$^{40}Ar/^{39}Ar$ Chronology of Late Pliocene and Early Pleistocene Geomagnetic and Glacial Events in Southern Argentina

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K-Ar dating and paleomagnetic directions from the lava sequence atop Cerro del Fraile, Argentina, contributed to the nascent Geomagnetic Polarity Time Scale (GPTS), recording the Réunion event, and the Olduvai and Jaramillo subchrons [*Fleck et al.*, 1972]. New stratigraphy, paleomagnetic analyses, $^{40}Ar/^{39}Ar$ incremental heating ages, and unspiked K-Ar dating of 10 lava flows on Cerro del Fraile place these eruptions between 2.181±0.097 and 1.073±0.036 Ma and enhance this unique record, which includes seven tills interbedded with the lavas. The Réunion event is recorded by three lavas with transitional, normal, and reversed polarity that yielded identical $^{40}Ar/^{39}Ar$ isochron ages and a weighted mean age of 2.136±0.019 Ma. When combined with $^{40}Ar/^{39}Ar$ ages from lavas on Réunion Island and a normal tuff in the Massif Central, the age of the Réunion event is 2.137±0.016 Ma and is older by ~50 kyr than the 2.086±0.016 Ma Huckleberry Ridge event. The onset and termination of the Olduvai are similarly constrained to 1.922±0.066 Ma and 1.775±0.015 Ma, whereas the onset of the Jaramillo occurred 1.069±0.011 Ma. A discordant age spectrum from another transitional lava gave a total fusion age of 1.61 Ma and an unspiked K-Ar age of 1.43 Ma. It is uncertain whether this corresponds to the Gilsa, Gardar, Stage 54, or Sangiran events, or represents an unrecognized period of geomagnetic instability. Deposition of till on the piedmont surface prior to 2.186 Ma and six subsequent tills between 2.186 Ma and ~1.073 Ma mark frequent glaciations of southern South America during marine oxygen isotope stages 82 to 48.

1. INTRODUCTION

Astrochronologic dating of sediments coupled with precise $^{40}Ar/^{39}Ar$ ages of key lava and tuff sequences triggered a major revision of the Geomagnetic Polarity Time Scale (GPTS) over the past dozen years [*Shackleton et al.*, 1990; *Hilgen*, 1991; *Cande and Kent*, 1995; *Berggren et al.*, 1995]. In addition to improving global stratigraphic correlation and validating space geodesy measurements of plate motions [*e.g.*, *Baksi*, 1994], an accurate and precise chronology of geomagnetic reversals and short-lived events or subchrons is critical to understanding how the Earth's magnetic field originates and is modulated within the core and lowermost mantle [*Gubbins*, 1999; *Glatzmaier et al.*, 1999; *Singer et al.*, 2002; *Hoffman and Singer*, this volume]. Yet, the existence and precise

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timing of several reversals or aborted reversal attempts, recorded as short-lived polarity events, including for example the Réunion event, are still disputed [*Kidane et al.*, 1999; *Baksi and Hoffman* 2000; *Baksi*, 2001; *Lanphere et al.*, 2002]. This reflects obstacles to magnetostratigraphic correlation among critical sedimentary sequences, difficulty in assigning uncertainties to astrochronologic ages, a limited number of salient volcanic materials available for study, and different K-Ar and $^{40}Ar/^{39}Ar$ approaches that have been used in various laboratories to date these volcanic rocks.

More than three decades ago, the Plio-Pleistocene lava sequence at Cerro del Fraile, Argentina yielded important confirmation of the fledgling GPTS, specifically revealing in a single, continuous, radioisotopically dated section a record of the three normal polarity events that occurred during the Matuyama reversed chron [*Fleck et al.*, 1972]. The information came from seven successive basaltic lava flows on which Fleck et al. [1972] obtained replicate K-Ar ages and paleomagnetic directions from hand specimens that were oriented in the field. We revisited this classic lava flow sequence that is interbedded with several glacial tills with goals of assessing in further detail its stratigraphy, and revising the chronology of geomagnetic and glacial events recorded through modern $^{40}Ar/^{39}Ar$ dating and paleomagnetic analysis.

We report the results of new stratigraphy, paleomagnetic analyses, $^{40}Ar/^{39}Ar$ incremental heating experiments, and unspiked K-Ar dating of a sequence of 10 lava flows from Cerro del Fraile. In light of these data, the timing of the Réunion event, the Olduvai subchron, and the Jaramillo subchron that are recorded in these lavas are critically examined and an initial Geomagnetic Instability Time Scale [GITS; *Singer et al.*, 2002] for the interval between 2.14 and 0.79 Ma is presented. Moreover, the temporal constraints provided by the combination of magnetic and radioisotopic data provide a unique opportunity to further quantify the number and timing of major glaciations of the southern Andes and to comment briefly on the pace of Pleistocene landscape evolution.

2. GEOLOGIC SETTING, STRATIGRAPHY, AND SAMPLING

Cerro del Fraile (50.5° S, 72.7° W) is an 8 km^2 mesa located 40 km east of the Andean Cordillera and 10 km south of Lago Argentino (Figure 1) that comprises Cretaceous sediment

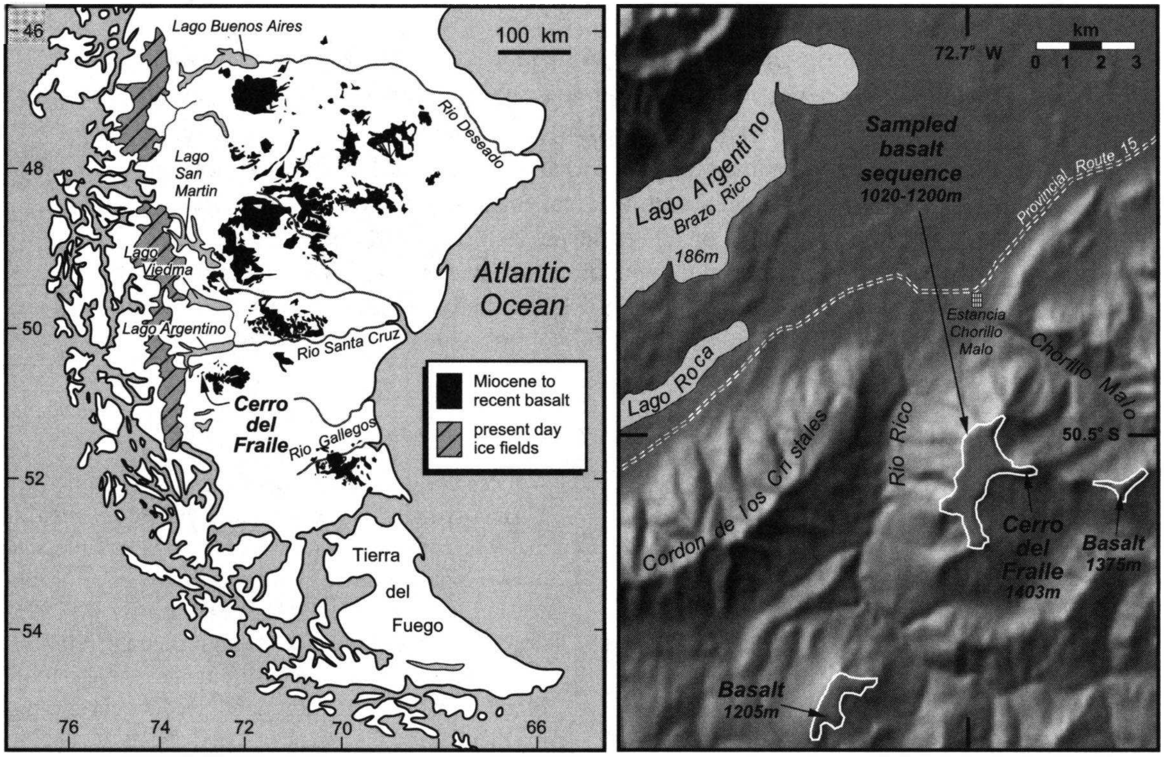

Figure 1. Location of Cerro del Fraile in southwestern Santa Cruz province, Argentina. The three mesas outlined in white on the shadowed digital elevation model comprise Plio-Pleistocene basalt flows or eroded volcanic necks that overlie Cretaceous marine sediment. Relief between Lago Argentino and the top of Cerro del Fraile is 1200 m. Access to the sampled section is by foot from Estancia Chorillo Malo on the gravel provincial route 15.

unconformably capped by Plio-Pleistocene basaltic lava flows [*Feruglio*, 1944; *Mercer*, 1969; *Fleck et al.*, 1972]. Where sampled by Mercer [1969] and Fleck et al. [1972] these lavas crop out between 1020 and 1200 masl and are interbedded with a series of glacial tills and fluvial sediments (Figure 2). Feruglio [1944] and Fleck et al. [1972] noted that the stratigraphy of the Plio-Pleistocene units varies along the northwestern exposure with some flows pinching out or thickening laterally. The section sampled by Mercer and described by Fleck et al. [1972] includes 8 lava flows which they numbered sequentially A–H and 6 interbedded glacial tills. Contact relations between the lava flows and tills, including baked soil atop the thickest tills, cobbles and fluvial sediment in some of the tills, and lack of ice-contact textures in any of the basalt flows, led Fleck et al. [1972] to conclude that glaciers advanced eastward at least six times across Cerro del Fraile. The ensuing tills, coarse outwash sediment, and soil were episodically buried and baked by the thick basaltic flows. We sampled an adjacent section through the exposure of Plio-Pleistocene units in 1996 and 1998 and found a vertical sequence of lava flows that we labeled 1 through 10 which are interbedded with at least 7 tills.

The stratigraphic sequence and relationship of the lavas analyzed by Fleck et al. [1972] to those which we have measured are illustrated in Figure 2. The key differences are that we identified and sampled a 2–3 m thick, discontinuous flow between Fleck et al.'s Flows E and F, and a 6–8 m thick, columnar-jointed and relatively continuous flow, overlain by a till between Fleck et al.'s Flows F and G (Figure 2). The latter till, which is 3–5 m thick, underlies our Flow 9 (Fleck et al.'s Flow G); however, we determined that the highest till, comprising a sparse lag of striated cobbles and granitic boulders up to 2 m in diameter, covers only the western portion of the mesa and our Flow 9 (Fleck et al.'s G; Figure 2). We did not find this highest (7th) till in the sequence underlying our Flow 10 (Fleck et al.'s H), which covers only the eastern third of the mesa (Figures 1 and 2).

Based on replicate analyses of whole-rock samples from 7 of the lavas, Fleck et al. [1972] obtained conventional K-Ar ages that range from 2.12±0.07 to 1.05±0.06 Ma when recalculated using the decay constants of Steiger and Jäger [1977] and weighting the ages by the inverse-variance [*Taylor*, 1982]. Excepting the lowermost flow, from which two of four experiments yielded a consistent age of 2.05 ± 0.04 Ma, the K-Ar ages agree with the stratigraphy (Figure 2). Progressive four-step alternating field (AF) demagnetization procedures used by Fleck et al. [1972] on 3–4 cores from oriented hand specimens of 5 of the same 7 flows yielded either normal or reversed magnetization directions (Figure 2). Flow B yielded an intermediate direction with a Virtual Geomagnetic Pole (VGP) of 32° N, 307°W [*Fleck et al.*, 1972; Figure 2]. For paleomagnetic meas-

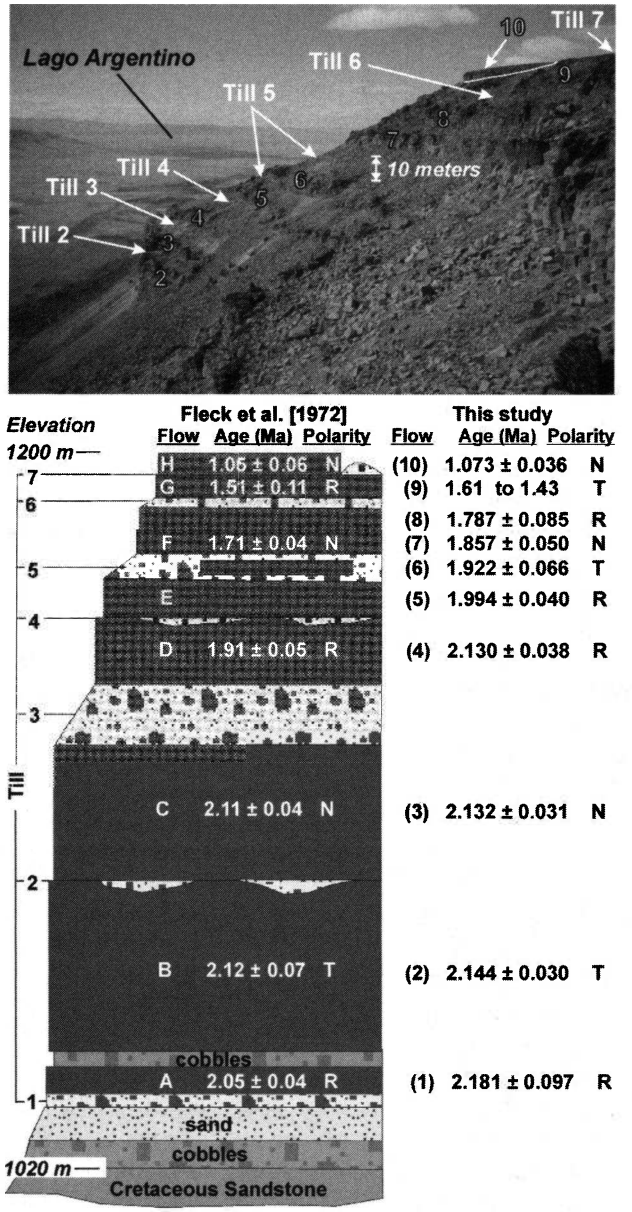

Figure 2. Stratigraphy of the upper 200 m on the western edge of Cerro del Fraile. Top: View north along the mesa. Basaltic lava flows are numbered 2–10. Six glacial tills are interbedded in this portion of the section. The oldest till and the overlying basalt flow number 1 are not visible. The large main body of Lago Argentino is visible 30 km in the distance to the northeast 1000 m below these lavas. Bottom: summary of the basalt and till sequence. Flow sequence A–H of Fleck et al. [1972] is shown with mean K-Ar ages updated using modern decay constants and with errors of replicate analyses weighted by the inverse of their variance, and the measured paleomagnetic directions. $^{40}Ar/^{39}Ar$ isochron and unspiked K-Ar ages for the 10 flows analyzed in this study are listed along with their paleomagnetic directions (N = normal polarity; R = reversed; T = transitional).

urements, we collected up to 10 cores over a several m^2 area on 8 of the 10 lava flows using a gasoline-powered, water-cooled diamond coring drill. These 2.5 cm diameter cores were oriented using magnetic and sun compasses. Because we ran out of water and sunlight at the end of a single day of drilling, cores from Flows 6 and 10 were drilled later from 50x20x30 cm oriented blocks. Samples for geochronology were chiseled from the outcrops at the same locations spanned by the drilling.

3. $^{40}Ar/^{39}Ar$ AND K-Ar WORK

3.1. Geochronologic Standards and the GPTS

The $^{40}Ar/^{39}Ar$ method requires that the age of a sample be calculated relative to a mineral standard which has been previously dated, usually by conventional K-Ar techniques. This has occasionally led to confusion when comparing ages determined in different laboratories and to erroneous conclusions regarding the timing of geomagnetic events [*e.g., Baksi,* 2001; *Lanphere et al.*, 2002]. The monitor minerals used here were sanidines from the Taylor Creek (TCs) and Alder Creek (ACs) rhyolites. The age of TCs was determined to be 27.92 Ma relative to the USGS 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 at 1.186 Ma relative to sanidine from the Fish Canyon tuff (FCs) with an age of 27.84 Ma taken from Cebula et al. [1986]. However, in light of recent 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±0.16 Ma for TCs and 1.194±0.007 Ma for ACs [*Renne et al.*, 1998], though a consensus regarding the age of the GA-1550 standard has not yet been reached [*Lanphere and Dalrymple*, 2000; *Lanphere et al.*, 2002].

Our decision to use the intercalibrated standard ages of Renne et al. [1998] reflects, in part, their consistency with astrochronologically determined ages of several magnetic chron boundaries. Adopting an age of 27.92 Ma for the TCs standard would shift the ages reported here 1.5% younger. Conversion of our ages to make them consistent with yet other values for standard ages [*e.g., Baksi et al.*, 1996; *Villeneuve et al.*, 2000] can be done simply using the equation in Dalrymple et al. [1993]. Via the intercalibration of Renne et al. [1998], the ages reported here correspond to an age of 28.02 Ma for the Fish Canyon sanidine (FCs) standard, that yields ages 0.6% older than the value of 27.84 Ma which was adopted by Cande and Kent [1995] and Berggren et al. [1995] to revise portions of the GPTS. The significance of the values chosen for standard minerals will become apparent below where our results are compared against published radioisotopic age determinations that bear on the timing of the Réunion event, Olduvai subchron, and other geomagnetic events.

In this paper, we calculate $^{40}Ar/^{39}Ar$ and K-Ar ages using the decay constants of Steiger and Jäger [1977] and report ±2F uncertainties that include analytical and inter-calibration terms. This is appropriate for comparing our results to $^{40}Ar/^{39}Ar$ ages from other studies, provided all ages are calculated relative to a common standard value as described above. An additional source of systematic error arises from uncertainty in the ^{40}K decay constant [*Renne et al.*, 1998], that contributes between 0.1 and 0.4% of uncertainty to each of our age determinations. Adding this latter error component is appropriate should our ages be com pared directly independent chronometers including U-Pb zircon or astrochronologic ages [*Renne et al.*, 1998].

3.2. The $^{40}Ar/^{39}Ar$ Methods

$^{40}Ar/^{39}Ar$ dating of the basaltic lavas followed the procedures outlined in Singer et al. [2004]. To avoid xenocrystic contamination, 125–315 μm holocrystalline groundmass separates of 50 or 100 mg each were prepared by crushing, sieving, magnetic sorting, and hand-picking under a binocular microscope. These were wrapped into 99.99% Cu foil packets and along with several packets of TCs or ACs standard grains were loaded into 5 mm i.d. quartz vials that were evacuated and sealed. Samples were irradiated for 1 or 2 hours at the Oregon State University Triga reactor in the Cadmium-Lined In-Core Irradiation Tube (CLICIT). 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 $[^{40}Ar/^{39}Ar]_K = 0.00086$; $[^{36}Ar/^{37}Ar]_{Ca} = 0.000264$; $[^{39}Ar/^{37}Ar]_{Ca} = 0.000673$. Incremental degassing using a resistance furnace, temperature measurement, gas clean-up, mass spectrometry, mass discrimination and blank corrections, and standard measurements using a CO_2 laser were similar to Singer et al. [2004].

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] and uncertainties multiplied by the square root of the MSWD where it is >1. The uncertainty in J, the neutron fluence parameter, was 0.5% to 0.6% (2σ); this uncertainty was also propagated into the final plateau and isochron ages for each analysis, yet it contributes less than 0.1% to the total uncertainty in these age determinations. For comparing to astro-chronologic ages, fully propagated uncertainties including the decay constant term are reported alongside the analytical uncertainties in Table 1.

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

Table 1. Summary of $^{40}Ar/^{39}Ar$ incremental heating experiments on basalt groundmass samples, Cerro del Fraile, Argentina

Flow #	Sample ID	Experiment	wt. mg	K/Ca total	Total fusion Age (Ma) ± 2σ	Increments used, °C	Age Spectrum ^{39}Ar %	Age Spectrum Age (Ma) ± 2σ	Age Spectrum MSWD	Isochron Analysis N	Isochron Analysis SUMS (N-2)	Isochron Analysis $^{40}Ar/^{36}Ar_i$ ± 2σ	Isochron Analysis Age (Ma) ± 2σ[d]	± 2σ[e]	Mag
10	CF-09	98G1342[a]	50	1.000	1.021 ± 0.096	830-1080	48.2	1.078 ± 0.015	0.72	4/11	1.03	297.0 ± 10.0	1.073 ± 0.036	± 0.041	N
9	CF-08	97GE629[a]	50	1.313	1.612 ± 0.060		*Discordant spectrum, use total fusion and unspiked K-Ar age as limits*								T
8	CF-07	96GE615[a]	50	0.362	1.778 ± 0.018	750-920	58.4	1.775 ± 0.020	0.68	7/16	0.82	294.0 ± 12.0	1.787 ± 0.085	± 0.090	R
7	CF-06	96GE614[a]	50	0.298	1.817 ± 0.015	675-925	72.1	1.834 ± 0.010	1.19	9/14	1.20	291.5 ± 8.4	1.857 ± 0.050	± 0.059	N
6	CF-11	UW10E99[b]	50	0.278	1.946 ± 0.238	775-920	64.6	2.052 ± 0.044	0.63	5/12	0.45	303.7 ± 3.6	1.922 ± 0.066	± 0.074	T
5	CF-05	96GE613[a]	50	0.494	1.973 ± 0.015	600-950	96.1	1.993 ± 0.010	2.40[c]	13/16	2.50[c]	295.0 ± 11.0	1.994 ± 0.040	± 0.053	R
4	CF-04	96GE612[a]	50	0.761	2.134 ± 0.014	820-1030	59.9	2.108 ± 0.011	4.60[c]	9/18	4.40[c]	289.0 ± 10.0	2.130 ± 0.038	± 0.053	R
3	CF-03	UW01E55[b]	100	0.330	2.160 ± 0.030	820-1080	94.0	2.163 ± 0.021	3.10[c]	9/14	2.20	296.4 ± 4.4	2.150 ± 0.045	± 0.058	
		96GE611[a]	50	0.397	2.096 ± 0.026	800-1020	71.7	2.132 ± 0.016	1.80	8/18	2.20	300.0 ± 14.4	2.106 ± 0.091	± 0.098	
							Combined isochron:			17/32	3.70[c]	297.4 ± 3.4	2.132 ± 0.031	± 0.048	N
2	CF-02	UW01E54[b]	100	0.306	2.100 ± 0.030	865-1150	81.7	2.160 ± 0.028	4.20[c]	8/16	0.25	296.0 ± 12.0	2.155 ± 0.079	± 0.087	
		96GE610[a]	50	0.431	2.290 ± 0.096	525-1140	100.0	2.280 ± 0.180	0.24	22/22	5.10[c]	295.8 ± 7.1	2.280 ± 0.180	± 0.184	
							Combined isochron:			30/38	1.40	298.4 ± 3.9	2.144 ± 0.030	± 0.048	T
1	CF-01	96GE609[a]	50	0.237	2.420 ± 0.098	610-1100	57.3	2.270 ± 0.120	0.69	12/14	0.65	300.2 ± 3.4	2.181 ± 0.097	± 0.104	R

[a]Measured in Geneva, ages calculated relative to 28.34 Ma Taylor Creek Rhyolite sanidine [*Renne et al.*, 1998].
[b]Measured in Wisconsin, ages calculated relative to 1.194 Ma Alder Creek Rhyolite sanidine [*Renne et al.*, 1998].
[c]MSWD or SUMS/(N-2) larger than expected due to incorporating additional plateau increments (see text for discussion).
[d]Analytical and intercalibration uncertainties only.
[e]Fully propagated uncertainties, including ^{40}K decay constant (see text and *Renne et al.*, 1998).

released, and (2) a well-defined isochron 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, the isochron ages (Table 1) are preferred over the weighted mean plateau ages. Many age spectra exhibit subtle discordances with small age differences (at the 95% confidence level) distinguishing ends of what otherwise would be statistically valid plateaus. Thus, for some experiments criteria 1, which is somewhat arbitrary, was relaxed to accommodate significantly larger fractions of gas into the age plateau and isochron calculations. Although this results in slightly excessive of MSWD and *SUMS/(N-2)* values, the reported isochron ages conservatively measure time since eruption.

3.3. The Unspiked K-Ar Method

Unspiked K-Ar dating differs from the conventional isotope dilution method in that argon extracted from the 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. 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 [*e.g., Guillou et al.*, 1998]. The groundmass from Flow 9 yielded a strongly discordant age spectrum and no plateau. Thus, using methods completely described in Singer et al. [2004], replicate unspiked K-Ar age determinations (Table 2) were completed at Gif-sur-Yvette, France on sub-samples of the same material prepared for $^{40}Ar/^{39}Ar$ analysis. The volume of the spike-free inlet system is calibrated by measuring mineral standards of known molar $^{40}Ar^*$ concentration, including GL-O glauconite, Mmhb-l horn-blende, LP-6 biotite, and HD-B1 biotite [see *Charbit et al.*, 1998, for details].

3.4. The $^{40}Ar/^{39}Ar$ and K-Ar Results

The dozen $^{40}Ar/^{39}Ar$ incremental heating experiments yielded nearly concordant to moderately discordant age spectra for all but Flow 9, which produced highly discordant results (Table 1, Figure 3). Plateau segments comprising 48–100% of the gas released characterize the other samples. As noted earlier, experiments on Flows 2, 3, 4, and 5 gave age spectra that met the rigorous criteria for defining an age plateau, but also additional gas steps that were only slightly discordant at the 95% confidence level (Figure 3). These few additional steps were included in the plateau and isochron age calculations, with resulting MSWD and *SUMS/(N-2)* values slightly higher than expected (Table 1; Figure 3). The relatively low apparent ages that characterize the low temperature increments from Flows 2, 3, and 4 suggest that minor argon loss, possibly associated with alteration, has affected these lavas. The age spectrum of Flow 4 suggests that in addition to minor argon loss, a small amount of ^{39}Ar recoil—leading to slightly decreasing apparent ages prior to the plateau (Figure 3)—may have occurred. Similarly, the strongly discordant spectrum from Flow 9 suggests that a combination of argon loss, accompanied by ^{39}Ar recoil—possibly reflecting petrographically undetectable alteration of matrix glass—have compromised this lava. The $^{40}Ar/^{36}Ar_i$ values of 300.2±3.4 and 303.7±3.4 from Flows 1 and 6 indicate that small amounts of excess argon are present in these basalt flows, whereas the other lavas contain an initial trapped component indistinguishable from the atmosphere. The isochrons calculated from each lava flow, including the combination of replicate plateau analyses from Flows 2 and 3, give preferred ages between 2.181±0.097 and 1.073±0.036 Ma that agree with the stratigraphic succession (Figure 2).

The uncertainty estimates for the K-Ar ages reported by Fleck et al. [1972] were made by taking a simple standard deviation of the ages from the replicate experiments on each whole-rock sample without regard to the size of the associated analytical errors. This approach underestimates the uncertainty of these measurements. A more appropriate estimate of the uncertainty for each K-Ar age is to take the inverse-variance weighted mean age and uncertainty [*Taylor*, 1982], as is done to calculate the $^{40}Ar/^{39}Ar$ plateau ages. When uncertainties are estimated in this manner, the $^{40}Ar/^{39}Ar$ isochron ages for Flows 1, 2, 3, and 10 are indistinguishable at the 95% confidence level from the K-Ar ages determined by Fleck et al. [1972], but are more precise (Figure 2). In contrast, the isochron ages from Flows 4 and 7 are ~10% older than the K-Ar ages.

Table 2. Replicate unspiked K-Ar analyses, groundmass from 9th flow, Cerro del Fraile, Argentina[a]

Flow #	Sample	Weight Molten (g)	K (wt. %)	$^{40}Ar^*$ (%)	$^{40}Ar^*$ (10^{-12}mol/g)	Age (Ma) ± 2σ	Weighted mean age (Ma) ± 2σ
9	CF-08	1.42223	0.668 ± 0.007	6.331	1.651	1.424 ± 0.030	
	CF-08	1.12758	" "	6.284	1.654	1.427 ± 0.031	1.425 ± 0.021

[a]K by flame photometry. Herve Guillou analyst at Gif-sur-Yvette, France.

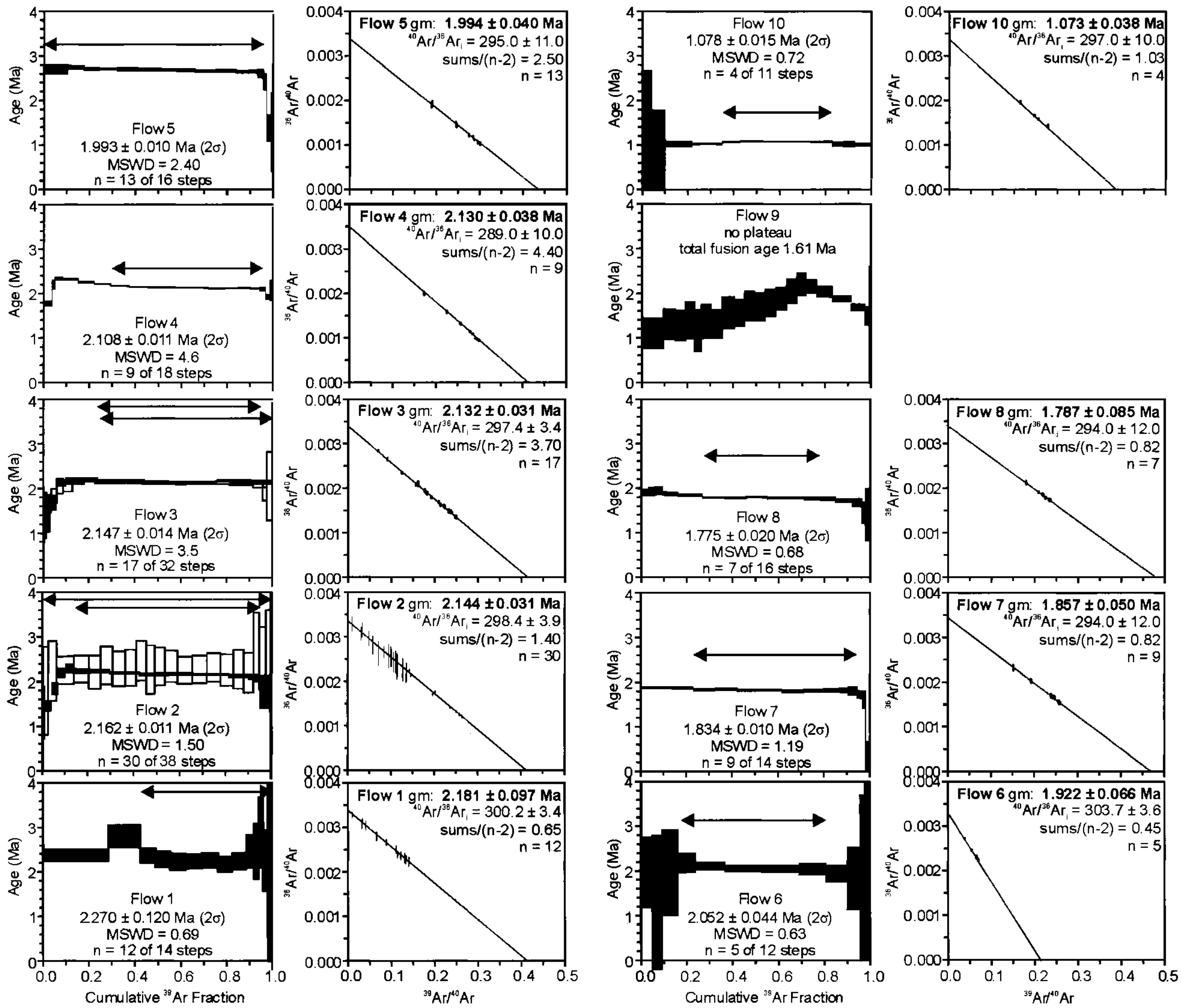

Figure 3. $^{40}Ar/^{39}Ar$ age spectra and inverse isochron diagrams for the 10 lava flows in Figure 2. Ages calculated relative to sanidines from the 28.34 Ma Taylor Creek Rhyolite sanidine or 1.194 ma Alder Creek Rhyolite (both equivalent to 28.02 Ma Fish Canyon Tuff sanidine).

The discordant $^{40}Ar/^{39}Ar$ result from Flow 9 (Figure 3) precluded generating an isochron for this lava. The total fusion age for this experiment, which should be equivalent to a K-Ar age, is 1.612±0.060 Ma; however, if the sample was affected by ^{39}Ar recoil to the extent that some ^{39}Ar leaked from it during irradiation, it is possible that unsupported radiogenic ^{40}Ar overestimates the time since eruption. Alternatively, argon loss during weathering may have lowered the apparent ages of the initial gas increments (Figure 3). The unspiked K-Ar age of Flow 9, 1.425±0.021 Ma (Table 2), is immune to ^{39}Ar recoil and significantly younger than the $^{40}Ar/^{39}Ar$ total fusion age. Its age is thus constrained to between 1.612±0.060 and 1.425±0.021 Ma and is identical to the K-Ar age of 1.51 ± 0.11 Ma determined by Fleck et al. [1972] (Figure 2).

4. PALEOMAGNETIC WORK

4.1. Methods

Magnetic data was processed in the Paleomagnetism Laboratory at the University of Massachusetts. Samples were measured on a 2G cryogenic magnetometer, model 755R, with alternating field and thermal demagnetization done using a Molspin AF demagnetizer and an ASC thermal demagnetizer, respectively. Susceptibility measurements were made using a Sapphire susceptibility meter.

Paleomagnetic samples were subjected to detailed demagnetization using both alternating field (AF) and thermal techniques. AF demagnetization was performed in steps from 0 to 100 mT, with 10 to 14 steps per sample. Thermal demagnetization, done at 10 or more temperature steps from room temperature to 600°C, used paired specimens with AF studies. Thermal demagnetization, as discussed below, turned out to be unsatisfactory and was not used further. Characteristic directions were determined for both demagnetization methods using line-fitting techniques [*Kirschvink*, 1980].

4.2. Results

Natural remanent magnetization (NRM) and demagnetization behavior was measured on a total of 73 samples from the 10 flows at Cerro del Fraile. Susceptibility measurements, made on each core and averaged for each site range, from 0.59 to 3.57 x 10^{-2} SI, with an average value for all flows of 1.54 x 10^{-2} SI. Mean natural remanent magnetization (NRM) prior to demagnetization is 2.73 A/m, but sites fall into two distinct groups (Table 3). Three flows (2, 7 and 9) have NRM values less than 1 A/m, with a mean of 0.75 A/m, while the remaining 7 flows have NRM values greater than 3 A/m, with a mean of 4.88 A/m.

Paired specimens from the same core for each site were demagnetized using both AF and thermal techniques with interesting results. AF demagnetization on both normal and reversed flows removed minor overprints at low levels (Figure 4A and C) with relatively straight-line decays to the origin. Median destructive fields are all greater than 20 mT and many are 50 to 60 mT. Cores yielding transitional directions were often an order of magnitude less intense, with overprints being removed by 20 mT (Figure 4D). Thermal demagnetization on companion samples showed removal of overprints up to 400°C (Figure 4B) and then slow decay towards the origin. The example shown in Figure 4B is the best of the thermal data; other specimens gave much more erratic results. The majority of thermal demagnetization studies were unable to give line-fitting results with a maximum angle of deviation (MAD) <5°. Due to this questionable behavior under thermal demagnetization, AF demagnetization was used on remaining samples and final results all use data obtained in this way. All AF produced directions were obtained from line-fitting with MAD values <5°.

Inclinations and declinations for all the flows, along with associated statistics and virtual geomagnetic poles (VGP) are given in Table 3 and plotted in Figure 5. Most flows show excellent within site statistics, precision parameters (k) and 95% circles of confidence (σ_{95}) of Fisher [1953]. Using a VGP latitude of <45° as a determination of transitional directions, the sequence of flows from bottom to top give a pattern of R-T-N-R-R-T-N-R-T-N (Figure 2). Although this data set is not large enough to warrant time-averaged field observations, the mean of the 7 normal and reversed flows (I=-61.8°, D=355.5°, α_{95} = 6.7°) is similar to, but slightly shallower than, results from Meseta del Lago Buenos Aries, 400 km north of Cerro del Fraile [*Brown et al.*, 2004]. The mean inclination is 5.8° shallower than the expected inclination at this latitude of 67.6°

Of the 3 sites with low NRM values, two of them have transitional directions, flows 2 and 9. None of the transitional flows show randomly scattered NRM directions or high NRM intensities usually attributed to lightning strikes, such as observed in flows from the southwestern United States recently studied by Tauxe et al. [2003]. All 3 flows have α_{95} values of 8.0° or less, and appear to accurately record the magnetic field at the time of their emplacement. As will be discussed below, the geochronology on transitional flows 2 and 6 indicate correspondence to known polarity boundaries.

Table 3. Summary of site mean paleomagnetic data from lavas of Cerro del Fraile, Argentina[a]

Flow#	Site	N/No	Polarity	J (A/m)	X (10^{-2} SI)	INC	DEC	K	α_{95}	Pole Lat	Pole Long
10[b]	H	3/3	N	-	-	-63	343	29	23	77	145
9	PFC 14	6/6	T	0.815	1.514	-58.5	108.4	72	8.0	19.4	56.1
8	PFC 13	8/9	R	4.228	1.113	58.2	188.3	393	2.8	-76.9	137.1
7	PFC 12	6/7	N	0.884	1.884	-69.9	324.2	68	8.2	68.1	175.0
6	PFC 15	7/7	T	3.152	0.847	-59.4	152.2	181	4.5	4.0	86.4
5	PFC 11	8/8	R	5.527	2.189	56.4	182.1	119	5.1	-76.4	114.5
4	PFC 10	7/7	R	3.576	3.565	63.5	189.8	75	7.0	-81.5	161.3
3	PFC 9	9/9	N	3.125	1.864	-58.4	5.2	204	3.6	78.1	307.1
2	PFC 8	9/9	T	0.541	0.588	14.5	10.9	78	5.9	31.3	300.0
1	PFC 7	8/8	R	5.432	1.802	57.5	164.3	153	4.5	-73.3	59.5

[a]N/No, number used in calculations/number measured; J, magnetic intensity; X, magnetic susceptibility; INC, inclination; DEC, declination; K and α_{95}, precision parameter and radius of 95% confidence circle [*Fisher*, 1953].
[b]Directional data from Fleck et al. [1972].

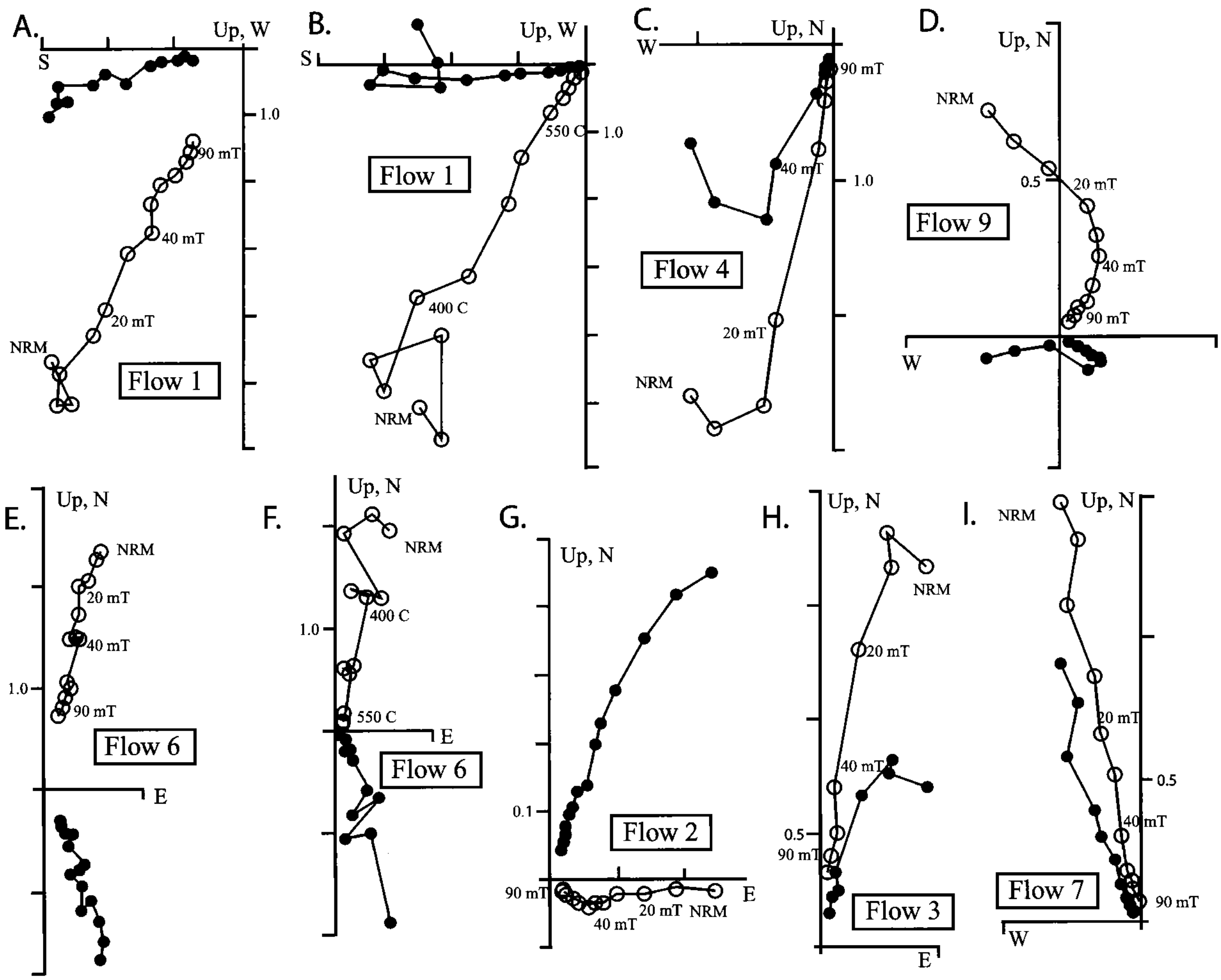

Figure 4. Vector end-point diagrams showing demagnetization behavior of normal, reversed, and transitional samples from Cerro del Fraile, Argentina. A, B, and C. Examples of demagnetization of samples with reversed directions. D, E, F, and G. Examples of transitional demagnetization behavior. H and I. Normal direction demagnetization examples. Open circles are projections onto the vertical plane; Solid circles are projections on to horizontal plane, Axes are labeled in A/m.

5. DISCUSSION

5.1. Toward a Geomagnetic Instability Time Scale for the Matuyama Chron

Refinements of the GPTS from 0–1.2 Ma have involved addition of several short-lived (<20 kyrs) geomagnetic "events" or cryptochrons, including excursions, aborted reversal attempts, and rapid back-to-back reversals, that have been calibrated using $^{40}Ar/^{39}Ar$ dating [*Singer et al.* 2002]. Although evidence from sediments and lava flows strongly suggests that at least 20 geomagnetic events occurred during the last 1.2 myr, the number and timing of events in the earlier part of the Matuyama reversed chron has remained more uncertain. Recently, however, sediment drifts in the North Atlantic Ocean that were deposited at high rates during the Matuyama Chron were cored at ODP sites 981, 983, and 984 and revealed a remarkably detailed record of reversals and excursions that are now astronomically dated [*Channell et al.*, 2002; 2003]. To the extent that these short-lived events can be temporally quantified, they will provide valuable tie points for global Plio-Pleistocene paleointensity stacks [*e.g., Guyodo and Valet*, 1999] as well as helping to refine models of the geodynamo that make explicit predictions as to the timing, frequency, and geometry of reversals and excursions [*e.g., Gubbins*, 1999; *Glatzmaier et al.*, 1999]. Here we review geomagnetic events during the Matuyama chron in light of the new radioisotopic ages from Cerro del Fraile and outline an initial Geomagnetic Instability Time Scale (GITS) [*Singer et al.*, 2002] for this interval (Figure 6).

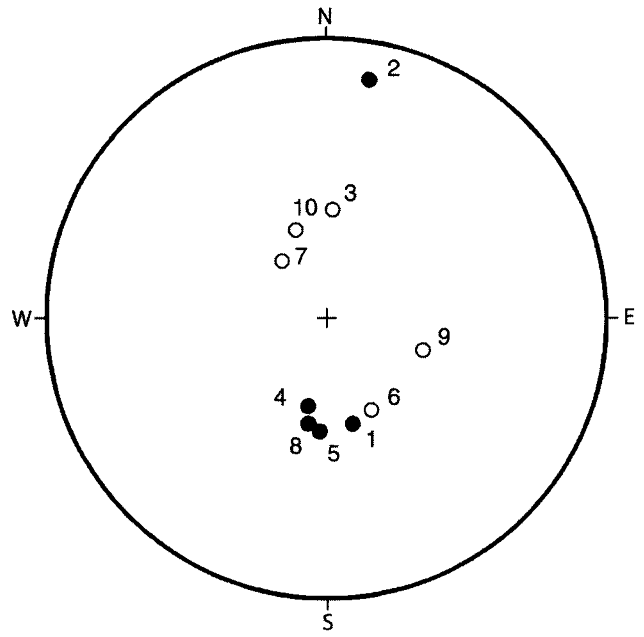

Figure 5. Equal area net mean inclination and declination, determined from principal component analysis, for each paleomagnetic site from Cerro del Fraile. Numbers correspond to flow number (Table 3). Open circles are upward pointing (negative) inclinations, solid circles are downward pointing (positive) inclinations.

5.1.1. The Réunion and Huckleberry Ridge events. The $^{40}Ar/^{39}Ar$ and unspiked K-Ar ages, together with the paleomagnetic directions, indicate that at least three intervals of normal polarity during the Matuyama reversed chron are recorded at Cerro del Fraile. The $^{40}Ar/^{39}Ar$ isochron ages suggest that the sequence of transitional—normal—reversed magnetic directions recorded in Flows 2, 3, and 4 correspond to the Réunion event. Because ages determined from each lava overlap one another at the 95% confidence level, the weighted mean of 2.136±0.019 Ma gives a very precise estimate of the time elapsed since the magnetic field transitioned from reverse to normal and back to reverse polarity.

The age of the Réunion event, and the possibility that it may comprise two separate intervals of normal polarity has been controversial [*Kidane et al.*, 1999; *Roger et al.*, 2000; *Baksi and Hoffman*, 2000; *Lanphere et al.*, 2002; *Baksi*, 2001]. Baksi and Hoffman [2000] and Lanphere et al., [2002] reviewed the geochronologic evidence, including unspiked K-Ar dated basalts from Gamarri, Ethiopia [*Kidane et al.*, 1999], and reached contrasting conclusions regarding whether the Réunion event comprises multiple periods of normal polarity. Baksi and Hoffman [2000] calculated the weighted mean $^{40}Ar/^{39}Ar$ plateau age of six normally or transitionally magnetized basalts from the Réunion Island at 2.139±0.034 (±2σ, normalized to standard values used here) and suggested that the K-Ar ages from Gamarri are suspect due to high ^{36}Ar contents and alteration. Using $^{40}Ar/^{39}Ar$ laser fusion and furnace incremental-heating techniques, Lanphere et al. [2002] re-dated sanidine from the transitionally magnetized Huckleberry Ridge Tuff (HRT) and concluded that that at least two geomagnetic events occurred between 2.2 and 2.0 Ma. From sanidine separated out of pumice at three geographically distinct sites in the HRT, Lanphere et al. [2002] pooled together the total fusion, plateau, and isochron ages to arrive at an extraordinarily precise age of 2.090±0.008 Ma (±2σ, normalized to standard values used here) that overlaps some of the K-Ar ages from Gamarri, but is significantly younger than the Réunion Island basalts dated by Baksi and colleagues.

Because the total fusion, age plateau and isochron ages determined on each HRT sanidine separate by Lanphere et al. [2002] are not independent from one another, it is inappropriate to calculate such a precise weighted mean age for the three HRT samples by pooling all nine ages including the total fusion, plateau, and isochron ages of each sample. This is particularly true because a small amount of excess argon was detected in the incremental heating experiments [*Lanphere et al.*, 2002]. The most appropriate way to compare the age determined by Lanphere et al. [2002] to our age for the Réunion event is to calculate the weighted mean of the three isochron ages from the HRT sanidine; this yields an age for the HRT of 2.086±0.016 Ma. The weighted mean age of the six basalt flows from Réunion Island [*Baksi et al.*, 1993; *Baksi and Hoffman*, 2000] and the three flows from Cerro del Fraile is 2.137±0.016 Ma, which is older than Lanphere et al.'s [2002] age for the HRT by 51±23 kyr. Because the 2.130±0.030 Ma Flow 4 at Cerro del Fraile is reversely magnetized and significantly older than the mean age of the HRT, it is clear that there are at least two separate normal or transitional periods of magnetic polarity between 2.14 and 2.08 Ma (Figure 6).

The weighted mean of the five unspiked K-Ar ages for normally magnetized lavas at Gamarri is 2.06±0.05 Ma [±2σ; *Kidane et al.*, 1999]. This age overlaps with the 2.086 ±0.016 Ma derived from Lanphere et al.'s three isochrons for the HRT event. Thus, rather than corresponding to the Réunion event as claimed by Kidane et al. [1999], the Gamarri lavas are either: correlative with the younger HRT event, or, as discussed by Baksi and Hoffman [2000], the Gamarri lavas are too young due to alteration and these K-Ar ages cannot be relied upon to provide an accurate chronology. $^{40}Ar/^{39}Ar$ incremental heating analyses of groundmass separates, using the methods and standards employed here, will be essential to resolving the age of the Gamarri lavas and assigning them to either the Réunion or HRT events.

The only other $^{40}Ar/^{39}Ar$ age that closely constrains the age of the Réunion event comes from sanidine dated by Roger et

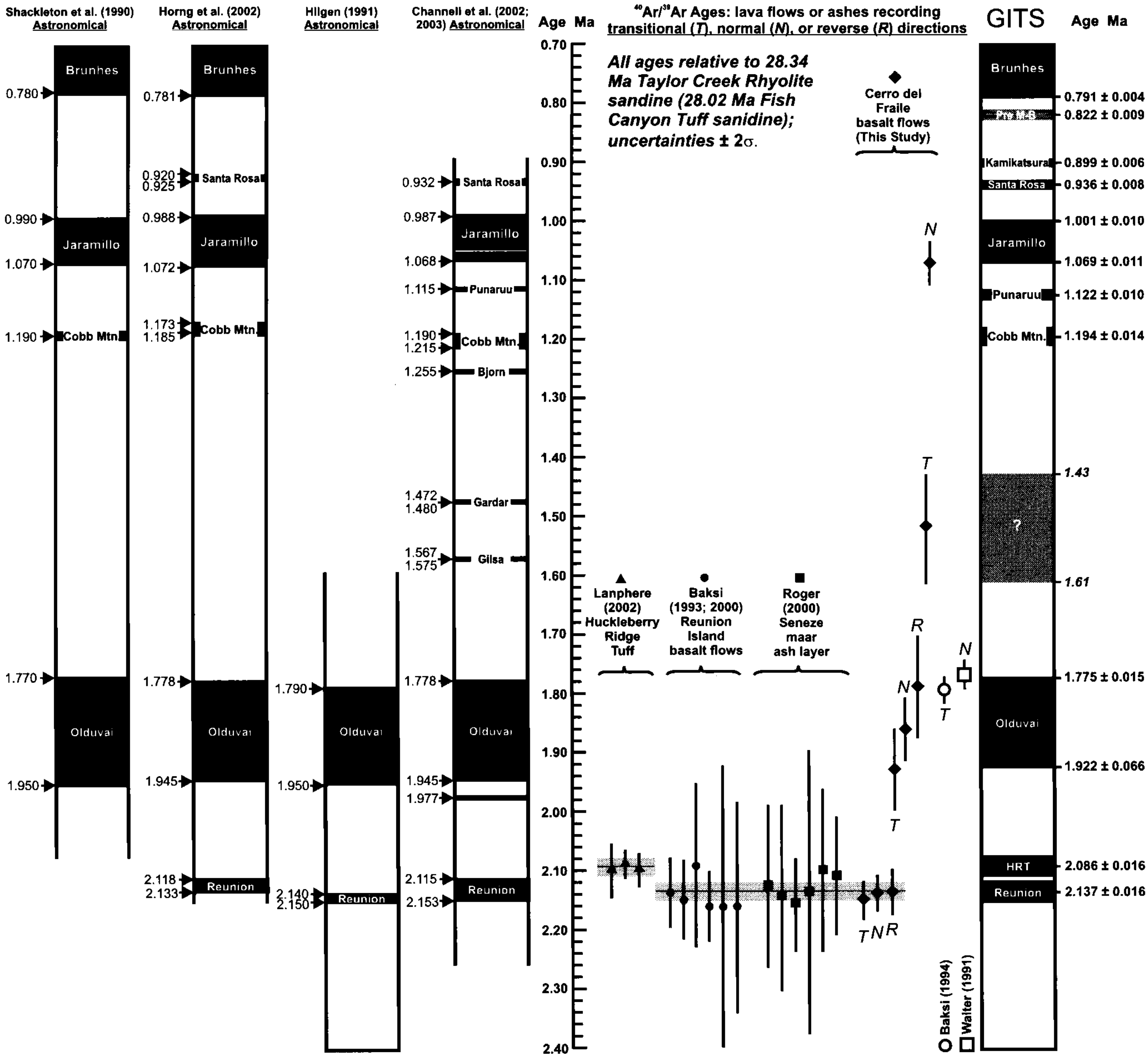

Figure 6. Comparison of $^{40}Ar/^{39}Ar$ radioisotopic ages from CerroFraile (♦) with other $^{40}Ar/^{39}Ar$ ages bearing on the age of the Réunion event [Baksi • = *Baksi and Hoffman*, 2000 and *Baksi et al.*, 1993; Roger ■ = *Roger et al.* 2000; Lanphere ▲ = *Lanphere et al.*, 2002], the Olduvai subchron boundaries [Baksi O = *Baksi*, 1994; Walter □ = *Walter et al.*, 1991], and astrochronologic timescales. Ages at right for the upper part of the Matuyama chron are from Singer et al. [2002] and Singer and Brown [2002]. HRT = Huckleberry Ridge event of Lanphere et al. [2002]. All radioisotopic ages are calculated, or normalized to 28.02 Ma for the Fish Canyon Tuff sanidine standard and reported at ±2σ. The shaded horizontal bands are the weighted mean ages and uncertainties of the Réunion event and Huckleberry Ridge event discussed in the text. The Réunion and Cobb Mountain events are intervals of normal polarity bounded by reversals [*Baksi et al.*, 1993; *Clement and Kent*, 1986], thus the Geomagnetic Instability Timescale (GITS) for the Matuyama chron includes at least 14 $^{40}Ar/^{39}Ar$-dated events.

al. [2000] at 2.10±0.02 Ma (±2σ, comparable directly to our ages via the 28.02 Ma value used for the FCs standard) that was recovered by drilling into a tephra within normally magnetized lacustrine sediment of the Senèze maar, France. Baksi [2001], however, pointed out several problems with the interpretation of Roger et al. [2000], including normalization of some the their ages to inconsistent value for one of two standards used, and the combination of five one-step total fusion ages and four two-step (partly degassed) fusion ages with the plateau ages from two laser incremental heating experiments to obtain a final weighted mean age. Because Roger et al.'s [2000] single-step total fusion ages were all younger than the plateau ages at the 95% confidence level, Baksi [2001] correctly stated that sanidine in this water-lain ash has been altered, and that the single-step total fusion ages should not be included in the mean age. The weighted mean of Roger et al.'s [2000] two plateau ages and the 5 fusion steps from the partly degassed crystals is 2.135±0.050 Ma, in excellent agreement with the ages from normally and transitionally magnetized basalt from Réunion Island [*Baksi and Hoffman*, 2000] and Cerro del Fraile (Figure 6). The acceptable single-crystal sanidine ages of Roger et al. [2000] have large uncertainties, thus when pooled together with the nine basalt flows the best estimate for the age of the Réunion event remains 2.137±0.016 Ma—that is to say, distinctly older than the Huckleberry Ridge event of Lanphere et al. [2002](Figure 6).

The radioisotopic age of 2.137±0.016 Ma for the Réunion event (±0.040 Ma with fully propagated errors) is consistent with a single short-lived normal polarity interval C2r,1n at 2.15–2.14 Ma in Cande and Kent's [1995] revised GPTS, as well as the astronomical ages estimated by Hilgen et al. [1991] from the Mediterranean sapropel record and Horng et al. [2002] using a giant piston core MD972143 from the Philippine Sea (Figure 6). Horng et al. [2002] detected transitional magnetic directions in a disturbed sandy layer below the normal polarity interval illustrated in Figure 6, however owing to the disturbances it is unclear whether this layer corresponds to an event earlier than 2.137 Ma.

It is notable that each of the three age determinations from Cerro Fraile, and the weighted mean of 2.137±0.016 Ma for all 14 radioisotopic ages, fall within the 38 kyr normal polarity interval between 2.153 and 2.115 Ma observed in North Atlantic drift sediments at ODP site 981 astronomically dated by Channell et al. [2003] (Figure 6). Evidence that the HRT event may have been recorded in ODP site 984 sediment includes a brief period of equator-crossing virtual geomagnetic poles associated with low paleointensity at about 2.06 Ma [*Channell et al.*, 2002]. Records to the southeast from site 981 also show shallow inclinations and low virtual geomagnetic poles at about 2.04 Ma which Channell et al. [2003] correlate to the HRT event.

5.1.2. The Olduvai Subchron. The $^{40}Ar/^{39}Ar$ ages of transitional, normal, and reversed polarity Flows 6, 7, and 8 help to tightly constrain the onset and termination of the Olduvai subchron. The only other salient $^{40}Ar/^{39}Ar$ data include the isochron age of 1.779±0.020 Ma (±2σ; normalized to standards used here) from a transitionally magnetized basalt on Moorea Island that was incrementally heated [*Baksi*, 1994] and the isochron age of 1.770±0.022 (±2σ; normalized to standards used here) obtained by totally fusing 36 aliquots of sanidine crystals from normally magnetized Tuff IF at Olduvai Gorge [*Walter et al.*, 1991]. The onset of the Olduvai subchron was recorded 1.922 ± 0.066 Ma by Flow 6 at Cerro del Fraile (Figure 6). The termination of the subchron must have occurred by the time Flow 8 erupted 1.787±0.085 Ma, because it is reversely magnetized. Since the age of Flow 8 overlaps the isochron ages for the transitionally magnetized basalt [*Baksi*, 1994] and the normal polarity tuff [*Walter et al.*, 1991], the weighted mean of these three ages, 1.775±0.015 precisely defines the termination of the Olduvai subchron (Figure 6). These new radioisotopic ages are consistent with GPTS of Cande and Kent [1995] and with the astrochronologic ages of Shackleton et al. [1990] and Hilgen [1991], but in detail best match the more recent astrochronologic estimates of Horng et al. [2002] and Channell et al., [2002] (Figure 6).

5.1.3. Event at 1.61–1.43 Ma. Flow 9 at Cerro Fraile records a transitional paleomagnetic direction that is imprecisely constrained between the $^{40}Ar/^{39}Ar$ total fusion and K-Ar ages of 1.61 and 1.43 Ma, thus it is unclear if a correlation exists with other potential records of transitional field behavior. For example, the Gilsa event has been controversial since is was originally defined by McDougall and Wensink [1966] as a brief period of normal polarity recorded in Icelandic lavas 1.61±0.05 Ma. Udagawa et al. [1999] undertook paleomagnetic measurements and reported two new conventional whole-rock K-Ar dates from the same Icelandic lavas that seemed to confirm an age of 1.62 Ma for the Gilsa event. However, Wijbrans and Langereis [2003] obtained $^{40}Ar/^{39}Ar$ laser incremental heating ages from the groundmass of basaltic lavas in these Icelandic sections; they concluded that no lavas are 1.61 Ma, that only the Réunion and Olduvai events are recorded, and the existence of a Gilsa event is questionable.

Clement and Kent [1986] discovered a short interval of steep positive inclinations in sediments from two cores at DSDP site 609 that, on the basis of extrapolating from bio- and magnetostratigraphic ages of known chron boundaries, and assuming average sedimentation rates, was estimated to have occurred 1.55 Ma. Clement and Kent [1986] correlated this excursional event with the Gilsa event in Iceland. Similarly, Biswas et al. [1999] discovered a prominent inclination anomaly in sediments of Osaka bay, Japan, that occurred between the Olduvai subchron and the Cobb Mountain event. Although an age was not assigned to this event, its position in the core suggests that it occurred during marine oxygen isotope stage 54, or about 1.60 Ma, which led Biswas et al. [1999] to suggest that this event may correspond to an early part of the Sangiran excursion recorded by sediment in Java [*Hyodo et al.*, 1992]. Unfortunately, the timing of the Sangiran excursion is very poorly constrained by fission-track ages from two tuffs above the main declination anomaly that are 1.51 and 1.48 Ma.

More recently, drift sediments from ODP sites 983 and 984 revealed clear evidence for two brief excursions, astronomically dated at 1.567–1.575 Ma and 1.472–1.480 Ma [*Channell et al.*, 2002], that fall within the period in question at Cerro del Fraile (Figure 6). Channell et al. [2002] correlated the older event with the Gilsa and named the younger the Gardar event after the drift deposit in which is was discovered (Figure 6). The imprecise age of Flow 9 at Cerro del Fraile limits the certainty of correlation with the Gilsa, Stage 54, Sangiran, or Gardar events, and does not rule out the possibility that it records a brief, previously unrecognized period of geomagnetic instability between the termination of the Olduvai subchron and the onset of the Cobb Mountain subchron (Figure 6).

5.1.4. Onset of the Jaramillo Subchron. The onset of the Jaramillo normal subchron is recorded by several transitionally magnetized basalt flows in the Punaruu Valley, Tahiti, one of which was incrementally heated to give an $^{40}Ar/^{39}Ar$ isochron age of 1.069±0.012 Ma (±2σ; normalized to standards used here) [*Singer et al.*, 1999]. The isochron age of normally magnetized Flow 10 at Cerro del Fraile, 1.073±0.036 Ma, is indistinguishable from that of the transitional basalt from Tahiti, thus it must record the very earliest Jaramillo time. The weighted mean age of these two lavas, 1.069±0.011 Ma gives the most precise radioisotopic constraint for the onset of this subchron and is identical to the estimated astronomical ages for this event (Figure 6).

5.2. Glacial History of the Southern Andes

Cerro del Fraile is one of several >1200 m high mesas located 30–40 km east of the Andean Cordillera that are capped by Plio-Pleistocene basaltic lavas interbedded with glacial till (Figure 1). From three of these mesas, including Cerro del Fraile, Mercer [1976; 1983] obtained K-Ar ages that revealed a fragmentary record of the earliest Cenozoic glaciations in South America. The others are Meseta del Lago Buenos Aires, 47° S, where till is preserved between basalt flows that were K-Ar dated at 7.01 and 4.58 Ma and $^{40}Ar/^{39}Ar$ dated at 7.49±0.10 and 5.12 ±0.08 Ma by us [*Ton That et al.*, 1999; ±2σ, normalized to standards used here], and Meseta Desocupada, 49.4°S, where till crops out between two reversely magnetized basalt flows K-Ar dated at 3.57 and 3.64 Ma [*Mercer*, 1983]. Thus, the oldest glaciations in Patagonia occurred in the earliest Pliocene prior to 5.12 Ma and at ca. 3.6 Ma during the Gauss chron. It remains unclear whether this piecemeal record reflects poor preservation, the limited extent of glaciers, or lack of large ice caps during the period between 5.12 Ma and the base of the section at Cerro del Fraile.

Contact relations between the lava flows and underlying tills, together with the $^{40}Ar/^{39}Ar$ ages indicate that glaciers advanced eastward out of the Andean Cordillera and deposited till at least seven times from prior to 2.181±0.097 Ma to some time between 1.61 and 1.073±0.036 Ma. Cerro del Fraile preserves the only known record of frequent glaciation in southern South America during this Plio-Pleistocene interval [*Mercer*, 1976; 1983]. The marine $\delta^{18}O$ time series during this period—between stage 82 and 48—suggests that climate oscillations recorded in the oceans were dominated by orbital obliquity with a ~40 kyr periodicity [*Shackleton et al.*, 1990; *Zachos et al.*, 2002]. Deposition of at least four separate tills in the ca. 220 kyrs between Flows 2 and 6 (Figure 2) is consistent with a Patagonian ice cap that waxed and waned at frequency similar to that of the oceans. Carbon isotope variations in the South Atlantic Ocean during the last 2.9 Ma reveal that the most significant change in deep water circulation was an abrupt lowering of $\delta^{13}C$ values 1.55 Ma, possibly induced by the rapid expansion of Antarctic sea ice, and followed by increased coupling between North and South Atlantic water [*Venz and Hodell*, 2002]. The youngest till at Cerro del Fraile may have been deposited during or shortly after this 1.55 Ma transition, and may mark the change from relatively small piedmont glaciers to significantly more extensive oscillations of the Patagonian ice cap.

Glaciations continued to frequent the Pleistocene with ice reaching its farthest eastward extent during Mercer's [1976] Greatest Patagonian Glaciation (GPG), between 1.168±0.014 and 1.016±0.010 Ma—the $^{40}Ar/^{39}Ar$ ages of basaltic lava flows that under- and overlie till ~100 km east of the Andes in the Rio Gallegos and Lago Buenos Aires valleys (Figure 1) [*Singer et al.*, 2004]. Till of the GPG, and several terminal moraines, including those corresponding to the Last Glaciation Maximum ~25 ka were deposited on the floors of wide valleys occupied by lakes including Lago Argentino and Lago Buenos Aires at elevations of ca. 200 m (Figure 1). Fission-track cooling ages from rocks within the main Cordillera led Thomson et al. [2001] to conclude that east of the modern topographic divide of the Patagonian Andes denudation since the Late Cretaceous was less than 3 km, owing largely to the rain-shadow in effect since Oligocene-Miocene uplift. We find it remarkable that since deposition of the 7th till and eruption of Flow 10 onto the piedmont surface at Cerro del Fraile 1.073 Ma, valleys have been deepened by >1000 m of erosion

(Figure 1) at a rate of ~1 cm/yr. Evidently, nearly all of this denudation, including incision into the piedmont leaving isolated basalt-capped mesas, and a dramatic change in the landscape, occurred rapidly during the Quaternary, driven by vigorous, repeated glaciation that created vast trough-shaped valleys [*Singer et al.*, 2004].

6. CONCLUSIONS

Nine of ten basalt flows that cap Cerro del Fraile, Argentina, yielded precise $^{40}Ar/^{39}Ar$ isochron ages between 2.186 and 1.073 Ma that are consistent with the stratigraphy. The 9th flow in the sequence gave a discordant age spectrum suggesting that ^{39}Ar recoil has compromised this sample; its age is broadly constrained by its $^{40}Ar/^{39}Ar$ total fusion and unspiked K-Ar ages. Paleomagnetic directions of the ten flows, together with the new age determinations, indicate that three lavas record the onset and termination of the Réunion event, three others constrain the onset, middle, and termination of the Olduvai subchron, and the uppermost normally magnetized lava erupted during the earliest part of the Jaramillo subchron. A fourth geomagnetic event, recorded by the transitionally magnetized 9th flow, is imprecisely constrained between 1.61 and 1.43 Ma; thus, correlation of this event with other global records of geomagnetic instability between the Olduvai and Cobb Mountain events is uncertain. At least 14 geomagnetic reversals or excursional events occurred between 2.14 and 0.79 Ma. Moreover, if one considers the Laschamp, Albuquerque, and Big Lost events in the Brunhes chron, the Geomagnetic Instability Time Scale (GITS) includes 18 radioisotopically-dated events during the last 2.14 myr, as well as several others identified in sediments that remain to be radioisotopically dated [*Singer et al.*, 2002].

Specifically, the transitional, normal, and reverse polarity Flows 2, 3, and 4 that record the Réunion event at Cerro del Fraile have a weighted mean age of 2.136±0.019 Ma that is indistinguishable from $^{40}Ar/^{39}Ar$ ages obtained from both normally magnetized lavas on Réunion Island and ash in the Senèze maar, France. The weighted mean $^{40}Ar/^{39}Ar$ age of all these rocks, 2.137±0.016 Ma, gives a very precise radioisotopic date for the Réunion event that is ~50 kyr older than the Huckleberry Ridge event at 2.086±0.016 Ma. The $^{40}Ar/^{39}Ar$ ages of transitional, normal, and reverse polarity Flows 6, 7, and 8 at Cerro del Fraile, together with those from a transitional basalt on Moorea and a normal polarity tuff at Olduvai gorge, constrain the Olduvai subchron to between 1.922± 0.066 and 1.775±0.015 Ma, in agreement with astrochronologic estimates. The onset of the Jaramillo normal subchron, defined by transitionally magnetized lavas at Punaruu Valley Tahiti, and the youngest normal polarity flow at Cerro del Fraile, occurred 1.069±0.011 Ma.

Deposition of till on the piedmont surface prior to 2.186 Ma and six subsequent tills between 2.186 Ma and ~1.073 Ma record periodic growth of the Patagonian ice cap, but do not coincide with any known shift in Southern Ocean conditions. After ~1.5 to 1.2 Ma, the Patagonian icecap began to expand more dramatically. Repeated eastward glacial advances rapidly incised the piedmont adjacent to the mountains, deepened by >1000 m glacial troughs 10's of km wide at a rate of ~1 cm/yr, and profoundly altered the modern landscape.

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