Average Pleistocene Climatic Patterns in the Southern Central Andes: Controls on Mountain Glaciation and Paleoclimate Implications

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ABSTRACT

Despite elevations of 5000–6800 m, modern glaciers occur along the southern Puna Plateau and the northern Sierras Pampeanas in the southern central Andes. The modern snowline rises from 5100 m in Sierra Aconquija to 5800 m in the Puna as a result of a westward decrease in precipitation from 450 to less than 100 mm/yr. During the Pleistocene these arid highlands experienced multiple cirque and valley glaciation that likely postdate the last interglacial period, although lack of age control prevents an absolute chronology. Glaciation in the Puna and along the eastern Puna edge produced a 300-m Pleistocene snowline (PSL) depression, while in the Sierras Pampeanas the PSL depression was at least 900 m. The greater PSL depression in the Sierras Pampeanas is best explained by a combination of cooling and increase of easterly moisture, whereas the PSL depression in the Puna appears more sensitive to moisture increases than temperature. Previously, glaciations in this region have been explained by increased precipitation, with a westward depression of the snowline caused by a northward shift of the Pacific anticyclone and equatorward shift of the westerlies. However, these PSL results require an increase of moisture from the east rather than from the west. Further, analysis of topographic data indicates that drainage-basin relief decreases north of 28°S. The regional landscape response suggests that the circulation patterns currently observed have persisted at least during the Pleistocene and perhaps during the past several million years.

Introduction

The southern central Andes offer a unique setting to study controls on mountain glaciation and snowline trends because of good exposures of well-preserved landforms and their location between two major circulation and precipitation regimes (fig. 1). The Late Cenozoic uplift of the northern Sierras Pampeanas and the Puna Plateau determined the relief of the semiarid to arid southern central Andes between 25° and 28°S. Despite peak elevations of over 6800 m and an average elevation of about 2000–3000 m (fig. 2*a*), modern glaciers are few in the region; during the Pleistocene, however, several of these high ranges were glaciated by cirque and small valley glaciers.

The chronology and number of glaciations are poorly known in this region (Penck 1920; Tapia 1925; Rohmeder 1943). Paleoenvironmental studies from this Andean sector are few and cover only the latest Pleistocene and Holocene (Markgraf 1984, 1989). A supposedly Late Pleistocene age for these glaciations is supported by the occurrence of tephra within a fluvial terrace in front of the Río Pajanguillo moraine in the southern part of Sierra Aconquija (Strecker et al. 1984). The terrace and the intercalated tephra can be traced downstream into the piedmont region and correlated with other fluvial terraces in the Santa María Valley, which are nested in pediments. The youngest pediment is dated 300 ka (Strecker et al. 1989); hence the glacial and fluvial sediments are younger.

The region today lies in the transition zone between two circulation and precipitation regimes: (1) the northeasterly and easterly moisture regime, which develops in response to a seasonal low-pressure system over the Argentine Chaco lowlands east of the Andes, and (2) the dry-cold westerly circulation related to the Pacific anticyclone that gains intensity during the winter months, when the Pacific high-pressure cell moves north to about 25°S from its summer location at about 32°S (Prohaska 1976; fig. 1; fig. 2*a*, 2*b*). The modern snowline reflects these circulation and precipita-

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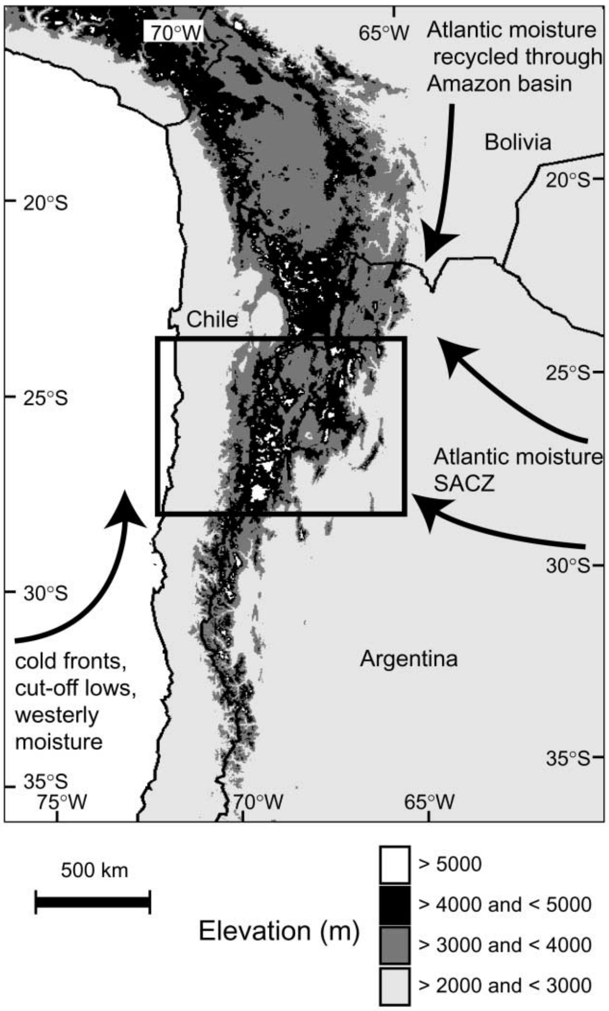

Figure 1. Location of the study area within the central Andes and including the southern Puna plateau. Primary moisture for the region is derived from the Atlantic via either the Amazon Basin or the South Atlantic Convergence Zone (*SACZ*), while only limited wintertime precipitation is derived from the Pacific.

tion patterns (fig. 3). Areas dominated by easterly moisture lie north of 28°S and are characterized by a westward-rising snowline, whereas the regions dominated by westerly moisture south of about 28°S have an eastward-rising snowline.

In order to explain Pleistocene glaciations, Hastenrath (1971) proposed that the glacial-age westerlies may have shifted as far north as 25°S. Increased precipitation and glaciation would then have resulted in a westward depression of the Pleistocene snowline in the high Andes, contrasting with the modern depression toward the east. In contrast, Paskoff (1977) hypothesized that the Andes between 27° and 30°S may have been in an arid corridor during glacial stages because of their transitional position between the two circulation systems.

In this article, we analyze modern and Pleistocene snowline trends and the extent of multiple Pleistocene glaciations to assess the parameters that caused mountain glaciations and infer regional climatic trends in the southern central Andes.

Methods

To develop a regionally meaningful snowline trend, snowline elevations were compiled for all highlands between 25° and 28°S and 65° and 69°30′W. The data are based on personal field observations in Sierra Aconquija, Sierra Quilmes, and the Cumbres Calchaquíes, several published accounts (Penck 1920; Tapia 1925; Rohmeder 1941; Hastenrath 1971; Nogami 1976), and stereoscopic airphoto analysis (1 : 50,000 scale). For regions where airphotos were unavailable the analysis was complemented by Landsat Thematic Mapper (TM) imagery (paths 231–233, rows 77–80), which has a resolution of 30 m and proved to be extremely helpful. The airphotos were taken between March and June and again in November 1968 while TM image acquisition dates are before the austral winter in March and April 1985 and 1986, when seasonal snow cover is at a minimum, that is, limited to permanent snow fields at the highest elevations.

Modern snowline was determined from field observations and published reports, complemented by airphoto and TM analysis, for all areas with glacial relief in northwest Argentina, whereas in Chile only TM image data were used. Geomorphological indicators of paleoglaciation such as cirques and moraines were identified first from the TM image data and then examined more closely on airphotos for all areas of glacial relief in Argentina. Elevations of both modern perennial snow cover and paleoglacial geomorphological features were then estimated from maps as described next.

The 1 : 250,000 topographic sheets of Cafayate, Santa María, Laguna Blanca, Laguna Helada, and Aconquija of the Instituto Nacional de Geología y Minería (Argentina) and Chilean topographic maps by the Instituto Geográfico Militar de Chile (1 : 250,000 scale), which cover the Chilean Cordillera and the entire Argentine Puna (sheets: Ojos de Salado, Chañaral, Copiapó, Nevado San Francisco), were used, as well as published geologic maps at 1 : 200,000 and 1 : 250,000 scales (Mercado 1982; Mueller and Perello 1982).

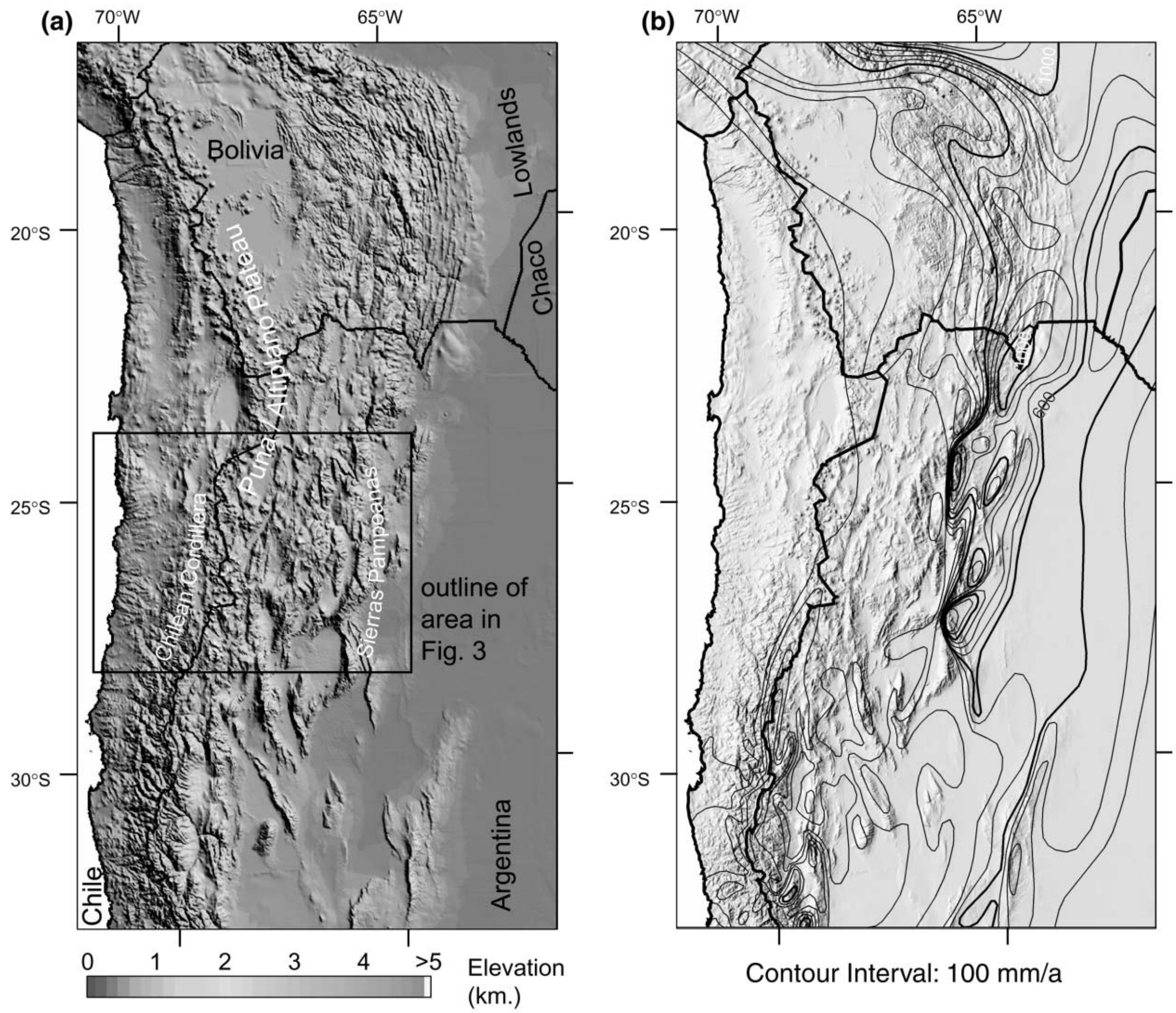

Figure 2. *a*, Shaded-relief topography (GTOPO30) of the central Andes. *b*, Average annual precipitation based on the WMO Climate Atlas for South America (World Meteorological Organization 1975).

Both modern and paleosnowline estimates of all important locations are given in tables 1 and 2 with respect to their level of accuracy. An "A" (see "Quality" column) defines modern snowline and paleoglacial-age landform elevations based on 1 : 250,000, 1 : 200,000, and 1 : 50,000 scale maps, spot elevations, aerial photographs, TM images, and personal field observations. Elevations denoted "B" were obtained by comparison of paleoglacial-age landforms of unknown elevation with neighboring peaks of known altitude. Elevations ranked "C" indicate measurements with the lowest level of confidence (i.e., peaks with glacial relief that in general are too far from one another to supply altitudes by interpolation).

Klein et al. (1999) presented detailed mapping of modern and local last glacial maximum (LLGM) glaciation in Peru and Bolivia, immediately north of our study area. Klein et al. estimated methodological errors that emerge when comparing modern perennial snowlines, modern equilibrium line altitudes (ELAs), and paleo ELAs using multiple methods for estimating both modern and paleo ELAs. The mean difference in that study between the lower limit of perennial snow cover and glaciological estimates of ELA was 146 m on a regional scale (Klein et al. 1999), while estimates of LLGM ELA varied from other estimates (Fox 1993) by >200 m in the most extreme cases as a result of observational bias, leading to an overall accuracy of snowline depression at any one point of ±100 to 200 m (Klein et al. 1999). As in those studies, we

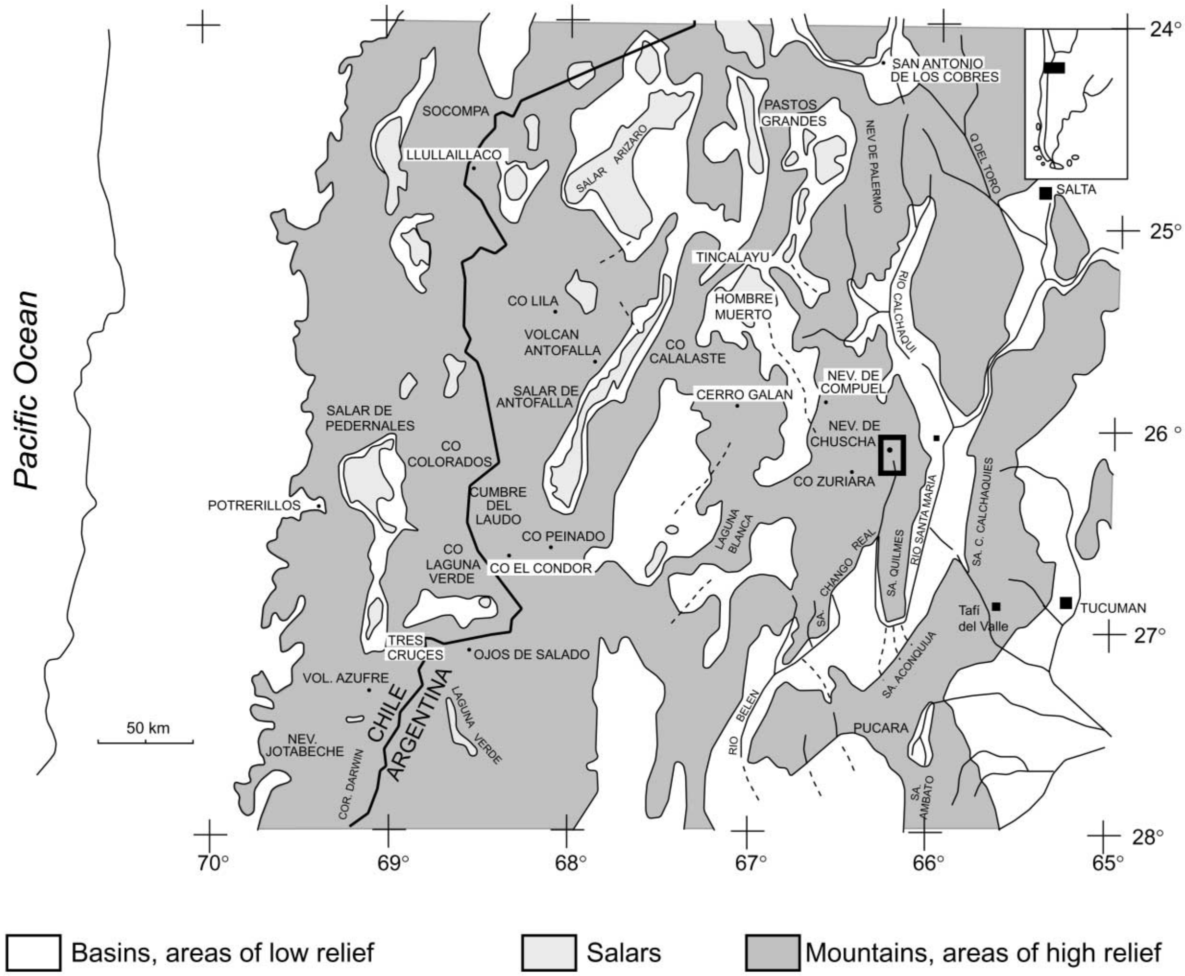

Figure 3. The study area showing locations of the snowline observations discussed in the paper (*black dots*). The principal peaks and ranges referred to in this article are indicated by name. The international border between Chile and Argentina is represented by the solid line. Box outlines area covered by figure 5.

are primarily concerned here with consistent snowline trends that are larger than the calculated uncertainty.

To assess long-term effects of precipitation in the western Andes, several morphometric analyses were carried out using the GTOPO30 topography data set (resolution ~1 km) from the U.S. Geological Survey, processed by the Grid module of ARCINFO(c). The following standard geomorphic analyses were performed to quantify spatial distribution of relief in the landscape: drainage-network extraction, residual and local relief, and minimum basin exhumation (see below). Because of the orographic effects of the meridionally oriented Andes and predominately western moisture sources south of 27°S, it is inferred that these parameters reflect the effects of a long-term fluvio-glacial landscape overprint.

Modern Climate

High-altitude climatic data in the study area are available only for the northern Sierras Pampeanas at Lagunas de Huaca Huasi in the southern Cumbres Calchaquíes (fig. 3, lat. 26.5°S) from the years 1977 to 1980. At Lagunas de Huaca Huasi, the predominant wind direction was from the west. Wind frequency from westerly directions increased during the winter, whereas during the summer northwesterly and easterly winds were characteristic. The easterlies account for 88%–96% of the annual precipitation in the area (Halloy 1982). These observations agree with precipitation data from the adjacent intramontane basins (Bianchi and Yañez 1992).

Because of the general north-south orientation of the Sierras Pampeanas and the adjacent ranges of

Table 1. Modern snowline (MSL) measurements

Location	Longitude	Latitude	Elevation (m)	MSL (m)	PSL[a]	Aspect[b]	Quality[c]
Volcan Bonete	69.00°W	27.43°S	6850	5800	Y	E	B
Cerro Piedra Parada	68.72°W	26.45°S	5920	5800	N	X	B
Cerros Pena Blanca	68.67°W	26.82°S	6020	5830	N	X	B
Cerro Ermitano	68.60°W	26.78°S	6187	5830	N	X	B
Sierra Nevada	68.55°W	26.48°S	6103	6103	N	X	B
Cumbre del Laudo	68.55°W	26.48°S	6400	5800	N	X	B
Nevado Leon Muerto	68.53°W	26.17°S	5793	5793	N	X	A
Ojos de Salado	68.53°W	27.10°S	6885	5700	Y	X	C
Nevado Tres Cruces	68.47°W	27.05°S	6330	5800	Y	E	B
Cerro de la Linea	68.35°W	26.80°S	5870	5830	N	X	B
Cerro Vallecito	68.32°W	26.20°S	6120	6120	N	X	B
Ojo de las Losas	68.30°W	27.03°S	6620	5700	Y	E	B
Cerro Dos Conos	68.28°W	26.80°S	5900	5830	N	X	B
Volcan Antofalla	67.90°W	25.55°S	6100	5750	N	X	B
Sierra Calalaste	67.40°W	25.67°S	5500	5400	N	X	B
Laguna Blanca	67.05°W	26.37°S	6200	5300	Y	E	B
Cerro Incahuasi	66.75°W	25.50°S	5167	5100	Y	E	A
Sierra Zuriara	66.52°W	26.25°S	5266	5200	Y	NE-E	B
Nevados de Compuel	66.38°W	25.54°S	5472	5200	Y	E-SE	C
Quilmes Filo Pishca Cruz	66.22°W	26.17°S	5200	5100	Y	E-W	A
Quilmes Nevado de Chuscha	66.18°W	26.15°S	5468	5100	Y	E-W	A
Aconquija Nevados del Candado	66.12°W	27.20°S	5350	5000	Y	S-W-E	A
Nevados del Cerillo	66.06°W	27.13°S	5550	5100	Y	E-W	A
Aconquija Cerro Laguna Verde	66.00°W	27.10°S	5100	5200	Y	E	A

[a] Locations where MSL also contains Pleistocene snowline (PSL) measurements are marked with a "Y"; where PSL is absent, they are marked with an "N."
[b] Aspect indicates trend of MSL; trends that are not discernible are denoted by an "X."
[c] "A" denotes the highest-quality measurements and "C" the lowest.

the Puna and the Andean Cordillera, the western regions receive progressively less precipitation from the easterly and northeasterly winds. These austral summer easterly winds condense and precipitate at two levels during their ascent of Sierra Aconquija and Cumbres Calchaquíes: at about 2500 m, where precipitation amounts to 2502 mm/yr, and at about 4500 m, where the amount is unknown (Rohmeder 1943; Wilhelmy and Rohmeder 1963; Werner 1972). As the winds rise on the next ranges to the west, at Sierra Quilmes and Sierra Chango Real (fig. 3), some additional condensation occurs. Measurements there are not available, but the arid vegetation cover of the ranges indicates that the precipitation is probably less than at Sierra Aconquija and Cumbres Calchaquíes. The transition from the subtropical rain forests of Tucumán to the grass-covered highlands of Tafí del Valle and into the semiarid Santa María Valley (fig. 3) can be appreciated on multispectral TM images. The images show the cloud buildup and orographic effects on rain and hence on vegetation density in this area, where precipitation measurements range between 145 and 230 mm/yr (Galvan 1981; Garleff and Stingl 1983). During torrential summer storms these easternmost ranges are often cloud covered and receive precipitation mainly in the form of hail. This results in snow-covered peaks, a situation rarely seen during the dry winter months in the east.

Precipitation and temperature data for the mountainous areas are available only from two locations: 404 mm/yr precipitation is reported at Tafí del Valle (fig. 3, lat. 26.8°S) for the period 1950–1970 (García Salemi 1977), and a mean annual temperature of 1.46°C and 385 mm/yr precipitation is reported from the 4250-m-high Lagunas de Huaca Huasi (fig. 3; Halloy 1982). Extrapolating from the 1.46°C mean annual temperature, the 0°C annual isotherm is located at approximately 4480 m, theoretically the lowermost limit for periglacial conditions. However, the lower limit of observed periglacial conditions is higher, at 4580 m (e.g., in the headwaters of Río Pajanguillo in the southern part of Sierra Aconquija [fig. 3]). Rock glaciers are widespread in both the Sierra Aconquija and the Nevados de Chuscha in the Sierra Quilmes (fig. 3), where they occur above 4800 m. The majority of rock glaciers are lodged on shadowy south-facing cliffs within steep-walled Pleistocene cirques. These rock glaciers are inferred to be active today due to the absence of vegetation or soils on their surface, poorly varnished rock surfaces, and a constant release of water during the summer. Occur-

Table 2. Pleistocene snowline (PSL) measurements

Location	Longitude	Latitude	Elevation (m)	PSL (m)	MSL[a]	Aspect[b]	Quality[c]
Volcan Bonete	69.00°W	27.43°S	6850	5500	Y	E	B
Ojos de Salado	68.53°W	27.10°S	6885	5500	Y	X	C
Nevado Tres Cruces	68.47°W	27.05°S	6330	5500	Y	E	B
Ojo de las Losas	68.30°W	27.03°S	6620	5500	Y	E	B
Laguna Blanca	67.05°W	26.37°S	6200	5000	Y	E	B
Cerro Incahuasi	66.75°W	25.50°S	5167	4800	Y	E	A
Sierra Zuriara	66.52°W	26.25°S	5266	5000	Y	NE-E	B
Nevados de Compuel	66.58°W	25.94°S	5472	4800	Y	E-SE	C
Quilmes Filo Pishca Cruz	66.22°W	26.17°S	5200	4800	Y	E-W	A
Quilmes Nevado de Chuscha	66.18°W	26.15°S	5468	4800	Y	E-W	A
Quilmes El Pabellon	66.13°W	26.15°S	5000	4800	N	E	A
Aconquija Nevados del Candado	66.12°W	27.20°S	5350	4300	Y	S-W-E	A
Nevados del Cerillo	66.06°W	27.13°S	5550	4400	Y	E-W	A
Aconquija Cerro Negro	66.05°W	27.12°S	5000	4600	N	W	A
Aconquija Cerro Laguna Verde	66.00°W	27.10°S	5100	4450	Y	E	A
Aconquija Abra del Toro	65.93°W	27.02°S	4600	4400	N	E	A
Aconquija Morro del Zarzo	65.92°W	26.98°S	5064	4800	N	NW	A
Aconquija Alto de Munoz	65.83°W	26.88°S	4437	4200	N	E	A
C.C. Cerro El Negrito	65.72°W	26.68°S	4660	4400	N	S	A
C.C. Alto de la Mina	65.70°W	26.62°S	4762	4650	N	SE	A
C.C. Qda. del Matadero	65.70°W	26.63°S	4250	4250	N	E	A
C.C. Alto de la Nieve	65.70°W	26.72°S	4634	4300	N	SE	A

[a] Locations where PSL also contains modern snowline (MSL) measurements are marked with a "Y"; where MSL is absent, they are marked with an "N."
[b] Aspect indicates trend of PSL; trends that are not discernible are denoted by an "X."
[c] "A" denotes the highest-quality measurements and "C" the lowest.

rence of rock glaciers at higher altitudes in Sierra Quilmes (fig. 3) as well as their absence in the arid Puna Plateau farther west shows that the limiting factor for their formation is neither topography nor temperature but rather moisture.

Climatic data for the Puna region between 25° and 28°S are scanty. At San Antonio de los Cobres at 3777 m (fig. 3, lat. 24.2°S), annual precipitation of 104 and 112 mm are reported; the bulk of the precipitation falls during the summer months and is related to easterly and northeasterly winds, while the winter months are dry (Ottonello de Reinoso and Ruthsatz 1982). Another source of summer precipitation is convective thunderstorms on the extensive plateau (Prohaska 1976). Farther south on the plateau, precipitation is only 61.7 mm/yr at Potrerillos (2850 m; fig. 3; 26.4°S, 69.4°W; Mercado 1982) and 61 mm/yr in the Salar de Pedernales area of Chile (26.25°S, 69°W; Mueller and Perello 1982). In contrast to the San Antonio area, a majority of the total precipitation along the western Chilean part of the Andes falls during the winter, even as the total amount decreases from south to north within the study area of this article. Therefore, the precipitation distribution is related to the occasional occurrence of polar outbreaks leading to cutoff events (Vuille 1996). Westerly storm tracks normally influence areas farther south, with 300 mm annual precipitation at 31°S (Miller 1976). Occasional cold-air incursions during the winter account for limited snowfall (*viento blanco*) in the Puna (Miller 1976). Thus, the Puna region is predominately influenced by summer precipitation, with decreasing amounts of rainfall toward the west. However, extremely low humidity and high daily surface temperatures often prevent summer rains from reaching the ground (Kanter 1937).

Modern Snowlines

Data for modern snowline elevations are plotted against longitude in figure 4 together with our estimates of Late Pleistocene snowline elevations. These transects display a snowline rising from the east to the west for both time periods.

Sierras Cumbres Calchaquíes (26.5°S, 65.7°W), Aconquija (27°S, 66°W), and Quilmes (26.2°S, 66.2°W). In an east-west transect through the northernmost Sierras Pampeanas, the modern snowline passes through the summit regions of Sierra Aconquija at an altitude of 5000–5100 m (fig. 3; Rohmeder 1941, 1943); the lower Cumbres Calchaquíes is below the snowline. At the Nevados de Chuscha (fig. 3) in the Sierra Quilmes, the modern snowline is at 5200 m. In contrast, the highest peaks in Sierra Chango Real to the southwest (26.7°S, 66.2°W) are below the

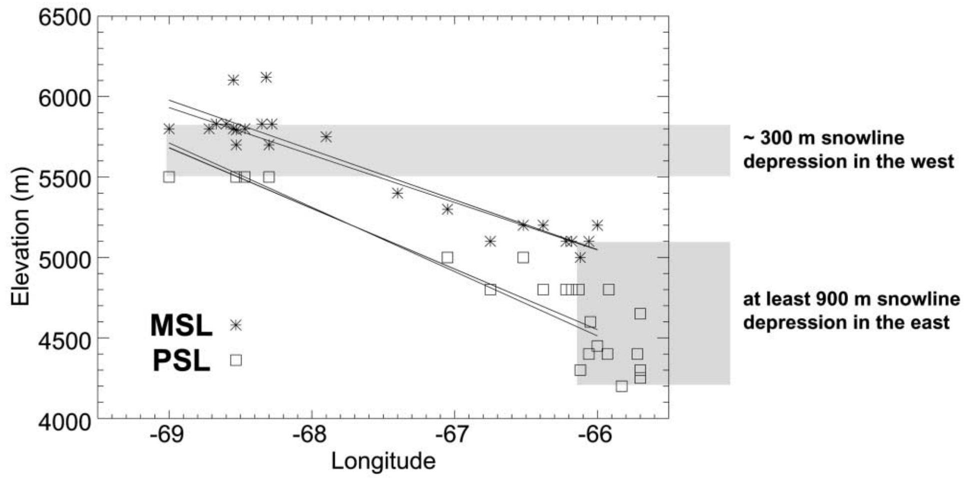

Figure 4. Summary of the MSL and PSL data. The 900-m or more snowline depression in the eastern ranges of Calchaquíes and Aconquija is best explained by temperatures 5°–7°C lower during the last glacial maximum compared to present. The presumed sensitivity of the hyperarid regions in the west would indicate some additional contribution to the snowline depression through increased precipitation.

modern snowline, although they reach altitudes of 5132 and 5277. Similarly, Cerro Cenizo (5262 m) and Cerro Azul (5000 m) at the southern Puna edge are below the modern snowline. Only ephemeral snow related to summer precipitation was detected on TM images.

Puna and Chilean Cordillera. Fifty-five kilometers west of Sierra Chango Real, the snowline rises to approximately 5300 m in the Sierra Laguna Blanca (fig. 3; 26.4°S, 67.1°W). Penck's (1920, p. 251) estimated elevation of 5600 m for the modern snowline is considered unreliable because the snowline is at 5200 m on Cerro Zuriara (26.3°S, 66.5°W) between Sierra Quilmes and Sierra Laguna Blanca and at 5500 m on Cerro Calalaste (fig. 3; 25.7°S, 67.4°W), about 80 km northwest of Sierra Laguna Blanca. The snowline rises to higher altitudes in the central and western part of the Argentine Puna.

Cerro Peinado (5740 m, 26.3°S, 68.2°W) is free of perennial snow, but other higher peaks in the southern region of Salar de Antofalla are snow covered. On Volcán Antofalla in the southern part of Salar Antofalla (fig. 3; 6100 m, 25.6°S, 67.9°W), the snowline is also above 5750 m, given that adjacent peaks with altitudes of about 5700 m are below the modern snowline (Cerro Cajero, 5700 m; Cerro de la Aguada, 5750 m).

The westward rise of the snowline continues into Chile. Prominent peaks such as Nevado de León Muerto (5793 m, 26.2°S, 68.5°W) have only minor accumulations of perennial snow. In contrast, the adjacent Cerros Colorados (6049 m) are snow covered, showing that the snowline here is at approximately 5800 m. An absence of perennial snow on Cerro Laguna Verde (5830 m, 26.3°S, 66.5°W) and on the adjacent Pico Wheelwright (5650 m) and the presence of snow on higher peaks such as Cerro de la Linea (5870 m) and Cerro Dos Conos (5900 m) corroborate the 5800-m snowline in this area. In the region south of Cerro Laguna Verde several volcanic peaks surpass 6000 m and have perennial snow accumulations above 5800 m. The only recent glaciers in the Argentine Puna occur in the area of Ojos de Salado (6885 m, 27.1°S, 68.5°W), at 6600 and 5800 m (Lliboutry et al. 1957).

The altitude of the snowline west of 69°00′ is not precisely known, although it must be above 5880 m since no perennial snow is detected on Nevado Jotabeche (5880 m, 27.7°S, 69.2°W) in the southern Cordillera de Darwin. Thematic Mapper images show only summertime snow here, as observed by Segerstrom (1964). South of 28°S, higher precipitation on the western slopes causes the snowline to descend to lower elevations on the Chilean side of the Andes. Hastenrath (1971) observed this reversal at about 30°S, and Lliboutry et al. (1957) reported small ice fields at 4800 m on Cerro Doña Ana (5690 m, 29.7°S).

The westward rise in snowline between 25° and 28°S demonstrates that the position of the snowline is controlled by the moisture-bearing easterly winds in the northernmost Sierras Pampeanas, Puna, and Chilean Cordillera. These trends can be traced into the northern Puna and the Bolivian/Peruvian Altiplano (Wright 1983; Jordan 1985; Klein et al. 1999). Furthermore, snowline trends show that occasional incursions of precipitation linked to cutoff lows does not cause a westward depression of the regional snowline, even at extremely high altitudes. Although *vientos blancos* may add to snow accumulation on the highest peaks, summer precipitation is obviously more significant. If westwind-derived precipitation were important, the peaks of the Chilean Cordillera de Darwin should be above the snowline.

Paleoclimate

Several Pleistocene glaciations have occurred in the study region. Multiple glaciations also occurred in the southernmost Andes since Late Miocene/Early Pliocene time (Mercer and Sutter 1981; Mercer 1983). Glacial tills as old as 3.26 Ma are also reported from the Bolivian Altiplano (Clapperton 1979). These tills and older deposits in Patagonia led Clapperton (1983) to propose a model of Andean glaciations where the relief necessary for glaciation had already been fully established in the Andes by the end of the Miocene. However, early investigators of Andean glaciations (e.g., Schmieder 1922; Troll 1937; Machatscheck 1944; Heim 1951; and Klammer 1957) questioned whether peak elevations in the Andes were sufficiently high during the early Quaternary to allow glaciation, given that only in middle to late Quaternary time was the uplift sufficient to increase the total relief in the region to its present topography.

Late Cenozoic tectonism documented in the northern Sierras Pampeanas (Strecker et al. 1989; Kleinert and Strecker 2001) requires reconsideration of these arguments. Well-documented glacial conditions in Patagonia existed already between 4.6 and 3.5 Ma (Mercer 1983; Rabassa and Clapperton 1990); at this time Sierra Aconquija, now more than 5000 m high, comprised only subdued hills, and the Santa Maria Valley region was still a lowland with braided-river channels and a semihumid climate similar to the present Argentine Chaco in the Andean foreland. Structural investigations, paleosol characteristics, and stable oxygen and carbon isotope analyses of paleosols indicate that most uplift in the Sierra Aconquija and Cumbres Calchaquíes began after 3.4 Ma and culminated after 2.9 Ma, causing aridification of the regions to the west (Pascual 1984; Strecker et al. 1989; Kleinert and Strecker 2001). Even if uplift rates had been extremely high, the altitude of the ranges in the Early Pleistocene probably was not sufficient to support glaciation in this part of the Andes. However, paleoglacial relief within the Puna and the Sierras Pampeanas supports repeated glaciation in these areas. Tapia (1925) found evidence for three recessional moraine systems in Sierra Aconquija, and Rohmeder (1941) suggested that moraines in that range might correspond to stages of the last Andean glaciation.

Farther north, modern and LLGM snowline changes in Peru and Bolivia have been used to constrain changes in temperature and precipitation during the last glacial maximum (LGM; Klein et al. 1999). They concluded that snowline depressions in areas where glaciation is moisture limited and the snowline is well above the 0°C isotherm must be due to increased precipitation during the LGM. Where glaciation is primarily temperature limited on the eastern side of the Andes, the amount of snowline depression is related to a modeled temperature depression of approximately 5°–7.5°C.

Multiple glaciations have been documented in the study area, but the chronology of these events is not known. This study in a climatic transition zone is concerned with the cumulative effects of glacial and fluvial erosion during the Pleistocene, which are expected to manifest themselves differently in the landscape depending on whether the primary moisture source is located in the east or west. For this reason it is not crucial to know the specific glacial chronology in this area but rather to determine maximum magnitudes and spatial patterns of snowline depressions as indicated by glacial landforms and deposits.

Cumbres Calchaquíes (26.5°S, 65.7°W) and Sierra Aconquija (27°S, 66°W). In contrast to modern snowline elevations, the Pleistocene snowline passed below the peaks of Cumbres Calchaquíes and caused limited glaciation in the southern part of the range (fig. 3). Cirques occur as low as 4250 m at the Quebrada del Matadero and reach about 4700 m on Cerro Alto de la Mina in the Laguna Huaca Huasi area. Common to all cirques and limited valley glaciers is their southerly and southeasterly aspect within protected topographic positions; this is particularly well demonstrated by small south-facing cirques at Cerro El Negrito and Cerro Alto de la Nieve. Slightly lower peaks to the north (Cerro El Pabellon, 4181 m; Cerro Agua Caliente, 3874 m) were not glaciated.

To the south, cirques are found at 4200 m on east- and northeast-facing slopes of Sierra Aconquija between Alto de Muñoz (4437 m, 26.9°S, 65.8°W) and Morro del Zarzo (5064 m, 27°S, 65.9°W). Rohmeder

(1941) reported the lowest cirque elevation in the region at 3800 m at the eastern slope of Cuesta de Medanito of Sierra Aconquija. Thematic Mapper images and aerial photographs do not exhibit the morphology of cirque glaciation typical of all the other investigated cirques, and such a low elevation is questionable. However, the regional snowline for the east-facing side of Sierra Aconquija was probably located between 4000 and 4200 m.

South of Morro del Zarzo the number of west-facing cirques increases. In contrast to the east-facing slopes, most cirques occur between 4400 and 4600 m (Tapia 1925). A typical example of these cirques and small valley glaciers is the area of the upper Rio Pajanguillo in the southern part of Sierra Aconquija (27.1°S, 66°W) where the southernmost cirque is located at 4600 m, situated below a higher cirque identified from a topographic swell that is a partly barren and polished basement rock surface with glacial striae. The Pleistocene glacier extended to an elevation of 3800 m and left high-standing moraines. The equilibrium line of a glacier (Meier and Post 1962) implies that the former ice-equilibrium line/snowline was likely located about halfway between the cirque floor and the terminal moraine. Therefore, the snowline would have been located at about 4400 m, a representative elevation for the western slopes of Sierra Aconquija. These moraines could have formed coevally with the moraines of Cumbres Calchaquíes in the Late Pleistocene, a suggestion supported by the correlation of fluvial terraces extending downstream into the piedmont region with other fluvial terraces in the Santa María Valley, which are of Late Pleistocene age (Strecker et al. 1984).

A strong rain shadow effect in Sierra Aconquija (27°S, 66°W) causes the cirque floors to be 400 m lower on east-facing than on west-facing slopes. The modern rainfall situation and the resulting contrast in the vegetation cover of the area shows this effect and a dependence on moisture from easterly and northeasterly sources. The morphological asymmetry is also visible on TM images; deep and wide glacial valleys occur only on the eastern slopes of the Aconquija range.

***Sierra Quilmes* (*26.2°S, 66.2°W*).** In the Sierra Quilmes, evidence for Pleistocene glaciation is only found on peaks higher than 4720 m (fig. 3), despite relief and aspect similar to the eastern ranges. A small east-facing cirque occurs on Cerro Pabellon at 4800 m, and impressive cirques with associated valley glaciation exist in the Nevados de Chuscha (fig. 3) of Sierra Quilmes (5468 m) along with Filo Pishca Cruz and Filo El Mishi. Large lateral and terminal moraines occur mainly on east-facing slopes. One of the most extensive moraines is found along Rio Suri Cienaga, where three smaller cirque glaciers coalesced into a large glacier.

In Sierra Quilmes, there is ample evidence for several separate stages of glaciation (fig. 5). Three generations of moraines are well preserved on the east-facing slopes. High, sharp-crested lateral moraines with convex and undissected slopes characterize the youngest moraines. Apart from the morphology of lateral moraines, well-preserved recessional moraines are also common for this stage of glaciation. Excellent examples of well-preserved recessional moraines that belong to this moraine generation are also found on west-facing slopes of the Nevados de Chuscha (Chuscha glaciation). The second generation of moraines is dissected by numerous small gullies. More gently inclined lateral moraine slopes further indicate advanced erosion. Furthermore, the terminal moraine arcs are less prominent and more dissected, as seen in the Río Suri Cienaga region (Suri Cienaga II glaciation). The oldest moraines (Suri Cienaga I glaciation) are severely altered by erosion; the terminal moraines are completely obliterated and lateral moraine crests are preserved as subdued hills. Evidence of this oldest stage is not widespread, but crosscutting topographic relationships below the Nevados de Chuscha at Rio Chuscha and Rio Suri Cienaga show the younger Suri Cienaga II and Chuscha glaciers cutting off and preserving the older moraine (fig. 5). Although the eastward-moving glaciers reached far into the narrow intramontane basin, no piedmont glaciers developed. On the western slopes of the range, no remnants of this oldest event can be seen. Furthermore, on the western side of the range, moraines generally occur only up to 2.5 km away from the cirques, and glacial scour was less pronounced. However, there are exceptions, such as south of Filo Pishca Cruz, where extensive moraines are seen. In this area, the largest glacier was fed by five cirques and extended approximately 4.5 km as measured from the head of the biggest cirques to the terminal moraine. This is a special case since the long axes of the two most important cirques are parallel to the north-south-trending ridge crest, and the western cirque walls, some of the highest points in the area, acted as a barrier for easterly and northeasterly moisture-bearing winds. However, east-facing slopes of Sierra Quilmes were significantly more affected by glacial processes than west-facing slopes. Glacial erosion in the east produced steeper and deeper cirques and also left volumetrically much larger deposits at the glacial termini. As with Sierra Aconquija, this asymmetry is interpreted to indicate predominantly easterly moisture-

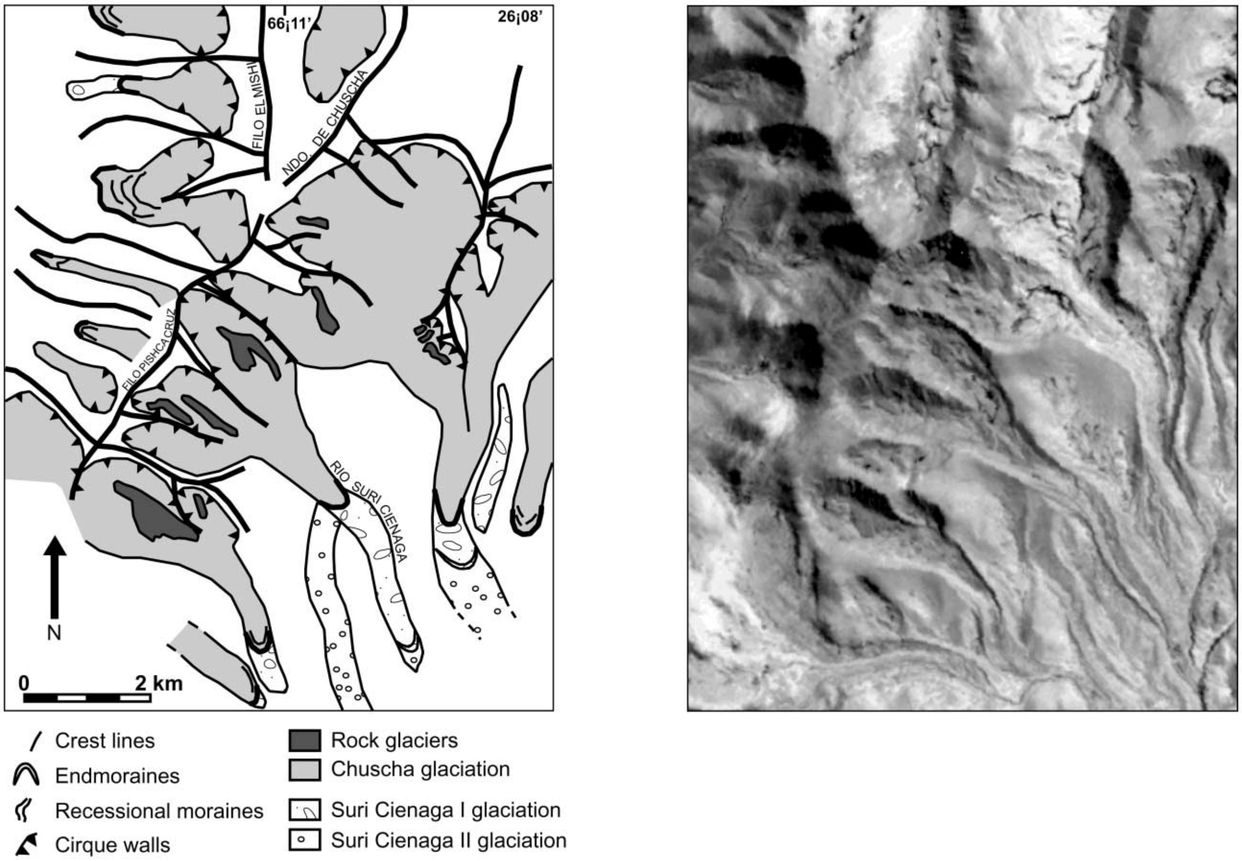

Figure 5. *Left*, paleoglaciation on Nevados de Chuscha within the Sierra Quilmes range showing multiple generations of moraines, dominant glaciation to the east and south, and limited glaciation to the west. *Right*, the same region as imaged by Band 7 of Landsat Thematic Mapper image row 78, path 231.

bearing winds at this location (26.2°S, 66.2°W). The morphologic asymmetry of both mountain ranges cannot be explained by lithologic differences because of their uniform composition in the glaciated areas.

The reason for the generally better preservation of glacial landforms in Sierra Quilmes is the absence of drainage systems with narrow and steep-walled canyons and high gradients such as those of the Sierra Aconquija. The majority of glaciers descended onto steep, high, and unconfined intramontane piedmont slopes that permitted free movement of ice. This unique setting is comparable to that of the eastern slopes of the North American Sierra Nevada, where glaciers descended from high altitudes to the margin of a dry piedmont lowland (see, e.g., Sharp 1972).

Puna and Chilean Cordillera. West and northwest of Sierra Quilmes, well-developed recessional moraines similar to the Chuscha stage of the Quilmes range are found at ~5000 m on Cerro Zuriara (26.3°S, 66.5°W) and on the Nevados de Compuel (fig. 3; 25.9°S, 66.6°W), as well as farther west in Sierra Laguna Blanca (fig. 3; 26.4°S, 67.1°W), where Penck (1920, p. 253) observed Pleistocene cirque floors at 5000 m. In the dissected peak region of Sierra Laguna Blanca, cirques and moraines indicate that glaciers developed only at the southern highest elevations. The effect of asymmetry is even more pronounced than in Sierra Quilmes, and glaciers developed only on the east-facing slopes of the range, although dissected terrain favorable for cirque glaciation also existed on the western slopes. The same asymmetry is found at the Puna edge on the Nevados de Palermo (fig. 3; 24.9°S, 66.4°W), where glacial landforms are absent on the west-facing slopes and cirque and valley glaciation occurred on the east and southeast side above 5100 m (Turner 1964). This is probably due to extreme cold-air incursions that redistribute snowfall to the eastern side (Vuille 1996).

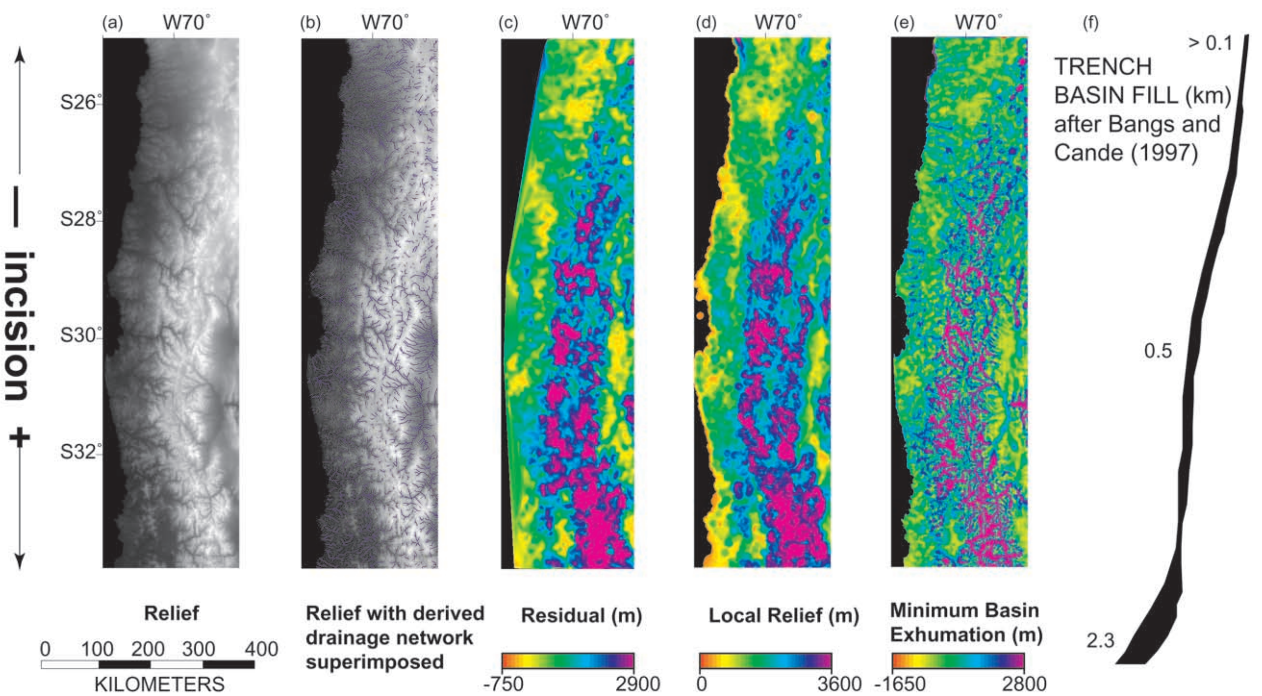

Figure 6. Morphometric analysis of GTOPO30 topography showing (*a*) relief, (*b*) relief with the derived drainage network superimposed, (*c*) topographic residual, (*d*) local relief within a 6-km circular area, (*e*) minimum basin exhumation. Part (*f*) depicts trench sediment fill after Bangs and Candy (1997).

Farther to the west, in the central Puna, elevations of over 5500 m were not high enough to produce glaciation. Examples of unglaciated peaks are Sierra Calalaste (fig. 3; 5500 m, 25.7°S, 67.4°W), Volcán Antofalla (6100 m, 25.6°S, 67.9°W), Cerro de la Aguada (5750 m), and Cerro Lila (5704 m). The Argentine-Chilean border area and the Chilean part of the Cordillera also do not possess any glacial landforms within our study area (e.g., Segerstrom 1964; Mortimer 1973; Mercado 1982; Mueller and Perello 1982), although many peaks rise above 6000 m (fig. 2*a*). Only fossil rock glaciers are reported from the Nevado Jotabeche and Cerro Cadillal in the southern Cordillera Darwin (fig. 3; 27.9°S, 69.2°W; Segerstrom 1964; Jenny and Kammer 1996).

In contrast to the north, paleoglacial landforms occur south of 27°S, where Penck (1920, p. 253) reported east-facing cirques at 5500 m elevation on Nevado Tres Cruces (6330 m, 27°S, 68.5°W) and others at 5500 m on Volcán Bonete (6850 m, 27.4°S, 69°W). On Ojos de Salado (fig. 3; 6885 m, 27.1°S, 68.5°W, the only modern glacier-supporting peak in the region; Lliboutry et al. 1957), the elevation of the Pleistocene snowline is not known; however, the snowline depression on neighboring peaks suggests it may have been above approximately 5500 m. Values of 4900 m for the Pleistocene snowline in the Laguna del Negro Francisco area around 27.4°S and 69.3°W are questionable (Nogami 1976) since glacial landforms in that region were not detected in this study or in the mapping project by Mercado (1982).

Geomorphic and Geologic Effects of Sustained Precipitation Patterns

The snowline data indicate that the present-day wind and precipitation regimes probably did not change significantly in the past. The permanence of the westerly related precipitation regime likely impacts the morphology of the landscapes of the western Andean flank. This is corroborated by the evolution of drainage networks and the relief caused by incision south of 28°S, where Pleistocene and modern snowlines are relatively low and decrease westward. Inspection of satellite images and the GTOPO30 digital elevation data clearly shows that channel incision is greatest south of 28°S and decreases northward (fig. 6*a*, 6*b*).

This southwardly increasing incision can be quantified using various DEM (digital elevation model) analyses that measure basin relief. For example, the calculation of the topographic residual subtracts a surface defined by channel bottoms (subenvelope surface) from a surface encompassing ridge tops (envelope surface), which shows the regional incision-related relief contrasts. Figure 6*c* displays the residuals for the western Andean slopes whose envelope and subenvelope points are defined by upstream contributing areas exceeding 31 km^2. High residuals are most pronounced in the regions receiving precipitation from the west, whereas small residuals define the arid sectors north of 28°S.

The northward decrease in topographic residuals is mimicked in the distribution of local relief. The local relief at each point is calculated as the range in elevations considered for a circular area with a radius of approximately 6 km around this point. Again, local relief is most pronounced in the fluvially and glacially overprinted areas south of 28°S, as shown by the increasing density and width of cyan-colored sectors in figure 6*d*.

Finally, the minimum basin exhumation is calculated by subtracting the digital topography from the envelope surface. In the north, basins are not significantly exhumed compared to drainage systems in the south. South of 32°S the landscape is deeply eroded and the Andes are relatively constant in width (fig. 6*e*).

The maintenance of the location of precipitation and erosion patterns in this region is also expressed by dramatic differences in trench-fill thickness (see, e.g., Bangs and Cande 1997). Whereas sediment thickness in excess of 2 km is reported from the trench region south of 33°S, where the maximum precipitation values are measured (fig. 6*f*), sediment thickness decreases abruptly to 0.5 km north of 33°S, further decreasing to nearly 0.1 km off the arid areas north of 28°S. We interpret these erosion and sedimentation phenomena as first-order results of sustained circulation similar to modern patterns and not as manifestations of lithologic differences and hence variable degrees of erodibility. This is supported by regionally consistent outcrops of Paleozoic and Mesozoic intrusive and volcanic complexes that encompass the entire study area and form north-south-trending belts; in addition, north of the transition zone at 28°S, there are areally extensive Tertiary ignimbrites that despite their high erodibility maintain their primary depositional character (Mápa Geológico de Chile 1982).

Discussion and Conclusion

Multiple glaciations have been documented in the study area, but the chronology of these events is not known. However, the lowest snowlines in the western part of the study area at any time during the Pleistocene were still higher than even the modern snowline in the eastern part. Glaciers on the western peaks are moisture limited, and any additional moisture would have resulted in snowline depression, but there has been at most only 300 m of snowline depression at any time during the Pleistocene, which is exceeded by snowline depressions in the eastern part of the study area (Sierra Quilmes and Sierra Aconquija), where moisture transport is from east to west.

A first-order comparison of both modern and Pleistocene snowlines shows the same trend of westward increasing elevations between 25° and 28°S (fig. 4). This is consistent with easterly moisture sources during the Pleistocene as well as in modern times and does not require large-scale shifts of the westerlies. If there had been a northward migration of precipitation associated with a shift in the westerlies in the past, a reversal in snowline trend (i.e., a rise to the east) should have resulted. However, not even the highest peaks in the Chilean Cordillera west of 69°W longitude show signs of former glaciation. The fact that glacial features are absent indicates that modern-day precipitation patterns prevailed during glacial stages. Also, wintertime precipitation associated with occasional equatorward-moving cold fronts (Vuille 1996) could not have increased.

Kuhn (1989) considers the relative influences of precipitation, temperature, relative humidity, and other factors in modeling the effects of perturbations in these parameters on the glacier mass balance. Klein et al. (1999) discussed the particular application of Kuhn's model to subtropical glaciers of the central Andes, especially in arid regions where sublimation is an important ablation process. Temperature depression is best estimated in the eastern part of the study area, where snowlines are lowest and the melt duration longest. In the arid western part where the melt season is shorter, snowline depressions are best explained in part by increased precipitation. The Pleistocene snowline depression in the Puna and in the adjacent Sierra Quilmes at the eastern Puna edge is about 300 m (fig. 4). Because glaciation in such regions of high aridity should be more susceptible to changes in precipitation than temperature, we interpret the Pleistocene snowline depression in these arid highlands to result from increased precipitation from easterly sources during the LGM.

In contrast to the Puna, the Sierra Aconquija and Cumbres Calchaquíes experienced a drastic snowline depression between 900 and 1000 m and snowlines decreased eastward (fig. 4). The extreme deviation from the parallel trends of the Puna snowlines implies that glaciation occurred in response to a decrease in temperature in this region, where precipitation was not a limiting factor, causing greater snowline depression than in the Puna, where glaciation is precipitation limited. The depression of the snowline was on the same order of magnitude in both ranges, suggesting that precipitation regimes in the two ranges did not differ significantly.

The estimated SL depression along the entire transect is above the maximum site-specific errors discussed by Klein et al. (1999) for Bolivia and Peru, especially in the east where this result is robust with respect to methodological and map errors. It is important to note that the PSL estimate in the west is estimated from a tight clustering of points at 5500 m and is constrained by the absence of paleoglacial features at lower elevations.

It could be argued that active volcanism did not permit formation of glaciers on the highest peaks in the southern central Andes. This is an important consideration for young volcanic edifices with perfectly preserved lava flows and craters such as Cumbre del Laudo (26.5°S, 68.6°W) or Cerro El Condor. Furthermore, it could be argued that glacial landforms on volcanoes were obliterated by violent explosions and subsequent avalanches, as documented on Volcán Socompa (Francis et al. 1985). Yet volcanic peaks at similar elevations that were last active during Mio-Pliocene time have not been glaciated either, and the absence of glacial features on Co. Aguas Blancas (5785 m; 7.8-Ma-old volcanics), Cerro Lila (5704 m; 10-Ma-old volcanics), and other Miocene volcanoes (Coira and Pezzutti 1976; B. L. Coira, pers. comm., 1984) such as Volcán Antofalla and Volcán Copiapó (>6000 m) make it improbable that volcanic activity accounts for the absence of glacial features.

The snowline trends in the southern central Andes support the contention that with the exception of El Niño effects, the atmospheric circulation patterns in the Andes were similar to those of the present and seem to have persisted throughout the Pleistocene (Nogami 1976, as referenced in Satoh 1979, p. 406). Decreasing drainage-basin relief north of 28°S suggests that current circulation patterns may have persisted for longer periods of time. While the coarse topographic data do not permit a detailed landscape analysis, the regional patterns of denudation that result from prevailing precipitation patterns are underscored by the GTOPO30 data.

Geologic data show that arid conditions have been in existence in the regions north of 28°S since at least Middle Miocene time; it is thus reasonable to assume that the erosion and sedimentation patterns have also remained approximately the same. This interpretation is supported by evidence of major climate-driven accretionary episodes in the southern Andes, where more than 1000-m-thick glacigenic sediments were deposited in the Chile Trench in the last 0.5 Ma (Behrmann et al. 1994). By analogy, had erosion and deposition changed significantly in the study area due to multiple glacial episodes, more pronounced topographic relief contrasts and greater volumes of trench fill would be expected. However, only negligible amounts of sediment in the trench are reported at these latitudes, while increasing precipitation and relief contrasts toward the south parallel an increase in sediment fill.

Wyrwoll et al. (2000) proposed a poleward displacement of the westerlies during LGM accompanied by slight, general widening using a general circulation model. On the basis of sedimentological data from marine gravity cores, Lamy et al. (1998) showed that frontal winter rain associated with the southern westerlies migrated as far north as 27.5°S in certain periods during the last 120 kyr. The cumulative effect of these periods has apparently not been significant enough to influence sediment fill at this latitude. Vuille (1996) demonstrated for the region between 23° and 25°S how more frequent incursions of equatorward-moving cold fronts or an intensification of the westerlies leading to more pronounced cutoff lows could deliver additional wintertime precipitation (snow at high elevations) without requiring a northward shift of the westerly wind system. Trauth et al. (2000) hypothesized that landslide clustering during the period between 40,000 and 25,000 ^{14}C yr B.P. resulted from an increase in effective precipitation in arid NW Argentina. This is supported by an analysis of salt cores from the Puna plateau, which show the same period characterized by enhanced precipitation in this region (Godfrey et al. 1997).

In conclusion, for the Andean climatic transition zone between easterly and westerly moisture sources at about 28°S, there is no reason to assume large-scale shifts of atmospheric circulation and precipitation patterns such as a northward shift of the westerlies. Thus, Pleistocene glaciation in the transition zone and regions farther north is best explained by a general temperature depression, coupled with a small concomitant increase in easterly precipitation in the Puna Plateau.

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