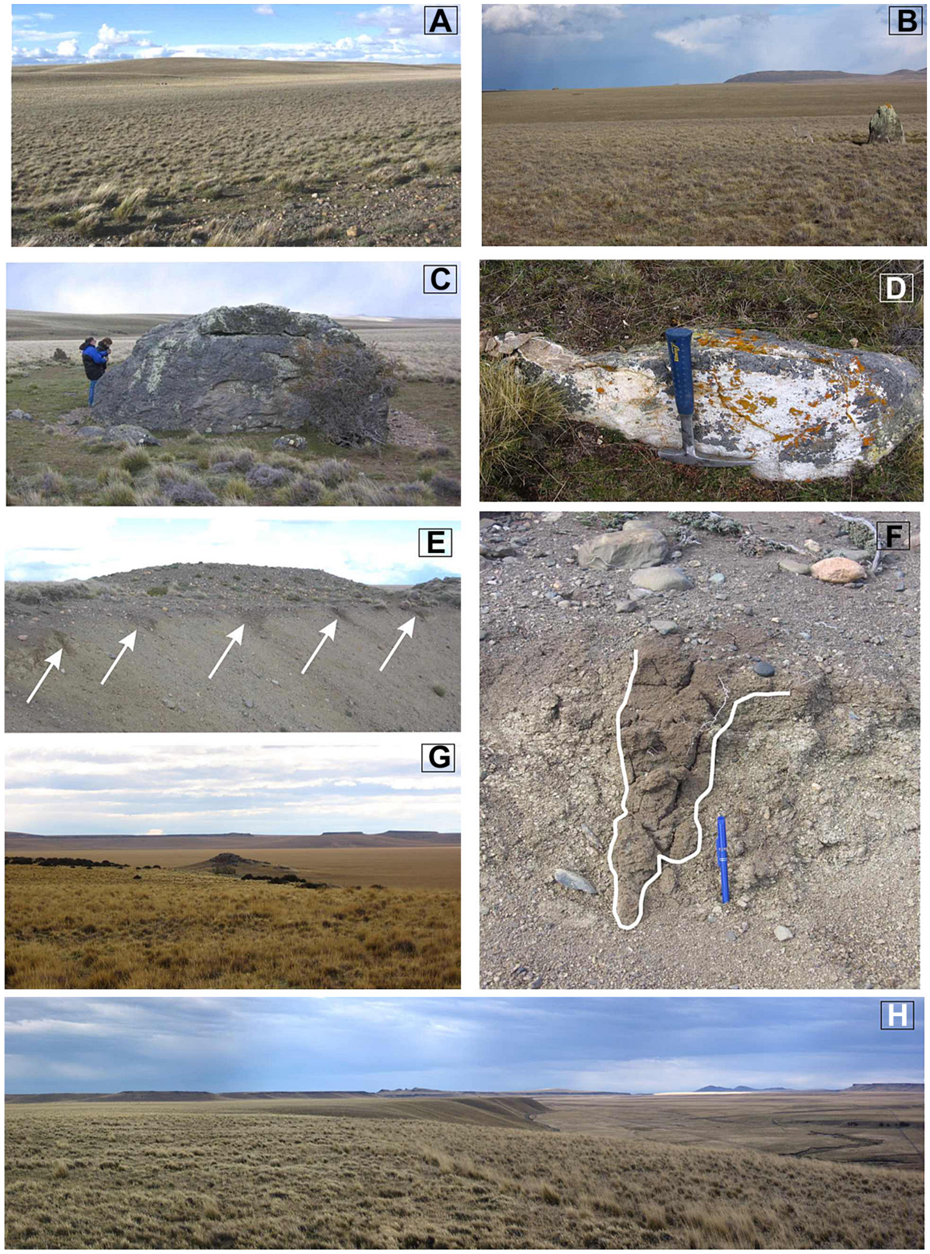

Fig. 7. Glacial features in the study area. A and B: gently undulating glacial landscape with few scattered boulders and abundant gravel. C: large volcanic boulders on top of the Petrus tableland moraines. D: Andean boulders partially covered by till in the lowlands. E: till exposed in an old quarry in the Petrus tableland, showing soils and sand wedges (arrows indicate sand wedges). F: detail of a decapitated sand wedge developed in till. G: Remnants of Cerro Piche almost entirely buried by glaciofluvial deposits of Outwash Fan III (see Fig. 1 for location). Front: Petrus tableland surface; back: volcanic tablelands on the north side of the Río Gallegos valley. H: Outwash Fan III cut by the Arroyo Carlota terrace system. Back left: Petrus tableland and Cuatro Marías cones; back right: southern tip of the Bella Vista tableland.

some of which are quartzite's derived from the Andes, are scattered on the surfaces of moraines (Fig. 7C,D). Elongated subglacial hills and boulder fields are found across the tablelands and also on their lee sides. Glacial deposits are particularly common at the foot of tableland escarpments. Tills have a clayey sandy silty matrix and a coarse fraction dominated by fine to medium with a few boulders. They include Patagonian Gravel and basalt clasts. Erosion by wind has left behind a lag gravel on till at the surface in many places (Fig. 7A). No end or lateral moraines or ablation till deposits were identified in the study area.

Sand wedges and involutions affect surface tills, as well as overlying gravel and buried argillic paleosols. The wedges are many decimetres long and separated from one another by 0.5–1 m (Fig. 7E,F). These features indicate the presence of permafrost in a periglacial tundra environment, coincident with glaciation to the south and west.

4.4. Glaciofluvial and fluvial landforms and sediments features

Meltwater produced three fan-shaped landforms with surfaces that are flat or dip gently to the north or northeastward (Fig. 3). The three fans were deposited by glacial meltwater streams related to different recessional margins of the Greatest Patagonian Glaciation. Outwash Fan I, the oldest of the three fans, has an apex at a valley that narrows between Tetas de la China and Descabezado cones. It was deposited by a meltwater stream originating from the Greatest Patagonian Glaciation ice margin to the Río Gallegos valley. Outwash Fan Level II was formed when the glacier retreated to the narrows between the Tetas de la China cones. It extended to the apex of Outwash Fan I and northeast to the present location of Laguna Potrok Aike. Arroyo Carlota has eroded both Fan I and Fan II, leaving several terraces above the present stream (Figs. 1 and 3). Outwash Fan III, the youngest of the three fans, was formed by meltwater streams flowing along North and South Arroyo Bandurrias to Arroyo Carlota and Rio Gallegos. Outwash spread over the Rio Gallegos alluvial plain and buried the Piche scoria cone (Fig. 7G,H). These deposits are part of Río Gallegos Terrace I. The extremely eroded Enano scoria cone in Arroyo Carlota is nearly completely buried by Outwash Fan I and III and by deposits of younger terrace treads (Figs. 5B and 8).

Three truncated levels of terraces can be traced along North and South Arroyo Bandurrias (Fig. 8). Both streams were part of the same fluvial system (the Bandurrias paleovalley) before Potrok Aike maar crater formed. During the maar eruption pyroclastic debris temporarily blocked the Bandurrias paleovalley at the Diego Ritchie police station (Fig. 1) forming a minor dam in the channel. Remnants of the dam can be seen on the lower slopes of the Policía scoria cone up to 4 m above the present valley floor. A small and shallow ephemeral lake formed upstream of the dam.

4.5. Other geomorphological processes and landforms

Gravity, wind and wave processes have also affected the landscape. Wind is the most continuous and ubiquitous geomorphological agent operating on the landscape today. A thin mantle of silty sand containing distal volcanic ashes covers much of the land surface. Deflation has deepened and enlarged volcanic and glacial basins, which become temporary shallow lakes after periods of rain and snowmelt. Sand dunes occur leeward of dry basins; the largest dunes are east of the Bella Vista volcanic tableland (Fig. 3; Mazzoni and Vázquez, 2009).

Slow mass movements have left a cover of colluvium on slopes. Rotational landslides are common along the edges of the basaltic tablelands, especially the Bella Vista tableland. The largest slump is near the Estancia Carlota (Fig. 1); the Caído scoria cone slipped from the Bella Vista plateau onto Río Gallegos Terrace I (Fig. 5B).

Former high-level beaches are preserved in the largest basins, indicating lake high stands during wet periods. These landforms are well developed around the Potrok Aike maar lake, and range from 21 m above present-day lake level to 35 m below (Anselmetti et al., 2009; Kliem et al., 2013).

5. Landscape evolution

Landscape reconstruction derived from geomorphological evidence allows us to establish the sequence of landscape-forming events in the Potrok Aike area and to discuss the time of formation of the maar. Fig. 9 shows the relative age of landforms linked to the marine oxygen isotope record (Lisiecki and Raymo, 2004).

5.1. Late Middle Miocene–Pliocene

The Middle Miocene landscape was characterized by low-relief plains, gently sloping to the east. The drainage was controlled by faults with northwesterly and westerly strikes. The tablelands are the result of Andean epirogenic uplift during the Miocene, which

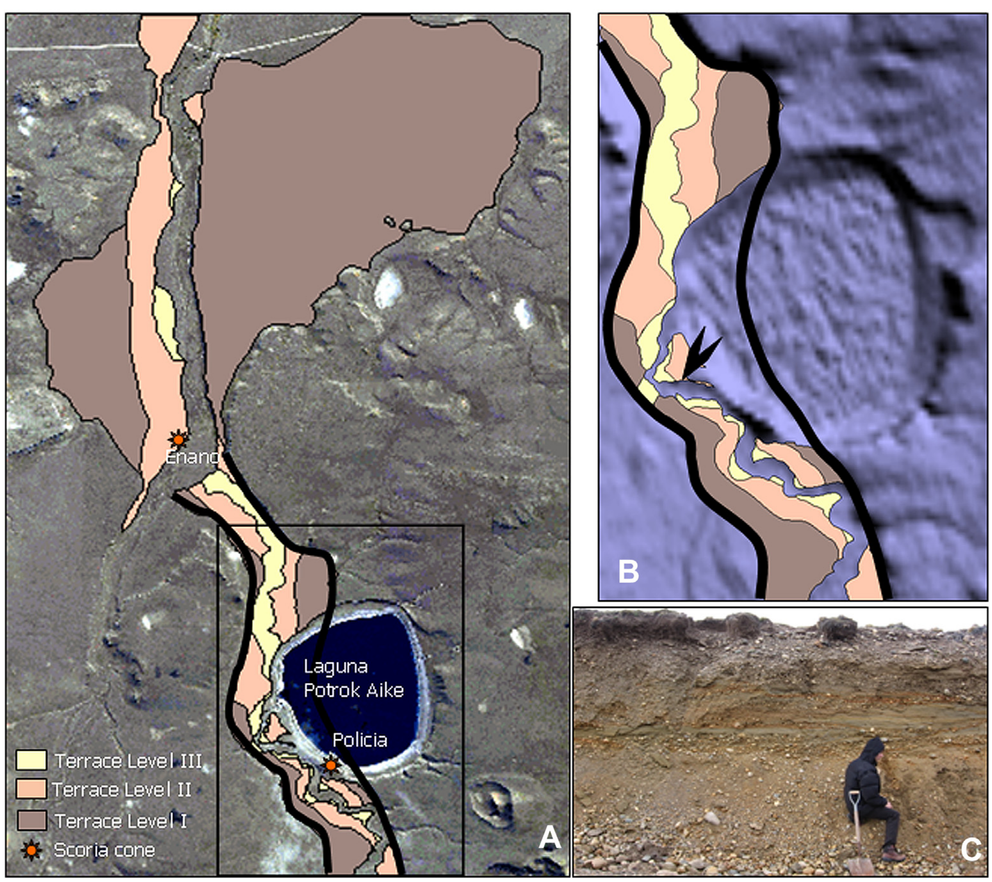

Fig. 8. Glaciofluvial terrace system developed along the Bandurrias paleovalley and Arroyo Carlota and truncated by the Potrok Aike maar. A: overview. B: detail. C: stratigraphic section of Terrace Level II (location is indicated by a black arrow in B). Scoria cones in the valley are shown in A as asterisks.

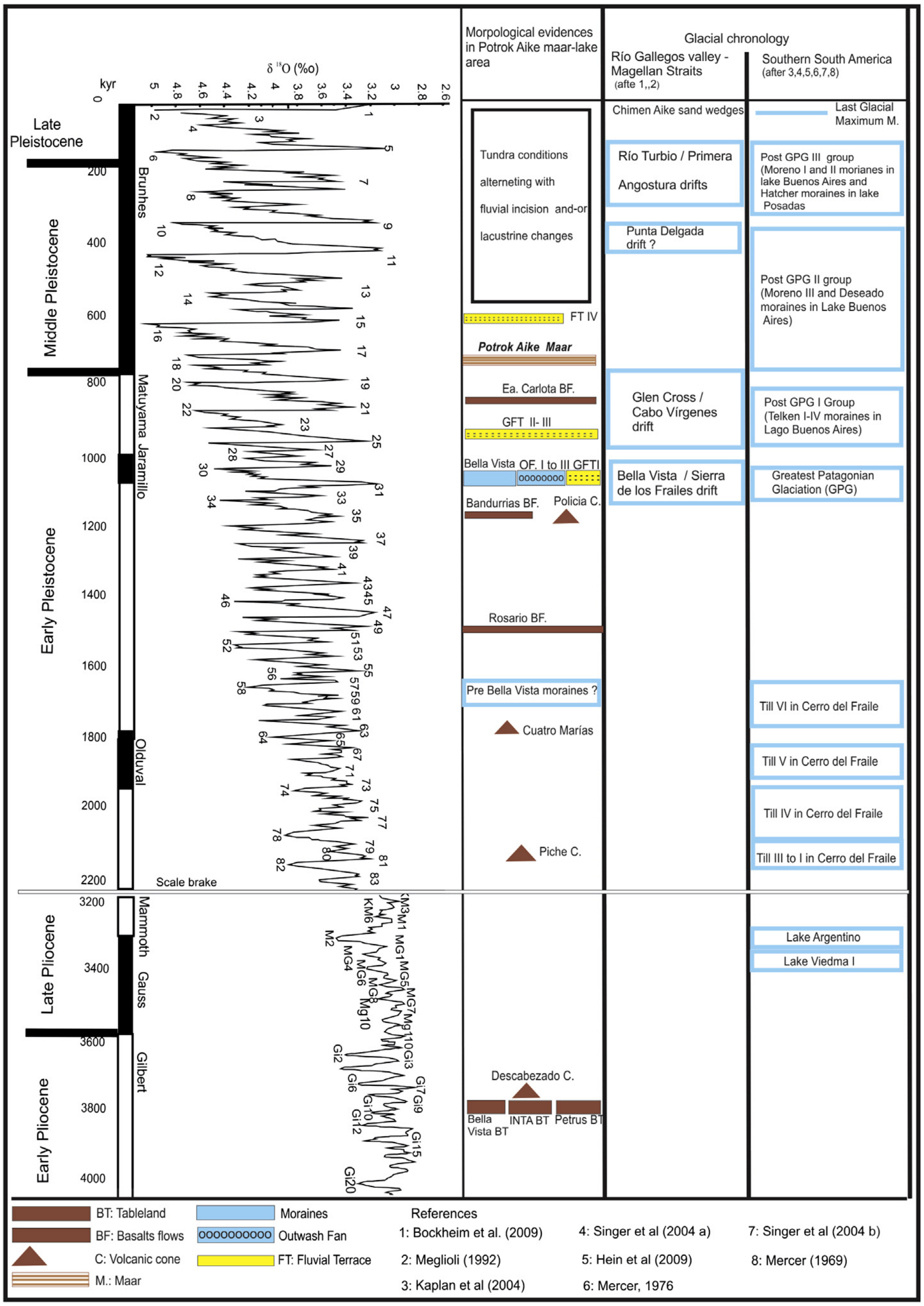

Fig. 9. Preliminary relationships of landforms in the Laguna Potrok Aike area. Morphological evidences and radiometric ages are compared with the glacial chronology of southern Patagonia and with the paleomagnetic and oxygen isotope stratigraphies (Lisiecki and Raymo, 2004; and papers cited therein) (Mercer, 1969; Kaplan et al., 2004; Hein et al., 2009).

promoted incision and valley widening by streams. Episodic fissure eruptions covered the sedimentary plains with basaltic lava flows. Radiometric data show that the lavas range in age from about 9.15 Ma (Mejia et al., 2004) to 3.78 Ma (Corbella, 2002). The centres from which the lava erupted are currently unknown; many of them probably were completely destroyed by subsequent glacial erosion.

5.2. *Early Pleistocene*

Volcanic activity continued during the Early Pleistocene, with the formation of Piche cone in the Rio Gallegos valley at 2.1 Ma (Meglioli, 1992). At least 90 m of river incision occurred sometime before the cone formed. The cone was later buried by gravels of Río Gallegos Terrace I (Corbella and Ercolano, 2002). This prominent terrace can be traced up-valley to the end moraine of the Greatest Patagonian Glaciation (ca 1 Ma).

Glaciers left "roches-moutonnées" on volcanic edifices and grooves on lava flows. They also produced west-trending elongated ground moraines and erratics, some of Andean provenance. Based on the location of the study area, beyond the end moraines of the Greatest Patagonian Glaciation, we hypothesize that glaciers covered the Laguna Potrok Aike area at least once before this glaciation. Researchers have previously established that several glacial advances occurred in the southern Patagonian Andes before the Greatest Patagonian Glaciation. Evidences of old glaciations have also been found in the Cerro del Fraile area (Singer et al., 2004a,b) and in the Lago Argentino and Lago Viedma regions (Rabassa et al., 2005; Coronato and Rabassa, 2011). Collectively, the evidence suggests that glaciers advanced during some of the cold stages of the Early Pleistocene (MIS 58 to MG4, Fig. 9).

5.3. Middle Pleistocene

The Rosario and Bandurrias basalt flows date to the Middle Pleistocene (Fig. 9). In addition, the greatest glacial advance occurred in Patagonia between 1.15 and 1.05 Ma (Ton-That et al., 1999; Singer et al., 2004a,b; Rabassa et al., 2005; Coronato and Rabassa, 2011). This advance is represented by the Bella Vista ground and terminal moraines in the Río Gallegos valley (Meglioli, 1992), reaching almost to the west margin of the study area, and by the Sierra de los Frailes Drift (Meglioli, 1992) along the Strait of Magellan (Fig. 10). No terminal moraines of Strait of Magellan glaciers were recognised around Laguna Potrok Aike, although a till overlying the Bandurrias basalt flow (1.19 Ma) indicates that ice reached the study area almost simultaneously with the Río Gallegos valley glacial advance. We postulate that the southern part of the study area is at the limit of the Greatest Patagonian Glaciation advance and that most of the area was influenced by an ice-proximal periglacial environment.

Geomorphological relations among Outwash Fans I, II and III lead us to infer a stepped retreat of the glacier lobe of the Sierra de los Frailes Glaciation in the Strait of Magellan. Outwash Fans I and II formed near the glacier margin, whereas Outwash Fan III was deposited by the Bandurrias meltwater stream far from the glacier margin. Meltwater channelled down Bandurrias valley eroded the distal part of Outwash Fan I and spread outwash over the former Río Gallegos alluvial plain. Outwash Fan III is older than 0.850 ± 0.03 Ma (Mejia et al., 2004), which is the age of a basalt flow on the former alluvial plain of the Rio Gallegos near Estancia Carlota (Fig. 3). There is evidence for at least four Middle Pleistocene glaciations in southern Patagonia and the Strait of Magellan after the Greatest Patagonian Glaciation (Meglioli, 1992; Coronato and Rabassa, 2011). No glacial landforms or till of these glaciations have been recognized in the study area, but outwash deposits can be traced up to 15 km south to the frontal moraines of the Cabo Vírgenes Glaciation forming Terrace Levels II and III, along Arroyo Bandurrias and Arroyo Carlota (Fig. 10). No meltwater streams of later glaciations could have flowed along those streams given the elevation differences between the study area and the Strait of Magellan. This result is in agreement with the glacial model of Pleistocene Patagonian glaciations proposed by Rabassa and Clapperton (1990), in which younger moraines are nested into older ones because progressive greater glacial erosion confined glaciers to valleys.

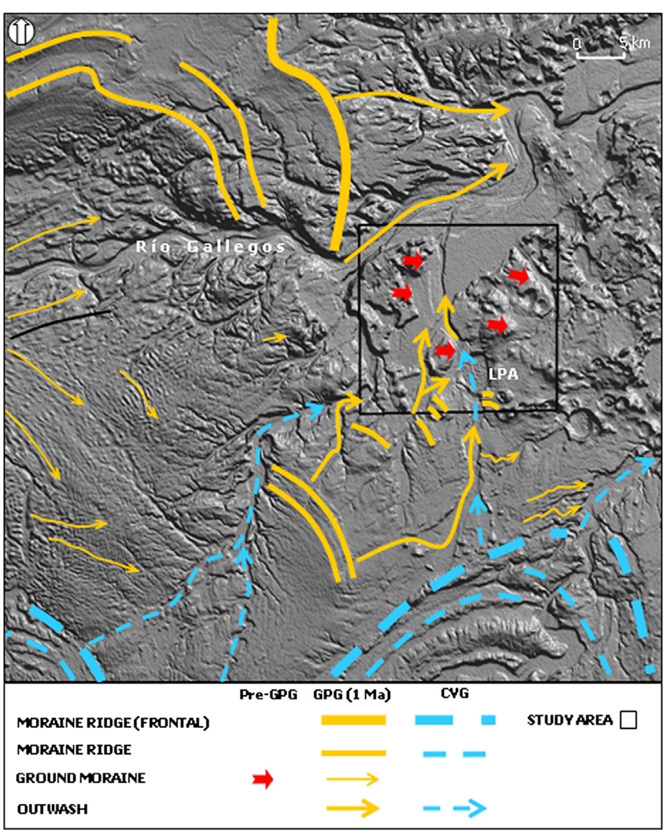

Fig. 10. Extent of Pleistocene glaciations in the study area. LPA: Laguna Potrok Aike. GGP: Greatest Patagonian Glaciation. CVG: Cabo Vírgenes Glaciation.

Arroyo Bandurrias I, II, and III outwash terraces are truncated by the Potrok Aike maar and are covered by pyroclastic deposits, indicating that these terraces are older than about 0.77 Ma. The absence of lower terraces along Bandurrias valley indicates that this valley carried no meltwater after the Cabo Vírgenes Glaciation. Fluvial activity persisted only along Arroyo Carlota, which contains Terrace Level IV and lower ones close to the present floodplain.

Large maars with diameters >4 km have been attributed to explosive phreatomagmatic eruptions during which ascending magma came into contact with permafrost (Beget et al., 1996). Accordingly, Potrok Aike maar may have formed during a cold period after the Cabo Vírgenes Glaciation. The genesis of the Potrok Aike maar could be considered as a chronological marker for tundra conditions which occurred after Cabo Vírgenes deglaciation stages. Because the only radiometric age on Potrok Aike tephra deposits (0.77 ± 0.24 Ma; Zolitschka et al., 2006) has a high degree of uncertainty, the cold interval during which the maar formed could date to anytime between MIS 24 and MIS 14 (Fig. 9).

Based on sand wedge studies, Bockheim et al. (2009) argued that the regional climate was cold (mean annual temperature −4 to −8 °C, or colder) and dry (main annual precipitation ≤100 mm) during Middle Pleistocene glacial periods. It was warmer (7 °C) and moister (≥250 mm) during interglacials, contributing to the formation of petrocalcic horizons. Argillic paleosoils indicate unusually moist interglacials (400 mm). Paleopedological evidence of a more humid and warmer climate during the older Pleistocene interglacials has also been found farther north (Schellmann, 2000). Landslides and high lake levels also are characteristic of wetter periods.

5.4. Late Pleistocene–Holocene

No major landforms of Late Pleistocene or Holocene age were identified in this study. Environmental changes during this time have been interpreted from Laguna Potrok Aike sedimentary cores and are presented in several papers (cf. Zolitschka et al., 2013 for an overview). This lacustrine environmental archive offers information about landscape processes not revealed by surficial landforms.

Glaciers of the Last Glaciation (ca 25 ka BP) were restricted to the western Río Gallegos valley and to the southern Strait of Magellan (McCulloch et al., 2005). The cold climate prevailing at that time accelerated mechanical weathering and created periglacial sand wedges in ancient till in the study area (Kliem et al., 2013).

Several elevated beaches around the Laguna Potrok Aike maar lake record fluctuations in lake level forced by climate fluctuations during the Holocene (Haberzettl et al., 2008; Anselmetti et al., 2009; Kliem et al., 2013). Lake-level changes affected base level in gullies on the flanks of the maar, promoting deepening and headward erosion. Young fluvial terrace levels eroded the till and exposed the Bandurrias basaltic flow at the mouth of the Arroyo South Bandurrias (Fig. 1).

During dry periods wind was the main agent affecting the landscape. Strong winds abraded bedrock and boulder surfaces, deflated areas not covered by soil and dry lakes and deposited a veneer of silty sand across over the landscape. Wind also carried volcanic ash from erupting Andean volcanoes to the study area at several times during the Late Pleistocene and the Holocene (Stern, 2007; Haberzettl et al., 2009; Wastegard et al., 2013).

6. Conclusions

Geomorphological mapping and morpho-stratigraphic relationships, together with regional and global comparisons, provide new insights into the evolution of the landscape in the Laguna Potrok Aike area. Valley deepening and widening, basalt eruptions and tectonics modified the Middle Miocene to Early Pliocene landscape.

Key conclusions of this study include:

1. Glaciers overrode volcanic tablelands in the study area one or more times after 3.78 Ma and before the Greatest Patagonian Glaciation (1 Ma). This evidence is against previous statements that this area was first covered by the Greatest Patagonian Glaciation.
2. Piche and Enano scoria cones and the former fluvial surface on which they lie were buried by outwash from the Greatest Patagonian Glaciation. The terrace system along the Río Gallegos valley is therefore younger than the Greatest Patagonian Glaciation.
3. Glaciers reached the study area from the south during the Greatest Patagonian Glaciation, preserving former drift and glacial features on the tablelands. The limit of this advance is not marked by conspicuous landforms, the radiometric age of 1.19 Ma on the Bandurrias basalt flow is a maximum age for this advance which fits to the Greatest Patagonian Glaciation regional chronology.
4. Outwash Fans I, II, and III record the stepped retreat of glaciers during the Greatest Patagonian Glaciation. Meltwater streams during the subsequent Cabo Vírgenes Glaciation reached the Laguna Potrok Aike area and formed the Outwash Terraces Levels II and III along Bandurrias valley. After the Cabo Vírgenes Glaciation, runoff in this valley was limited to seasonal precipitation and melt of winter snowfall.
5. The truncated outwash terrace system in the Bandurrias valley indicates that the Potrok Aike maar formed after the Cabo Vírgenes deglaciation. The extraordinary size of this maar suggests a possible contact of ascending magma and ground ice and thus the presence of regional permafrost.
6. Phreatomagmatic eruptions created numerous maars in this part of the Pali Aike Volcanic Field. A likely contributing factor is the availability of meltwater or ground ice. D/d ratios on most of the maars indicate that Potrok Aike maar is probably one of the oldest maars in this volcanic field.
7. Periglacial conditions during cold periods alternated with minor fluvial erosion during interglacial periods that occurred from the Middle to Late Pleistocene. Wind has been the main regional geomorphic process operating during the Holocene; mass wasting and erosion along lake shorelines have operated locally, especially during wetter periods. Middle and Late Pleistocene landforms, however, have suffered little modification since their formation remaining nearly “fossilised”. The major evidences of regional environmental changes that occurred during the Late Pleistocene to Holocene should be stored in lacustrine sediment records of Laguna Potrok Aike.

This study presents new data and interpretations that frame the results obtained from the study of the lacustrine sediment records of the “Potrok Aike Maar Lake Sediment Archive Drilling Project” (PASADO). Additional detailed surficial geological and geophysical investigations as well as radiometric dating are needed to achieve a better understanding of landscape evolution in this part of southern Patagonia.

Acknowledgements

This research was supported by grants from ANPCYT-FONCYT (PIP N° 06-02338-02) and the Universidad Nacional de la Patagonia Austral (PI 29/A195). We thank the owners of Carlota and Bella Vista ranches and the staff at the Potrok Aike-INTA Station for allowing access to their properties. The Dirección Provincial de Medio Ambiente de la Provincia de Santa Cruz (Environmental Agency of Santa Cruz Province) provided logistical support. J. Caballero and J. Szeuzuk (UNPA-UARG) helped us in the field. We thank Jorge Rabassa (CADIC-CONICET), F. Ponce (CADIC-CONICET) and B. Zolitschka (University of Bremen) for constructive remarks on earlier versions of this manuscript. We also express our sincere thanks to the reviewers G. Schellman and J.J. Clague for their suggestions and encouragement.

References

Ameghino, F., 1889. Contribución al conocimiento de los mamíferos fósiles de la República Argentina. Actas Academia Nacional de Ciencias de Córdoba 13, 229–445.
Anselmetti, F.S., Ariztegui, D., Batist, M.D., Gebhardt, A.C., Haberzettl, T., Niessen, F., Ohlendorf, C., Zolitschka, B., 2009. Environmental history of southern Patagonia unravelled by the seismic stratigraphy of Laguna Potrok Aike. Sedimentology 56, 873–892.
Beget, J.E., Hopkins, D.M., Charron, S.D., 1996. The largest known Maaars on Earth, Seward Peninsula, Northwest Alaska. Arctic 49, 62–69.
Bockheim, J., Coronato, A., Ponce, F., Ercolano, B., Rabassa, J., 2009. Relict sand wedges in southern Patagonia and their stratigraphic and paleoenvironmental significance. Quaternary Science Reviews 28, 1188–1199.
Caldenius, C., 1932. Las Glaciaciones Cuaternarias en Patagonia y Tierra del Fuego. In: Ministerio de Agricultura de la Nación, vol. 95. Dirección General de Minas y Geología, Buenos Aires, 148 p.
Carn, S.A., 2000. The Lamongan volcanic field, East Java, Indonesia: physical volcanology, historic activity and hazards. Journal of Volcanology and Geothermal Research 95, 81–108.
Cas, R.F., Wright, J.V., 1987. Volcanic Succession: Modern and Ancient. Allen & Unwin, London, 529 p.
Chelotti, L., Trinchero, E., 1991. Cuerpos intrusivos en la Cuenca Austral: Nuevos estudios. Boletín de Informaciones Petroleras 25, 39–51.
Clapperton, Ch., 1993. Quaternary Geology and Geomorphology of South America. Elsevier, Amsterdam, 779 p.
Corbella, 1999. Dataciones radimétricas en Pali Aike, Patagonia Austral. XIV Congreso Geológico Argentino, Salta, Actas, II, pp. 265–268.
Corbella, H., 2002. El campo volcano-tectónico de Pali Aike. In: Haller, M. (Ed.), Geología y Recursos Naturales de Santa Cruz. Asociación Geológica Argentina, Buenos Aires, pp. 285–302.
Corbella, H., Ercolano, B., 2002. In: Cabaleri, N., Cingolani, C.A., Linares, E., López de Luchi, M.G., Ostera, H.A., Panarello, H.O. (Eds.), 2002. Acerca del valle medio e inferior del río Gallegos. Patagonia austral -Argentina, vol. II. Actas del XV Congreso Geológico Argentino, Buenos Aires, pp. 661–666.
Corbella, H., Chelotti, L., Pomposiello, C., 1996. Neotectónica del Rift Jurásico Austral en Pali-Aike, Patagonia extrandina, Santa Cruz, Argentina. XIII Congreso Geológico Argentino. Actas II, 383–393.
Coronato, A., Rabassa, J., 2011. Pleistocene glaciations in southern Patagonia and Tierra del Fuego. In: Ehlers, J., Gibbard, P. (Eds.), Quaternary Glaciations – Extent and Chronology, Part IV – A Closer Look. Elsevier Developments in Quaternary Science, vol. 15, pp. 715–727.
Dessanti, R.N., 1973. Sobre el control estructural de algunos rasgos geomorfológicos del Noroeste de la Patagonia. Revista de la Asociación Geológica Argentina 28, 95–96.
Diraison, M., Coppold, P.R., Gapais, D., Rosello, A.E., 1997. Magellan Strait, part of a Neogene rift system. Geology 25, 703–706.

D'Orazio, M., Agostini, S., Mazzarini, F., Innocenti, F., Manetti, P., Haller, M.J., Alfredo Lahsen, A., 2000. The Pali Aike volcanic field, Patagonia: slab-window magmatism near the tip of South America. Tectonophysics 321, 407–427.
Fidalgo, F., 1973. Sobre los bajos sin salida en Patagonia. Revista de la Asociación Geológica Argentina 28, 91–92.
Fidalgo, F., Riggi, J.C., 1970. Consideraciones geomorfológicas y sedimentológicas sobre los rodados Patagónicos. Revista Asociación Geológica Argentina 25, 430–443.
Fleagle, J.G., Bown, T.M., Swisher III, C.C., Buckley, G.A., 1995. Age of the Pinturas and Santa Cruz Formations. In: Actas del VI Congreso Argentino de Paleontología y Bioestratigrafía, Trelew, Argentina, pp. 129–135.
Gebhardt, A.C., De Batist, M., Niessen, F., Anselmetti, F.S., Ariztegui, D., Kopsch, C., Ohlendorf, C., Zolitschka, B., 2011. Origin and evolution of the Laguna Potrok Aike maar, Southern Patagonia. Journal of Volcanology and Geothermal Research 201, 357–363.
Gebhardt, A.C., Ohlendorf, C., Niessen, F., De Batist, M., Anselmetti, F.S., Ariztegui, D., Zolitschka, B., 2012. Seismic evidence of a highly dynamic lake development in Southeastern Patagonia during the Late Pleistocene. Sedimentology 59, 1087–1100.
Gevrek, A.I., Kazanci, N., 2000. A Pleistocene, pyroclastic-poor maar from central Anatolia, Turkey: influence of a local fault on a phreatomagmatic eruption. Journal of Volcanology and Geothermal Research 95, 309–317.
Gogorza, C., Sinito, A.M., Ohlendorf, C., Kastner, S., Zolitschka, B., 2011. Paleosecular variation and paleointensity records for the last millennium from southern South America (Laguna Potrok Aike, Santa Cruz, Argentina). Physics of the Earth and Planetary Interiors 184, 41–50.
Gogorza, C.S.G., Irurzun, M.A., Sinito, A.M., Lisé-Pronovost, A., St-Onge, G., Haberzettl, T., Ohlendorf, C., Kastner, S., Zolitschka, B., 2012. High-resolution paleomagnetic records from Laguna Potrok Aike (Patagonia, Argentina) for the last 16,000 years. Geochemistry, Geophysics, Geosystems. http://dx.doi.org/10.1029/2011GC003900.
Haberzettl, T., Fey, M., Lücke, A., Maidana, N., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M., Zolitschka, B., 2005. Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). Journal of Paleolimnology 33, 283–302.
Haberzettl, T., Corbella, H., Fey, M., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M., Wulf, S., Zolitschka, B., 2007. Lateglacial and Holocene wet-dry cycles in southern Patagonia: chronology, sedimentology and geochemistry of a lacustrine record from Laguna Potrok Aike, Argentina. The Holocene 17, 297–310.
Haberzettl, T., Kück, B., Wulf, S., Anselmetti, F., Ariztegui, D., Corbella, H., Fey, M., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M., Zolitschka, B., 2008. Hydrological variability in southeastern Patagonia and explosive volcanic activity in the southern Andean Cordillera during Oxygen Isotope Stage 3 and the Holocene inferred from lake sediments of Laguna Potrok Aike, Argentina. Palaeogeography, Palaeoclimatology, Palaeoecology 259, 213–229.
Haberzettl, T., Anselmetti, F.S., Bowen, S.W., Fey, M., Mayr, C., Zolitschka, B., Ariztegui, D., Mauz, B., Ohlendorf, C., Kastner, S., Lücke, A., Schäbitz, F., Wille, M., 2009. Late Pleistocene dust deposition in the Patagonian steppe – extending and refining the paleoenvironmental and tephrochronological record from Laguna Potrok Aike back to 55 ka. Quaternary Science Reviews 28, 2927–2939.
Hasenaka, T., Carmichael, I.S.E., 1985. A compilation of location, size and geomorphological parameters of volcanoes of the Michoacan-Guanajuato Volcanic field, Central Mexico. Geofísica Internacional 24, 577–607.
Hein, A., Hulton, N., Dunai, T., Schnabel, C., Kaplan, M., Naylor, M., Xu, S., 2009. Middle Pleistocene glaciation in Patagonia dated by cosmogenic-nuclide measurements on outwash gravels. Earth and Planetary Science Letters 286, 184–197.
Kaplan, M., Ackert, R., Singer, B., Douglass, D., Kurz, M., 2004. Cosmogenic nuclide chronology of millennial-scale glacial advances during the O-isotope stage 2 in Patagonia. Geological Society of America Bulletin 116, 308–321.
Kastner, S., Ohlendorf, C., Haberzettl, T., Lücke, A., Mayr, C., Maidana, N.I., Schäbitz, F., Zolitschka, B., 2010. Southern hemispheric westerlies control the spatial distribution of modern sediments in Laguna Potrok Aike, Argentina. Journal of Paleolimnology 44, 887–902.
Kliem, P., Enters, D., Hahn, A., Ohlendorf, Ch., Lisé-Pronovost, A., St-Onge, G., Wastegård, S., Zolitschka, B., the PASADO science team, 2013. Lithology, radiocarbon chronology and sedimentological interpretation of the lacustrine record from Laguna Potrok Aike, southern Patagonia. Quaternary Science Reviews 71, 54–69.
Lisiecki, L.E., Raymo, M.E., 2004. A Pliocene–Pleistocene stack of 57 globally distributed benthic delta ^{18}O records. Paleoceanography 20, 1–17.
Lorenz, V., 2003. Maar-diatremes volcanoes, their formation, and their setting in hard-rock or soft-rock environments. Geolines 15, 7283.
Lorenz, V., 2007. Syn- and post-eruptive hazards of maar-diatremes volcanoes. Journal of Volcanology and Geothermal Research 159, 285–312.
Mayr, C., Lücke, A., Stichler, W., Trimborn, P., Ercolano, B., Oliva, G., Ohlendorf, C., Soto, J., Fey, M., Haberzettl, T., Janssen, S., Schäbitz, F., Schleser, G.H., Wille, M., Zolitschka, B., 2007. Precipitation origin and evaporation of lakes in semi-arid Patagonia (Argentina) inferred from stable isotopes (d18O, d2H). Journal of Hydrology 334, 53–63.
Mayr, C., Lücke, A., Maidana, N.I., Wille, M., Haberzettl, T., Corbella, H., Ohlendorf, C., Schäbitz, F., Fey, M., Janssen, S., Zolitschka, B., 2009. Isotopic and geochemical fingerprints on lacustrine organic matter from Laguna Potrok Aike (southern Patagonia, Argentina) reflect environmental changes during the last 16,000 years. Journal of Paleolimnology 42, 81–102.
Mazzoni, E., Vázquez, M., 2009. Desertification in Patagonia. In: Latrubesse, E. (Ed.), Natural Hazards and Human-exacerbated Disasters in Latin American. Elsevier Developments in Earth Surface Processes, pp. 351–357.
McCulloch, R., Fogwill, C., Sudgen, M., Bentley, M., Kubik, P., 2005. Chronology of the last glaciation in central Strait of Magellan and Bahía Inútil. Geografiska Annaler 87A, 289–312.
Mejia, V., Opdycke, D., Vilas, J., Singer, B., Stoner, J., 2004. Plio-Pleistocene time-average field in the southern Patagonia recorded lava flows. Geochemistry, Geophysics, Geosystems 5 (3), 1–15.
Meglioli, A. 1992. Glacial geology of southernmost Patagonia, the Strait of Magellan and Northern Tierra del Fuego. Ph.D dissertation, Lehigh University, Bethlehem, MA.
Mercer, J., 1969. Glaciation in Southern Argentina more than two million years ago. Science 164, 823–825.
Mercer, J., 1976. Glacial history of southernmost South America. Quaternary Research 6, 125–166.
Methol, E., 1967. Consideraciones acerca de los "pequeños bajos sin salida". Revista de la Asociación Geológica Argentina 22, 295–311.
Rabassa, J., Clapperton, Ch, 1990. Quaternary glaciations of the southern Andes. Quaternary Science Reviews 9, 153–174.
Rabassa, J., Coronato, A., Salemme, M., 2005. Chronology of the late Cenozoic Patagonian glaciations and their correlation with biostratigraphic units of the Pampean region (Argentina). Journal of South American Earth Sciences 20, 81–103.
Ramos, V., 2002. El magmatismo neógeno de la Cordillera Patagónica. In: Haller, M.J. (Ed.), 2002. Geología y Recursos Naturales de Santa Cruz, XV Congreso Geológico Argentino, Relatorio, vol. 1. Asociación Geológica Argentino, Buenos Aires, pp. 187–200.
Recasens, C., Ariztegui, D., Gebhardt, C., Gogorza, C., Haberzettl, T., Hahn, A., Kliem, P., Lisé-Pronovost, A., Lücke, A., Maidana, N.I., Mayr, C., Ohlendorf, C., Schäbitz, F., St-Onge, G., Wille, M., Zolitschka, B., the PASADO Science Team. New insights into paleoenvironmental changes in Laguna Potrok Aike, southern Patagonia, since the Late Pleistocene: the PASADO multiproxy record. The Holocene, in press.
Ross, P.S., Delpit, S., Haller, M.J., Nemeth, K., Corbella, H., 2011. Influence of the substrate on maar-diatreme volcanoes – an example of a mixed setting from the Pali Aike volcanic field, Argentina. Journal of Volcanology and Geothermal Research 201, 253–271.
Scalabrini Ortiz, J., Spikermann, J.P., Medina, F., 1985. Geología y geomorfología de Santa Cruz entre los paralelos 51° y 52° de lat. Sur. In: Boelcke, O., Moore, D.M., Roig, F.A. (Eds.), Transecta Botánica de la Patagonia Austral. CONICET, Royal Society and Instituto de la Patagonia, pp. 41–48.
Schellmann, G., 2000. Landscape evolution and glacial history of Southern Patagonia since the Late Miocene – some general aspects. Zentralblatt für Geologie und Paläontologie, Teil I, 1013–1026.
Singer, B.S., Ackert, R.P., Guillou, H., 2004a. 40Ar/39Ar and K-Ar chronology of Pleistocene glaciations in Patagonia. Geological Society of American Bulletin 116, 434–450.
Singer, B., Brown, L., Rabassa, J., Guillou, H., 2004b. 40Ar/39Ar Ages of Late Pliocene and Early Pleistocene Geomagnetic and Glacial Events in Southern Argentina. In: AGU Geophysical Monograph "Timescales of the Internal Geomagnetic Field", pp. 175–190.
Smith, C.B., Lorenz, V., 1989. Volcanology of the Ellendale Lamproite Pipes. In: Geological Society of Australia, Special Publication, vol. 14, pp. 505–519.
Skewes, M.A., 1978. Geología, petrología, quimismo y origen de los volcanes del área de Pali-Aike, Magallanes, Chile. Anales del Instituto de la Patagonia, Punta Arenas 9, 95–106.
Stern, Ch, 2007. Holocene tephrochronology record of large explosive eruptions in the southernmost Patagonian Andes. Bulletin of Volcanology 70, 435–454.
Ton-That, T., Singer, B., Mörner, N., Rabassa, J., 1999. Datación de lavas basálticas por 40Ar/39Ar y geología glacial de la región del Lago Buenos Aires. Revista de la Asociación Geológica Argentina 54, 333–352.
Trombotto, D., 2002. Inventory of fossil cryogenic forms and structures in Patagonia and the mountains of Argentina beyond the Andes. South African Journal of Science 98, 171–180.
Uliana, M.A., Briddle, K.T., 1987. Permian to late Cenozoic evolution of northern Patagonia: main tectonic events, magmatic activity, and depositional trends. In: McKenzie, G.D. (Ed.), Gondwana Six: Structure, Tectonics, and Geophysics. American Geophysical Union Monograph, vol. 40, pp. 271–286.
Volkheimer, W., 1972. Sobre el origen de los bajos sin salida en la Patagonia extrandina Septentrional. Revista de la Asociación Geológica Argentina 27, 410–413.
Wastegård, S., Veres, D., Kliem, P., Hahn, A., Ohlendorf, Ch., Zolitschka, B., The PASADO Science Team, 2013. Towards a late Quaternary tephrochronological framework for the southernmost part of South America – the Laguna Potrok Aike tephra record. Quaternary Science Reviews 71, 81–90.
White, J.D.L., 1991. The depositional record of small, monogenetic volcanoes within terrestrial basins. In: Fisher, R.F., Smith, G.A. (Eds.), Sedimentation in Volcanic Settings. Society for Sedimentary Geology Special Publication, vol. 45, pp. 155–171.
Wille, M., Maidana, N.I., Schäbitz, F., Fey, M., Haberzettl, T., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schleser, G.H., Zolitschka, B., 2007. Vegetation and climate dynamics in southern South America: the microfossil record of Laguna Potrok Aike, Santa Cruz, Argentina. Review of Palaeobotany and Palynology 146, 234–246.

Wood, C.A., 1980. Morphometric analysis of cinder cone degradation. Journal of Volcanology and Geothermal Research 8, 137–160.
Zolitschka, B., Schäbitz, F., Lücke, A., Clifton, G., Corbella, H., Ercolano, B., Haberzettl, T., Maidana, N., Mayr, C., Ohlendorf, C., Oliva, G., Paez, M.M., Schleser, G.H., Soto, J., Tiberi, P., Wille, M., 2006. Crater lakes of the Pali Aike volcanic field as key sites of paleoclimatic and paleoecological reconstructions in southern Patagonia, Argentina. Journal of South America Earth Science 2, 294–309.
Zolitschka, B., Anselmetti, F., Ariztegui, D., Corbella, H., Francus, P., Lücke, A., Maidana, N., Ohlendorf, C., Schäbitz, F., Wastegard, S., 2013. Environment and climate of the last 51 ka – new insights from the Potrok Aike maar lake sediment archive drilling project (PASADO). Quaternary Science Reviews 70, 1–12.