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Terminal Moraines, Outwash Plains, and Lake Terraces in the Vicinity of Lago Cardiel (49°S; Patagonia, Argentina)—Evidence for Miocene Andean Foreland Glaciations

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Abstract

Nine late Miocene glacier advances are identified in the Lago Cardiel region (49°S, 72°15′W in southern South America), a region that until now has been assumed to be unglaciated. Several dating results indicate a minimum age of 6.4 Ma for four advances of the Monte San Lorenzo lobe terminating east of Lago Cardiel and 6.6 Ma for the three oldest glaciations of the San Martín lobe terminating south of this lake. Two further advances have a minimum age of 5.4 Ma. Eleven to 14 m.y. old basaltic lava, which partly covers Patagonian Gravel, indicates the maximum age of these advances. The two oldest terminal moraines of the San Martín glacier are only modestly incised into the Patagonian Gravel suggesting an age of 9 to 10.5 Ma. These age estimates are especially accurate for both meseta glaciations of the San Lorenzo lobe. These glaciers were about 240 km long during their Miocene maximum, which is four times their length during the Last Glacial Maximum. Hence, the late Miocene glacier advances require colder and/or more humid conditions that were considerably longer lasting than the Pleistocene glaciations. Due to glacial meltwater, Lago Cardiel was significantly larger and served as a regional catchment area during these early glaciations in southern South America. The erratic boulders of the southeastern lake terraces at more than 350 m above modern lake level may be attributed to the oldest late Miocene moraine or outwash plain.

Introduction

Two icefields cover the southern Patagonian Andes between 46°15′ and 51°30′S; the Southern Patagonian Icefield (SPI) covers 13,000 km^2, and the Northern Patagonian Icefield (NPI) covers 4200 km^2 (Fig. 1). Both are remnants of the Last Glacial Maximum ice cap, during which the eastern outlet glaciers advanced more than 200 km into the Andean foreland (Wenzens, 2002). Large glacial piedmont lakes such as Lago Buenos Aires, Lago Pueyrredón, Lago San Martín, Lago Viedma, and Lago Argentino document the enormous erosional potential of glaciers.

Until to the 1970s it was generally assumed that only two glaciations had occurred in Patagonia. This assumption was based on Caldenius (1932), who differentiated four ice limits. Caldenius suggested that the three youngest margins, Fini-, Goti-, and Daniglacial, correlate to advances of the Last Glacial ice sheet in northwestern Europe. According to Caldenius, the maximum extent of the Patagonian ice cap is represented by the Initioglacial ice margin. More than 50 years later, Mörner and Sylwan (1989) subdivided the Initioglacial moraine complex east of Lago Buenos Aires into two phases and measured the paleomagmatism of the proglacial sediments. The reversed polarity of both Initioglacial deposits indicates that these glaciations occurred during the Matuyama epoch, which means between 0.78 and 2.58 Ma. However, these glaciations do not represent the oldest advances in this area. Later, Malagnino (1995) mapped terminal moraines north of Lago Buenos Aires situated on the meseta Pampa del Río Guenguel (Fig. 2 [1]), which are older than the Initioglacial ice limit. *Meseta* is a Spanish term for an extensive tableland, comparable to a plateau. Mercer (1976) identified till at 1430 m in between 3.55 and 3.48 m.y. old basalt lavas in Meseta Desocupada north of Lago Viedma (Fig. 2 [①]). Since Mercer did not observe any additional glacial or fluvioglacial deposits in between older basalts dated at 4.5 Ma, he attributed the newly found till to be from the first glacier advance in Patagonia. Later, 30- to 40-m-thick tills were described by Mercer and Sutter (1982) at 1550 m in between 4.6 and 7.0 Ma basalt layers at the northern escarpment of Meseta del Lago Buenos Aires (Fig. 2 [②]). Schellmann (1998) provided evidence for 3.5 Ma till east of the Initioglacial ice margin in Río Santa Cruz valley, east of Lago Argentino (Fig. 2 [③]). Wenzens (2000) recognized that the oldest glaciation in Río Shehuen valley, east of Lago Viedma (Fig. 2 [④]) occurred well before 3.0 Ma. In Figure 2, the extent of the glacier lobes during the most extensive advance is represented. Only east of Lago Pueyrredón does the Initioglacial ice limit correspond with the most extensive advance. Therefore, "Initioglacial" is a type section that is no longer appropriate.

This study investigates the glacio-morphological development of the Andean foreland between Río Chico and Río Shehuen, with Lago Cardiel in the center (Fig. 3). This lake is a closed depression 80 km east of Lago San Martín and is hydrographically isolated from the Andes. Until recently, it was assumed that Lago Cardiel lies "beyond the reach of past and present Andean glaciers and their melt water" (Markgraf et al., 2003). The following will show that several late Miocene glacier advances from the glacierized granite massif Monte San Lorenzo (3706 m a.s.l.) and from the northern part of the South Patagonian Icefield occurred, which terminated in the area surrounding Lago Cardiel. To do this, it is necessary to summarize the geological development of this region since the Miocene and to reconstruct the important aspects of the different ages of the basalt lavas for the temporal classification of the morphological processes. The age determination methods of basalt lavas are presented briefly, as well as the possibilities for using Landsat TM-image interpretation for geomorphological mapping. Also the criteria, which have led to identifying terminal moraines and to the differentiation between outwash plains and fluvial deposits, are explained. A summary of the

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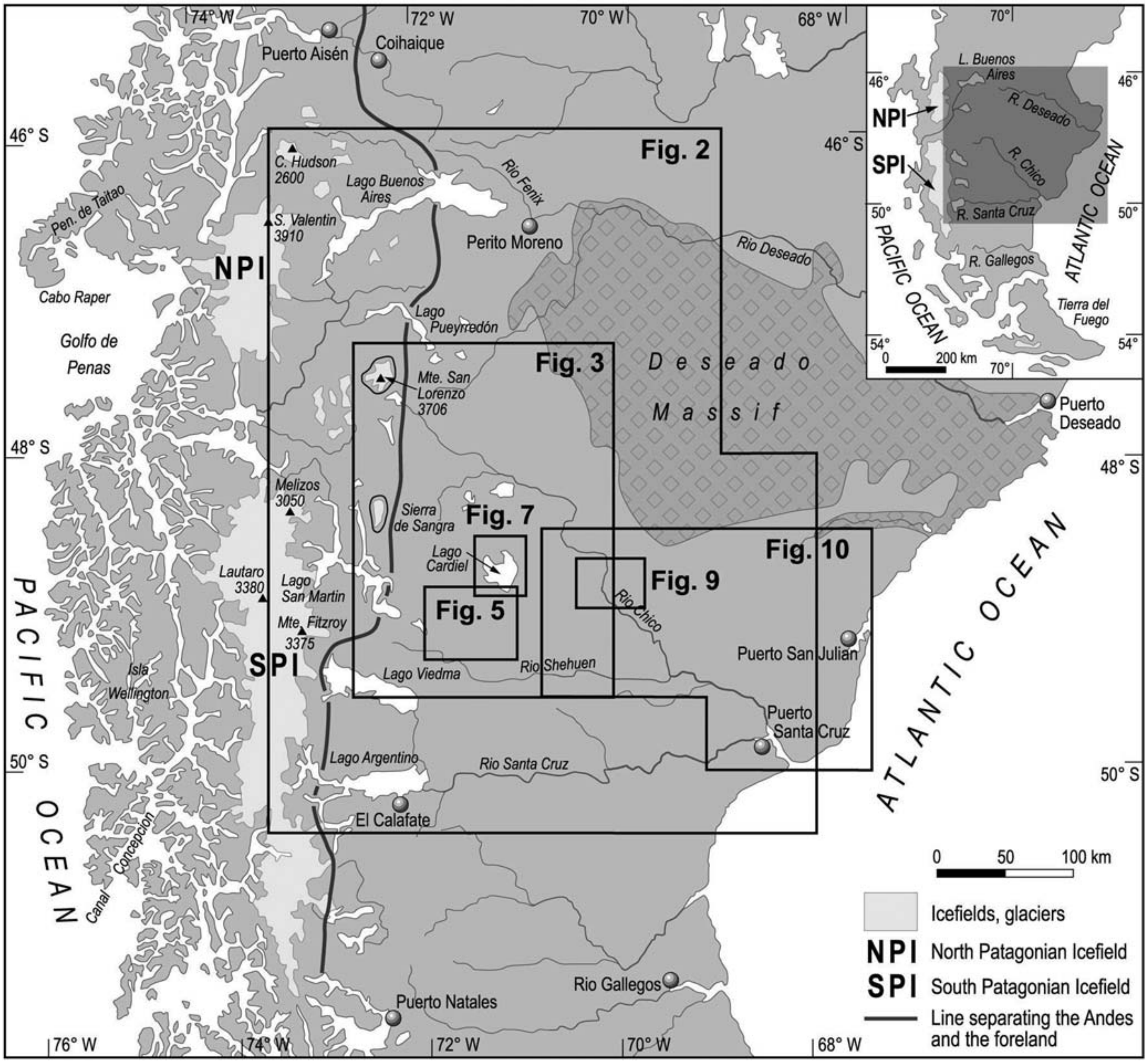

FIGURE 1. The South and North Patagonian Icefields and the eastern Andean foreland. The boxes show the location of geomorphological maps.

previous state of knowledge of the morphogenesis of the investigation area follows. The main part is composed of the presentation of the Miocene glaciations in this area.

Methods

GEOMORPHOLOGICAL MAPPING COMBINING INTERPRETATION OF LANDSAT TM DATA AND FIELD WORK

Remotely sensed data from the EROS Data Center in Sioux Falls, South Dakota (U.S.A.), especially Landsat 3, 4, and 5 multispectral scanner (MSS) images, provide a valuable tool to aid with the monitoring of mountain regions (Figs. 4A and 4B). The advantage of utilizing remote sensing is particularly evident in areas like Patagonia where access is extremely limited and large-scale maps are unavailable. By using satellite photos it is possible to select specific areas for field studies. The combination of Landsat 3, 4, and 5 MSS images is particularly suitable for classifying different rock types and surface deposits. Different types and scales of satellite images were interpreted, followed by fieldwork in order to verify hypotheses about relief development, after which the diversely formed landscape can be classified.

The geomorphological mapping includes the recording of the different deposits of basalt lavas, Patagonian gravel *sensu stricto*, and all younger fluvial, fluvioglacial, and lacustrine sediments as well as moraines and outwash plains east of the Andes between Monte San Lorenzo in the north and Lago San Martín in the south. A map showing the glacial limits, the location of river terraces of Río Shehuen and of the Río Chico valley had already been published (Wenzens, 2000, Fig. 2). Detailed geomorphological mapping was carried out in the northern, eastern, and southern surroundings of Lago Cardiel (Figs. 5 and 7) as well as north, east, and west of Gobernador Gregores (Figs. 9 and 10). Since the surfaces of the mapped terminal moraines were completely leveled, except for two ridges, they could not be recognized

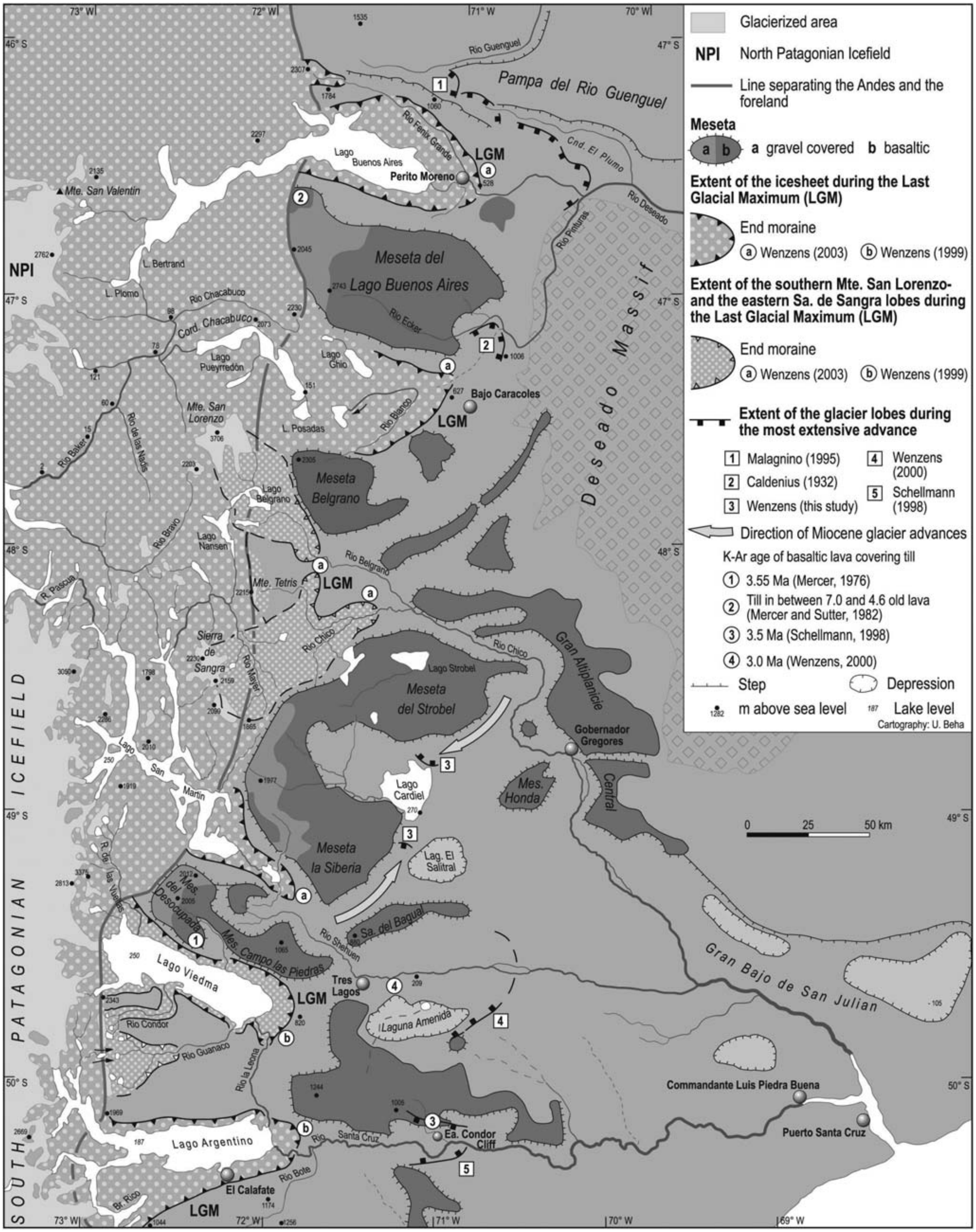

FIGURE 2. Geological and morphological setting between Lago Buenos Aires and Lago Argentino.

on the satellite photos. The criteria used to identify terminal moraines are the predominance of large boulders with diameters >1 m and, above all, the occurrence of angular erratic boulders of Andean origin. The assignment of mapped terminal moraines to different catchment areas is based on the frequency of granitic boulders (>50 cm diameter), which originate from the Monte San Lorenzo massif, or the predominance of large basaltic boulders (>1 m diameter), which were eroded from the basaltic mesetas. According to size and roundness of

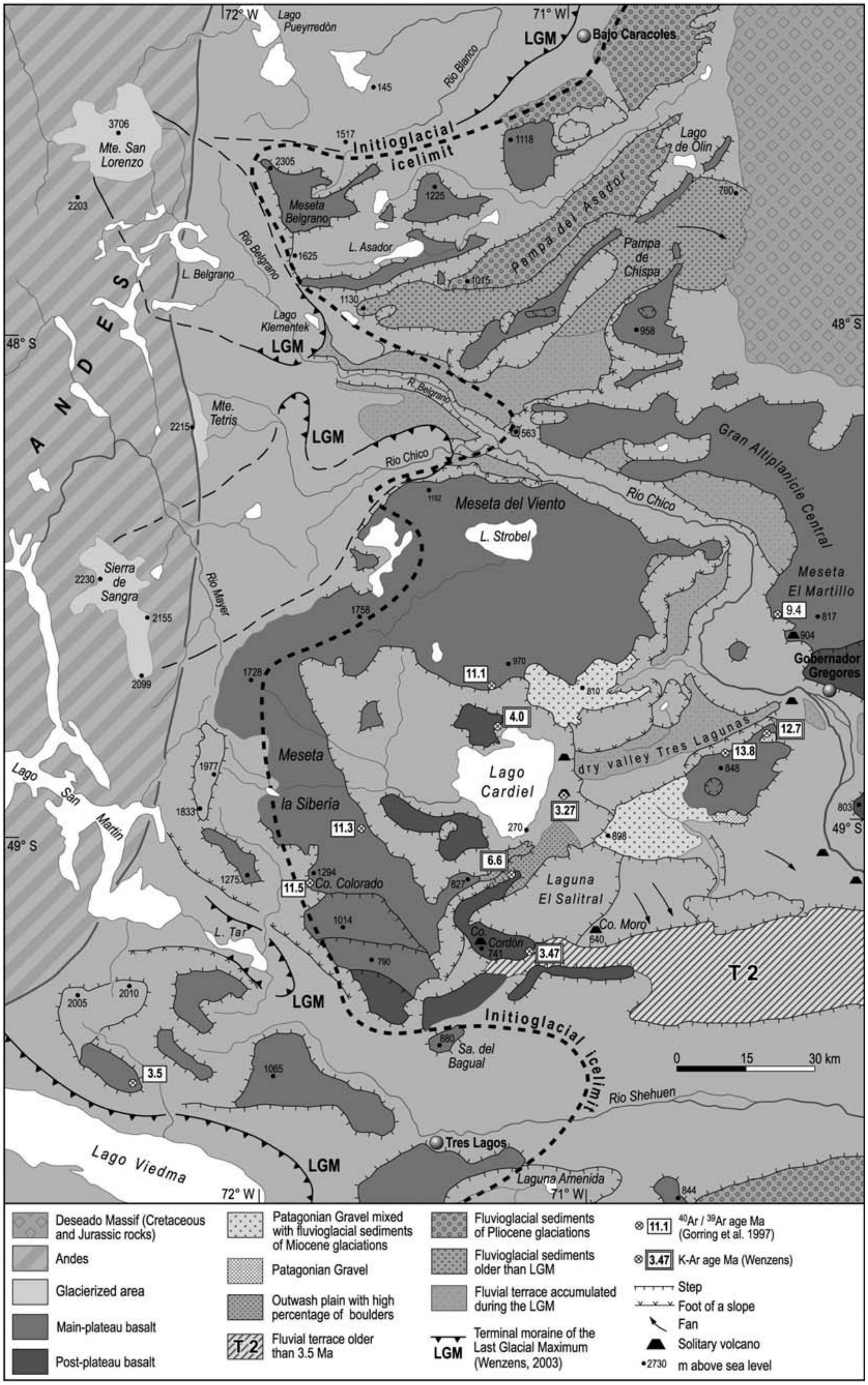

FIGURE 3. The Andean foreland between Lago Pueyrredón and Lago Viedma with the distribution of basaltic plateaus, gravel covered surfaces, the Initioglacial icelimit (Caldenius, 1932), and the terminal moraines of the Last Glacial Maximum (LGM).

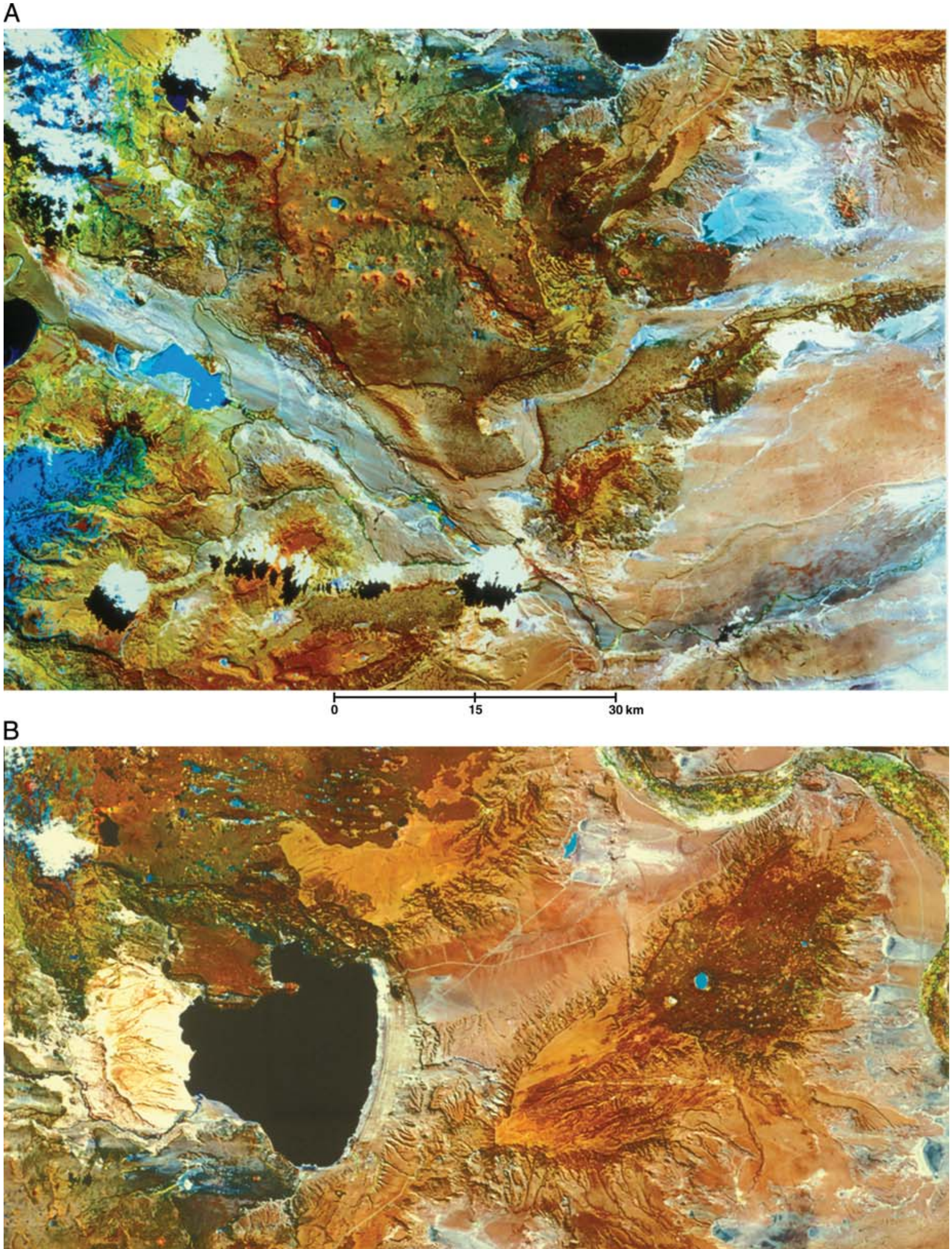

FIGURE 4. (A) Landsat ETM satellite composite image with bands 3, 4 and 5, showing Lago Cardiel in the northeast and Lago San Martin in the southwest. (B) Landsat ETM satellite composite image with bands 3, 4 and 5, showing Lago Cardiel in the west and Río Chico in the east.

the largest boulders, they are classified as fluvial, fluvioglacial, or glacial accumulations.

This is true especially for the deposits east of Lago Cardiel, whose morphological classification was conducted completely in the field. The size and number of the boulders decrease rapidly in the outwash plains, downstream from the terminal moraines. Fluvial terraces occur only in the Río Chico valley, and the well-rounded fluvial pebbles are rarely larger than 25 cm. Even if most of the deeply weathered granite boulders >50 cm diameter were partially well rounded, such deposits represent terminal moraines, since they also always contained individual angular boulders, which excludes fluvial transport (Figs. 8B and 8C). Mapping of the terminal moraines and outwash plains accumulated by the San Martín lobe was done with more ease. On satellite photos they appear as yellowish level areas, due to their cover of eolian sediments (Fig. 4A). In the scarp face, all of these terminal moraines contain numerous large basalt boulders, as well as non-basaltic erratic boulders (Figs. 6A, 6B, 8A).

POTASSIUM-ARGON AGE DETERMINATION

The K-Ar dating technique has become an important method for precise dating of basaltic lava flows. The samples were analyzed at Mass Spec Services (Division of Geonuclear), Orangeburg, NY, U.S.A. Based on the data in Table 1, the minimum error assigned to any determination is rounded up to ±2.5%. Pre-existing radiometric dates are $^{40}Ar/^{39}Ar$ ages, which were obtained by total fusion of purified whole-rock matrix fractions (Gorring et al., 1997). The K-Ar and $^{40}Ar/^{39}Ar$ dating methods are described by Dickin (1995). In general, total-fusion $^{40}Ar/^{39}Ar$ dates are regarded as more precise than conventional K-Ar ages. All cited $^{40}Ar/^{39}Ar$ and K-Ar ages indicate the minimum age of sedimentary deposits, which are underlain by the dated lava. However, fluvial pebbles in the northeast of Tres Lagunas are underlain and overlain by a lava dated at 4.4 ± 2 Ma (Fig. 9).

Previous Work on Miocene Relief Development in Patagonia

A long-lasting marine transgression period associated with the deposition of fine-grained molasse sediments from the early to middle Miocene ended in this region 15 Ma (Ramos, 1989). It can be assumed that there were no larger differences of altitude between the southern Andes and their eastern foreland, since these fine-grained deposits are also distributed close to the Andes. Gravel deposits, several meters thick and originating from the Andes, cover these molasse sediments and document the onset of uplift and erosional processes in the Andes. The gravels generally are 5–6 cm in diameter and may reach up to 10 cm. They are embedded in a sandy, partly cemented matrix. Fidalgo and Riggi (1965) named them Patagonian Gravel *sensu stricto.* Due to its grain size and proximity to the Andes, Patagonian Gravel cannot have been deposited by glacial or fluvioglacial processes. Subsequent morphogenesis redeposited some of the gravel into lower areas and mixed it with glacial, fluvioglacial, fluvial, and marine deposits. These mixed sediments are also frequently called Patagonian Gravel (Mercer, 1976). This study uses the original definition of Patagonian Gravel only: they were accumulated soon after the sedimentation of the molasse and are always located on high-lying mesetas. The Patagonian Gravel represents a time specific sedimentary horizon that is pre-glacial.

Both the Andes and the eastern mesetas were affected by another phase of uplift. Basaltic lava flows occurred at several faults near the Andes south of Lago Buenos Aires and north of Lago Viedma (Panza and Nullo, 1994). In the study area, $^{40}Ar/^{39}Ar$ and K-Ar age determination permits the differentiation of two sequences of basaltic lava flows (Gorring et al., 1997). The first sequence has ages between 13.8 and 9.4 Ma and covers the largest elevated mesetas of extra-Andean Patagonia (Fig. 3). Following Gorring et al., these mesetas are called main-plateau basalt mesetas. Near the Andes, they are located between 2000 and 1000 m a.s.l. and dip toward 800 m a.s.l. in an eastern and southern direction. It was not until this strong Andean uplift that the altitude of the Andes initiated the glaciation of the highest Andean regions. The second sequence of basaltic lava has ages between 6.6 and 3.3 Ma. These post-plateau lavas cover small low-elevation mesetas, fluvial and shore terraces, as well as moraines and outwash plains, indicating preceding erosional and accumulation phases. The age determination of both sequences provides new conclusions concerning the dating of Miocene glaciations in South America.

Since dependable and sufficient evidence for the Miocene climate development in southern South America is unavailable, the paleoclimatic views, which were reconstructed for this epoch in the northern Antarctic Peninsula, are presented. Parts of eastern Antarctica as well as the northern Antarctic Peninsula (62°S, 60°W) have been glaciated since the Oligocene (Troedson and Smellie, 2002; Barett, 2001; Barker et al., 1999). Maximum growth of the Antarctic ice cap occurred during the late Miocene (Ehrmann, 1994). The same is true for the Antarctic Peninsula (Pirrie et al., 1997). Due to the age of the main-plateau basalt lavas, between ca. 13.8 and 9.4 Ma, it can be assumed that the climatic conditions for extensive Andean foreland glaciation in southern Patagonia may not have existed until the late Miocene.

Study Area

Lago Cardiel (360 km^2) has no outlet and is situated at the eastern margin of a 3500 km^2 great depression. It is surrounded by 1000-m-high main-plateau basalt mesetas to the north and west (Fig. 3). The geologic and geomorphic conditions are completely different to the northeast, east, and southwest of the lake. To the northeast, a gravel meseta is modestly cut into the main-plateau basalt meseta and stretches up to the Río Chico valley in the east (Figs. 4B and 7). Río Chico was formed by meltwater of the southern Monte San Lorenzo and eastern Sa. de Sangra glaciers. Both mountains are located on the eastern margin of the Andes. South of its confluence with Río Belgrano, the Río Chico branches in two dry valleys. Dry valley Cañadón León, stretching toward the Atlantic, begins 90 m above the valley floor southeast of Gobernador Gregores (Fig. 9). There, it is cut into post-plateau basalt mesetas with altitudes between 500 and 700 m a.s.l. Two high gravel mesetas of different elevation (M1 and M2) border it to the south (Fig. 10). M1 level steeply declines toward Río Chico delta in the south and surrounds a significantly lower M2 meseta in the north. M2 level is dissected by the eastern extension of Cañadón León, called M3 level. These three meseta levels gently decline toward the coast. Gravel with diameters up to 20 cm dominate their surfaces. The largest cobbles reach 30 cm. Spurs of M1 level end at 300 m within a distance of 10 to 15 km to the littoral zone. East of both icefields, M1 level is the highest meseta extending almost to the Atlantic Ocean, representing the oldest accumulation phase in this area.

The Tres Lagunas dry valley begins 40 m above the current valley floor northwest of Gobernador Gregores (Fig. 9) and is the continuation of the youngest river terrace (Wenzens, 2005). It terminates with a 145-m-high escarpment at Lago Cardiel (270 m) in the west (Fig. 7). The 5-km-wide Tres Lagunas dry valley was cut into the gravel meseta, which apparently used to surround the eastern lake completely. The southern gravel meseta steeply declines toward Laguna El Salitral in the south and passes into a main-plateau basalt meseta in the east. At the valley slope of Río Chico, this basalt covers Patagonian Gravel at 780 m. A basalt sample was dated at 12.7 Ma

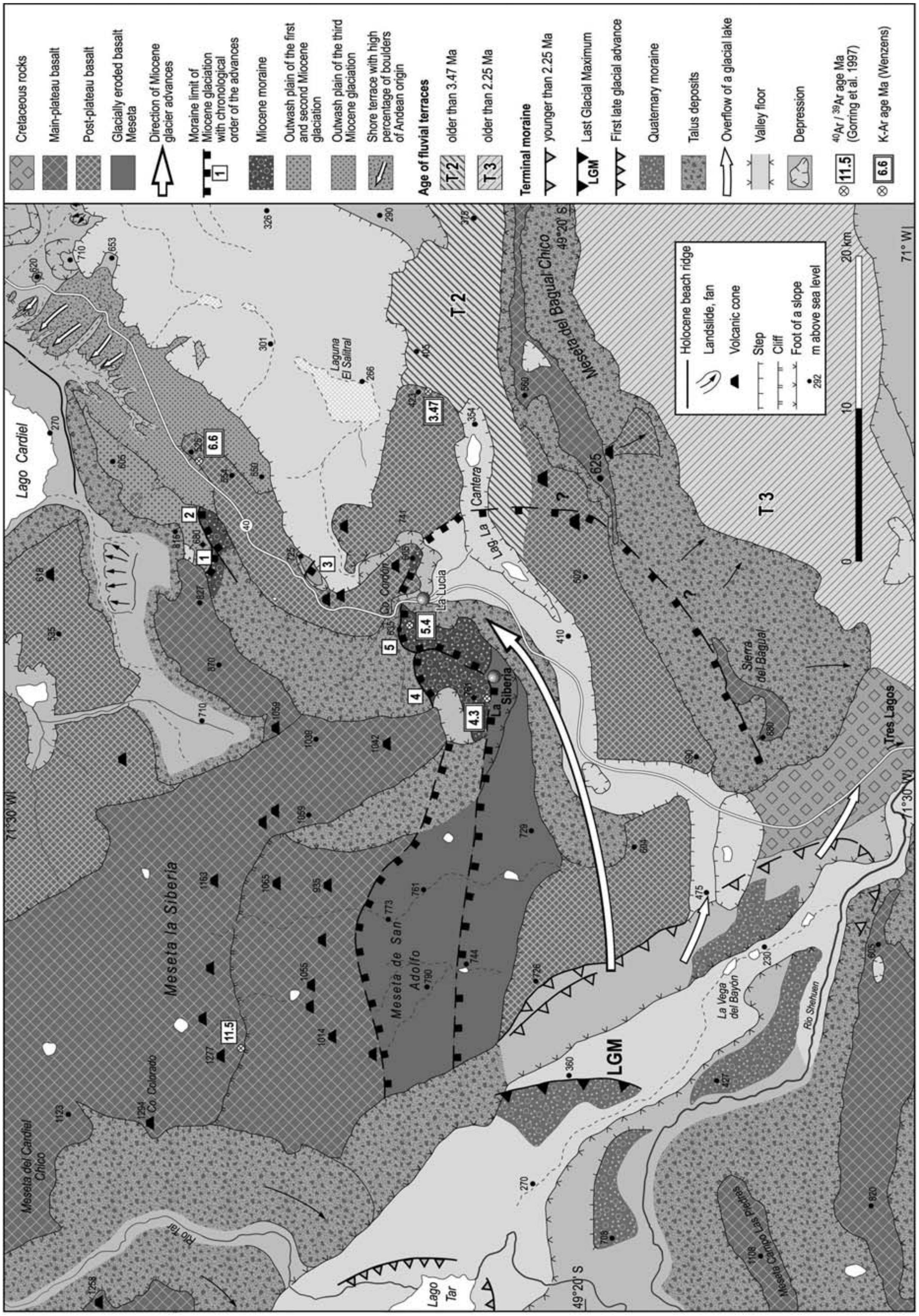

FIGURE 5. Extent of Miocene glacier advances south of Lago Cardiel.

A

B

C

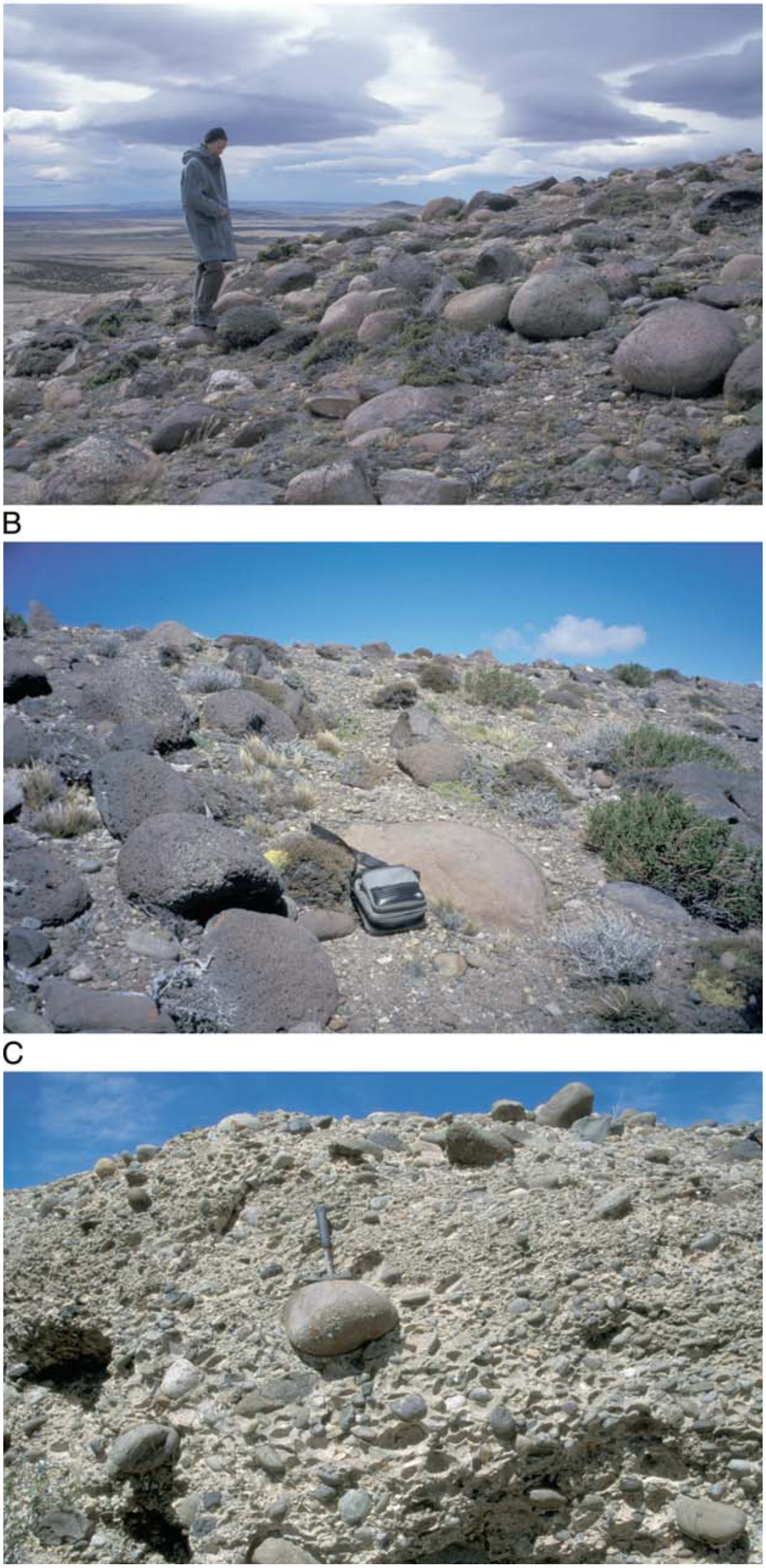

FIGURE 6. (A) Cut of Miocene terminal moraine 5 of the San Martín lobe; in the background volcano Cerro Cordón. (B) Cut of the oldest Miocene terminal moraine, 12 km south of Lago Cardiel. (C) Cliff of the south-eastern shore terrace (480 m a.s.l.) consisting of beachrock.

using the K-Ar dating technique (Fig. 9). Twenty-one km further west, a sample of this basalt was dated by Gorring et al. (1997) at 13.8 Ma using the $^{40}Ar/^{39}Ar$ method.

South of the Tres Lagunas dry valleys, gravel- and boulder-covered shore terraces surround the lake (Fig. 7). K-Ar dating of different post-plateau basalt lavas provided evidence for the existence of the lake several million years ago. For example, 3.27 m.y. old basalt covers beach gravel on the top of Cerro Gorro at the eastern lake shore at 436 m a.s.l. The depression of Lago Cardiel is considerably older. A 4 m.y. old basalt lava gently slopes toward the lake and ends at the

TABLE 1

K-Ar ages and ^{40}Ar and K concentration. Whole rock potassium age determination of basalt samples and the analysis were obtained from MASS SPEC Services, Division of Geonuclear, Inc., Orangeburg, NY, U.S.A.

MSS sample no.	Grid	Altitude (m a.s.l.)	Basis and location	Isotopic age (Ma)	^{40}Ar (^{x}) (scc/g $\times 10^{-5}$)	^{40}Ar (^{x}) (%)	K (%)
KA 036064	48°49′S	780	Patagonian Gravel, 15 km southwest of	12.7 ± .3	0.029	60.9	0.59
	70°23′W		Gobernador Gregores		0.029	56.9	0.58
KA 025914	49°07′S	523	Outwash plain, 9 km south of Lago Cardiel	6.6 ± .2	0.21	48.2	0.84
	71°12′W				0.22	51.0	0.83
KA 015738	48°52′S	395	Fluvial pebble, 49 km southeast of Gobernador Gregores	6.4 ± .4	0.24	34.5	0.96
	69°36′W				0.24	55.9	0.96
KA 036063	49°14′S	630	Terminal moraine, 3 km west of Cerro Cordón	5.4 ± .1	0.26	67.4	1.24
	71°21′W				0.26	67.4	1.24
KA 015736	48°43′S	525	Fluvial pebble, northeast of Tres Lagunas	4.4 ± .2	0.10	42.8	0.62
	70°39′W				0.10	49.7	0.62
KA 036062	49°16′S	773	Lateral moraine, 7 km west of Laguna La Cantera	4.3 ± .2	0.36	39.0	2.11
	71°25′W				0.35	37.3	2.11
KA 015735	48°48′S	421	Miocene Santa Cruz Formation, northwest of Lago Cardiel	4.0 ± .2	0.23	61.3	1.50
	71°14′W				0.24	61.8	1.50
KA 025913	49°15′S	422	Fluvial pebble, 11 km east of Cerro Cordón	3.47 ± 0.9	0.15	54.0	1.11
	71°09′W				0.15	56.0	1.11
KA 015737	48°58′S	433	Shore terrace, 4 km east of Lago Cardiel	3.27 ± .16	0.14	72.6	1.14
	71°03′W				0.15	72.1	1.14

northern lake shore at 400 m a.s.l. In the south, a shore terrace at 500 m a.s.l. is partly covered with a 6.6 m.y. old basalt lava.

Miocene Glaciations

MIOCENE TERMINAL MORAINES, OUTWASH PLAINS AND LAKE TERRACES OF THE SAN MARTÍN LOBE

In contrast to the southern Monte San Lorenzo lobe, which has been turned to the southeast by the main-plateau basalt meseta Belgrano, the San Martín lobe was able to erode parts of Meseta La Siberia situated in the east (Figs. 4A and 5). This main-plateau basalt meseta has an elevation above 1100 m a.s.l. As shown on topographic maps and satellite images, east of Lago Tar, a step of 300 m leads to Meseta de San Adolfo at 800 m a.s.l. There, all volcanic vents have been eroded. Its surface has been leveled by glaciers advancing eastward. Due to the decreasing erosional potential, a spur of Meseta La Siberia, which extends far to the south, has been preserved. Immediately below the end of this spur, a 2-km-wide moraine begins at 750 m a.s.l. and passes to a curved terminal moraine (Fig. 5 [4]). This moraine consists of a mixture of both predominantly rounded boulders from the Andean basement and numerous angular basalts reaching diameters up to several meters (Fig. 6A). South of the spur's end, the moraine is covered by a basaltic lava flow, which was dated at 4.3 Ma using the K-Ar dating technique (Table 1). Although glacial deposits were eroded further to the south, an erosional relic of the main-plateau basalt meseta Sierra del Bagual (880 m a.s.l.) indicates the maximum glacier extent in the south.

West of Estancia La Siberia, the southern part of Meseta de San Adolfo was lowered during a younger glacier advance. Moraines extend another 7 km to the north, where the terminal moraine's gravel and boulders are strongly cemented and intersected by Ruta 40 (Fig. 5 [5]). A remnant of this moraine is located east of Ruta 40 just south of Cerro Cordón (741 m a.s.l.). The glacier advance apparently terminated in front of the 100-m-higher post-plateau basalt meseta. A K-Ar dated 5.4 m.y. old lava stream crosses the moraine one km south of the 635-m-high terminal moraine. Therefore, the minimum age of the older advance must be significantly older than 5.4 Ma.

However, earlier glacier advances extended considerably further. A main-plateau basalt meseta outlines the northwestern margin of the oldest glacier advance (Figs. 5 and 7). The lava flow covers Patagonian Gravel at an elevation of 820 m a.s.l. An erosional remnant of the Patagonian Gravel is preserved in front of the basalt meseta at 815 m a.s.l. Immediately to the south, a moraine rampart consists predominantly of large angular basaltic boulders with diameters up to 2 m and a few non-basaltic boulders up to 1 m (Fig. 6B). It is a terminal moraine (Fig. 7 [1]) whose outwash plain stretches over 12 km in a northeastern direction up to Lago Cardiel. Its surface is covered with angular basalt deposits and some clasts of resistant rock types of Andean origin. A younger glacier advance extends 2 km further to the north. Only the northwestern part of its terminal moraine (750 m a.s.l.) is preserved (Fig. 7 [2]). The proglacial gravel field intertwines with the outwash plain of the older advance and is separated by a 20-m-high step from another lower outwash plain. It contains a lot of angular basalt boulders, which are partly exposed and range in diameter up to 2 m. Numerous rounded non-basaltic deposits with diameters up to 50 cm are accumulated in shallow depressions. To the south, the plain is covered by a 6.6 m.y. old lava flow. This gravel field correlates to a younger glacier advance. Only a small remnant of the terminal moraine juts out of the lava field 5.5 km north of the Cerro Cordón volcano (Fig. 7 [3]). The thickness of the debris visible at the slope down to Laguna El Salitral, and the abundance and size of the varied boulders verify that this accumulation is a relic of the terminal moraine. The reconstruction of the eastern margins of these three at least 6.6 m.y. old glacier advances of the San Martín lobe is impossible due to the tectonic subsidence of Laguna El Salitral.

The outwash plains of these three glacier advances obviously sloped to the former lake level of Lago Cardiel (Fig. 7). The youngest plain merges into a lacustrine terrace to the northeast. It is 650 m high near its escarpment at Laguna El Salitral, and it slowly declines toward Lago Cardiel, where it ends with a steep cliff at 480 m. The basis of the gravel deposits is composed of a 3- to 5-m-thick beachrock consisting of consolidated, unstratified cobbles and boulders of Andean origin, whereas only few basalts were observed (Fig. 6C). As many of the boulders have diameters of 50 cm and some are as large as 75 cm, it can be concluded that these sediments originate from lacustrine reworking of a former moraine or outwash plain because of the high quantity of boulders and the lack of sorting and stratification. Both the shore terrace and the 500 m outwash plain in the south differ significantly due to the petrographic composition of their boulders, although their elevations are similar where they laterally merge.

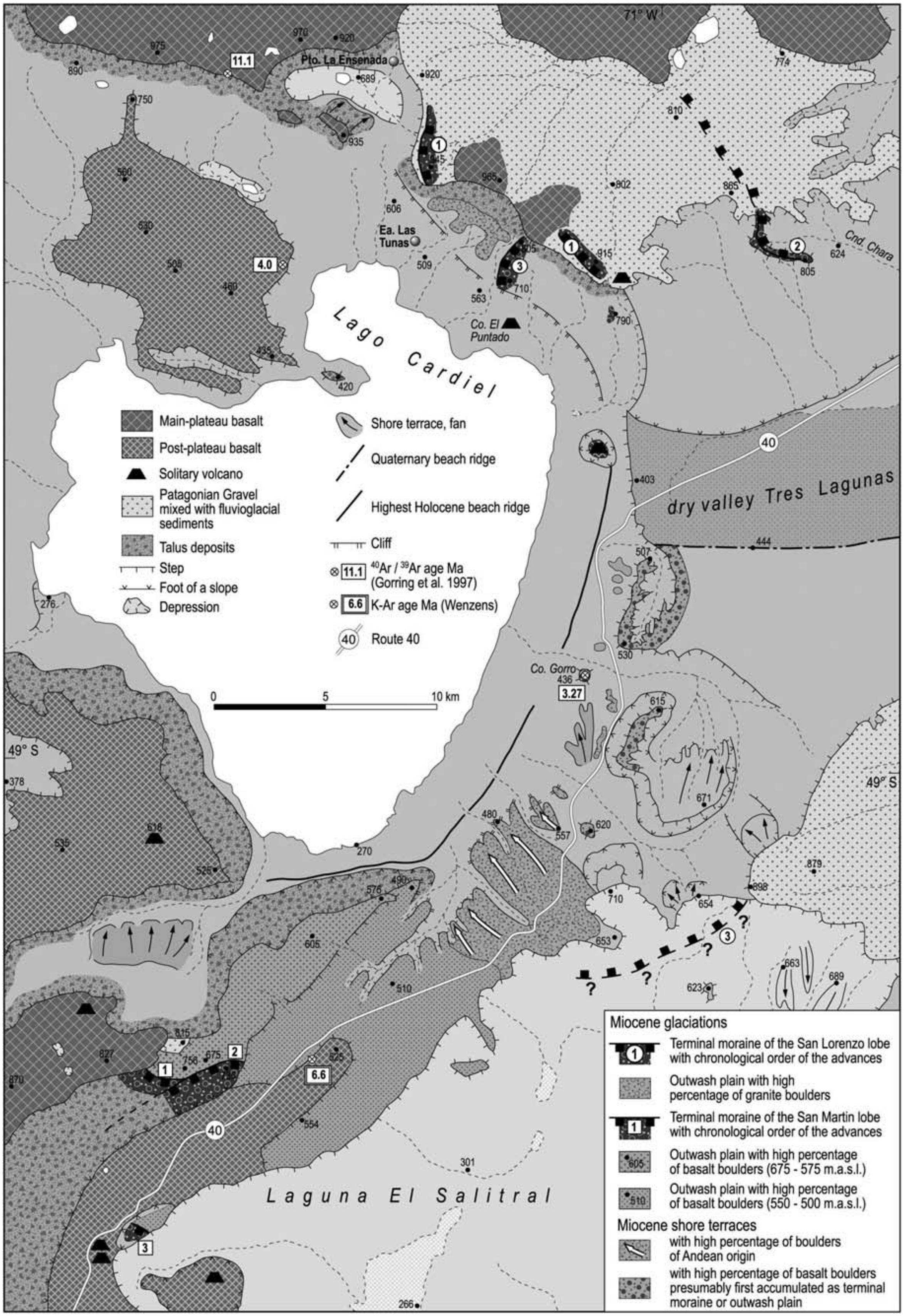

FIGURE 7. Lago Cardiel and its northern, eastern, and southern surroundings with Miocene terminal moraines, outwash plains, and shore terraces.

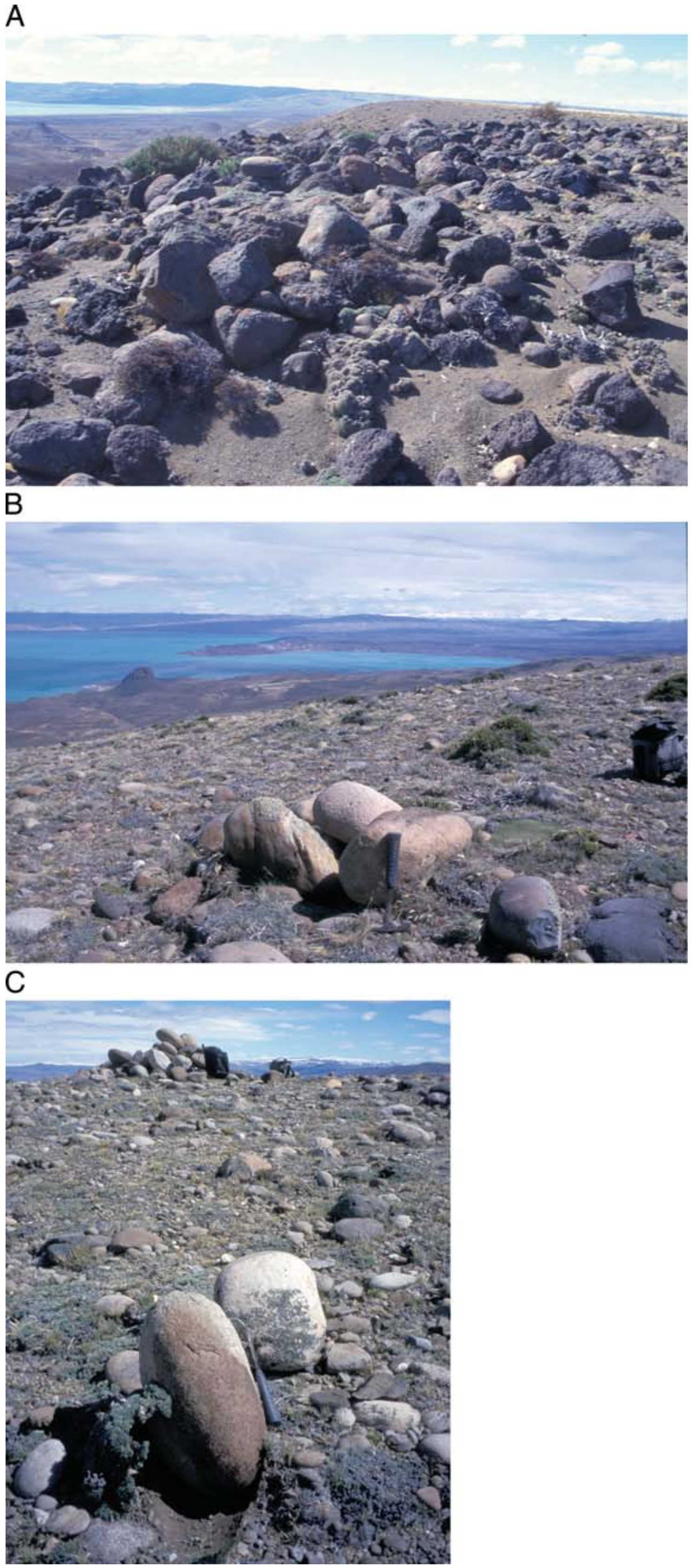

FIGURE 8. (A) A 615-m-high shore terrace, consisting of erratics, particularly basaltic boulders. (B) Relic of the oldest strongly eroded Miocene terminal moraine of the Monte San Lorenzo glacier, 675 m above Lago Cardiel. The volcano El Puntado juts near the shore. (C) An 840-m-high surface of the second oldest Miocene terminal moraine of the Monte San Lorenzo glacier. In the background is Meseta El Maartillo (910 m a.s.l.).

A broad valley separates this area from a shore terrace at 605–620 m a.s.l. in the north, which is covered by numerous angular basaltic boulders, some with diameters of 1–2 m, and by some rounded non-basaltic blocks up to 40 cm (Fig. 8A). Due to abundance and size of the basaltic boulders, the thickness of the debris, and the fact that in the vicinity of this terrace basaltic lava flows are missing, there is no doubt that glaciers transported the boulders. The wealth of the basaltic erratic boulders is the reason to believe that the glacier advanced from the south. To the north this terrace is lowered, the surface has an elevation of 500–530 m. Presumably, it is the product of wave erosion and denudation.

MIOCENE TERMINAL MORAINES OF THE MONTE SAN LORENZO LOBE NORTHEAST OF LAGO CARDIEL

Completely different geomorphic conditions were recognized to the north of the Tres Lagunas dry valley in between the shoreline and the escarpment of the 900-m-high gravel meseta, which lies within a distance of only 6 km. Shore terraces that are similar to those in the south were formed neither at 500 m nor at 600 m a.s.l.; instead, smaller plain relics at different elevations up to about 700 m are covered with beach gravel and some boulders. This suggests that the former lake level was at least 700 m a.s.l. The relief, which is characterized by strong erosion and mass movements, changes above 710 m a.s.l. A curved 20-m-high ridge, stretching from north (805 m) to south (710 m), is located 2 km north of the volcanic vent of Cerro Puntado. All features indicate a terminal moraine (Fig. 7 [③]): The coarse clastic debris is very heterogeneous and contains numerous boulders, including strongly weathered granites with diameters greater than 50 cm and some basaltic boulders up to 2 m in diameter, just as a proglacial gravel fan to the northwest, which is subject to fluvial incision. East of the terminal moraine, the terrain declines steadily and steeply from the meseta escarpment to about 400 m. The decline was likely caused by glacial erosion in the upper section of the area. This glacier advance is documented by both the sequence of glacio-morphologic features and the preservation of large boulders. It nearly reached up to the present lake shore and initiated the incision of the Tres Lagunas dry valley into the gravel meseta. Relics of moraines accumulated during this advance are preserved below the escarpment of the northern gravel meseta near the slope to the Tres Lagunas dry valley at 770–790 m a.s.l., too. Due to the occurrence of many granite boulders, the catchment area of this glacier must have been the Monte San Lorenzo Mountain.

The sediments on the northern gravel meseta consist mainly of Patagonian Gravel mixed with fluvioglacial deposits. In contrast, near the 900-m-high escarpment to Lago Cardiel, strongly weathered granite boulders with diameters of 50 cm occur (Fig. 8B). The abundance of boulders, especially along the upper slope of the escarpment, gives evidence of a strongly eroded terminal moraine within close proximity (Fig. 7 [①]). A fluvial transport of these boulders on this flat surface, which slopes gently to the east, can be excluded. The local preservation of these moraine relics may be explained by the fact that retrogressive erosion from the lake has only reached the meseta at a few locations.

Relics of a terminal moraine are preserved 8 km east of the escarpment at the southern margin of the meseta (Fig. 7 [②]). There, a spur, covered with many boulders extends into the Tres Lagunas dry valley. This 5-m-high ridge is 2.5 km long and 850 m a.s.l. The moraine contains numerous erratic boulders, which mainly are strongly weathered granites with diameters up to 50 cm and some angular basaltic boulders; which means a fluvial transport can be excluded (Fig. 8C). The glacial till is interbedded with consolidated Patagonían Gravel. The features described above provide evidence for at least two advances of meseta glaciations north of the Tres Lagunas dry valley. The terminal moraines of these three advances are located within a distance of 230–240 km of Monte San Lorenzo, which is four times its length during the Last Glacial Maximum (Wenzens, 2005).

MIOCENE TERMINAL MORAINE OF THE MONTE SAN LORENZO LOBE EAST OF THE RÍO CHICO VALLEY

Downstream of the confluence of the Río Belgrano and the Río Chico, the river cuts into the main-plateau basalt mesetas. East of Gobernador Gregores, the meseta Gran Altiplanicie Central sinks from over 800 m a.s.l. to between 700 and 575 m a.s.l. (Fig. 9). Remnants of a terminal moraine were observed immediately west of the escarpment of the main-plateau basalt meseta El Martillo at 830 m a.s.l. (Fig. 9 [④]). The size of granite and basalt boulders visible at the steep eastern slope verify that this small ridge is a relic of a terminal moraine. Due to strong fluvial erosion, only small parts of the outwash plain are preserved, namely south of the terminal moraine and at the eastern end of the gravel meseta north of the Tres Lagunas dry valley. During the melting phase the incision of Río Chico started; remnants of the oldest fluvial terrace are situated to the west of the terminal moraine at 750 m a.s.l., ~65 m below the outwash plain. A relic of a younger fluvial terrace at 480 m is preserved east of Tres Lagunas dry valley 130 m above the valley bottom of Río Chico. Here, 4.4 m.y. old basalt lava separates gravel layers, indicating a minimum age of the terminal moraine 4. Another minimum age for this advance could be attained in the region of the M1-Meseta (Fig. 10). In the western section of meseta M1, an isolated lava flow of the post-plateau sequence covers gravel at 445 m a.s.l. An age determination by K-Ar dating resulted in 6.4 ± 0.2 Ma, indicating that the terminal moraine 4 originated before 6.4 Ma. For M1 level, an age of at least 6.4 Ma is confirmed by its considerable relief difference of 180–220 m from the 3.5 m.y. old T2 terraces in the delta of Río Shehuen and Río Santa Cruz (Wenzens, 2000).

Results and Interpretation

AGE DIFFERENTIATION OF THE MIOCENE GLACIER ADVANCES COMPARED WITH THE CLIMATIC DEVELOPMENT OF THE NORTHERN ANTARCTIC PENINSULA

This paper verifies for the first time that the onset of large glaciations in South America occurred in the late Miocene. K-Ar dating results in a minimum age of 6.6 Ma for the three oldest advances of the San Martín lobe terminating south of Lago Cardiel (Figs. 5 and 7) and a minimum age of 6.4 Ma for all Miocene advances of the San Lorenzo lobe, terminating east of Lago Cardiel. However, both minimum ages are too young, since south of Lago Cardiel, the moraines of the first two advances only cut ~30–50 m into the main-plateau meseta, whose lava is ca. 11.5 Ma old. Similar temporal relationships also exist northeast of Lago Cardiel. Here, the two oldest advances of the San Lorenzo lobe are plateau glaciations, whose glacial and fluvioglacial sediments lie also only a few meters below the 11.1 m.y. old main-plateau basalt meseta. In contrast, the third advance of the San Lorenzo lobe ended 100–200 m below the terminal moraine of the oldest advance. This advance must therefore be quite a bit younger. The third advance of the San Martín lobe could be of similar age. Its outwash plain has a minimum age of 6.6 Ma. This minimum age is also to be used for the shore terrace, which is adjacent to the outwash plain, and declines from 600 m to 480 m a.s.l. As non-basaltic boulders dominate this lacustrine terrace (Fig. 6C), which probably consists of the reworked southern terminal moraine from the third Monte San Lorenzo glacier advance, it is likely that both advances from Monte San Lorenzo and the Lago San Martín area occurred during the same glaciation period. The possibility that this shore terrace could be a littoral reworking of the southern outwash plain or the terminal moraine of the third advance of the San Lorenzo glacier is indicated in Figure 7 (③).

The origin of the 615-m-high shore terrace southeast of Cerro Gorro, which is predominantly composed of large basalt boulders, is difficult to explain. It is probable but cannot be proven that lacustrine processes have reworked the terminal moraine or outwash plain of an older glacier advance from Lago San Martín. If that was the case, these erratic boulders (Fig. 8A) document the oldest Miocene glacier advance in South America. The ages of the fourth and fifth advances of the San Martín Lobe, which have minimum ages of 5.4 Ma, as well

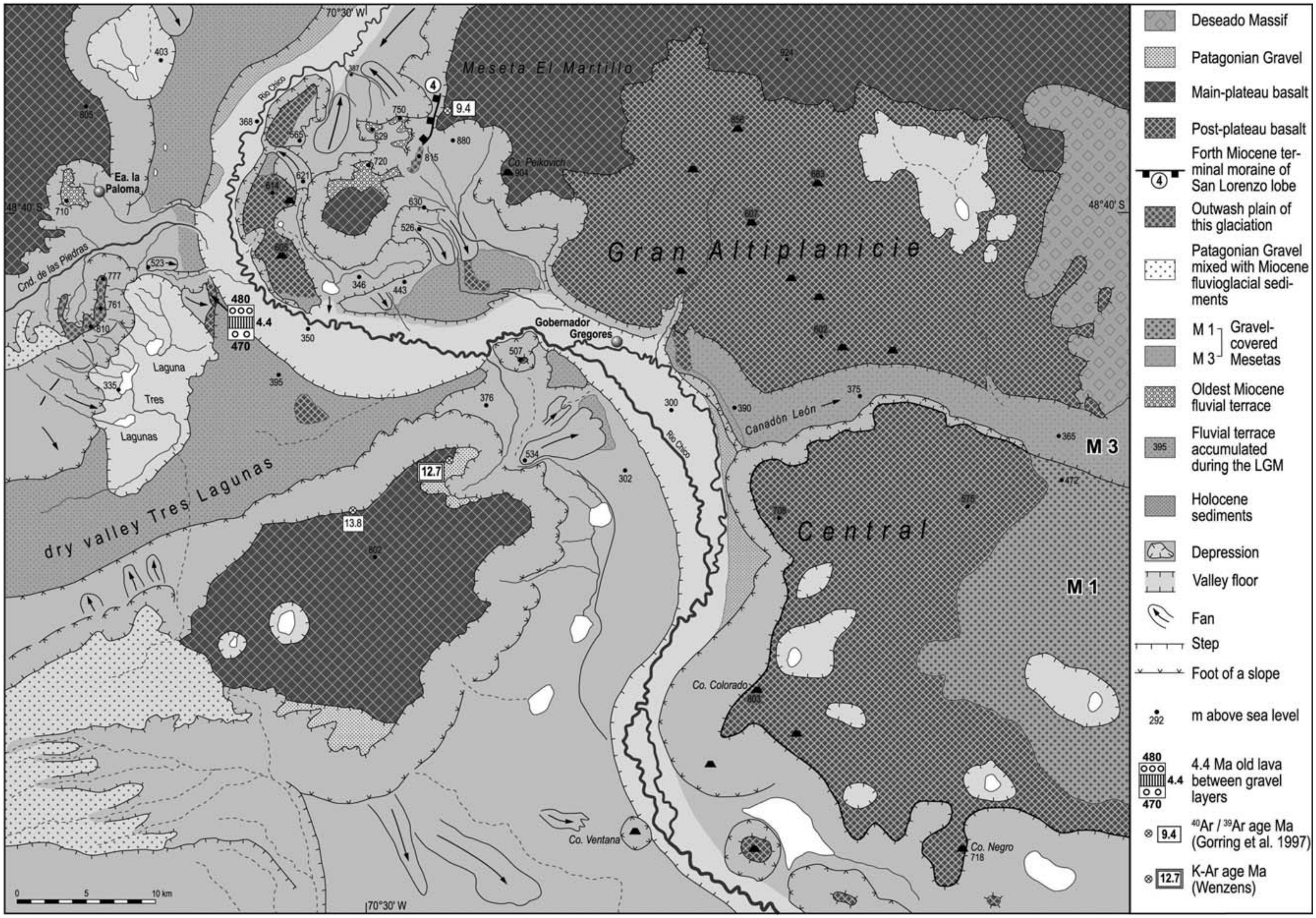

FIGURE 9. Map of the Río Chico valley near Gobernador Gregores showing a Miocene terminal moraine and relics of the adjacent outwash plain and the oldest and youngest fluvial terraces.

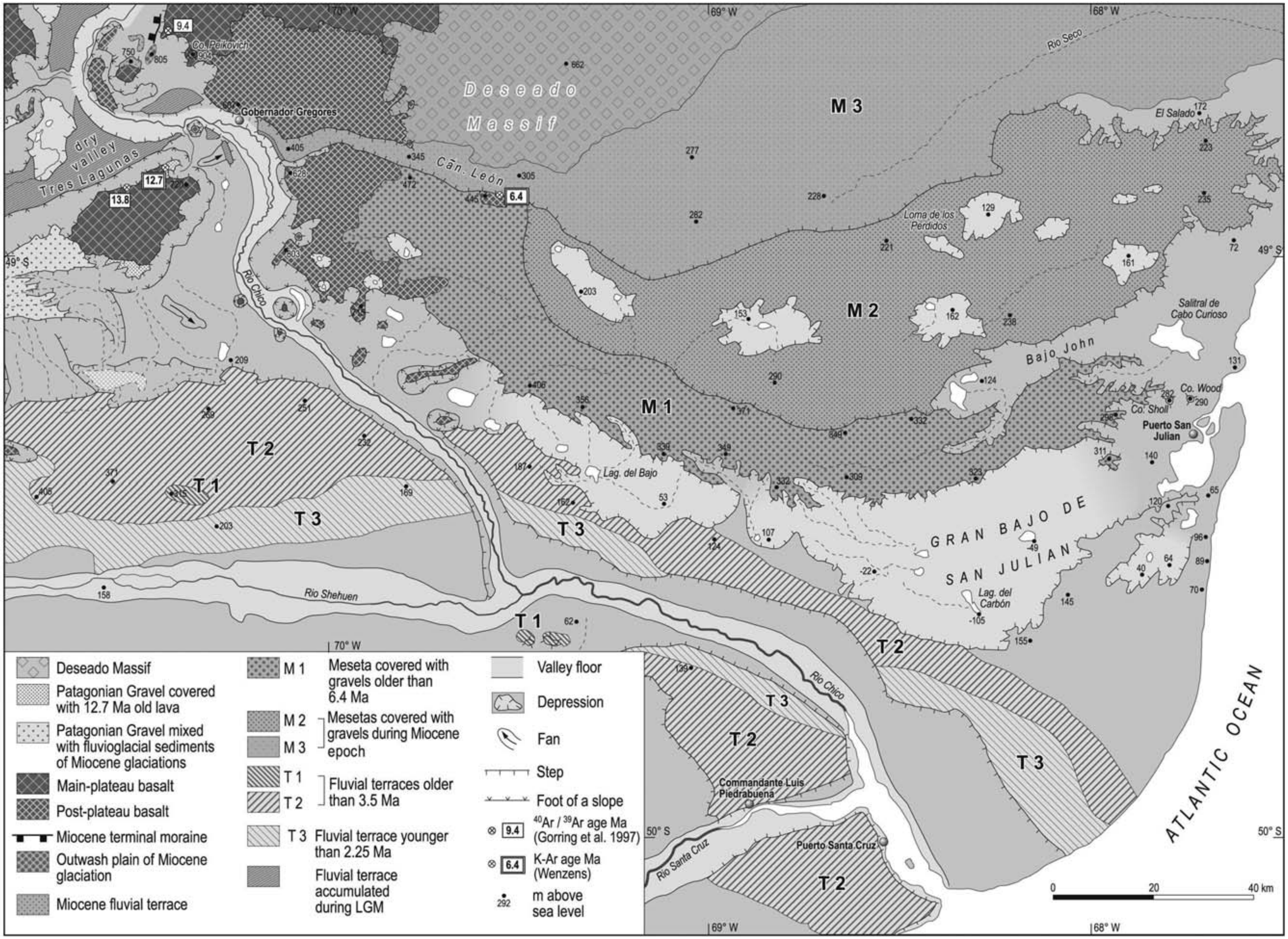

FIGURE 10. Lower course of Río Chico showing the terminal moraine of a Miocene advance, the distribution of gravel covered mesetas, and fluvial terraces.

as the age for the fourth advance of the San Lorenzo Lobe, with a minimum age of 6.4 Ma, are hard to evaluate.

As further dating indications in the study area are lacking, a more specific geochronologic stratification of these advances can be attempted by referring to results by Pirrie et al. (1997). These authors investigated Miocene glacio-marine sediments on James Ross Island (64°00′S, 57°30′W), northern Antarctic Peninsula. Their results indicate a continuation of cooling between 14 and 5 Ma. Phases of climatic warming were identified around 10.5 Ma, between 9 and 8.5 Ma, and between 7.6 and 6.6 Ma. They hypothesized a period of global warming between 4.8 and 3.6 Ma. Since this warm phase corresponds for the most part with the warm phase proven by Mercer (1976) north of the Lago Viedma in the Meseta Desocupada (Fig. 2 [①]) between 4.5 and 3.55 Ma, a temporal comparison of the Miocene glaciation in both regions seems reasonable.

It seems appropriate to suppose that both terminal moraines (1 and 2) of the San Martín lobe, which terminated immediately south of Lago Cardiel, and both terminal moraines (1 and 2) east of Lago Cardiel have been accumulated during the Antarctic cooling period between 10.5 and 9 Ma. A phase of glacier retreat is supposed for the study area during the Antarctic episode of climatic amelioration between 9 and 8.5 Ma, because the subsequent advances of the San Martín and Monte San Lorenzo glaciers (terminal moraines 3) took place on a lower level in both study areas. These glacier advances likely occurred during the cooling period between 8.5 and 7.6 Ma. The climatic amelioration between 7.6 and 6.6 Ma suggests a long-term glacier retreat. The two youngest terminal moraines (4 and 5) of the San Martín lobe with a minimum age of 5.4 Ma may have been accumulated during the Antarctic cooling phase, which occurred between 6.6 and 4.8 Ma.

As the difference in altitude between the M1 gravel meseta east of Gobernador Gregores, which is at least 6.4 Ma old, and the outwash plain of the advance 4 of the Monte San Lorenzo lobe is about 300 m, this advance must be considerably older than 6.6 Ma.

Conclusions

The eruption of main-plateau basalts between 46°30′ and 49°30′S was associated with the uplift of the southern Andes, which altered the climatic parameters. Those climatic conditions that initiated the increasing glaciation of the Antarctic Peninsula now also influenced the morphological processes in the study area since ca. 11 Ma. Regardless of whether the chronological comparison of the late Miocene glaciation of West Antarctica and Patagonia is the case or not, the glacial or fluvioglacial sediments on the lacustrine terrace of Lago Cardiel lying above 600 m a.s.l. give evidence for the oldest Miocene glaciation in the study area. Even if the ages of the individual Miocene terminal moraines cannot be assigned definitely, it is striking that during the ca. 5 m.y. interval between the first (10.5 Ma) and the last (4.8 Ma) Miocene advance, only 4 to 5 advances occurred.

It is likely that during the late Miocene, glaciers also advanced in regions with strong Pliocene and Quaternary glaciations, such as the areas to the east of Lago Buenos Aires and Lago Argentino. If that was the case, they did not reach the maximum extent of the younger glaciations, or all Miocene glacial and fluvioglacial sediments are eroded. The study area takes a special position, insofar as the region in the south and east of Lago Cardiel, which was glaciated during the Miocene, has hardly been eroded fluvially. Lago Cardiel is the remnant of a considerably larger lake, which has played an important role during the earliest glaciations in southern South America. Its highest lacustrine terraces are preserved at more than 350 m above the modern lake level (270 m a.s.l.). The lake was the erosional base of meltwater from glaciers of Monte San Lorenzo and Lago San Martín since the late Miocene. During the third Miocene advance of the San Lorenzo lobe the glacier initiated the incision of the Tres Lagunas dry valley into the 900-m-high gravel meseta. Since then, downward erosion of the valley bottom occurred. The current dry valley is the continuation of the youngest river terrace of Río Chico. During and after the Last Glacial Maximum, the river drained the meltwater from San Lorenzo and Sa. de Sangra lobes into Lago Cardiel (Wenzens, 2005).

The discrepancy between the extent of the first three late Miocene advances of Monte San Lorenzo glacier (240–220 km) and the extent of the Last Glacial Maximum advance (50 km) requires completely different climatic and perhaps also relief conditions for both glacial periods. Presumably glacial periods and episodes of climatic amelioration during the late Miocene were considerably longer as has been proved for this period of time on the Antarctic Peninsula.

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