

The age and constitution of Cerro Campanario, a mafic stratovolcano in the Andes of Central Chile

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ABSTRACT

Cerro Campanario, a towering landmark on the continental divide near Paso Pehuenche, is a glacially eroded remnant of a mafic stratovolcano that is much younger than previously supposed. Consisting of fairly uniform basaltic andesite, rich in olivine and plagioclase, the 10-15 km³ edifice grew rapidly near the end of the middle Pleistocene, about 150-160 ka, as indicated by ⁴⁰Ar/³⁹Ar and unspiked K-Ar analyses of its lavas.

Key words: ⁴⁰Ar/³⁹Ar dating, Basaltic andesites, Stratovolcanoes, Middle Pleistocene.

RESUMEN

La edad y formación del cerro Campanario, un estratovolcán máfico de la Cordillera de Talca. El Cerro Campanario, un destacado hito natural en la divisoria continental cerca de Paso Pehuenche, es el remanente dejado por erosión glacial de un estratovolcano máfico más joven de lo supuesto anteriormente. Tal como lo indican los análisis ⁴⁰Ar/³⁹Ar y K-Ar de sus bastante uniformes lavas de andesitas basálticas, ricas en olivina y plagioclasa, su edificio de 10-15 km³ creció rápidamente hacia fines del Pleistoceno medio (150-160 ka).

Palabras claves: Dataciones ⁴⁰Ar/³⁹Ar, Andesitas basálticas, Estratovolcanes, Pleistoceno medio.

INTRODUCTION

Cerro Campanario, an eroded remnant of a mafic volcanic cone, forms a prominent spire on the Andean crest at 35.9°S, just northeast of Laguna del Maule (Fig. 1). Situated only 7 km NNE of Paso Pehuenche, the peak is widely visible to travellers

using the Trans-Andean highway connecting the Provinces of Talca and Mendoza. At 3,943 m, it is, by far, the highest peak in the district, conspicuous and grand in its magnificent isolation. Geologists have long considered the volcano to be rather old,

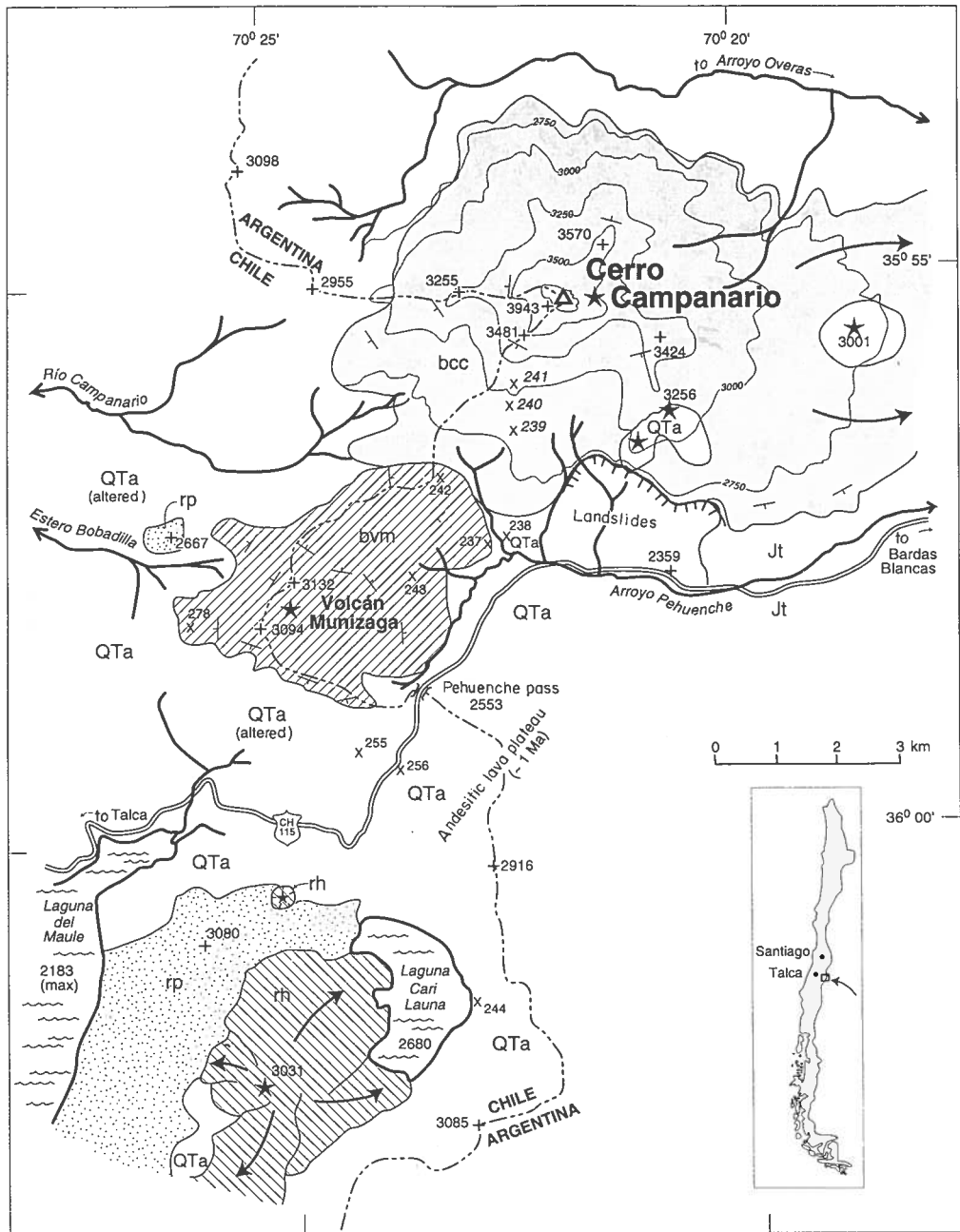


FIG. 1. Reconnaissance geologic map of Paso Pehuenche-Cerro Campanario area, emphasizing main volcanic units and present-day drainage systems. Contour lines shown for Cerro Campanario only; interval 250 m. **Symbols:** Δ - summit of Cerro Campanario; $+$ - selected elevations (in meters); \star - main vent locations for eruptive centers; x - locations of samples in tables 1 and 2; dip symbols show approximate (primary) attitudes of stacks of lava flows; arrows show flow directions of arroyos and lavas. Geologic units: **rh**- postglacial rhyolite lavas; **rp**- Pleistocene rhyolite lavas; **bcc**- basaltic andesites of Cerro Campanario; **bvm**- basaltic andesites of Volcán Munizaga; **QTa**- older andesitic lavas and pyroclastic strata, mostly early Pleistocene, but including probable Pliocene strata east of Paso Pehuenche; **Jt**- Jurassic sedimentary strata, mostly Formación Tordillo and lesser Grupo Mendoza.



FIG. 2. View northeastward toward Cerro Campanario from 8 km southwest of the 3,943-m summit. Low sunlit divide near center of photo is 2,553 m Paso Pehuenche, crossed by the international highway. Extending toward viewer from the craggy stratified fragmental summit is a large black buttress 2,700-3,500 m in elevation that consists of SW-dipping mafic lava flows (site of our samples; Tables 1, 2; Fig. 1). Left and right skyline ridges (3255 m and 3424 m, respectively; see figure 1) are also radially dipping lava ramparts, glacially eroded, each consisting of 8-15 thin mafic lava flows. Lavas of the rampart at right are banked against remnants of an older mafic volcano, including pale crag that represents its shallow intrusive core. At left central edge of photo, middle ridge is part of Volcán Munizaga. In left foreground, lowest ridge consists of pyroxene-andesite lavas about 1 m.y. old (see LdM-255; Table 1). Foreground surface is glaciated plateau of similar (old) andesite lava flows, veneered discontinuously by reworked rhyolitic pumice that was originally deposited as subplinian fallout from postglacial eruptions at Laguna Cari Launa (Fig. 1) and Loma de los Espejos (6 km west of Fig. 1).

early Pleistocene or even Pliocene in age (González and Vergara, 1962), owing principally to its erosively degraded, skeletal condition (Fig. 2). The authors

here present new data showing that Cerro Campanario is only about 150,000 years old.

COMPOSITION AND STRUCTURE OF THE EDIFICE

Cerro Campanario consists of a pyroclastic central core facies that interfingers radially outward into a peripheral shield-like apron of shingled mafic lava flows. The radius of the stratified fragmental central facies is about 1 km and that of the lava apron an additional 2-3 km, giving an edifice diameter of 6-8 km. The authors have not visited all parts of the edifice, but reconnaissance on foot and by helicopter suggests that its lavas and juvenile scoriae are quite uniform basaltic andesite (54% SiO₂; Table 1) rich in phenocrysts of olivine (0.3-1.5 mm; 3-6%) and plagioclase (0.5-4 mm; 20-30%) along with minor titanomagnetite and very sparse clinopyroxene.

Because the volcano was built upon an irregularly glaciated surface of Jurassic sedimentary rocks and early Pleistocene pyroxene-andesite lavas (Fig. 1; Table 1) as high as 3,000 m in elevation, the volume of Cerro Campanario is smaller than it might appear. The central part of the edifice is unlikely to have been more than 200 m higher than the present-day eroded summit, suggesting an original thickness at the core estimated to have been no more than 1,200 m. For the lava apron, most of the volume is medial and well exposed in four radial ramparts (Figs. 1, 2) preserved at 3,000-3,400 m elevation, whereas only a small fraction is represented by the

TABLE 1. CHEMICAL COMPOSITIONS OF LAVA FLOWS.

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI 900°C
Co.Campanario											
LdM-239	54.2	1.23	18.0	8.20	0.14	4.55	7.60	3.83	1.48	0.37	0.24
LdM-240	54.1	1.18	17.85	8.22	0.15	4.16	7.74	4.22	1.56	0.36	<0.01
LdM-241	54.4	1.20	18.0	8.04	0.14	4.46	7.63	3.88	1.48	0.36	<0.01
Pyroxene-andesite lava flows near Paso Pehuenche											
LdM-238	62.3	0.87	16.95	5.23	0.15	1.83	4.28	5.16	2.44	0.40	n.d.
LdM-244	59.4	0.85	18.15	6.38	0.11	2.05	5.30	4.63	2.42	0.31	n.d.
LdM-255	57.7	1.04	17.2	7.81	0.19	2.93	6.70	3.92	1.82	0.27	1.65
LdM-256	55.0	1.11	17.85	8.21	0.16	3.32	8.46	3.73	1.57	0.30	2.85
Volcán Munizaga											
LdM-237	54.0	1.06	17.95	8.80	0.16	4.51	7.72	3.56	1.57	0.27	0.40
LdM-242	53.1	1.20	19.05	8.57	0.15	3.65	8.66	3.78	1.18	0.28	0.31
LdM-243	50.3	1.03	18.45	9.45	0.16	6.77	9.49	3.06	0.71	0.22	1.60
LdM-278	54.7	1.16	17.9	8.67	0.15	4.14	7.23	3.84	1.52	0.30	0.32

Sample locations are shown on figure 1. FeO* - total iron calculated as FeO.

LOI - 'loss on ignition' (weight loss when sample powder is heated to 900°C; largely H₂O loss in these samples). Analyses by wavelength-dispersive XRF on fused glass disks in U.S. Geological Survey Laboratory, Lakewood, Colorado. D. Siems analyst. Major-element data recalculated volatile-free to 99.6 wt % totals (leaving 0.4 wt % for unanalysed trace elements and halogens); n.d.- no data.

distal packages of thin lava flows that follow paleotopography to elevations as low as 2,500 m. The authors estimate the eruptive volume to have been 10-15 km³, of which about half has survived glacial erosion.

Ten or more near-vertical dikes intrude the towering central cone, most prominently on the west flank. Some of them extend all the way to the true summit, providing the strength to support the stratified pyroclastic material making up the jagged summit spire (Fig. 3). The original central vent of the volcano (probably a succession of overlapping ejecta-rimmed craters during its eruptive lifetime) lay slightly east of the present summit and has been hollowed out by glacial erosion to form an eastward-opening cirque. The vent cirque is illustrated in figure 3 as well as in Foto 18 of González and Vergara (1962). It is common for glaciated strato-volcanoes to be centrally gutted in this manner, owing to greater susceptibility to erosion of the fragmental core facies (often acid-fumarolically altered) relative to the more durable lava apron.

Varying with proximity to the rim of the now-destroyed crater complex, the radial dips of the pyroclastic core strata making up the summit cone range from less than 5° to 35° (Fig. 3), whereas the apron lavas generally dip only 5-15° outward (Fig.

2). The core strata reflect hundreds of eruptive pulses and several modes of pyroclast ejection, including fountaining that produced agglutinated spatter, strombolian eruptions that deposited crudely sorted scoria-fall layers, and phreatomagmatic steam blasts that produced very poorly sorted, ash-rich layers. Dense lithic ejecta are subordinate but common, representing fragments of shallow basement rocks and of groundwater-quenched, poorly vesiculated juvenile magma.

It is important to appreciate that the fragmental core facies and the lava apron grew concurrently, so that at any stage in the growth history of the volcano they would have interfingered at roughly 1 km (or less) outboard of the central crater. Lava flows of the peripheral apron would be fed variously by coalescence of fountain-fed spatter, by effusive overflow of lava-filled craters, and by crater-breaching and flank-vent effusions. On steep medial flanks of the cone, the lavas are rubbly and generally only 1-5 m thick, but on the gently dipping apron (remnant ramparts; Fig. 2) some flows thicken to 8-10 m and a few to 15-20 m, owing to diminishing slope and to the effect of cooling on viscosity (*e.g.*, Naranjo *et al.*, 1992). Although volumetrically dominant on the apron, the lava flows are interbedded there with subordinate sheets of scoriaceous rubble



FIG. 3. East face of summit spire of Cerro Campanario, showing top 300 m of the fragmental core facies. Agglutinated pyroclastic deposits at right and left dip radially and steeply outward. Thin vertical dikes cut summit strata, which dip gently west, away from the viewer. Black scoria layer about 10 m below top is itself 8-10 m thick. Craggy gendarme 200 m ENE (right) of summit consists of agglutinated ejecta that dip steeply back (SW) into former crater, now erosively excavated.

representing lava-flow breccia, fallout from the more vigorous vent-clearing explosions, scoria falls, small sector-confined scoria flows, and remobilized slope debris. All the authors' evidence indicates subaerial eruptions, and they have observed none of the extensive hyaloclastites, slender-column entablatures, or subhorizontal columns typical of subglacial or englacial emplacement.

This kind of mafic stratovolcano, cored and crowned by a fragmental facies that interfingers radially with a peripheral shield-like apron of thin lava flows, is especially common in the Oregon Cascades (e.g., North Sister, Three Fingered Jack, and Mounts Thielsen, Washington, and McLoughlin; as illustrated in Wood and Kienle, 1990). Comparable Chilean centers include Volcán Planchón, Volcán Punitagudo, and Cerro Manantial Pelado (10 km northwest of Volcán Descabezado Grande).

Eruptive lifetimes of such relatively homogeneous, basaltic andesite stratocones are seldom well known, but are likely to be short, lasting as little as a few centuries or as long as several thousand years. This is comparable in duration of activity to small shield volcanoes (in arcs), but much shorter-lived than typical andesite-dacite stratocones, which may erupt intermittently for 10^4 - 10^6 years (Hildreth

and Lanphere, 1994; Singer *et al.*, 1997). For example, in Oregon, the 1,100 m mafic cone-plus-shield called Mount Bachelor (~ 25 km³) grew in about 1,000 years (Scott and Gardner, 1992); in New Zealand, the 900 m mafic cone Mount Ngauruhoe (2-3 km³) has grown in 2,500 years (Donoghue *et al.*, 1995); in Nicaragua, 1250 m Volcán Momotombo (12-15 km³) has grown in ~ 4500 years (Kirianov *et al.*, 1988); and in El Salvador, the 650 m mafic stratocone, Volcán Izalco (~ 2 km³), originated only two centuries ago in 1770 (Carr and Pontier, 1981). Each is compositionally and volcanologically similar (not identical) to Cerro Campanario.

Some predominantly mafic cones are longer-lived, but longevity usually entails magma storage and differentiation that produces a wider range in composition. A well studied example only 45 km west of Cerro Campanario is the 1,000 m late Pleistocene edifice, Volcán Tatara (Singer *et al.*, 1997). As a discrete component of a much longer-lived compound center, the 25 km³ Tatara cone was itself intermittently active for about 70 k.y. Though mostly mafic (52-57 % SiO₂), the eruptive products of Volcán Tatara also include many silicic andesites, a few dacites, and a rhyolite as well (Singer *et al.*, 1997, Fig. 6). No such evolved products have been

TABLE 2. COMPLETE $^{40}\text{Ar}/^{39}\text{Ar}$ INCREMENTAL-HEATING DATA FOR CERRO CAMPANARIO SAMPLES.

Temperature °C	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}^a$	$^{36}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}^*$ (10^{-13} mol)	% $^{40}\text{Ar}^*$	K/Ca	^{39}Ar cumulative %	Apparent age $\pm 1\sigma$ ka ^b
LdM-240	Whole rock^c		201 mg	J=0.0001211\pm0.0000006		Total gas age=144 \pm 2 ka		
500	13.664	1.555	0.04418	0.040	5.35	0.32	2.6	159.6 \pm 13.8
550	5.598	1.465	0.01671	0.007	13.79	0.33	7.0	168.8 \pm 7.3
600	2.835	1.371	0.00737	0.131	26.95	0.36	14.8	167.0 \pm 3.7
650	1.877	1.315	0.00427	0.185	38.13	0.37	26.7	156.5 \pm 2.5
700 ^d	1.673	1.276	0.00369	0.232	40.79	0.38	42.2	149.1 \pm 1.8
730	1.822	1.191	0.00425	0.177	36.17	0.41	54.5	143.9 \pm 2.5
760	2.116	1.199	0.00525	0.156	31.08	0.41	65.4	143.8 \pm 3.1
790	2.697	1.378	0.00731	0.122	23.81	0.36	74.1	140.3 \pm 3.1
830	3.877	1.762	0.01156	0.010	14.41	0.28	81.6	130.5 \pm 3.9
880	6.614	2.043	0.02109	0.008	8.16	0.24	88.2	118.1 \pm 4.9
925	12.140	1.747	0.04117	0.001	0.91	0.28	92.0	23.9 \pm 9.0
975	18.073	1.449	0.06002	0.004	2.48	0.34	96.6	98.1 \pm 22.5
1050	34.798	4.803	0.11470	0.009	3.68	0.10	100.0	280.0 \pm 46.6
Weighted mean plateau age								146 \pm 2
Isochron age								156 \pm 4
LdM-241	Plagioclase^e		100 mg	J=0.0003890 \pm 0.0000012		Total gas age = 261 \pm 136 ka		
800	40.787	24.866	0.14287	0.002	1.24	0.02	7.8	361.8 \pm 1655
900	13.896	24.571	0.05258	0.002	1.97	0.02	23.0	195.6 \pm 205.4
1000	4.889	23.309	0.02189	0.003	4.85	0.02	47.5	168.8 \pm 46.2
1100	3.177	20.981	0.01524	0.004	9.73	0.02	75.7	219.8 \pm 46.6
1200	11.221	19.748	0.04149	0.004	4.46	0.02	91.1	355.5 \pm 123.1
1300	9.097	18.164	0.03316	0.003	7.86	0.03	100.0	507.6 \pm 196.9
Weighted mean plateau age								212 \pm 29
Isochron age								180 \pm 47

^a Corrected for ^{37}Ar and ^{39}Ar decay, half-lives of 35 days and 259 years, respectively.

^b $\lambda_{\epsilon} = 0.581 \times 10^{-10}/\text{yr}$; $\lambda_{\beta} = 4.692 \times 10^{-10}/\text{yr}$. Errors reflect $\pm 1\sigma$ analytical uncertainty.

^c Ages calculated relative to sanidine from Alder Creek rhyolite (1.19 Ma; Turrin *et al.*, 1994; see text).

^d Temperature and age of plateau steps are in italics.

^e Ages calculated relative to HDB-1 biotite (24.29 Ma; Wijbrans *et al.*, 1995; see text).

found at Cerro Campanario. If Cerro Campanario is as uniformly mafic as the authors' existing evidence suggests, its active lifetime probably lasted less

than 10^4 years, comparable to the examples cited above.

PREVIOUS AGE ESTIMATES

In their pioneering regional reconnaissance, González and Vergara (1962) referred to Cerro Campanario as 'Plioceno-Pleistoceno', lumping the volcano with the Formación Cola de Zorro on their map. Drake (1976) did not date Cerro Campanario itself, but he inferred its age to fall in the range 1.3-0.6 Ma on the basis of his K-Ar determinations for several lavas and ignimbrites nearby. The

authors' ongoing mapping of the Laguna del Maule region demonstrates that Cerro Campanario is stratigraphically younger than all the relevant units dated by Drake (samples 43 through 46; 0.68-1.16 Ma).

Vergara and Munizaga (1974) presented a whole-rock K-Ar age of 1.97 ± 0.60 Ma (5.7% radiogenic Ar and 1.49 wt% K_2O) for sample Ca-6 of Munizaga (1978), one of a sequence of mafic lava flows

collected by Munizaga at the south base of Cerro Campanario. Although it was listed as a 'pyroxene andesite' in the analytical tables of Vergara and Munizaga (1974) and Munizaga (1978), the authors recovered Ca-6 and several related samples from the rock archives of the Departamento de Geología (Universidad de Chile) and verified in hand-specimen and in thin-section that the suite consists of olivine-plagioclase mafic andesites unequivocally of Cerro Campanario type. The K_2O content of Ca-6 (1.49 wt%) is close to those of the authors' present Cerro Campanario samples (Table 1). Munizaga's (1978) modal determinations (Table No. 2) for two lavas in

the stack with Ca-6 show phenocryst contents (20–30% plagioclase, 2–4% olivine, minor opaques and clinopyroxene) similar to those of Ca-6 and the authors' own samples. These observations leave little doubt that the dated sample Ca-6 represents an olivine-andesite lava from Cerro Campanario and not a pyroxene-andesite lava of the subjacent plateau (Figs. 1, 2). The authors speculate that the 1.97 Ma age reflects either an unknown analytical problem or too high a blank when Ca-6 was dated in 1971 by Munizaga as a guest researcher in the Sao Paulo Geochronology Laboratory, which was then largely dedicated to dating Precambrian rocks.

NEW AGE DETERMINATIONS

METHODS

Reconnaissance study of Cerro Campanario was undertaken during preparation of a volcanological geologic map of the Laguna del Maule region (Hildreth *et al.*, 1991; Drake and Hildreth, 1992; Servicio Nacional de Geología y Minería, in prep.). The samples analyzed were collected from massive zones of successive lava flows at 2,850–3,025 m (Fig. 1) on the SSW slope of the edifice. Each sample is fresh, nonvesicular, unoxidized, and rich in plagioclase and (iddingsite-free) olivine phenocrysts, with only traces of glass in the nearly holocrystalline groundmass. Because the lavas contain euhedral plagioclase as big as 4 mm, the authors first analyzed a plagioclase separate (from sample LdM-241). After determining an unexpectedly young age, they chose to verify it by analyzing a whole-rock sample (LdM-240) of the directly subjacent lava flow.

Plagioclase grains from the 180–500 μm sieve fraction of sample LdM-241 were etched in an ultrasonic bath for 10 minutes in 5% HF, followed by 10 minutes in de-ionized H_2O , before removing inclusion-bearing grains under a binocular microscope. A cleaned plagioclase separate of 100 mg was loaded into a pure copper foil packet and placed, along with other samples and 9 aluminum packets containing the neutron flux monitor mineral HD-B1 biotite, into a quartz vial 127 mm long and 6 mm in diameter. This vial was evacuated, sealed, and later irradiated for two hours at the Oregon State University Triga Reactor in the cadmium-lined

inner core facility (CLICIT) where it received a total fast neutron dose of $\sim 1.8 \times 10^{17}$ n/cm². Similarly, a 9 mm diameter, 1 mm thick whole-rock wafer of sample LdM-241 weighing 201 mg, was loaded into a quartz vial monitored with Alder Creek rhyolite sanidine packets and irradiated for 30 minutes in the Oregon State CLICIT facility, receiving a neutron dose of $\sim 4 \times 10^{16}$ n/cm². Undesirable isotopes produced during neutron bombardment include small amounts of ⁴⁰Ar derived from K, plus ³⁶Ar and ³⁹Ar produced from Ca. For young materials with low radiogenic ⁴⁰Ar contents, it becomes increasingly important to correct measured ratios for these effects; reactor corrections for the CLICIT facility are: [⁴⁰Ar/³⁹Ar]_K = 0.00086; [³⁶Ar/³⁷Ar]_{Ca} = 0.000264; and [³⁹Ar/³⁷Ar]_{Ca} = 0.000673 (Singer and Pringle, 1996).

The ⁴⁰Ar/³⁹Ar method is a relative dating technique in which the age of an 'unknown' sample is calculated relative to the ages of well-characterized standard minerals used as neutron flux monitors. HD-B1 biotite has a recommended K-Ar age of 24.21 ± 0.32 Ma (Lippolt and Hess, 1994), but a multi-grain ⁴⁰Ar/³⁹Ar incremental-heating analysis of this standard gave a plateau age of 24.29 ± 0.03 Ma (Wijbrans *et al.*, 1995). Alder Creek rhyolite sanidine yielded indistinguishable ⁴⁰Ar/³⁹Ar plateau and isochron ages with a mean of 1.19 ± 0.01 Ma (Turrin *et al.*, 1994). In the present study, neutron fluence monitor packets were incrementally heated and the mean ⁴⁰Ar/³⁹Ar ratio from 5–7 plateau steps was used to calculate a J-value at each monitor point within the quartz vials. Accordingly, J-values for samples LdM-240 and LdM-241 were obtained by interpolation between

the adjacent monitor positions and ages were calculated relative to 24.29 Ma for HD-B1 biotite (for sample LdM-241) and 1.19 Ma for Alder Creek rhyolite sanidine (for LdM-240).

At the University of Geneva $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology Laboratory, samples were loaded into the vacuum system, introduced to the resistance furnace, and degassed at 600°C (LdM-241 plagioclase) or 450°C (LdM-240 whole-rock) prior to incremental heating analysis. Experience has shown that low temperature degassing of young whole rock and plagioclase samples in this manner removes a substantial proportion of adsorbed atmospheric argon and improves total system blanks. Purified gas increments liberated successively between 500-1050°C (LdM-240 whole-rock) and 800-1300°C (LdM-241 plagioclase) were measured isotopically using a MAP-216 spectrometer. Procedures for gas clean-up, mass spectrometry, and estimation of analytical uncertainties are given by Singer and Pringle (1996). Errors reported at the 1 σ level for each individual gas analysis reflect internal factors including analytical precision of the peak signals, the system blank, spectrometer mass discrimination, and reactor corrections. Because the uncertainty in the measured J-values affects all gas samples in a uniform, non-random manner, this additional uncertainty of 0.3% (LdM-241) or 0.5% (LdM-240) was propagated into the calculated total fusion, weighted mean plateau, and isochron ages.

The accuracy of eruptive ages determined by $^{40}\text{Ar}/^{39}\text{Ar}$ analyses is governed by how well the age of the neutron flux monitor mineral is known, and by geological factors including the abundance and behavior of glass, alteration phases, or inherited components. The ages of the two neutron fluence

standards used are probably accurate to within $\pm 1\%$, and this does not pose a problem with respect to conclusions drawn in this study. The pattern of apparent ages *versus* % ^{39}Ar released in an age spectrum diagram can provide tests for argon loss from glass or alteration phases and can show whether inherited or excess argon has contributed to spuriously old apparent ages. Indeed, the ability to define an age plateau characterized by a contiguous group of concordant ages and to calculate an isochron age using only the data defining a plateau is one of the principal advantages of the $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-heating technique (Singer and Pringle, 1996).

As an independent test, replicate age determinations were made on a groundmass separate from sample LdM-240 using an unspiked K-Ar technique (Cassignol and Gillot, 1982) at Gif-sur-Yvette, France. The sample was crushed and sieved to obtain the 0.25-0.125 mm fraction and then ultrasonically washed in $\text{HC}_2\text{H}_3\text{O}_2$ in order to remove phases formed by alteration. K and Ar measurements were performed on the microcrystalline groundmass, which best represents material that crystallized during solidification of the lava. Phenocrysts and xenocrysts, which sometimes carry excess ^{40}Ar , were removed by routine magnetic and heavy-liquid separations. Potassium was determined by atomic absorption and flame emission spectrometry. Argon was extracted from 1-3 g groundmass splits by radio-frequency induction heating in a high-vacuum glass line, then purified with a titanium sponge and Zr-Al getters. Argon was analysed using a 180° mass spectrometer (radius 6 cm; accelerating potential 620 volts) working in a semistatic mode.

RESULTS

Complete $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-heating data for both samples are given in table 2, and the age spectra and inverse isotope correlation diagrams are shown in figure 4. The plagioclase separate from LdM-241 gave an integrated total fusion age of 261 \pm 136 ka, which is equivalent to a K-Ar age for this sample. Although the apparent ages increase at higher temperature (larger fractions of ^{39}Ar released), all six steps are indistinguishable in age at the 95% confidence level and define a weighted mean plateau

age of 212 \pm 29 ka (Fig. 4). The six 'plateau' points define an isochron of 180 \pm 47 ka with an $^{40}\text{Ar}/^{36}\text{Ar}$ intercept of 297.5 \pm 2.4. The poor precision reflects low radiogenic argon yields, producing large uncertainties for each step as well as low dispersion along the isochron. Because isochron calculations combine quantitative estimates of analytical precision and internal disturbance of the sample (dispersion of points about the isochron, measured by the $\text{sums}/(n-2)$ term; York, 1969), without assuming

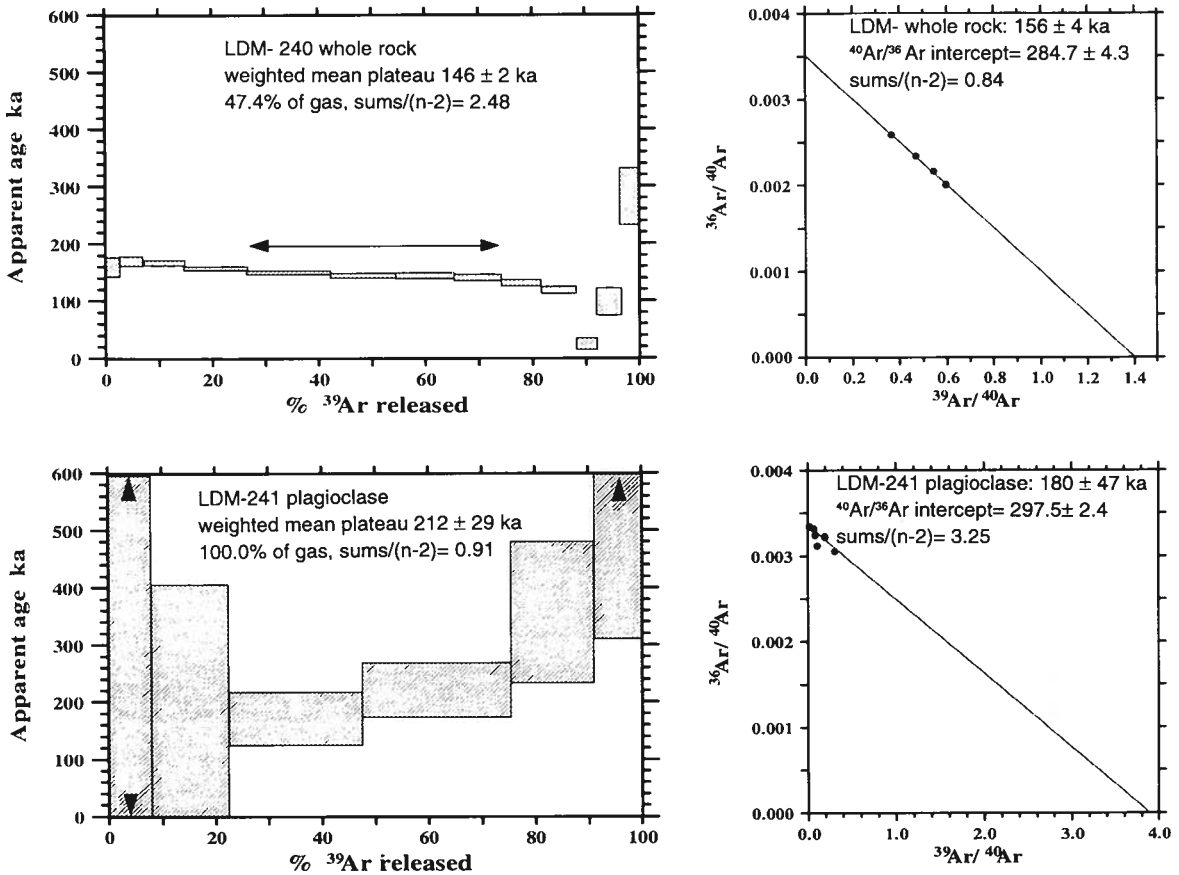


FIG. 4. ^{40}Ar - ^{39}Ar incremental-heating age spectra and inverse isochron correlation diagrams for Cerro Campanario samples. Thickness of bar for each step indicates uncertainty in individual ages. For LdM-240, Total Fusion age is 144 ± 2 ka; using four central increments only (arrow), weighed mean plateau age is 146 ± 2 Ka, and isochron age is 156 ± 4 ka. See table 2 for data and text for discussion of plagioclase separated from LdM-241, a lava flow directly overlying LdM-240.

an atmospheric value for the initial argon present, isochron ages are strongly preferred over plateau ages (as elaborated by Singer and Pringle, 1996).

Whole-rock sample LdM-240 yielded a more complex discordant age spectrum with a total fusion age of 144 ± 2 ka. The initial 86% of gas released defines a progressive downward staircase-style spectrum, whereas apparent ages increase in the last two steps (Fig. 4). The most probable cause of progressively decreasing apparent ages in a poly-phase volcanic sample is that during irradiation some ^{39}Ar was redistributed within the sample due to recoil effects. Theoretical and experimental evidence indicates that ^{39}Ar may recoil out of fine-grained K-rich phases (including glass, mesostasis, or clay that release argon at low temperature) and may subsequently become implanted into K-poor

phases such as olivine or pyroxene that release argon at much higher temperature (Turner and Cadogan, 1974). The result is that apparent ages calculated from low-temperature and high-temperature gas steps have no geological significance. However, the intermediate temperature steps are commonly unaffected by recoil and can yield plateau ages corresponding to the crystallization age of the sample (e.g., Dalrymple and Ryder, 1993). In the case of the LdM-240 whole-rock spectrum, four gas increments released between 730 - 790°C comprising 47% of the total gas, gave concordant ages that define a weighted mean plateau age of 146 ± 2 ka (Fig. 4). The isochron defined by the four plateau points is 156 ± 4 ka and has an $^{40}\text{Ar}/^{36}\text{Ar}$ intercept of 284.7 ± 4.3 . That the intercept ratio is slightly lower than the atmospheric value of 295.5 is probably a

TABLE 3. K-Ar AGES OF SAMPLE LdM-240 BY UNSPIKED CASSIGNOL METHOD.

Sample	wt% K	Weight molten (g)	⁴⁰ Ar* (%)	⁴⁰ Ar* (10 ⁻¹³ mol/g)	Age (ka) (± 1σ)
LdM-240	1.512 ± 0.015	2.72146	1.491	3.975	152 ± 2
LdM-240	1.512 ± 0.015	1.09175	1.147	3.869	148 ± 3
Weighted mean age = 150 ± 2					

*Argon extraction by method of Cassignol and Gillot (1982). Age calculations based on constants of Steiger and Jäger (1977).

subtle artifact of ³⁹Ar recoil. (Recalculating the plateau age by assuming a trapped ⁴⁰Ar/³⁶Ar ratio of 284.7 yields an age of 156±1 ka. This age is identical to the

isochron age and indicates that any recoil effects contribute less uncertainty than do other analytical errors). The older apparent age for the last gas step may reflect degassing of refractory olivine or pyroxene xenocrysts (or inclusions within these phases), or a poorly controlled high-temperature blank component derived from the resistance furnace. Thus, the isochron age of 156±4 ka gives the authors' most reliable estimate of the time elapsed since eruption of the LdM-240 lava flow.

The replicate unspiked K-Ar determinations for sample LdM-240 gave a weighted mean age of 150±2 ka (Table 3), which is indistinguishable from its ⁴⁰Ar/³⁹Ar isochron age.

DISCUSSION AND IMPLICATIONS

Cerro Campanario lavas contain some plagioclase crystals with complicated oscillatory zoning, dissolution surfaces with overgrowths, intergrown compound grains, and polycrystalline clots intergrown with olivine, suggesting a complex pre-eruptive thermal and compositional history for the magma (see discussion of such processes at the Tatara San Pedro complex by Singer *et al.*, 1995). Glass (melt) inclusions in plagioclase (and fewer in olivine) are potential sites for retention of excess argon contributed to the magma from the mantle or crust, trapped within phenocrysts during crystal growth, and unable to degas during depressurization and eruption. In extreme cases, this type of excess argon may contribute to apparent ages far exceeding the true eruptive age (*e.g.*, Esser *et al.*, 1996). Alternatively, plagioclase xenocrysts plucked from old crustal wallrocks and entrained into the magma may not degas completely before eruption and, depending on their age, even a minute quantity of such inherited xenocrysts can severely increase apparent ages calculated for Pleistocene samples (Singer *et al.*, 1996).

The atmospheric value of the ⁴⁰Ar/³⁶Ar ratio for LdM-241 plagioclase, coupled with the fact that total

fusion and isochron ages are indistinguishable, argues against incorporation of any significant inherited component, either in the form of xenocrysts or as excess argon from undegassed melt inclusions. Similarly, the total fusion, plateau, and isochron ages from the LdM-240 whole-rock sample are indistinguishable at the 95% confidence level. This provides strong evidence that any effects of ³⁹Ar recoil, xenocryst inheritance, and excess argon on the calculated ages are small or negligible. The authors emphasize that any argon contributed from inherited or excess components would lead to apparent ages only older, not younger, than the true eruptive ages of the Cerro Campanario lavas.

The authors conclude that the lavas sampled, and probably all of Cerro Campanario, erupted in the later part of the middle Pleistocene, the authors' preferred estimate of 150-160 ka, being based on concordant ⁴⁰Ar/³⁹Ar and unspiked K-Ar results. Accordingly, the spectacular erosion that sculptured the edifice (Figs. 2, 3) took place during stades of the last Pleistocene glaciation and during the later part of the penultimate glaciation (marine oxygen-isotope stage 6).

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