Supplementary Material

1. Sample preparation

Ash beds were crushed using a tungsten mill. The crushed samples were then sieved at 300 μm. A water flotation method was used to separate and remove the very fine grain size material (less than 20 microns), resulting in a fine material with mineral grains ranging from 20 to 300 μm. The material was then separated with a magnetic separator at a current of 1.8A using a Frantz unit. The non-magnetic material was then run through heavy liquid density separation method using Methyl Iodide from Geoliquids Inc. Minerals denser than 3.33g/cm^3 sank and collected, were zircons were expected to be found. Single grains zircons were then hand-picked using a transmitted light microscope.

2. Laboratorial procedures

Ten to twenty grains were selected for annealed at 900°C for 48 hours. Grains from each sample were then separately chemically abraded, in bulk, for 12 hours in 3 ml Teflon beakers at 210°C with 12N HF inside a pressure dissolution vessel. Following chemical abrasion, the grains were then individually placed inside 3ml Teflon beakers rinsed and cleaned. The cleaning of grains consisted of several steps. In the first step, grains are left for 12 hours (overnight) in 6.2N HCl inside 3ml Savilex beaker at 80°C on a hot plate. In the second step, the grains were cleaned using 7N HNO$_3$, which consisted of a 45 min hot bath on a sonicator with and an additional 60 min hot bath on hotplate at 80°C. The 7N HNO$_3$ was then removed from the beakers and the process repeated three times before moving to total dissolution of the grains. Total dissolution consisted of grains being placed individually in microcapsules in 12N HF for 48 hours at 210°C. After total dissolution, microcapsules were then placed on a hotplate at 120°C uncapped to evaporate the remaining HF remaining from the total dissolution. Subsequently, 6.2N HCl was added to the microcapsules and put back in the oven for 12 hours at 180°C for total conversion. After the conversion of acids, the microcapsules were then placed on a hot at 80°C to evaporate the 6.2N HCl remaining from conversion. After evaporation, 3.1N HCl was added to the microcapsules before eluting Pb and U using micro columns. The micro columns were first cleaned using four steps alternating 6.2N HCl and ultrapure H$_2$O. Samples were collected in 7ml savillex beakers. Cleaning of 7 ml beakers are done in a three-step process of 12h in 6.2N HCl, 12h in 12N

HF, and 12h of 6.2N HCl on the hotplate at 80°C. General chemical abrasion procedures are followed after Mattinson (2005).

3. Data acquisition

After the full laboratorial procedures, the samples were dissolved into a silica gel and gently placed on outgassed Re filaments. Isotopic ratios were acquired using Thermal Ionization Mass Spectrometry. Samples were run using a either the Thermo Finnigan TRITON or Isotopx Phoenix in the Department of Earth Sciences, University of Geneva, Switzerland. Lead (Pb) measurements were acquired in dynamic mode on the SEM (Triton) or the Daly (Pheonix). Auto focusing and Peak centering were performed at the beginning of each block, which consisted of 20 cycles each. Lead baseline was monitored by mass 203.5. Interferences on mass ^{202}Pb and ^{205}Pb were monitored by masses 201 and 203, repectively. EARTHTIME ^{202}Pb-^{205}Pb-^{235}U-^{233}U and EARTHTIME ^{205}Pb-^{235}U-^{233}U were used as spikes (Parrish et al., 2006; Parrish and Krogh, 1987). Each measured ratio was corrected for fractionation using a ^{202}Pb/^{205}Pb of 0.99989 when the ^{202}Pb-^{205}Pb-^{235}U-^{233}U and EARTHTIME was used. When EARTHTIME ^{205}Pb-^{235}U-^{233}U was used Pb fractionation was assumed to be 0.13±0.5 % a.m.u (2 S.D). All common Pb measured was assumed to be from laboratorial blanks. Any sample that contained over 1pg of common Pb was considered to be contaminated and and discarded.

Uranium measurements were made in static mode on Faraday cups 10^{12} Ω resistors as UO_2^+. Auto focusing and peak centering was performed at the beginning of every block, with each block consisting of 20 cycles each. Baselines were monitored on ±0.5 mass units. ^{238}U/^{235}U of the sample and blank was assumed to be 137.88 (Chen and Wasserburg, 1980). The oxide correction in U measurements was assumed ^{16}OU/^{18}OU = 0.002. Uranium decay constant values were used from Jaffey et al. (1971).

Raw U-Pb data was reduced using U-Pb Redux (Bowring et al., 2012) and the data reported in TS.1. Uncertainty and error propagation algorithm used in Redux software is described in McLean et al. (2011). For the initial Th disequilibrium deviation was calculated using ^{208}Pb and a Th/U of the magma was assumed to be 3.5 (Blackburn et al., 2013).

4. Ash bed age interpretation

All zircons considered in the age distribution of the ash are interpreted as ash-fall deposits from near-by volcanic eruptions, even though the exact source cannot be known. Individual

zircon grains from each sample were analyzed and subsequently the youngest subset of grains from the age distribution of each sample were selected for the final weighted mean age. Ages reported in Fig. 2 and throughout the text are $^{206}Pb/^{238}U$ weighted mean Th-corrected ages. Uncertainties are reported as X/Y/Z; X includes analytical uncertainty, Y includes additional tracer (ET2535) calibration uncertainty, and Z includes additional ^{238}U decay constant uncertainty. The final weighted mean ages are interpreted as a depositional age for the ash beds. Chemical abrasion is assumed to eliminate the effect of Pb loss in individual grains. Therefore, dispersion of individual grains bigger than the analytical uncertainty in individual grains were assumed to record prolonged residence of zircon in the magmatic systems as well as intramagmatic recycling.

5. Sample Description

5.1. Ash bed LL3

Ash bed LL3 is located at stratigraphic height 54 m in the Las Loicas section. Zircon yield was moderate to high ca. > 50 grains. Zircons crystals ranged from 40-80 μm in size. Grains were mainly rounded with aspect ratio of 1:3 with rare prismatic crystals being rare. Radiogenic Pb ranged from 3 to 10 pg (TS.1). A total of nine grains were selected to represent the age distribution of the sample, with 5 grains being discarded for being too old (>~150 Ma) and considered either inherited grains or prolonged magmatic residence, or magmatic recycling. A total of four younger grains (z23, z25, z26, z32) that overlapped were considered for the final weighted mean age of the ash bed. The final weighted mean age of the ash bed is 139.238 ± 0.049/0.061/0.16 Ma, MSWD = 0.56

5.2. Ash bed LL9

Ash bed LL9 is located in stratigraphic height 41 m in the Las Loicas section. Zircon yield was moderate to high ca. > 50 grains. Zircons crystals ranged from 40-80 μm in size. Grains were mainly prismatic with aspect ratio of 1:8. Radiogenic Pb ranged from 2.5 to 14 pg (TS.1). A total of eleven grains were selected to represent the age distribution of the sample, with 7 grains being discarded for being too old (>~150 Ma) and considered either inherited grains or prolonged magmatic residence, or magmatic recycling. A total of four younger grains (z2, z12, z51, z55) that overlapped were considered for the final weighted mean age of the ash bed of 139.956 ± 0.063/0.072/0.17 Ma, MSDW 0.34

5.3. Ash bed LL10

Ash bed LL10 is located in stratigraphic height 31 m in the Las Loicas section. Zircon yield was moderate to high ca. > 50 grains. Zircons crystals ranged from 40-80 μm in size. Grains were mainly prismatic with aspect ratio of 1:8. Radiogenic Pb ranged from 1 to 6 pg (TS.1), notably lower than other the other samples. A total of eight grains were selected to represent the age distribution of the sample, with 4 grains being discarded for being too old (>~150 Ma) and considered either inherited grains or prolonged magmatic residence, or magmatic recycling. A total of four younger grains (z41, z42, z44, z45) that overlapped were considered for the final weighted mean age of the ash bed of 140.338 ± 0.083/0/091/0.18 Ma, MSWD = 1.1

5.4. Ash bed LL13

Ash bed LL13 is located in stratigraphic height 2 m in the Las Loicas section. Zircon yield very low ca. > 10 grains. Zircons crystals ranged from 40-80 μm in size. Grains were mainly prismatic with aspect ratio of 1:8. Radiogenic Pb ranged from 7 to 8 pg (TS.1). The only three three grains that overlapped and reasonably respecting stratigraphic superposition were selected to represent the age of the sample, with 7 grains being discarded for being too (>~450 Ma) and having no geological meaning to the age of the sample. A total of 3 younger grains (z9, z33, z34) that overlapped were considered for the final weighted mean age of the ash bed of 142.039 ± 0.058/0.069/0.17 Ma, MSWD 3.5.

5.5. Ash bed LY5

Ash bed LY5 is located 1.5 m below the contact of the Vaca Muerta Fm. and the Tordillo Fm (FS. 1B). Zircon yield was high ca. > 150 grains. Zircons crystals ranged from 20-100 μm in size. Grains were mainly prismatic with aspect ratio of 1:8 and rounded grains with aspect ratio of 1:3 were also very common. Due to its proximity to the Tordillo Fm, a silisiclastic unit, this sample had a significant amount of inherited grains in the sample distribution. In a first batch of dated grains by CA-ID-TIMS the age distribution had a very large interval 180-450 Ma. Therefore, to optimize time we scanned the distribution of ages of the sample via LA-ICP-MS U-Pb geochronology. Grains were imaged via Cathodoluminescence and 250 grains were analyzed. Subsequently, the twenty youngest grains, based on Concordia ages, were selected to be analyzed via CA-ID-TIMS to obtain a reliable depositional age for the ash bed. A total of seven grains were selected to represent the

age distribution of the sample, with thirteen grains being discarded for being too old ($>\sim$150 Ma) and considered either inherited grains or prolonged magmatic residence or magmatic recycling. A total of four younger grains (z10, z20, z38, z44) that overlapped were considered for the final weighted mean age of the ash bed of 147.112 ± 0.078/0/088/0.18 Ma, MSWD = 0.81. Radiogenic Pb ranged from 1 to 6 pg (TS.1).

5.6. Ash bed MZT-81

Ash bed MZT-81 is located in stratigraphic height ca. 22.5 m in the Mazatepec section. Zircon yield high ca. > 100 grains. Zircons crystals ranged from 40-80 μm in size. Grains were mainly prismatic with aspect ratio of 1:8. Radiogenic Pb ranged from 1 to 6 pg (TS.1), notably lower than other the other samples. A total of eight grains were selected to represent the age distribution of the sample, with 5 grains being discarded for being too old ($>\sim$150 Ma) and considered either inherited grains or prolonged magmatic residence, or magmatic recycling. A total of four younger grains (z41, z42, z44, z45) that overlapped were considered for the final weighted mean age of the ash bed of 140.512 ± 0.031/0/048/0.16 Ma, MSWD = 0.56

6. Age-depth modelling - Bchron Code

library(Bchron)

```
mydata2 = read.table(file='\\Users\\fortesd0\\Documents\\R\\win-
library\\3.4\\Bchron\\OregonPliens.txt', header=TRUE)
GlenOut = Bchronology(ages=mydata2$ages,
        ageSds=mydata2$ageSds,
        calCurves=mydata2$calCurves,
        positions=mydata2$position,
        positionThicknesses=mydata2$thickness,
        ids=mydata2$id,
        predictPositions=seq(0,8400,by=10),iterations = 10000)
plot(GlenOut,main="NeuquenBchron",xlab='Age (Ma)',ylab='Depth (cm)',las=1)
summary(GlenOut)
summary(GlenOut, type='convergence')
summary(GlenOut, type='outliers')


Output <- cbind(apply(GlenOut$thetaPredict, 2, quantile,  probs = c(.0025)),
    apply(GlenOut$thetaPredict, 2, quantile,  probs = c(.5)),
    apply(GlenOut$thetaPredict, 2, quantile,  probs = c(.975)))
write.csv(Output, file = 'whatever.csv', quote=FALSE, row.names = FALSE)
```

```
acc_rate = summary(GlenOut, type = 'acc_rate')
plot(acc_rate[,'age_grid'], acc_rate[,'50%'], type='l', ylab = 'cm per year', xlab = 'Age (k cal
years BP)', ylim = range(acc_rate[,-1]))
lines(acc_rate[,'age_grid'], acc_rate[,'2.5%'], lty='dotted')
lines(acc_rate[,'age_grid'], acc_rate[,'97.5%'], lty='dotted')
sed_rate = summary(GlenOut, type = 'sed_rate', useExisting = FALSE)
plot(sed_rate[,'position_grid'], sed_rate[,'50%'], type='l', ylab = 'Years per cm', xlab = 'Depth
(cm)', ylim = range(sed_rate[,-1]))
lines(sed_rate[,'position_grid'], sed_rate[,'2.5%'], lty='dotted')
lines(sed_rate[,'position_grid'], sed_rate[,'97.5%'], lty='dotted')


write.csv(sed_rate, file = 'NeuquenBchron_sed_rates.csv', quote=FALSE, row.names =
FALSE)
write.csv(GlenOut, file = 'NeuquenBchron_sed_rates.csv', quote=FALSE, row.names =
FALSE)
```

7. Supplementary Figures – Fig. S
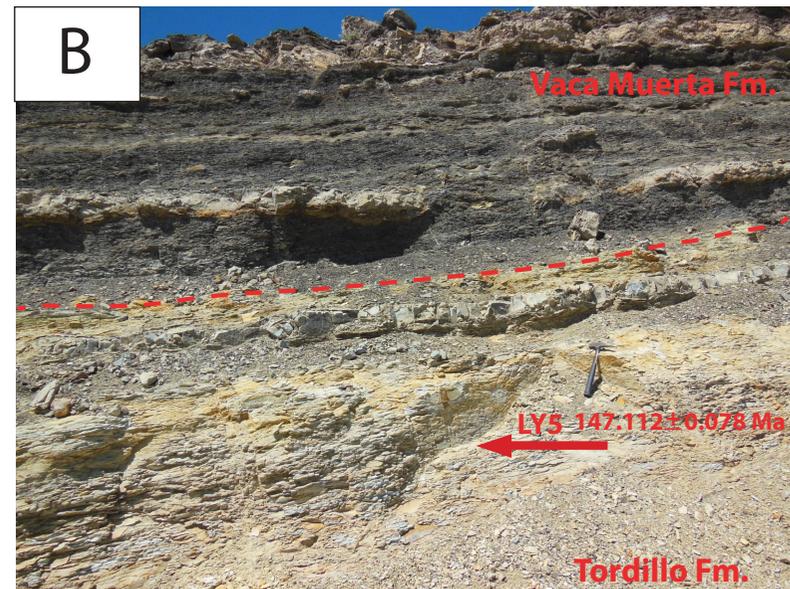
8. Data tables

8.1. U-Pb geochronology data table TS.1

| Fraction | Dates (Ma) | | | | | Composition | | | | | | |
	206Pb/ 238U <Th> a	±2σ abs	207Pb/ 235U b	±2σ abs	Th/ U d	Pb* (pg) e	Pbc (pg) f	206Pb/ 238U i	±2σ %	207Pb/ 235U i	±2σ %
LL3											
z1	139.43	0.11	138.0	1.1	0.97	10.4	0.75	0.021852	0.080	0.1456	0.88
z2	139.36	0.11	138.75	0.76	0.88	9.76	0.43	0.021842	0.079	0.14642	0.59
z11	139.47	0.12	138.7	1.3	0.80	3.37	0.27	0.021858	0.088	0.1464	0.98
z21	139.45	0.11	139.8	1.1	0.97	7.21	0.48	0.021856	0.082	0.1476	0.84
z22	139.44	0.12	139.2	1.2	0.79	4.10	0.22	0.021853	0.086	0.1469	0.93
z23	**139.16**	**0.14**	**136.4**	**1.5**	**0.90**	**4.68**	**0.42**	**0.021809**	**0.10**	**0.1437**	**1.2**
z25	**139.244**	**0.067**	**136.71**	**0.70**	**0.75**	**5.08**	**0.21**	**0.021822**	**0.048**	**0.14413**	**0.55**
z26	**139.27**	**0.10**	**139.45**	**0.77**	**0.79**	**7.78**	**0.37**	**0.021826**	**0.075**	**0.14721**	**0.59**
z32	**139.23**	**0.13**	**139.2**	**1.1**	**0.90**	**6.41**	**0.37**	**0.021820**	**0.093**	**0.1469**	**0.88**
LL9											
z2	**139.98**	**0.11**	**144.6**	**5.2**	**0.73**	**8.68**	**1.02**	**0.021938**	**0.077**	**0.1531**	**3.9**
z5	140.191	0.063	141.2	1.2	0.47	14.0	0.40	0.0219707	0.045	0.1492	0.90
z7	140.19	0.14	141.7	2.3	0.53	8.56	0.46	0.021971	0.097	0.1498	1.8
z12	**139.99**	**0.16**	**150**	**11**	**0.37**	**1.94**	**0.55**	**0.021938**	**0.11**	**0.159**	**8.2**
z33	140.456	0.071	141.3	1.0	0.47	10.3	0.24	0.022013	0.051	0.1493	0.78
z34	140.814	0.078	141.5	1.7	0.78	5.62	0.21	0.022071	0.056	0.1495	1.3
z51	**139.87**	**0.22**	**153**	**15**	**0.37**	**2.54**	**0.96**	**0.021919**	**0.16**	**0.162**	**11**
z52	140.67	0.11	143.6	5.0	0.81	3.13	0.34	0.022048	0.078	0.1519	3.7
z53	140.18	0.14	140.7	2.5	0.65	5.33	0.29	0.021970	0.10	0.1486	1.9
z54	140.35	0.11	142.4	3.3	0.71	3.72	0.27	0.021997	0.080	0.1506	2.5
z55	**139.945**	**0.097**	**141.5**	**2.5**	**0.50**	**6.57**	**0.39**	**0.021932**	**0.070**	**0.1495**	**1.9**
LL10											
z11	140.51	0.13	140.1	1.4	0.82	4.08	0.37	0.022023	0.096	0.1479	1.1
z12	141.20	0.35	140.2	3.8	0.93	1.01	0.24	0.022134	0.25	0.1481	2.9
z13	140.61	0.26	139.6	3.0	0.93	2.57	0.49	0.022039	0.18	0.1474	2.3

z14	140.68	0.23	139.5	2.6	1.10	2.78	0.45	0.022052	0.16	0.1473	2.0
z41	**140.37**	**0.21**	**138.0**	**2.2**	**0.84**	**2.17**	**0.28**	**0.022001**	**0.15**	**0.1456**	**1.7**
z42	140.29	0.12	140.3	1.2	1.14	6.31	0.45	0.021990	0.085	0.1481	0.94
z44	140.32	0.16	139.8	1.2	1.02	4.86	0.32	0.021994	0.12	0.1476	0.96
z45	140.55	0.27	138.3	2.8	0.87	1.42	0.19	0.022029	0.19	0.1459	2.2
MZT-81											
z4	**140.478**	**0.079**	**140.57**	**0.74**	**0.42**	**10.4**	**0.54**	**0.022016**	**0.057**	**0.14848**	**0.57**
z6	**140.504**	**0.083**	**140.41**	**0.85**	**0.53**	**9.91**	**0.60**	**0.022021**	**0.060**	**0.14830**	**0.65**
z7	141.03	0.12	141.7	1.3	0.43	3.31	0.30	0.022103	0.088	0.1498	0.97
z8	**140.518**	**0.047**	**140.39**	**0.25**	**0.53**	**11.1**	**0.17**	**0.0220228**	**0.033**	**0.14828**	**0.19**
z10	**140.528**	**0.061**	**140.22**	**0.45**	**0.53**	**10.9**	**0.33**	**0.0220243**	**0.044**	**0.14809**	**0.34**
z11	140.85	0.10	140.4	1.1	0.48	6.49	0.51	0.022075	0.075	0.1483	0.83
z12	141.22	0.29	141.4	3.4	0.47	2.47	0.60	0.022134	0.21	0.1494	2.6
z15	141.02	0.14	140.1	1.4	0.53	5.98	0.58	0.022102	0.099	0.1479	1.1
LL13											
z9	**142.106**	**0.085**	**142.49**	**0.76**	**0.64**	**8.39**	**0.41**	**0.022275**	**0.060**	**0.15066**	**0.57**
z33	**141.93**	**0.11**	**142.2**	**1.2**	**0.76**	**7.49**	**0.51**	**0.022247**	**0.076**	**0.1503**	**0.88**
z34	**142.05**	**0.12**	**142.6**	**1.1**	**0.93**	**7.09**	**0.39**	**0.022267**	**0.081**	**0.1508**	**0.80**
LY5											
z10	147.8	1.1	144	13	0.71	0.665	0.56	0.02319	0.77	0.152	9.7
z19	148.07	0.42	146.8	4.9	0.51	1.49	0.51	0.023221	0.29	0.1556	3.6
z20	**147.12**	**0.26**	**144.5**	**3.0**	**0.77**	**3.92**	**0.75**	**0.023071**	**0.18**	**0.1529**	**2.2**
z22	148.01	0.36	147.0	3.8	0.39	1.34	0.34	0.023211	0.25	0.1558	2.8
z38	**146.99**	**0.29**	**145.3**	**3.3**	**0.74**	**2.07**	**0.45**	**0.023050**	**0.20**	**0.1539**	**2.5**
z44	**147.118**	**0.086**	**146.49**	**0.82**	**0.75**	**3.37**	**0.15**	**0.023071**	**0.058**	**0.15520**	**0.60**
z67	147.740	0.093	147.09	0.96	0.49	6.20	0.41	0.023168	0.064	0.1559	0.70

a Corrected for initial Th/U disequilibrium using radiogenic 208Pb and Th/U[magma] = 3.50000.

b Isotopic dates calculated using $\lambda238$ = 1.55125E-10 (Jaffey et al. 1971) and $\lambda235$ = 9.8485E-10 (Jaffey et al. 1971).

c % discordance = 100 - (100 * (206Pb/238U date) / (207Pb/206Pb date))

d Th contents calculated from radiogenic 208Pb and 230Th-corrected 206Pb/238U date of the sample, assuming concordance between U-Pb Th-Pb systems.

e Total mass of radiogenic Pb.

f Total mass of common Pb.

g Ratio of radiogenic Pb (including 208Pb) to common Pb.

h Measured ratio corrected for fractionation and spike contribution only.

i Measured ratios corrected for fractionation, tracer and blank.

8.2. Age-depth model data table TS.2

Stratigraphic Height (m)	Age (Ma)	Std Err (2 S.D) (Ma)	Stratigraphic Height (m)	Age (Ma)	Std Err (2 S.D) (Ma)
54	139.24	0.05	15	141.31	0.56
53	139.30	0.15	14	141.37	0.56
52	139.35	0.20	13	141.43	0.52
51	139.41	0.22	12	141.50	0.51
50	139.46	0.23	11	141.56	0.50
49	139.51	0.23	10	141.62	0.49
48	139.57	0.24	9	141.68	0.47
47	139.62	0.23	8	141.74	0.44
46	139.68	0.24	7	141.80	0.40
45	139.73	0.23	6	141.86	0.36
44	139.79	0.22	5	141.92	0.33
43	139.84	0.21	4	141.97	0.23
42	139.90	0.17	3	142.04	0.06
41	139.96	0.07	2	142.10	0.32
40	140.00	0.10	1	142.15	0.42
39	140.03	0.12			
38	140.07	0.12			
37	140.11	0.13			
36	140.15	0.13			
35	140.18	0.13			
34	140.22	0.13			
33	140.27	0.12			
32	140.31	0.11			
31	140.35	0.08			
30	140.42	0.23			
29	140.48	0.30			
28	140.54	0.37			
27	140.60	0.41			
26	140.66	0.43			
25	140.72	0.46			
24	140.78	0.50			
23	140.84	0.50			
22	140.90	0.52			
21	140.96	0.53			
20	141.02	0.55			
19	141.08	0.56			
18	141.14	0.55			
17	141.20	0.56			
16	141.26	0.56			

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