The Puelche Volcanic Field: extensive Pleistocene rhyolite lava flows in the Andes of central Chile

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ABSTRACT

A remote volcanic field in the rugged headwaters of the Río Puelche and Río Invernada (35.8°S) constitutes the largest cluster of Quaternary rhyolite lava flows yet identified in the Andean Southern Volcanic Zone. The Puelche Volcanic Field belongs to an intra-arc belt of silicic magmatic centers that extends, at least, 140 km north-south and lies well east of the volcanic front but nonetheless considerably west of the intraplate extensional fields of basaltic and alkaline centers of pampean Argentina. The authors' mapping has distinguished one shallow intrusive mass of early Pleistocene biotite rhyodacite (70.5% SiO_2), 11 eruptive units of mid-Pleistocene high-K biotite-rhyolite lava (71.3-75.6% SiO_2), and 4 eruptive units of basaltic andesite (53.95-4.9% SiO_2), the conduits of which cut some of the rhyolites. Basal contacts of the rhyolite lava flows (and subjacent pyroclastic precursors) are generally scree covered, but glacial erosion has exposed internal flow structures and lithologic zonation superbly. Thicknesses of individual rhyolite lava flows range from 75 m to 400 m. Feeders for several units are well exposed. Cliff-draping unconformities and intracanyon relationships among the 11 rhyolite units show that the eruptive sequence spanned at least one glacial episode that accentuated the local relief. Lack of ice-contact features suggests, however, that all or most eruptions took place during non-glacial intervals probably between 400 ka and 100 ka. Post-eruptive glacial erosion reduced the rhyolites to several non-contiguous remnants that altogether cover 83 km^2 and represent a surviving volume of about 21 km^3. Consideration of slopes, lava thicknesses, and paleotopography suggest that the original area and volume were each about three times greater. Phenocryst content of the rhyolites ranges from 1 to 12%, with plagioclase>>biotite>FeTi oxides in all units and amphibole conspicuous in the least silicic. The chemically varied basaltic andesites range from phenocryst-poor to phenocryst-rich, exhibiting large differences in proportions of clinopyroxene, olivine, plagioclase, and xenocrystic quartz. Compositional bimodality of the volcanic field is striking, there being no Quaternary eruptive units having SiO_2 contents between 55 and 70%. Major and trace element compositions of the mafic and silicic rocks are nonetheless typical of continental-margin arc suites, not of intracontinental suites. The lack of intermediate eruptive units and the differences between the mafic and rhyolitic lavas in Sr-isotope composition suggest that the rhyolites fractionated from a hybrid parent rather than continuously from basaltic magma. The rhyolites may contain larger contributions of upper-crustal partial melts than do silicic products of the volcanic-front centers 30 km to the west.

Key words: Volcanic field, Pleistocene, Andes, Central Chile.

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RESUMEN

El Campo Volcánico Puelche: extensos flujos riolíticos pleistocenos en los Andes de Chile central. Un remoto campo volcánico, ubicado en las escarpadas nacientes de los ríos Puelche e Invernada (35,8°S), constituye el principal agrupamiento de lavas riolíticas cuaternarias conocido hasta la fecha en la Zona Volcánica Meridional de los Andes. El Campo Volcánico Puelche pertenece a un cinturón intra-arco de centros magmáticos silíceos que se extiende, por lo menos, sobre 140 km en dirección norte-sur. Esta faja yace significativamente más al este que el frente volcánico pero, a pesar de ello, considerablemente más al oeste que los campos volcánicos extensionales intraplaca representados por los basaltos alcalinos de la pampa argentina. Se distingue en él un cuerpo hipabisal riodacítico (70,5% SiO_2) con biotita del Pleistoceno temprano, 11 unidades eruptivas de lava riolítica de biotita de alto contenido en potasio (71,3-75,6% SiO_2) y cuatro unidades eruptivas de andesitas basálticas (53,9-54,9% SiO_2), cuyos conductos cortan a algunas de las riolitas. Los contactos basales de las lavas riolíticas y sus infrayacientes precursores piroclásticos están generalmente cubiertos por derrubios, pero la erosión glacial ha expuesto, de manera espectacular, sus estructuras de flujo, zonaciones litológicas internas y algunos de sus alimentadores. El espesor de las lavas riolíticas varía entre 75 y 400 m. Discordancias de borde de acantilado y relaciones de relleno de valle entre las 11 unidades riolíticas muestran que la secuencia eruptiva abarcó al menos un episodio glacial, el cual acentuó el relieve local. La falta de rasgos asociados a contacto con hielo sugiere, sin embargo, que todas las erupciones tuvieron lugar durante intervalos no-glaciales, probablemente entre 400 ka y 100 ka. Erosión glacial post-eruptiva redujo a las riolitas a varios remanentes aislados que, en conjunto, cubren 83 km^2 y representan un volumen actual de 21 km^3. Consideraciones basadas en las pendientes, espesores de las lavas y la paleotopografía sugieren, sin embargo, que tanto el área como el volumen original fueron aproximadamente tres veces mayores. El contenido en fenocristales de las riolitas varía entre 1 y 12%, con plagioclasa >> biotita > oxidos de FeTi en todas las unidades y escasa anfíbola pero conspicua en las rocas menos silíceas. Las andesitas basálticas (pobres a ricas en fenocristales), son de quimismo variable. Muestran grandes diferencias en sus porcentajes de fenocristales de clinopiroxeno, olivino, plagioclasa y cuarzo, este último en xenocristales. Destaca la bimodalidad del campo volcánico, desconociéndose unidades eruptivas cuaternarias con contenidos en SiO_2 entre 55 y 70%. Las composiciones en elementos mayores y trazas tanto de las rocas máficas como silíceas son, sin embargo, típicas de series de arco en margen continental, y no de series intracontinentales. La falta de unidades eruptivas intermedias y las diferencias en la isotopía de Sr entre las rocas máficas y las silíceas sugieren que las riolitas fraccionaron, más bien, a partir de un magma parental híbrido que, en forma contínua, a partir de un magma basáltico. Estas riolitas podrían contener mayores contribuciones en fundidos parciales de la corteza superior que los productos silíceos de los centros del frente volcánico, ubicados 30 km más al oeste.

Palabras claves: Campo volcánico, Riolitas, Pleistoceno, Andes, Chile central.

INTRODUCTION

An extensive field of Pleistocene rhyolite lava flows, previously unstudied, lies in the remote headwaters of the Río Puelche and Río Invernada, centered 25 km north of Laguna del Maule and 30 km east of Central Los Cipreses (Fig. 1). Here called the Puelche Volcanic Field, this cluster of rhyolites, accompanied by four basaltic andesite vents, is 20-35 km east of the Quaternary volcanic front of the Andean Southern Volcanic Zone (SVZ). The Quaternary volcanic arc is especially broad at this latitude (35.4°-36.2°S), consisting of, at least, 150 discrete volcanic vents of Pleistocene and Holocene age scattered 40-50 km eastward from the volcanic front (Fig. 1), which is here marked by the Descabezado group (Hildreth and Drake, 1992) and Volcán Tatara-San Pedro (Singer *et al.*, 1997). The Puelche Volcanic Field lies within this relatively wide reach of the SVZ, but it is also part of a south-trending intra-arc belt of large Quaternary silicic centers that includes the Calabozos Caldera and Laguna del Maule (Fig. 1) as well as Volcán Domuyo (36°39'S, 70°26'W; Llambías *et al.*, 1978) about 60 km south of Laguna del Maule.

Dacites (63-68% SiO_2) or rhyodacites (68-72% SiO_2) are usually the most evolved magmatic products erupted at arc volcanoes. Rhyolites (>72% SiO_2) are less common, especially at volcanic-front centers, and this is still more emphatically true for high-silica rhyolites (75-77% SiO_2). Such compositions are instead characteristic of intracontinental volcanic fields, predominantly in extensional settings. For example, in North America, although high-silica rhyolite is widespread in the Basin and Range Province and thousands of cubic kilometers of it

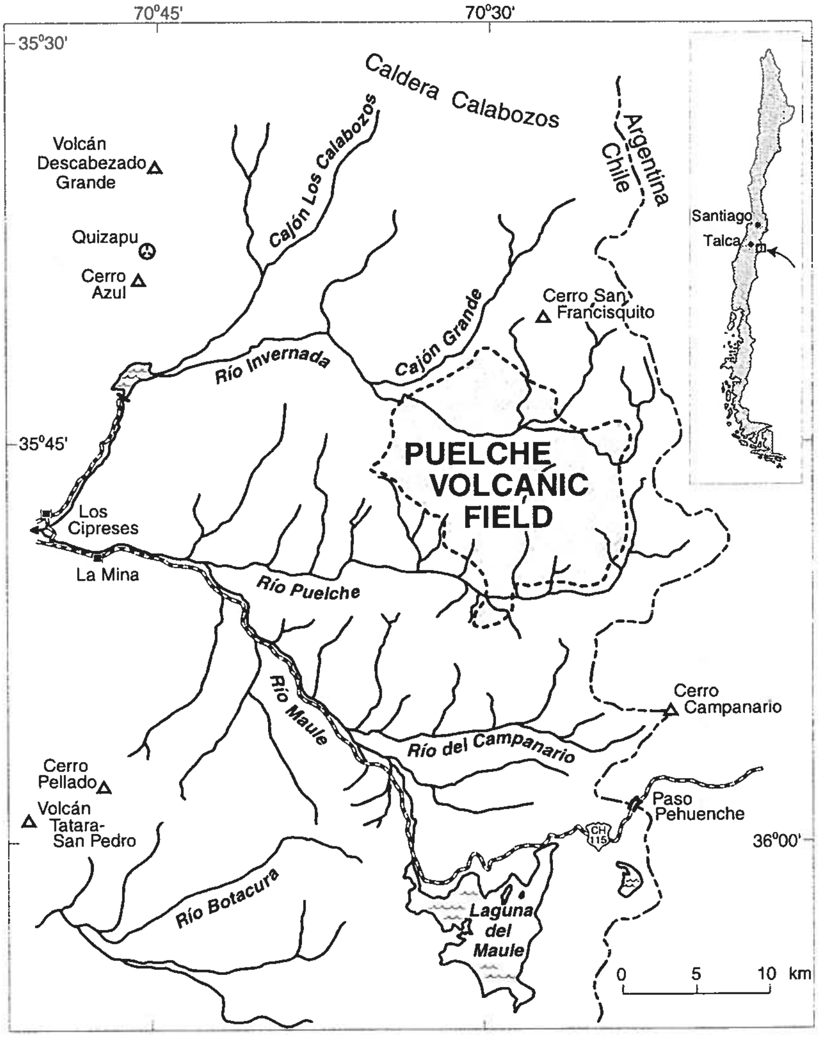

FIG. 1. Location of the Puelche Volcanic Field in the upper parts of the drainage systems of the Río Puelche and Río Invernada, 100-120 km east of Talca and midway between the Laguna del Maule and Caldera Calabozos silicic volcanic fields. Except for the two roads shown, the region is roadless.

have erupted from intracontinental Quaternary volcanoes at Yellowstone, Long Valley, and the Jemez Mountains, Quaternary occurrences are rare within the 1,100-km-long Cascade arc and only two Quaternary examples (Katmai and Okmok) have been identified in the 2500-km-long Alaska-Aleutian arc. The numerous occurrences of high-silica rhyolite in the intra-arc belt of silicic volcanic centers in the Andean SVZ are therefore of significant interest from the point of view of understanding processes of magma generation and evolution.

PREVIOUS WORK

The Puelche rhyolites were first recognized geologically in the course of a long backpack traverse by R.E. Drake and M.N. Christensen in 1970. Drake noted their glaciated, but fresh condition and their commonly spherulitic textures, and he published a biotite K-Ar age of 0.3±0.1 Ma (Drake, 1976) for the northernmost of the rhyolite lavas (Fig. 2), thereby establishing the mid-Pleistocene age of the volcanic field. The field lies within the enormous area reconnoitred by González and Vergara (1962), but their photo-interpretive map makes it clear that they did not go there. The area has remained one of the blankest spots on the geologic map of Chile.

TERRAIN AND ACCESS

Geologic neglect of the Puelche region results from the difficulty of access. The Paso Pehuenche road (Fig. 1) is open only in summer, and the next road penetrating the Andean high country is 90 km farther north, at the Río Teno. The uninhabited Puelche region is visited seasonally by border collies, sheep, and one or two shepherds-on-horseback **(arrieros)**, but their roofless summertime outposts **(puestos)** remain south of the Río Puelche and north of the Río Invernada. Both rivers are difficult to ford and their gorges are precipitous, arduous, even dangerous to cross. South of the volcanic field, the west-flowing reach of the Río Puelche (Fig. 1) drops from 2,200 m to 1,500 m in the course of 17 km. Surfaces of the rhyolite plateaux nearby attain elevations greater than 3,100 m. The area is treeless, snowcovered much of the year, and, though well watered, largely barren (Figs. 3-8). The sparsity of shrubs and even of bunchgrasses reflects the ubiquitous rhyolite screes as well as windscour by a veneer of sandy fallout from the 1932 eruption of Quizapu (Hildreth and Drake, 1992), remobilized so often by the eponymous **puelche**.

Most of the authors' mapping was done on foot in 1984, under conditions the first author remembers as one of the most trying of his many backpacking expeditions. Additional sampling and observations were undertaken by helicopter in 1998. Nearly all of the locally erupted units have been sampled, but the authors' study still amounts only to an unevenly detailed reconnaissance. In particular, much could be learned by investigating the Pleistocene welded tuffs that underlie the Puelche rhyolite lavas. Establishing their sources (which are not local) and their correlatives elsewhere would necessarily be part of unravelling a multi-sheet ignimbrite sequence that extends far into Argentina. Such an undertaking would be a major contribution to regional Quaternary stratigraphy and to understanding Andean magmatism. The contribution at hand deals only with the local cluster of rhyolite lavas.

REGIONAL GEOLOGY

The Pleistocene rhyolites rest on Quaternary ignimbrites, stacks of Tertiary andesite-dacite lavas, and thick, complexly varied sections of Tertiary silicic and intermediate pyroclastic rocks-dominantly ignimbrites, welded and nonwelded. Countless dikes cut the Tertiary volcanic rocks, reinforcing the authors' impression that many of the (unstudied) Tertiary lavas and pyroclastic deposits represent proximal volcanic facies. About 8-12 km southwest of the Puelche rhyolite field, the subjacent Tertiary volcanic assemblages bank against the 80-Ma tonalitic-to-granodioritic El Indio pluton (González and Vergara, 1962; Nelson *et al.*, 1999), which separates the undeformed to openly folded Tertiary volcanic province from strongly deformed Mesozoic volcanic and sedimentary rocks farther west. Within the Puelche Volcanic Field itself, there is a single 2 km long window through the Cenozoic volcanic rocks, along the upper gorge of the Río Invernada, that exposes deformed Mesozoic redbeds, presumably part of the north-striking Malargüe fold-and-thrust belt (Ramos *et al.*, 1996) that extends for 100 km farther east.

The Quaternary ignimbrites certainly include Unit V (0.3 Ma) of the Loma Seca Tuff (**ig3**; Fig. 2) and possibly Unit L (0.8 Ma) and Unit S (0.15 Ma), as well (Hildreth *et al.*, 1984b; Grunder and Mahood, 1988). A rhyolitic ignimbrite, distinctive but as yet uncorrelated and undated, underlies much of the Puelche Volcanic Field (**ig2**; Fig. 2). In addition, a 650 m thick horizontal stack of welded ignimbrites forms the continental divide just east of the upper Río Invernada (**ig1**; Fig. 2); a K-Ar age of 1.06±0.04 Ma was measured by Drake (1976) for the top sheet of the stack.

All parts of the area mapped (Fig. 2) were glacially eroded recurrently during the Pleistocene, even the highest summits. Because this upland region was one of scour and removal rather than deposition, however, glacial deposits are limited to a few small cirque moraines and valley-filling debris in the uppermost parts of several drainages. No glaciers remain in the area today, but it is to the Pleistocene glaciations that one owes the superb exposures (Figs. 3-9).

GEOLOGY OF THE PUELCHE VOLCANIC FIELD

Eleven mid-Pleistocene rhyolitic eruptive units have been defined on the basis of field relations (Fig. 2), phenocryst contents (Table 1), and bulk compositions (Table 2). Of the eleven, three lie north of the Río Invernada and one is an intracanyon flow along it. South of that river, two eastern units

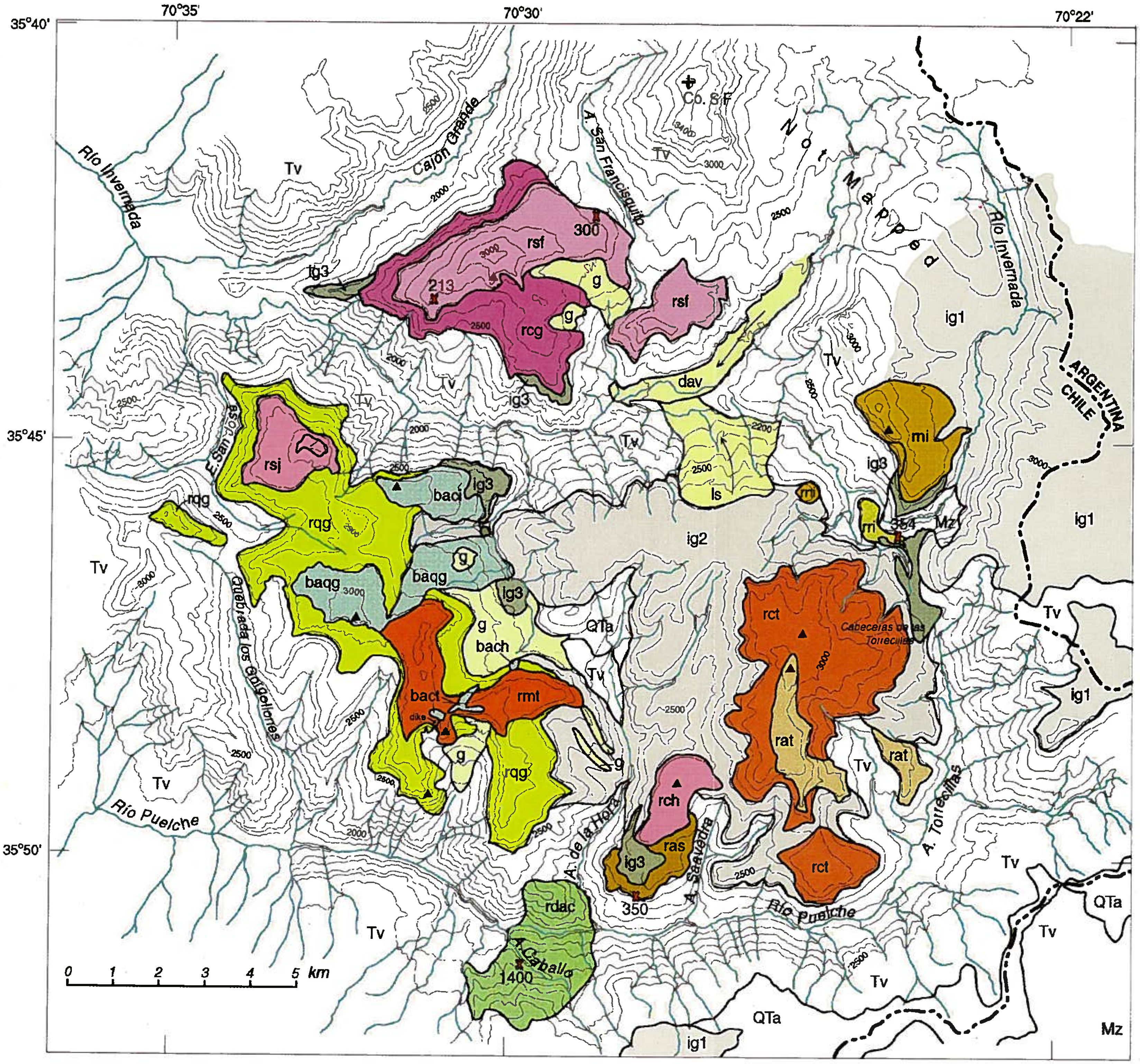

FIG. 2. Reconnaissance geologic map of the Puelche Volcanic Field. Contour interval 100 m. Eruptive unit labels: **ras**- Rhyolite of Arroyo Saavedra; **rat**- Rhyolite of Arroyo de Torrecillas; **rcg**- Rhyolite of Cajón Grande; **rch**- Rhyolite of Campo La Hora; **rct**- Rhyolite of Cabeceras de las Torrecillas; **rmt**- Rhyolite of Mesa 3028; **rni**- Rhyolite North of Río Invernada; **rqg**- Rhyolite of Quebrada Los Gorgollones; **rri**- Rhyolite of Río Invernada; **rsf**- Rhyolite of Arroyo San Francisquito; **rsj**- Rhyolite of Estero San José; **rdac**- Rhyodacite of Arroyo del Caballo; **bach**- Basaltic Andesite of Cajón de la Hora; **baci**- Basaltic Andesite of Cajón Invernada; **bact**- Basaltic Andesite of Cerro 3057; **baqg**- Basaltic Andesite of Quebrada Los Gorgollones. Two lava flows each are indicated for units **rsj** and **rni**. Three sets of Quaternary ignimbrites discussed in text are labelled, from oldest to youngest, **ig1**, **ig2**, and **ig3**. Unpatterned basement includes: **Mz**- deformed Mesozoic sedimentary rocks; **Tv**- varied but undivided Tertiary volcanic rocks, mostly slightly deformed, presumed Miocene and Pliocene; **QTa**- subhorizontal preglacial andesite- dacite lavas, mostly ridge- capping remnants. Quaternary surficial deposits (pale yellow) include: **g**- glacial deposits; **dav**- debris avalanche; **ls**- landslide. Red **X** marks sites of five dated samples; age in ka. Vents identified for Quaternary eruptive units are indicated by black triangle (omitted for small map units **bach** and **bact** for clarity). At north edge of map, **Co.S.F.**- Cerro San Francisquito, an andesitic edifice for which Drake (1976) measured a K- Ar age of 2.0±0.3 Ma.

TABLE 1. ESTIMATED PHENOCRYST CONTENT OF PUELCHE LAVAS.

Unit	Sample%	SiO_2	Plagioclase	Biotite	Oxides	Amphibole	Quartz	Total
ras	RP-1	73.5	1-2	<1	tr	tr	0	1-2
ras	RP-10	73.4	1-2	<1	tr	tr	0	1-2
ras	LdM-472	73.6	1-2	<1	tr	0	0	1-2
rat	LdM-477	73.3	1	tr	tr	0	tr	1
rat	LdM-478	73.3	1	tr	tr	0	0	1
rcg	LdM-494	75.3	1-2	tr	tr	0	0	1-2
rch	RP-11	75.6	3-5	<1	tr	0	tr	4-5
rch	LdM-470	75.4	3-4	<1	tr	0	tr	3-5
rct	RP-6	71.7	8-10	1-2	tr	tr	0	9-12
rct	RP-7	72.1	7-10	1-2	tr	1	0	10-12
rct	LdM-467	71.3	5-8	1	tr	1-2	0	8-10
rct	LdM-475	71.5	3-5	1	tr	tr	0	5-7
rct	LdM-476	71.6	3-4	<1	tr	1-2	0	5-7
rmt	RP-3	73.5	5-7	1	tr	tr	0	6-8
rni	RP-5	72.8	3-5	1	tr	0	0	4-6
rni	LdM-474	72.8	3-5	<1	tr	0	tr	4-5
rqg	RP-4	74.1	5-6	1	tr	0	0	6-7
rqg	RP-13	74.2	5-7	1	tr	0	0	6-8
rqg	LdM-463	74.2	5-7	1	tr	0	0	6-8
rqg	LdM-468	74.0	6-9	1	tr	0	0	8-10
rqg	LdM-469	74.1	6-9	1	tr	tr	tr	8-10
rri	LdM-466	73.4	2-3	1	tr	0	tr	3-4
rsf	LdM-493	75.4	1	<1	tr	0	tr	1-2
rsf	D2-1-6E	75.5	2	tr	tr	0	0	2
rsj	LdM-464	75.2	2-3	<1	tr	0	tr	2-4
rdac	C84-12	70.5	8-10	1	<1	0	tr	10-12
Mafic Rocks			**Plagioclase**	**Olivine**	**Oxides**	**Cpx**	**Quartz**	**Total**
rch	RP-12	50.6	3-5	1	0	tr	0	4-6
bach	C84-11	54.9	3-4	tr	tr	tr	tr	5
baci	LdM-465	53.9	15-20	3-4	0	1	0	20-25
bact	C84-10	54.3	1-2	0	tr	tr	tr	1-2
baqg	C84-9	54.5	1	2-3	0	1-2	0	4-6

SiO_2 is given in weight %, phenocrysts in volume % estimated from thin sections. **Cpx-** clinopyroxene; **tr-** trace (<0.5%). Trace zircon was seen in RP-1.Several samples were stained in search of traces of sanidine, with negative results.

form the plateau west of Arroyo de las Torrecillas (Fig. 2), two south-central units lie between Arroyo Saavedra and Arroyo de la Hora, and three units are in the southwestern part of the field west of Arroyo de la Hora (Fig. 2). Each of the 11 units was emplaced as one or more flows of viscous rhyolite lava that spread radially from effusive vents to form tabular sheets, each several km² in area and 100-400 m thick. Although their blocky and pumiceous primary surfaces have generally been stripped by glacial erosion, little has been deposited on top of the rhyolites, permitting their tabular forms to control a landscape dominated by rhyolite plateaux separated by great glacial canyons. Numerous lobes of rhyolite no doubt branched from the main masses and poured down paleocanyons as intracanyon lava flows, but remnants of such subsidiary tongues have survived erosion by late Pleistocene glaciers in only a few places.

In addition to the rhyolites, the authors describe below an early Pleistocene rhyodacite cut by the gorge of the Río Puelche and four mid-to-late Pleistocene eruptive units of basaltic andesite, all in the southwestern sector of the volcanic field and all erupted from vents that penetrate one or more of the mid-Pleistocene rhyolites.

PHYSICAL STRUCTURE OF THE RHYOLITE LAVAS

All of the Puelche rhyolites are lava flows, rather than lava domes, in that each exhibits a length:height ratio greater than 10:1, reflecting much more lateral movement away from the vent than upward movement above it. All were emplaced as viscous extrusions of coherent lava. No evidence was found that any originated by fountaining, agglutination, and homogenization of pyroclasts prior to spreading as lava flows. Such processes have elsewhere produced lava-like rheomorphic ignimbrites, typically of peralkaline silicic composition or, exceptionally, of high-temperature subalkaline rhyolite (Mahood, 1984; Henry and Wolff, 1992).

Extrusion of rhyolite lava has never been observed. It is generally assumed that structurally simple rhyolite lava flows >100 m thick are fed endogenously, enlarging from a vent dome by radial spreading or by sluggish downslope movement, first as a stubby coulée and, if slope and magma supply permit, eventually as a channelized lava stream. Although the exposed flow surface chills to solid glass in tens of seconds (Fink and Griffiths, 1998, Fig. 3), the viscous molten interior can remain liquid and mobile for years or decades, inflating and advancing in response to continuous or fitful magma supply from the conduit. Models for calculating extrusion intervals and solidification times for thick silicic lava flows yield results ranging from about a year for small coulées to a few centuries for huge flows several hundred meters thick (de Silva *et al.*, 1994; Duffield *et al.*, 1995; Manley, 1996; Fink and Griffiths, 1998).

Lithologic zonation of the Puelche lavas is typical of thick rhyolite effusions elsewhere (Christiansen and Lipman, 1966; Bonnichsen and Kauffman, 1987; Duffield *et al.*, 1995). The normal pattern is for a devitrified felsite interior to be surrounded by a dense glassy envelope that grades upward and outward into a thin pumiceous carapace. Vesiculation of the carapace reflects the modest pressure gradient within the flow itself, permitting the small remaining fraction of magmatic water retained after ascent and effusion to exsolve only within the outer few meters of lava adjacent to the atmosphere. Zones of cooling and crystallization develop in part during flowage and in part after flow ceases, thus becoming both disrupted by and superimposed upon the structural zones (foliation, brecciation) that develop concurrent with flow. Devitrified felsite is the normal interior lithology that results from protracted cooling of a thick sheet of rhyolite, so the routine failure of a thick glassy exterior shell to crystallize reflects rapid cooling. The glassy envelope can be unusually thick or even predominant in rainy climates and where ice-contact meltwater or lakes provide abundant aqueous coolant. Fine-grained crystallization of the groundmass takes place fastest when the lava is still hot, so devitrification is generally an immediately post-eruptive process, rarely a secular process in Cenozoic rocks. That devitrification is already underway during flowage is shown by mutual folding of adjacent glassy, spherulitic, and devitrified flow laminae and by blocks of flow-foliated devitrified rhyolite incorporated into generally glassy basal flow breccias.

Being brittle, the chilled glassy exterior is repeatedly brecciated by fitful flow of the viscous liquid interior and, perhaps, also by internal inflation of the sheet by continued endogenous magma supply from the vent. The breccia zone atop the flow, owing to more severe folding and shearing at the free surface, can extend to depths of 10-50 m, and it commonly passes into devitrified rock that lies beneath the glassy zone or is structurally caught up in it. Lateral breccia zones on steep flow fronts and margins crumble and avalanche into aprons of talus, which, while the flow is still active, can be overrun and thus contribute to the basal breccia. Compared to unloaded surface breccias, basal breccia zones of rhyolites tend to be thinner (<1-5 m, rarely 10 m), to be more compact and locally rewelded, to consist of denser, less pumiceous glass, but to contain a higher proportion of ash among the blocks, probably owing to greater comminution beneath the load of the moving flow. Locally, the basal breccia can be layered, possibly owing to recurrent avalanching at the overrunning flow front or to downslope shear beneath a thick flow; it can also incorporate fragments of the substrate or of the fused tuff sometimes produced when thick silicic lavas overrun precursory pumiceous pyroclastic deposits (Christiansen and Lipman, 1966). The transition from basal breccia into the coherently foliated flow interior is generally abrupt and crudely planar, in contrast to the equivalent transition beneath the upper breccia zone which is typically raggedly irregular, even faulted and folded. Glacial erosion has removed the primary flow margins from all of the Puelche rhyolite flows and, in stripping flow surfaces, has left only a few blocky remnants of the upper breccia zones. Reciprocally, however, glaciated exposures of lava-flow interiors are excellent.

Internally, flow foliation (flow-layering, flow-banding) is ubiquitous, though locally obscured by crystallization. Layers range in thickness from millimeters to meters, are generally subparallel, but commonly fluidal or lenticular, and are usually defined by differences in vesicularity, color, microlite content, or extent, style, and coarseness of groundmass crystallization. The layers are thought to develop by differential flowage and shear within the highly viscous rhyolitic liquid, some perhaps originating in the conduit, others during spreading of the lava sheet. The foliation is often subhorizontal near the base, but is usually inclined or contorted higher in the flow, typically ramping or fanning upward in the directions of spreading. Such upsweeping foliation is thought to be produced in the still-advancing or inflating liquid core by the growing resistance to flowage at progressively thickening-solidifying flow fronts and by the buttressing effects of peripheral aprons of talus breccia, resulting in flow paths of least resistance toward the upper free surface. If a flow spreads on a gently sloping substrate (rather than being channelized by levees down a steep slope), the foliation may sweep upward toward parallelism with the flow margins as well as with the principal flow front, thus producing in three dimensions a boat-shaped layered structure within each flow lobe. On the scale of a whole flow lobe, concentric corrugations (in plan view) with amplitudes of many meters typically mark the primary surfaces of rhyolite lava flows (see Foto 25 of González and Vergara, 1962). These may, in part, be a surface expression of the upturned foliation, but many are simply late folds superimposed by horizontal compression of the stiffening carapace as the flow stops advancing. Only one or two remnants of such primary surface corrugations (ogives) have survived glacial erosion in the Puelche Volcanic Field.

On the smaller scale of an outcrop, however, complex folding (commonly disharmonic), breakage, and shear of flow layers are widespread, especially near flow margins and on upper surfaces. Tight folding of glassy laminae coexists on a sub-meter scale with boudinage of brittler devitrified laminae. Fused microbreccias consisting of deformed and disrupted segments of black glassy flow laminae interspersed with abundant 1-2 cm fragments of pale felsite (derived by break-up of coexisting laminae) might, at first glance be confused with lithic-rich eutaxitic welded tuff.

Spherulites are especially conspicuous in Puelche rhyolites because erosion has stripped the flows of much, but not all, of their primary glassy envelopes. Spherulites are concentrated in the innermost part of the glassy zone and in the variably devitrified transition to the finely crystalline interior, depth levels that are well exposed here. Usually pink or grey, most are dense spheroids having a radial structure of finely fibrous silica and feldspar crystallites (Iddings, 1888). Generally, 1-20 mm in diameter but occasionally much larger, spherulites tend to be most densely distributed in layers and lenses concordant with adjacent glassy laminae. Some are solitary in the glassy host, and some nucleate on phenocrysts or on lamina boundaries and thus grow as hemispherulites. Lithophysae (Iddings, 1888) and less regularly shaped gas cavities, each typically 1-8 cm across and lined by one or more thin shells of lithoidal rhyolite, are far less common than spherulites in the Puelche lavas, but have similar distribution in zones of incipient devitrification.

Everywhere superimposed on the flow foliation are near-vertical or inclined cooling joints, which tend to be columnar in lower glassy zones, but are more commonly throughgoing shrinkage fractures that separate subvertical slabs, especially in the overlying crystalline zones (Figs. 3, 4). The polygonal columns are typically 0.5-1.5 m across, whereas the shrinkage fractures are generally irregular and more widely spaced, usually by 2-5 m or more.

Vents for effusive rhyolite lavas are seldom exposed, because they long remain concealed beneath the thickest, most erosion-resistant parts of the flows they produce. Slight magma withdrawal at the termination of effusion can leave a small surface depression that marks the vent site for some uneroded flows. Sometimes, vent domes extrude that stand slightly higher than the general surface of the surrounding lava flow, but remains of such bulges appear to have survived glacial erosion at only one or two rhyolite vents in the Puelche Volcanic Field (units **rni** and **rsf**, below). Nonetheless, four feeders have been recognized, each

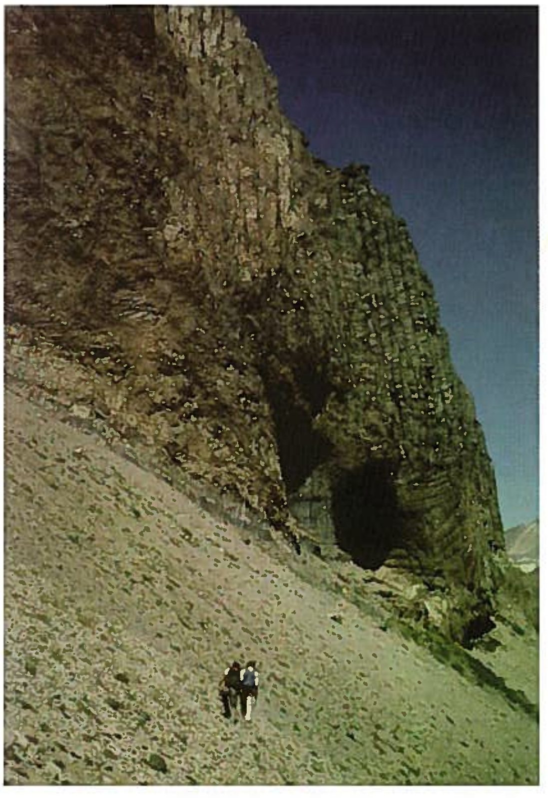

FIG. 3. Base of Rhyolite of Arroyo Saavedra (unit **ras**) at sample site RP-1 (Fig. 2). Gently curved flow foliation in dark grey-brown glassy zone is subhorizontal. Near-vertical cooling joints are columnar in glassy zone but slab-like and more widely spaced in tan to pale grey devitrified felsite above. Scree covers thin basal flow breccia and underlying pyroclastic ejecta.

FIG. 4. Southwest face of Rhyolite of Campo La Hora (**rch**) (cf. Figs. 2, 8). Dark grey glassy curved columns are each about 1 m wide. Less regular shrinkage joints in tan devitrified felsite above are spaced 5-10 m. Visible part of cliff is 70-80 m high. Gently dipping, layered, lower 10-15 m superficially resembles fallout but is actually flow foliation in glassy lava, which was brecciated and, along some layers, sheared and granulated beneath the main mass of the 100-m-thick flow, as it moved downslope to the right. Columns developed after flowage ceased and do not penetrate the chilled and sheared basal zone (cf. Fig. 3).

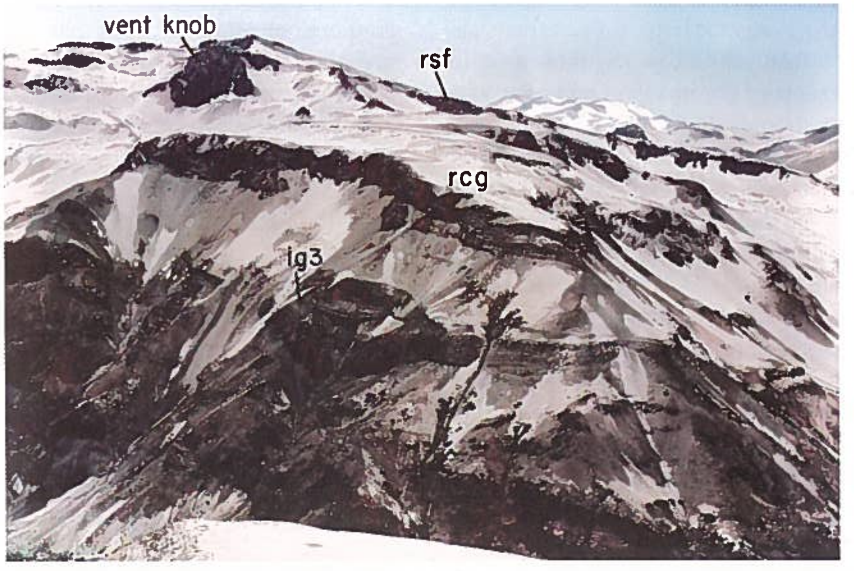

FIG. 5. View northwest across Invernada canyon to high-silica rhyolite lava units **rcg** and **rsf** and vent remnant of unit **rsf**. Canyon-rim plateau is 150-m-thick lava flow of **rcg**, which overlies welded ignimbrite sheet (**ig3**; probably Unit V of Loma Seca Tuff) seen thickening into axis of paleovalley cut in Tertiary andesitic lavas. Skyline rim at left and east-dipping lava-flow rim at right are unit **rsf**, which issued from steeply foliated vent preserved (in left distance) as 300-m-high knob of dense coherent rhyolite. Light-colored surfaces are mantled with pumiceous fallout from 1932 eruption of Quizapu. Snow-clad mountain in right distance is Cerro del Medio in the Calabozos caldera.

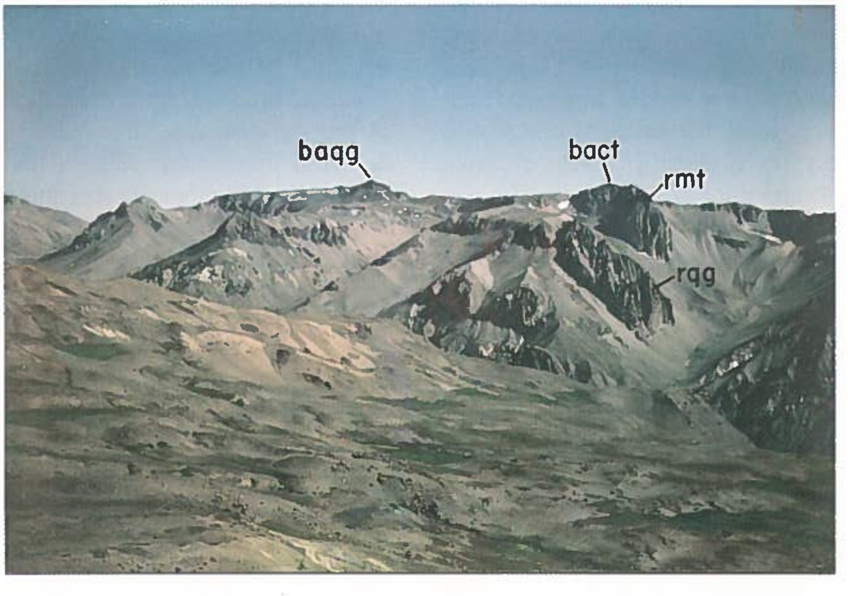

FIG. 6. View northward across gorge of Río Puelche to steeply jointed rhyolite feeders for units **rqg** and **rmt**, which form gently dipping lava plateaux. Lower feeder is exposed for 600 m vertically and is continuous with the lower plateau-forming rhyolite lava flow, 250-m-thick (cf. Fig. 2). Upper feeder has 450 m vertical exposure and is continuous with the 150-m-thick rhyolite lava that forms the skyline plateau. Lowest exposure of lower feeder is at 2,200 m elevation, skyline plateau at over 3000 m. Also indicated are craggy scoria-cone remnants at vents for mafic units **baqg** (peak 3107) and **bact** (peak 3057). Drainage in left distance is Quebrada Los Gorgollones.

now a bold knob or an upward-widening throat several hundred meters wide (Figs. 5, 6) that consists largely of coherent lithoidal rhyolite and is characterized by steep flow foliation and near-vertical jointing, with subordinate inclined jointing limited to glassy lateral contact zones. Each feeder is exposed on rugged cliffs, the upper parts of which merge laterally into cliffs of the subhorizontal lava sheets that erupted there. Three-dimensional exposure is thus inadequate to be sure whether the feeders are equant or elongate in plan view, but their lack of expression on (or beyond) adjacent glaciated plateaux (Figs. 5, 6) suggests that all four are equant. Even had the rhyolite magma been dike-supplied at greater depths, it would not be unusual for locally concentrated upward flow at shallow levels within the dike to result in one or more central (point-source) vents at the surface (Delaney and Pollard, 1981).

Deposition of pyroclastic ejecta normally precedes effusion of silicic lavas and may also take place between successive pulses of effusion. Pumice cones and rings commonly mark rhyolitic vents, and several postglacial examples are well exposed at nearby Laguna del Maule (Fig. 1). Layers of pumiceous fallout, typically subplinian or plinian, are also common products of rhyolite vents, as are small proximal pyroclastic flows and stratified vent-clearing deposits rich in coarse lithic fragments that include glassy cognate blocks, both dense and vesicular. Exposures of such pyroclastic deposits are rare in the Puelche Volcanic Field, in part due to glacial erosion, but principally owing to the ubiquitous rhyolitic screes that obscure the bases of most of the lava-flow cliffs (Figs. 3-8). Proximal pyroclastic deposits are probably widespread beneath the lava flows and the adjacent screes, but only three limited exposures were observed during our reconnaissance and none was studied carefully.

No direct evidence was found for ice-contact emplacement of the rhyolites, despite the subsequent glacial erosion of all of them. Some evidence might well have been destroyed by that erosion, especially along the canyons intermittently occupied by glaciers. The thick lower glassy zones (with columnar joints) displayed by a few of the rhyolitic lava flows (Figs. 3, 4) apparently reflect rapid cooling, perhaps accelerated by steam flux generated when the lavas overran arroyos, snowfields, or ice. Nonetheless, excellent widespread exposure, normal uncomplicated basal contacts, thick devitrified flow interiors, absence of thick piles of hyaloclastite breccia, lack of glacial deposits under the rhyolites, and emplacement of several lava flows on or near canyon floors all suggest that the Puelche rhyolites erupted during one or more non-glacial intervals.

RHYOLITIC ERUPTIVE UNITS

The **Rhyolite North of the Río Invernada (rni)** consists of two lava flows, both extruded at a vertically jointed vent complex exposed on the 300 m high southwest-facing cliff just north of the big bend where the course of the upper Río Invernada turns from southward to westward (Figs. 1, 2). The flows are compositionally identical biotite-plagioclase rhyolites (72.8% SiO_2) with about 5% phenocrysts. The lower flow is 100-125 m thick and is exposed only at the base of the cliff beneath the upper one, which is as thick as 300 m. Nothing remains of the primary surface of the upper flow; its glacially scoured eastern slope descends gently to the glaciated valley of the upper Río Invernada, and the great western cliff has been excavated intermittently as an open cirque. An isolated 2700-m knob across the river 2 km southwest of the cirque (Fig. 2) is a 500-m-wide rhyolite remnant 50-150 m thick, which is probably an eroded outlier of this formerly more extensive eruptive unit, banked against the far side of the paleocanyon. The rhyolite lavas rest on andesitic fragmental rocks to the north and on Quaternary ignimbrite to the south; their eastern slope appears to be lapped by another, younger, ignimbrite, but this area is at the limit of the authors' reconnaissance.

The **Rhyolite of the Río Invernada (rri)** is a remnant of a single intracanyon lava flow of phenocryst-poor biotite-plagioclase rhyolite (73.4% SiO_2) that erupted from an unidentified vent northeast or southeast of it. The rhyolite remnant is 100-150 m thick and forms a curving interfluvial ridge between gorges of the Río Invernada and one of its tributaries (Fig. 2). The rhyolite overlies the contact between deformed Mesozoic redbeds and subhorizontal Tertiary pyroclastic deposits; it is overlain in turn by one of the Quaternary ignimbrites, probably Unit V or Unit S of the Loma Seca Tuff. The base of the rhyolite slopes downstream from 2,450 m to 2,350 m in elevation, about 150-300 m lower than the bases of the extensive rhyolites 1 km north and south of it (units **rni** and **rct**). Because the intracanyon rhyolite flow is inset between and below those units, it would generally be expected to be younger, but until more comprehensive radiometric dating is undertaken, such an interpretation remains tentative. An incompletely devitrified sample of the intracanyon flow gave a total-fusion $^{40}Ar/^{39}Ar$ age of 326±2 ka, but consideration of its concave-down step-heating spectrum suggests the likelihood of some Ar loss and a minimum age for the older steps of about 354 ka.

Two thick lava flows of phenocryst-poor biotite-plagioclase rhyolite are exposed between Cajón Grande and the Río Invernada (Fig. 2). Although the flows are extensively superimposed, of similar composition, and appear to have issued from the same vent complex, the authors describe them separately because they are apparently of different ages and have contrasting relationships to pre-eruptive topography. The older flow, the **Rhyolite of Cajón Grande (rcg)**, is a great 300-m-thick sheet of high-silica rhyolite (75.3% SiO_2) that still covers 13 km^2 despite the glacial canyons cut on all sides. Its irregular but crudely planar base slopes southeastward to 2,450 m (Fig. 5) and westward to as low as 2270 m at its eroded downstream end (Fig. 2). It rests on Tertiary andesitic lavas and tuffs and locally on Quaternary ignimbrite (Fig. 5). At 2800 m, the highest part of its glacially scoured surface is near the center of its present-day distribution and lies adjacent to the effusive vent of the overlying flow (unit **rsf**); from this the authors infer that the vent location was approximately the same for both lavas.

The upper flow in the same area is the **Rhyolite of Arroyo San Francisquito (rsf)**, another sheet of high-silica rhyolite (75.5% SiO_2) that covers about 9.5 km^2 today. Its high point at about 3,050 m and a 2,950 m crag about 0.5 km south of there, appear to be parts of the vent dome and effusive throat of this flow, respectively. The vent remnant is erosionally almost isolated as a vertically jointed crag 350 m wide (Fig. 5) and consists of massive lava (and subordinate peripheral breccia) well exposed on encircling cliffs as high as 300 m. The main glaciated remnant of the flow forms a high ridge and plateau at elevations of 2,750-3,050 m, and its greatest surviving thickness is 300-350 m on the cliff facing Cajón Grande. The base of the flow descends westward from 2,800 m near the vent to an elevation as low as 2,550 m at its eroded southwest nose. The base also drops gently northeastward from the vent (Fig. 5) and then pitches steeply into Arroyo San Francisquito (Fig. 2). Beyond this arroyo to the southeast, an erosionally detached (compositionally identical) remnant 100-200 m thick forms a glacially scoured plateau and drapes a paleoslope southward toward the Río Invernada, reaching an elevation as low, today, as 2,250 m. It is this impressive filling of paleotopography, not observed in the lower flow (unit **rcg**) that suggests (but does not prove) that the upper flow is significantly younger. For the upper flow, Drake (1976) reported a K-Ar age of 0.3±0.1 Ma from the northeastern lobe, and a new sample from the southwestern nose of the main part of the flow yields a $^{40}Ar/^{39}Ar$ isochron age of 213±12 ka.

The high plateaux in the eastern part of the Puelche Volcanic Field consist largely of the **Rhyolite of Cabeceras de las Torrecillas (rct)**, which represents remnants of two or more lava flows (71.3-72.1% SiO_2) that today cover about 16 km^2. Least silicic of the mid-Pleistocene rhyolites, this unit is also generally the richest in phenocrysts, containing 6-12% plagioclase, biotite, and, distinctively, amphibole. Rare amphibole is seen in a few other Puelche rhyolite samples, but in none but this unit is amphibole a prominent euhedral phenocryst (0.5-1.5 mm long), unrimmed in glassy samples and typically constituting about 1-2% of the rock (Table 1). Only on the north-facing cliffs of the plateau were two distinct flow units observed, each about 100 m thick and each having a 20 m thick glassy basal zone and a dominant felsitic interior. Two samples from the plateau top have only 5-7% phenocrysts, whereas two samples from the lower flow unit at the north end have 8-12%, as does a sample from the lower southern mesa, which was isolated by erosion from the main plateau (Fig. 2). These relations suggest zonation in pre-eruptive crystal content and perhaps the existence of cryptic flow contacts not observed in aerial photographs or during our field reconnaissance. Much of the glacially scoured surface of the rhyolite plateau is at elevations of 2,950-3,100 m. The irregular base of the unit is exposed at 2,650-2,850 m on glacially eroded scarps to the north, east, and west, but the base descends northeastward to 2,600 m toward the Invernada canyon and southward to 2,500 m at the rim of the Puelche gorge. The vent is not obvious, but is probably an effusive zone hidden beneath the high north-central part of the flow. The flow is typically about 250 m thick in the south and as thick as 400 m in the north. In view of its thickness and apparent absence of confining paleotopography, the unit was no doubt very much more extensive prior to glacial erosion.

The **Rhyolite of Arroyo de Torrecillas (rat)** overlies the previous unit (**rct**) and drapes down from the high plateau into the main canyon to its east (Fig. 2). Unlike the phenocryst-rich amphibole-bearing rhyolite (**rct**) it drapes, this flow consists of nearly aphyric biotite-plagioclase rhyolite (Table 1) and is distinctly more evolved (73.3% SiO_2). As high as 3,140 m on the glaciated plateau, the flow is today as thick as 150-200 m on the east-facing cliffs. The intracanyon remnant to the east, also glacially scoured, is 50-125 m thick and its base is as low as 2,400 m. The severe unconformity it drapes and the 700 m of relief on its base suggest that emplacement of this rhyolite and the one beneath it (**rct**) were separated by an episode of canyon-cutting glacial erosion. Although the flow covers only 3 km^2 today, its topographic distribution implies that it had been much more extensive prior to erosion by the glacial episodes that followed it.

The most extensive unit of the Puelche Volcanic Field is the **Rhyolite of Quebrada Los Gorgollones (rqg)**, which is the basal lava flow throughout the southwestern sector. Although it covers, at least, 26 km^2, samples from all parts of it are essentially identical (amphibole-free) biotite-plagioclase rhyolite containing 74.0-74.2% SiO_2 and 6-10% phenocrysts (Tables 1, 2). Its vertically jointed feeder is exposed on a cirque wall 1.5 km north of the Río Puelche, near the southern limit of present-day remnants of the flow. This rhyolitic throat, the transition from conduit to outflow lava, is 600 m wide at its lowest exposure (Fig. 6). From the feeder the lava spread eastward and northwestward as a great sheet (Fig. 2) and must also have flowed southward into the area now occupied by the Puelche gorge. Away from the upward-flaring feeder, the irregular base of the preserved sheet is widely at 2,650-2,800 m, but it slopes eastward to elevations as low as 2,500 m (Fig. 7), descends northwestward to 2,400 m along Estero San José, and drapes the wall of the Invernada canyon to as low as 2,250 m. Having been apparently unconfined by paleotopography, the original extent of this unit was no doubt much greater than today (Fig. 7). The glacially stripped surface of the rhyolite has a maximum elevation today of 2,950 m where it is protected by an overlying shield of basaltic andesite (unit **baqg**) near the center of the rhyolite's preserved distribution; the outflow surface declines gently away from that high in all directions (Fig. 7). The thickness of the sheet today is generally 200-300 m, except near the feeder where vertical exposure is as great as 600 m.

In direct contact above the unit just described (**rqg**) is a similar biotite-plagioclase rhyolite lava flow, the **Rhyolite of Mesa 3028 (rmt)**, which is less extensive (5 km^2), slightly less silicic (73.5% SiO_2), and contrasts with the unit beneath it in having a small amount of amphibole. Its vertically jointed feeder, about 500 m wide at its lowest exposure, is well exposed (Figs. 6, 7) on a cirque headwall only 1 km north of the feeder for the underlying flow. Most of the flow forms a subhorizontal sheet 150-250 m thick that supports a glacially scoured plateau at about 3,000 m. The feeder, however, has a vertical exposure of 450 m, and the eastern lava lobe descends to an elevation of 2,600 m in Arroyo de la Hora, unconformably draping the rim of the underlying rhyolite (**rqg**), a relationship that suggests a significant interval of erosion between the two eruptions.

The northwestern end of extensive unit **rqg** is overlain by another distinctive unit, the **Rhyolite of Estero San José (rsj)**, which is a phenocryst-poor high-silica rhyolite (75.2% SiO_2) with only small amounts of plagioclase and biotite. On the rim of the Invernada canyon at the confluence of Estero San José, three rhyolitic lava flows are stacked; the lowest is the major unit **rqg**, the middle one is the main 2.6-km^2 remnant of unit **rsj**, and the unsampled top one (<50 m thick and covering only 0.15 km^2) is also assigned (arbitrarily) to unit **rsj** on the map (Fig. 2). The middle flow (the main mass of unit **rsj**) is 200-300 m thick, and its irregular basal contact slopes from as high as 2,850 m in the southeast to as low as 2650 m in the west. The vents are unknown for the middle and upper flows, which are both gently dipping remnants of glacially eroded lava sheets. At 2,700-3,000 m elevation, they are at a level similar to that of the comparably phenocryst-poor high-silica rhyolite unit **rsf**, which vented 5 km northeast, on the other side of the Invernada canyon. Correlation is certainly possible, though it would require having filled the paleocanyon with as much as 1,000 m of rhyolite to permit overflow on the

FIG. 7. Upper part of vent-throat remnant of rhyolite unit **rmt** on left and southeastern plateau of outflow lava **rqg** in lower center (cf. Fig. 2). View southeast from western plateau of **rmt** (Fig. 2) toward Cerro Campanario on skyline, 20 km distant. In feeder, note flow foliation dipping to right, intersected by jointing, which is mostly near vertical, but is locally oriented perpendicular to the feeder's free right margin. In 200-m-thick lava flow of **rqg**, note black glassy base, steep jointing in tan to grey felsite interior, and absence of an upper glassy zone, which was stripped by ice. The unconfined lava flow probably extended much farther in all directions prior to glacial widening of the canyons. In distance, far wall of the upper Río Puelche consists of late Tertiary intermediate lava flows and light-colored ignimbrites, another of which is mostly concealed by the foreground scree.

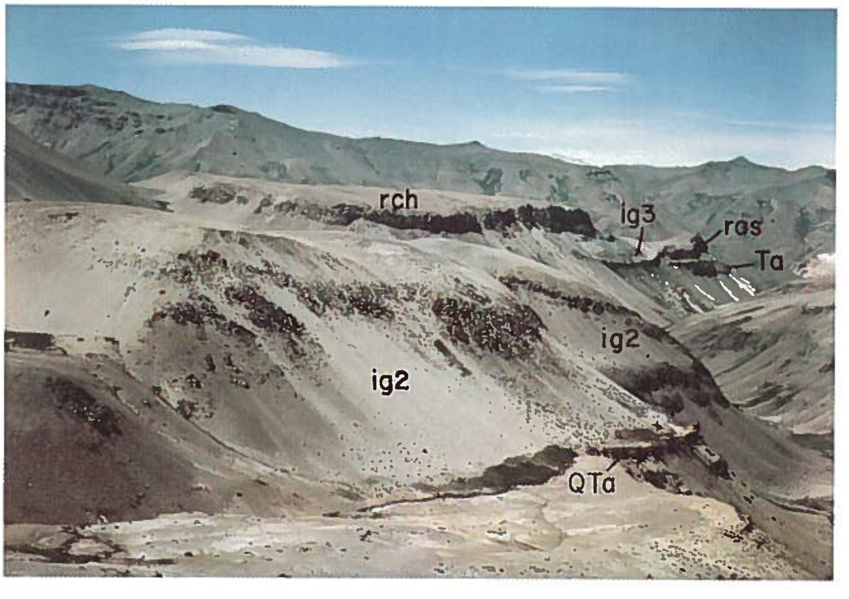

FIG. 8. View southward down Arroyo de la Hora. Isolated mesa Campo La Hora in middle distance is 1.8-km^2 remnant of high-silica rhyolite lava **rch**, its eroded scarp here 100-150 m high. Below it to the right, cliffy point is 200-m-thick remnant of rhyolite lava **ras**, which is lapped by a 50-m ledge of welded ignimbrite (**ig3**; probably Unit V of the Loma Seca Tuff) and overlies andesite breccia (lowest cliff in shadow) and white ignimbrite (probably Tertiary). In foreground, rounded ridges are 300-m-thick rhyolitic ignimbrite (**ig2**), older than the Puelche rhyolite lavas, that rests on andesitic lavas (**QTa**; ledge at lower right) and erupted from an unknown, non-local source. On left skyline, southeast of the Río Puelche canyon, gently dipping stack of andesite lavas (probably Pliocene or early Quaternary) is part of the continental drainage divide.

TABLE 2. CHEMICAL COMPOSITION OF ERUPTIVE PRODUCTS.

Sample	Unit	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K2O	P_2O_5	LOI	Original Total	Rb	Sr	Y	Zr	Nb	Ba
Puelche Lavas																			
RP-1	ras	73.5	0.26	14.05	1.30	0.05	0.38	1.02	4.56	4.43	-	0.35	99.27	168	123	24	215	10	744
RP-10	ras	73.4	0.28	14.06	1.37	0.06	0.42	1.12	4.45	4.39	0.05	~	99.86	165	128	23	233	10	756
LdM-472	ras	73.6	0.28	14.11	1.37	0.06	0.26	0.96	4.38	4.46	0.09	0.49	98.69	172	118	20	224	11	764
LdM-477	rat	73.3	0.30	14.28	1.45	0.06	0.29	1.06	4.54	4.28	0.09	0.44	98.85	146	127	19	242	9	771
LdM-478	rat	73.3	0.29	14.26	1.36	0.06	0.30	1.08	4.49	4.33	0.09	0.35	98.74	163	127	21	230	11	741
LdM-494	rcg	75.3	0.23	13.16	1.22	0.05	0.22	0.84	4.00	4.55	0.07	0.39	99.28	175	87	15	151	10	660
RP-11	rch	75.6	0.19	12.99	1.04	0.04	0.34	0.74	4.08	4.57	-	1.06	98.93	192	80	20	140	9	599
RP-12(incl.)	rch	50.6	1.32	18.96	9.72	0.16	4.90	9.24	3.54	0.85	0.26	1.20	98.74	23	521	33	120	5	280
LdM-470	rch	75.4	0.20	13.42	1.04	0.05	0.18	0.72	3.95	4.60	0.06	2.99	96.29	182	71	16	130	9	630
RP-6	rct	71.7	0.40	14.52	2.07	0.07	0.60	1.66	4.29	4.17	0.09	0.46	98.84	151	175	22	247	9	728
RP-7	rct	72.1	0.36	14.30	1.91	0.06	0.66	1.59	4.38	4.15	0.09	0.51	99.60	168	178	27	239	9	701
LdM-467	rct	71.3	0.40	14.89	2.11	0.07	0.61	1.69	4.26	4.11	0.15	1.30	97.83	161	181	19	243	11	717
LdM-475	rct	71.5	0.39	14.73	2.09	0.05	0.50	1.60	4.36	4.21	0.13	0.59	98.63	154	177	20	246	12	729
LdM-476	rct	71.6	0.39	14.58	2.04	0.07	0.59	1.64	4.33	4.19	0.13	0.57	98.70	151	168	21	240	8	709
RP-3	rmt	73.5	0.27	13.96	1.50	0.05	0.49	1.22	4.24	4.35	0.05	1.16	98.43	172	129	22	188	10	684
RP-5	rni	72.8	0.31	14.32	1.53	0.06	0.48	1.25	4.48	4.32	0.06	0.83	98.79	169	162	23	254	9	747
LdM-474	rni	72.8	0.32	14.47	1.50	0.06	0.32	1.20	4.43	4.35	0.11	0.31	98.67	167	148	20	251	12	758
RP-4	rqg	74.1	0.22	13.84	1.19	0.05	0.32	0.95	4.24	4.65	-	1.52	98.61	175	110	23	173	9	706
RP-13	rqg	74.2	0.24	13.65	1.27	0.05	0.41	0.99	4.16	4.63	-	0.75	98.54	178	109	23	180	10	666
LdM-463	rqg	74.2	0.24	13.95	1.28	0.05	0.25	0.89	4.20	4.48	0.09	0.46	98.48	153	96	18	165	9	739
LdM-468	rqg	74.0	0.31	13.77	1.42	0.08	0.27	0.60	4.78	4.31	0.10	0.31	99.12	143	56	34	232	14	699
LdM-469	rqg	74.1	0.26	13.71	1.33	0.06	0.29	0.97	4.20	4.54	0.09	0.31	98.94	173	105	19	180	9	697
LdM-466	rri	73.4	0.29	14.30	1.38	0.05	0.22	1.04	4.39	4.47	0.09	0.42	98.93	174	131	21	226	10	746
LdM-493	rsf	75.4	0.23	13.17	1.10	0.05	0.22	0.73	4.00	4.57	0.08	0.34	99.13	190	78	14	145	12	615
D2-1-6E	rsf	75.5	0.20	13.11	1.05	0.04	0.32	0.77	3.99	4.66	-	2.65	97.27	180	80	17	149	8	617
LdM-464	rsj	75.2	0.24	13.25	1.16	0.04	0.19	0.83	4.03	4.54	0.08	0.45	98.88	183	94	17	153	9	608
C84-12	rdac	70.5	0.51	15.71	2.34	-	0.52	1.34	4.93	3.65	0.12	2.11	97.64	118	181	36	298	10	737
C84-11	bach	54.9	1.18	17.76	8.94	0.15	3.87	7.01	4.01	1.57	0.25	-	99.85	48	487	24	147	5	359
LDM-465	baci	53.9	1.10	18.20	8.13	0.15	4.87	8.07	3.53	1.37	0.29	0.60	98.95	36	550	20	157	8	412
C84-10	bact	54.3	1.01	17.30	7.97	0.14	4.70	9.25	3.43	1.29	0.20	0.81	99.60	43	574	18	116	2	284
C84-9	baqg	54.5	1.01	17.74	7.71	0.13	5.38	7.79	3.75	1.29	0.27	0.15	99.37	31	602	16	138	2	354
Regional Ignimbrites																			
RP-2	ig2	74.4	0.21	13.60	1.07	0.06	0.20	0.82	4.03	5.18	-	0.94	98.11	*165	-	-	*149	-	*724
RP-8	ig2	74.4	0.21	13.68	1.06	0.05	0.22	0.81	3.74	5.46	-	5.32	93.90	*217	-	-	*141	-	*695
RP-9	ig3	70.0	0.50	15.24	2.21	0.06	0.47	1 28	5.15	4.61	0.10	0.35	98.66	*179	-	-	*400	-	*748
LdM-473	ig3	69.9	0.54	15.45	2.28	0.07	0.36	1.14	5.13	4.67	0.09	0.50	98.74	166	140	46	436	15	808

The ten major oxides (reported in weight percent) are normalized to H_2O-free totals of 99 6 weight percent (allowing 0.4 weight percent for trace oxides and halogens); determinations by wavelength-dispersive XRF in U.S.G.S. laboratory at Lakewood, Colorado; D.F. Siems, analyst. Rb, Sr, Y, Zr, Nb and Ba (in parts per million) determined by energy-dispersive XRF by P.E. Bruggman and D.F. Siems. Rb, Zr, and Ba with (*) determined by INAA (cf. Table 3). Precision and accuracy are discussed by Bacon and Druitt (1988) and Baedecker (1987). FeO* is total iron calculated as FeO. 'Original Total' is the volatile-free sum of the ten oxides, as analysed, before normalization, with total iron calculated as Fe_2O_3 LOI= weight loss on ignition at 900°C. RP-12 (incl.) is magmatic inclusion of basalt abundant in rhyolite unit **rch**.

south rim. The present-day remnants of the three-flow rhyolite stack drape the south wall of the modern canyon from an elevation >3000 m down to 2,250 m, or 750 m vertically, so transient canyon filling to such a depth would not have been volcanologically unreasonable.

Among the apparently youngest rhyolites in the Puelche Volcanic Field are two lava flows that cap the relatively low plateaux between Arroyo de la Hora and Arroyo Saavedra, *ca.* 300-500 m lower than the flanking plateaux formed by units **rct** and **rqg** (Fig. 2). The older of the pair, the **Rhyolite of Arroyo Saavedra (ras)**, is a sheet of phenocryst-poor biotite-plagioclase rhyolite (73.5% SiO_2) 150-200 m thick that covers about 2.4 km^2 just west of the arroyo of that name. The 200 m high south-western cliff exposes some of the most spectacular jointing in the volcanic field, much of it polygonally columnar and extending vertically through the entire flow. The near-vertical columns transect sub-horizontal to curviplanar flow layering (Fig. 3). The basal 10-20 m is black glass, mostly perlitic and crumbly but containing nonhydrated obsidian corestones as big as 10 cm. Most of the flow is pale grey felsite that weathers tan to brown like most Puelche rhyolite, though a few black glassy domains recur high in the flow interior. The marginal cliffs have receded an unknown, but large amount by spalling and glacial erosion, so little or none of the primary glassy carapace survives. The flow rests on white nonwelded ignimbrite and fragmental andesitic strata, both probably Tertiary in age, and the un-complicated basal contact of the lava shows no evidence of ice-contact deposition. The base of the flow remnant slopes gently toward the Río Puelche, dropping from 2,450 m in the northeast to 2,250-2,300 m in the southwest. Nonhydrated obsidian yielded a K-Ar age of 350±20 ka.

Overlying the rhyolite just described (**ras**) is a high-silica rhyolite lava flow (75.5% SiO_2), the **Rhyolite of Campo La Hora (rch)**, which caps the section locally and forms the 2-km^2 plateau of that name (Figs. 2, 8). It is separated from the lava flow below (unit **ras**) by a 30-80-m-thick, welded to nonwelded sheet of Quaternary ignimbite (Fig. 8), probably Unit V of the Loma Seca Tuff (0.30±0.03 Ma; Hildreth *et al.,* 1984a). At 75-150 m, this is the thinnest of the Puelche rhyolite lavas. Its relative thinness is probably a primary feature as it appears to have been modified only slightly by glacial scour. The plateau surface slopes a few degrees southward (Fig. 8), but the basal contact of the flow dips gently west from 2,650 m to as low as 2500 m along its eroded western scarp, suggesting that a paleovalley near the course of Arroyo de la Hora (Fig. 2) had been established prior to its eruption. At the downvalley (southwestern) limit of the remaining exposure, the coherently jointed interior of the flow rests on a 10-15 m flow-foliated zone in which the gently dipping flow layers are internally brecciated, sheared, even granulated, but not folded (Fig. 4). Superficially resembling fallout, these slope-parallel glassy flow layers were evidently chilled, then crushed and sheared, as the main mass of the flow moved slowly downslope. Directly above the layered base is a zone 25-35 m thick of inclined and curving, glassy, polygonal columns, each column typically about 1 m wide (Fig. 4). The upper half of the flow is tan-weathering pale-grey felsite, and on the plateau surface are preserved remnants of the original glassy to pumiceous carapace, virtually unique in the Puelche Volcanic Field.

The Rhyolite of Campo La Hora is also unique in the volcanic field, as far as the authors have observed, in containing abundant magmatic inclusions of olivine-plagioclase **basalt** (50.6% SiO_2). Within the coherently columnar, as well as the sheared flow-layered, glassy zones, most of the 1-15 cm enclaves are angular, evidently broken up after incorporation by viscous flow of the chilling rhyolite. In the felsite zone, however, most of the basalt blobs are unbroken, equant or lenticular, and commonly have rounded, crenulate, or amoeboid margins, but no chilled glassy rinds. Most are finely vesicular and have a finely holocrystalline ground-mass. They are widely distributed vertically and laterally within the rhyolite flow, typically making up 1-3% of the outcrop and locally much more. So numerous are the basaltic inclusions that, weathering out of the crumbly glassy zones, they form extensive lag-gravel pavements on the benches and plateau at the base of the scarp surrounding the rhyolite mesa. No other kind of inclusion was observed accompanying the millions of basaltic blobs and blebs. A batch of basalt, presumably dike-fed, evidently invaded the rhyolite magma body sufficiently long before its eruption to become convectively well distributed. On the other hand, the interaction time was not long enough to permit the basaltic blobs to be hybridized toward an inter-mediate composition more typical of mafic enclaves in rhyolites (Bacon and Metz, 1984).

BASALTIC ANDESITE ERUPTIVE UNITS

Basaltic andesites erupted from four discrete vents in the western part of the Puelche Volcanic Field (Fig. 2). The products of all four are glacially eroded, but all four are younger than at least some of the rhyolites.

The **Basaltic Andesite of Quebrada Los Gorgollones (baqg)** is a glacially eroded remnant of a modest shield of mafic lavas (54.5% SiO_2) that erupted at Peak 3107. This peak is a rugged fragment (Figs. 2, 6) of a small cinder cone consisting of stratified scoria, which is oxidized, both loose and agglutinated, and intruded by dikes and irregular masses of lava. The vent penetrates the lower rhyolite flow (unit **rqg**) and the shield lavas overlie it. These lavas also bank against an eroded scarp of the upper rhyolite flow (unit **rmt**), drape over the eastern scarp of the lower rhyolite, and form an apron that descends 3 km northeastward (Fig. 2) to an eroded terminus as low as 2300 m. Exposures of this apron, which is clearly younger than both rhyolites, consist of as many as 8 thin mafic lava flows. Maximum exposed thickness of the shield is 50-70 m, on the scarps west of the vent scoria cone, or 110 m including the cone remnant itself. The phenocryst-poor lavas contain small amounts of olivine, clinopyroxene, and plagioclase (Table 1).

The **Basaltic Andesite of Cerro 3057 (bact)** is another, even smaller, cinder-cone remnant only 200 x 350 m in area, along with a thin outlying remnant of rubbly mafic lavas (54.3% SiO_2) about 900 m long. Both remnants rest on the previously glaciated surface of the upper rhyolite plateau (unit **rmt**), and the mafic lavas drape down its northern scarp (Fig. 2). On a cirque headwall adjacent to the feeder for the upper rhyolite, a mafic dike is well exposed (Fig. 9), cutting the rhyolite and feeding into the overlying scoria cone. The lavas and scoria are even poorer in phenocrysts (Table 1) than nearby unit **baqg**, containing 1-2% plagioclase, a trace of clinopyroxene, and little or no olivine. The scoria-cone remnant consists of oxidized cinders, well-stratified, and intruded and locally armored by thin lavas. Its maximum surviving thickness is about 50 m, and the lava remnant to its northeast is thinner still. Most of the unit has been eroded away.

The **Basaltic Andesite of Cajón de la Hora (bach)** is a third vent remnant, even less remaining than the others. The 200 m wide ovoid remnant (Fig. 2) consists of coarse, oxidized, bedded scoria and agglutinate (54.9% SiO_2). It is well-exposed on the sidewall of a cirque valley tributary to Arroyo de la Hora, but is surrounded by rhyolitic scree. Although its contacts are thus obscured, the authors infer that it erupted through the lower rhyolite (unit **rqg**), and it may subsequently have been overrun by the nearby upper rhyolite (unit **rmt**). It contains several percent plagioclase phenocrysts, small amounts of olivine and clinopyroxene, quartz xenocrysts, and abundant rhyolitic xenoliths 1-10 cm, most of them partially melted and presumed to be derived from the rhyolite lava flow it penetrated.

The **Basaltic Andesite of Cajón Invernada (baci)** is a stack of thin mafic lava flows (53.9% SiO_2) that erupted from a vent on what today is the south rim of the deep canyon of the Río Invernada (Fig. 2). A small vent plug ringed by sloughing oxidized scoria is well exposed at the source of 15-20 lava flows that cap the canyon rim for about 2 km eastward. From the vent at 2,800 m, the stack dips gently east, descending to 2,400 m at its eroded terminus. As thick as 150 m, the stack of mafic lavas is part of a glacially eroded shield that originally was no doubt much more extensive. The vent penetrates about 100 m of rhyolite lava of unit **rqg**, which, in turn, overlies Tertiary ignimbrites and intermediate lavas and tuffs. In contrast to the three phenocryst-poor mafic units already described, these lavas are rich in small (0.1-1 mm) phenocrysts of plagioclase and olivine with lesser amounts of clinopyroxene (Table 1).

EARLY PLEISTOCENE RHYODACITE

Just south of the mid-Pleistocene volcanic field, a 6-km^2 exposure of flow-banded biotite-plagioclase rhyodacite (70.5% SiO_2) is cut by the gorge of the Río Puelche. Consisting largely of white to grey felsite, the mass probably also extruded as a lava dome, but most of what remains is shallowly intrusive (at the level preserved) into Tertiary volcanic deposits, which are predominantly ignimbrite and presumed to be Miocene. A glassy marginal zone of crumbly dark-grey perlite a few meters thick is exposed widely around the edge of the otherwise devitrified rhyodacite body. Parts of the rhyodacite are acid-altered locally, along with some adjacent host rocks. Cut by several dark-colored dikes along the Puelche gorge, the shallow intrusion extends to

FIG. 9. View northeastward to feeder for basaltic andesite unit **bact**, cutting rhyolite lava **rmt** (see Fig. 2). Dike is 5 m thick below, widening to 15-20 m above, where it fed mafic lava-flow apron and scoria cone, two dark remnants of which cap the rhyolite ridgecrest at the upper left. At right, medium-grey, flow-foliated rhyolite is upper part of flaring feeder of plateau-capping unit **rmt** (triangle in Fig. 2; also cf. Figs. 6, 7).

below river level, having 400 m of vertical exposure along the gorge and total relief of 750 m south of the river.

Here called the **Rhyodacite of Arroyo del Caballo (rdac)**, the rock is slightly less silicic than all of the younger rhyolites and is richer in phenocrysts than most of them (Table 1); it contains as many as 10% plagioclase phenocrysts, some as long as 3-6 mm, in contrast to the younger rhyolites in which feldspars rarely exceed 2 mm. Such second-order distinctions should not be over-emphasized, however, as the rhyodacite is chemically and mineralogically fairly similar to the rhyolites (Table 1; Figs. 10, 11). A massive whole-rock felsite sample gave a K-Ar age of 1.4±0.5 Ma, several times as old as the rhyolites. Nonetheless, the rhyodacite intrusion crops out only 3-4 km from vents for some of the younger rhyolites (Figs. 2, 6), so it may well have been a magmatic precursor, perhaps an early product of the same thermal episode that later generated the rhyolites.

IGNIMBRITES IN THE PUELCHE VOLCANIC FIELD

None of the ignimbrite sheets underlying and intercalated with the Puelche lavas are thought to have erupted locally, and none have been studied in any detail. There appear to be at least four groups, but the authors emphasize that these observations are only a cursory reconnaissance.

a- Tertiary silicic ignimbrites: Several are prominent on the walls of the Puelche and Invernada canyons; they are generally nonwelded, zeolitized, white to pale green, mildly deformed, and interstratified with andesitic lavas and breccia sheets.

b- A gently dipping stack of several welded ignimbrites, altogether as thick as 650 m, forms the continental divide at the northeastern limit of the Puelche Volcanic Field (Fig. 2; **ig1**) and caps ridges and plateaux that extend many kilometers

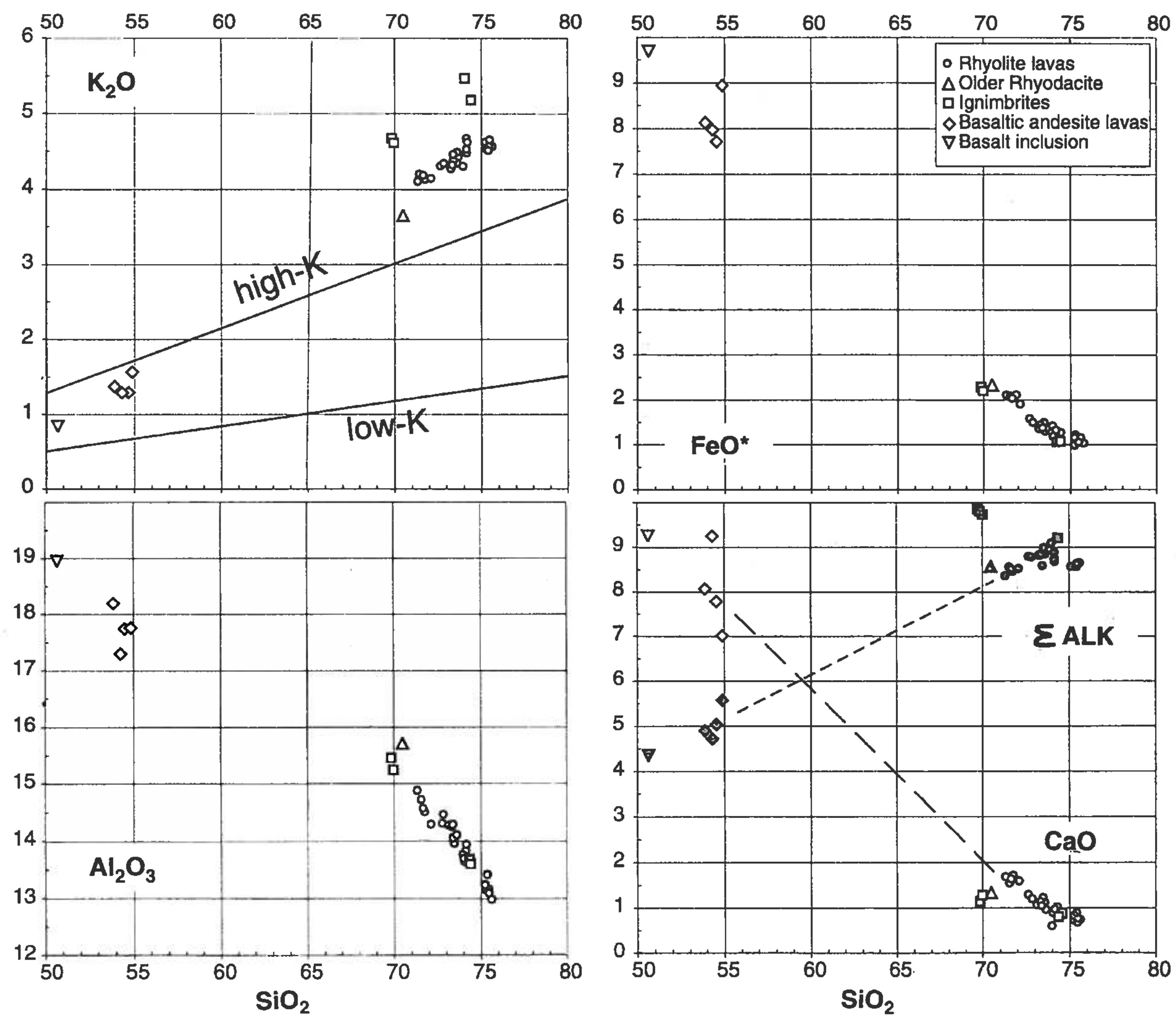

FIG. 10. Variation of K_2O, Al_2O_3, FeO*, CaO, and total alkalies ($Na_2O + K_2O$) *versus* SiO_2, all in wt %. Symbols identified in inset. In lower right panel, symbols for total alkalies are shaded, to distinguish them from CaO data. All data in table 2. FeO* is total iron calculated as FeO. High- and low-K field lines from Ewart (1979).

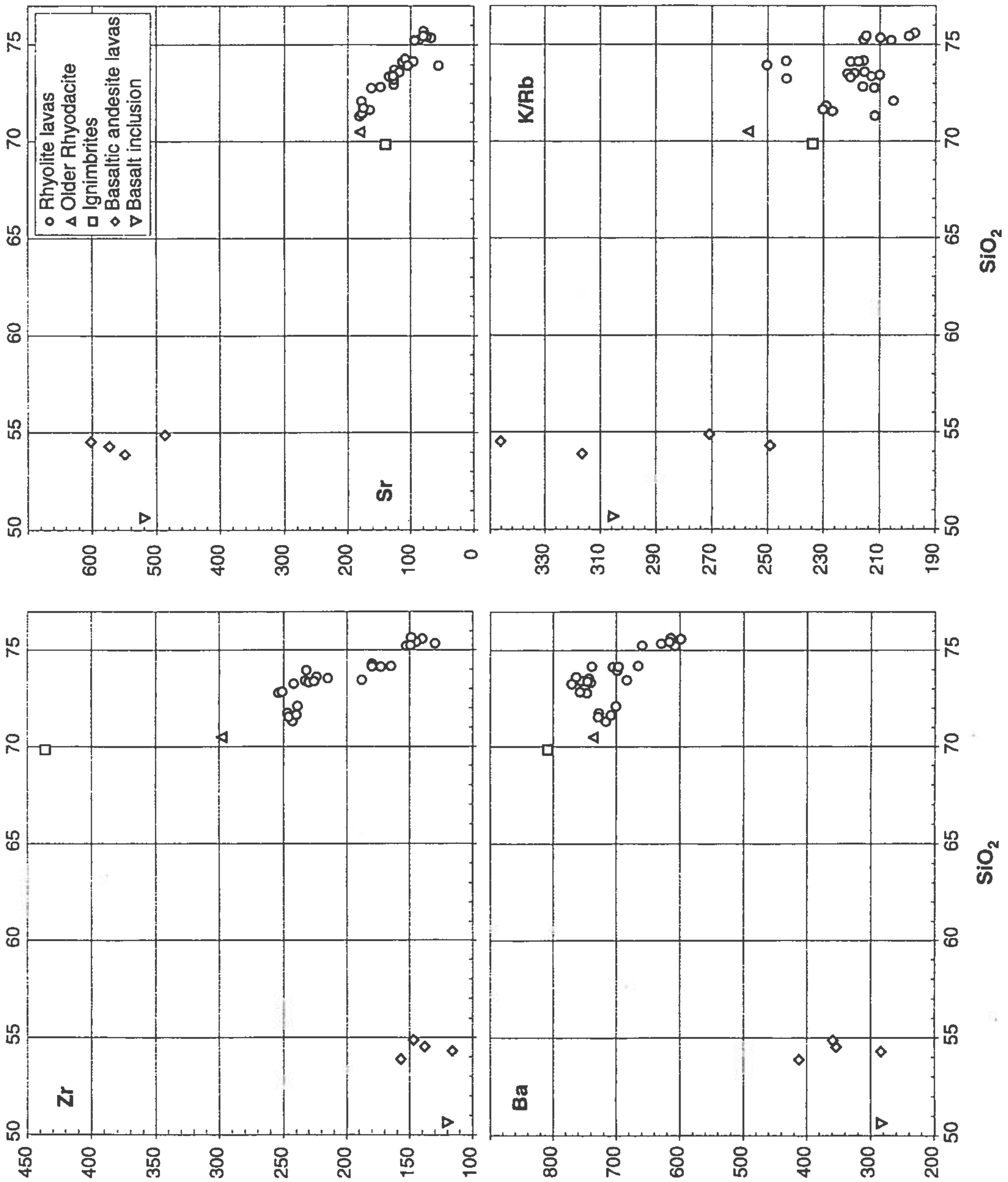

FIG. 11. Variation of Zr, Sr, Ba (each in ppm), and K/Rb *versus* wt % SiO_2. Symbols identified in inset. Data in Table 2.

into Argentina. Drake (1976) measured a K-Ar age of 1.06±0.04 Ma for the top sheet of the stack, and his field notes and bulk K_2O determination (3.04%) suggest a pyroxene-plagioclase dacite composition. Remnants on the divide south of the Río Puelche (Fig. 2) may or may not be correlative.

c- A welded rhyolitic (74% SiO_2; Table 2) ignimbrite 300-600 m thick directly underlies the Puelche rhyolite lavas in the central and eastern parts of the volcanic field (Fig. 2; **ig2**). Its base is exposed on the south wall of the Invernada canyon and along Arroyo de la Hora (Fig. 8), where it overlies altered Tertiary pyroclastic rocks and fresher (possibly Pliocene or early Quaternary) andesitic lavas. A nonwelded basal zone 20-30 m thick is locally exposed, and two tiers of vertically jointed welded tuff are widely (but not everywhere) separated by a bench-forming interval of lesser welding. All the cooling zones are phenocryst-poor, having <5% plagioclase with traces of amphibole and biotite in the matrix and still fewer crystals in the abundant 1-8 cm fiamme. Near the top of the upper subunit the crystal-poor fiamme are joined by finely vesicular magmatic blobs 1-70 cm in diameter, ranging from equant to flattened, and rich in amphibole and plagioclase (with minor biotite). Lithic fragments, mostly <5 cm but as big as 30 cm, are unusually abundant in both subunits and include, distinctively, a predominance of flow-banded rhyolite lavas as well as various andesites and tuffs.

d- Intracanyon remnants of the Loma Seca Tuff (Fig. 2; **ig3**), consisting of welded dacite to rhyodacite ignimbrites of mid-Pleistocene age, were erupted from the Calabozos caldera (Fig. 1) about 20 km north of the Río Invernada (Hildreth *et al.*, 1984b; Grunder and Mahood, 1988). Emplaced across more deeply incised Pleistocene topography than was the rhyolitic ignimbrite (**ig2**), the Loma Seca outflow sheets were largely confined to canyons, from which most deposits have subsequently been eroded (Figs. 5, 8). Most of the surviving exposures form 30 to 75 m thick welded ledges, much thinner than the older ignimbrites just mentioned. Although the Loma Seca remnants also have abundant crystal-poor fiamme, they lack the abundant rhyolite lithics characteristic of the rhyolitic ignimbrite (**ig2**), instead of containing distinctive hydrothermally altered lithics that produce rotten haloes in the host matrix. The matrix contains 5-10% plagioclase phenocrysts, the fiamme fewer, and the sparse mafic silicates are mainly pyroxenes (with traces of biotite). The canyon-wall remnants indicated in figure 2 (**ig3**) could all be Loma Seca ignimbrite Unit V (0.30±0.03 Ma), but data are insufficient to exclude that some of them might be Unit S (0.15±0.03 Ma).

PETROGRAPHY

All the Puelche rhyolite lavas contain plagioclase and biotite as the principal phenocrysts and Fe-Ti oxides as ubiquitous accessories (Table 1). Amphibole is a common phenocryst only in the lowest-silica rhyolite, unit **rct**, but rare euhedral unrimmed amphibole was also seen in thin-sections of units **ras** and **rmt** (Table 1). A grain or two of quartz occur in each of several sections. No sanidine was identified.

The rhyolites richest in phenocrysts are units **rct**, **rqg**, and **rmt**, which contain about 6-12%, always predominantly plagioclase. The phenocryst-poorest are units **ras**, **rat**, **rcg**, and **rsf**, which have only 1-2% but are never strictly aphyric. There is no systematic correlation between phenocryst content and SiO_2 content (Table 1), although the chemically least evolved samples tend to have more crystals and the high-silica rhyolites tend to be phenocryst-poor.

Plagioclase phenocrysts are 0.2-2 mm long, are generally both zoned and twinned, and nearly all are clear. Only rare grains, typically large ones, have sieve textures or other evidence of complex magmatic histories. Most are free crystals, but some are intergrown with biotite, oxides, and other plagioclase crystals or occur in loose clusters with them. Plagioclase is not systematically larger in phenocryst-richer units; the largest (2 mm) grains occur in both the crystal-poorest and crystal-richest rhyolite units.

Biotite is present at the 0.1-1% level in all samples and may reach 2% in the phenocryst-richest ones (Table 1). It generally occurs as 0.1-1 mm books and flakes, but rare grains are as large as 2-3 mm. Most grains are free; a few are clustered with plagioclase. Pleochroic from pale yellow-brown to dark brown in densely glassy rocks, biotite is increasingly oxidized to foxy red or dark red-brown with progressive devitrification, presumably owing to dehydrogenation that accompanied water loss during crystallization of the host glass.

Oxide microphenocrysts, probably including both titanomagnetite and ilmenite, are generally present as 0.1-0.3 mm equant grains. In a few samples, all the oxide grains are smaller than 0.1 mm, and in others some rare grains are as large as 0.4-0.5 mm.

Sparse quartz phenocrysts (0.4-0.6 mm) occur in a few samples (Table 1), generally only one or two in each thin section.

Amphibole euhedra, 0.2-1.5 mm long and pleochroic from pale yellow-brown or green to dark brown, are common in unit **rct** and rare in the other rhyolites. Generally free crystals, they are unrimmed in glassy rocks but tend to develop opaque rims if the host glass devitrifies. In the amphibole-bearing rocks, the biotite/amphibole ratio ranges from 5:1 to 1:2.

Groundmass textures of the rhyolites range from nearly aphyric obsidian to fully devitrified felsite, generally depending on position in the cooling zonation of the particular lava flow. Many glassy samples show incipient to intermediate devitrification in thin section. Microlites <0.01-0.03 mm long can be widely scattered or fluidally distributed. Still finer devitrification occurs in vague blotches, in domains of incipient spherulitic crystallization, or in sharply defined, radially fibrous, brown spherulites. In thin section, most spherulites are 0.1-2 mm in diameter, and some nucleate on phenocrysts. In the Puelche rhyolites examined, the crystallinity is seldom seriate but tends to be trimodal: Phenocrysts and microphenocrysts down to 0.1 mm, microlites an order of magnitude smaller, and micron-scale devitrification.

The intrusive rhyodacite (unit **rdac**) from the Puelche gorge has 8-10% plagioclase phenocrysts 0.1 mm to 6 mm long, much bigger than in any of the rhyolites. Nearly all are clean (not sieved, resorbed, or rimmed) but many are intergrown in clots of 3-10 feldspar crystals or clustered with biotite and oxide grains. Biotite crystals (~1%) are 0.1-1 mm and Fe-Ti oxide grains (<1%) are 0.1-0.4 mm in diameter. The rhyodacite body has a glassy (perlitic) rind, but the groundmass of the authors' sample from the interior is fully devitrified, consisting of intergrown feldspar and silica crystals 0.01-0.03 mm across, sprinkled with tiny oxide and biotite microlites.

The four basaltic andesite units are all mutually distinguishable. All have plagioclase and clinopyroxene and only one unit (**bact**) appears to lack olivine phenocrysts, but the amounts and proportions of these species differ markedly (Table 4). Most plagioclase is 0.1-1 mm, but is as large as 2 mm in unit **baci**, the only one of the basaltic andesites rich in feldspar. In all the units, many of the 1-2 mm plagioclase crystals have sieved cores and clear rims, whereas nearly all grains smaller than 1 mm are clear throughout. Olivine and clinopyroxene are generally 0.1-0.5 mm, but rare grains are 1-2 mm. Opaque oxides occur as free microphenocrysts (0.1-0.2 mm) in two units, but appear only as groundmass microlites (<0.05 mm) in the others (Table 1). Quartz xenocrysts (with fine-grained pyroxene-rich reaction rims) are common in two of the units sampled. As the authors took only one sample of each mafic unit, they have no information about the range of internal variability in these multi-flow sequences.

COMPOSITION

Major and trace element compositions are given in tables 2 and 3 for samples of every rhyolite and basaltic andesite unit described, as well as for a few ignimbrite samples.

For the **rhyolite** lavas, SiO_2 ranges from 71.3 to 75.6 wt% and Al_2O_3 inversely from 14.9 to 13.0 wt% (Fig. 10). All are subalkaline and nearly all have a small amount of normative corundum (0-0.8%C) in their CIPW norms. Macdonald *et al.* (1992; p. 13-16) showed that about half of the pristine nonhydrated subalkaline obsidians worldwide likewise have minor contents of normative corundum. Nonetheless, all

TABLE 3. INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS (INAA) AND ISOTOPE DATA.

	Rhyolites								Mafic Lavas				Ignimbrites			
Unit	ras	rmt	rni	rct	ras	rch	rqg	rsf	Inclusion in rch	baqg	bact	bach	ig2	ig2	ig3	
Sample	RP-1	RP-3	RP-5	RP-7	RP-10	RP-11	RP-13	D2-1-6E	RP-12	C84-9	C84-10	C84-11	RP-2	RP-8	RP-9	
SiO_2	**73.5**	**73.5**	**72.8**	**72.1**	**73.4**	**75.6**	**74.2**	**75.5**	**50.6**	**54.5**	**54.3**	**54.9**	**74.4**	**74.4**	**70.0**	
Cs	6.8	6.0	6.0	6.1	6.6	7.6	6.3	7.3	1.8	1.3	1.3	0.7	6.2	7.0	6.3	Cs
Hf	6.1	5.1	5.9	6.3	6.2	4.1	5.0	4.3	2.6	3.0	2.5	3.4	4.7	4.6	10.4	Hf
Ta	1.06	1.05	1.06	1.02	1.04	1.27	1.08	1.30	0.27	0.37	0.31	0.43	1.02	0.96	1.10	Ta
Th	20.0	20.3	20.1	20.0	19.5	25.0	20.7	25.4	3.0	3.5	5.1	5.7	19.4	18.8	20.0	Th
U	4.8	5.1	5.1	5.0	4.7	6.5	5.3	6.4	0.9	0.95	1.3	1.4	4.7	4.7	4.6	U
Sc	2.11	2.80	2.59	3.73	2.20	2.17	2.64	2.21	26.8	19.5	26.8	19.3	2.11	2.07	7.31	Sc
Cr	<1	<2	<2	1.7	2.1	1.3	<1	1.0	55	136	41	13	<1	<1	1.85	Cr
Co	1.1	1.7	0.7	2.4	1.1	0.7	1.1	0.8	30	28	23	26	0.4	0.5	1.4	Co
Zn	38	34	39	43	41	28	34	28	93	85	78	79	34	28	58	Zn
Sb	0.6	0.4	0.3	0.4	0.6	0.4	0.4	0.3	<0.5	0.2	<0.4	<0.4	0.5	0.4	0.7	Sb
La	31	31	32	31	31	28	31	29	27	17	15	19	31	30	41	La
Ce	58	53	57	57	57	49	55	51	35(?)	35	29	37	56	53	84	Ce
Nd	22	20	22	23	20	17	19.5	18.5	26	20	18	22	18	18	37	Nd
Sm	3.7	3.6	4.0	4.2	3.7	3.0	3.7	3.1	5.65	4.2	4.0	4.7	3.55	3.4	8.4	Sm
Eu	0.63	0.54	0.65	0.71	0.64	0.42	0.54	0.46	1.38	1.1	1.03	1.22	0.54	0.52	1.34	Eu
Tb	0.39	0.35	0.42	0.48	0.41	0.32	0.38	0.36	0.81	0.47	0.55	0.67	0.43	0.41	1.18	Tb
Yb	2.2	2.0	2.2	2.2	2.3	1.8	2.1	1.8	2.7	1.5	1.7	2.2	2.0	1.9	4	Yb
Lu	0.31	0.27	0.29	0.32	0.3	0.27	0.28	0.28	0.40	0.22	0.26	0.33	0.29	0.29	0.58	Lu
Rb/Cs	25	29	28	28	25	25	28	25	13	24	33	69	27	31	28	Rb/Cs
Zr/Hf	35	37	43	38	38	34	36	35	46	46	46	43	32	31	38	Zr/Hf
Ba/La	24	22	23	23	24	21	21.5	21	10.4	21	19	19	23	23	18	Ba/La
Ba/Ta	700	650	705	690	730	470	620	475	1040	960	920	835	710	725	680	Ba/Ta
Ba/Th	37	34	37	35	39	24	32	24	93	101	56	63	37	37	37	Ba/Th
Th/U	4.2	4.0	3.9	4.0	4.1	3.8	3.9	4.0	3.3	3.7	3.9	4.1	4.1	4.0	4.3	Th/U
Th/Ta	19	19	19	20	19	20	19	19.5	11.1	9.5	16.5	13.3	19	20	18	Th/Ta
La/Ta	29	29.5	30	30	30	22	29	22	100	46	48	44	30	31	37	La/Ta
La/Th	1.6	1.5	1.6	1.6	1.6	1.1	1.5	1.1	9.0	4.9	2.9	3.3	1.6	1.6	2.1	La/Th
La/Sm	8.4	8.6	8.0	7.4	8.4	9.3	8.4	9.4	4.8	4.0	3.8	4.0	8.7	8.8	4.5	La/Sm
La/Yb	14.1	15.5	14.5	14.1	13.5	15.6	14.8	16.1	10.0	11.3	8.8	8.6	15.5	15.8	10.3	La/Yb
$^{87}Sr/^{86}Sr$		0.70440±4	0.70439±3		0.70431±5	0.70429±3			0.70386±4	0.70393±5		0.70395±4				
$^{206}Pb/^{204}Pb$		18.649				18.647			18.617	18.565						
$^{207}Pb/^{204}Pb$		15.605				15.602			15.613	15.596						
$^{208}Pb/^{204}Pb$		38.514				38.507			38.519	38.438						

Sample locations in figure 2. Trace elements (in ppm) determined by instrumental neutron activation analysis (INAA) at U.S.G.S. laboratory in Reston, Virginia, by J. Grossman and J.S. Mee; precision and accuracy discussed by Bacon and Druit (1998). Isotopic determinations at Oxford by S. Moorbath and P. Taylor by methods discussed by Hildreth and Moorbath (1988).

the Puelche rhyolites are fairly rich in alkalies, the ranges of which are: K_2O 4.11-4.66 wt%; Na_2O 3.95-4.56 wt%; Rb 143-192 ppm; and Cs 6.0-7.6 ppm. Within the Puelche rhyolite suite, Na_2O/K_2O decreases from 1.03-1.11 for the rocks with 71-72% SiO_2 to only 0.86-0.89 for the high-silica rhyolites. All are high-K rhyolites (Fig. 10) by the scheme of Ewart (1979), but so too is the vast majority of continental-margin and intracontinental rhyolites (Fig. 11 of Macdonald *et al.*, 1992).

The Puelche rhyolites are nonetheless richer in K_2O than most other rhyolites from continental-margin arc suites around the Pacific (Ewart, 1979). Relative to Ewart's (1979) compilation of (limited) data for *Andean* rhyolites, the Puelche lavas tend to be a bit low in Ca and Sr, slightly elevated in Na and Rb, and close to the averages for all other elements. Relative to the worldwide data set for subalkaline rhyolitic obsidians presented by Macdonald *et al.* (1992), the Puelche rhyolites consistently occupy the mid-range. The average values they calculate for **continental-margin rhyolites** (Table 7 of Macdonald *et al.*, 1992) fall within the ranges of the Puelche rhyolites for all elements reported here (Tables 2, 3) except K, Rb, Cs, and Th, which are modestly more enriched (than those *averages*) in all of the authors' samples.

Compared to many highly evolved intra-continental rhyolites, these continental-margin Puelche rhyolites are not as strongly enriched in Nb (8-14 ppm), Ta (1.0-1.3 ppm), Th (19-25 ppm), U (5-7 ppm), Rb (143-192 ppm), Zn (28-43 ppm), Y (14-34 ppm), or Yb (1.8-2.3 ppm). Nor are they as depleted in MgO, TiO_2, Al_2O_3, Ba, or Sr as most intracontinental rhyolites (cf. the authors' Figs. 10, 11 with Figs. 29, 40 of Macdonald *et al.*, 1992).

In spite of the authors' failure to identify any sanidine in thin sections or stained slabs, the Ba *versus* SiO_2 variation pattern (Fig. 11) suggests sanidine fractionation. K/Ba is fairly constant at 47-49 in the 71-73% SiO_2 rocks but rises steadily thereafter to 60-64 in the high-silica rhyolites, suggesting subtraction either of sanidine or of unusually Ba-rich biotite. Likewise, despite the rarity of zircon in these rocks, the Zr *versus* SiO_2 trend of figure 11 indicates control by zircon fractionation. The sharp declines of Zr and Ba concentrations with increasing SiO_2 might conceivably reflect greater retention of alkali feldspar and zircon in residues of higher-silica partial melts that were extracted and erupted as discrete batches, but cryptic fractionation of zircon and sanidine (or Ba-rich biotite) from the pre-eruptive magma reservoir is a simpler, perhaps more realistic, mechanism.

Such ratios as K/Rb (198-250), Rb/Sr (0.9-2.5), Ba/Ta (500-700), Ba/Nb (70-80), and Ba/La (21-24) are in the normal ranges for rhyolitic members of continental-margin arc suites. Th/U (3.8-4.2) is slightly more elevated than most. Zr/Hf is 38-43 in the less evolved Puelche rhyolites and as low as 34 in the high-silica rhyolites, consistent with the trend toward lower Zr/Hf in highly fractionated rhyolites worldwide (Macdonald *et al.*, 1992; Fig. 59). Rare-earth element (REE) patterns for Puelche rhyolites (Fig. 12) are steeply fractionated for light REE (La/Sm 7-9), fairly flat for heavy REE, and exhibit modest negative Eu anomalies (Eu/Eu*=0.47-0.58).

The early Pleistocene **rhyodacite** (unit **rdac**; sample C84-12; Table 2) is more corundum-normative than the rhyolites, having 1.5%C in its CIPW norm, despite being both richer in Na than the rhyolites and fully crystalline; *i.e.*, its aluminous character is not simply attributable, as so often, to loss of Na during hydration of a glassy groundmass. The rhyodacite is richer than the Puelche rhyolites in Ti, Fe, Y, and Zr, as well as in Al and Na; it is considerably less enriched than the rhyolites in K and Rb (Figs. 10, 11).

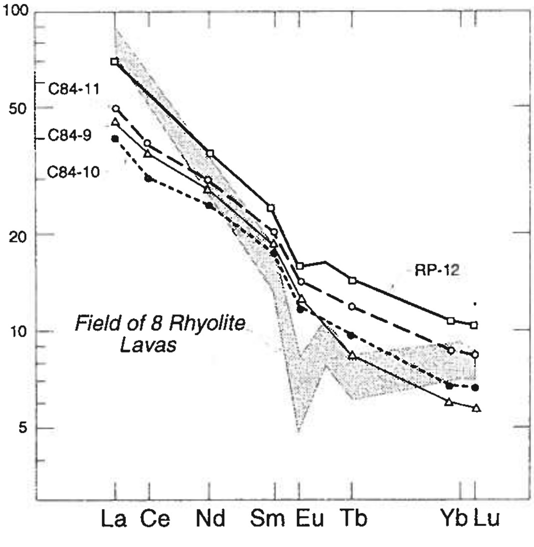

FIG. 12. Chondrite-normalized rare-earth element concentrations of 8 Puelche rhyolite lavas, 3 mafic lavas, and one basaltic magmatic inclusion (RP-12) in rhyolite unit **rch**. Data in table 3.

The **mafic lavas** in the Puelche Volcanic Field are all strongly hypersthene-normative (CIPW *Hy*=14.6-19.4%). The four basaltic andesites are slightly quartz-normative (CIPW *Q*=1.6-2.3%) but the basaltic inclusion in unit **rch** is not. All five mafic samples plot well inside the calcalkaline field on a conventional AFM diagram, but their FeO*/MgO ratios scatter widely (1.4-2.3), suggesting a range of variability analogous to that of the heterogeneous basaltic andesites (Ferguson *et al.*, 1992) erupted at the Tatara-San Pedro volcanic complex, 40 km southwest (Fig. 1). The ranges in Cr (13-136 ppm), Rb (31-48 ppm), Sr (487-602 ppm), CaO (7.01-9.25%), and MgO (3.87-5.38%) among basaltic andesites that range only one percent in SiO_2 (53.9-54.9%) illustrate the heterogeneity (Figs. 10, 11). Nonetheless, all five mafic samples are medium-K, high-alumina, low-Mg products representative of continental-margin arc suites, their association with high-K rhyolites notwithstanding.

Relative to other basaltic andesites in the district (Laguna del Maule area, Descabezado cluster, Tatara-San Pedro-Pellado cluster), within the same ranges of SiO_2 and MgO, those in the Puelche Volcanic Field are among the richest in K_2O (1.29-1.57%), Rb (31-48 ppm), Ba (284-412 ppm), Zr (116-157 ppm), and Th (3.5-5.7 ppm). They have low and remarkably varied (Fig. 11) K/Rb values (250-345) and relatively high Ba/Sr (0.50-0.75) and Rb/Sr (0.05-0.10). REE patterns (Fig. 12) are moderately steep (La/Yb=8.6-11.3) but unexceptional for basaltic andesites in the district. In most other compositional respects (Tables 2, 3) the mafic Puelche lavas are likewise well within the ranges already documented for nearby centers (Frey *et al.*, 1984; Hildreth and Moorbath, 1988; Ferguson *et al.*, 1992).

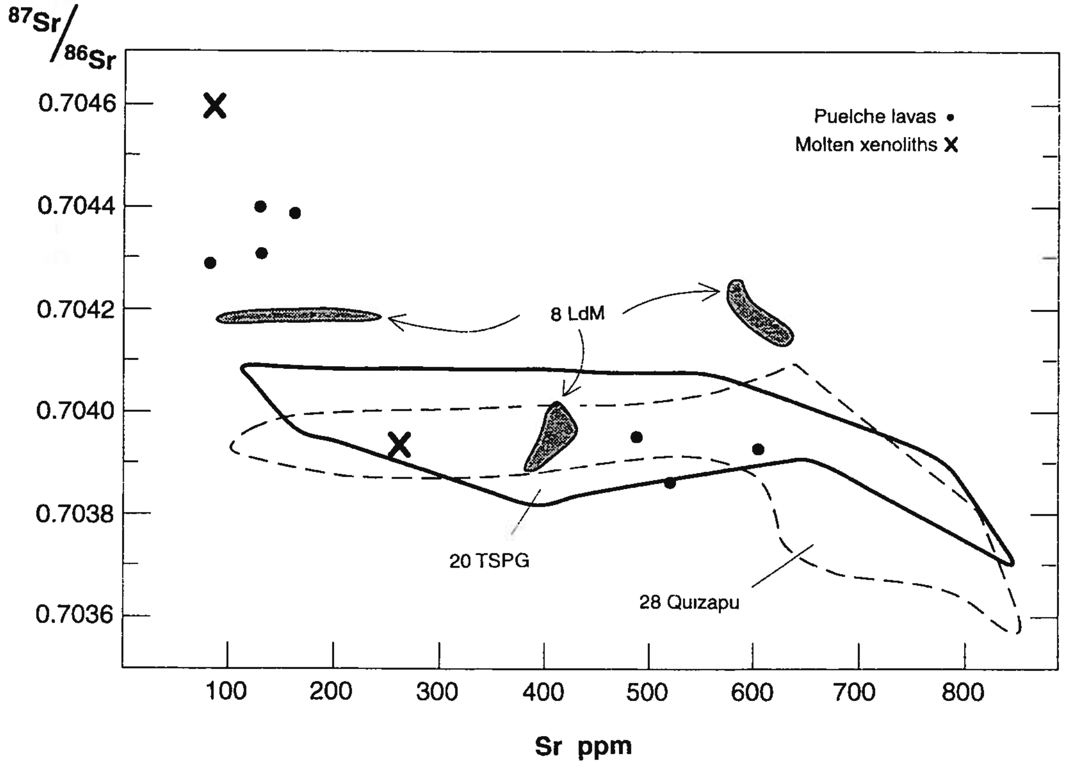

FIG. 13. Sr-isotope ratios *versus* Sr contents of 4 rhyolite lavas and 3 basaltic-andesite lavas from the Puelche Volcanic Field. Data in Tables 2, 3. Analytical methods and precision discussed in Hildreth and Moorbath (1988). Shown for comparison are data fields for some other Quaternary volcanic centers nearby (all located in Fig. 1): 28 samples from the Quizapu-Cerro Azul-Descabezado Grande cluster (Hildreth and Moorbath, 1988), 20 samples from the Tatara-San Pedro-Pellado-Guadal cluster (**TSPG**; Davidson *et al.*, 1987; Feeley *et al.*, 1998), and 8 samples from the Laguna del Maule complex (**LdM**; three shaded fields; Frey *et al.*, 1984). Data for two frothy granitoid xenoliths (75.5% and 70.5% SiO_2), in advanced states of partial remelting when ejected during the plinian pumice eruption of Quizapu in April 1932, illustrate two contrasting compositional trends made possible by silicic crustal contributions to local magmas.

ISOTOPE RATIOS OF Sr AND Pb

Pb-isotope data are given in table 3 for two Puelche rhyolites, one basaltic andesite lava, and the basaltic inclusion in unit **rch**. With one small difference, all the isotopic ratios are in the same narrow ranges identified for the Quizapu-Cerro Azul-Descabezado Grande cluster (Hildreth and Moorbath, 1988) and for the Tatara-San Pedro-Pellado cluster (Davidson *et al.*, 1988), both to the west of the Puelche Volcanic Field (Fig. 1). Those ranges are: $^{206}Pb/^{204}Pb$=18.58-18.64; $^{207}Pb/^{204}Pb$=15.58-15.63; and $^{208}Pb/^{204}Pb$=38.43-38.57. The small difference is that the Puelche rhyolites have still slightly more elevated values of $^{206}Pb/^{204}Pb$, like those of products erupted from the nearby (Fig. 1) Calabozos caldera (18.64-18.655; Barreiro *et al.*, 1982), which assimilated upper-crustal contributions prior to eruption (Grunder, 1987).

Sr-isotope data are given in table 3 for four Puelche rhyolites, two basaltic andesite lavas, and the basaltic inclusion in unit **rch**. Figure 13 illustrates that the four rhyolites are isotopically distinguishable, thus not simply successive leaks from a static reservoir, and that their Sr is more radiogenic than that of any other Quaternary lava yet analysed isotopically at this latitude in the SVZ. The basaltic inclusion (sample RP-12) contains the *least* radiogenic Sr among the Puelche samples analysed, but none of the mafic samples is isotopically primitive for the district (Fig. 13), where some higher-Sr lavas are as nonradiogenic as 0.7036. As elaborated by Hildreth and Moorbath (1988) and by Davidson *et al.* (1987, 1988), virtually all mafic lavas in the region contain, at least, modest crustal contributions, but the geologically young, relatively nonradiogenic, crustal host rocks provide little isotopic leverage for modifying the mantle-derived isotopic signatures of the parental magmas. According to the rationale of Tormey *et al.* (1995, Fig. 14), the Puelche basaltic andesites should contain moderate contributions from mafic lower crust and the rhyolites considerable additional contributions from partial melting of the upper crust.

Two granitoid xenoliths, which were in advanced states of melting when ejected (along with 10 km^3 of rhyodacite pumice) during the 1932 plinian eruption of Quizapu (Hildreth and Drake, 1992), illustrate two (of many) potential styles of crustal contamination (Fig. 13). (1) Melt contributions from young granitoids accelerate trace-element evolution of affected magma batches but have little capacity to modify them isotopically (for the reasons just given above). In uncommon cases, Sr-isotope ratios of basaltic magmas can even be lowered by nonradiogenic crustal contributions (Hildreth and Drake, 1992). (2) Melt contributions from older or more evolved (higher Rb/Sr) crustal rocks elevate both incompatible trace-element contents *and* isotope ratios of the mafic or intermediate magmas incorporating them. If such crustal partial melts were to be generated locally in large volume and avoided being overwhelmed by the mafic magma promoting the melting, they might segregate and erupt as rhyolites. Intermediate degrees of partial mixing and subsequent fractionation could yield a spectrum of rhyolite compositions, reflecting varied proportions of chemical and isotopic hybrid parentage.

VOLUMES ERUPTED

The original eruptive volumes of Puelche lavas are impossible to estimate accurately, owing to canyon cutting by vigorous rivers and to repeated advances of glaciers that not only occupied and enlarged the canyons, but scoured the plateaux. Erratic blocks, many of unknown derivation, are scattered on the highest surfaces and are abundant in the valleys. None of the rhyolites retain primary flow margins, and their devitrified cores are exposed on cliff faces everywhere. Several very thick flows extend into draping remnants on canyon walls or rims that must have fed lengthy intracanyon lobes that have almost everywhere been removed. Although erosion here has been greatest in the valleys and was thus predominantly lateral with respect to the rhyolites, the evidence that the overlying mafic shields were glacially reduced to thin remnants indicates that most surfaces of the rhyolite plateaux, generally stripped of their pumiceous and blocky upper carapace, were also reduced vertically by, at least, tens of meters.

Nonetheless, as recorded in table 4, the authors have attempted by judicious guesswork to estimate what volumes of rhyolitic lava might reasonably

FIG. 14 Quaternary volcanic fields 33-37°S, showing north-south arrangement of Calabozos, Puelche, Laguna del Maule, and Domuyo silicic centers. This silicic belt lies east of the volcanic front and diverges farther from it southward; it overlaps the Malargüe fold-and-thrust belt and lies well west of the extensional domain marked by abundant fissure-aligned vents for intracontinental Quaternary basalts. All true rhyolite (>72% SiO_2) lavas identified to date are indicated individually by open circles. In addition, some Quaternary ignimbrites that erupted at the Diamante and Calabozos calderas and in the Laguna del Maule volcanic field are wholly or in part rhyolitic. Triangles (Δ) indicate polygenetic stratovolcanoes of Quaternary age, some extinct but many still active. Solid circles indicate selected lesser vents, mostly monogenetic-but they are generally omitted from the patterned volcanic fields where they are exceedingly numerous (see parenthetical estimates). Data in Chile from many sources, extensively the authors' fieldwork; relations in Argentina largely from Llambías *et al.* (1978), Bermúdez and Delpino (1989), Manceda and Figueroa (1995), and Ramos *et al.* (1996).

have been emplaced. Using the authors' 1:50,000-scale geologic map (the basis of figure 2), the present-day area of each rhyolite unit was measured and an average thickness assigned, permitting the surviving volumes to be approximated with uncertainties on the order of 25 percent (Table 4). Then, the most speculative step was to consider how much more extensive each flow might have been, judging from its thickness, the present-day canyons carved around it, and the likely paleo-topography interpreted from its sloping substrate and proximity to long-lived drainages. Based on the fictive original areas thus postulated, presumptive primary volumes of lava were calculated on the basis of average thicknesses only slightly greater than those observed now (Table 4). Summing the postulated areas yields 260 km², about 3.1 times greater than the surviving area of 83.4 km², implying that the rhyolite lavas might have been essentially contiguous in blanketing most of the landscape

TABLE 4. ESTIMATED VOLUME OF ERUPTIVE UNITS.

Eruptive Unit	Present-day Area km²	Present-day Thickness Avg (m)	Present-day Volume km³	Postulated Original Area x*	Postulated Original Thickness Avg (m)	Postulated Original Volume km³
ras	2.4	200	0.5	3x	200	1.5
rat	3.0	150	0.45	5x	250	3.8
rcg	13.0	300	3.9	2x	300	7.8
rch	1.8	100	0.2	5x	200	1.8
rct	15.7	300	4.7	3x	350	16.5
rmt	5.1	200	1.0	4x	250	5.1
rni	3.7	200	0.75	3x	250	2.8
rqg	26.2	250	6.6	3x	250	19.7
rri	0.4	100	0.04	10x	250	1.0
rsf	9.5	250	2.4	3x	300	8.6
rsj	2.6	250	0.65	5x	300	3.9
Totals	**83.4**	—	**21.2**	**(3.1x) 260 km²**	—	**72.5**

Postulated Original Area (x*) is multiplier of present-day area to obtain subjectively estimated primary extent of each lava unit considered likely or possible on the basis of unit thickness, glaciated topography, and paleodrainage system. Pyroclastic ejecta not accounted for would further increase volumes erupted. Present-day data are measured from topographic maps with 50-m contour intervals. Errors for present-day areas are less than 5 percent, but for average (Avg) thicknesses as great as 25 percent. Eruptive units are identified in figure 2 and described in the text.

from the Río Puelche to Cajón Grande (Figs. 1, 2), a conclusion not unreasonable in view of comparably extensive contiguity in several other rhyolitic lava fields (*e.g.*, Mahood, 1980; Hildreth *et al.*, 1984a; Bonnichsen and Kauffman, 1987; Bailey, 1989). The presumptive primary volume of rhyolite lava calculated is 72.5 km³, about 3.4 times greater than the 21.2 km³ that survives today (Table 4).

No attempt has been made to estimate lost or concealed volumes of rhyolitic pyroclastic deposits that preceded or accompanied emplacement of the lavas. Rarely does the rhyolitic ejecta amount to less than 10 percent of the volume of the associated lava in well-studied eruptions, and commonly the pyroclastic material volumetrically exceeds the lava, sometimes greatly. Neither was any attempt made to estimate what fractions of the four eruptive units of basaltic andesite might have been removed by erosion. Having much greater fluidity than the rhyolites, the mafic lavas may have extended even farther down paleocanyons, thus implying correspondingly greater fractional losses.

GEOCHRONOLOGY

Five radiometric ages have been determined for Puelche rhyolites (Table 5). Although most are not very precise, all confirm the Pleistocene age of the volcanic field inferred from field relations and freshness of the rocks. A massive holocrystalline whole-rock sample of the shallowly intrusive (to barely extrusive) rhyodacite cut by the gorge of the Río Puelche (unit **rdac**) gave an early Pleistocene K-Ar age of 1.4±0.5 Ma.

Drake (1976) reported a K-Ar age of 0.3±0.1 Ma for biotite separated from the upper flow of high-silica rhyolite (unit **rsf**) at the north end of the volcanic field just south of Cerro San Francisquito (Fig. 2). In 1985, by then using a much higher-vacuum extraction line, Drake determined a high-precision age of 0.35±0.02 Ma for nonhydrated obsidian from near the base of unit **ras**.

Two whole-rock samples were recently dated by the $^{40}Ar/^{39}Ar$ incremental-heating method in Singer's laboratory in Genève (for details of procedures, see Hildreth *et al.*, 1998, and references therein). Each gave a somewhat disturbed spectrum with either no plateau or a limited one (Table 5), probably owing to Ar loss and Ar heterogeneity, reflecting the whole-rock combination of plagioclase and biotite phenocrysts, extensive but incomplete fine-grained devitrification, and retention of some groundmass glass. Ages of a new sample from unit **rsf** range from a Total Fusion age of 163±2 ka to an Isochron age of 213±12 ka, generally supporting Drake's (1976) middle Pleistocene (K-Ar) age determination on the same unit.

For the intracanyon rhyolite lava flow along the upper gorge of the Río Invernada (unit **rri**), a partly glassy sample gave a Total Fusion age of 326±2 ka and an imprecise Isochron age of about 354 ka. Because the base of this lava is only about 50 m above the river and 150-300 m lower than bases of flanking units **rni** and **rct** (Fig. 2), it had been anticipated (apparently incorrectly) that the intracanyon flow would yield a younger age than the other rhyolites, including dated unit **rsf**. In retrospect, however, it is evident that part of rhyolite unit **rsf** drapes down from its high plateau to an eroded

TABLE 5. GEOCHRONOLOGICAL DATA.

Potassium-argon ages and analytical data

Sample Number	Eruptive Unit	Material Analysed	wt% K_2O	Radiogenic 10^{-13}mol/g	^{40}Ar %	Calculated Age	Laboratory
C84-12	rdac	whole rock	3.386	70.05	8	1.4± 0.5 Ma	SNGM
D2-1-6E	rsf	biotite	6.62	31.1	2	0.3 ±0.1 Ma	Berkeley
RP-1	ras	obsidian	4.480	22.49	31.4	0.35±0.02 Ma	Berkeley

$^{40}Ar/^{39}Ar$ incremental heating data

Sample Number	Eruptive Unit	Material Analysed	Total Fusion Age	Plateau Age	Isochron Age	Laboratory
LdM-493	rsf	whole rock	163±2 ka	191±3 ka	213±12 ka	Genève
LdM-466	rrl	whole rock	326±2 ka	none	354 ka	Genève

Sample locations are indicated in Figure 2. K-Ar data for sample D2-1-6E were reported by Drake (1976). RP-1 was analyzed by R.E. Drake in 1985; C84-12 by C. Pérez de Arce in 1996. $^{40}Ar/^{39}Ar$ determinations by Singer in 1998; methods were identical to those described by Hildreth et al. (1998); stated errors are ± 1 sigma. For sample LdM-493, the isochron age is preferred; the low-temperature six (of twelve) steps define the plateau; the six higher-temperature steps are younger than the plateau. For sample LdM-466, no plateau was obtained; a concave-down spectrum suggests some loss of Ar; the oldest steps yield about 354 ka, which can be considered a minimum age.

terminus near the confluence of the Invernada and Arroyo San Francisquito (Fig. 2) at an elevation (2,250 m) even lower than the intracanyon remnant of unit **rri** about 7 km upstream.

It would require an intensive program of high-precision radiometric dating to work out the eruptive sequence of these scattered units and the detailed history of successive canyon filling by the rhyolites and repeated reincision of the gorges by the rivers and glaciers.

DISCUSSION

Eleven eruptive units of mid-Pleistocene rhyolite lava, each consisting of one or a few lava flows 100-400 m thick, were emplaced on a rugged terrain that had been deeply incised by rivers and accentuated by several pre-rhyolite glaciations. One early Pleistocene rhyodacite may predate much of the glacial history. Glacial scour and fluvial erosion postdating the rhyolites may have removed two-thirds or more of their original volume. Because this erosion isolated the remnants into six non-contiguous outcrop areas, age relationships among the eleven rhyolites are only partially established stratigraphically. Intracanyon lava flow remnants and draping by younger rhyolites of the high-relief topography cut on older ones suggest that the sequence of rhyolite eruptions spanned, at least, one glacial episode and lasted altogether perhaps a few hundred thousand years, probably between 400 and 100 ka. The meager evidence for ice-contact emplacement, even in canyons, suggests that most eruptions took place during non-glacial intervals, prompting the speculation that deglacial unloading might have favored eruptive leakage during structural readjustment of the brittle upper crust. Eruption of the basaltic andesites through the heart of the rhyolite volcanic field, apparently within about 100,000 years, suggests that, whether by consolidation or eruptive depletion, the silicic reservoir by then no longer constituted a buoyancy barrier to penetration by deeper-derived batches of mafic magma.

WHY NOT RHYOLITIC IGNIMBRITE?

Why did so substantial a volume of rhyolitic magma extrude spasmodically in several pulses rather than catastrophically as ignimbrite? Dacitic to rhyolitic ignimbrites of Pleistocene age are common in the district. In addition to ignimbrites mentioned in this report, several Pleistocene sheets in the 50-250 km^3 range erupted just north and south of the Puelche Volcanic Field (Hildreth *et al.*, 1984b; 1991a). Because biotite-rhyolite and hornblende-rhyolite magmas necessarily contain several weight percent water prior to eruption, extrusion as lava indicates non-explosive exsolution of that water during the depressurization intrinsic to conduit ascent (Eichelberger *et al.*, 1986; Hildreth and Drake, 1992; Westrich and Eichelberger, 1994). Implicitly, therefore, ascent rates were slow, permitting permeable escape of the gas exsolving during ascent as well as of any gas already exsolved in the reservoir. At high ascent rates, vesiculation would outrun permeable gas escape, accelerating the magma column and leading to explosive fragmentation prior to extrusion (Jaupart and Allègre, 1991). Integrity of the roof of the reservoir is also indicated, since collapse or sagging of the roof would increase the discharge rate, likewise favoring fragmentation.

COMPOSITIONAL BIMODALITY

Absence of intermediate magma compositions in 'bimodal' suites is an old problem. In the Puelche Volcanic Field, eruptive products having 55-70% SiO_2 are lacking, rhyolites are dominant, and the mafic lavas not only are volumetrically minor, but are younger than the rhyolites. The nearest contemporaneous (Pleistocene) andesite-dacite centers are 15-30 km distant (Fig. 1). Among the silicic lavas, the rhyodacite (unit **rdac**) is clearly the oldest and the high-silica rhyolites (units **rcg**, **rch**, **rsf**, **rsj**) are among the youngest. No strictly simple differentiation sequence is demonstrable, however, because, in addition to the lack of established age relationships among the six isolated remnants, rhyolite unit **rmt** (73.5% SiO_2) overlies unit **rqg** (74% SiO_2). Nonetheless, the mineralogical and chemical similarity and the compositional continuity (Figs. 10, 11) among the silicic lavas suggest that all evolved by crystal-liquid fractionation from a common crustal magma reservoir.

As shown by the Sr-isotopic data of Figure 13, however, the rhyolites are unlikely to have fractionated continuously all the way from basalt. More likely, the proximate parent of the rhyolites was a hybrid magma produced by mixing between voluminous crustal melts and the mantle-derived mafic magma that induced the crustal melting (Hildreth, 1981; Hildreth *et al.*, 1991b). Mahood and Halliday (1988, Fig. 4) demonstrated that rhyolites generally reveal their hybrid parentage isotopically, reflecting Sr and Nd contributions (in each volcanic field) relatable to **both** the closely associated basalts and the crustal basement of the particular geologic province. Relatively few rhyolites have ever been shown to be unadulterated partial melts of the mid-to-upper crust, as the rhyolites are rarely as isotopically evolved as readily fusible crustal rocks locally available (as illustrated in Fig. 13).

Hildreth and Moorbath (1988) showed that, along the volcanic front of the SVZ, **most** of the crustal contributions are added to mantle-derived magmas while they are still deep in the crust and still fairly mafic. For several dacitic and rhyodacitic magmas, however, linkage between fractionation and additional assimilation in the **upper** crust has been demonstrated at a few SVZ volcanoes (Grunder, 1987; Hildreth and Moorbath, 1988; Tormey *et al.*, 1995). Davidson *et al.* (1988) showed further that, despite chemical evidence for nearly universal crustal contamination, most upper-crustal rocks in this part of the SVZ lack sufficient isotopic contrast with the ascending mafic magmas to modify their Sr, Nd, and Pb isotopic signatures very much. The data of figure 13 suggest therefore that, although elevation of their Sr-isotope ratios is modest, the Puelche rhyolites contain a substantially greater fraction of upper-crustal material than do the most highly evolved products of the volcanic-front centers nearby.

NORTH-SOUTH BELT OF RHYOLITE-PRODUCING CENTERS

True rhyolite (>72% SiO_2) has erupted repeatedly during the Quaternary, in great volumes, at Volcán Domuyo, Laguna del Maule, the Puelche Volcanic Field, and the Calabozos caldera, which taken together define a north-south belt (Fig. 14) that parallels the strike of the Malargüe fold-and-thrust belt, but diverges markedly from the NNE-trending Andean volcanic front. Excluded from consideration here are rhyodacites (68-72% SiO_2), which are present at many additional centers in the region (*e.g.,* Nevados de Chillán, Tatara-San Pedro group, Descabezado group, Laguna Mondaca, and Volcán Peteroa) and generally represent the most evolved members of compositional arrays continuous from andesite and dacite. True rhyolites are uncommon on volcanic fronts worldwide, rarely erupt from stratovolcanoes, and are commonly separated by compositional gaps from the arrays of products erupted nearby . Like the Puelche suite (Figs. 10, 11), many rhyolite-producing volcanic fields are thus 'bimodal'. Unlike the Puelche field, most are in zones of tectonic extension, either intra-arc or intracontinental. Rhyolite usually erupts from isolated, clustered, or fissure vents that can be (1) peripheral to major volcanic edifices, (2) parts of compositionally diverse, multi-vent, distributed volcanic fields, or (3) ring-fault calderas; these modes of occurrence are represented in figure 14 by Cerro Amarillo, Laguna del Maule, and the Diamante caldera, respectively.

The belt of Quaternary rhyolitic centers (Fig. 14) overlaps the (Tertiary) Malargüe fold-and-thrust belt (Manceda and Figueroa, 1995), which remained in active compression, at least through the late Miocene and perhaps into the Pliocene (Ramos *et al.*, 1996). Farther north, the Diamante caldera and nearby rhyolites (Fig. 14) are likewise superimposed on the fold-and-thrust belt where it impinges against the Cordillera Frontal (Ramos *et al.,* 1996). The basement of neither rhyolite-producing belt appears to have switched over during the Quaternary from compression to regional extension, as none of the rhyolitic volcanic areas are cut by tectonic normal faults, and the extension-influenced fields of Quaternary alkali basalts (Bermúdez and Delpino, 1989) lie 50-100 km to the east (Fig. 14). The rhyolitic centers thus need to be considered manifestations of intra-arc magmatism rather than products of back-arc extension. This is supported by the district-wide association of the rhyolites with basaltic andesites and ordinary arc andesites, rather than with alkali basalts and trachytes like those common on the Argentine pampas.

In the Cascade Range of western North America, Quaternary rhyolite-rich centers (*e.g.,* Newberry, Medicine Lake, and Lassen) have developed along the eastern (inboard) margin of the volcanic chain, where intracontinental extensional faulting is actively impinging on the arc. Likewise in Mexico, several rhyolite-rich centers of Quaternary or Pliocene age (*e.g.,* La Primavera, Los Azufres, Amealco, Huichapan, Los Humeros, Las Derrumbadas) have developed along the northern (inboard) side of the broad volcanic arc within zones of modest tectonic extension (Ferriz and Mahood, 1986). Although extensional faulting is not known to have affected the intra-arc belts of rhyolitic centers at 34-37°S in the Andean SVZ, it may be that these parts of the arc have passed into a neutral condition of crustal stress, transitional (in space and time) between the Neogene compression and uplift of the Andes and the Pliocene-Quaternary back-arc extension encroaching from the east.

The rhyolitic eruptions **began** during the early Quaternary at the Calabozos Caldera and the Puelche Volcanic Field, in the Pliocene at Laguna del Maule, and perhaps also as early as the Pliocene at Volcán Domuyo. Parallelism of the rhyolite belts with the strike of the Tertiary fold-and-thrust belt, rather than with the volcanic front (Fig. 14), suggests that their distribution is more strongly influenced by intracrustal processes than by the material flux from the subducting plate. Cessation of overthrusting and relaxation of compressional stress in belts along the eastern margin of the arc may, in the last few million years, have created locally neutral or incipiently extensional stress regimes favorable to aggregation and storage of crustal partial melts. Although surely more complicated geologically, much of the regional magmatic pattern can be accounted for in a conceptual framework wherein: **1-** throughput of basalt, engendering only limited crustal melting, is favored by extensional strain inboard of the arc; **2-** complex magmatic plumbing and prolonged storage at many crustal depths, promoting advanced crust-mantle hybridism and numerous small magma batches, are favored by the compressional stress regime beneath the volcanic front; and **3-** coalescence of lenses of silicic partial melt, extracted from crustal rocks after only limited or moderate hybridism with the dikes or underplating sills of mafic magma that induced the melting, may be favored under the neutral or incipiently extensional stress regimes characteristically transitional between arc and back-arc (Hildreth, 1981; Ferriz and Mahood, 1986).

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