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Chronology of the Late Cenozoic Patagonian glaciations and their correlation with biostratigraphic units of the Pampean region (Argentina)

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Abstract

The absolute chronology of the Patagonian glaciations is one of the most complete in the world and probably the best available for the Southern Hemisphere outside Antarctica. The oldest known Patagonian glaciations took place between approximately 7 and 5 Ma (Latest Miocene–Earliest Pliocene). A minimum of eight glaciations occurred in the Middle–Late Pliocene (Oxygen Isotopic Stages 54–82). The Great Patagonian Glaciations (GPG) developed between 1.168 and 1.016 Ma (OIS 30–34; Early Pleistocene). After the GPG, 14–16 cold (glacial/stadial) geoclimatic events intercalated with their corresponding warm (interglacial/interstadial) equivalents. Thirteen post-GPG moraines have been identified, some of the Early–Middle Pleistocene and others of the Last Glaciation (LG). The LG reached its maximum around 25,000 and ended nearly 16,000 calendar years ago (OIS 2; Late Pleistocene). Finally, two readvances (or stationary phases) took place during the Late Glacial (15,000–10,000 ^{14}C years BP). During these glacial events, climatic and environmental changes had a great influence on the landscape and Patagonian/Pampean ecosystem development during the last 5 Myr. Loess/paleosol sequences probably developed in the Pampas along this period, as in northern China, though much more poorly preserved. The model of replacement of the terrestrial Pampean faunas since the LGM proposes the exchange of Patagonian for Brazilian species in the Holocene with megafauna extinction. If this model fits previous cycles as well, regional faunistic interchange would have taken place at least 14 times since the GPG and perhaps more than 50 times since the Early Pliocene. These mechanisms should be taken into consideration in the study of paleobiogeographical distribution, ecosystem displacements, and extinction processes since 5 Ma. The environmental impact of climatic changes also should be considered when analyzing the early peopling of Patagonia during Late Glacial times.

Keywords: Biostratigraphic units; Late Cenozoic glaciations; Loess; Mammal paleontology; Ocean isotope record; Pampas; Patagonia

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Resumen

La cronología absoluta de las glaciaciones patagónicas es una de las más completas del mundo, y probablemente la mejor de que se dispone en el Hemisferio Sur, fuera de la Antártida. La glaciación más antigua reconocida se desarrolló entre ca. 7 y 5 Ma (Mioceno final-Plioceno inicial). Un mínimo de ocho glaciaciones ocurrieron en el Plioceno medio-tardío (Estadíos Isotópicos de Oxígeno-EIO 54-82). La "Gran Glaciación Patagónica" (GGP) tuvo lugar entre 1,168 y 1,016 Ma (EIO 30-34; Pleistoceno temprano). Luego de ella, hubo 14-16 épocas geoclimáticas frías, glaciales/estadiales, intercaladas con sus correspondientes equivalentes cálidos, interglaciales/interestadiales. Se han identificado 13 morenas post-GGP, algunas del Pleistoceno temprano-medio, y otras, de la Última Gran Glaciación (UGG). Ésta alcanzó su máximo (Último Máximo Glacial, UMG) hacia 25.000 y finalizó hacia 16.000 años-calendario atrás (EIO 2; Pleistoceno tardío). Finalmente, tuvieron lugar dos nuevos reavances glaciarios (o fases estacionarias) durante el Tardiglacial (15.000-10.000 años ^{14}C A.P.). Durante estos eventos glaciales se produjeron cambios climáticos y ambientales, que tuvieron gran influencia en el desarrollo del paisaje y los ecosistemas patagónicos y pampeanos en los últimos 5 millones de años. Secuencias de loess/paleosuelos se desarrollaron probablemente en la Región Pampeana, en forma similar a lo que ocurrió en China Septentrional, si bien con menor preservación. El modelo de reemplazo de

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las faunas terrestres pampeanas desde la UGG propone el cambio de estirpes patagónicas por brasílicas (Holoceno), con extinción de megafauna. Si este modelo es aplicable a ciclos anteriores, el intercambio faunístico regional habría tenido lugar por lo menos 14 veces desde la GGP, y más de 50 desde el Plioceno temprano. Estos mecanismos deberán ser tenidos en cuenta en el estudio de la distribución paleobiogeográfica, el desplazamiento de los ecosistemas y los procesos de extinción desde 5 Ma. El impacto ambiental de los cambios climáticos debe ser asimismo considerado al analizar el poblamiento temprano de Patagonia en el Tardiglacial.

1. Introduction

The climate of the planet suffered significant variations during the Cenozoic, particularly since the Miocene. These climatic changes are related to various causes, including continental displacement due to plate tectonics, the modification of greenhouse gas content in the lower atmosphere, and changes in astronomical parameters, such as the eccentricity of the Earth's orbit, obliquity of the planet's axis, and equinoctial precession. This process of climate deterioration probably initiated near the end of the Mesozoic and culminated with the recurrence of multiple cold–warm climatic cycles in the Miocene, which led to the development of global ice ages.

Understanding of Late Cenozoic glaciations in southern Patagonia has made significant progress in the past decade, thanks mainly to the application of absolute dating techniques following the pioneer work of John Mercer (e.g. Mercer, 1969, 1976; Meglioli, 1992; Clapperton, 1993; Ton-That et al., 1999). These dating techniques have enabled the correlation of the Patagonian glacial record (perhaps the most complete in the Southern Hemisphere outside Antarctica and probably one of the best in the world) with other glaciated regions and the global marine isotopic sequence (Shackleton, 1995).

Likewise, the stratigraphic and biostratigraphic units of the Pampean region of central Argentina have been chronologically linked by means of paleomagnetic dating techniques, which provides a basis for regional and planetary correlation (Cione and Tonni, 1999).

This article attempts to establish the absolute chronological correlation of (1) the Patagonian terrestrial glacial sequences through application of ^{40}Ar/^{39}Ar dating techniques on volcanic rocks associated with the glacial landforms and deposits and, more recently, cosmogenic isotope dating techniques on erratic boulders and glacial erosional surfaces (Kaplan et al., 2004); (2) oceanic isotopic sequences (OIS) based on the relative content of δ^{18}O in benthonic forams; and (3) the magnetostratigraphy of Pampean continental sequences, referred to the global magnetostratigraphic column. It also aims to identify the number and relative magnitude of the cold climatic events at the global scale, which could have had an impact in the genesis of the Pampean sediments and the evolution and distribution of the corresponding paleofaunas.

The regions discussed herein are shown in Fig. 1. The Patagonian localities cited in the text are found along the Patagonian and Fuegian Andes between lat. 38 and 55°S and the adjacent Patagonian plains. The Pampean stratigraphic units have been recognized in the Pampean region of central eastern Argentina between 30 and 36°S.

2. Methodology

We compare and attempt to correlate the OIS (Kennett, 1995; Shackleton, 1995) with (1) the results of several regional studies (Mercer, 1976; Meglioli, 1992; Clapperton, 1993; Ton-That et al., 1999) that provide absolute and paleomagnetic chronologies of the currently known Late Cenozoic Patagonian glaciations and (2) the Pampean biostratigraphic column (Cione and Tonni, 1999). Links between the records emerge from the magnetostratigraphic chronology presented by Cione and Tonni (1999), which enables us to compare them on absolute time magnitudes. Because, in many of the studied Pampean units, loess is one of the most significant components, we also present a comparison with the Chinese loess sequence (Rutter et al., 1991).

The temporal boundaries of the Late Cenozoic chronological units cited herein are presented in Table 1 to provide a clear definition of the terms we use.

3. Previous work

3.1. Climatic variability at the global scale

Global climate variations since the end of the Mesozoic have long been recognized through the study of the isotopic composition of calcareous shells of benthonic forams, as well of other marine organisms (Kennett, 1995). These results indicate that the climate would have been quite warm between the Late Cretaceous and the Eocene–Oligocene boundary, after which a progressive deterioration would become particularly significant during the Early Miocene–Early Pliocene, when Antarctic ice sheets extended over the entire southern continent and the global ice ages began. Since, at least the Late Miocene (~6 Ma) to the present, a marked cyclicity in the atmospheric δ^{18}O content is observed, which becomes progressively more abrupt and provides higher relative isotopic values toward the end of the Pliocene (Fig. 2). In general terms, three zones may be recognized in this curve: (1) the first, from the beginning of the presented record (6 Ma) to the Middle Pliocene (3 Ma), is characterized by high relative δ^{18}O values and a marked cyclicity of high frequency and reduced amplitude; (2) the

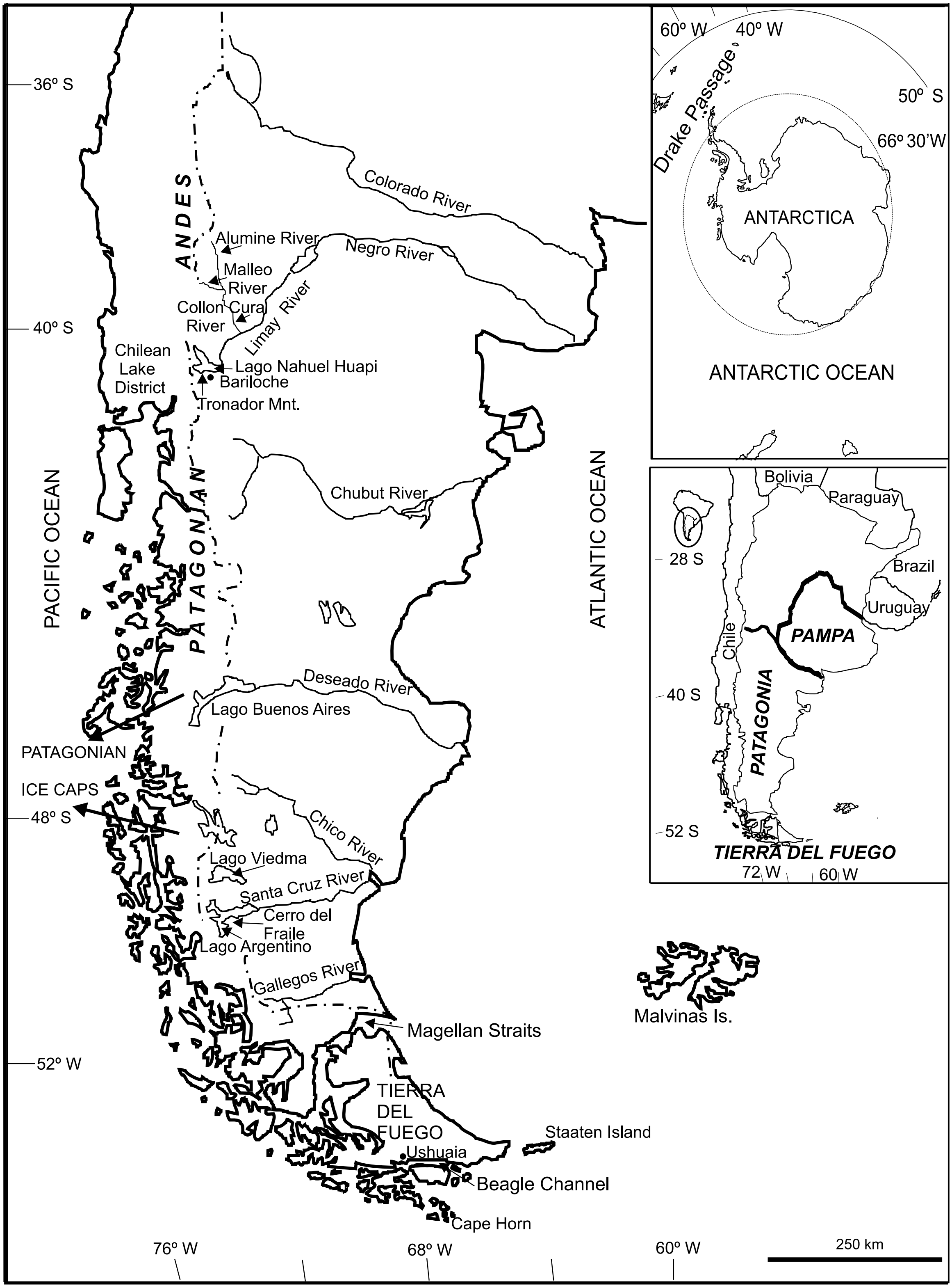

Fig. 1. Location map, Patagonia, Fuegian, and Patagonian Andes, Pampa. Note the geographical relationship of the studied region with the Antarctic Peninsula, the Drake Passage, and therefore, the Antarctic circumpolar current.

second, between the Middle Pliocene and the Early Pleistocene (~1 Ma), presents intermediate relative $\delta^{18}O$ values and a cyclicity of smaller frequency and higher intensity; and (3) the third, between the Early Pleistocene and the present, is characterized by cycles of even smaller frequency, maximum amplitudes, and higher relative values of the entire available sequence. These three zones may reflect changes in the climate-forcing processes associated

Table 1
Time boundaries of the Late Cenozoic chronological units

Chronological Units	Age
Late pleistocene-holocene boundary	10,000 ^{14}C years BP
Late glacial	15,000–10,000 ^{14}C years BP
Middle-late pleistocene boundary	OIS 5e, 125 ka
Early-middle pleistocene boundary	Brunhes-matuyama chron boundary, 0.778 Ma
Pliocene-pleistocene boundary	Top of the olduvai subchron, 1.75 Ma
Early-late pliocene boundary	Gilbert-Gauss chron boundary, 3.58 Ma
Miocene-pliocene boundary	Base of the C3 Thvera subchron, 5.2 Ma
Middle-late miocene boundary	12 Ma

with variations in the terrestrial orbit around the Sun (Berger and Loutre, 1991).

During the first period (Late Miocene–Middle Pliocene), cyclicity would have been determined by the dominance of equinoctial procession over other orbital variables, with an average cycle of approximately 23 kyr. In the second interval (Middle Pliocene–Early Pleistocene), the obliquity of the Earth's rotational axis (in relation to the ecliptic plane) would have been dominant, with a cycle of approximately 41 kyr. During the third period (Early Pleistocene–Holocene), the eccentricity of the terrestrial orbit would have been the dominant factor, with a cycle of approximately 100 kyr. These orbital variables may have determined the characteristics of the global climate beyond other forcing elements (e.g. tectonics, oceanic currents) in the studied period, though local and regional conditions also may have played significant roles. The shorter extent of the colder events in the Late Miocene–Early Pleistocene period would have impeded the full growth of the large continental ice sheets of the Northern Hemisphere, which would have reached their maximum development only during the last one million years. Nevertheless, the existing climatic and environmental conditions would have been cold enough to allow the genesis of mountain ice sheets in both hemispheres, though no synchronous growth has yet been proved.

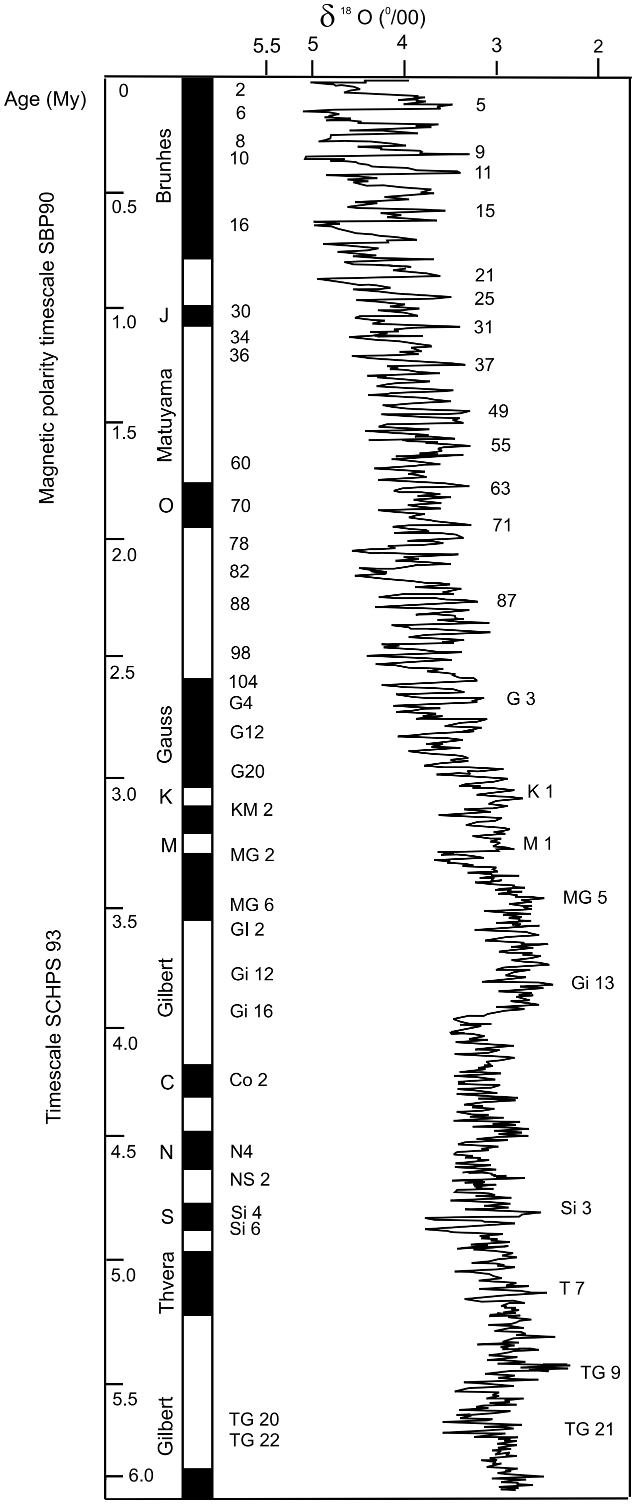

Fig. 2. δ^{18}O curve for benthonic forams, according to Shackleton (1995); Opdyke (1995) for ODP Site 846, south Atlantic.

3.2. Late Cenozoic glaciations in southernmost South America

Since, the nineteenth century, the study of Patagonian glaciations has peaked the interest of many investigators. Charles Darwin (1842) observed erratic boulders in the Río Santa Cruz Valley (lat. 50°S/long. 71°W), far from the Andean ranges, to which he assigned a glacial origin—though he interpreted them as products of iceberg deposition in the ocean, following the established paradigm of the times. Although other studies of local character were developed, it was the Swedish geologist Carl Caldenius who first achieved a full study of the Patagonian Pleistocene glaciations. In his glacial map, covering Lago Nahuel Huapi (lat.41°S) to Cape Horn (lat. 56°S), Caldenius (1932) identified moraines corresponding to four glacial events which he named 'Initioglacial,' 'Daniglacial,' 'Gotiglacial,' and 'Finiglacial,' thus assuming a direct correlation with the Scandinavian glacial model. He considered these units succesive recessional phases of the last glaciation and

Fig. 3. Basalt-till sequence at Cerro del Fraile. Note the basalt flows (darker beds) interbedded with the tills (lighter beds). The uppermost lava flow is Lava Flow 2. Photo credit: J. Rabassa.

observed the existence of inner morainic belts, younger than the last glacial maximum (LGM), which he named 'post-Finiglacial' advances. Although his stratigraphic scheme is mostly valid and his glacial map is outstanding for its detail and precision, the chronostratigraphic scheme is unfortunately wrong; he underestimated the age of some morainic belts, most likely because he was impressed by the excellent state of preservation of the landforms, even in some of the outermost (and older) arcs. This preservation is due to the extremely dry climate of the Patagonian steppes, which were reached by eastward-moving glaciers expanding from the Andean piedmont. This high degree of preservation would have never taken place in the Scandinavian or Baltic regions, where no well-preserved pre-Last Glaciation (Late Pleistocene) moraines are known.

Later, Feruglio (1944) described with great precision a sequence of basaltic lava flows with interbedded tills at Cerro del Fraile, Santa Cruz province (lat. 51°S, Figs. 1 and 3), just north of the Magellan Straits. He recognized the great antiquity of the glacial deposits and assigned them to a Pliocene age, older than the maximum glacial extent (Great Patagonian Glaciation, GPG), thus offering an extraordinary, pioneer contribution to the knowledge of pre-Quaternary glaciations of Patagonia before absolute dating was available. Years later, and working at the full regional scale, Feruglio (1950) also recognized the existence of four major Pleistocene glacial events, which he named 'Pichileufuense inferior,' 'Pichileufuense superior,' 'Barilochense,' and 'Nahuelhuapiense,' thus retaining Caldenius's (1932) fourfold scheme but linking each event to geomorphological positions that indicated clearly different (and older) ages. Thus, he recognized that the Pichileufuense landforms and sediments were found on topographical divides, whereas the deposits of later glacial events were located within the valleys excavated in them. Therefore, Feruglio (1950) established the criteria that later allowed the identification of a Quaternary 'canyon-cutting event' (Rabassa and Clapperton, 1990) in Patagonia. Likewise, he first established the possible correlation of the glacial deposits with both the 'Rodados Patagónicos' or 'Rodados Tehuelches' ('Patagonian Gravel Formation,' 'Patagonian Shingle Formation'; Darwin, 1842; Caldenius, 1940), which he considered of glaciofluvial origin, and the events of loess deposition in those regions, which he called "infraglacial" (i.e. the nonglaciated Pampas of eastern central Argentina) (Feruglio, 1950).

Flint and Fidalgo (1964) studied the glacial deposits in the northern Patagonian Andes (lat. 39°–43°S) and proposed a three-glaciation model based on what they named the 'Pichileufu,' 'El Cóndor,' and 'Nahuel Huapi' drifts. In their 1969 paper, they suggested that the Pichileufu Glaciation might be older than the Late Pleistocene. Fidalgo and Riggi (1965) identified four main glacial drifts at Lago Buenos Aires (lat. 47°S), as well as the glaciofluvial origin of at least a portion of the Patagonian gravels. Mercer (1969) and Mercer and Sutter (1981) studied many outcrops of glacial deposits interbedded with volcanic rocks, in which radiometric and paleomagnetic dating techniques were applicable, as well as Feruglio's (1944) Cerro del Fraile locality (absolute dating was recently updated by Singer et al., 2004a). Mercer (1976) first chronologically established the existence of Patagonian glaciations throughout the entire Quaternary period, frequent Pliocene glaciations, and even Late Miocene tills, recognizing as well the

Table 2
Late Miocene–Holocene erosional and depositional history of the Maurice Ewing Bank, southwest Atlantic (slightly modified from Ciesielki et al., 1982; Clapperton, 1993), showing implications for glacial events in Patagonia

Paleomagn. Epoch	Period	Age (Ma)	Event	Implicancies	Patagonian record
Brunhes	Middle-Late Pleistocene	0.0–0.7	Discontinuous sedimentation	Discontinuous glaciation	Repeated glaciations
Late Matuyama	Middle Pleistocene	0.7–1.0	Ice-rafting	Glaciation	Uncertain data (Daniglacial?)
Late Matuyama	Early Chapadmalalan	1.0–1.2	Maximum erosion	Maximum glaciation	GPG
Late Matuyama	Late Pliocene-Early Pleistocene	1.2–1.8	Erosion	Glaciation	GPG
Early Matuyama	Late Pliocene	2.13–2.43	Limited sedimentation	Weak glaciation	Five glaciations
Late Gauss	Late Pliocene	2.43–2.8	Wide sedimentation	Long interglacial	No glacial deposits
Gilbert-Gauss	Middle Pliocene	3.0–3.9	Erosion	Glacitaions	1–4 (?) Glacitaions
Gilbert	Early Pliocene-Late Miocene	3.9–4.6	Sedimentation	Interglacial	No glacial deposits
Gilbert	Early Pliocene-Late Miocene	4.65–7.4	Erosion	First important glaciations	First Patagonian glaciations

correlation of these glacial episodes with global cold periods. Porter (1981) identified four major glaciations in the Chilean Lake District (lat. 39°–41°S) and defined their chronology throughout the Pleistocene. Ciesielski et al. (1982) proposed a correlation model of the erosional and depositional history of the Maurice Ewing Bank (lat. 55°S), southwestern Atlantic Ocean, with the Patagonian glaciations (Table 2) on the basis of Mercer's (1976) chronoestratigraphic scheme. In this model, the great antiquity of the Patagonian glacial events and their relationship with global paleoclimatic episodes is confirmed.

More recently, Mörner and Sylwan (1989), Sylwan (1989); Schlieder (1989), Rabassa and Clapperton (1990), Meglioli (1992), Rabassa and Evenson (1996), Wenzens (1999a,b; 2000), Wenzens et al. (1996), Schellmann (1998, 1999, 2003), Singer et al. (1998, 1999, 2004b), Kaplan et al. (2004), and Rabassa and Coronato (2002), among others, have stressed the great antiquity and complexity of the Patagonian glacial sequence. Ton-That et al. (1999) first proposed a correlation of the glacial sequences of Lago Buenos Aires and Cerro del Fraile with the global marine isotopic sequence, following Shackleton et al. (1990, 1995). A recent revision of the Patagonian glaciations has been presented by Coronato et al. (2004a,b), in which they indicate the development of the GPG at around 1 Ma, as well as evidence of (1) several pre-GPG cold periods between 7 and 2 Ma, (2) three post-GPG glaciations during the Early and Middle Pleistocene, (3) the Last Pleistocene Glaciation, and (4) two main episodes of glacial stabilization during the Late Glacial (15–10 ^{14}C ka BP), during the definitive recession of the ice front toward mountain environments.

3.3. The Pampean sedimentary sequences

The Pampean sedimentary sequences were fully described firstly by Ameghino (1889). Many authors contributed to the knowledge about these units during the twentieth century, which makes it impossible to cite all of them here. The reader is referred to Alberdi et al. (1995) for a general overview of the issue.

Cione and Tonni (1999), using the geological, sedimentological, paleontological, and magnetostratigraphic (Orgeira, 1990) information, proposed a chronostratigraphic column composed of 'stages.' These sedimentary sequences, including fluvial, aeolian, lacustrine, mass-movement, and piedmont deposits, bear very important vertebrate fossil faunas, particularly mammals, that have been used to define the Late Cenozoic South American Land Mammal Ages (SALMA; Pascual et al. 1996). These units start as early as the Middle Miocene with the Chasicoan stage and extend until the Holocene with the Platan stage. The lithological and paleobiological variations found in these units are interpreted as related to regional and global Late Cenozoic climatic changes. They are also considered indicators of the effect that those climatic changes have had on Pampean ecosystems, particularly the cold–warm climatic cycles that characterized the glacial–interglacial cycles.

4. Patagonian glaciations and their relationship with the Pampean sequences

The excellent preservation of the ancient and complex morainic arcs and other glacigenic deposits of Patagonia is the result of the predominantly dry environmental conditions that have dominated extra-Andean Patagonia since at least the Latest Miocene. Moreover, the presence of glacigenic deposits interbedded with volcanic flows along most of the Late Cenozoic, starting in the Latest Miocene and continuing throughout the Pliocene and Pleistocene, has allowed, by means of absolute dating of the associated volcanic rocks, the assignation of minimum and maximum limiting ages to most of the different glacial units related to these flows. Therefore, the absolute chronology of the Patagonian glaciations has become one of the most complete in the world and the best available in the Southern Hemisphere, outside of Antarctica.

The chronological correlation of the Patagonian glacial events, identified by means of morainic arcs and/or tills interbedded with lava flows, and the Pampean biostratigraphic units have been illustrated in various graphs, separated by time periods (Figs. 4–7). Thus, all Patagonian glaciations known at the moment have been represented with the ages of the limiting volcanics, their magnetostratigraphy (if available), and their approximate chronological position if the limiting ages are too broad. Likewise, in the same temporal and magnetostratigraphical scale, the sequence of Pampean stages (in the sense of Cione and Tonni, 1999) has been depicted to allow for their respective correlation.

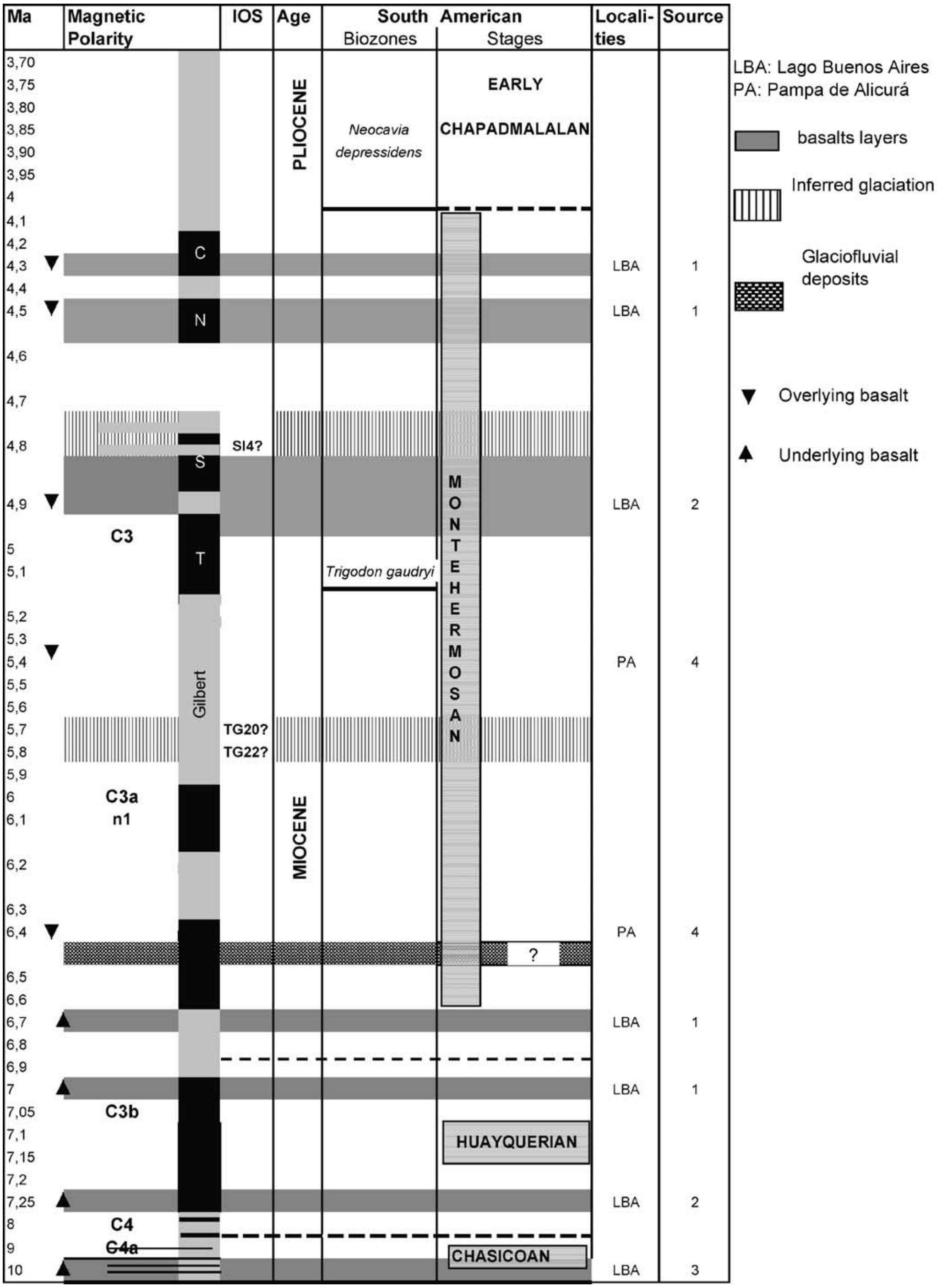

Fig. 4. Chronostratigraphic table of the Late Miocene–Early Pliocene glaciations and their relationship with the Pampean sequence, according to Cione and Tonni (1999). Sources: (1) Mercer, 1983; (2) Rabassa, 1997; (3) Ton-That et al., 1999; (4) Schlieder, 1989.

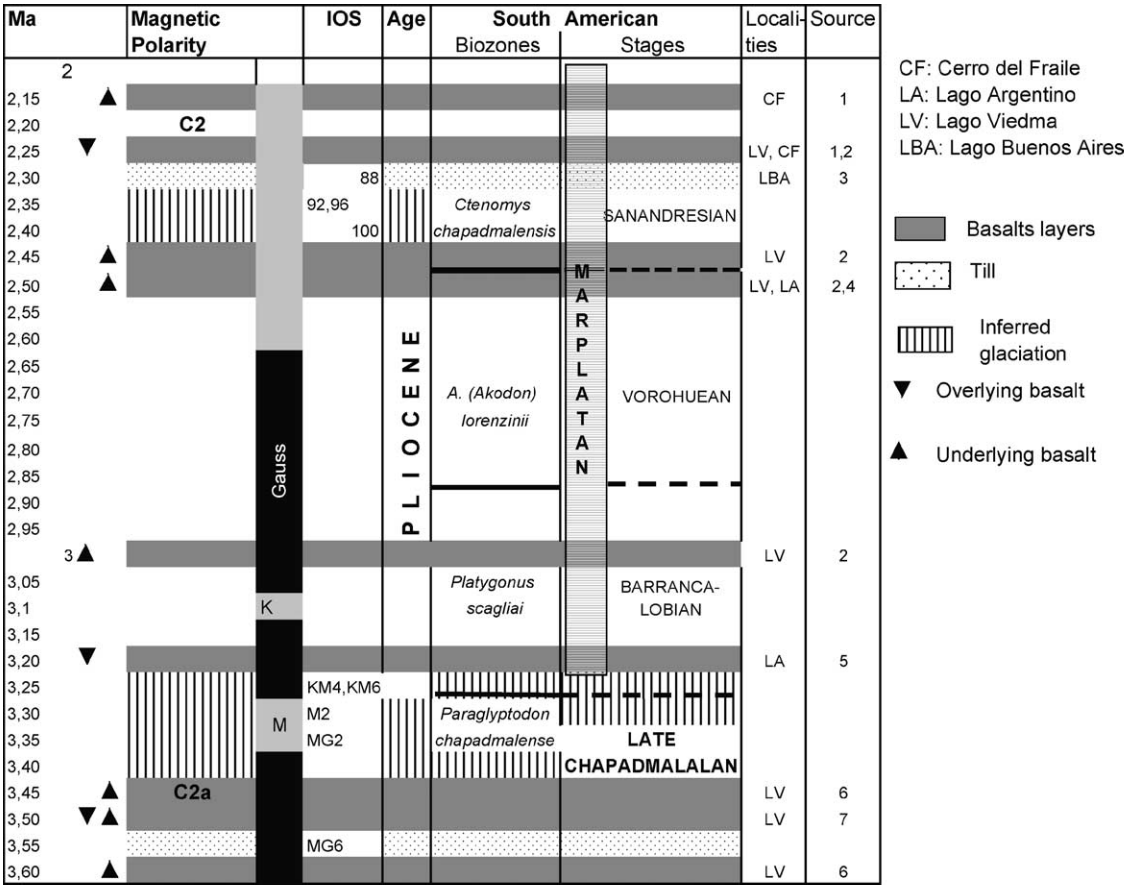

Fig. 5. Chronostratigraphic table of the Middle–Late Pliocene glaciations and their relationship with the Pampean sequence, according to Cione and Tonni (1999). Sources: (1) Rabassa, 1999; (2) Wenzens, 2000; (3) Sylwan, 1989; (4) Schellman, 1998; (5) Mercer, 1969. (6) Mercer, 1976; (7) Mercer et al., 1975.

The recognized Patagonian glaciations extend since the Latest Miocene along the entire Pliocene and Pleistocene but become more frequent after the Late Pliocene. During the Early Pleistocene, several pre-GPG glaciations have been identified; the GPG appears at the end of this period. Later, three major glacial epochs, with a minimum of 12 glacial readvances, have been recognized in the Latest Pliocene–Early Pleistocene and Middle and Late Pleistocene.

4.1. Glaciations of the Latest Miocene–Early Pliocene during the Huayquerian (?), Montehermosan, and Early Chapadmalalan

At the northern margin of the Meseta del Lago Buenos Aires (lat. 47°S), which is entirely covered by volcanic rocks, till deposits of over 30 m in thickness are found interbedded with basaltic flows (Mercer, 1976; Clapperton, 1993). Mercer (1969, 1976) and Mercer and Sutter (1981) obtained whole-rock K/Ar ages for the under- and overlying lavas of 7.34 ± 0.11 to 6.75 ± 0.08 and 5.05 ± 0.07 to 4.43 ± 0.09 Ma, respectively, which assigns a most likely Latest Miocene age to these glacial deposits (Busteros and Lapido, 1983; Ardolino et al., 1999). These data suggest these deposits belong to the oldest Late Cenozoic glacial events in Patagonia and indicate that the Patagonian Andes in those times bore at least isolated icecaps with discharge, outlet glaciers that clearly extended more than 30 km east from the mountain front. In this same locality, Thon-That et al. (1999) obtained ^{40}Ar/^{39}Ar ages of 7.38 ± 0.05 Ma for the underlying flow and 5.04 ± 0.04 Ma for the overlying flow, confirming in general terms the probable Latest Miocene (or, at most, Miocene–Pliocene boundary) age of this first Patagonian glaciation.

Fig. 4 shows four basalt flows with overlying tills between 10 and 6.7 Ma and three basalt flows with underlying tills between 4.9 and 4.3 Ma at the Lago Buenos Aires region. In addition, no till was found below the Meseta Guanabara basalt, Lago Buenos Aires (Fig. 1), dated at 9.87 Ma (Ton That et al., 1999). Although no absolute ages may be yet assigned to these tills, their comparison with the OIS indicates that they would correspond to the C3 (a and b) chron. During this period, the oceanic sequences (Shackleton, 1995; Opdyke, 1995) locate the strongest thermal lowering between 5.7 and 5.9 Ma, a period between the limiting ages of these tills. This correlation suggests that at least a major extra-Andean glaciation could have taken place in southern Patagonia between Isotopic Stages TG 20 and TG 22, Gilbert chron.

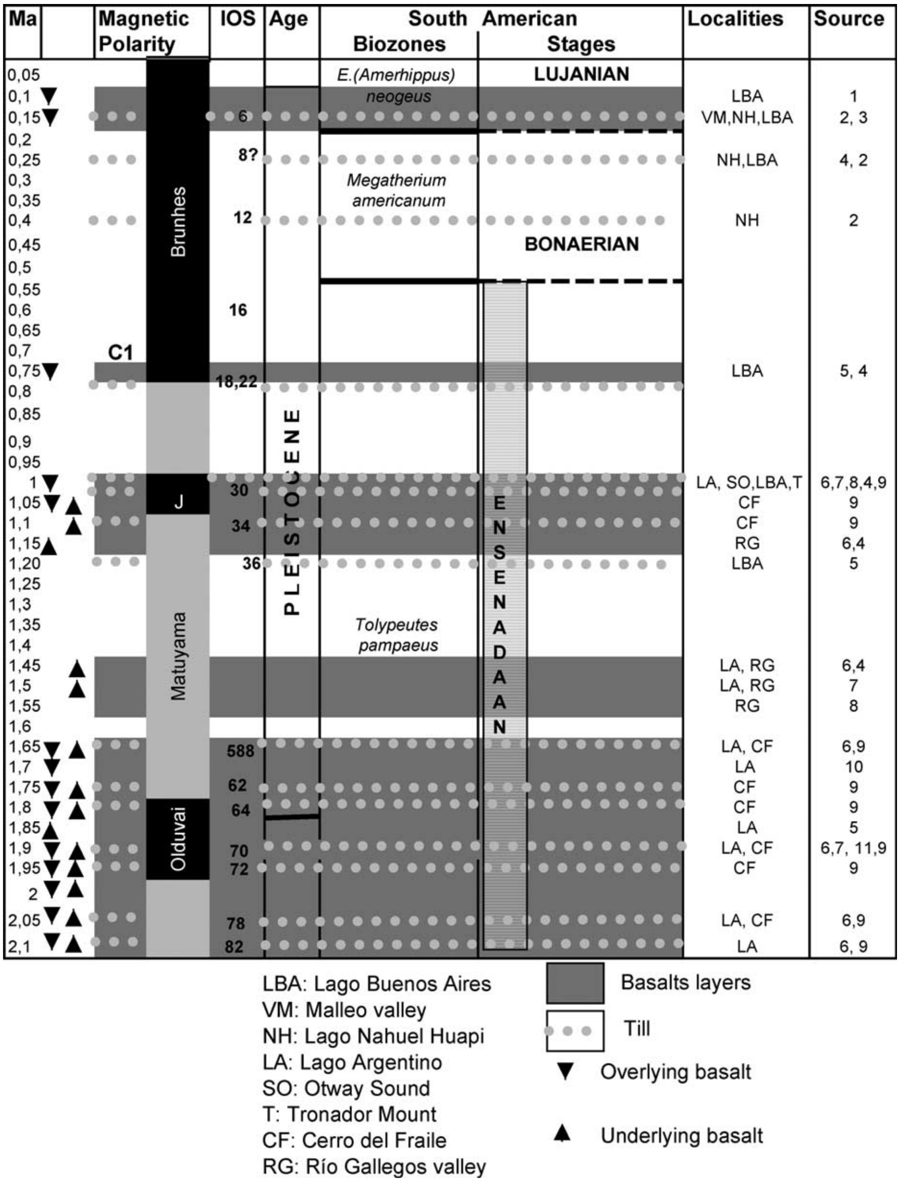

Fig. 6. Chronostratigraphic table of the Late Pliocene–Pleistocene glaciations and their relationship with the Pampean sequence, according to Cione and Tonni (1999); Verzi et al. (2002). Sources: (1) Guillou and Singer, 1997; (2) Rabassa and Evenson, 1996; (3) Mercer, 1982; (4) Ton-that et al., 1999; (5) Sylwan, 1989; (6) Mercer, 1976; (7) Mercer, 1983; (8) Meglioli, 1992; (9) Rabassa, 1997; (10) Mercer, 1969; (11) Schellmann, 1998.

Schlieder (1989) had recognized very coarse conglomerates along the Río Aluminé Valley, northern Patagonia (Fig. 1), and assigned them to the glacial events of the Late Miocene on the basis of the whole-rock K/Ar ages of the limiting basalts. He also proposed that the Alicurá Formation, originally assigned to the Lower Quaternary by Dessanti (1972) and later, as the Alicurá Member of the Caleufu Formation, to the Miocene–Pliocene (González Díaz et al., 1986), actually corresponds to the Late Miocene; its age is limited by the overlying basalts, dated 6.41±0.13 Ma and 5.26±0.14 Ma. According to this interpretation, the Alicurá Formation is the distal glaciofluvial unit of the Latest Miocene Patagonian Andean glaciations, whose water and sedimentary discharge would have been concentrated by the Río Aluminé and Río Collón Curá (Fig. 1), tributaries of the paleo-Río Limay, already a main regional stream of Atlantic slope in those times (Rabassa, 1975). The interpretation of a glaciofluvial origin for the Alicurá Formation, related to ancient glaciations, has been proposed by Gracia (1958), though no absolute age was defined (González Díaz and Nullo, 1980).

4.2. *Glaciations of the Middle Pliocene during the Late Chapadmalalan and Early Marplatan*

Evidence of Middle–Late Pliocene glaciations may be found in southern Patagonia as well. In the Lago Viedma region (Fig. 1), glacigenic deposits interbedded

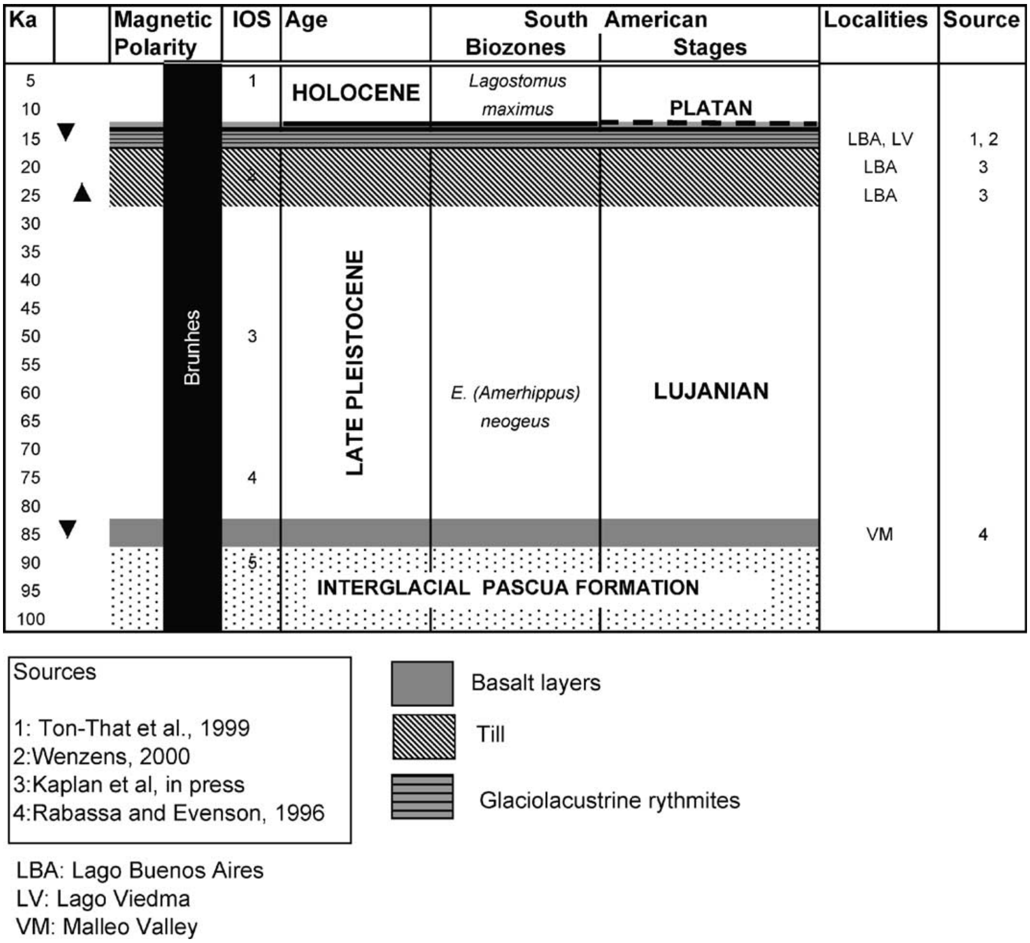

Fig. 7. Chronostratigraphic table of the Late Pleistocene–Holocene glaciations and their relationship with the Pampean sequence, according to Cione and Tonni (1999), Verzi et al. (2002).

with basaltic flows have been identified at Mesetas Chica and Mesetas Desocupada (lat. 49°S; Mercer, 1976, 1975). At Meseta Chica, a till bed appears between two flows K/Ar dated at 3.55 ± 0.19 and 3.68 ± 0.03 Ma, and another till unit overlies a lava flow dated at 3.46 ± 0.22 Ma. At Meseta Desocupada, a till layer occurs between lava flows dated as 3.48 ± 0.09 and 3.55 ± 0.07 Ma.

Wenzens (2000) obtained limiting ages of 3.0 and 2.25 Ma for glacigenic deposits north and east of Lago Viedma. Sylwan (1989) indicated the presence of till at Lago Buenos Aires corresponding to OIS 88, during the Gilbert geomagnetic epoch and coincident with the limiting ages proposed by Wenzens (2000) and those of the basaltic flows that underlie till at Cerro Fortaleza, Lago Argentino (Schellmann, 1998, 1999).

Mercer (1976) obtained an age of 2.79 ± 0.15 Ma for a lava flow that buries till at Cóndor Cliff, Río Santa Cruz Valley (lat. 50°S; Fig. 1). Younger glacigenic deposits appear over these flows, whereas the materials corresponding to the GPG are located at the base of these 'mesetas,' or tablelands. This finding clearly shows that even as early as the Middle Pliocene in some regions, the Patagonian glaciers expanded from the mountain icecaps to geographical locations close or equivalent to those that the outlet glaciers achieved during the maximum Pleistocene expansion (GPG). However, these conditions are probably exclusive to southernmost Patagonia, because there is no evidence of a similar extension of the mountain icecap in northern Patagonia.

However, at Mount Tronador (lat.41°S; Fig. 1), volcanics, lahars, and pyroclastic flows of the Tronador Formation (K/Ar dated at 3.2 and 2.0 Ma, though much younger ages were obtained as well; Greco, 1975; González Díaz and Nullo, 1980) appear to infill deep valleys, possibly of glacial origin, carrying pebble-sized clasts of striated and faceted volcanics (Rabassa et al., 1986). These units should be redated with more modern techniques, but it is basically acceptable that this portion of the northern Patagonian Andes was already covered by a local mountain ice sheet during the Middle Pliocene.

The relative chronology of tills and basaltic flows (Fig. 5) is compared with the global climatic variability obtained from the OIS (Fig. 2). This analysis indicates that several cold climatic events and their consequent glacier advances took place between the Middle and Late Pliocene in the Buenos Aires, Viedma, and Argentino lakes region. The first event would have taken place around 3.5 Ma, during OIS MG 6, Gauss normal polarity, of Middle Chapadmalalan age of the Pampean sequence; the second one occurred during OIS 100, 96, 92, and 88, with Matuyama reversed polarity, during the Late Marplatan or Sanandresian in the *Ctenomys chapadmalensis* biozone, according to the Pampean biostratigraphy. Tills over- and underlie lava flows dated at 3.20 Ma (Lago Argentino) and 3.45 Ma (Lago Viedma; Mercer, 1976), respectively, and they enclose cold peaks found at OIS KM4, KM6, M2, and MG2, which took place during the Late Chapadmalalan, *Paraglyptodon chapadmalense* biozone (Cione and Tonni, 1999).

4.3. Glaciations of the Late Pliocene and Earliest Pleistocene during the Sanandresian and Early Ensenadan stages

Feruglio (1944) described the glacigenic sequences at Cerro del Fraile (lat 50°33″S, Figs. 1 and 3) interbedded between volcanic flows and considered them of Pliocene age. These flows were K/Ar dated by Mercer (1975), (1976) as between 2.08 and 1.03 Ma, during the Matuyama chron. Mercer (1976) identified six piedmont glaciations during this period. Recent studies by Rabassa et al. (1996), Guillou and Singer (1997), Singer et al. (1999, 2004b), and Ton-That et al. (1999) (Fig. 3, Table 3) have enabled the redating of this sequence by ^{40}Ar/^{39}Ar incremental heating techniques and the provision of precision magnetostratigraphy. In these studies, a minimum of seven glaciations have been recognized, as well as a likely glaciofluvial deposit at the base of the profile, all which would have taken place between 2.16 and 1.43 Ma. These glaciations would have developed during OIS 82–48 (Matuyama chron; Ton-That, 1997, 1999). Finally, a younger glaciation covered the uppermost lava flow, dated at 1.08 Ma, and thus probably is equivalent to the GPG (OIS 30–34).

4.4. Glaciations of the Early Pleistocene during the Middle Ensenadan stage

At the base of Mount Tronador (lat. 41°S, Fig. 1), northern Patagonia, Rabassa et al. (1986) and Rabassa and Clapperton (1990) identified glacigenic deposits interbedded with volcanic flows. These rocks were K/Ar dated at 1.36 and 1.32 Ma, which gives them an Early Pleistocene age prior to the GPG. However, the volcanic flow overlying both the Garganta del Diablo tillite and the glacial surfaces eroded on the Cretaceous granites has been redated by ^{40}Ar/^{39}Ar techniques by B. Singer (pers. comm.; sample TR-01) at 1.021±0.102 Ma. Therefore, this glaciation could be much younger and even equivalent to the GPG.

The GPG (Mercer, 1976; Rabassa and Clapperton, 1990; Rabassa, 1999; Coronato et al., 2004a,b) represents

Table 3
Stratigraphy, radiometric dating, and magnetostratigraphy of Cerro del Fraile (slightly reinterpreted and modified from Singer et al., 1999)

Cerro del Fraile stratigraphy	K–Ar Age (Ma) (Fleck et al., 1972)	^{40}Ar/^{39}Ar Age (Ma) (Singer et al., 1999)	Paleomagnetic direction	Subchron identified and approximate correlation with Pampean units (Verzi et al., 2002)
Uppermost Till 1 and scattered erratic boulders				Late Ensenadan
Uppermost Lava flow 1	1.05±0.05	1.08±0.01	Normal	Onset Jaramillo Late Ensenadan
Till 2				Middle Ensenadan
Lava flow 2	1.51±0.03	1.43±0.02[a]	Transitional	Middle Ensenadan
Till 3				Early Ensenadan
Lava flow 3	1.71±0.01	1.76±0.04	Reversed	Early Ensenadan
Lava flow 4		1.83±0.03	Normal	Olduvai Early Ensenadan
Till 4				Early Ensenadan
Lava flow 5		1.89±0.03	Transitional	Onset Olduvai Early Ensenadan
Till 5				Early Ensenadan
Lava flow 6		1.95±0.01	Reversed	Early Ensenadan
Till 6				Early Ensenadan
Lava flow 7	1.91±0.01	1.89±0.03	Reversed	Early Ensenadan
Till 7 (thickest)				Earliest Ensenadan
Lava flow 8	2.11±0.02	2.07±0.04	Normal	Reunion Latest Sanandresian
Till 8				Latest Sanandresian
Lava flow 9	2.12±0.03	2.24±0.09	Transitional	Onset Reunion Latest Sanandresian
Till 9				Latest Sanandresian
Lava flow 10	2.05±0.01	2.16±0.06	Reversed	Late Sanandresian
Glaciofluvial deposits and Till 10 (?)				Late Sanandresian
Sands and cobbles				?
Marine sandstones				Cretaceous

[a] Unspiked K-Ar age (Guillou and Singer, 1997).

the maximum expansion of the ice in extra-Andean Patagonia. Its geographical distribution was correctly mapped by Caldenius (1932) and corresponds to the 'Initioglacial' event. The morainic arcs pertaining to the GPG are well preserved, though somewhat less so than in the later sequences. In northern Patagonia, the GPG corresponds to the Pichileufu drift (Flint and Fidalgo, 1964, 1969) or at least to its outermost expansion. Most likely, the GPG represents more than one glacial advance, and in the type area—the Río Pichileufu Valley east of San Carlos de Bariloche (lat. 41°S, Fig. 1)—at least three clearly defined morainic arcs have been observed. During this glacial episode, ice tongues reached the Atlantic coast in the continental area for the first time in the Cenozoic, south of the Río Gallegos valley, and expanded deeply into the present submarine platform.

Mercer (1976) estimated the age of the GPG, based on K/Ar dating of lava flows underlying glacigenic deposits in different localities south of the Río Gallegos Valley, as between 1.47 ± 0.1 and 1.17 ± 0.05 Ma. Meglioli (1992) obtained total fusion, whole-rock ^{40}Ar/^{39}Ar ages of 1.55 ± 0.03 Ma at the Bella Vista basalt, Río Gallegos Valley (Fig. 1), which is covered by glacial erratics and thereby provides a basal limiting age for the GPG. Ton-That et al. (1999) redated the Bella Vista basalt, according to incremental heating ^{40}Ar/^{39}Ar techniques, at 1.168 ± 0.007 Ma; the observed discrepancy results from the higher precision of this technique. Likewise, Ton-That et al. (1999) provided the first reliable upper limit for the GPG by means of the incremental heating ^{40}Ar/^{39}Ar dating of the Telken basalt, which covers the Initioglacial (=GPG) deposits at Lago Buenos Aires (Fig. 1), at 1.016 ± 0.005 Ma. The GPG thus would have developed during OIS 30–34, and maybe even OIS 36, and likely included more than one glacial advance (Fig. 6). The Pampean stage corresponding to the GPG is the Middle Ensenadan.

After the GPG, the deposits corresponding to the subsequent Patagonian glaciations (Daniglacial and Gotiglacial according to Caldenius, 1932; post-GPG 1, 2, and 3 according to Coronato et al., 2004a,b) are located in inner positions, more depressed in the landscape, and sometimes nested inside the GPG limits but far from them. This circumstance is different than that in the Northern Hemisphere's Scandinavian and Laurentian ice sheets, where younger ice expansions, in most cases, reached the outer positions of the older glaciations and even extended beyond them. These conditions could be due to either the smaller intensity of the Southern Hemisphere cold episodes after OIS 30–34 or local phenomena. The Southern Hemisphere OIS do not show significant deviations from their equivalents from the Northern Hemisphere; moreover, they suggest similar intensities and chronology. Therefore, the interpretation of these circumstances should be investigated through local phenomena. The evidence suggests that episodes of valley deepening took place during most of the Pleistocene, particularly in the Middle and Late Pleistocene. Of these episodes, the most important would have taken place after the GPG, in which later glaciations were forced to develop a morphology of discharge glaciers entrenched in their valleys. The dominant glacier morphology during the GPG would have been large piedmont lobes of great extension but relatively reduced thickness. This characteristic would have been favored by the preexisting landscape, with little incision of the piedmont valleys. The event has been named the 'canyon-cutting event' by Rabassa and Clapperton (1990) and Rabassa and Evenson (1996), in comparison to similar episodes that occurred in the Rocky Mountains. This valley-deepening event would have taken place due to (1) increased erosion related to greater discharge during the interglacial periods (climatic origin), (2) increased erosion related to the tectonic ascent of the Patagonian Andes (tectonic origin), or (3) a combination thereof. The much larger magnitude of deepening between the GPG deposits and later events, compared with that between the latter, suggests that the second alternative probably is correct. The cited tectonic rising must have taken place between 1.0 and 0.8 Ma, because in the next post-GPG glaciation, the glaciers already were entrenched (Ton-That et al., 1999). This event may have contributed even more intensively to the development of 'rain shadow' conditions in extra-Andean Patagonia, but its effective influence in the extra-glaciated Pampean region remains unknown.

The glacial event immediately after the GPG is known as Daniglacial from Caldenius (1932) or post-GPG-1 from Coronato et al. (2004a,b). This unit is characterized by conspicuous and well-preserved morainic arcs located in inner positions relative to the GPG and entrenched in younger valleys. It was named the 'El Cóndor drift' by Flint and Fidalgo (1964, 1969), who included within it the Gotiglacial but considered it Late Pleistocene in age. Subsequently, Rabassa et al. (1990) and Rabassa and Evenson (1996) proposed the subdivision of the El Cóndor drift into two units, La Fragua and Anfiteatro, in the type area of the Río Limay Valley (lat. 41°S, Fig. 1) or their equivalents, San Huberto and Criadero de Zorros drifts, in the Río Malleo Valley (lat. 39°S, Fig. 1). This subdivision was based on detailed mapping in both valleys, where the aforementioned units are clearly separated in both distance and elevation. The La Fragua and Anfiteatro drifts also appear along the dirt road beyond the San Carlos de Bariloche Airport (Fig. 1), where Flint and Fidalgo (1964) defined the El Cóndor drift, but the differentiation of the drift bodies is more difficult there due to the existence of ice-contact glaciolacustrine sediments and several proglacial lake coastlines. The La Fragua drift is assigned to Caldenius's (1932) Daniglacial.

In Lago Buenos Aires, Ton-That (1997), and Ton-That et al. (1999) obtained limiting ages for the Daniglacial drift by means of incremental heating $^{40}Ar/^{39}Ar$ dating of two lava flows associated with the glacial deposits. The Telken basalt is the first (1.016±0.005 Ma); it covers the Initioglacial deposits (GPG) and predates the Daniglacial or post-GPG-1 deposits. Moreover, the Telken basalt presents a transitional paleomagnetic polarity that corresponds to the upper portion of the Jaramillo subchron (Fig. 6). The second is the Arroyo Page basalt, dated 0.760±0.007 Ma, of normal magnetic polarity (Fig. 6), which covers the recessional outwash deposits of the Daniglacial. Thus, the post-GPG-1 or Daniglacial event would have taken place possibly around OIS 18–20, immediately before the Early–Middle Pleistocene, as indicated by the Matuyama–Brunhes paleomagnetic transition dated at 0.78 Ma (Singer and Pringle, 1996).

The Pampean sequences include the Ensenadan, *Tolypeutes pampaeus* biozone in this period.

4.5. Glaciations of the Middle Pleistocene during the Bonaerian stage

The most important glacial event at the end of the Middle Pleistocene is the Gotiglacial period (Caldenius, 1932); however, in more southern localities such as Buenos Aires, Viedma, and Argentino lakes, Skyrring and Otway sounds, Magellan Straits, and Tierra del Fuego (Fig. 1), a previous glaciation, defined as post-GPG 2, has been recognized (Coronato et al., 2004a,b).

The Gotiglacial event corresponds to the younger portion of the El Cóndor drift (Flint and Fidalgo, 1964), the Anfiteatro drift of the Upper Río Limay Valley (Rabassa and Evenson, 1996), and the Criadero de Zorros drift of the Río Malleo Valley (Rabassa et al., 1990) in northern Patagonia.

The Gotiglacial or its stratigraphic equivalents appear in all studied localities as very well-preserved morainic arcs, located in elevations above the range of the Last Glaciation (LG) and several tens of kilometers downvalley from its terminal moraines. Its state of preservation is excellent, and thus, it clearly explains why Caldenius (1932) and Flint and Fidalgo (1964) mistook them for deposits of the LG. The assignation of these deposits to this glaciation was possible only through radiometric dating of associated volcanic rocks.

At Río Malleo Valley (lat. 39°S, Fig. 1), the Pino Santo basandesite was originally dated by K/Ar at 0.207 Ma (Rabassa et al., 1990). This flow infills a glacial valley excavated in post-Criadero de Zorros drift times. This basandesite was redated by B. Singer (pers. comm., Sample PSA-01) at 0.089±0.004 Ma by incremental heating $^{40}Ar/^{39}Ar$ techniques. In both cases, the dates confirm the pre-Late Pleistocene age of the Criadero de Zorros drift (Gotiglacial). In the Río Limay Valley, the Anfiteatro drift correlates with the Criadero de Zorros drift (Rabassa and Evenson, 1996; Rabassa, 1999), according to their surficial morphology and respective altitudinal positions with respect to the LG deposits. A TL date performed on glaciofluvial sands incorporated with the Anfiteatro Moraine gave an age of 0.065 Ma (Amos, 1998), implying that the Anfiteatro drift would have formed during OIS 4 (Early Late Pleistocene). This TL date should be considered a minimum age because no other site in the Patagonia morainic arcs assigned to OIS 4 is found as far downslope from the LG moraines (Kaplan et al., 2004).

In the Lago Buenos Aires region (lat. 47°S, Fig. 1), a lava flow of normal magnetic polarity, which erupted from the Cerro Volcán, postdates the post-GPG 2 and post-GPG 3 (Gotiglacial) deposits and predates those of the LG (Coronato et al., 2004a). This flow was dated by whole-rock K/Ar by Mercer (1982) as 0.177±0.056 Ma. Ton-That et al. (1999) obtained a $^{40}Ar/^{39}Ar$ plateau age of 0.123±0.005 Ma and an unspiked K/Ar age of 0.128±0.002 Ma (Guillou and Singer, 1997). These dates were later confirmed by cosmogenic isotope (^{3}He) exposure dates from pyroxene concentrates, which provided an average age of 0.128±0.003 Ma (Ackert et al., 1998; Singer et al., 1998) as a weighed mean of four sites and two locations. These ages also confirm that the ^{3}He production rates at lat. 47°S are constant during the past 100 ky.

On the basis of this evidence, it is possible to confirm a pre-LG age for the Gotiglacial period and its equivalent units (post-GPG 3, post-GPG 2). The glacial deposits included in this unit may have formed in OIS 6, but they also could have originated in previous Middle Pleistocene cold periods, such as those during OIS 8–16 (Fig. 6).

4.6. Glaciations of the Late Pleistocene during the Lujanian stage

The glacigenic deposits of the LG are those formed in the Late Pleistocene, after the Sangamon interglacial or OIS 5. The estimated age of the glacigenic deposits of this period may start at a maximum of 85 ka, because the process of formation of the Patagonian Andes mountain ice sheet was undoubtedly slow and took at least 30 ka after the maximum of the Last Interglacial. Therefore, ice expansion could have taken place only at an advanced stage of OIS 4.

The LG was named Finiglacial by Caldenius (1932) and the Nahuel Huapi drift by Flint and Fidalgo (1964). This denomination has been preserved by subsequent authors. Moreover, Clapperton (1993) proposed the name “Llanquihue Glaciation” for the LG in South America, with its type area in the Lago Llanquihue, Chilean Lake District (lat. 40–41°S, Fig. 1; Lowell et al., 1995); the Nahuel Huapi drift is its lateral equivalent on the eastern slope of the Andes.

The LG deposits form morainic bodies of extremely well-preserved morphology, very fresh appearance, abrupt slopes, and abundant erratic boulders on the surface. More reliable chronological dates for the LG come precisely from the Lago Llanquihue area (Chile). There, successive studies by Mercer (1976); Porter (1981), and Lowell et al. (1995) provide an

Fig. 8. Basaltic erratic boulders on top of moraines of the Last Glaciation, Lago Buenos Aires, sampled by R. Ackert for cosmogenic isotopic dating techniques. Photo credit: J. Rabassa.

adjusted chronology based on radiocarbon dates. According to these authors, there were ice expansions during OIS 4, recessions during OIS 3 (Mid-Wisconsin interstadial; Laugenie, 1984; Rabassa and Clapperton, 1990), and readvances during OIS 2. The external positions of OIS 4 ice generally were reached and even surpassed by OIS 2 readvances, when the LGM took place around 20 ^{14}C ka BP.

In the Lago Buenos Aires region, recent work by Kaplan et al. (2004) confirms the age of the LGM through cosmogenic isotope dating (Fig. 8), thereby differentiating five glacial episodes, of which the outermost corresponds to the LGM. The respective ages, expressed in calendar years, extend from 25 ka for the outermost Fenix V Moraine to 16 ka for the innermost Fenix I Moraine. An AMS radiocarbon age of 15.3 ± 0.3 ka BP in post-LGM glaciolacustrine deposits confirms the validity of these exposure ages and provides an upper limiting age for the LGM in the region.

The development of the cold events of OIS 4 and 2 corresponds partially to the Lujanian, *Equus (Amerhippus) neogeus* biozone of Pampean stratigraphy (Cione and Tonni, 1999; Verzi et al., 2002; Fig. 7).

4.7. Extraglacial aeolian deposits: the Pampean loess

In the Pampean region, as in other basins in the Northern Hemisphere, loess accumulated during glacial periods, whereas paleosols developed during the interglacials. This trend is clearly noted in many stratigraphic columns of the region (Zárate and Blasi, 1993; Iriondo, 1999; Muhs and Zárate, 2001). However, though there are frequent references to the presence of loess and paleosols in the Pampean deposits (Tonni et al., 1999a,b), the sequence is composed of fragmentary portions with numerous erosional hiatuses, which are difficult to correlate. Only a few paleosols are known and named, and these are difficult to differentiate and even more difficult to date. The intensity of the erosional processes during the glacial episodes may have erased from the sequences most of the pedogenetic horizons formed during interglacial times. Therefore, some of the loess beds or associated sediments could correspond to more than one cold event, which would result in a superposition of beds where erosional uncomformities are poorly identified due to their lithological similarity. Nevertheless, the problem of the Pampean loess is highly complex and beyond the scope of this paper; the reader therefore is referred to the previously cited research.

It is important to consider a comparison of the Pampean sequences with those in northern China, where perhaps the most complete and best preserved loess sequences in the world are located. The sedimentological, paleopedological, and magnetostratigraphic aspects of these sequences have been studied in detail by Rutter et al. (1991), which enables their OIS correlation. Fig. 9 shows the type section of the Baoji-type Chinese loess sequence and its magnetostratigraphic chronology. In this figure, the Pampean units, following Cione and Tonni (1999); Verzi et al. (2002), have been incorporated to help depict the relationships between the Chinese loess sequence and the Pampean units of equivalent age.

The Chinese sequence is characterized by extraordinary preservation of the loess units formed during glacial epochs due to the aeolian accumulation from the Gobi Desert or the Tibetan piedmont deserts. These loess beds show the development of paleosols, generated during warmer

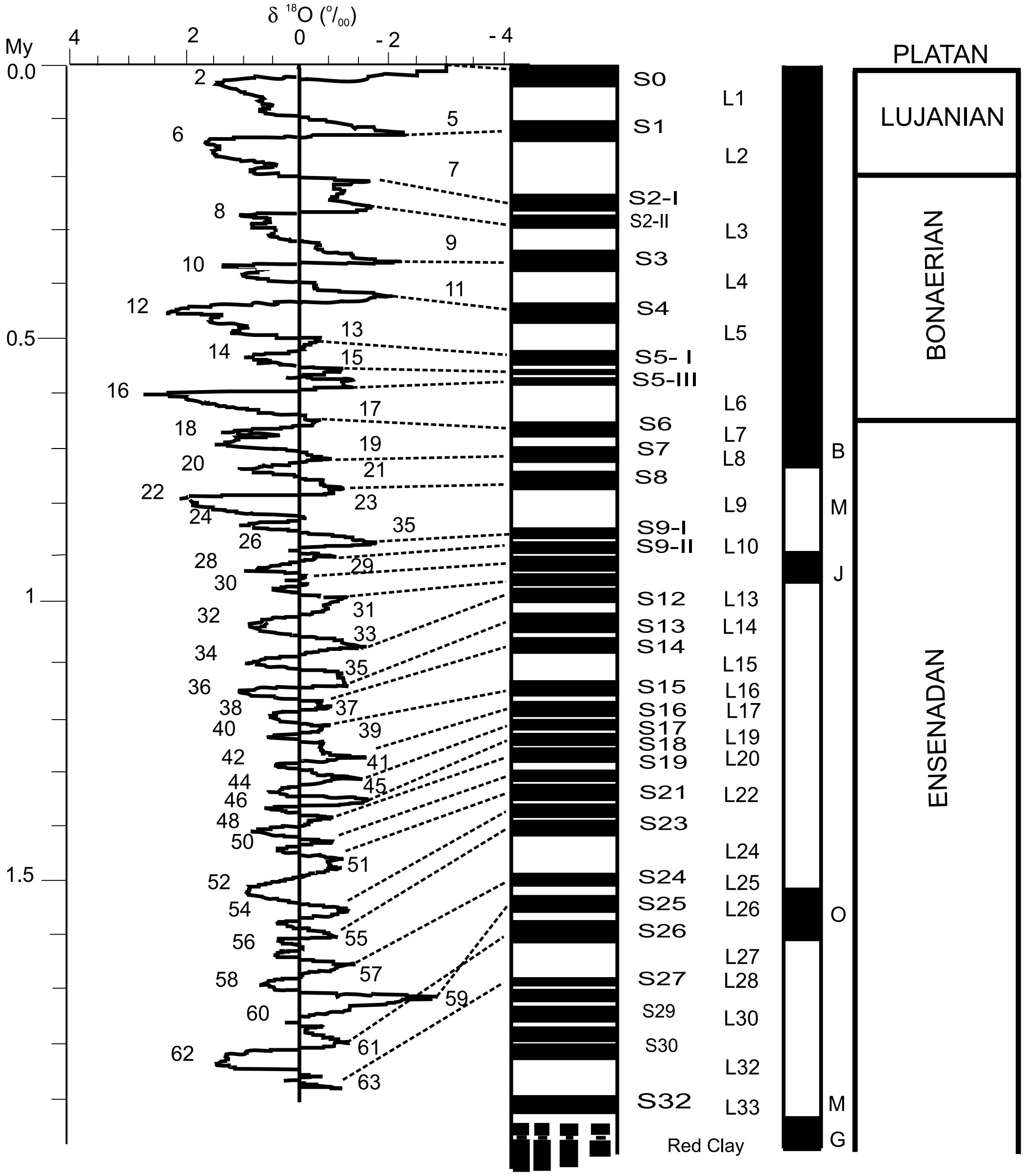

Fig. 9. Baoji-type Chinese loess sequence compared with the oceanic isotopic global and magnetostratigraphic records, according to Rutter et al. (1991), and its relationship with the Pampean sequences, according to Cione and Tonni (1999) and Verzi et al.(2002).

interglacial epochs. The intensity of its paleopedological development is related to the influence of monzonic atmospheric currents coming from oceanic sectors south and east of China. In turn, the rapid loess accumulation at the end of each pedogenetic episode preserved the paleosols and integrated an exceptional record that has been linked precisely to the global OIS, at least from OIS 1 to OIS 61 (Rutter et al., 1991). The extraordinary Chinese loess sequence suggests that the Pampean loess units may be much more complex than previously considered and that so-called 'Pampean single loess beds' actually may involve two or more cold events. This finding should be taken into account when analyzing faunal records in stratigraphic columns.

5. Repeated climatic deterioration and induced environmental changes

5.1. Late Miocene

In addition to astronomical forcing, other causes of climatic deterioration and the subsequent Patagonian mountain glaciations also should be considered. For example, the tectonic processes that slowly elevated the Patagonian Cordillera and originated the Scotia Arc (Ramos, 1999a,b) should not be set aside in this analysis. The Patagonian Andes would have started its elevation process, at least partially, in the Late Oligocene or Early

Miocene (González Bonorino, 1973; Rabassa, 1975). The great pyroclastic eruptions that originated the tuffs and ignimbrites of the Collón Curá Formation in northern Patagonia (~15 Ma; Rabassa, 1975) indicate such tectonic processes. Incremental heating ^{40}Ar/^{39}Ar dating on an ignimbritic pumice overlying the Pilcaniyeu Ignimbritic Member of the Collón Curá Formation (Rabassa, 1975) provides an age of 10.85 ± 0.033 Ma (B. Singer, pers. comm.), which may be interpreted as the age of the last pyroclastic episodes of the Miocene cycle, representing the final emplacement of the Patagonian Andes at elevations comparable to its present position. The summit accordance line of the northern Patagonian Andes is located around 2200 m a.s.l., whereas the regional, permanent snowline is placed today at 2000 m a.s.l., which allows many small cirque glaciers and snow fields to persist, even during the present Interglacial (Rabassa et al., 1980). The regional snowline would have descended significantly during all cold episodes at least since the Late Miocene, thus favoring the formation of larger mountain glaciers and perhaps even extending beyond the mountain piedmont.

It is also important to note that the definitive glacierization of western Antarctica took place in the Early Miocene. The glacierization of eastern Antarctica started in the Early Tertiary, when the continent achieved its present polar position (Kennett, 1995), but that of western Antarctica and the Antarctic Peninsula did not occur until the Drake Passage opened, between the Peninsula and Tierra del Fuego, in southernmost South America (Fig. 1). The Drake Passage is the consequence of the dismembering of both continents due to the continuous easterward movement of the Scotia plate since the Early Tertiary. This movement also generated the distortion of the Fuegian Andean axis from a N–S to an E–W position, the displacement of the southern Georgias away from the South American continent, and the formation of a volcanic, oceanic insular arc at the southern Sandwich Islands, where the Scotia plate subducts under the Atlantic oceanic plates. The environmental consequence of this new geographic configuration was the installation of the Antarctic circumpolar current in the Early Miocene (~22 Ma), which isolated the Antarctic Peninsula from the temperate oceanic currents of lower latitudes and contributed to the lowering of the Antarctic oceanic waters. This environmental scenario would allow the rapid and definitive cooling of the polar and subpolar air masses, generating the glacierization of the Antarctic Peninsula (Ciesielski et al., 1982; Table 2) and, subsequently, of the Fuegian and Patagonian Andes.

5.2. Since the Pliocene to the Late Pleistocene

The climatic variations identified in the global OIS (Fig. 2) and confirmed by the terrestrial Patagonian glacial record (Figs. 4–7) are very important and had a significant influence in the development of the Pampean ecosystems.

During the glacial–interglacial cycles, significant eustatic movements took place, including sea-level lowering in glacial periods of at least several tens of meters in cold events and up to 100–140 m during full glacial episodes. Therefore, as a consequence of the global sea-level changes during glaciations, the submarine platform became partially exposed. Thus, climatic continentality of the surrounding areas increased, which resulted in the increase of extreme temperatures, precipitation diminution, and lack of a sea moderating effect as the coastline moved away. This process occurred in Pampa and Patagonia, with almost a duplication of the emerged continental areas and certain climatic continentalization (Fig. 10). For the Latest Pleistocene, this important finding indicates the

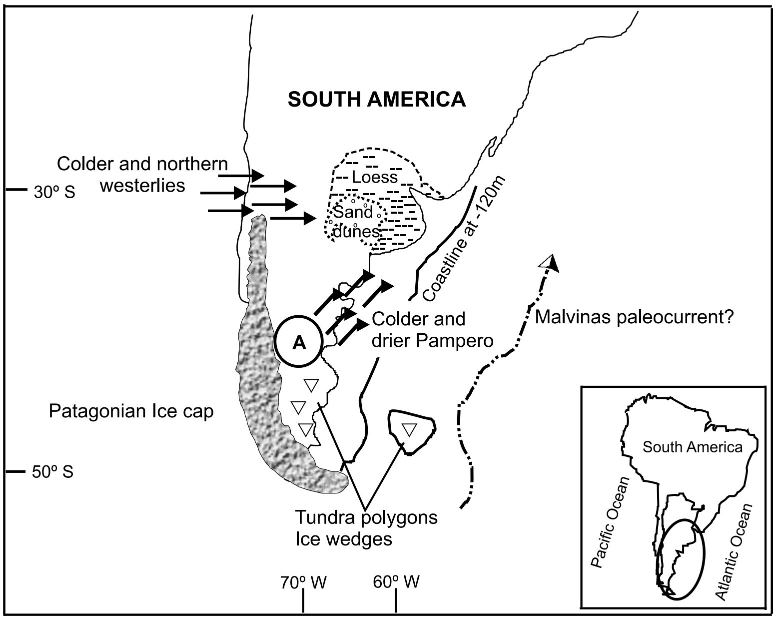

Fig. 10. Environmental conditions in South America during the Last Glaciation (OIS 2–4), modified from Clapperton (1993).

environmental conditions and available space for human colonization in the Pampean and Patagonian regions.

As a consequence of coastline mobility, the position of the littoral marine currents, particularly the Brazil and Malvinas currents (Fig. 10), was affected. During the glacial epochs, their encountering front was displaced northward, modifying the Pampean winter storm pattern and probably diminishing the oceanic influence and increasing water deficit. Moreover, sea-level lowering provoked diminished marine depth between Patagonia and Malvinas, forcing an eastward displacement of the Malvinas current and a further increase in climatic continentality along the present littoral sector. These changes, as a result of the glacial–interglacial cycles, took place at least 15 times during the last My and perhaps more than 50 times since the beginning of the Pliocene. The cumulative effects of these environmental changes remain unknown.

The mean surface sea temperatures (MSST) diminished significantly during the glaciations, lowering at least 5–6°C in southern South Africa (lat.30°–32°S) during OIS 2 (Tyson and Partridge, 2000) and with even a larger decrease near the polar zones. This lowering in MSST certainly influenced the evaporation and mobility of marine currents and consequently diminished the mean annual temperature in all continental areas. Northern Patagonia would have been of at least 5–6°C cooler and perhaps much more in the southern regions (Heusser, 1989; Clapperton, 1993).

The climatic conditions during the glacial episodes influenced the displacement of the oceanic anticyclonic centers, both in the Pacific and the Atlantic. In the case of the southern Pacific anticyclone, its northward movement determined that those regions previously free of cold, dry “westerlies” were progressively affected by such winds (Fig. 10). The increasing aeolian action led to the development of intensive deflation processes, with the genesis of hydroaeolian depressions, salt lakes, and endorheic basins, as well as the dune field formation in northern Patagonia and western Buenos Aires province (Clapperton, 1993; Iriondo, 1999). This aeolian activity was also responsible for loess accumulation in the Pampean region, Entre Ríos, Uruguay, and southern Brazil (Fig. 1), beyond the dune belts where the Pampean vegetation—though thinner than in interglacial times—was capable of retaining the fine sand-coarse silt fractions. The Río Salado of Buenos Aires province (lat. 35°S, Pampean region, Fig. 1) had a similar role as a sand trap, originating the La Chumbiada (Dillon and Rabassa, 1985) and Guerrero (Fidalgo et al., 1975) members of the Luján Formation during the Late Pleistocene (OIS 4–2). Similar conditions would have taken place in most, if not all, of the glacial events during the rest of the Pleistocene and before, because the Río Salado has long occupied a very ancient (Cretaceous) tectonic basin (Ramos, 1999a,b). Moreover, a northward displacement of the anticyclonic centers probably generated changes or at least higher variability in the aeolian sediment supply, contributing to the Pampean loess formation and incorporating epiclastic products from western Argentina and the central Andes (Iriondo, 1999; Muhs and Zárate, 2001).

The climatic changes also generated cyclic modifications in the vegetational cover of Pampas and Patagonia. The displacement and even supression of the Patagonian Andes forest then took place, concealed between the glacier front and the 0°C annual isotherm to the west and the led to shrubby steppe environments and the 300 mm annual isohyeth eastward. Tundra conditions appeared as well, with permanent or transient frozen ground, at least around the ice margins, though the eastward expansion could have been even larger (Heusser in Bujalesky et al., 1997). A spatial reduction of the Pampean grassy prairies and the disappearance of their Patagonian equivalents also took place since the Early–Middle Miocene, replaced by north- and eastward-expanding monte and steppe ecosystems.

The well-known, profound faunal changes that took place in the Pampean Late Pleistocene and Holocene also must be taken into consideration. The Brazilian faunal advance over the Argentine pampas (Tonni and Cione, 1995) would have accompanied the climatic changes, such as the drier, colder climate, the predominant of Patagonian faunas during the glacial epochs, and warmer, wetter Brazilian faunas during the interglacials. This faunal replacement, clearly observed during the Pleistocene–Holocene transition and more recently in the Late Holocene, probably took place with similar characteristics during each glacial ‘termination,’ perhaps more than 100 times since the Late Miocene (Fig. 2). The consequences of the high frequency of these displacements on the Pampean faunas, from both taxonomic and biogeographical points of view, remain hypothetical but should not be ignored in paleobiological and paleoenvironmental reconstructions.

Particularly during the Last Termination (‘Late Glacial,’ the last 5000 ^{14}C years of the Pleistocene, and the earliest Holocene), the pollen variations in Tierra del Fuego indicate deep environmental changes that follow the regional and global climatic changes (Heusser, 1998). A tundra paleoenvironment, inferred from palynological records of fossil peat at Lago Fagnano (Bujalesky et al., 1997) and characterized by the absolute lack of arboreal (*Nothofagus* spp.) pollen, was dominant during a glacial phase of the Penultimate glaciation (OIS 6) and likely was present during the LG. In Late Glacial times as the glacier receded, this tundra environment probably was rapidly replaced by park vegetation, with isolated *Nothofagus* spp. forest patches in a grassy steppe environment. These conditions are particularly evident in the Harberton peatbog (lat. 54°S; Beagle Channel, Fig. 1) pollen profile (Heusser, 1989), in which the recession of the Beagle Glacier from its outermost LGM positions enabled the partial recovery of Fuegian forests as early as 14.8 ^{14}C ka BP. At that moment and for several hundred years, the forest started its slow but steady recovery, advancing from (still) theoretical refuges located at the present submarine platform or perhaps Staaten Island (Isla de los Estados; lat. 55°S, long. 64°W; Fig. 1), as suggested by the pollen record (Coronato et al., 1999). However, at least twice, around 13 and 11 ^{14}C ka BP, the arboreal pollen content practically disappears from the record and is entirely replaced by Gramineae and *Empetrum*, which indicate a return to cold regional conditions that may have forced a new east-northeastward recession of the Fuegian forest toward its Pleistocene refugia. But near 10.2 ^{14}C ka BP, the content of the pollen records indicates that the forest restarted its expansion into the Isla Grande de Tierra del Fuego and reached similar conditions to those of the present in the first millenium of the Holocene, though the present conformation of the forest appears only near 8 ^{14}C ka BP. These cold Late Glacial episodes (hereafter, Late Glacial I and Late Glacial II) may be comparable in both chronological and intensity terms with their Northern Hemisphere equivalents, the Oldest?/Older? Dryas and Younger Dryas. Nevertheless, the pollen record undoubtedly indicates that the Late Glacial II event was more intense and extreme than the first, but its environmental consequences on the forest are still unknown.

These paleoenvironmental modifications would have had severe consequences in the entire studied region, though it is understandable that their characteristics and intensity would have not been identical across the huge Patagonian and Pampean geography. Undoubtedly, they played an important role in the early peopling of Pampa and Patagonia; the human expansion in southern South America may have started immediately after the LGM (∼25 calendar ka) and most certainly after the last phase of morainic construction (∼16 calendar ka; Lago Buenos Aires; Kaplan et al., 2004). The southward-heading human groups, probably looking for regions with a higher density of surviving Pleistocene megammals, underwent not only the progressive environmental changes typical of the Last Termination but also the two Late Glacial cold episodes, which affected them and the regional biota in a similar manner.

5.3. Archaeofaunistic evidence

The archaeofaunistic record is another source to indicate the dramatic environmental changes that occurred by the end of the Pleistocene and the beginning of the Holocene, or the Lujanian and Platan in Pampean ages (Cione and Tonni, 1999). In this sense, several differences and similarities in those faunas associated with Patagonian archaeological contexts dated between 13 and 8 ^{14}C ka (Miotti and Salemme, 1999) have been noted with those identified from the Lujanian age and its biozone (Equus [A.] neogeus), as identified in the Pampas (Cione and Tonni, 1999). Even though there are no qualified mammal records from the Late Pleistocene in Patagonia, the archaeofaunas may be a good indicator to relate Patagonian and Pampean climates and environments. The record of Pleistocenic megamammals (*Hippidion saldiasi*, *Lama gracilis*, *Lama owenii*, *Mylodon* sp.) and a bird species (*Rhea americana*) in Patagonian archaeological sites from the Late Pleistocene–Early Holocene transition could be equivalent to those from the Pampean exposures and/or archaeological sites; that is, they could be interpreted as Lujanian in age.

As has been pointed out by Nabel et al. (2000: 408), ‘Most of the genera that dominated during the Pleistocene in the Pampean area occur for the first time in the Ensenadan, but are represented by other species in the Bonaerian and Lujanian,’ though ‘there was certainly a very important turnover at the species level at these ages.’

From the archaeofaunal point of view, some families and/or genera recur in both regions, though the species could be different. This status might be interpreted as environmental differences or a matter of anthropogenic selection. However, many coincidences occur, at least for the megamammals. In this sense, there are two relevant paleoecological characteristics identified from Patagonian and Pampean archeological sites. First, equids, camelids, giant sloths, armadillos, and ostrich-like birds existed in Pampean and Patagonian contexts between 13.0 and 8.5 ^{14}C ka BP.

Second, three faunal associations can be differentiated at the regional level. Whereas *Hippidion sp.-Mylodon (?) listai-Lama oweni* have been found in the Andean piedmont and extra-Andean Patagonia, the *Lama gracilis-Hippidion sp.-Rhea cf. americana* (or its equivalent) association is frequent in extra-Andean Patagonia, and *Equus (Amerhippus)-Hippidion sp.-Megatherium americanum-Rhea americana* usually appears in the Pampean region. Also, an ever-present species in these contexts is *Lama guanicoe*, which extends throughout the Holocene and is of Platan age in terms of the Pampean region (Miotti and Salemme, 1999).

Therefore, it seems reasonable that during the Late Pleistocene and Early Holocene, the faunas in both regions correspond, at least in part, to that of the *Equus (Amerhippus) neogeus* biozone (Cione and Tonni, 1999). Most are characteristic of grassy or gramineous steppe environments, which represent cold and arid or semiarid climates; there probably were slight differences in the diversity, frequency, and presence of burrowers and grazers depending on the sector.

Before 9 ^{14}C ka BP, and taking into account the presence of *Rhea americana* as far south as lat. 47°S—a species replaced by *Pterocnemia pennata*, present today in the area—milder conditions in southern Patagonia can be inferred. After that time, *Rhea* returned to its present distribution, not farther south than lat. 38°S. Although during the Holocene, conditions were arid-semiarid in Patagonia, in the Pampas, a few more humid episodes have been verified during the Early Holocene by the presence of *Scapteromys* sp. and *Holochilus* sp. (Tonni, 1990).

In Patagonia, environmental changes for the Late Pleistocene–Early Holocene transition have been detected through palynological results more than through faunal records; nevertheless, after 9 ^{14}C ka, the environment changed to a shrubby steppe, and most Pleistocenic species had already disappeared, which meant an important change for the human societies colonizing the ample plains, who had to adapt to these new environments.

After that and during the Holocene, or Platan age (Cione and Tonni, 1999; Verzi et al., 2002), environmental conditions changed to more arid than the present ones, except for the already mentioned short humid pulses (Tonni, 1990; Páez et al., 2003). Even though those events would not have been long enough to influence mammal distribution, the major and definitive replacement of subtropical faunas occurred as late as approximately 1900 BP, when some species were already distributed up to lat. 38°S (Tonni and Cione, 1995). Present faunal biodiversity in Pampa and Patagonia thus has been settled very recently, during the Late Holocene.

6. Conclusions

The glacial–interglacial cycles have generated significant variations in the environmental conditions in the Pampean and Patagonian regions in southernmost South America. These variations are inferred from a study of landforms, sedimentary units, and archaeofaunistic components and are largely coincident with the evidence provided by the paleovertebrate record.

The variations in length and frequency of the cold–warm climatic cycles indicate that the intensity of the extreme isotopic content peaks of the global oceanic record became larger toward the Early Pleistocene. Thus, climate became more extreme, and pleni-glacial conditions were gradually achieved at lower latitudes after the Antarctic Peninsula glaciated during the Middle Miocene and piedmont glaciers occurred in Patagonia in the Latest Miocene. This change occurred because, with shorter and milder cycles, the glacial conditions were not functional during long enough periods to allow the building and persistence of extensive ice fields in the Patagonian Cordillera. Only in the Late Pliocene were appropriate conditions reached to develop a continuous mountain ice sheet at latitudes near 36°S to Cape Horn (lat. 56°S; Fig. 1), which would have grown recurrently in each subsequent glacial cycle during the Pleistocene and up to the LG.

The high climatic variability recorded since the Late Miocene in Pampa and Patagonia was a consequence of changes in the astronomical, orbital parameters. These parameters would have predominated in different times (Fig. 2): (1) equinoctial precession from the Late Miocene to the Middle Pliocene, developing cycles of approximately 23–19 ky during the Huayquerian, Montehermosan, and Chapadmalalan; (2) obliquity from the Late Pliocene to the Early Pleistocene, with cycles of approximately 41 ky during the Marplatan and Lower Ensenadan; and (3) eccentricity from the Middle to Late Pleistocene, with cycles of 100 ky during the Late Ensenadan, Bonaerian, and Lujanian (cf. Ruddiman et al., 1986; Opdyke, 1995; deMenocal and Bloemendal, 1995). The shorter cycles would have impeded the formation of the Patagonian mountain ice sheet during the Late Miocene–Middle Pliocene, favoring instead the development of local glaciers, for which the sedimentary record is still scarce.

The main conclusions of this article relate to the correlation of the Patagonian glaciations, the Chinese loess sequence, the paleoenvironmental conditions, and the Pampean stratigraphy since the Late Miocene. These results have been summarized in Tables 4 and 5.

The oldest Patagonian glacigenic deposit (Table 4) formed during the Montehermosan, though it is not clear if it corresponds to a glacial event during the cold peaks OIS TG 20–22 in the Latest Miocene or even somewhat later during OIS Si 4–Si 6 (Earliest Pliocene). In these periods, global temperatures would have been lower than during the Early Chapadmalalan (Early Pliocene). In the Late Chapadmalalan, local glaciation would have taken place, at least in the Lago Viedma area (Table 4).

Colder-than-present environmental conditions appeared only after 2.6 Ma (Sanandresian). Before 3 Ma, the climatic conditions were always warmer than the last Pleistocene interglacials (OIS 1-Present, OIS 5, and OIS 7), according to the global isotopic record (Fig. 2), with the exception of short events at 3.12, 3.3, 3.35, 4.8–4.9, and 5.7–5.8 Ma during the Chapadmalalan and Montehermosan.

The accumulation of the oldest Chinese pure loess beds would have taken place around OIS 98 (2.4–2.5 Ma, latest Vorohuean–earliest Sanandresian times; Table 5), whereas the first loess unit of significant thickness (named L32 in Fig. 9; Rutter et al., 1991) has been chronologically placed at 2.2–2.3 Ma (OIS 82–86), during the deposition of the Early Sanandresian (Table 5). However, loess-like beds have been mentioned in older Pampean units at least since the Montehermosan and perhaps even before (e.g. Zavala and Quattrocchio, 2001). The Pampean loess/soil sequences are much more poorly developed than the Chinese ones, mainly due to either (1) the feeble pedogenetic effect during the interglacials or (2) a powerful erosional action over the interglacial soils during the cold cycles. The Sanandresian is also the time of development of frequent Patagonian glaciations, though of unknown longitudinal extension (Table 5).

The Early Ensenadan is correlated with the recurrent glaciations at Cerro del Fraile. The Late Ensenadan is characterized by the largest extension of the Patagonian glaciers in the GPG and the subsequent, still important Daniglacial events. During Ensenadan times, 24 loess units were deposited in the Chinese sequence (Table 5). This era represents a time of shifting from the 41 ky to the 100 ky cycle predominance in the global record (Fig. 2) and the establishment of full glacial conditions.

During the Bonaerian, several smaller glaciations and the Gotiglacial 1 events (Early Illinoian; OIS 8–16) took place, while four loess units were deposited in China (Table 5). Finally, the Lujanian hosted the Gotiglacial 2

Table 4
Patagonian glaciations, Chinese loess, environmental conditions, and Pampean stratigraphy during the Late Miocene and Early Pliocene

		Pampean Stratigraphy (Verzi et al., 2002)	Ma	OIS (Shackleton et al., 1990, 1995)	Patagonian glaciations	Loess in China (Rutter et al., 1991)
Pliocene	M	Late Chapadmalalan	3.20–3.60	MG 6? High temperatures. Local glaciation	Lago Viedma (3.5–3.6 Ma)	No record
	Gilbert	Early Chapadmalalan	3.60–4	High temperatures Cold peaks in Gi 2- Gi 10 -Gi12	No record	No record
	C	Montehermosan	4–6.8	Lower temperatures than in the Chapadmalalan	First Patagonian till >4.96<7.25-6.75 Ma	No record
	N					
	S					
	T					
Miocene	G			Sidujfall Si 4–Si 6? TG 20–22?		
	C3a					
	C3b					
		Huayquerian	6.8–8.7		No record	No record
	C4					
	C4a	Chasicoan	8.7–10	Andean ascent	No till cover at Meseta Guanabara (LBA): 9.87 Ma; LBA	No record
				End of the Patagonian subtropical climate	Post Collón Curá Fm. Ignimbrite: 10.85 Ma	

Table 5
Patagonian glaciations, Chinese loess, environmental conditions, and Pampean stratigraphy during the Late Pliocene and Pleistocene

		Pampean stratigraphy (Verzi et al., 2002)	Ma	OIS (Shackleton et al., 1990, 1995)	Glaciations in Patagonia	Loess in China (Rutter et al., 1991)
Pleistocene	Brunhes	Lujanian	0.01–0.2	2-4-6	Nahuel Huapi Anfiteatro Gotiglacial 2	2 loess
		Bonaerian	0.2–0.55	8-10-12-16	La Fragua Gotiglacial 1 (Smaller Glaciations?)	4 loess
	J	Ensenadan	0.55–2.15	18-20-22? 30-34	Daniglacial GPG	24 loess
	O			58-60-68-70-72-78-82: base of Ensenadan?	C° del Fraile (7 glaciations)	
Pliocene		Sanandresian	2.15–2.5	86-88-96	Lago Viedma >2.25 <2.53–2.48 Ma (Wenzens, 2000)<2.5 Ma (Schellman, 1998)	3 loess
				-Strong cyclicity-short cycles-brief but intense cold events	Lower glaciofluvial unit at C° del Fraile >2.16 Ma	
					LBA 2.3	
	Gauss	Vorohuean	2.5–2.95	98-100-104 G2-G4-G6 G10-G14 (rise in temperature)	No record	Basal Loess “Red clays”
	K	Barrancalobian	2.95–3.20	Dominance of high temperatures; except at KM 2	No record	No record

event (Late Illinoian, OIS 6) and the LG (Wisconsinan, OIS 4–2); two major loess units were deposited in northern China (Table 5).

The analysis of the global isotopic record, the Pampean stratigraphy, and the Patagonian terrestrial glacial evidence rejects the Mid-Pliocene Antarctic full deglaciation hypothesis (Bruno et al., 1997), because the climate would have been maintained within the levels of the glacial–interglacial cycles in that epoch, and there is no regional evidence of a very high sea level that could provide scientific support to this theory.

Thus, during the lapse of the Montehermosan to the Lujanian, at least 50 complete cold–warm climatic cycles existed, which forced the regional development of the Patagonian–Pampean ecosystems. This large-scale climatic variability should be taken into consideration when discussing paleoecological, paleobiogeographical, and evolutionary characteristics of the Late Cenozoic Pampean faunas.

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