

PETROCHEMISTRY AND AGE OF RHYOLITIC PYROCLASTIC FLOWS WHICH OCCUR ALONG THE DRAINAGE VALLEYS OF THE RIO MAIPO AND RIO CACHAPOAL (CHILE) AND THE RIO YAUCHA AND RIO PAPAGAYOS (ARGENTINA)

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ABSTRACT

Forty-five pumice fragments were collected for study from different outcrops of pyroclastic flows which occur within the Central Valley and both the Andean Main and Coastal Ranges, along the valleys of the Río Maipo and Río Cachapoal in Chile, and within the eastern Andean foothills along the valleys of the Río Papagayos in Argentina. The samples are crystal-poor high-silica rhyolites characterized by very restricted concentration ranges of Rb = 103-156 ppm, Sr = 62-86 ppm, and Zr = 57-89 ppm. Average values of $^{87}\text{Sr}/^{86}\text{Sr} = 0.70594$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51255$, and $\delta^{18}\text{O} = 10.1$, determined for selected samples, are markedly distinct from previously reported values for volcanic rocks from the Southern Andes of Central Chile. Fission-track dating of zircon separates from samples collected in the vicinity of Santiago and Rancagua yielded ages of 0.47 ± 0.07 m.y. and 0.44 ± 0.08 m.y., respectively, consistent with the Upper Pleistocene age determined on stratigraphic grounds for similar deposits in Argentina. The similarity in age, trace element, and isotopic composition of the pumice fragments from the various outcrops, combined with their geochemical distinctness with respect to other volcanic rocks in the region, suggest that these pyroclastic flows were emplaced in a single or series of closely spaced eruptions, $450,000 \pm 60,000$ years ago. On the basis of the distribution and thickness of the deposits, a single source, the Maipo volcanic complex, is inferred and an approximate volume of 450 km^3 , for the pyroclastic flows is estimated.

RESUMEN

Se estudiaron cuarenta y cinco muestras de pómez recogidas en distintos afloramientos de flujos piroclásticos, en la Depresión Longitudinal, en la Cordillera de la Costa y la vertiente occidental de la Cordillera Principal a lo largo de los valles de los ríos Maipo y Cachapoal en Chile y en el margen oriental de la Precordillera, a lo largo del valle del río Papagayos en Argentina. Las muestras corresponden a riolitas, con escasos cristales y alto contenido en sílice, caracterizadas por un reducido rango de concentraciones de Rb = 103-156 ppm, Sr = 62-86 ppm, y Zr = 57-89 ppm. Las razones promedio de $^{87}\text{Sr}/^{86}\text{Sr} = 0.70594$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51255$ y $\delta^{18}\text{O} = 10.1$, en muestras seleccionadas, son notablemente diferentes a los valores obtenidos en estudios anteriores, en rocas volcánicas de la zona sur de los Andes Centrales de Chile. Dataciones por el método de trazas de fisión ("fission-track"), en circones separados de muestras recogidas en los alrededores de Santiago y Rancagua, dieron edades de 0.47 ± 0.07 Ma y 0.44 ± 0.08 Ma, respectivamente. Estas edades son compatibles con aquellas determinadas mediante criterios estratigráficos en depósitos semejantes en Argentina. La similitud en edad, el contenido de elementos trazas y la composición isotópica de los distintos afloramientos, combinados con la geoquímica distintiva que diferencia a estas rocas de otras rocas volcánicas de la región, sugieren que estos flujos piroclásticos fueron emplazados durante una erupción o una serie de erupciones cercanamente espaciadas, hace 450.000 ± 60.000 años, desde un mismo centro. En base a la distribución y espesores de los afloramientos, se infiere que este centro es el Complejo Volcánico Maipo y que el volumen de estos flujos piroclásticos es, probablemente, de 450 km^3 .

INTRODUCTION

Just west of Santiago, along the road to and in the vicinity of the International Airport in the community of Pudahuel, the surface geology consists of a plain of gentle hills and terraces formed by deposits of volcanic ash containing pumice and other lithic fragments. Lithologically similar deposits occur at the surface further to the west, in the valley of the Río Maipo and Río Puangue, to the south, in the vicinity of Rancagua as well as west of Rancagua in the valleys of the Río Cachapoal and Río Rapel, to the east, within the Andean Main Range Front in the valleys of the Río Maipo, Río Codegua and Río Cachapoal, and along the eastern foothills of the Andes in the valleys of the Río Papagayos and Río Yaucha (Fig. 1). These outcrops have been thoroughly described by the authors quoted in the next paragraph.

Polanski (1962) described vertical variations in the degree of welding within the deposits of the Río Papagayos and Río Yaucha in Argentina. He concluded that these deposits were volcanic in origin; the most welded ones resembling ignimbrites. He noted that these deposits thickened within the drainage valleys leading to the Maipo volcano and suggested the "huge explosion caldera of the laguna del Diamante", in which this volcano was developed, as their source (Figs. 2 and 3). The ash-deposits in the northern Central Valley of Chile, once interpreted as pumice moraines (Brüggen, 1950; Karzulovic, 1960), were later reinterpreted as either mudflows (Segerstrom *et al.*, 1964), lahars (Stiefel, 1965) or pyroclastic flows (Guest and Jones 1970). They were studied sedimentologically by Santana (1971) who concluded, following Polanski, that these deposits represent pyroclastic

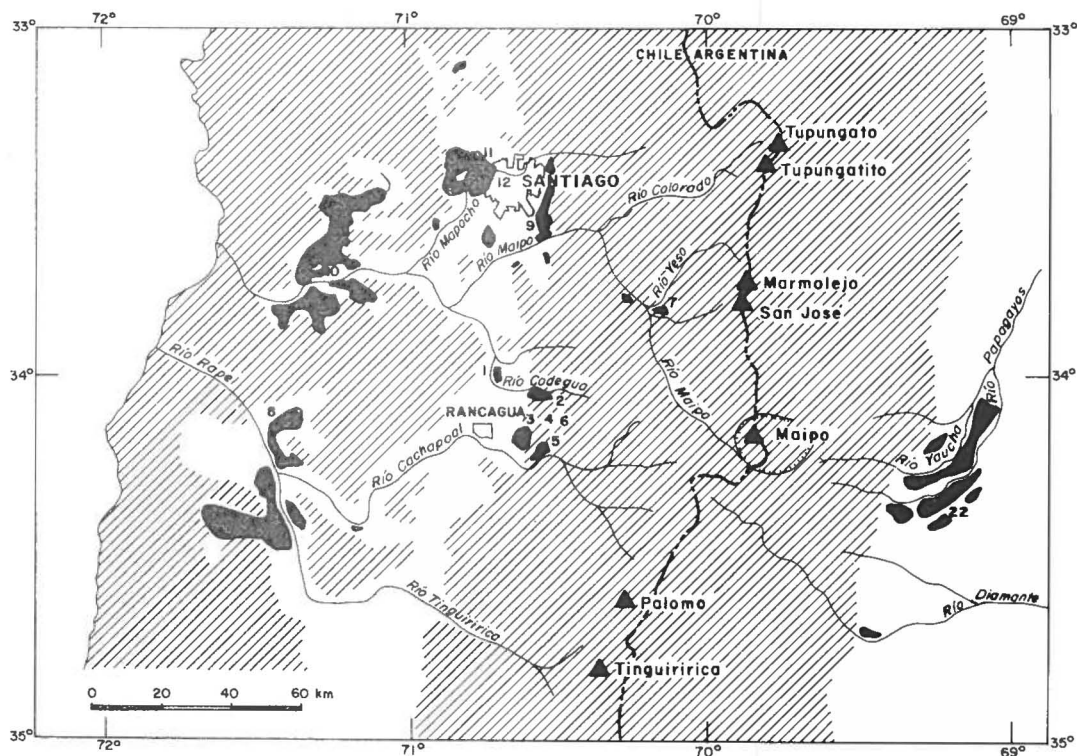


FIG. 1. Distribution of outcrops of the pyroclastic flow deposits within the Central Valley, Main Range and Coastal Range along the valleys of the Río Maipo and Río Cachapoal in Chile, and within the eastern Andean Precordillera along the valleys of the Río Yaucha and Río Papagayos in Argentina (modified after Santana, 1971). Numbers indicate sample localities referred to in the text, tables, and other figures. Shaded areas are topographically high and include both the Main and the Coastal Ranges. Also indicated are major volcanic centers and the extent of the depression inferred to be a ring caldera within which the Maipo volcano is located.

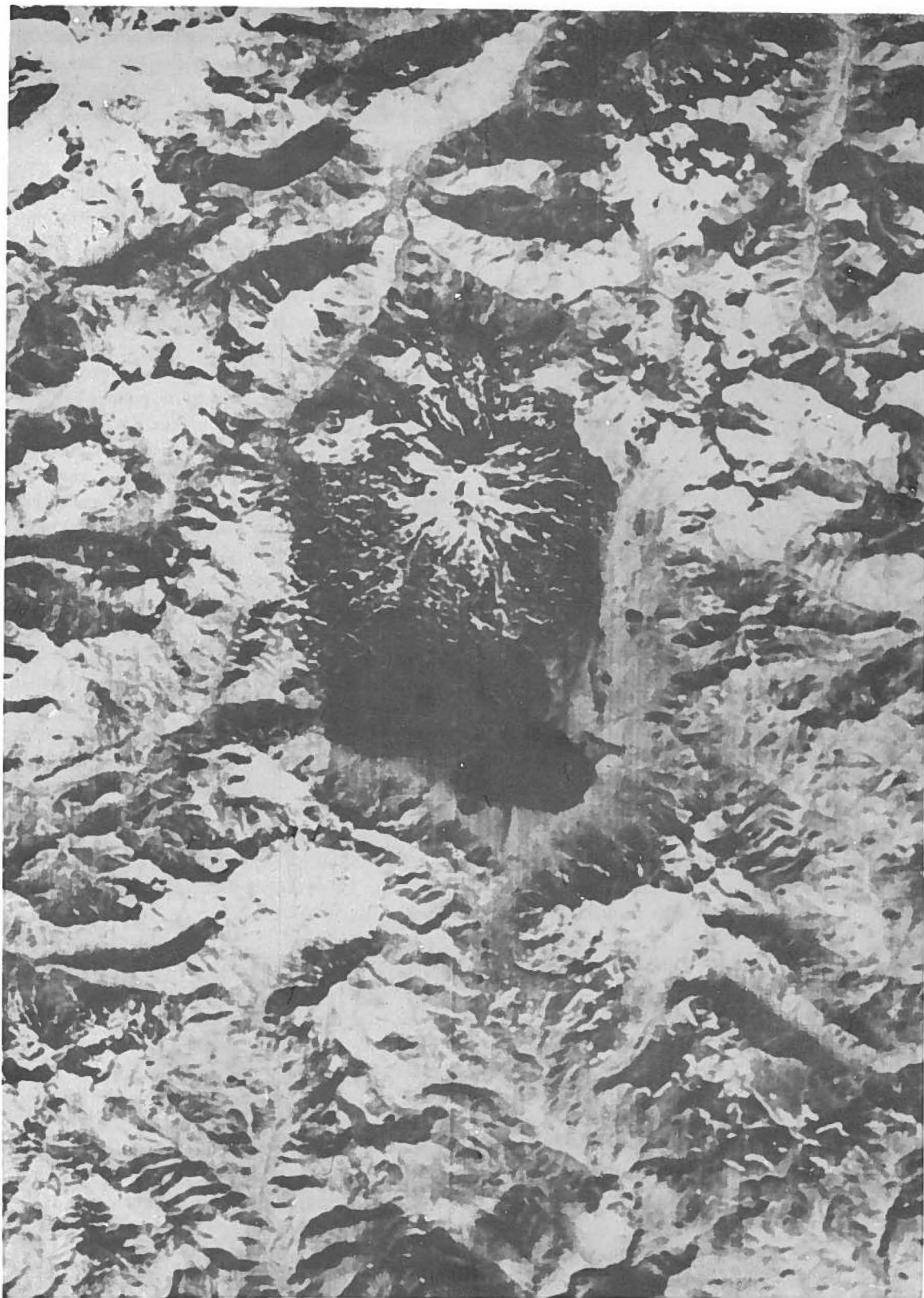


FIG. 2. Satellite view of the elliptic (20 x 15 km) Laguna del Diamante Caldera. The Maipo Volcano was built in its western half. Scale 1:250,000.



FIG. 3. Northward view of the Maipo Volcano. In foreground Upper Jurassic red sandstones of the caldera rim.

flows derived from the Maipo volcano. A similar interpretation had been reached previously by Borde (1958, 1966), who suggested the San José or the Maipo volcanoes as their possible source.

Although the distribution of these deposits along the Río Papagayos, Río Yaucha, and Río

Maipo are consistent with the Maipo volcano being their source (Fig. 1), the mechanism of emplacement of these deposits along the Río Cachapoal and Río Rapel is problematic, since these drainage systems are separated from the Maipo volcano by a high topographic wall.

Polanski (1962), based on stratigraphic evidence, suggested that the age of the deposits in the Andean foothills of Argentina is Late Pleistocene. A significant question related to the age of all the outcrops of lithologically similar pyroclastic deposits indicated in figure 1, is whether or not they are contemporaneous or could have been emplaced in a sequence of separate events.

This paper presents geochemical and geochronological analyses of fragments of pumice collected from various outcrops of these ash-deposits. The geochemical data confirm the close similarity of these widely dispersed deposits, and in conjunction with the geochronological data suggest that these pyroclastic flows formed and were emplaced in a single large eruption, approximately 450,000 years ago, which formed a caldera within which the Maipo volcano is located. The extent of such an event (see Discussion), if it were to reoccur, would have catastrophic consequences for the main population centers of Chile, in particular Santiago. The petrochemical data also confirm and give further emphasis to the previously suggested differences between volcanism in the northern (33° - 36° S) and southern (36° - 46° S) parts of Central-South Chile, and the previously suggested similarities between volcanism in the northern part of Central-South Chile and in Northern Chile (Moreno, 1974; López-Escobar *et al.*, 1976; Hildreth *et al.*, 1984).

PETROCHEMISTRY

Samples of pumice were collected from the various deposits of the ash flows in the northern part of the Central Valley of Chile, from river valleys within both the Coastal Range and the Main Range, and from the eastern Andean foothills of Argentina. Sample localities are given in figure 1. Over five kilograms of pumice fragments were collected from outcrops near Santiago (locality Nr. 12) and Rancagua (locality Nr. 6) for obtaining mineral separates for age dating, but typically 5-10 individual pumice fragments were collected from the other localities. The fresh central portion of the largest 3-5 samples from each locality were

ground up for chemical analysis. The resultant 45 samples were analyzed for Sr, Rb, Zr, Ba, La, Ce, and Y by X-ray fluorescence techniques. Three samples, one from the vicinity of Santiago (locality Nr. 11), one from the vicinity of Rancagua (locality Nr. 6), and one from Argentina (locality Nr. 22) were analyzed for major and trace element compositions and for isotopic ratios of Sr, Nd, O, and Pb. These data are presented in Table 1 and illustrated in figures 4, 5 and 6.

Petrographic examination of thin sections, cut from representative pumice samples, indicate that they are all very similar, consisting of highly ve-

TABLE 1. MAJOR AND TRACE ELEMENT AND ISOTOPIC COMPOSITION OF THREE PUMICE FRAGMENTS AND A GLASSY RHYOLITE DOME AT LAGUNA DEL MAULE*

Sample location**	Nr. 11	Nr. 6	Nr. 22	Laguna del Maule
SiO ₂	75.8	75.1	74.1	73.4
TiO ₂	0.15	0.12	0.10	0.19
Al ₂ O ₃	13.3	12.2	12.2	14.2
FeO	0.7	0.65	0.55	1.6
MgO	0.2	0.15	0.17	0.21
CaO	0.45	0.39	0.50	0.63
Na ₂ O	4.3	4.1	4.2	5.36
K ₂ O	3.9	4.1	4.2	4.0
LOI	—	3.0	3.4	—
Total	98.8	99.81	99.42	99.59
Rb	141	154	141.9	150
Sr	64	70	72.4	94
Ba	715	769	745	717
Zr	76	78	79	193
Y	24	26	26	20
Th	15.1	11.2	11.5	19.3
U	4.4	5.2	4.9	—
Sc	2.1	2.5	2.3	2.5
Cs	4.2	4.0	3.9	5.0
La	20.3	16.1	19.1	30
Ce	48.4	33.4	36.5	62.6
Nd	17.2	16.2	—	22.8
Sm	3.7	3.8	3.64	4.04
Eu	0.57	0.51	0.50	0.64
Yb	1.51	1.35	1.33	1.88
Lu	0.27	0.29	0.28	—
⁸⁷ Sr/ ⁸⁶ Sr	0.70591	—	0.70596	0.70418
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512546	—	—	0.512733
δ ¹⁸ O	10.0	9.14	11.1	7.3
²⁰⁶ Pb/ ²⁰⁴ Pb	18.56	—	—	—
²⁰⁷ Pb/ ²⁰⁴ Pb	15.55	—	—	—
²⁰⁸ Pb/ ²⁰⁴ Pb	38.34	—	—	—

* Trace elements in ppm; — indicates not done; Rb and Sr determined by isotope dilution; La, Ce, Nd, Sm, Eu, Yb, Lu, Th, U, Sc, Cs, Fe, and Na determined by Instrumental Neutron Activation; all other elements by X-ray fluorescence.

** Localities from figure 1.

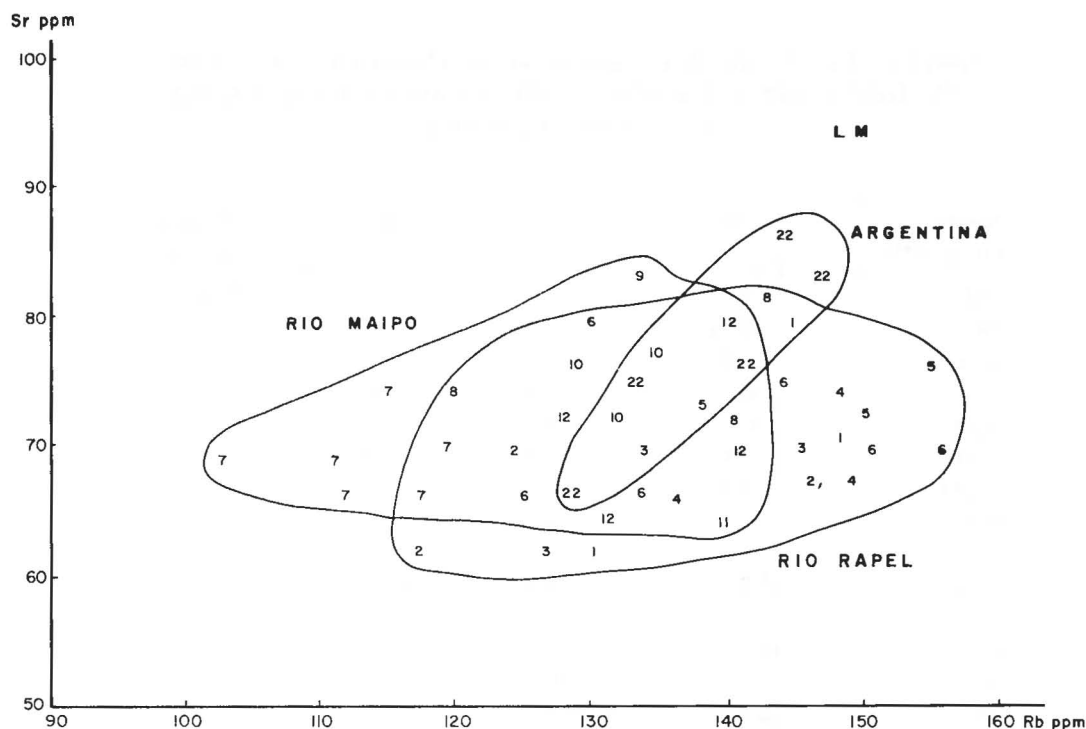


FIG. 4. Sr and Rb compositions of pumice fragments collected from the outcrops indicated in figure 1. The range of compositions is indicated for all the samples collected from the drainage valleys of the Río Papagayos in Argentina and the Río Maipo and Río Rapel in Chile. The figure illustrates that the composition of pumice fragments from each of these separate drainage valleys is very similar, that the range of composition of the entire collection of 45 pumice fragments is very narrow, and that other rhyolites in the Southern Andes of Central Chile, such as the rhyolites from Laguna del Maule (LM) are distinct in composition from the pumice fragments.

siculated, in some cases partially devitrified, clear and colorless silicic glass, with an index of refraction of 1.475. The pumice fragments contain only a very small proportion of crystals, mainly un-twinned oligoclase-plagioclase, biotite, and minor titanomagnetite. Polanski (1962) noted sanidine within the pyroclastic deposits in Argentina, but no sanidine was observed in any of the samples collected from either Argentina or Chile as part of this study.

The very small volume proportion of crystals within the pumice fragments precludes making a reasonable modal estimate by point counting. However, an estimate of the modal proportion of mineral phases was obtained from the mineral separates made from the large collections of pumice obtained in the vicinity of Santiago and Rancagua. Two kilograms of pumice from each of these localities were crushed and panned to float away as much glass as possible. The heavy residues were then crushed a little finer and separated into density fractions with heavy liquids. Both initial samples yielded 80-90 grams of plagioclase, 4-5

grams of biotite, and 2-3 grams of titanomagnetite, suggesting modal proportions of approximately 5 weight percent, less than 1 weight percent, and less than 1 weight percent for these phases, respectively.

The mineral separates from each of these localities also yielded minor amounts of zircons, which were the basis for the fission-track dating discussed below, as well as trace amounts of sphene, apatite, clinopyroxene, orthopyroxene, amphibole, almandine garnet, andradite garnet, microcline, monazite, and lithic fragments. Microprobe analysis of the pyroxenes, garnets, and amphiboles indicated substantial compositional heterogeneity, suggesting that along with the microcline, monazite and the lithic fragments, these rare constituents are probably xenocrysts incorporated in the magma prior to or during eruption. The very similar yield of both major and minor mineral constituents obtained from the pumice fragments from these two distinct localities attests to the petrological similarity of the samples from each location, which is apparent from the thin sections.

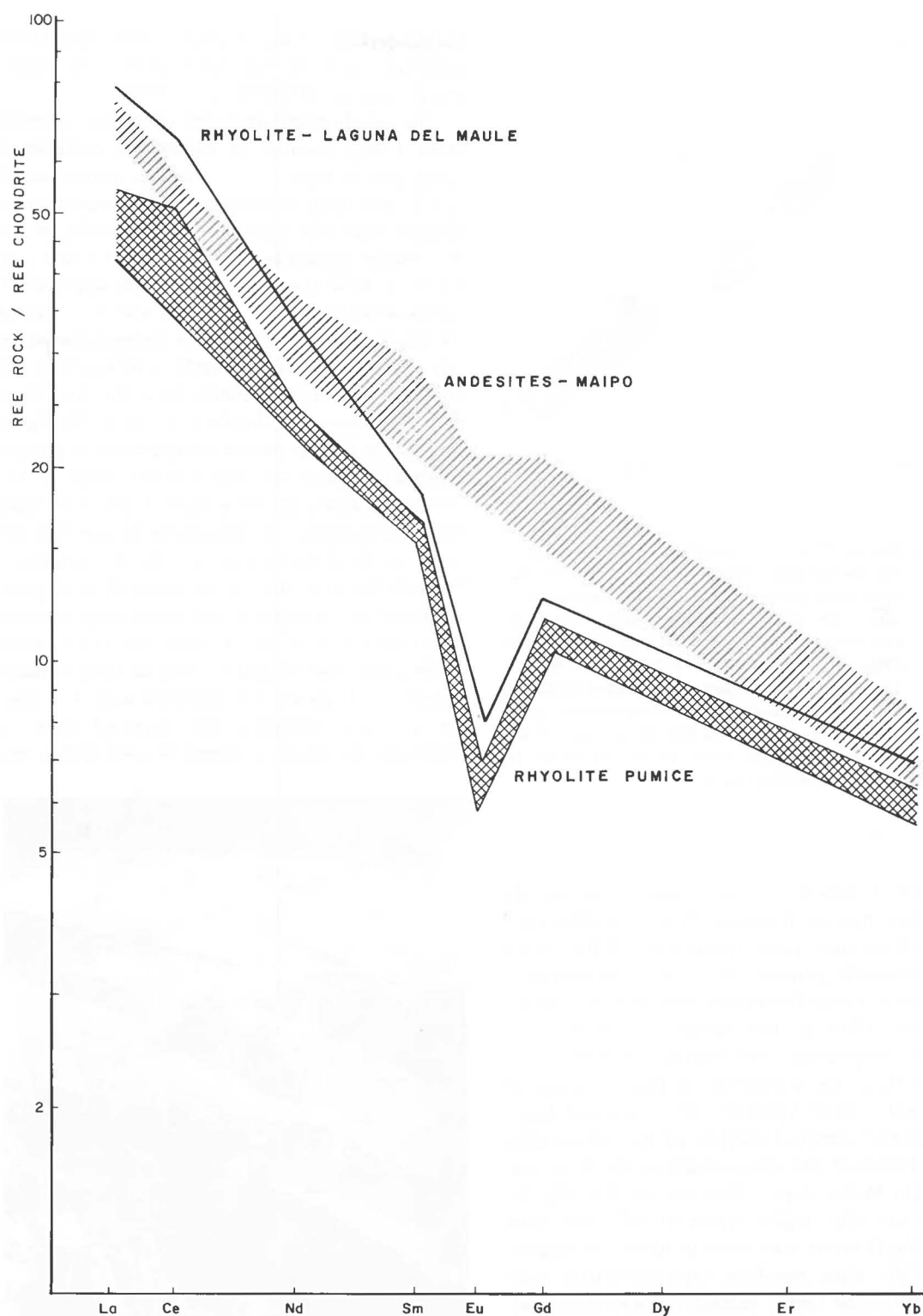


FIG. 5. Rare earth element composition normalized to a chondritic meteorite of three pumice fragments collected from the sample localities indicated in figure 1. Data and sample numbers are listed in Table 1. Also shown are the REE composition of a rhyolite from Laguna del Maule (Frey *et al.*, in press) and the range of REE compositions for andesites from the Maipo Volcano (Stern *et al.*, 1984). The rhyolite pumice fragments have lower LREE than either the rhyolite from Laguna del Maule or the andesites from the Maipo Volcano.

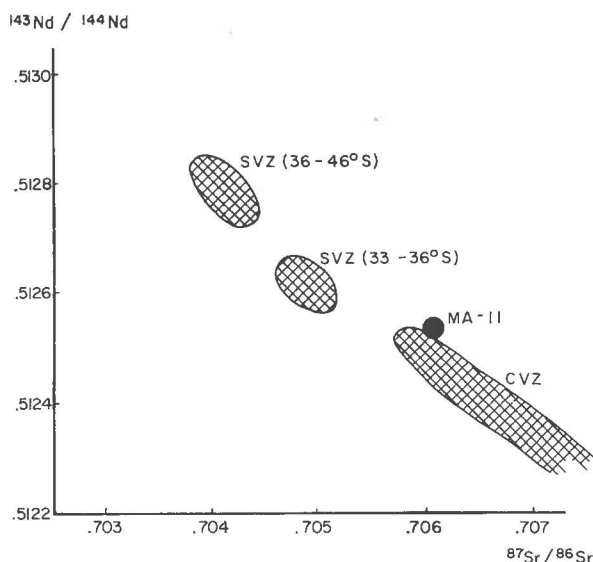


FIG. 6. Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ comparing the isotopic compositions of a pumice fragment from locality Nr. 11 (Figure 1 and Table 1) with other recent Andean volcanic rocks from the central volcanic zone (CVZ) of Northern Chile and Southern Peru (Thorpe and Francis, 1979), the southern part of the southern volcanic zone (SVZ, 36-46°S) of Central-South Chile (Stern *et al.*, 1984), and the northern part of the southern volcanic zone (SVZ, 33-36°S) in Central Chile (Stern *et al.*, 1984).

Table 1 presents major element compositions for three pumice fragments from the aforementioned locations. These samples are all high silica (74-75 weight percent SiO_2) rhyolites characterized by $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios of approximately unity. Polanski (1962, p. 195, sample Nr. 1) reports a similar composition, with slightly lower SiO_2 but higher H_2O , for a fragment of pumice collected from outcrops in Argentina, and Guest and Jones (1970) give chemical analysis of two ash-samples from Pudahuel and the junction of the Río Yeso and Río Maipo (Fig. 7; locality Nr. 7 in Fig. 1), which are also slightly lower in SiO_2 but with $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios also close to unity. No equivalent high silica rhyolites have previously been reported in the recent volcanic centers of Central-South Chile. The most nearly similar rocks are glassy rhyolite domes at Laguna del Maule, none of which have greater than 74 weight percent SiO_2 and all of which have greater than 1.0 weight percent FeO and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios less than unity

(Table 1; Frey *et al.*, in press). Pyroclastic flows associated with the Calabozos caldera are dacites and rhyodacites (Hildreth *et al.*, 1984).

The geochemical similarity of pumice samples from a large number of widespread localities is illustrated in figures 2 and 4 with respect to Rb and Sr. The fields of composition are delineated for samples collected from the drainage valley of the Río Maipo (localities Nrs. 7, 9, 10, 11, and 12), for those from the Río Rapel and its upper tributaries (localities Nrs. 3, 4, 5, 6, and 8) including the Cachapoal as well as Estero Codegua (localities Nrs. 1 and 2) which is actually a tributary of the Río Maipo, and for samples from the Río Papagayos in Argentina (locality Nr. 22). The figure shows that the Rb and Sr compositions of pumice fragments within the ash deposits from all the diverse localities and from each of the three separate river drainages are remarkably similar. The full range of Sr compositions for the 45 samples is from 62-86 ppm, and for Rb from 103-156 ppm. Although not illustrated, the entire range of compositions for Y is 20-31 ppm, and for Zr from 57-89 ppm. The analytical error at these concentration levels would be approximately ± 5 ppm for all these elements. The observed range of variations for these elements is well within the

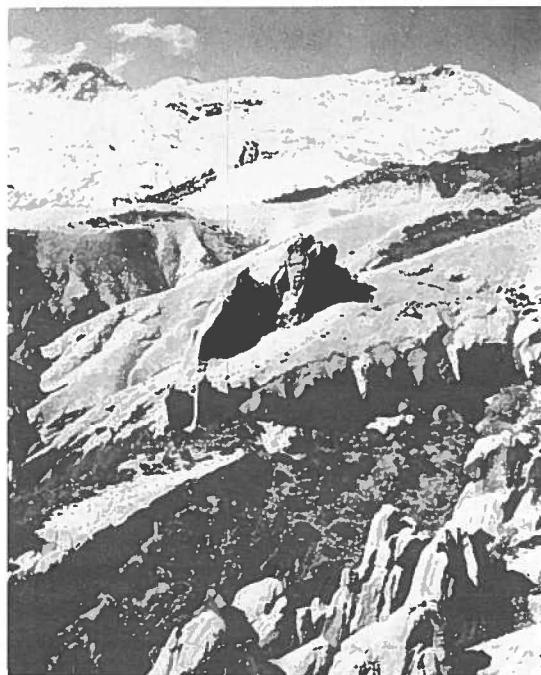


FIG. 7. Southward view of the Río Yeso and Río Maipo junction ash flow deposits. Unwelded upper section crops out at the upper center.

limits of the total range of chemical variation, documented for a single large rhyolitic eruption, such as the Bishop Tuff in the western U.S.A. (Hildreth, 1981). These chemical variations within deposits formed from a single eruption have been attributed to chemical zonation within a large silicic magma chamber (Smith, 1979).

Figure 5 illustrates the rare earth element composition of the same three samples for which major elements were determined (Table 1). These rhyolites have a significant negative Eu anomaly, indicative of crystal-liquid fractionation, involving plagioclase, as does the low Sr content of these samples. Rhyolites from Laguna del Maule have neither the very low Sr content (Fig. 4, Table 1) nor the extreme negative Eu anomaly that the pumice fragments from the northern Central Valley of Chile have. The pumice fragments also have lower total REE, particularly LREE, and Zr contents than the rhyolites from Laguna del Maule, as well as compared to andesites from the Maipo volcano (Fig. 5; López, 1984; Stern *et al.*, 1984). The low total LREE and low Zr content of the pumice fragments suggest the possible role in the petrogenesis of the rhyolites of crystal-liquid fractionation involving zircon, apatite, or sphene,

all of which contain high concentrations of LREE, as well as other trace elements.

Figure 6 illustrates the Sr versus Nd isotopic compositions of the pumice fragments (Table 1), compared to other volcanic rocks in Chile. The pumice fragments have the highest $^{87}\text{Sr}/^{86}\text{Sr}$ and the lowest $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of any samples previously reported in Central-South Chile. The oxygen isotopic composition of the pumice fragments are also higher than any previously reported for volcanic rocks from this region (Stern *et al.*, 1984). The oxygen isotopic compositions were determined on whole rock samples, but are considered representative of the original magma because of the low degree of devitrification observed in the thin sections. With respect to these three isotopes, the pumice fragments are more similar to recent volcanic rocks from Northern Chile than to other recent volcanic rocks from Central-South Chile (Fig. 6). Despite the differences in the Sr, Nd, and O isotopic ratios of the pumice samples, and other recent volcanic rocks from Central-South Chile, the Pb isotopic ratios of the pumice fragments are similar to the other volcanic rocks of the Andes (Barreiro, 1984; Stern *et al.*, 1984).

GEOCHRONOLOGY

The age of pumice fragments from a locality just west of Santiago (locality Nr. 12; Fig. 1) and a locality just east of Rancagua (locality Nr. 6; Fig. 1) were determined by fission-track dating methods (Naeser, 1967; 1969) on zircon separates. This age is considered to be the age of emplacement of the pyroclastic flows from which the pumice fragments were extracted. Zircon microcrysts from each locality were mounted on a teflon sheet, polished, and etched in a melt of 14.4 grams NaOH + 20.0 grams KOH at 220°C for about 24 hours to enhance the visibility of spontaneous fission tracks within the zircons. In order to determine the uranium content of the zircons, the teflon mounts were covered with a low-uranium muscovite sheet and irradiated in the reactor at the U.S. Geological Survey Laboratory in Denver, Colorado. This process caused the uranium within the zircons to break down resulting in induced tracks in both the zircons and the muscovite. Since

the zircons were not etched after this irradiation, the induced tracks they contain are not observed and do not interfere with the counting of the spontaneous fission tracks. The muscovite sheets are separated from the teflon mounts and etched in 48% concentrated HF at 25°C for 12 minutes. The number of spontaneous fission tracks within the zircons and the number of induced tracks within the muscovite sheets are counted with extreme care being taken to count on the area of the muscovite sheets that correspond exactly to an equivalent area counted on a zircon grain.

Figure 8 is a plot of the number of spontaneous versus induced fission tracks for 28 zircon grains: 14 from locality Nr. 12, west of Santiago, and 14 from locality Nr. 6, east of Rancagua. With relatively little scatter, these data define two isochrons which give the ages of the samples. The results for each locality are given in Table 2. The results indicate that the sample from west of Santiago is

0.47 ± 0.07 million years old and the sample from east of Rancagua is 0.44 ± 0.08 million years old. The two results are within analytical error, and all

28 points may be considered to define a single age of 0.45 ± 0.06 million years.

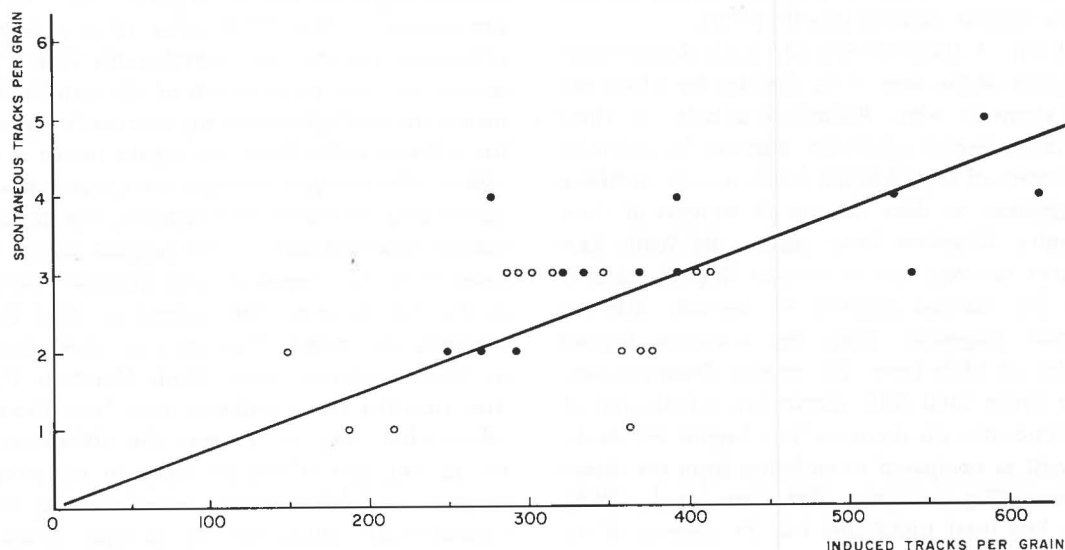


FIG. 8. Spontaneous versus induced fission tracks for zircon separates obtained from pumice fragments collected in the vicinity of Santiago (locality Nr. 12, closed circles) and Rancagua (locality Nr. 6, open circles). The line drawn as a best fit through all 28 points defines an isochron of $450,000 \pm 60,000$ years (Table 2).

TABLE 2. FISSION-TRACK AGE DETERMINATIONS ON ZIRCON MICROCRYSTS SEPARATED FROM PUMICE SAMPLES COLLECTED FROM PYROCLASTIC FLOWS IN THE NORTHERN-CENTRAL VALLEY OF CHILE

Sample location*	Number of grains counted	Spontaneous tracks counted	Spontaneous track density (tracks/cm ²)	Induced tracks counted	Induced track density (tracks/cm ²)	Age in millions of years**
Locality Nr. 12	14	46	101.68×10^3	5854	1293.98×10^4	0.47 ± 0.07
Locality Nr. 6	14	32	77.52×10^3	4332	1049.42×10^4	0.44 ± 0.08
Combined	28	78	90.17×10^3	10186	1177.57×10^4	0.45 ± 0.06

* Samples localities indicated in figure 1.

** The age is determined by means of Naeser's (1967) equations with a neutron flux (neutrons/cm²) of 9.90×10^4 for both samples.

DISCUSSION

Within the analytical uncertainty of the fission-track method of age determination, the emplacement of pyroclastic flows within the Río Maipo and Río Rapel valleys may be considered as a single event. The age of this event, $450,000 \pm 60,000$ years, is consistent with the Upper Pleistocene age suggested by Polanski (1962) for the pyroclastic flows in the valleys of the Río Yaucha and Río Papagayos in Argentina. Given the analytical uncertainty, it can not be determined if the individual outcrops of the pyroclastic flows were emplaced in a single day, a few years apart, or even 10,000 to 50,000 years apart. The application of the fission-track method to a larger sampling of zircons could reduce this uncertainty somewhat, but never altogether.

The similarity of the petrochemistry of the pumice fragments collected from the various outcrops of the pyroclastic flows, combined with the distinctness of their petrochemical characteristics compared to other recent volcanic rocks in Central-South Chile, all point to a common origin for the pyroclastic flows, a conclusion reached previously on the basis of their sedimentological similarities by Santana (1971). The narrowly defined age brackets for two lobes of these pyroclastic flows in the northern Central Valley of Chile suggests that all the material was derived from a single source, in a single or series of closely spaced eruptions.

The welded nature of the pyroclastic flows in the localities along the eastern Andean piedmont in Argentina indicates that they are relatively near their source (Polanski, 1962). Polanski notes that these flows thicken within the drainage valleys leading to the Maipo volcano, which is located within a distinct depression, which Polanski considered to be a caldera, "la caldera de la laguna Diamante", formed by the extrusion of the rhyolite pyroclastics. Although recent field work has not encountered any outcrops of equivalent rhyolite pyroclastics close to the Chilean side of this caldera, the outcrops within the Río Maipo, both within the Main Range as well as westward in the Central Valley and Coastal Range, are consistent with an origin from the region of the Maipo volcano, as proposed by Polanski (1962) and earlier suggested by Borde (1958).

A high topographic wall currently exists bet-

ween the Maipo volcano and the upper drainage of the Río Cachapoal, making the mechanism of emplacement of pyroclastic units, derived from the region of the Maipo volcano within the Río Cachapoal and Río Rapel valleys problematic. One possible solution is that no such dramatic topographic separation existed between the Río Maipo and Río Cachapoal drainages at the time of eruption. Charrier (1981, Fig. 152) has mapped horizontally bedded, undeformed mesas of basalts and andesites surrounding the western edge of the collapse caldera in which the current Maipo volcano occurs. The older pre-caldera units have their upper surfaces at elevations over 4,000 meters and are thus slightly higher than the topographic wall separating the Río Maipo and Río Cachapoal drainages. If this elevation represents a paleo-surface at the time of eruption of the rhyolite pyroclastic flows it would explain their presence within both drainage systems.

It should also be taken into account that this region was less eroded and heavily glaciated at the time of the eruption of the pyroclastic flows, so that the flows could have traveled over the surface of the ice into the different drainage valleys. This would also explain the almost total lack of pyroclastic deposits within the Chilean Main Range west of the Maipo volcano, as well as their occurrence in the lower valleys of both the Río Maipo and Río Cachapoal. Contact between the hot pyroclastic and ice would tend to add to the process of fluidization of the pyroclastic flows and explain their extreme mobility which is evidenced by how far away from their source they have moved. The $\delta^{18}\text{O}$ of oceanic sediments are at a maximum 450,000 years ago, suggesting cooler temperatures and perhaps increased glaciation at this time compared to the present (Hays *et al.*, 1976).

Santana (1971) estimates the current surface area of these pyroclastic deposits to be $1,300 \text{ km}^2$. Assuming that the deposits in the northern part of the Central Valley of Chile were originally continuous, their area, including Argentina, prior to dissection and/or burial, must have been approximately $15,000 \text{ km}^2$. The westernmost outcrops of the pyroclastic flows within the Coastal Cordillera are 10-20 meters thick; those near Santiago are at least 30 meters thick (Segerstrom *et al.*, 1964);

and outcrops in the Cajón del Maipo and the valley of the Río Papagayos and Río Yaucha in Argentina are greater than 100 meters in thickness, and in some areas greater than 200 meters thick (Polanski, 1962). An average value of 30 meters thickness would imply a reconstructed volume of approximately 450 km^3 for the pyroclastic flows, making the eruption of the Maipo 450,000 years ago one of the largest known to have occurred in the last million years.

Outcrops of the pyroclastic flows may be considered as a paleo-surface marker to determine relative rates of either tectonic movement or erosional downcutting during the last 450,000 years. For instance Varela (1976) described an outcrop of similar ashes in Laguna de Taguatagua ($34^\circ 30' \text{ Lat. S}$ - $71^\circ 10' \text{ Long. W}$). It underlies, separated by an erosional unconformity, 12.5 m of lacustrine sediments. C^{14} dating and extrapolation of sedimentation rate of the lake deposits point to an age of 57,000 years BP for the sediments. He concluded that the volcanic ash has a glacial age, probably Riss or eventually Mindel. On the other hand, the outcrop at the junction of the Río Yeso and Río Maipo occurs 150 meters above the current river bed suggesting a maximum integrated uplift and erosion rates of approximately 0.3 millimeters per year in this part of the Andes. This estimate is somewhat lower than the 0.8 millimeters per year calculated for the Río Cachapoal, near the Central Valley (Charrier, in prep.).

The date of the formation and emplacement of the pyroclastic flows is also, presumably, the date of formation of the 15 by 20 kilometer caldera within which the Maipo volcano is located. If the Maipo volcano can be approximated by a cone 15 kilometers in diameter at the base and 2 kilometers in elevation, then a maximum average rate of magma supply to produce this volcano in the last 450,000 years is $236 \text{ km}^3/\text{m.y.}$ Since the Upper Pleistocene volcanic centers in this region of the Andes are about 50 kilometers apart, this rate is equivalent to $4.7 \text{ km}^3/\text{m.y.}$, per kilometer of arc-length. This volume fits better with the estimates of Baker and Francis (1978), who calculated a magma production rate of $3.8 \text{ km}^3/\text{m.y.}$, per kilometer of arc-length, for a 375 kilometer long segment of the Central Andes ($19^\circ 30' \text{ S}$ to $22^\circ 30' \text{ S}$) averaged over the last 6 m.y., than with those of Hildreth *et al.* (1984), who computed a magma production rate of at least $25 \text{ km}^3/\text{m.y.}$, per kilo-

meter of arc-length, for the 45 kilometers that they mapped in the vicinity of the Calabozos caldera, in the Southern Andes of Central Chile (35° S).

Rhyolitic pyroclastics are considered to be characteristic of the Central as opposed to the Southern Andes (Thorpe and Francis, 1979). Other caldera and pyroclastic outflow complexes have been documented in the northern part of the southern volcanic zone of Central-South Chile (Hildreth *et al.*, 1984), suggesting that this region of the Andean volcanic chain is more similar to the Central Andes than to further south in the Southern Andes. The high Sr and O isotopic ratios and the low Nd isotopic ratios of the rhyolitic pumice fragments reported here are more similar to the isotopic ratios for volcanic rocks from the Central Andes than for those from further south in the Southern Andes (Stern *et al.*, 1984). Assimilation of crustal material has clearly been a significant aspect of the petrogenesis of these rhyolites, although extensive crystal-liquid fractionation producing the large negative Eu anomaly and low LREE, Sr, and Zr content of these rhyolites must also have been important.

The re-occurrence frequency of large eruptions of silicic magmas has been documented at a number of locations, such as Yellowstone Park in the U.S.A., to be on the order of hundreds of thousands of years (Smith, 1979). Hildreth *et al.* (1984) document large multiple pyroclastic eruptions of the Calabozos caldera complex 0.8, 0.3, 0.15 million years ago. They outline a model in which the rate of magma supply and the crustal stress distribution that controls the migration of magmas to the surface are important factors in causing the development of large, multicyclic caldera complexes and associated silicic pyroclastic flows, in a region that is typically characterized by andesitic composite volcanoes. Another eruption of rhyolitic pyroclastics from the Maipo volcano such as the one that occurred previously may not happen again if the dynamics of magma supply and passage through the crust have changed significantly below the region of this volcano. On the other hand, other volcanic centers in the region, such as Tupungato and Marmolejo, might be suitable candidates for such explosive eruptions in the future. We concur with the conclusion of Hildreth *et al.* (1984) that "the long record of voluminous silicic pyroclastic activity, and the

existence of ring-structure calderas of late Quaternary age in the 33°S to 36°S segment of the Andean Cordillera have important implications for the safety of several major cities near the mouths of Andean canyons, . . . " Given the current levels of erosion in the Andes, an eruption today, similar to that documented in this paper, would be expected to funnel more of the erupted pyroclas-

tic material through the city of Santiago than during the explosion of the Maipo caldera about 450,000 years ago. The results would clearly be catastrophic. More work is required to fully understand the potential for the repeat of such an event and to identify the possible precursor activity which might foreshadow such an event.

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REFERENCES

- BAKER, M. C. W.; FRANCIS, P. W. 1978. Upper Cenozoic volcanism in the Central Andes; ages and volumes. *Earth Planet. Sci. Lett.*, Vol. 41, No. 2, p. 175-187.
- BARREIRO, B. A. 1984. Lead isotopes and Andean magma genesis. In *Andean Magmatism: Chemical and Isotopic Constraints* (Harmon, R. S.; Barreiro, B. A.; eds.), Shiva Press, p. 21-30. London, England.
- BORDE, J. 1958. Las depresiones tectónicas del Maipo inferior; glaciaciones y cenizas volcánicas. *Inform. Geogr.*, Edit. Universitaria, Año 5°, p. 6-15. Santiago, Chile.
- BORDE, J. 1966. Les Andes de Santiago et leur avant-pays: Etude de géomorphologie. *Union Franc. d'Imprim.*, 559 p. Bordeaux, France.
- BRUGGEN, J. 1950. Fundamentos de la Geología de Chile. *Inst. Geogr. Militar (Chile)*, 374 p. Santiago.
- CHARRIER, R. 1981. Geologie der chilenischen Hauptkordillere zwischen 34° und 34° 30' südlicher Breite und ihre tektonische, magmatische und paläogeographische Entwicklung. *Berliner Geowissenschaft. Abhandlung*, (A), No. 36, 270 p.
- CHARRIER, R., in prep. Hoja El Teniente, Carta Geológica de Chile 1:250.000, Serv. Nac. Geol. Miner.
- FREY, F. A.; GERLACH, D. C.; HICKEY, R. L.; *et al.* (in press). Petrogenesis of the Laguna del Maule volcanic complex, Chile (36°S). *Contr. Mineral. Petrol.*
- GUEST, J. E.; JONES, G. P. 1970. Origin of ash-deposits in the Santiago area, Central Chile. *Geol. Mag.*, Vol. 107, No. 4, p. 369-381.
- HAYS, J. D.; IMBRIE, J.; SHACKLETON, N. J. 1976. Variations in the earth's orbit: pacemaker of the Ice Ages. *Science*, Vol. 195, p. 1121-1132.
- HILDRETH, W. 1981. Gradients in silicic magma chambers; implications for lithospheric magmatism. *J. Geophys. Res.*, Vol. 86, No. B11, p. 10153-10192.
- HILDRETH, W.; GRUNDER, A. L.; DRAKE, R. E. 1984. The Loma Seca Tuff and the Calabozos Caldera: a major ash-flow and caldera complex in the Southern Andes of Central Chile. *Geol. Soc. Am., Bull.*, Vol. 95, p. 45-54.
- KARZULOVIC, J. 1960. Características de los depósitos de cenizas volcánicas en Chile Central. *Inform. Geogr.*, Edit. Universitaria, Año 7°, p. 205-206. Santiago, Chile.
- LOPEZ-ESCOBAR, L. 1984. Petrology and chemistry of volcanic rocks of the Southern Andes. In *Andean Magmatism: Chemical and Isotopic Constraints* (Harmon, R. S.; Barreiro, B.A.; eds.), Shiva Press, p. 47-71. London, England.
- LOPEZ-ESCOBAR, L.; FREY, F. A.; VERGARA, M. 1976. Andesites from Central-South Chile; trace elements abundances and petrogenesis. In *Int. Assoc. Volcanol. and Chem. Earth's Interior, Symp. Andean Antarctic Probl.*, Proc. (González-Ferrán, O.; ed.), p. 725-761. Santiago, Chile, 1974.

- MORENO, H. 1976.** The Upper Cenozoic volcanism in the Andes of southern Chile. *In* Int. Assoc. Volcanol. and Chem. Earth's Interior, Symp. Andean Antarctic Probl., Proc. (González-Ferrán, O.; ed.), p. 143-171. Santiago, Chile, 1974.
- NAESER, C. W. 1967.** The use of apatite and sphene for fission-track age determinations. *Geol. Soc. Am., Bull.*, Vol. 78, p. 1523-1526.
- NAESER, C. W. 1969.** Etching fission-tracks in zircons. *Science*, Vol. 165, p. 388.
- POLANSKI, J. 1962.** Estratigrafía, neotectónica y geomorfología del Pleistoceno pedemontano entre los ríos Diamante y Mendoza. *Asoc. Geol. Argent., Rev.*, Vol. 27, No. 3-4, p. 127-149.
- SANTANA, R. 1971.** Les cendres volcaniques de la vallée du Cachapoal-Rapel, Chili. *Cahiers de Geogr., Quebec*, No. 35, p. 315-332.
- SEGERSTROM, K.; CASTILLO, O.; FALCON, E. 1964.** Quaternary mudflow deposits near Santiago, Chile. *U.S. Geol. Surv., Prof. Pap.*, 475-D, No. 152, p. D144-D148.
- SMITH, R. L. 1979.** Ash-flow magmatism. *Geol. Soc. Am., Spec. Pap.*, No. 180, p. 5-27.
- STERN, C. R.; FUTA, K.; MUEHLENBACHS, K.; et al. 1984.** Sr, Nd, Pb and O isotope composition of Late Cenozoic volcanics, northernmost SVZ (33-34° S). *In* Andean Magmatism: Chemical and Isotopic Constraints (Harmon, R. S.; Barreiro, B. A.; eds.) Shiva Press, p. 96-106. London, England.
- STIEFEL, J. 1965.** Lahares glaciocánicos recientes y depósitos comparables del Pleistoceno Chileno. *Soc. Geol. Chile, Resúmenes*, No. 10, p. 7-16.
- THORPE, R. S.; FRANCIS, P. W. 1979.** Variations in Andean andesite compositions and their petrogenetic significance. *Tectonophysics*, Vol. 57, p. 53-70.
- VARELA, J. 1976.** Geología del Cuaternario de Laguna de Taguatagua, Provincia de O'Higgins. *In* Congr. Geol. Chileno, No. 1, Actas, Vol. 1, p. D81-D114. Santiago.