$^{40}Ar/^{39}Ar$ and K-Ar chronology of Pleistocene glaciations in Patagonia

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ABSTRACT

During the Pleistocene, east of Lago Buenos Aires, Argentina, at 46.5 °S, at least 19 terminal moraines were deposited as piedmont glaciers from the Patagonian ice cap advanced onto the semi-arid high plains adjacent to the southern Andes. Exceptional preservation of these deposits offers a rare opportunity to document ice-cap fluctuations during the last 1.2 m.y. $^{40}Ar/^{39}Ar$ incremental-heating and unspiked K-Ar experiments on four basaltic lava flows interbedded with the moraines provide a chronologic framework for the entire glacial sequence. The $^{40}Ar/^{39}Ar$ isochron ages of three lavas that overlie till 90 km east of the Cordillera at Lago Buenos Aires, and another 120 km from the Andes along Río Gallegos at 51.8 °S that underlies till, strongly suggest that the ice cap reached its greatest eastward extent ca. 1100 ka. At least six moraines were deposited within the 256 k.y. period bracketed by basaltic eruptions at 1016 ± 10 ka and 760 ± 14 ka. Similarly, six younger, more proximal moraines were deposited during an ~651 k.y. period bracketed by an underlying 760 ± 14 ka basalt and the 109 ± 3 ka Cerro Volcán basalt flow that buried all six moraines. Coupled with in situ cosmogenic surface exposure ages of moraine boulders, the 109 ka age of Cerro Volcán implies that moraines deposited during the penultimate local glaciation correspond to marine oxygen isotope stage 6. Further westward toward Lago Buenos Aires, six additional moraines younger than the Cerro Volcán basalt flow occur. Surface exposure dating of boulders on these moraines, combined with the ^{14}C age of overlying varved lacustrine sediment, indicates deposition during the Last Glacial Maximum (LGM, 23–16 ka). Although Antarctic dust records signal an important Patagonian glaciation at 60–40 ka, moraines corresponding to marine oxygen isotope stage 4 are not preserved at Lago Buenos Aires; apparently, these were overrun and obliterated by the younger ice advance at 23 ka. Notwithstanding, the overall pattern of glaciation in Patagonia is one of diminishing eastward extent of ice during successive glacial advances over the past 1 m.y. We hypothesize that tectonically driven uplift of the Patagonian Andes, which began in the Pliocene, yet continued into the Quaternary, in part due to subduction of the Chile rise spreading center during the past 2 m.y., maximized the ice accumulation area and ice extent by 1.1 Ma. Subsequent deep glacial erosion has reduced the accumulation area, resulting in less extensive glaciers over time.

Keywords: South America, ice ages, $^{40}Ar/^{39}Ar$, paleoclimatology, geochronology, glacial geology.

INTRODUCTION

Glaciers are sensitive recorders of climate change, and their deposits provide a proxy record for past changes in temperature and precipitation. Correlating terrestrial records of climate change with the more continuous, orbitally tuned marine record and those preserved in polar ice cores is hampered by poor chronology and incomplete preservation. Yet, linkage of these records is necessary to understand the global response to climate change and further constrain the underlying mechanisms that promote transitions between glacial and interglacial conditions. In the past decade, several types of deposits and geochronometers have been used to establish proxy records of terrestrial climate changes during the Pleistocene, including, for example, U-Th dating of speleothems (e.g., Ludwig et al., 1992; Bar-Matthews et al., 1999) and lacustrine sediments (e.g., Bobst et al., 2001; Ku et al., 1998), and $^{40}Ar/^{39}Ar$ dating of fluvio-deltaic sediments (e.g., Karner and Renne, 1998). Glacial deposits have long been exploited to study past climate, but beyond the range of radiocarbon dating their utility has been limited by the difficulty in acquiring precise chronologic controls (e.g., Dalrymple, 1964; Mercer, 1983; Gillespie et al., 1984; Phillips et al., 1990, 1997; Gillespie and Molnar, 1995).

The Patagonian Ice Fields (Fig. 1) are the largest glaciers in the Southern Hemisphere outside of Antarctica, and moraines marking their past fluctuation in size provide a long-term record of mid-latitude Southern Hemisphere glaciation. Developing a well-dated glacial chronology for this region is key to addressing the following questions: (1) Are Andean glaciations out of phase with Antarctica? (2) Were Andean glaciations in phase with those of the Northern Hemisphere? (3) When did ice reach its greatest extent in southern South America? And, (4) What, if

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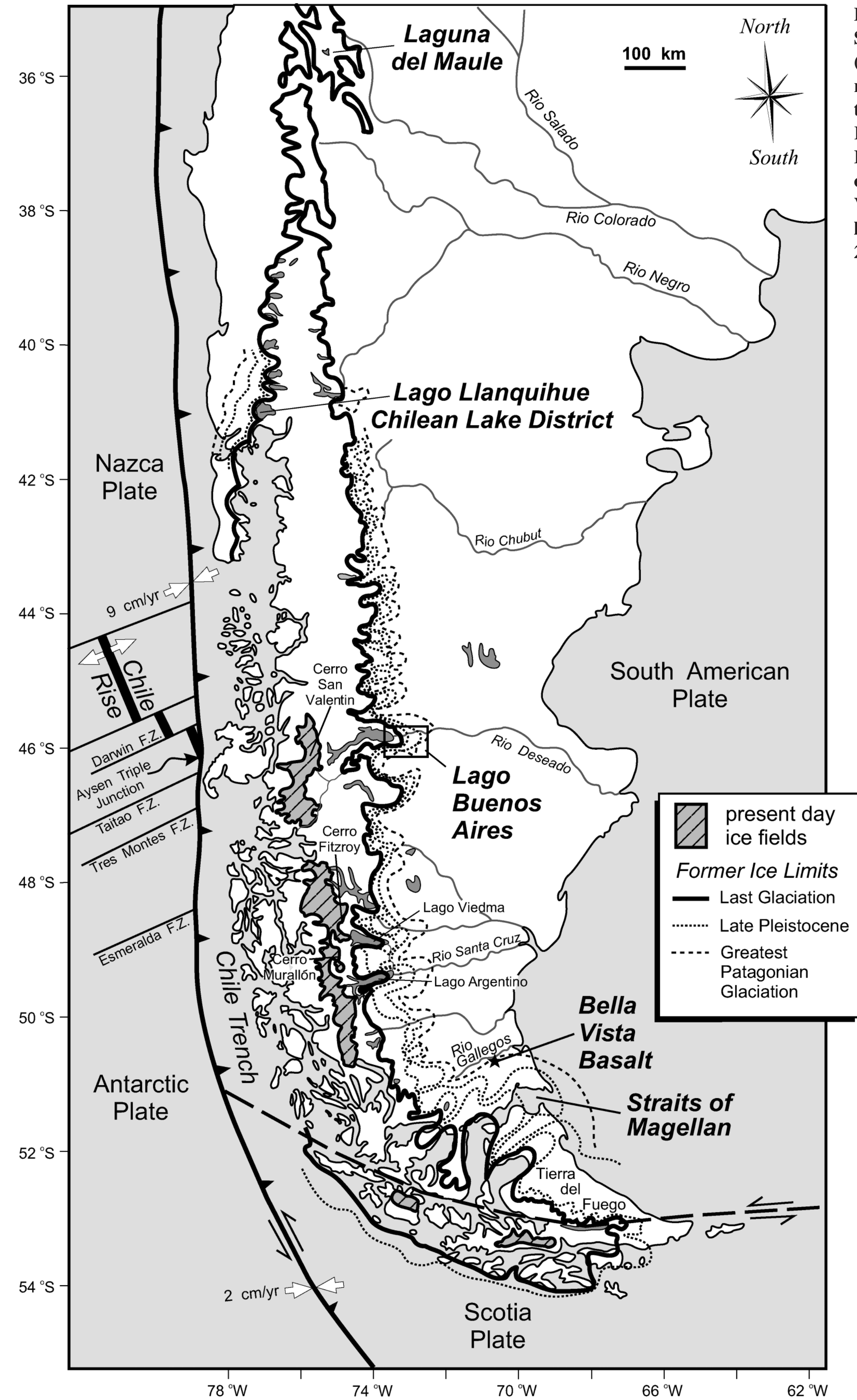


Figure 1. Glacial deposits of southern South America after Caldenius (1932) and Clapperton (1993; and references therein). Chile Rise and tectonic boundaries from Ramos and Kay (1992) and Gorring et al. (1997). Inset at Lago Buenos Aires gives area of Figure 2. Note that Estancia Bella Vista Basalt is located along Río Gallegos 520 km south of area in Figure 2. F.Z.—fracture zone.

any, is the pattern of movement of the Antarctic Polar Front during successive glaciations?

That these questions remain unanswered reflects the following sources of uncertainty: Cores raised from Antarctic ice and southern ocean sediment, though well studied, preserve paleoclimate records that may not be representative of the entire Southern Hemisphere (Mercer, 1983; Denton and Hughes, 1983). This is evident in the ongoing debate over temporal relationships between proxy records in Antarctic ice and Southern Ocean sediment and those from the Northern Hemisphere (e.g., Steig et al., 1998; Blunier et al., 1998; Blunier and Brook, 2001; Lea, 2001; Steig and Alley, 2002). The chronology of glaciations in the Southern Hemisphere based on extensive radiocarbon dating in the Chilean Lake District and New Zealand is similar to that of the Northern Hemisphere (Denton et al., 1999). However, these results are inconsistent with many Antarctic and Southern Ocean records; thus, the extent of synchronized, hemisphere-wide changes in temperature during the last glacial-interglacial transition remains unclear. Moreover, the terrestrial record is only well dated to ca. 40 ka (Denton et al., 1999). On several mountain ranges the greatest extent of ice during the last glaciation preceded by tens of thousands of years that of the largest Northern Hemisphere ice sheets, yet the little available evidence from the southern Andes is equivocal (Clapperton, 1993; Gillespie and Molnar, 1995). Mid-latitude Southern Hemisphere climate is dominated by the moisture-bearing westerly winds that control the position of the Antarctic Polar Front (e.g., Heusser, 1989; Markgraf, 1989; Markgraf et al., 1992; Hulton and Sugden, 1997; McCulloch et al., 2000; Singer et al., 2000), yet there is no consensus as to whether colder climates force the Westerlies to the north or the south. Temporal reconstructions of maximum glacier extent at various latitudes along the southern Andes could potentially track migration of the Westerlies and Antarctic Polar Front, thereby providing a key boundary condition for global climate modeling.

The high plains east of the southern Andes and modern Patagonian Ice Fields contain a sequence of terminal moraines and drift sheets that record fluctuations in the size of the ice cap. Tills and moraines range in age from late Miocene to Holocene (Mercer, 1969, 1976, 1982, 1983; Fleck et al., 1972; Mercer and Sutter, 1982; Mörner and Sylwan, 1989). These deposits are extraordinarily well preserved, owing to low rates of erosion in the arid climate, regional uplift, which has left the older deposits intact on interfluves, and cover by Plio-Pleistocene lava flows. On the basis of K-Ar ages obtained from basaltic lavas north of the Straits of Magellan between 53 and 51 °S, Mercer (1976) inferred that terminal moraines associated with the easternmost extent of ice, the so-called ‘‘Greatest Patagonian Glaciation,’’ date to between ca. 1.2 and 1.0 Ma. Mercer (1983) later conceded, however, that evidence for the 1.0 Ma upper age limit was inconclusive and that the GPG was broadly bracketed by lavas K-Ar dated at 1.2 Ma and 0.17 Ma. Notwithstanding, these glacial landforms are among the oldest on Earth, exceeded in age only by some Antarctic moraines (e.g., Brook et al., 1993).

The $^{40}Ar/^{39}Ar$ and unspiked K-Ar methods have become powerful tools with which late Pleistocene basaltic to rhyolitic lava flows can, under favorable conditions, be dated precisely (e.g., Heizler et al., 1999; Singer et al., 2000; Guillou et al., 1997). We present $^{40}Ar/^{39}Ar$ and unspiked K-Ar age determinations from five basaltic lava flows that overlie several of the moraines east of Lago Buenos Aires at 46.5 °S (Fig. 1), plus a lava that underlies till at 51.8 °S along Río Gallegos. Focus on the youngest of these lava flows explores some of the obstacles that confront efforts to obtain accurate radioisotopic ages from youthful basalt. Combined with new mapping of the relationship of these moraines and associated outwash deposits to the basaltic lavas, the radioisotopic ages provide a set of chronological constraints for these glacial sediments spanning the past 1.2 m.y.

The measurement of cosmogenic nuclides produced in situ has recently provided a means of directly dating individual terrestrial landforms, including glacial deposits (e.g., Phillips et al., 1990, 1997; Brook et al., 1993). A new chronology for the youngest part of the record at Lago Buenos Aires has been constrained by cosmogenic ^{10}Be, ^{26}Al, ^{3}He, and ^{36}Cl surface exposure ages of morainal boulders and the ^{14}C age of varved lacustrine sediment. These results, which are introduced briefly here, are presented in detail in the companion paper by Kaplan et al. (2004)

GEOLOGIC SETTING AND BACKGROUND

The southernmost Andes form a narrow, yet imposing mountain belt for more than 2000 km between 36 °S and 55 °S (Fig. 1) that comprises a Mesozoic batholith that intruded into and deformed Paleozoic sediments (Ramos and Kay, 1992; Rabassa and Clapperton, 1990). Their mean elevation decreases from ~3800 m at 38 °S to 2000 m at 45 °S, but at 46 °S a dramatic increase to over 4000 m at Cerro Valentin occurs, and elevations above 3500 m continue southward to 50 °S before declining toward the Strait of Magellan. This remarkably high topography coincides with the lithospheric region most strongly uplifted and presumably heated during Miocene to Holocene subduction of several segments of the Chile Rise spreading center (Thomson et al., 2001), a gap between the southern and austral volcanic arcs, which is, not surprisingly, the location of the modern Patagonian Ice Fields (Fig. 1).

The southern Andes were glaciated repeatedly since the late Miocene, (Fig. 1; Caldenius, 1932; Feruglio, 1950; Fleck et al., 1972; Mercer, 1976, 1983; Porter, 1981; Mercer and Sutter, 1982; Rabassa and Clapperton, 1990; Denton et al., 1999). Evidence for the Miocene and Pliocene glaciations comprises scattered tills interbedded with basaltic lava flows east of the mountains that have been dated using K-Ar and more recently $^{40}Ar/^{39}Ar$ methods (Fleck et al., 1972; Mercer and Sutter, 1982; Ton That et al., 1999). The eastward extent of these Miocene and Pliocene ice advances is uncertain; however, they appear to have been relatively small in comparison to the Pleistocene glaciations that are the focus of this study.

The southern Andes lie astride the locus of westerly winds that are inferred to have shifted between 50 °S and 45 °S, concurrent with northward expansion and retreat of the Antarctic Polar Front (e.g., Heusser, 1989; Markgraf, 1989; Markgraf et al., 1992). Inverse modeling of the Patagonian ice cap by Hulton et al. (1994) and Hulton and Sugden (1995, 1997) suggests that the extent of ice is sensitive to both the precipitation carried by the westerly winds and the amount of area above the snowline in the southern Andes. The record of ice advances is best known from the humid west side of the Andes in the vicinity of Lago Llanquihue, at 41 °S in the Chilean Lake District (Fig. 1), where extensive radiocarbon dating (Mercer, 1976; Porter, 1981; Lowell et al., 1995; Denton et al., 1999) has identified evidence of five advances between ca. 36 and 18 ka. Older glacial deposits near Llanquihue are deeply weathered and beyond the realm of radiocarbon dating. To establish a longer record of glaciation, we have focused on the arid east side of the Andes adjacent to Lago Buenos Aires, 600 km south of Lago Llanquihue (Fig. 1). This area lies well within the influence of the Westerlies during both the last glaciation and presumably older ice ages.

First mapped by Caldenius (1932), glacial drift deposited by a large lobe of the Patagonian ice cap extends in broad arcs across the Lago Buenos Aires basin at 46.5 °S (Figs. 1 and 2). The moraines span more than 50 km north to south, up to 60 km east of Lago Buenos Aires, and comprise perhaps the most complete and intact sequence of Quaternary moraines in the world (Clapperton, 1993). Later mapping by Feruglio (1950), Fidalgo and Riggi (1965), Mörner and Sylwan (1989), Sylwan (1989), Malagnino (1995), and Ton That et al. (1999) revealed that 15 or more terminal moraines are preserved. In his monumental cartography, accomplished well before radiocarbon or other isotopic dating methods, Caldenius (1932) suggested that these moraines were deposited in four groups, three of which were correlative with moraines dating to the last glaciation (<20 ka) in northern Europe. It took 50 yr and the advent of radioisotopic dating before John Mercer (1982, 1983) was able to obtain a K-Ar age from the basaltic lava flow issued from the Strombolian cone of Cerro Volcán that penetrates and overlies Caldenius' Daniglacial moraine belt. Mercer's (1982) whole-rock K-Ar age of 177 ± 56 ka (±1σ uncertainty) was reported without supporting analytical data but demonstrated that Caldenius had greatly underestimated the ages of these moraines. In a concurrent reconnaissance study of igneous activity unrelated to the glacial geology, Baker et al. (1981) also reported an imprecise K-Ar age of 300 ± 100 ka (±1σ) for Cerro Volcán (their sample no. P88).

Using paleomagnetic directions obtained from undisturbed glacial sediments associated with eight of the moraines, Mörner and Sylwan (1989) discovered that seven of the most distal, eastern moraines were deposited during the Matuyama Reversed Chron more than 780 ka (Johnson, 1980; Shackleton et al., 1990; Singer and Pringle, 1996). Our initial survey (Ton That et al., 1999) confirmed the results of Mörner and Sylwan (1989) by providing the first $^{40}Ar/^{39}Ar$ ages from two lavas: one is normally magnetized, overlies outwash gravel, and gave an isochron age of 760 ± 14 ka (±2σ). The other transitionally magnetized flow overlies glacial till containing large, 2 m diameter erratics, and is 1016 ± 10 ka. These dates, plus one from near Rio Gallegos 520 km to the south, are discussed further in light of new $^{40}Ar/^{39}Ar$ and K-Ar experiments on three additional basaltic lavas and new mapping east of Lago Buenos Aires.

SURFICIAL GEOLOGY AND QUATERNARY STRATIGRAPHY OF THE LAGO BUENOS AIRES BASIN

Moraine crests, associated outwash plains and terraces, and basaltic lava flows were mapped onto a 1:100,000 topographic base and corresponding Landsat thematic mapper image (Fig. 2) during six field campaigns between 1996 and 2003. The main focus has been along a transect eastward from Lago Buenos Aires to the town of Perito Moreno and southeastward from there along National Highway Route 40. The gross glacial morphology consists of four outwash plains, each of which steps up to the east, with a prominent escarpment capped by a moraine ridge along their western margins. Additional moraines, most of which are partially eroded by younger outwash, occur east of each escarpment moraine. Five basaltic lava flows that erupted along the transect are interbedded with the glacial deposits and provide stratigraphic and chronologic controls.

We have retained the fourfold grouping of Caldenius (1932) based on the gross morphology of the moraine sequence, but because of its erroneous chronologic implications, we have abandoned his fourfold nomenclature (Fig. 1). Instead, we assign informal names to each moraine group. Roman numerals designating individual moraines within each group ascend eastward (Figs. 2 and 3).

Glacial Deposits

Menucos Moraine

A topographically minor ridge at 370 masl characterized by large blocks of basalt up to 20 m diameter and other drift is designated the Menucos moraine (Fig. 2). The Menucos moraine is distinguished from other moraines to the east in that it was deposited on varved lacustrine sediment (Fig. 3; Caldenius, 1932). Along the Río Fenix Chico, the top of the 75 m section of varved sediment shows increasing evidence of deformation westward toward Lago Buenos Aires. Thus, we interpret the folding and thrusting as a result of glacial tectonics associated with readvance of the Lago Buenos Aires ice lobe. Three radiocarbon ages from the varved sediment correspond to a calendar age of 15.8 ± 0.6 ka (±2σ) (Kaplan et al., 2004); thus, the Menucos moraine represents a readvance subsequent to 15.8 ka.

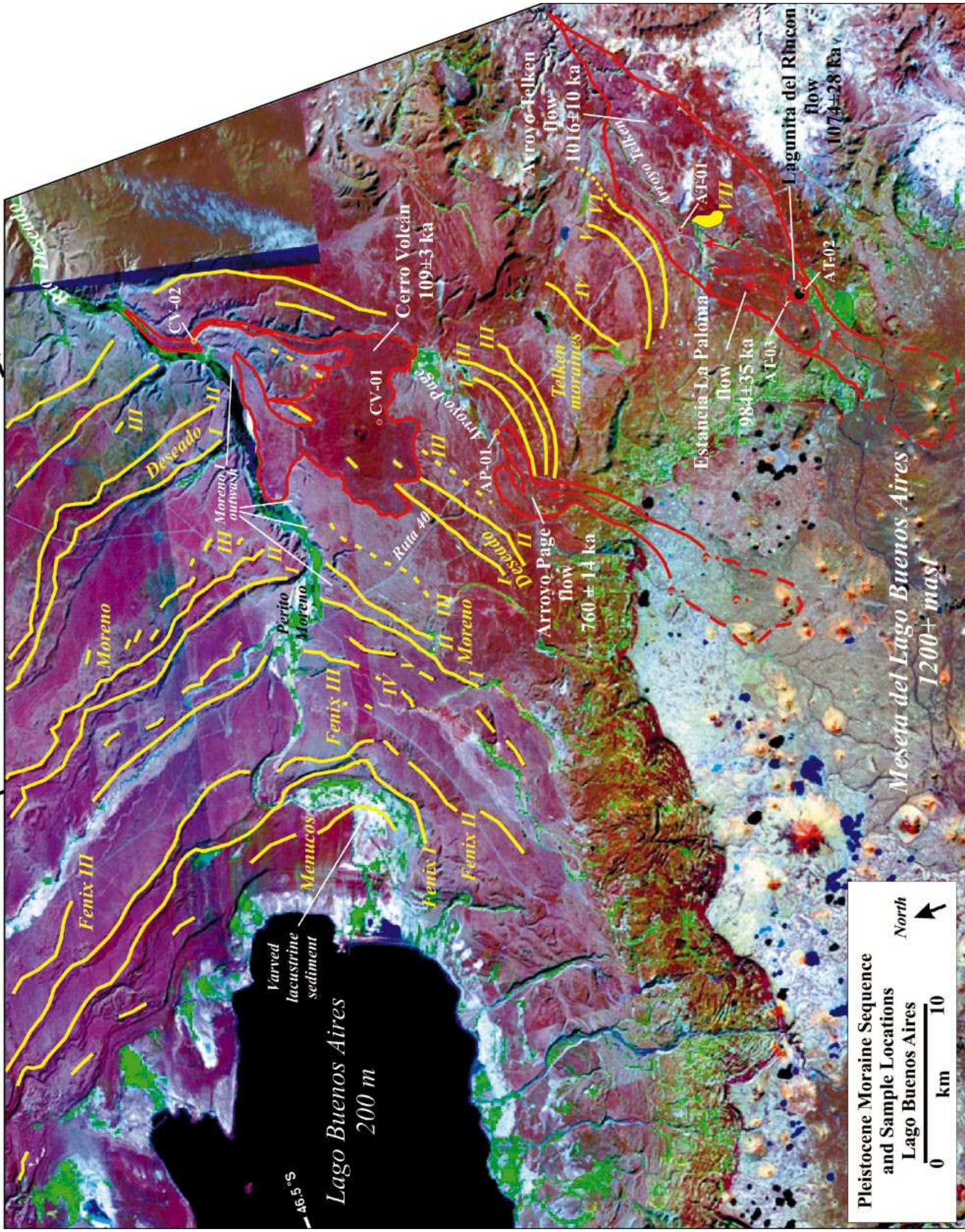
Fenix Moraine Complex

East of the Menucos moraine, the Fenix moraine complex consists of five moraines that increase in age to the east; we have numbered these I-V in descending stratigraphic order (Figs. 2 and 3). The generally sharp-crested moraine ridges rise to 450–480 masl, display 20–50 m of relief, are up to 500 m wide, and together with associated outwash deposits extend 6 km east to west (Figs. 2 and 3). Roadcut exposures indicate that they consist mainly of reworked outwash and flow till, intercalated with minor deformed silty lacustrine sediments and basal till. The varved sediments underlying the Menucos moraine are banked upon, and therefore are clearly younger than, the Fenix I moraine (Caldenius, 1932; Fig. 3).

Spectacular sized (up to 20 m high) subrounded blocks of columnar jointed basalt with striations and glacial polish stand along the crests of the Fenix I and II moraines. Similar blocks occur but are less abundant and smaller on the Fenix III–V moraines. A large basaltic block on the Fenix IV moraine crest gave an $^{40}Ar/^{39}Ar$ isochron age of 117.5 ± 0.9 Ma and has a calc-alkaline composition indicating a Mesozoic source in the Cordilleran batholith ~75 km to the west (Ton That et al., 1999). These blocks were the target of our intial effort to date the Fenix moraines using in situ cosmogenic ^{3}He (Singer et al., 1998a), but their antiquity has led to ingrowth of He nuclides due to decay of U that complicates the use of this nuclide as a chronometer (Kaplan et al., 2004). Erratic cobbles and boulders of granite, rhyolite, diorite, gneiss, schist, and other lithologies clearly derived from the Andean Cordillera >50 km to the west are common and also occur on the older moraine groups to the east. These boulders yielded cosmogenic ^{10}Be and ^{26}Al surface exposure ages discussed in the Kaplan et al. companion paper. The intervening outwash plains between these moraines consist of coarse gravel with clear, braided stream networks (Fig. 2). The Fenix III moraine is largely covered or eroded by outwash gravel derived from the Fenix I and II moraines, with only a few isolated hills exposed (Fig. 2). The Fenix IV and V moraines are also buried by this outwash gravel, but to a lesser extent. Outwash from the Fenix moraines also overlies portions of the Cerro Volcán basalt flow in the Río Deseado Valley.

Moreno Moraine Complex

The Moreno moraine complex comprises at least three terminal moraines and associated outwash gravels that are all older than the Cerro Volcán basalt flow. East of the town of Perito Moreno, the Moreno I moraine crest tops a prominent 80-m-high, west-facing escarpment (Figs. 2 and 3). One–2 kilometers further east, the Moreno II moraine has a broader


Pleistocene Moraine Sequence
and Sample Locations
Lago Buenos Aires
North
0
10
km
Lago Buenos Aires
200 m
Varved
lacustrine
sediment
Meseta del Lago Buenos Aires
1200+ masl
Arroyo Page
flow
760 ± 14 ka
Estancia La Paloma
flow
984±35 ka
Lagunita del Rincon
flow
1074±28 ka
Arroyo Telken
flow
1016±10 ka
Cerro Volcán
109±3 ka
CV-01
CV-02
AP-01
AT-01
AT-02
AT-03
Telken
moraines
Moreno
outwash
Perito
Moreno
Ruta 40
Río Deseado
Deseado
Moreno
Menucos
Fenix I
Fenix II
Fenix III
46.5°S
71°W

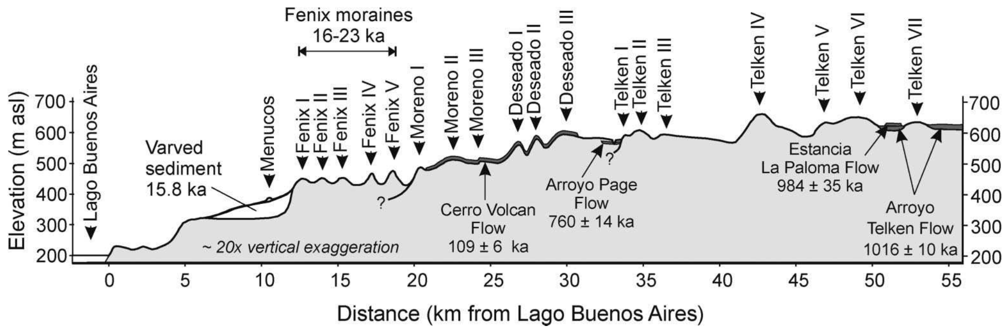


Figure 3. Topographic profile from Lago Buenos Aires east to Perito Moreno and south to Arroyo Telken (see Fig. 2).

crest, up to 20 m higher than the Moreno I ridge, that grades into a 5-km-wide plain of coarse outwash gravel. To the north, the Moreno III moraine is preserved as a discontinuous group of low hills north of the town of Perito Moreno and east of the Moreno II moraine (Fig. 2). In places the Moreno II moraine appears to have truncated the Moreno III deposits. To the southeast along Route 40, the Moreno III moraine crest is not preserved. However, evidence of a former ice margin is inferred from a 5-m-high escarpment that truncates an outwash plain older than that associated with the Moreno II moraine (Figs. 2 and 3). Outwash graded to the Moreno I moraine forms a discontinuous terrace at ~460–440 masl along the south side of the Río Deseado Valley (Fig. 2). This terrace, along with the expansive outwash from Moreno II and III moraines, is buried by the Cerro Volcán basalt flow (Fig. 4A); hence, these moraines are older than the lava. In contrast, the Cerro Volcán lava flow nowhere buries the Fenix or Menucos moraines or their associated outwash gravels in the Río Deseado, consistent with our interpretation that the latter deposits are younger than the Moreno moraines.

Figure 2. Landsat mosaic of Lago Buenos Aires region. Moraine crests denoted as yellow lines; dashes indicate topographic highs reflecting ice marginal deposits that have been partially eroded. Nomenclature and numbering scheme for moraines is discussed in text. Five basaltic lava flows are outlined in red and labeled. Note several fragments of outwash terrace graded to Moreno I moraine are denoted; this terrace is buried by lava from Cerro Volcán. Sample localities for $^{40}Ar/^{39}Ar$ and K-Ar dating are shown as red circles.

Deseado Moraine Complex

East of the Moreno moraines, at slightly higher elevations, the Deseado complex consists of two prominent moraine crests and a more easterly ice marginal deposit, the ages of which are bracketed by over- and underlying lava flows (Figs. 2 and 3). The eastern margin of the Moreno outwash plains is an 80-m-high escarpment topping out at 550 masl capped by the Deseado I moraine. One kilometer further east lies the Deseado II moraine. These moraines are nearly continuous across the basin. Near the canyon of the Río Deseado, they are partly buried by the basaltic lava flows of Cerro Volcán (Figs. 2 and 4A). Part of the surface of the Deseado outwash gravel to the east projects westward to an elevation perhaps 20–40 m higher than the present Deseado II moraine. Thus, we infer an earlier Deseado III ice margin, from which no ice contact deposits remain (Fig. 3). Four kilometers east of the high point on the Deseado III outwash surface, a basalt flow crops out in Arroyo Page and is overlain by a 3 m veneer of coarse gravel on the northernmost extent of its surface (Fig. 4B). We map this gravel deposit as outwash derived from the Deseado III ice margin and infer that this group of moraines is older than Cerro Volcán and younger than the Arroyo Page basalt flow.

Telken Moraine Complexes

The easternmost moraines are also the highest, most morphologically subdued, and oldest of those in the Lago Buenos Aires region. We have designated these six moraines plus a till deposit as the Telken moraines. East of Arroyo Page three low ridges each 5–20 m in relief are designated the Telken I, II, and III moraines. These moraine crests are likely correlative to ridges that also continue northward from the Rio Deseado Valley (Fig. 2). At their southern end, the Telken I–III moraines are truncated by the valley into which the Arroyo Page basalt flowed northward over coarse, weathered gravel (Fig. 4B). Therefore, these moraines are older than the valley and the infilling lava flow. A 5-km-wide outwash plain separates the Telken III from the Telken IV moraine. The Telken IV moraine is 120 m high and 2–3 km wide, making it the largest moraine crest preserved in the region (Figs. 2 and 3). Farther southeast, the Telken V and VI moraines are less well defined; however, somewhat rare—yet large—erratic boulders can still be found along their broad crests and proximal slopes, indicating an origin as an ice-marginal deposit. One km southeast of where Route 40 crosses Arroyo Telken, the road climbs a 35-m-tall hill covered by till with abundant, variably ventifacted erratic boulders up to 2 m in diameter. This hill overlooks, and is surrounded by, the Arroyo Telken basalt flow (Fig. 4C) and thus pre-dates the basalt that flowed around it. Because there is no conclusive evidence that this lone hill is a moraine, we designate this deposit as the Telken VII till (Figs. 2 and 3). Neither the mapping of Caldenius (1932) nor our search identified glacial deposits farther to the east. Thus, the Telken VII till reflects the maximum observed extent of ice from the Lago Buenos Aires lobe and is the local equivalent of Mercer's (1976) Greatest Patagonian Glaciation at this latitude.

Basaltic Lava Flows

Radioisotopic ages were obtained from six basaltic lava flows; four of these provide the chronology and stratigraphic framework for the interbedded glacial deposits (Fig. 5). Five of these lavas erupted in the Lago Buenos Aires region, the sixth crops out 520 km to the south at 51.8 °S along the Rio Gallegos (Fig. 1). The stratigraphic relationships of the lava flows with one another and to moraines and

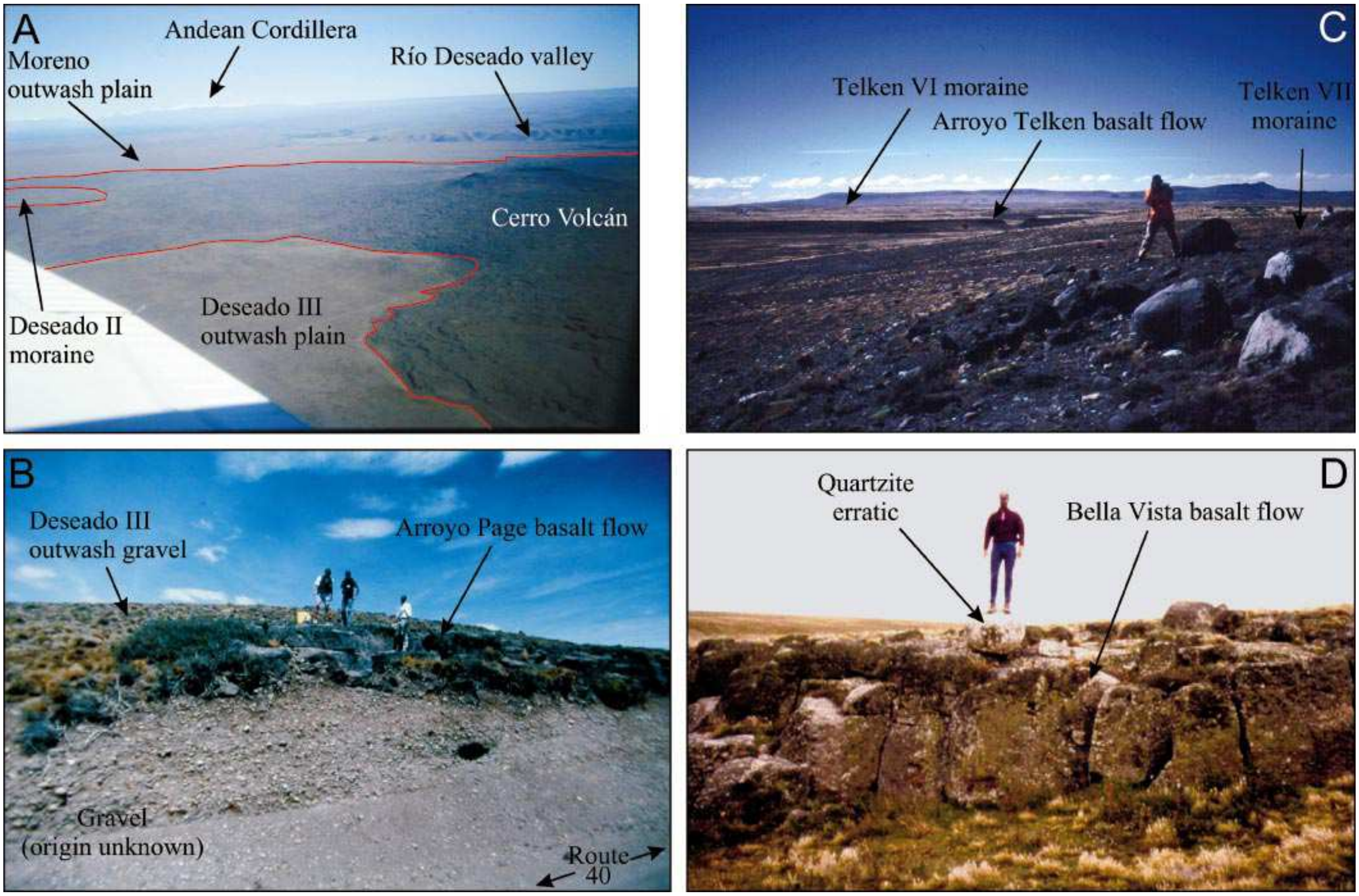


Figure 4. Illustration of stratigraphic relationships between basaltic lava flows and glacial deposits. (A) View northwest from light plane over 109 ka Cerro Volcán basalt flow and Deseado III outwash plain. Andean Cordillera is 60 km west of aircraft. (B) 760 ka Arroyo Page basalt flow exposed in roadcut along Route 40. (C) View northwest from Telken VII till. Note large erratic boulders on till surrounded by 1016 ka Arroyo Telken basalt flow. Quartzite erratic derives from Andean Cordillera 120 km west of this location. (D) Outcrop of 1168 ka Estancia Bella Vista basalt flow, 51 °S along Río Gallegos (see Fig. 1).

outwash deposits both in the Lago Buenos Aires area and along the Río Gallegos are described below.

Lagunita del Rincon Basalt

This olivine-augite-plagioclase phyric alkali basalt lava flow vented from a 42-m-high, 2-km-diameter scoria and tuff cone whose crater is infilled by Lagunita del Rincon (Fig. 2). The stratigraphic relationship of this flow with the larger Arroyo Telken flow is uncertain due to cover by soil and vegetation. $^{40}Ar/^{39}Ar$ results (below) suggest that the Lagunita del Rincon flow is older than the Telken flow, but its relationship to the Telken VII till that underlies the Arroyo Telken basalt is uncertain.

Arroyo Telken Basalt

This extensive olivine-augite phyric basaltic lava, partly mapped by Caldenius (1932), flowed from one or more vents at >1000 m elevation on Meseta del Lago Buenos Aires to cover >85 km^2 (Fig. 2). Low relief on the flow surface, which is covered by loess, soil, and bunch grass at higher elevations, has hampered efforts to firmly establish the source. The flow is 1–2 m thick near Estancia La Paloma, where it crops out below the Estancia Paloma flow. Adjacent to the north side of Route 40, 2 kilometers east of Arroyo Telken, the Arroyo Telken basalt flow forms a plain at 605 masl, where it overlies the Telken VII till (Fig. 4C).

Estancia Paloma Basalt

This highly olivine-phyric basaltic lava crops out along the western side of Lagunita del Rincon; it flowed from the 170-m-high scoria cone 2.5 km west of Lagunita del Rincon, covers ~15 km^2, and overlies the Arroyo Telken basalt flow immediately south of Estancia La Paloma, where it is 2 m thick (Fig. 2).

Arroyo Page Basalt

This olivine-augite phyric basaltic lava is 2 m thick where it crops out at 570 masl along Arroyo Page at the intersection with Route 40 (Fig. 4B). The lava presently covers ~50 km^2 and flowed from an undetermined source on Meseta del Lago Buenos Aires at least 1250 masl; it subsequently cascaded over the escarpment of Miocene lavas along the northern margin of Meseta del Lago Buenos Aires and flowed down nearly 700 m of relief into the upper drainage of Arroyo Page (Fig. 2). Based on elevations and outcrop trends, Page Creek had downcut through the Telken I, II, and III moraines and the outwash gravels to the west of these features prior to emplacement of the Arroyo Page basalt (Fig. 3). Thus, the Arroyo Page basalt flow is younger than all the Telken deposits. Baker et al. (1981) determined a whole-rock K-Ar age of 200 ± 100 ka (±1σ) for this lava.

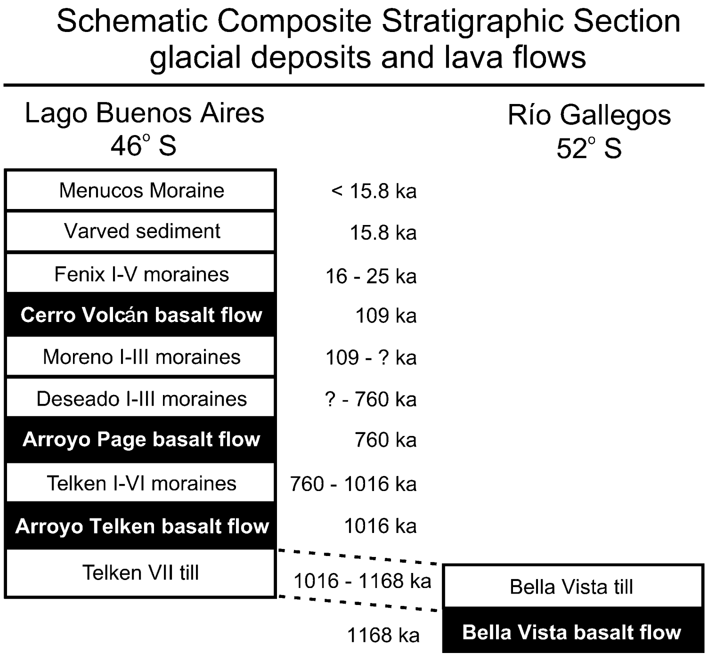


Figure 5. Schematic composite section of glacial deposits and interbedded lava flows at Lago Buenos Aires and Río Gallegos. Telken VII and Bella Vista tills are the easternmost and most expansive glacial deposits at respective latitudes (see Fig. 1). Ages of stratigraphic units are discussed in the text.

Cerro Volcán

Recognized by Caldenius (1932), Cerro Volcán is a 120-m-high, 1-km-wide strombolian cone that rises to 666 masl (Figs. 2 and 4A). Smaller vents to the northwest and southeast of the main vent suggest a single fissure-type eruption from a 3-km-long fracture (Fig. 3). Mercer (1982) and Baker et al. (1981) reported whole-rock K-Ar ages of 177 ± 56 ka (±1σ), and 300 ± 100 ka (±1σ), respectively, from this basalt. Lava from this eruption covers 50 km^2, partly buries the Deseado I and II moraines, the Deseado III outwash surface, and overlies the outwash gravel surfaces that grade to the Moreno moraines (Figs. 2, 3, and 4A). The flow surface is remarkably fresh, comprising glassy titanaugite-olivine-plagioclase phyric pahoehoe with pressure ridges 3–4 m high surmounting much of its surface. In shallow depressions, the flow is sparsely covered by deposits of pale gray ash up to 10 cm thick (from the 1991 eruption of Hudson Volcano, 100 km to the northwest), loess, and grass. Where the flow descended northward into the Río Deseado, it became impounded, pooled to 5–10 m thickness, and cooled slowly enough that columnar jointing developed. Several sites on pressure ridges of this lava are used to calibrate long-term local production rates of cosmogenic nuclides and constrain erosion rates (Ackert et. al., 2003).

Bella Vista Basalt

Some 520 km south of Lago Buenos Aires, a 2–3-m-thick basaltic lava flow crops out south of the Río Gallegos 2 km east of Estancia Bella Vista (Fig. 1). This flow erupted from vents in the northwest corner of the 1000 km^2 Pali Aike volcanic field to fill a shallow paleovalley cut into Pliocene lavas. The Bella Vista basalt flow underlies glacial drift comprising scattered erratic boulders and blocks of metamorphic lithology between 0.5 m and 20 m in diameter that were transported 120 km from the Andean Cordillera (Caldenius, 1932; Meglioli, 1992; Fig. 4D). This drift represents Caldenius' (1932) easternmost and oldest glacial deposit (Fig. 1) and corresponds to Mercer's (1976) type section for the Greatest Patagonian Glaciation. Here, the northeastern boundary of the Greatest Patagonian Glaciation drift is confined within the same paleovalley occupied by the Bella Vista basalt flow. This flow was first dated by Mercer (1976), who obtained a whole-rock K-Ar age of 1.17 ± 0.05 Ma (±1σ) that provided a relatively precise lower age limit for the Greatest Patagonian Glaciation (Mercer, 1983). Meglioli (1992) revisited the flow and obtained a $^{40}Ar/^{39}Ar$ total fusion age of 1.55 ± 0.03 Ma (±1σ), significantly older than Mercer's K-Ar age. To resolve the discrepancy between the ages reported by Mercer (1976) and Meglioli (1992), and to test whether the glacial drift at Estancia Bella Vista may correlate with the Telken VII till at Lago Buenos Aires, we have redated the Estancia Bella Vista basalt using the $^{40}Ar/^{39}Ar$ incremental heating method. Our age determination resolves the discrepancy and places relatively precise constraints on the timing of the Greatest Patagonian Glaciation in the region that encompasses Lago Buenos Aires and Río Gallegos (Fig. 1).

SAMPLES AND ANALYTICAL METHODS

$^{40}Ar/^{39}Ar$ Dating

$^{40}Ar/^{39}Ar$ dating of the basaltic lavas followed the procedures outlined in Singer et al. (2000, 2002). To minimize the potential for contamination by xenocrysts, 125–315 μm holocrystalline groundmass separates weighing 100–200 mg each were prepared by crushing, sieving, magnetic sorting, and hand-picking under a binocular microscope. Owing to its youth and importance for constraining not only the glacial history, but also cosmogenic nuclide production rates in this region (Ackert et al., 2003), three different subsamples were prepared from the Cerro Volcán flow: from the vitrophyric surface sample CV-01 (Fig. 6A), both plagioclase phenocrysts and matrix glass were separated and purified as above. From sample CV-02 of the columnar-jointed flow interior (Fig. 6B), aliquots of holocrystalline groundmass were prepared. The CV-01 samples were washed ultrasonically in 4% HCl, 3% HNO_3, and deionized water to remove possible calcite in vesicles and fine superficial clay or alteration. The vesicle-free CV-02 sample was cleaned only in acetone and water. X-ray mapping of the glassy and holocrystalline matrix material was done using the University of Wisconsin–Madison Cameca SX-50 electron microprobe to determine the crystallinity and distribution of potassium in the CV-01 and CV-02 samples (Fig. 6).

The $^{40}Ar/^{39}Ar$ method requires that the age of a sample be calculated relative to a mineral standard that has been previously dated, usually by conventional K-Ar techniques. The monitor minerals used here were sanidines from the Taylor Creek (TCs) (Duffield and Dalrymple, 1990) and Alder Creek (ACs) (Turrin et al., 1994) rhyolites. The age of TCs was determined to be 27.92 Ma relative to the U.S. Geological Survey primary standard SB-3 biotite at 162.9 Ma (Duffield and Dalrymple, 1990; Lanphere and Dalrymple, 2000). Turrin et al. (1994) measured the age of ACs

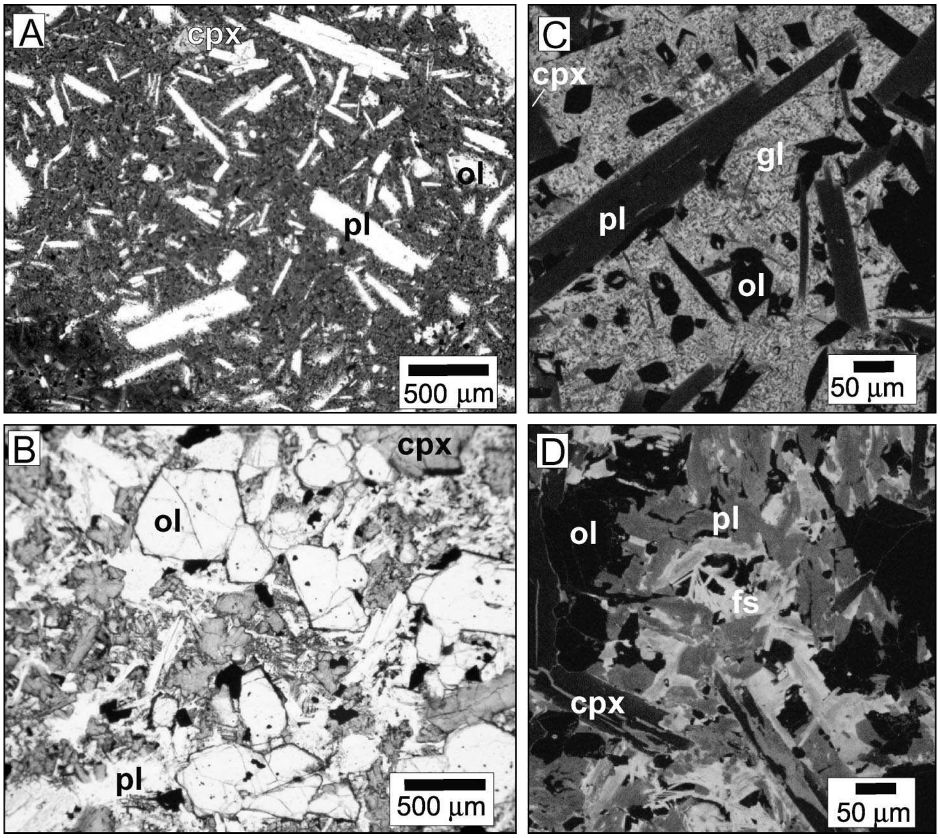


Figure 6. Photomicrographs and Kα x-ray maps of potassium distribution in polished thin sections from Cerro Volcán basalt flow. Plane light images of: (A) vitrophyric sample CV-01 showing >600-µm-long laths of plagioclase and smaller olivine and titanaugite phenocrysts in a black, glassy matrix; (B) holocrystalline sample CV-02, showing interlocking network of plagioclase, olivine, titanaugite, and oxides. In x-ray maps, bright areas are richer in potassium. (C) In this map of CV-01, potassium is entirely in light-toned matrix glass; prismatic plagioclase and equant olivine and pyroxene phenocrysts are dark. (D) X-ray map of CV-02, showing that potassium resides exclusively in anorthoclase feldspar laths (fs) smaller than 50–100 µm that are zoned to higher potassium concentrations at their rims. Larger plagioclase microphenocrysts are medium-toned; large olivine and pyroxene phenocrysts are dark. Ol—olivine, pl—plagioclase, cpx—clinopryoxene, fs—alkali feldspar, gl—glass.

at 1.186 Ma relative to 27.84 Ma sanidine from the Fish Canyon tuff. In light of intercalibration of these $^{40}Ar/^{39}Ar$ standards relative to 98.79 ± 0.96 Ma GA-1550 biotite, we have adopted ages of 28.34 Ma for TCs and 1.194 Ma for ACs (Renne et al., 1998); however, a consensus regarding the age of the GA-1550 standard has not yet been reached (Lanphere and Dalrymple, 2000). Adopting an age of 27.92 Ma for the TCs standard would shift the ages reported here ~1% younger but would not alter any of our conclusions.

The groundmass and plagioclase samples, wrapped into 99.99% Cu foil packets, and several flux monitor packets were loaded into 5 mm i.d. quartz vials that were evacuated and sealed. Samples were irradiated for either 2 hr with TCs monitors or 30 min with ACs monitors at the Oregon State University Triga reactor in the Cadmium-Lined In-Core Irradiation Tube (CLICIT), where they received a fast neutron dose of between 0.5 and 2.0 × 10^{17} n/cm^2. Corrections for undesirable nucleogenic reactions on ^{40}K and ^{40}Ca, based on previous measurements of Ca- and K-free salts (Wijbrans et al., 1995), are $[^{40}Ar/^{39}Ar]_K = 0.00086$; $[^{36}Ar/^{37}Ar]_{Ca} = 0.000264$; $[^{39}Ar/^{37}Ar]_{Ca} = 0.000673$.

Isotope ratio measurements were made in a MAP 216 spectrometer at the University of Geneva or a MAP 215–50 instrument with a modified Nier source, 90° electrostatic filter, and Balzers SEV-217 electron multiplier operated at a sensitivity of 1×10^{-15} mol/V in the University of Wisconsin–Madison Rare Gas Geochronology Laboratory. Mass discrimination was monitored using air pipettes and was 1.0070 ± 0.0009 in Geneva and 1.0037 ± 0.0002 or 1.0024 ± 0.0002 per atomic mass unit at Madison during analytical periods. Furnace degassing, temperature measurement, gas clean-up, mass spectrometry, and blank corrections were similar to Singer et al. (2000, 2002).

For each analysis, uncertainties include estimates of the analytical precision on peak signals, the system blank, and spectrometer mass discrimination. Inverse-variance-weighted mean plateau ages and standard deviations were calculated according to Taylor (1982). At the University of Wisconsin-Madison, monitor minerals were measured using the 25 W CO_2 laser. Precision estimates for monitors, based on six to seven measurements each, along the

TABLE 1. SUMMARY OF $^{40}Ar/^{39}Ar$ INCREMENTAL HEATING RESULTS FROM BASALTIC LAVA GROUNDMASS SEPARATES

Basalt flow	Sample ID	Location within Santa Cruz Province, Argentina		Age spectrum			Isochron		
		Latitude (°S)	Longitude (°W)	Steps	MSWD	Plateau ka ± 2σ	*SUMS* *(N-2)*	$^{40}Ar/^{36}Ar_i$	Age† ka ± 2σ
Cerro Volcán	CV-98-02	46°35.42′	70°40.44′	26 of 38‡	1.1	108 ± 2	1.12	295.1 ± 1.8	109 ± 6
Arroyo Page	AP-96-01	46°43.91′	70°50.03′	9 of 13	0.5	764 ± 10	0.60	295.9 ± 0.6	760 ± 14
Estancia La Paloma	AT-98-03	46°55.31′	70°48.21′	8 of 10	1.2	987 ± 15	2.20	295.3 ± 6.5	984 ± 35
Arroyo Telken	AT-96-01	46°52.38′	70°44.22′	9 of 15	1.6	1014 ± 2	1.80	293.8 ± 3.8	1016 ± 10
Lagunita del Rincon	AT-98-02	46°54.95′	70°48.30′	8 of 10	2.8	1047 ± 13	3.20	286.6 ± 7.6	1074 ± 28
Estancia Bella Vista	BV-96-02	51°51.34′	70°38.02′	10 of 12	1.0	1170 ± 6	1.20	295.9 ± 3.0	1168 ± 14

†Calculated using decay constants of Steiger and Jäger (1977); relative to 28.34 Ma Taylor Creek Rhyolite sanidine standard.
‡Combination of three incremental heating experiments. MSWD—mean square of weighted deviates.

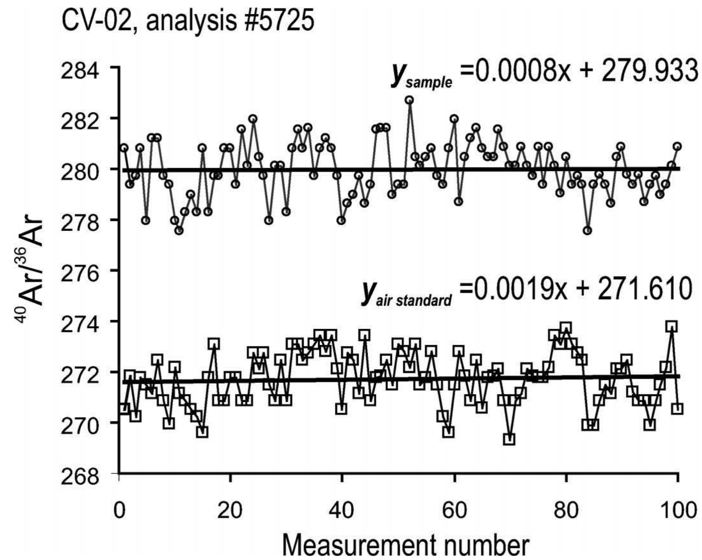


Figure 7. $^{40}Ar/^{36}Ar$ ratio measured during analysis #5725 of CV-02 sample and corresponding air standard. Linear regression gives y-intercept values that are used to calculate moles of radiogenic argon in sample. This is done by comparing the number of moles of ^{40}Ar in calibrated dose in Table 2 to air standard, using ideal gas law to obtain n. See text for details. Complete set of isotope ratio measurements for all samples is in Data Repository (see footnote 1).

vials suggest that the uncertainty in *J,* the neutron fluence parameter, was less than 0.5%; this uncertainty was also propagated into the final plateau and isochron ages for each analysis and contributes less than 0.1% to the total uncertainty in these age determinations. Finally, $^{40}Ar/^{39}Ar$ and K-Ar ages were calculated using the decay constants of Steiger and Jäger (1977) and are reported with $\pm 2\sigma$ uncertainties.

Criteria used to determine whether an incremental heating experiment gave meaningful results were: (1) plateaus must be defined by at least three contiguous steps all concordant in age at the 95% confidence level and comprising >50% of the ^{39}Ar released, and (2) a well-defined isochron, calculated using the algorithm of York (1969), exists for the plateau points as defined by the F-variate statistic *SUMS/(N-2).* Because the isochron approach makes no assumption regarding the trapped component and combines estimates of analytical precision plus internal disturbance of the sample (scatter about the isochron), the isochron ages (Table 1) are preferred over the weighted mean plateau ages.

Unspiked K-Ar Dating

The unspiked K-Ar technique differs from the conventional isotope dilution method in that argon extracted from the groundmass sample is measured in sequence with purified aliquots of an atmospheric argon standard at an identical total pressure during each measurement. This is done by changing the volume of the mass spectrometer via an adjustable bellows. The sequential measurement at a single pressure suppresses mass discrimination effects. Differences between the $^{40}Ar/^{36}Ar$ ratio of the atmospheric argon standard and the sample can reveal quantities of radiogenic $^{40}Ar^*$ as small as 0.2% of the total ^{40}Ar (Cassignol and Gillot, 1982). The sensitivity of the mass spectrometer at the CEA-CNRS (Centre National de la Recherche Scientifique) laboratory at Gif-Sur-Yvette, France, of 5.1×10^{-12} moles per Volt with an amplifier background of 75 mV for ^{40}Ar (10^9 ohm resistor) and 5.75 mV for ^{36}Ar (10^{11} ohm resistor), combined with excellent signal stability during the measurements (Fig. 7), permit basaltic samples of Late Pleistocene and Holocene age weighing as little as 1 g to be dated precisely (Guillou et al., 1997, 1998).

Replicate unspiked K-Ar age determinations (Table 2) were completed on subsamples of glass from CV-01 and holocrystalline groundmass from CV-02 that were prepared for the $^{40}Ar/^{39}Ar$ analyses. K contents were determined by atomic and flame emission spectrophotometry to better than 1% precision. Argon was extracted by radio frequency heating from groundmass samples that weighed 0.8–1.1 g, introduced into an ultrahigh vacuum glass line, and purified with titanium sponge and Zr-Al getters. Isotopic analyses were performed on quantities of argon between 1 and 3×10^{-11} moles using a 180°, 6-cm-radius mass spectrometer with an accelerating potential of 620 V. The spectrometer was operated in static mode, but its volume was varied to give equal ^{40}Ar signals for the air aliquots and the samples; beam sizes were measured simultaneously on a double

TABLE 2. ISOTOPIC DATA AND AGES FROM UNSPIKED K-Ar EXPERIMENTS ON SAMPLES FROM CERRO VOLCÁN

Sample ID	Analysis number	Weight Molten (g)	K content (wt.%)	$^{40}Ar/^{36}Ar$ sample $\pm 2\sigma$	$^{40}Ar/^{36}Ar$ air std. $\pm 2\sigma$	$^{40}Ar/^{36}Ar$ calib. dose $\pm 2\sigma$	$^{40}Ar_{rad}$ (%)	$^{40}Ar_{rad}$ (10^{-13}mol/g)	Age $\pm 2\sigma$ (ka)†	Weighted mean age (ka)
CV-02 Holocrystalline groundmass from columnar-jointed flow interior; location: 46°35.417′ S, 70°40.440 W (analyzed June 2000)										
CV-02	5725	0.96103	1.950 ± 0.013	279.933 ± 0.010	271.610 ± 0.103	270.868 ± 0.038	2.973	3.680 ± 0.059	108.8 ± 4.1	
CV-02	5741	1.10557	1.950 ± 0.013	284.637 ± 0.173	273.008 ± 0.131	271.051 ± 0.046	4.086	3.646 ± 0.069	107.8 ± 4.6	108.6 ± 3.1
ISG-H‡	5749			272.300 ± 0.054	272.625 ± 0.057	271.187 ± 0.043	−0.120			
ISG-H	5760			270.610 ± 0.043	270.844 ± 0.046	271.392 ± 0.043	−0.086			
CV-01 Matrix glass from pahoehoe surface of flow; location: 46°44.747′ S, 70°47.437 W (analyzed March–May 1997)										
CV-01	4935	0.79914	2.170 ± 0.022	277.305 ± 0.044	273.586 ± 0.049	273.566 ± 0.049	1.341	4.913 ± 0.090	131.0 ± 5.0	
CV-01	4957	0.85804	2.170 ± 0.022	277.045 ± 0.028	273.805 ± 0.036	273.960 ± 0.041	1.169	4.693 ± 0.073	125.0 ± 5.0	128.0 ± 4.0
ISG-H	4929			273.731 ± 0.060	273.269 ± 0.068	273.550 ± 0.066	0.169			
ISG-H	4959			273.511 ± 0.055	274.191 ± 0.060	273.995 ± 0.044	−0.249			
ISG-H	4967			273.515 ± 0.060	273.658 ± 0.060	273.965 ± 0.052	−0.052			

†Calculated using decay constants of Steiger and Jäger (1977) using methods described in text.
‡Zero age basalt standard (see text).

Faraday collector in sets of 100 using a 1 s integration time (Table 2). The instrumental atmospheric argon correction was monitored via repeated measurements of a zero-age standard material ISH-G that we found to contain between −0.249 and 0.169% radiogenic $^{40}Ar^*$ during the analyses of samples CV-01 and CV-02 (Table 2). Two measurements of air are made for each sample. The first is inlet to the mass spectrometer from the same line and at the same pressure as the sample and used for the calculation of the percentage of $^{40}Ar^*$ in the sample. The second is a calibrated dose of air that is inlet through a separate vacuum line. The volume of this spike-free inlet system is calibrated by measuring mineral standards of known molar $^{40}Ar^*$ concentration, including GL-O glauconite, Mmhb-l hornblende, LP-6 biotite, and HD-B1 biotite (see Charbit et al., 1998, for details). The calibrated doses of air, combined with the ISG-H standard and the atmospheric reference gas, provide a cross check that the procedural blanks are atmospheric in composition. Moreover, using the ideal gas law, the calibrated dose allows molar ^{40}Ar contents in the air aliquot to be subtracted from that of the sample. Thus, the moles of radiogenic $^{40}Ar^*$ in the sample can be calculated to a precision of 0.2% (±2σ) (Guillou et al., 1997, 1998).

RESULTS

The $^{40}Ar/^{39}Ar$ incremental heating results are summarized in Table 1; age spectra and isochrons are illustrated in Figures 8 and 9, and complete data are in the Data Repository.[1] The Estancia Bella Vista, Estancia La Paloma, Arroyo Telken, Lagunita del Rincon, and Arroyo Page samples yielded nearly concordant spectra with small percentages of high-temperature gas giving slightly younger ages than the weighted mean plateau ages (Fig. 8). The discordant, slightly younger steps may reflect either poorly characterized high-temperature blanks or subtle ^{39}Ar recoil artifacts in pyroxene or olivine (e.g., Turner and Cadogan, 1974). Well-defined isochrons were calculated from the plateau steps in each sample; in all cases the trapped component is atmospheric in composition, and we interpret the isochrons (Table 1, Fig. 8) to reflect the time since eruption of these lavas.

The $^{40}Ar/^{39}Ar$ incremental heating results from the three Cerro Volcán subsamples are

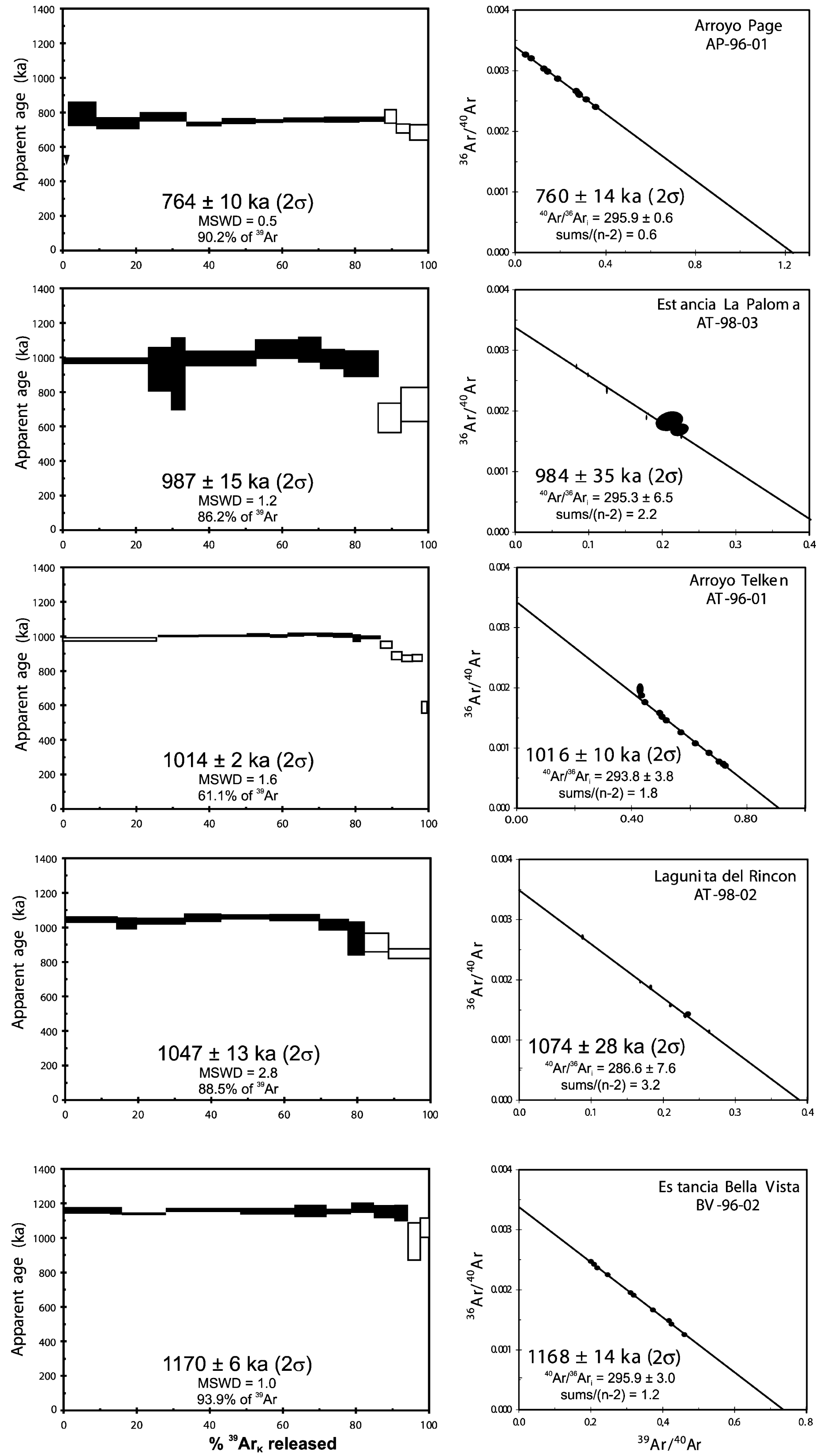


Figure 8. Age spectra and isochrons depicting $^{40}Ar/^{39}Ar$ experimental results from Estancia Bella Vista, Lagunita del Rincon, Arroyo Telken, Estancia La Paloma, and Arroyo Page basalt flows. Black filled boxes define plateau ages; only these points were used to calculate isochrons, which give preferred age for each of these lavas. Uncertainties ±2σ.

[1]GSA Data Repository item 2004045, analytical data from six incremental heating experiments, is available on the Web at http://www.geosociety.org/pubs/ft2004.htm. Requests may also be sent to editing@geosociety.org.

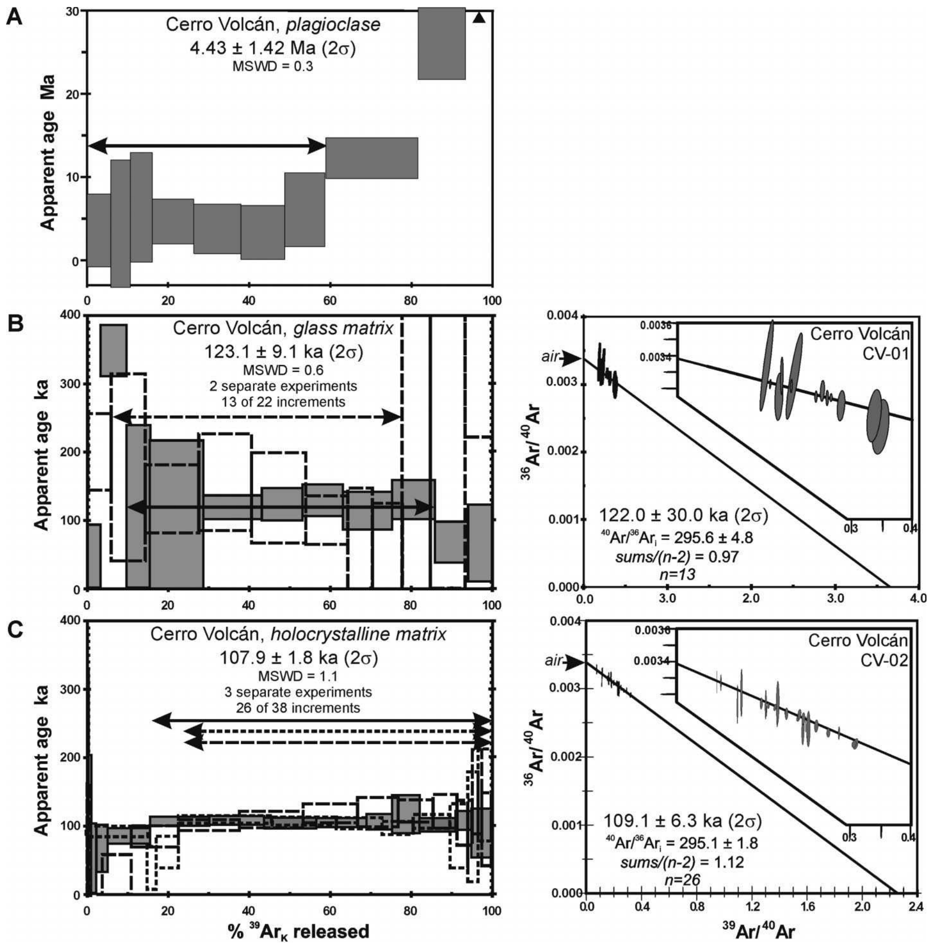


Figure 9. Age spectra and isochrons depicting $^{40}Ar/^{39}Ar$ experimental results from the Cerro Volcán basalt flow. (A) Age spectrum from plagioclase in vitrophyric sample CV-01. Although gas steps released below ~950 °C define a plateau at 4.4 Ma, higher-temperature steps gave much older apparent ages and are strongly discordant. We interpret these apparent ages to reflect an inherited, possibly ancient crustal, argon component. (B) Two experiments on glass from vitrophyric surface sample CV-96–01. Sample contained less radiogenic argon, hence uncertainties in plateau ages and combined isochron are larger than in C. (C) Three experiments on holocrystalline CV-98–02 groundmass; plateau segments comprise 26 individual analyses used to calculate combined isochron of 109.1 ± 6.3 ka, which gives preferred age for this lava. Uncertainties ±2σ.

more complex. Plagioclase from the glassy surface sample gave a strongly discordant spectrum with a ''plateau'' age of 4.4 Ma but ages of 13 to >30 Ma in higher-temperature steps (Fig. 9A). Because of its youthful morphology, and ages obtained from the matrix samples (below), we infer that the feldspar contains an ancient, incompletely degassed xenocrystic component (Singer et al., 1998b; Heizler et al., 1999) that was possibly derived from underlying Jurassic rhyolite (Baker et al., 1981). Replicate experiments on glass from the surface sample gave partly discordant age spectra, whose plateau steps gave a weighted mean age of 123.1 ± 9.1 ka and a poorly constrained isochron of 122.0 ± 30.0 ka (Fig. 9B). The large uncertainties of individual gas analyses and the isochron reflect radiogenic ^{40}Ar contents averaging <6%. In comparison to the glass, three experiments on holocrystalline matrix gave more precise apparent ages, reflecting radiogenic ^{40}Ar contents up to 14% per step and 9% on average (Data Repository; see footnote 1) that define overlapping, nearly concordant age spectra with 20–25% of the low-temperature gas steps yielding apparent ages younger than the weighted mean plateau age of 107.9 ± 1.8 ka (Fig. 9C). The combined isochron calculated from the plateau steps is 109.1 ± 6.3 ka with a $^{40}Ar/^{36}Ar$ ratio of 295.1 ± 1.8 (Fig. 9C). Although minor diffusional loss of argon is suggested by these age spectra, the combined isochron from this sample defines what we consider to be the most reliable age for the Cerro Volcán basalt flow.

The unspiked K-Ar ages of the glass from CV-01 and the holocrystalline matrix from CV-02 are 128.0 ± 4.0 ka and 108.6 ± 3.1 ka (Table 2). These ages are identical at the 95% confidence level to the plateau and isochron ages for these subsamples (Fig. 8, B and C) but do not overlap one another. On the basis of our field mapping (Fig. 2), aerial observations (Fig. 4A), and similar chemical composition (Gorring et al., 2003), we are confident that the glassy and holocrystalline samples are from the same lava flow.

Virtually all of the K in the surface samples resides in the matrix glass, whereas it is concentrated in feldspar microphenocrysts in the holocrystalline sample (Fig. 6, B and D). Thus, a possible explanation for the $^{40}Ar/^{39}Ar$ age of the glass being older than that of the holocrystalline sample is ^{39}Ar recoil out of the glass during irradiation (Turner and Cadogen, 1974). However, the fact that the K-Ar ages of the two subsamples, which cannot be affected by ^{39}Ar recoil, also differ similarly in age argues strongly against significant ^{39}Ar recoil from the glass. Instead, we suggest that very small amounts of K (and Na) diffused out of the basaltic glass in response to hydration weathering over the past 109 k.y. (Cerling et al., 1985), leading to unsupported radiogenic ^{40}Ar, and *both* K-Ar and $^{40}Ar/^{39}Ar$ ages for the glass that exceed the time elapsed since eruption by 13%. Because of these potential problems with the glass in CV-01, the K-Ar and $^{40}Ar/^{39}Ar$ data from this sample do not provide reliable age constraints on the timing of moraine deposition.

Instead, we rely on the weighted mean of the K-Ar and $^{40}Ar/^{39}Ar$ isochron ages of CV-02, which is 108.7 ± 2.8 ka, for our best estimate of time elapsed since the Cerro Volcán eruption. Considering the large analytical uncertainties (reported here at ±2σ), the whole-rock K-Ar ages obtained from Cerro Volcán by Baker et al. (1982) and Mercer (1982) of 300 ± 200 ka and 176 ± 112 ka, respectively, are indistinguishable from our age, which represents better than an order of magnitude improvement in precision.

AGES OF GLACIAL DEPOSITS AND THEIR IMPLICATIONS

The $^{40}Ar/^{39}Ar$, and K-Ar ages of lava flows, combined with ^{14}C ages of varved sediment, and surface exposure ages of boulders on the Fenix and Moreno moraines discussed in Kaplan et al. (2004) provide new constraints on the glacial chronology of the Lago Buenos Aires basin (Fig. 5) and address issues that are important in understanding mechanisms that influenced glacial fluctuations locally and throughout the southern Andes. Here we elaborate on the Moreno and older deposits, whereas Kapan et al. (2004) focus on the Fenix moraine complex.

The easternmost, most distal Pleistocene moraines and till were correlated from Lago Epuyén at 41 °S to the Straits of Magellan at 52 °S (Fig. 1) on the basis of their position, alteration, morphology, and erosion (Caldenius, 1932). The new $^{40}Ar/^{39}Ar$ ages from the Bella Vista and Arroyo Telken basalt flows provide strong evidence that the mapping and correlation proposed by Caldenius is indeed valid, and that the Greatest Patagonian Glaciation occurred between 1168 ± 14 ka and 1016 ± 10 ka (Fig. 5). The Telken VII till records the most extensive eastward position of glaciers observed at Lago Buenos Aires; the ice advanced and had retreated prior to 1016 ± 10 ka, when the till was buried by the Arroyo Telken lava flow. The lack of till, erratics, or outwash gravel on the 1074 ± 28 ka Lagunita del Rincon cone or flow is suggestive, albeit inconclusive evidence, against ice having advanced between 1074 ka and 1016 ka. Mercer (1976) concluded that the Greatest Patagonian Glaciation occurred after 1.2 Ma based on his own reconnaissance and Caldenius' (1932) mapping of drift north of the Strait of Magellan combined with K-Ar ages of 1170 ± 100 ka from the Bella Vista basalt flow and 1240 ± 20 ka from another more easterly basalt flow, both of which underlie the drift. A third lava flow with a K-Ar age of 170 ± 70 ka overlies the same drift and provided the only firm upper stratigraphic constraint on the Greatest Patagonian Glaciation (Mercer, 1976). Inconclusive stratigraphic evidence from Cerro Fraile (10 km south of Lago Argentino, 49.5 °S, Fig. 1), where the youngest preserved till may be overlain by a lava with a K-Ar age of 1050 ± 100 ka (Fleck et al., 1972; Mercer, 1976), was later determined to be invalid (Mercer, 1983), leaving the Greatest Patagonian Glaciation broadly constrained to between 1.2 Ma and 170 ka. Our $^{40}Ar/^{39}Ar$ age of 1168 ± 14 ka for the Bella Vista basalt provides a more precise lower limit on the timing of the Greatest Patagonian Glaciation at 52 °S latitude than Mercer's (1976) K-Ar ages (Fig. 5).

The areal extent of ice in the southern part of Patagonia ca. 1100 ka was impressive, encompassing 300,000 km^2 compared to 100,000 km^2 during the LGM (Fig. 1; Clapperton, 1990). Although the extent of late Miocene and Pliocene glaciers is not known in detail, their deposits are found no more than 30–50 km from the Andean foothills (Mercer, 1969; Fleck et al., 1972; Mercer and Sutter, 1982; Mercer, 1983). The location of these tills, interbedded with Late Miocene–Pliocene lavas near the tops of mesetas (lava-capped plateaus), suggests deposition on broad plains subsequently uplifted and isolated by erosion and deepening of the adjacent lake-filled valleys that emerge from the eastern flank of the Cordillera. Early Pleistocene drift is not found elsewhere in the southern mid-latitudes. Mercer (1983) suggested that the absence of glacial drift corresponding in age to the Greatest Patagonian Glaciation in New Zealand was a consequence of the recent uplift of the Southern Alps of New Zealand to near their present elevation during only the last half of the Pleistocene Epoch.

That the most extensive glaciers in Patagonia formed prior to 1 Ma contrasts with the benthic marine $\delta^{18}O$ record from ODP site 677 (Fig. 9). Maxima in $\delta^{18}O$ are less extreme prior to 800 ka and are interpreted to reflect lower global ice volumes (Shackleton and Hall, 1989; Fig. 9). However, neither the reason for the timing of the Greatest Patagonian Glaciation, nor the cause of the reduced extent of successive glaciations, is clear. Three hypotheses offered by Clapperton (1990) to explain the latter were: (1) Tectonic subsidence reduced the ice accumulation area over time; (2) Progressive deepening of major valleys meant that successively larger volumes of ice were required to sustain glaciers of similar areal extent; or (3) Antarctic ice shelves may have been wider, leading to climatic conditions that favored the growth of glaciers at more northerly latitudes than otherwise possible. An additional possibility is that it was significantly colder or wetter in this region 1 Ma than during later ice ages, although we are not aware of evidence to support or refute such a claim.

We find the idea of a tectonic control intriguing and hypothesize a link between ice extent, uplift of the Patagonian Andes, and subduction of the Chile rise spreading center beneath the region. The Chile rise separates the Nazca and Antarctic plates, intersecting the trench to form the Aysen triple junction along the South American continental margin at 46°S (Fig. 1). Between ca. 14 Ma and the present day, the Aysen triple junction and its young, hot, buoyant spreading ridge migrated northward through a series of ridge-trench collisions beneath the length of the Patagonian Andes between 52 °S and 46 °S (Ramos and Kay, 1992; Gorring et al., 1997; 2003; Thomson et al., 2001). Today, mountain peaks with elevations as high as 3630 m at Cerro Murallón, 3375 m at Cerro Fitzroy at 50 °S, and 4058 m at Cerro San Valentin at 46 °S contrast sharply with lower maximum elevations of 2000–2800 m between 46 °S and 39 °S, where the mantle and lower crust have not been impacted by subduction of ocean ridge segments (Fig. 1; Thomson et al., 2001; Rabassa and Clapperton, 1990).

On the basis of zircon and apatite fission track cooling ages from the Patagonian batholith between 52 and 46 °S, Thomson et al. (2001) concluded that the locus of maximum rates of uplift, cooling, and denudation migrated eastward 200 km, from along the west coast ca. 30 Ma to near the present-day topographic divide by ca. 8 Ma, in response to rapid convergence between the Nazca and South American plates. North of 46 °S, Thomson (2002) also found evidence along transpressional faults for very fast rates of uplift between ca. 7 and 2 Ma (Fig. 1). The fission track data of Thomson et al. (2001) and Thomson (2002) indicate that rocks formerly at ~2–3 km depth that are currently exposed on the eastern side of the Patagonian batholith cooled rapidly through the partial annealing zone for apatite, i.e., to below 60 °C, by 8–2 Ma. Denudation of several kilometers by fluvial, and later glacial, erosion in response to uplift facilitated exhumation of the batholith (Thomson et al., 2001). These data imply that uplift, which initiated and attained its peak rate during the Pliocene, most probably continued into the Quaternary.

Murdie and Russo (2000) show that seismic shear wave velocities in the mantle are highly attenuated under the Andes, where the recently subducted trace of the Chile Rise spreading center is probably located (Fig. 1). Moreover "slab-window" volcanism (Gorring et al., 2003), including the Pleistocene lavas at Lago Buenos Aires, which are a subject of this paper, attests to asthenospheric upwelling through the subducted spreading ridge segments and presumably heating of the crust beneath the axis of the Cordillera when the spreading ridge axis passed eastward beneath the Andes during the last 2–3 m.y. We suggest that initial uplift of the Patagonian Andes to elevations needed to sustain the first glaciers by 5 Ma (Mercer and Sutter, 1982) later produced the highest mountain elevations, in part due to subduction of the spreading ridge during the Quaternary.

We infer that an ice cap capable of feeding several large outlet glaciers grew at ~1.2–1.1

Ma in response to this newly elevated topography. Modeling by Hulton and Sugden (1995, 1997) suggests that owing to high precipitation rates on the western side of the Andes snow accumulation on the Patagonian ice cap is extraordinarily sensitive to altitude of the local topography. Presently, uplift of only 100 m along portions of the Cordillera would be sufficient to bring much larger areas into the ice accumulation zone and facilitate extensive buildup of glaciers (Hulton and Sugden, 1997).

If our hypothesis is correct, glaciers corresponding to the Greatest Patagonian Glaciation reflect the culmination of uplift of the southern Andes by ~1.2 Ma. Afterwards, glacial erosion progressively reduced the area of the ice accumulation zone, causing a corresponding increase in the ablation zone, and therefore shorter outlet glaciers during successive advances. This pattern is consistent with numerical models (e.g., Oerlemans, 1984), which suggest that glacial erosion is particularly effective at the equilibrium line altitude. Thus, during periods of several hundred thousand years encompassing many changes from glacial to interglacial climate, lowering of the bedrock surface reduces the area of coldest temperature where ice forms above the equilibrium line altitude, leading to shorter glaciers and nested moraines over time (Oerlemans, 1984; MacGregor et al., 2000).

A record of ice advances younger and progressively less extensive than those recorded by the Telken VII (local Greatest Patagonian Glaciation) till is provided by the Telken I-VI moraines, which were deposited in the ~256 k.y. period between 1016 ka and 760 ka, the ages of the Telken and Page lavas, respectively (Fig. 5). Ice contact landforms of this age are rarely preserved, having only been documented in Antarctica (Brook et al., 1993). If one assumes that each of the large Telken moraine complexes represents the integrated response of the ice cap to a prolonged episode of climate deterioration or a major glaciation, it suggests the intriguing possibility that these six moraines record the response of the Patagonian Ice Cap to forcing at the 41 k.y. obliquity period that dominates this interval in the marine $\delta^{18}O$ record (Fig. 10).

Field relations coupled with $^{40}Ar/^{39}Ar$, K-Ar, and limited cosmogenic surface exposure dating (Kaplan et al., 2004) indicate that the six Deseado and Moreno moraines were deposited during an ~651 k.y. period between 760 ka and 109 ka (Fig. 5). These moraines and outwash are older than the 109 ± 3 ka Cerro Volcán flow by which they are partly buried. This lava flow also buries the outwash gravel plains that are graded to the three Moreno moraines; thus, these deposits are also older than 109 ± 3 ka (Fig. 4C). Three cosmogenic surface exposure ages of boulders on the Moreno I moraine range between 172 ± 18 and 115 ± 11 ka (Kaplan et al., 2004).

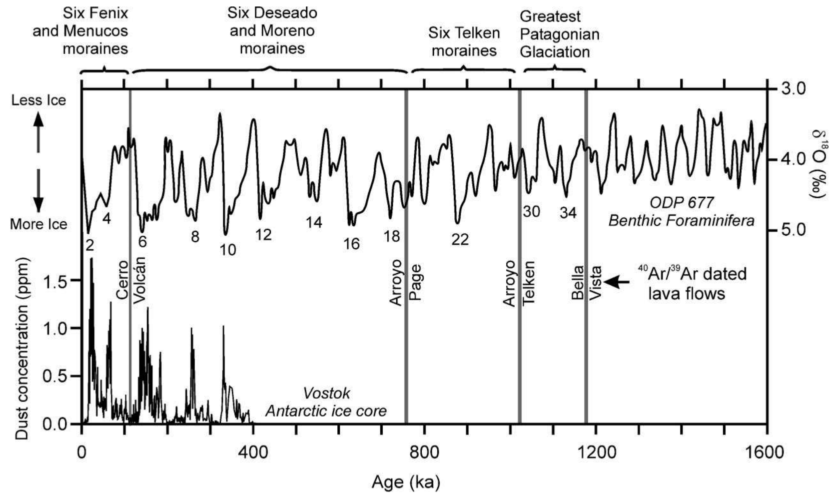


Figure 10. Comparison of moraine record and dated lava flows at Lago Buenos Aires and Río Gallegos with orbitally tuned ^{18}O record from benthic foraminifera in core from equatorial Pacific Ocean Drilling Program site 677 (Shackleton and Hall, 1989). Dust concentration profile from Vostok, Antarctica; ice core is from Petit et al. (1999). Dust has been isotopically fingerprinted to Patagonian source (Basile et al., 1997) with peak concentrations corresponding to windblown loess produced during glacial maxima. Note that no moraines corresponding to ^{18}O stage 4 have been found at Lago Buenos Aires.

It is conceivable that the six preserved moraines correspond to the 100 k.y eccentricity cycle that dominates the marine $\delta^{18}O$ record during the last 750 k.y. (Fig. 10); however, it is more likely that the Deseado and Moreno moraine complexes reflect multiple advances within only two major (100 k.y.) glaciations. The easternmost (ice proximal) deposits of these moraine complexes are partly eroded, suggesting that evidence of additional ice advances has been removed. Moreover, this scenario is consistent with cosmogenic surface exposure ages of the six Fenix moraines (Kaplan et al., 2004) that all date to the LGM. This suggests that the moraine complexes record multiple advances during a single glaciation. If this were the case, it would imply that deposits corresponding to some global ice volume maxima (Fig. 10) are not preserved. Presumably, these would have been overrun and obliterated by younger glacial advances. A third possibility is that the older moraines may not be related to global glaciation (as inferred from the marine $\delta^{18}O$ record). Testing between these alternative hypotheses awaits further detailed cosmogenic surface exposure dating of the Moreno and Deseado moraines.

If the Deseado and Moreno moraine complexes do record fluctuations within a single ~100 k.y. glaciation cycle, it would imply that deposits corresponding to some global ice volume maxima (Fig. 10) are not preserved, presumably having been overrun and obliterated by younger glacial advances. This, in turn, would imply that a climatic signal with significant variability is superimposed on the overall trend of decreasing ice extent during the last 1 m.y., which presumably reflects the tectonic history of the southern Andes and deepening of the glacial valleys discussed earlier.

Three cosmogenic surface exposure ages of between ca. 190 and 120 ka were obtained from the Moreno I moraine (Kaplan et al., companion paper). When combined with the limiting age provided by the overlying 109 ± 3 ka Cerro Volcán flow, the exposure ages are consistent with deposition of the moraine during the penultimate glaciation (marine $\delta^{18}O$ stage 6, ca. 130–190 ka, Fig. 10). These westernmost and morphologically most youthful moraines that predate the Cerro Volcán flow are also truncated by the Canyon of the Río Deseado, which contains outwash gravel from the much younger (23–16 ka; see below) Fenix moraines (Figs. 2 and 3). Thus, the Moreno I moraine clearly was deposited prior to the last local glacial maximum, and both the radioisotopic and cosmogenic dating indicate that it could not have been deposited during $\delta^{18}O$ stage 4 (Fig. 10). Although a single exposure age may be consistent with at least part of the Moreno I moraine dating to interstadial stage 5d, we consider this possibility remote for the previous interglacial. The assumption of zero erosion that leads to the young age is clearly unrealistic and leads to an underestimate of its actual exposure age (Kaplan et al., companion paper). Independent evidence comes from dust particles in the Vostok, Antarctica, ice core (Petit et al., 1999), which have Sr and Nd isotope compositions indicating a Patagonian source (Basile et al., 1997). Maximum dust concentrations in the Vostok core illustrated in Figure 9 occur between the 180 ka and 140 ka levels, whereas levels during marine $\delta^{18}O$ stage 5d remain relatively low (Basile et al., 1997; Petit et al., 1999), suggesting a far colder, drier climate along the southern Andes during $\delta^{18}O$ stage 6 than in stage 5d. A $\delta^{18}O$ stage 6 age, i.e. much older than the Fenix moraines, is also consistent with the large topographic step between the Moreno and Fenix moraine complexes (Fig. 3). Clapperton (1993) reviewed stratigraphic evidence that stage 6 ice marginal deposits may be preserved at several localities throughout Patagonia, but the Moreno moraine group is the first such deposit linked to stage 6 through radioisotopic and cosmogenic surface exposure dating.

Indirect evidence for significant ice advance during marine $\delta^{18}O$ stage 4 (70–60 ka) comes from the dust maxima during $\delta^{18}O$ stages 2, 4, and 6 in the Vostok and Dome C ice cores in east Antarctica (Fig. 10; Basile et al., 1997; Petit et al., 1999). However, no moraine associated with stage 4 is preserved east of Lago Buenos Aires; apparently, geomorphic evidence for this advance was obliterated by ice that advanced during stage 2 and deposited the Fenix V moraine (Figs. 2 and 3). The depositional record preserved at Lago Buenos Aires is therefore consistent with many pertinent observations summarized by Clapperton (1993, p. 375), who wrote: ''There are no sites in the Andes where it can be demonstrated conclusively that a moraine or sedimentary horizon was formed by a glacier advance at ca. 70,000 yr BP.''

New cosmogenic surface exposure ages of moraine boulders on the Fenix I, II, III, and V moraines, combined with the ^{14}C ages of the varved sediment (Kaplan et al., 2004) indicate that at least five ice advances between ca. 23 and 16 ka occurred during the LGM as defined by the marine $\delta^{18}O$ record (Fig. 3). Between 17 and 15 ka the Lago Buenos Aires glacier had retreated such that an ice-dammed proglacial lake was impounded behind the Fenix I moraine and another readvance took place subsequently, depositing the Menucos moraine (Kaplan et al., 2004). These results lend credence to the notion that the glacial advances in this area were more-or-less in phase with global glacial maxima.

Because they formed well beyond the ~40 k.y. age limit of radiocarbon, few deposits corresponding to marine $\delta^{18}O$ stages 6 and 4 have been dated directly by isotopic methods. Those that have give the impression that strong regional influences may be superimposed on global climatic forcing (Gillespie and Molnar, 1995). For example, cosmogenic ^{36}Cl and ^{10}Be dating of Bull Lake and Pinedale moraines in the Wind River Mountains, Wyoming, yielded ages between 130 and 95 ka and 23 and 16 ka, respectively, also suggesting extensive glaciations during stages 6 or 5d and 2, but perhaps not during stage 4 (Phillips et al., 1997; Chadwick et al., 1997). Though 1300 km to the southwest on the east side of the Sierra Nevada, California, ^{36}Cl dating of several moraines suggests that during each of marine $\delta^{18}O$ stages 6, 5d, 4, and 2, glaciers of successively smaller sizes advanced eastward (Phillips et al., 1990). The Wind River record is similar to the Lago Buenos Aires chronology, i.e., stage 6 or 5d moraines are well-preserved, yet there is no evidence of a stage 4 ice advance preserved beyond prominent stage 2 deposits. This suggests that during the last 100 k.y. cycle, the magnitude of glaciations in the northern Rockies and southern Andes was consistent with those of the Northern Hemisphere ice sheets and a dominantly global forcing mechanism. In contrast, the Sierra Nevada record is consistent with smaller glaciers during stage 2 than during stage 4, contrasting not only with the Wind River and Lago Buenos Aires data, but also with the continental ice sheet record and ice volume global proxy from the marine $\delta^{18}O$ record that ice sheets were more extensive and voluminous during stage 2 than during stage 4 (Fig. 10). These observations highlight the need for further isotopic dating of glacial deposits older than stage 2 to delineate regional departures from the global signal and address their underlying causes (Gillespie and Molnar, 1995).

The Lago Buenos Aires Valley may hold further clues to the late glacial history of the southern Andes. For example, no deposits corresponding to the 12.5–11.5 ka Younger Dryas cold period have yet been found within the otherwise well-dated moraine sequence in the Chilean Lake District (Lowell et al., 1995; Denton et al., 1999). Caldenius (1932) recognized some small late glacial moraines within the Cordillera but did not study them in detail. Ninety kilometers west of the Fenix I moraine, far recessed into the Cordillera, a glacier that descended northward down the Río Aviles deposited a moraine that protrudes into Lago General Carrera (as Lago Buenos Aires is known in Chile). This moraine delineates a small, yet significant response of the ice cap that might, through surface exposure dating under way, reveal the timing of an important climate reversal and thereby extend the glacial chronology for this valley from >1 Ma into the Holocene.

CONCLUSIONS

$^{40}Ar/^{39}Ar$ and unspiked K-Ar dating of basaltic lava flows provides new constraints on the timing of Pleistocene glaciations in southern Patagonia. Care must be taken in the choice of material for dating, however, as both matrix glass or whole-rock samples containing xenocrysts may give erroneous ages that exceed the time since eruption. Pure feldspar-rich holocrystalline groundmass—devoid of olivine, pyroxene, and plagioclase phenocrysts—is unlikely to have experienced K mobility or contain inherited Ar and can thus yield precise and accurate ages from basalt as young as 100 ka.

The ages of six basaltic lavas interbedded with moraines and glacial outwash were determined using the $^{40}Ar/^{39}Ar$ incremental-heating method: The 1168 ± 14 ka Estancia Bella Vista flow along Río Gallegos (51.8 °S) underlies till associated with the easternmost extent of Pleistocene ice 120 km from the Cordillera Darwin along the northern side of the Strait of Magellan, whereas 520 km to the north near Lago Buenos Aires, the 1016 ± 10 ka Arroyo Telken flow overlies till 90 km east of the Andean mountain front. These ages confirm the original mapping and correlation of the easternmost till deposits proposed by Caldenius (1932) and constrain Mercer's (1976) ''Greatest Patagonian Glaciation'' to between 1168 and 1016 ka. Even if the deposits are not strictly correlative, the $^{40}Ar/^{39}Ar$ ages indicate that the ice extent in southern Patagonia 1 Ma was significantly larger than during the LGM and during the last several glaciations. The difference may reflect the growth of the ice cap in response to Pliocene to Quaternary uplift as a result of rapid plate convergence and heating of the lithosphere beneath the southern Andes via subduction of the Chile rise spreading center. We suggest that uplift increased the area of ice accumulation after 2 Ma, but subsequent vigorous glacial erosion and deepening of valleys reduced the accumulation area, thereby generally diminishing the extent of ice during later advances.

Our mapping indicates that at least 19 terminal moraines (or remnants of ice-contact deposits) are preserved east of Lago Buenos Aires. Six of these moraines were deposited between eruption of the 1016 ± 10 ka Arroyo Telken basalt flow and the 760 ± 14 ka Arroyo Page flow; six more westerly moraines, the Deseado moraines, are younger than Arroyo Page flow, but pre-date the 109 ± 3 ka Cerro Volcán basalt flow. The six Fenix moraines immediately east of Lago Buenos Aires were deposited during the LGM between 23 and 16 ka on the basis of cosmogenic surface exposure ages of boulders and ^{14}C dating of lacustrine sediment (Kaplan et al., 2004). The Moreno moraine group pre-dates the 23 ka Fenix V moraine, is overlain by the 109 ka Cerro Volcán flow, and yields preliminary cosmogenic surface exposure ages of ca. 190–120 ka. Thus, one or more of these moraines very likely dates to the interval of marine $\delta^{18}O$ stage 6. Consistent with previous studies throughout Patagonia, no moraines corresponding to marine $\delta^{18}O$ stage 4 are preserved east of Lago Buenos Aires. We surmise that the stage 4 ice advance suggested by the Antarctic ice core dust record was less extensive than that of the last local glacial maximum ca. 23 ka. Because this pattern is consistent with the sizes of the polar ice sheets inferred from the global marine $\delta^{18}O$ record, we suggest that generally during the last 100 k.y. glacial cycle, a global rather than regional or tectonic forcing mechanism was the dominant factor controlling the magnitude of glaciations in the southern Andes.

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REFERENCES CITED

Ackert, R.P., Singer, B.S., Guillou, H., Kaplan, M.R., and Kurz, M.D., 2003, Long-term cosmogenic ^{3}He production rates from $^{40}Ar/^{39}Ar$ and K-Ar dated Patagonian lava flows at 47 °S: Earth and Planetary Science Letters, v. 210, p. 119–136.

Baker, P.E., Rea, W.J., Skarmeta, J., Caminos, R., and Rex, D.C., 1981, Igneous history of the Andean Cordillera and Patagonian plateau around latitude 46 °S: Philosophical Transactions of the Royal Society of London, v. 303, p. 105–140.

Bar-Matthews, M., Ayalon, A., and Wasserburg, G.J., 1999, The eastern Mediterranean paleoclimate as a reflection of regional events; Soreq Cave, Israel: Earth and Planetary Science Letters, v. 166, p. 85–95.

Basile, I., Grousset, F.E., Revel, M., Petit, J.R., Biscaye, P.E., and Barkov, N.I., 1997, Patagonian origin of glacial dust deposited in East Antarctica (Vostok and Dome C) during glacial stages 2, 4, and 6: Earth and Planetary Science Letters, v. 146, p. 573–589.

Blunier, T., and Brook, E.J., 2001, Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period: Science, v. 291, p. 109–112.

Blunier, T., Chappellaz, J., Schwander, J., Dallenbach, A., Stauffer, B., Stocker, T.F., Raynaud, D., Jouzel, J., Clausen, J.B., Hammer, C.U., and Johnson, S.J., 1998, Asynchrony of Antarctic and Greenland climate change during the last glacial period: Nature, v. 394, p. 739–743.

Bobst, A.L., Lowenstein, T.K., Jordan, J.E., Godfrey, L.V., Ku, T.L., and Luo, S., 2001, A 106 ka paleoclimate record from drill core of the Salar de Atacama, northern Chile: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 173, p. 21–41.

Brook, E.J., Kurz, M.D., Ackert, R.P., Denton, G.H., Brown, E.T., Raisbeck, G.M., and Yiou, F., 1993, Chronology of Taylor Glacier advances in Arena Valley, Antarctica, using in situ cosmogenic ^{3}He and ^{10}Be: Quaternary Research, v. 39, p. 11–23.

Caldenius, C.G., 1932, Las glaciaciones Cuaternarias en la Patagonia and Tierra del Fuego: Geografiska Annaler, v. 14, p. 1–164.

Cassignol, C., and Gillot, P.Y., 1982, Range and effectiveness of unspiked potassium-argon dating, *in* Odin, G.S., ed., Numerical dating in stratigraphy: New York, Wiley, p. 159–179.

Cerling, T.E., Brown, F.H., and Bowman, J.R., 1985, Low-temperature alteration of volcanic glass: Hydration, Na, K, ^{18}O, and Ar mobility: Chemical Geology, v. 52, p. 281–293.

Chadwick, O.A., Hall, R.D., and Phillips, F.M., 1997, Chronology of Pleistocene glacial advances in the central Rocky Mountains: Geological Society of America Bulletin, v. 109, p. 1443–1452.

Charbit, S., Guillou, H., and Turpin, L., 1998, Cross calibration of K-Ar standard minerals using an unspiked Ar measurements technique: Chemical Geology, v. 150, p. 147.

Clapperton, C.M., 1990, Quaternary glaciation in the Southern Hemisphere: An overview: Quaternary Science Reviews, v. 9, p. 299–304.

Clapperton, C.M., 1993, Quaternary geology and geomorphology of South America: New York, Elsevier, 779 p.

Dalrymple, G.B., 1964, Potassium-argon dates of three Pleistocene interglacial basalt flows from the Sierra Nevada, California: Geological Society of America Bulletin, v. 75, p. 753–758.

Denton, G.H., and Hughes, T.J., 1983, Milankovitch theory of ice ages: Hypothesis of ice-sheet linkage between regional insolation and global climate: Quaternary Research, v. 20, p. 124–144.

Denton, G.H., Heusser, C.J., Lowell, T.V., Moreno, P.I., Andersen, B.G., Heusser, L.E., Schluchter, C., and Marchant, D.R., 1999, Interhemispheric linkage of paleoclimate during the last glaciation: Geografiska Annaler, v. 81, p. 107–153.

Duffield, W.A., and Darymple, G.B., 1990, The Taylor Creek Rhyolite of New Mexico: A rapidly emplaced field of lava domes and flows: Bulletin of Volcanology, v. 52, p. 475–487.

Feruglio, E., 1950, Descripción geológica de la Patagonia: Buenos Aires, Dirección General Yaciminetos Petroliferos Fiscales, v. 3.

Fidalgo, F., and Riggi, J.C., 1965, Los Rodados Patagónicos de la Meseta del Guenguel y alrededores (Santa Cruz): Revista de la Asociación Geológica Argentina, v. 20, p. 273–325.

Fleck, R.J., Mercer, J.H., Nairn, A.E.M., and Peterson, D.M., 1972, Chronology of late Pliocene and early Pleistocene glacial and magnetic events in southern Argentina: Earth and Planetary Science Letters, v. 16, p. 15–22.

Gillespie, A., and Molnar, P., 1995, Asynchronous maximum advances of mountain and continental glaciers: Reviews of Geophysics, v. 33, p. 311–364.

Gillespie, A., Huneke, J.C., and Wasserburg, G.J., 1984, Eruption age of a ~100,000-year-old basalt from $^{40}Ar/^{39}Ar$ analysis of partially degassed xenoliths: Journal of Geophysical Research, v. 89, p. 1003–1048.

Gorring, M.L., Kay, S.M., Zeitler, P.K., Ramos, V.A., Rubiolo, D., Fernandez, M.I., and Panza, J.L., 1997, Neogene plateau lavas: Continental magmas associated with ridge collision at the Chile triple junction: Tectonics, v. 16, p. 1–17.

Gorring, M., Singer, B., Gowers, J., and Kay, S.M., 2003, Plio-Pleistocene basalts from the Meseta del Lago Buenos Aires, Argentina: Evidence for asthenosphere-lithosphere interactions during slab-window magmatism: Chemical Geology, v. 193, p. 215–235.

Guillou, H., Garcia, M.O., and Turpin, L., 1997, Unspiked K-Ar dating of young volcanic rocks from Loihi and Pitcairn hot spot seamounts: Journal of Volcanology and Geothermal Research, v. 78, p. 239–249.

Guillou, H., Carracedob, J.C., and Day, S.J., 1998, Dating of the upper Pleistocene–Holocene volcanic activity of La Palma using the unspiked K–Ar technique: Journal of Volcanology and Geothermal Research, v. 86, p. 137–149.

Heizler, M.T., Perry, F.V., Crowe, B.M., Peters, L., and Appelt, R., 1999, The age of Lathrop Wells volcanic center: An $^{40}Ar/^{39}Ar$ dating investigation: Journal of Geophysical Research, v. 104, p. 767–804.

Heusser, C.J., 1989, Southern Westerlies during the last glacial maximum: Quaternary Research, v. 31, p. 423–425.

Hulton, N.R.J., and Sugden, D.E., 1995, Modeling mass balance on former maritime ice caps: A Patagonian example: Annals of Glaciology, v. 21, p. 304–310.

Hulton, N.R.J., and Sugden, D.E., 1997, Dynamics of mountain ice caps during glacial cycles: The case of Patagonia: Annals of Glaciology, v. 24, p. 81–90.

Hulton, N., Sugden, D., Payne, A., and Clapperton, C., 1994, Glacier modeling and the climate of Patagonia during the Last Glacial Maximum: Quaternary Research, v. 42, p. 1–19.

Johnson, R.G., 1980, Brunhes-Matuyama magnetic reversal dated at 790,000 yr B.P., by marine astronomical correlations: Quaternary Research, v. 17, p. 135–147.

Kaplan, M.R., Ackert, R.P., Jr., Singer, B.S., Douglass, D.C., and Kurz, M.D., 2004, Cosmogenic nuclide chronology of millennial-scale glacial advances during O-isotope stage 2 in Patagonia: Geological Society of America Bulletin, v. 116, p. 308–321.

Karner, D.R., and Renne, P.R., 1998, $^{40}Ar/^{39}Ar$ geochronology of Roman volcanic province tephra in the Tiber River Valley: Age calibration of middle Pleistocene sea-level changes: Geological Society of America Bulletin, v. 110, p. 740–747.

Ku, T.-L., Luo, S., Lowenstein, T.K., Li, J., and Spencer, R.J., 1998, U-series chronology of lacustrine deposits in Death Valley, California: Quaternary Research, v. 50, p. 261–275.

Lanphere, M.A., and Dalrymple, G.B., 2000, First-principles calibration of ^{38}Ar tracers: Implications for the ages of $^{40}Ar/^{39}Ar$ fluence monitors: U.S. Geological Survey Professional Paper 1621, 10. p.

Ludwig, K.R., Simmons, K.R., Szabo, B.J., Winograd, I., Landwehr-Jurate, M., Riggs, A.C., and Hoffman, R.J., 1992, Mass-spectrometric ^{230}Th- ^{234}U-^{238}U dating of the Devils Hole calcite vein: Science, v. 258, p. 284–287.

Lea, D.W., 2001, Ice ages, the California Current, and Devils Hole: Science, v. 293, p. 59–60.
Lowell, T.V., Heusser, C.J., Andersen, B.G., Moreno, P.I., Hauser, A., Heusser, L.E., Schluchter, C., Marchant, D.R., and Denton, G.H., 1995, Interhemispheric correlation of late Pleistocene glacial events: Science, v. 269, p. 1541–1549.
MacGregor, K.R., Anderson, R.S., Anderson, S.P., and Waddington, E.D., 2000, Numerical simulations of glacial-valley longitudinal profile evolution: Geology, v. 28, p. 1031–1034.
Malagnino, E.C., 1995, The discovery of the oldest extra-Andean glaciation in the Lago Buenos Aires Basin, Argentina: Quaternary of South America and Antartica Peninsula, v. 9, p. 69–83.
Markgraf, V., 1989, Reply to C.J., Heusser's ''Southern westerlies during the last glacial maximum'': Quaternary Research, v. 31, p. 426–432.
Markgraf, V., Dodson, J.R., Kershaw, A.P., McGone, M.S., and Niholls, N., 1992, Evolution of Late Pleistocene climates in the circum-south Pacific land areas: Climate Dynamics, v. 6, p. 193–211.
McCulloch, R.D., Bentley, M.J., Purves, R.S., Hulton, N.R.J., Sugden, D.E., and Clapperton, C.M., 2000, Climatic inferences from glacial and palaeoecological evidence at the last glacial termination, southern South America: Journal of Quaternary Science, v. 15, p. 409–417.
Meglioli, A., 1992, Glacial geology and chronology of southernmost Patagonia and Tierra del Fuego, Argentina and Chile [Ph.D. thesis]: Bethlehem, Pennsylvania, Lehigh University, 298 p.
Mercer, J.H., 1969, Glaciation in southern Argentina more than two million years ago: Science, v. 164, p. 823–825.
Mercer, J.H., 1976, Glacial history of southernmost South America: Quaternary Research, v. 6, p. 125–166.
Mercer, J.H., 1982, Holocene glacier variations in southern South America: Striae, v. 18, p. 35–40.
Mercer, J.H., 1983, Cenozoic glaciation in the Southern Hemisphere: Annual Reviews of Earth and Planetary Science, v. 11, p. 99–132.
Mercer, J.H., and Sutter, J.F., 1982, Late Miocene-earliest Pliocene glaciation in southern Argentina: Implications for global ice sheet history: Paleogeography, Paleoclimatology, Paleoecology, v. 38, p. 185–206.
Mörner, N.-A., and Sylwan, C., 1989, Magnetostratigraphy of the Patagonian moraine sequence at Lago Buenos Aires: Journal of South American Earth Sciences, v. 2, p. 385–389.
Murdie, R.E., and Russo, R.M., 2000, Variations in seismic attenuation in the Chile Ridge subduction region, southern Chile [abs.]: Eos (Transactions, American Geophysical Union), v. 81, p. F911.
Oerlemans, J., 1984, Numerical experiments on large-scale glacial erosion: Zeitschrift für Gletscherkunde und Glazialgeologie, v. 20, p. 107–126.
Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delay, G., 1999, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica: Nature, v. 399, p. 429–436.
Phillips, F.M., Zreda, M.G., Smith, S.S., Elmore, D., Kubik, P.W., and Sharma, P., 1990, Cosmogenic chlorine-36 chronology for glacial deposits at Bloody Canyon, eastern Sierra Nevada: Science, v. 248, p. 1529–1532.
Phillips, F.M., Zreda, M.G., Gosse, J.C., Klein, J., Evenson, E.B., Hall, R.D., Chadwick, O.A., and Sharma, P., 1997, Cosmogenic ^{36}Cl and ^{10}Be ages of Quaternary glacial and fluvial deposits of the Wind River Range, Wyoming: Geological Society of America Bulletin, v. 109, p. 1453–1463.
Porter, S.C., 1981, Pleistocene glaciation in the Southern Lake District of Chile: Quaternary Research, v. 16, p. 263–292.
Rabassa, J., and Clapperton, C.M., 1990, Quaternary glaciations in the southern Andes: Quaternary Science Reviews, v. 9, p. 153–174.
Ramos, V.A., and Kay, S.M., 1992, Southern Patagonian plateau basalts and deformation: Backarc testimony of ridge collisions: Tectonophysics, v. 205, p. 262–282.
Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., and DePaolo, D.J., 1998, Intercalibration of standards, absolute ages and uncertainties in ^{40}Ar/^{39}Ar dating: Chemical Geology, v. 145, p. 117–152.
Shackleton, N.J., and Hall, M.A., 1989, Stable isotope history of the Pleistocene at ODP Site 677: Scientific Results, Proceedings of the Ocean Drilling Progam, v. 111, p. 295–316.
Shackleton, N.J., Berger, A., and Peltier, W.R., 1990, An alternative astronomical calibration of the lower Pleistocene timescale based on ODP site 677: Transactions of the Royal Society of Edinburgh, Earth Sciences, v. 81, p. 251–261.
Singer, B.S., and Pringle, M.S., 1996, Age and duration of the Matuyama-Brunhes geomagnetic polarity reversal from ^{40}Ar/^{39}Ar incremental heating analyses of lavas: Earth and Planetary Science Letters, v. 139, p. 47–61.
Singer, B.S., Ackert, R.P., Kurz, M.D., Guillou, H., and Ton That, T., 1998a, Chronology of Pleistocene glaciations in Patagonia: A ^{3}He, ^{40}Ar/^{39}Ar, & K-Ar study of lavas and moraines at Lago Buenos Aires, 46 °S, Argentina: Geological Society of America Abstracts with Program, v. 30, no. 7, p. A299.
Singer, B.S., Wijbrans, J., Nelson, S.T., Pringle, M.S., Feeley, T.C., Dungan, M.A., 1998b, Inherited argon in a Pleistocene andesite lava: ^{40}Ar/^{39}Ar incremental-heating and laser fusion analyses of plagioclase: Geology, v. 26, p. 427–430.
Singer, B., Hildreth, W., and Vincze, Y., 2000, ^{40}Ar/^{39}Ar evidence for early deglaciation of the central Chilean Andes: Geophysical Research Letters, v. 27, p. 1663–1666.
Singer, B.S., Relle, M.R., Hoffman, K.A., Battle, A., Guillou, H., Laj, C., and Carracedo, J.C., 2002, Ar/Ar ages of transitionally magnetized lavas on La Palma, Canary Islands, and the Geomagnetic Instability Timescale: Journal of Geophysical Research, v. 107, p. 2307, doi:10.1029/2001JB001613.
Steig, E.J., and Alley, R.B., 2002, Phase relationships between Antarctic and Greenland climate records: Annals of Glaciology, v. 35, p. 451–456.
Steig, E.J., Brook, E.J., White, J.W.C., Sucher, C.M., Bender, M.L., Lehman, S.J., Morse, D.L., Waddington, E.D., and Clow, G.D., 1998, Synchronous climate changes in Antarctica and the North Atlantic: Science, v. 282, p. 92–95.
Steiger, R.H., and Jäger, E., 1977, Subcomission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 5, p. 320–324.
Sylwan, C.A., 1989, Paleomagnetism, paleoclimate, and chronology of late Cenozoic deposits in southern Argentina [Ph.D. thesis]: Sweden, Stockholm University, 110 p.
Taylor, J.R., 1982, An introduction to error analysis: Mill Valley, California, University Science Books, 270 p.
Thomson, S.N., 2002, Late Cenozoic geomorphic and tectonic evolution of the Patagonian Andes between latitudes 42 °S and 46 °S: An appraisal based on fission-track results from the transpresional Liquiñe-Ofqui fault zone: Geological Society of America Bulletin, v. 114, p. 1159–173.
Thomson, S.N., Hervé, F., and Stöckhert, B., 2001, Mesozoic-Cenozoic denudation history of the Patagonian Andes (southern Chile) and its correlation to different subduction processes: Tectonics, v. 20, p. 693–711.
Ton-That, T., Singer, B., Mörner, N., and Rabassa, J., 1999, Datación de lavas basalticas por ^{40}Ar/^{39}Ar geología glacial de la region del lago Buenos Aires, provincia de Santa Cruz, Argentina: Revisita de la Asociación Geológica Argentina, v. 54, p. 333–352.
Turner, G., and Cadogan, P.H., 1974, Possible effects of ^{39}Ar recoil in ^{40}Ar-^{39}Ar dating: Geochimica Cosmochimnica Acata, Supplement 5, Proceedings of the Fifth Lunar Science Conference, p. 1601–1615.
Turrin, B.D., Donnelly-Nolan, J.M., and Hearn, B.C., 1994, ^{40}Ar/^{39}Ar ages from the rhyolite of Alder Creek, California: Age of the Cobb Mountain Normal-Polarity Subchron revisited: Geology, v. 22, p. 251–254.
Wijbrans, J.R., Pringle, M.S., Koppers, A.A.P., and Scheveers, R., 1995, Argon geochronology of small samples using the Vulkaan argon laserprobe: Proceedings of the Dutch Academy of Sciences, v. 98, p. 185–218.
York, D., 1969, Least squares fitting of a straight line with correlated errors: Earth and Planetary Science Letters, v. 5, p. 320–332.

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