CRYSTALLIZATION CONDITIONS OF EPIZONAL LEUCOGRANITE PLUTONS IN THE LIGHT OF COMPOSITIONAL ZONING OF PLAGIOCLASE, HIGH ANDES (30° S), CHILE

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ABSTRACT

The epizonal plutons (Permotriassic) discussed in this paper are located in the high Andes Cordillera at 30° S. They consist of high-SiO_2 leucogranites which can be equigranular (medium-grained) or porphyrytic depending upon the level of intrusion. Plagioclase were developed throughout the crystallization span of the magma. Early plagioclase phenocrysts crystallized deep in the crust and have normal zoning and resorption effects. Late plagioclase phenocrysts crystallized in shallow chambers and have a An-enriched and normally zoned rim around a non resorbed core.

An increase in the H_2O content of dry magma in the source area, combined with a decrease in pressure during its ascense, could cause the partial resorption exhibited by the early plagioclase. The influx of meteoric water at shallow levels could explain the reverse zoning observed in the late plagioclase. It seems that the normal zoning of the late plagioclase outer zone was developed after the H_2O saturation was reached.

Compositional variations among acidic volcanics of the Matahuaico Formation (volcanic equivalents of the studied plutons) are interpreted as due to eruptions of different batches of melts from the same source instead of magmas produced by different degrees of low pressure differentiation.

RESUMEN

Los plutones epizonales (permotriásicos) que se presentan en este trabajo se ubican en la alta Cordillera de los Andes y están constituidos por leucogranitos ricos en SiO_2. Estos cuerpos se han agrupado de acuerdo a la textura que predomina en plutones leucograníticos de grano medio y porfíricos los que, a su vez, están relacionados con el nivel de emplazamiento. Observaciones petrográficas indican que la plagioclasa cristalizó durante todo el período de cristalización magmática. Las plagioclasas tempranas representan una etapa de cristalización ocurrida en las profundidades de la corteza; ellas presentan zonación normal y bordes corroídos. Las plagioclasas tardías se desarrollaron después que el magma alcanzó niveles cercanos a la superficie; ellas tienen el núcleo sin efectos de reabsorción y una zona más cálcica alrededor de él.

El aumento en el contenido de H_2O del magma, inicialmente seco, provocado por influjo de un pulso magmático de composición similar, pero levemente más rico en H_2O, y el descenso de la presión, causado por el ascenso magmático, habrían dado como resultado la reabsorción parcial de las plagioclasas tempranas. Por otra parte, la incorporación de agua meteórica a través de las paredes verticales de la cámara epizonal habría provocado la zonación inversa de las plagioclasas tardías, a medida que el H_2O se difundía hacia el centro del plutón. La zonación normal de la zona externa de estas plagioclasas se habría formado en condiciones de saturación de H_2O.

Las variaciones composicionales detectadas entre las rocas volcánicas ácidas de la Formación Matahuaico, consideradas como equivalentes extrusivos de los plutones estudiados, se interpretan, más bien, como erupciones de diferentes "horneadas" de fundido, que como efusiones de magmas diferenciados en cámaras emplazadas epizonalmente.

INTRODUCTION

Leucogranite plutons and related volcanics discussed in this paper are well exposed along the steep flanks of the Rio Claro-Rio Turbio valley, 70 km east from the Pacific Coast at latitude 30°S.

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Compositional variations in minerals formed at different stages, combined with field and petrographic observations, detect variable conditions of crystallization.

The aim of this study is to use the plagioclase composition to determine the crystallization events that took place during the rise and emplacement of the epizonal leucogranitic magma. Zoning and resorption of the plagioclase are thought to reflect conditions that affected the plutons as a whole.

There are several studies concerning plagioclase zoning. These can be roughly grouped into those explaining the minor zoning, and those dealing with the major zoning and resorption.

Minor zoning includes short wavelength zones (sometimes not detected by optical methods) with a relatively small fluctuation in the An content (oscillatory zoning). It is considered as a product of internal influences, closely related to the diffusion-reaction model (Phemister, 1934) or to the diffusion-supersaturation model (Hills, 1936; Bottinga *et al,* 1966). The latter considers that the low rate diffusion of An molecules, soon after An-rich plagioclase is formed, produces precipitation of slightly more sodic plagioclase. More information on this type of zoning is given by Smith (1974).

Major zoning (including long wavelength zones and patchy zones among others) and resorption of plagioclase were carefully studied by Vance (1962, 1965) and Wiebe (1968). These authors consider that external influences, such as changes in P, T, a_{H_2O}, may produce important disturbances in the equilibrium conditions. Pringle *et al.* (1974) provide additional factors that control the zoning pattern of plagioclase, which are related to the "relative effectiveness of the rates of diffussion in the magma and the heat removal from the system". Recently Loomis (1979) has thermodynamically shown that the water content is the most important factor that produces disequilibrium crystallization of the plagioclase, whereas the effect of pressure on liquidus temperature has been overestimated (Loomis and Welber, 1982).

GEOLOGY AND PETROGRAPHY

Leucogranite plutons (and related volcanics) broadly represent the final stage of the Permo-triassic anorogenic magmatism related to crustal expansion in the area (Parada, 1983). They can be considered as A-type granites (anorogenic, anhydrous and somewhat alkaline, *cf.* Collins *et al.* 1982) which are genetically associated with S-type granitoids, and represent products of different degrees of partial melting of the lower crust (Parada, in prep.).

This paper deals only with the shallow leucogranite plutons (Monte Grande pluton is excluded). Four of these plutons (Alcohuas, Paiguano, Rivadavia and El Calvario), aligned subparallel to the western limit of the Hercynian granitoids, are shown in Fig. 1. Petrographically, they can be grouped into equigranular (Alcohuas and Paiguano) and porphyrytic leucogranite plutons (Rivadavia and El Calvario).

EQUIGRANULAR (MEDIUM-GRAINED) LEUCOGRANITE PLUTONS: ALCOHUAS AND PAIGUANO

They are located in the southern part of the studied area. Both plutons are lens-like bodies, about 9 km long and 1 km wide, probably connected downward. The northern extreme of Alcohuas pluton ends abruptly whereas the southern one (out of the studied area) gradually becomes very narrow. Similar straitness is observed in the southern extreme of Paiguano pluton which culminates with several parallel, few meters wide dykes.

These plutons were emplaced at high levels in the crust along NS and NNW-trending faults. They apparently represent the feeders of the rhyolitic lava flows and ignimbrites of the Matahuaico Formation (Permian; Letelier, 1977). The host rocks consist of Hercynian tonalites and granodiorites (Carboniferous) and volcanics of the mentioned formation. Lacking chemical interaction contacts frequently occur, suggesting relatively dry conditions for the magma emplacement and/or solidification from the margins to the center of the body (see below).

Upper Triassic sedimentites of Las Breas Formation (Dedios, 1967) partially overlie the northern part of Paiguano pluton. Furthermore, basal conglomerates of this formation, exposed in the central and nothern part of the area, contain

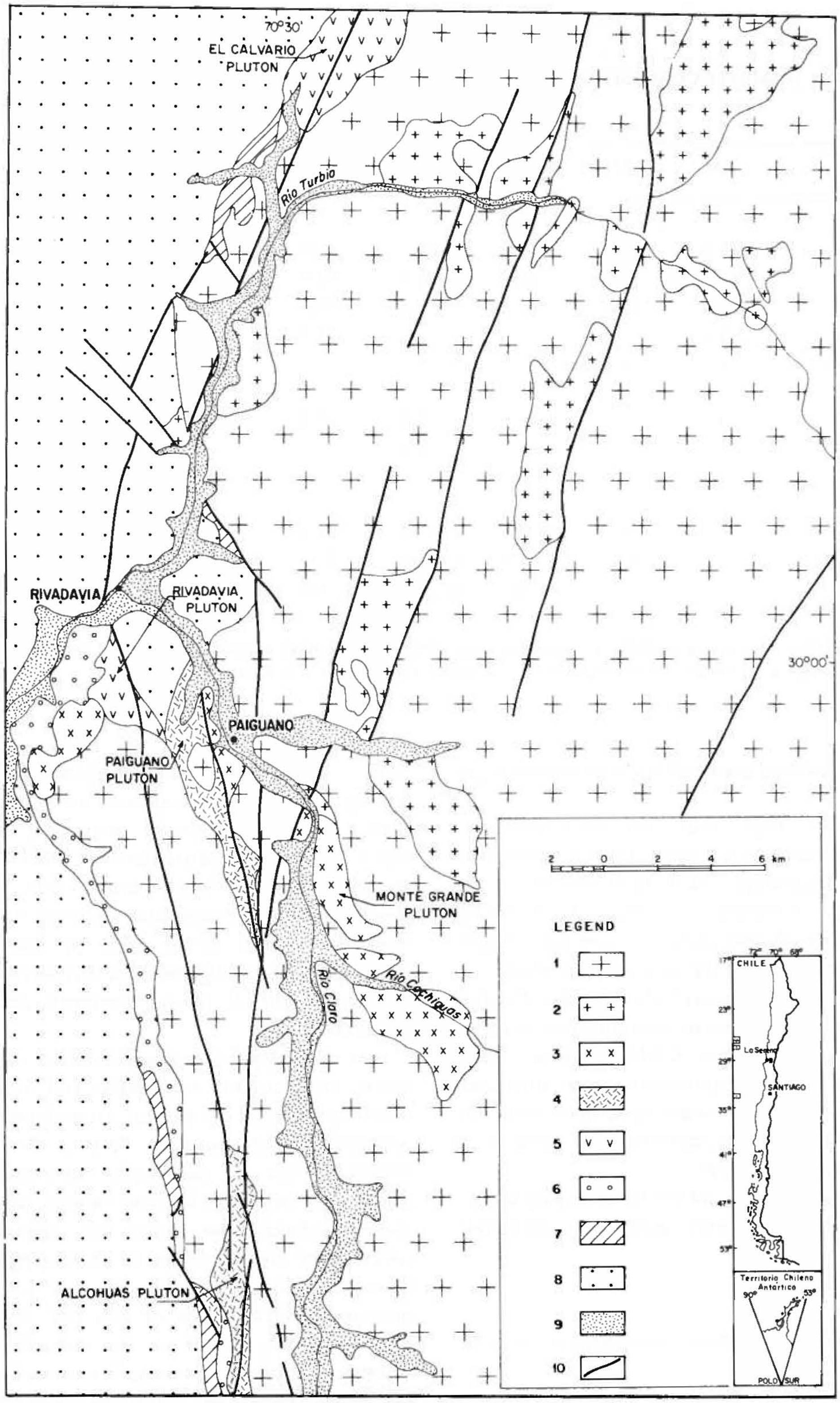

FIG. 1. Geological map of the studied area after, Parada (in prep.). 1) Hercynian tonalites (Carboniferous); 2) Peraluminous S-type granitoids (Permotriassic); 3) Equigranular (coarse-grained) A-type leucogranites (Permotriassic); 4) Equigranular (medium-grained) A-type leucogranites (Permotriassic); 5) Porphyry A-type leucogranites (Permotriassic); 6) Permian volcanics (Matahuaico Formation); 7) Upper Triassic sedimentites (Las Breas Formation); 8) Post-Triassic formations; 9) Quaternary deposits; 10) Fault.

TABLE 1. MODAL COMPOSITION OF EQUIGRANULAR LEUCOGRANITES (MEDIUM-GRAINED)

SAMLE	19	0321	0214B	2001	2003	QM-2	QA-1	QA-2	0323
Quartz	25.8	45.3	38.3	40.3	32.6	46.4	32.3	29.8	44.0
Perthite	44.1	36.8	46.9	42.7	40.0	38.1	32.5	40.9	43.9
Plagioclase	24.1	16.8	14.8	15.5	24.6	12.8	31.8	25.3	8.5
Biotite	1.9				0.4		1.9	1.3	
Amphibole ☆	3.4	1.1				2.3			
Opaque	0.7			0.7	2.4	0.4	1.4	0.9	1.5
Muscovite*			tr.	0.8				0.5	2.1
Calcite									
Color Index	6.0	1.1		0.7	2.8	2.7	3.3	2.2	1.5
Perthite type		P, S, O	S, I, P	S, P, O	S, P, O	I, P, O	P	P, O	S, P, O
K-f twin			Mc	Mc, Cb	Mc, Cb	Mc, Cb	Mc	Mc, Cb	Mc, Cb

S = string perthite; P = patch perthite; I = irregular vein perthite; O = other perthite types; Mc = microline twin; Cb = Carlsbad twin; the order means relative abundace; ☆ = degraded to chlorite; * = secondary.

large and rounded clasts of rhyolite and leucogranite.

Texturally, these rocks are medium-grained subsolvus granites (~ 1.0 mm). Table 1 summarizes the modal mineralogy and textural features.

K-feldspar is perthitic. Carlsbard twins and the grid twinning of microcline are common. Albite-rich plagioclase is slightly sericited and often crystallizes as large subhedral phenocrysts. Discrete plagioclase grains of early crystallization occur as inclusions within large K-feldspar host. These grains together with bipiramidal quartz inclusions show corroded rims. Some specimens from the Alcohuas body show symplectitic intergrowths of quartz and alkali-feldspar.

Biotite, amphibole and Fe-Ti oxides are scarce. They commonly appear partly or completely altered.

PORPHYRYTIC PLUTONS: RIVADAVIA, EL CALVARIO

Initially, these plutons were described as rhyolites belonging to the Rivadavia Formation (Dedios, 1967). They represent the highest level of the leucogranite intrusions emplaced within the Hercynian granitoids, and partly covered by stratified rocks of the Matahuaico (Dedios, 1967) and Las Breas formations. They present more irregular shapes than the equigranular plutons and show steep and slightly curved walls. The cross-cutting relation between Paiguano and Rivadavia plutons appears to indicate block movements during this magmatic event.

The porphyry leucogranites consist of phenocrysts and inclusions (crystalline and lithic inclusions) surrounded by a felsic groundmass. Modal compositions are listed in Table 2. Phenocrysts mainly consist of idiomorphic quartz, whereas crystalline inclusions include quartz, plagioclase and K-feldspar from either the granitoid host rocks or the crystal mushes of the cooling magma. Reaction rims are present in most K-feldespar inclusions which consist of very fine "drops" of quartz aligned parallel to the corroded crystal margins. Lithic inclusions largely consist of granites and minor, more basic granitoids, suggesting they come mainly from the early crystallized margins (autholiths).

TABLE 2. MODAL COMPOSITION OF PORPHYRY LEUCOGRANITES

SAMPLE	0215	0319A	0319B	1912	3105	3104
Phenocrysts						
Quartz	20.0	2.8			21.0	24.0
Plagioclase		5.0				
Biotite	0.1		1.4	0.4		
Opaque			2.2			
TOTAL	20.1	7.8	3.6	0.4	21.0	24.0
Inclusions						
Quartz		20.6	19.2	15.8		
Plagioclase	13.0	10.2	25.0	22.8	6.2	7.0
K-feldspar	17.1	13.8	6.0	15.4	14.2	16.8
Lithic	8.4				1.6	
TOTAL	38.5	44.6	50.2	54.0	22.0	23.8
Groundmass						
Quartz	*	*	28.0	*	*	*
Alkaline feldspar	*	*	18.4	*	*	*
Biotite						0.2
TOTAL	39.9	44.8	46.4	45.6	56.0	52.2
Alteration Minerals						
Chlorite	0.2	0.2	0.1			
Calcite		2.6	0.8			

* = Identified mineral, but not counted

ROCK CHEMISTRY

The average chemical analyses of Table 3 show that the equigranular A-type leucogranites have high SiO_2 content and a $(Na_2O + K_2O)/Al_2O_3$ molar ratio slightly lower than unity, but contain sufficient CaO to be considered metaluminous. The more aluminous character of the porphyry leucogranites given by the alkali/alumina molar ratio (Table 3), seems to reflect a relative concentration of fledspar inclusions instead of upward differentiation of the magma body.

Representative analyses of the main varieties of erupted magmas (Table 3) indicate the presence of high-SiO_2 rhyolitic ignimbrites (metaluminous) and

TABLE 3. CHEMICAL ANALYSIS OF LEUCOGRANITES AND RELATED RHYOLITES

	1	2	QU-1+	QU-7+	QU-2+
SiO_2	77.53	78.08	76.37	72.35	70.28
TiO_2	0.06	0.18	0.18	0.29	0.20
Al_2O_3	11.41	11.35	11.22	15.67	15.46
Fe_2O_3	0.76	0.49	1.67	1.82	1.99
FeO	0.82	0.49	2.50	1.18	2.03
MgO	0.13	0.16	0.07	0.48	0.38
CaO	0.45	0.74	0.21	0.46	0.36
MnO	0.02	0.02	0.01	0.04	0.01
Na_2O	3.43	2.62	5.30	2.48	4.90
K_2O	4.56	4.47	2.02	3.21	2.53
P_2O_5	0.03	0.05	0.03	0.04	0.03
H_2O	0.43	0.45	–	1.97	1.28
NK/A*	0.93	0.81	0.96	0.48	0.70
NKC/A**	1.00	0.93	1.00	0.54	0.74

1 = average of four equigranular leucogranites; 2 = average of two porphyry leucogranites.
* $Na_2O + K_2O/Al_2O_3$ molar ratio.
** $Na_2O + K_2O + CaO/Al_2O_3$ molar ratio.
\+ Rhyolites of Matahuaico Formation.

low-SiO_2 rhyolitic lava flows (peraluminous). High-SiO_2 ignimbrites have SiO_2 and $(Na_2O + K_2O)/Al_2O_3$ molar ratio similar to the equigranular A-type leucogranites, but the latter have K_2O in excess of Na_2O. It is interesting to note that the high-SiO_2 ignimbrites represent more than 60% of the 800 m thick Matahuaico Formation (assuming no significant compositional variations among different ignimbritic flows) and the plutonic equivalent members of low-SiO_2 rhyolites such as QU-2 and QU-7 are absent. Fractionation seems to have played a secondary role in the evolution of this leucogranite magma (Parada, 1983).

ANALYTICAL PROCEDURE AND LIMITATIONS

The analytical results and their interpretation are based on plagioclase composition of two equigranular leucogranite representative samples (QA-2 and 0323; center and margin of Alcohuas pluton and Paiguano pluton, respectively). The samples were analyzed at Tohoku University by a Hitachi X-560S scanning electronprobe microanalyzer, with a solid state energy dispersive spectrometer. Synthetic and natural minerals were used as standards. See Fujimaki and Aoki (1980) for detailed procedures and accuracy. Rock compositions were determined at the University of Chile by C. Nieto using wet chemical methods.

The small number of analyzed samples involved in this study is a limitation to be considered; however, it is partially balanced with the striking homogeneous composition of the plutons.

Compositionally zoned plagioclase phenocrysts do not show optical perturbations and most of them are somewhat altered to sericite and clay minerals. This makes both the selection of points to be analyzed, as well as the carring out of systematical analyses of a large number of points per grain difficult. Unaltered cores and rims were invariably measured in all selected phenocrysts, whereas intermediate areas were sporadically analyzed.

HIGH PRESSURE CRYSTALLIZATION

According to petrographic inspection, plagioclase and β-quartz are the earliest phases to crystallize. These phases occur as phenocrysts, showing resoption effects, and also as inclusions in large K-feldspar and quartz phenocrysts. The possibility of considering such phyric plagioclases as xenocrysts from the granitoid country rocks must be ruled out because: 1) their compositions are more compatible with those observed in plagioclases associated with granitic magmas (Ab-rich plagioclase, Fig. 2) than with those expected in plagioclases associated with the host rock tonalites; 2) they have a small amount of Or component. This appears to represent the only crystallized feldspar (as a binary system) from the melt. Both the level of magma emplacement and the presence of plagioclase and quartz as early-stage phases are indicative of a high pressure (~ 8 Kb) H_2O-undersaturated (~ 2 wt% H_2O) initial granitic magma (Cann, 1970, Harris *et al.*, 1970; Whitney, 1975).

Core and rim compositions in plagioclase reflect normal zoning. The An content of different cores ranges between $An_{10.3}$ and $An_{1.8}$ and that of different rims ranges between $An_{6.8}$ and $An_{1.0}$. Optical discontinuities due to zoning are not observed, which apparently results when the rate of heat removal is slower than the diffusion rate of the plagioclase components in a H_2O deficient magma under constant presure (Pringle *et al.*, 1974). The absence of an An-rich zone around the resorbed core may indicate that the equilibrium growth of early plagioclase was not renewed.

The origin of resorption in plagioclase has been extensively discussed by Vance (1965) and Loomis and Welber (1982). The externally-controlled conditions that modify the undercooling (the liquidus temperature minus the actual temperature) of a system, such as increase in both temperature and H_2O content and variations of pressure under anhydrous conditions, would play the most important roles. In this case an increase in temperature due to mixing of two chemically distinct magmas is unlikely to produce the highly differ-

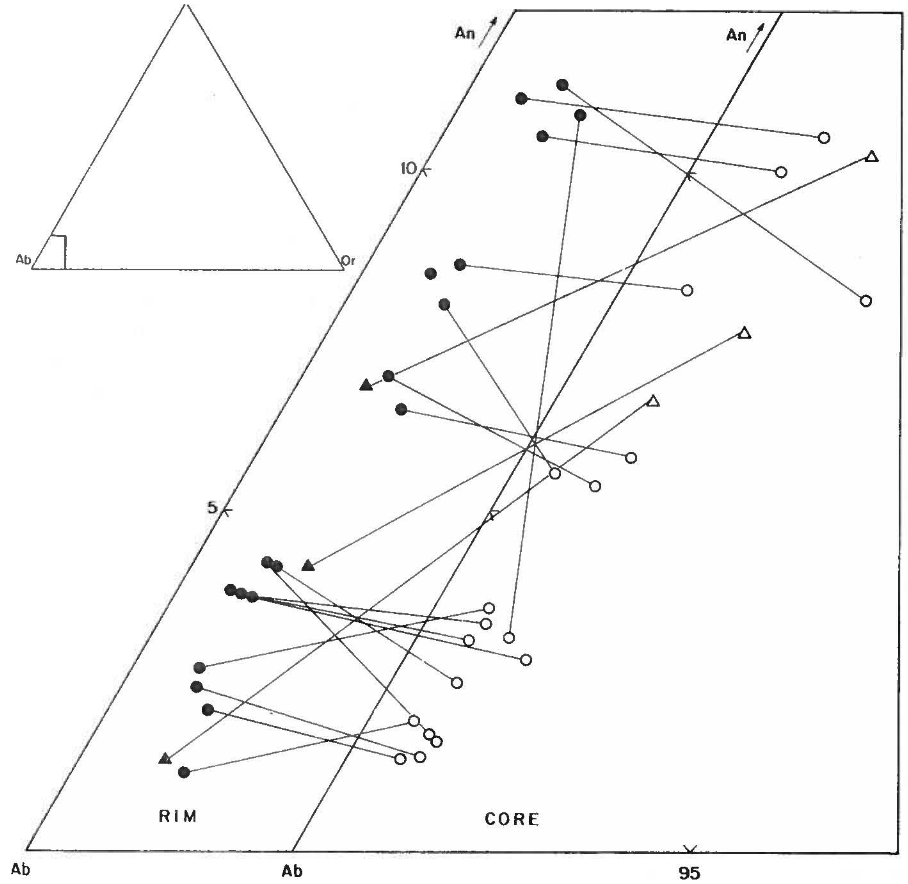

FIG. 2. Compositional zoning of plagioclase phenocrysts. Open triangle: core of early plagioclase phenocrysts; solid triangles: rim of early plagioclase phenocrysts. Open circle: core of late plagioclase phenocrysts; solid circles: rim of late plagioclase phenocrysts.

entiated high-SiO_2 granites. On the other hand, a new injection of hotter magma of similar composition would not have significantly affected the already small degree of undercooling of the initial magma, deduced from the small amount of early phenocrysts.

An increase in the H_2O content of a dry melt causes a noncrystallization stage due to a significant reduction of the undercooling (Loomis and Welber, 1982). The influx of a chemically similar magma but with a higher H_2O content would tend to move the liquidus and solidus curves downward, to do the resorption operative through the mechanism explained in Fig. 4. Magma stirring may enhance the diffusivity of H_2O in the dry melts, thus the incorporation of H_2O would affect the magma reservoir as a whole in a geologically reasonable time. However, the final H_2O content in the magma must be sufficiently low to allow the magma to rise toward shallow levels in the crust, without intersecting the H_2O-saturated granite solidus.

The occurrence of granitic magmas with different H_2O content as products of the same magmatic episode is likely to occur if fusion in the source area takes place under variable P_{H_2O} conditions. Variation in the available water during fusion is closely related to a source inhomogenity and/or a change in degree of fusion of a H_2O-deficient lower crust (Parada, 1983).

Similar effects on liquidus and solidus temperatures of a magma result from the well-known sudden drop in pressure related to upward movement of a H_2O-deficient melt (Vance, 1965; Wiebe, 1968; Pringle *et al.,* 1974; Stull, 1978). If one assumes that crystallization of the melts rapidly increases in shallow levels, the resorption due to a fall in pressure can, to some extent, be underestimated, unless the magma has run a very long path from the source region (see Loomis and Welber, 1982). If both mechanisms were operative, they could have probably taken place independently in successive stages.

LOW PRESSURE CRYSTALLIZATION

PREVIOUS CONSIDERATIONS

Crystallization conditions in a shallow magma chamber can be deduced from late plagioclase zoning which continously records events within plutons.

Although optically homogeneous, late plagioclase phenocrysts have delicate reverse zoning (Fig. 2). Composition determinations at sporadical intermediate points indicate a normal zoning pattern in the outer zone. The range of different core compositions is $An_{10.0-1.4}$, whereas the range among outer zones is $An_{11.2-2.1}$. The effects of the main geological variables (pressure, temperature and water content) on plagioclase zoning can be estimated. The possibility of significant pressure variations in the shallow magma is neglected, despite some short magma rising could occur during eruptions. Increase in temperature is unlikely to occur because rising of hotter magma to shallow conduits is probably accompanied by vertical displacement toward the surface of preexisting melts which impede homogenization. Thus the lowering in liquidus and solidus temperatures to yield disequilibrium plagioclase growths may again result after increasing the H_2O content of the melt.

Any attempt to reproduce the processes that took place during the late plagioclase zoning, must account for:

a) The liquid/phenocryst ratio in the magma did not substantially decrease when the epizonal level was reached, because the large volume of late feldspar and quartz phenocrysts represent a low pressure crystallization (nearly eutectic). This implies that undersaturated conditions probably survived until the accumulation of magma in shallow chambers.

b) The H_2O-saturated conditions for the final stage of crystallization which is inferred from the presence of graphic intergrowth of quartz and feldspar. Furthermore, the best estimate for the temperature of these feldspar crystallization (about 700°C, Parada, 1983) is consistent with solidus temperature of H_2O-saturated granitic magma at low pressure (~ 1 Kb).

c) The initiation of feldspar crystallization from the vertical walls of the lens-shaped plutons. This is suggested by several lines of reasoning. Firstly the high rate of heat removal from the magma near the cooled walls enhace the feldspar crystallization in the earlier stage of the low pressure magma differentiation. Secondly, the slightly higher An content of the plagioclase phenocrysts in the margin sample (average: $An_{7.3}$) compared to phenocrysts in the center sample (average: $An_{5.0}$) reflects that differentiation in the shallow plutons increases inward. Thirdly, experimental results on the development of granitic textures indicate that the externally nucleated crystals (nucleation on walls) are formed prior to the crystals nucleated within the magma body (Swanson, 1977). The presence of the autoliths before mentioned, could represent fragments disrupted from the early crystallized margins.

d) The absence of resorption effects in cores of late plagioclase phenocrysts together with the small difference between rim and core composition (Fig. 3) are indicative of uninterrupted crystallization in which core and rim were mainly developed from the same melt.

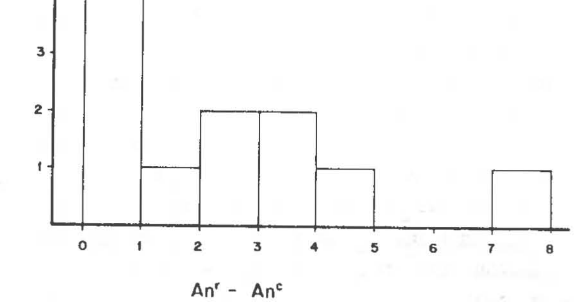

FIG. 3. Hystogram for the compositional differences between rim and core of late plagioclase phenocrysts.

CRYSTALLIZATION HISTORY

The magma crystallization must have taken place in variable H_2O-saturation conditions. Soon after emplacement at shallow depth, the renewed crystallization would have started from the walls in H_2O-undersaturated conditions. The structures controlling the magma emplacement could have served as conduits for meteoric water circulation. Such water probably reached the shallow lens-shaped plutons through their vertical walls. As the H_2O influx from the walls proceeded, decreasing H_2O-undersaturation of the marginal magma gradually occurred. Under such conditions the liquidus and solidus temperature of the marginal melt would gradually decrease permitting the reverse zoning (Fig. 4) without core resorption.

The presence of a significant volume of meteoric water is also deduced by the large volume of explosive eruptions represented by the ignimbrites of the Matahuaico Formation. The amount of vapor needed for ignimbritic eruptions cannot be attributed to a single mechanism of H_2O exsolution (Williams and McBirney, 1979).

Advanced stages of magma crystallization along its borders produced an important "mush zone" (crystales + liquid) in the sense of Loomis and Welber (1982) that obstructed, to some extent, the external water infusion. However, H_2O from the "mush-zone" (after saturation) may have been more easily redistributed in the remainder magma because H_2O diffusion increases as H_2O-undersaturation decreases (Shaw, 1974). Therefore, the increase in An content in growing phenocrysts from the residual magma occurred as a product of disequilibrium growth under gradual increase of H_2O content of the magma.

The continuos normally zoned rim may represent the final stage of crystallization, probably in H_2O-saturated conditions or in water-rich but still water-undersaturated conditions (see McDowell, 1978). It is likely that the normally zoned rim crystallized in equilibrium with K-feldspar.

It is interesting to note that the presence of plagioclase phenocrysts with different An content in the same sample, probably reflects magma stirring due to successive eruptions that brought together phenocrysts developed in different sites of the magma body. Perhaps the addition to the residual liquid of earlier plagioclase phenocrysts (e.g.

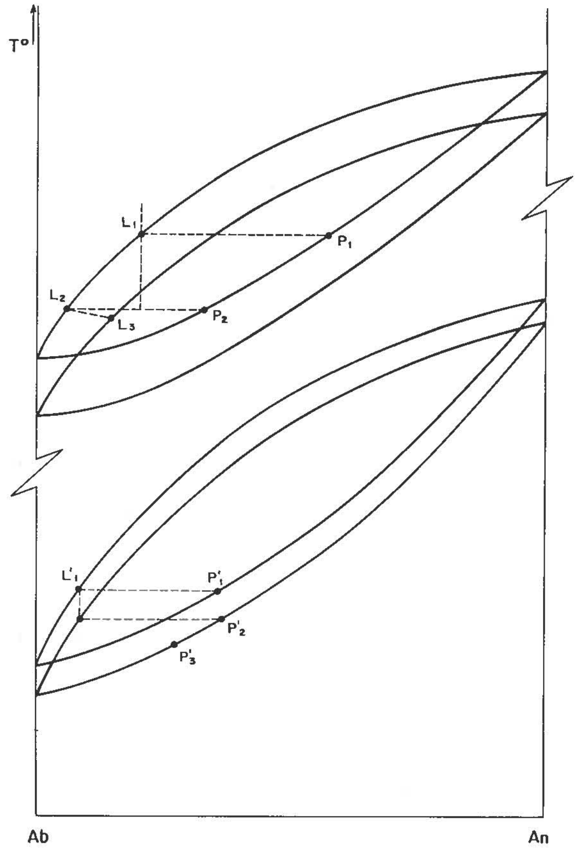

FIG. 4. Upper diagram: Schematic phase diagram of the H_2O-deficient albite-anorthite system to show the normal zoning and resorption mechanism of the early plagioclase phenocrysts. Initially fractional crystallization from liquids L_1 to L_2 at high pressure could lead to crystallization of normally zoned plagioclase from P_1 to P_2. An increase of H_2O content in a dry magma combined to a sudden drop of pressure due to upward movements of the melt causes a non-crystallization stage as product of decrease of the undercooling. Resorption seemed to be a short-lived process to prevent crystallization of a more sodic rim. The exact liquid path (L_2-L_3) depends, among other factors, on the rate of heat loss (presumably low). Lower diagram: Schematic phase diagrams of the albite-anorthite system at low pressures to show reverse zoning of late plagioclase phenocrysts. Increase of H_2O content (due to the influx of meteoric water) in shallow magma could cause disequilibrium growth of P'_2 on P'_1. Note that the composition of P'_2 depends on the shape of the diagram. If no resorption occurs the liquid composition does not change significatively. Crystallization of normally zoned outer zones (P'_2-P'_3) probably took place under H_2O-saturation or near saturation conditions.

from the mush zone) richer in An than those in which the liquid is in equilibrium could also produce sporadic normal zoning in late phenocrysts (see Fig. 2).

FINAL COMMENTS

There are no field evidences of a large chamber that accumulated the melt generated deep in the crust. Only the homogeneous non-tapped Monte Grande pluton (coarse-grained), may be interpreted as a relatively deep step of magma collection. In fact, the maximum estimate pressure of 2.5 Kb for the feldspar crystallization in Monte Grande (Parada, 1983) is significantly higher than the assumed depth (pressure) of emplacement for the studied plutons, considered as the conduits of the igneous materials of the Matahuaico Formation.

The occurrence of low and high-SiO_2 rhyolites (or other volcanic compositions not detected in the present study) at different positions within the stratigraphic column of the Matahuaico Formation, together with the lack of low-SiO_2 granites in the equivalent plutons, cannot be easily attributed to successive eruptions of a compositionally and thermally zoned silicic chamber at shallow depth in the sense of Hildreth (1981), unless low-SiO_2 granites were located in the lowermost part of the bodies (not exposed). However, such hypothetical distribution is unlikely to occur if crystallization and compositional variations of the magma start from the walls to the center of the body. An alternative is to consider that magma differentiation took place in the source region. However, the small amount of supercooling of the magma at depth, given by the small amount of early phenocrysts, reflects that this differentiation is not significant. Furthermore, crustal extension regime, assumed during this magmatism, favors the magma rise through deep faults as soon as a critical volume of melt is reached, preventing a long-lived differentiation at depth.

In the author's opinion, the above described process would result if the same conduits evacuate melts of slightly different composition generated by partial fusion of an inhomogeneous source (Fig. 5). As it was mentioned before, rhyolitic magma with some compositional variations is likely to be generated during a single magmatic stage. Generation of these melts increase the

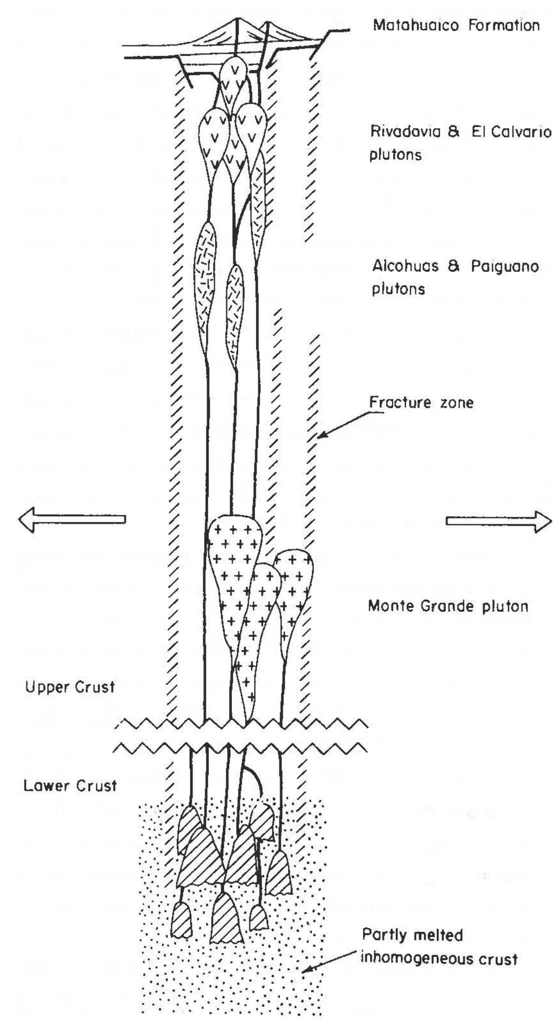

FIG. 5. Sketch for the leucogranite magmatism under study. Granitic magma is generated in the lower crust under extension conditions. The influence of mantle derived basaltic magma on the fusion of crustal materials is not ruled out. Extracted melts are assembled at different levels within the upper crust. Compositional variations in related volcanics could represent inhomogenity of the source area (see text).

possibility that two slightly different magmas (e.g. in H_2O content) tend to be homogenized in the source region, favoring the resorption of early plagioclase phenocrysts before they reach higher levels in the crust. The ascense of magma may have continuously taken place to prevent the formation of low-SiO_2 granites at shallow level. On the other hand, primary high-SiO_2 granitic melts were formed several times during the magmatic span, where the studied plutons represent the final stage.

Successive ignimbritic eruptions should interrupt the magma differentiation via thermogravitational diffusion of H_2O and other components. Conversely, such eruptions could enhance diffusion of resorbed meteoric water in the melt to permit the reverse zoning of late plagioclase at shallow depth.

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REFERENCES

BOTTINGA, Y.; KUDO, A.; WEIL, D. 1966. Some servations on oscillatory zoning and cystallizat of magmatic plagioclase. Am. Miner., Vol. 51, p. 792-806.

CANN, J. R. 1970. Upward movement of granitic magma. Geol. Mag., Vol. 107, No. 4, p. 335-340.

COLLINS, W. J.; BEAMS, S. D.; WHITE, A. J. R.; *et al.* **1982.** Nature and origin of A-type granites and particular reference to Southeastern Australia. Contrib. Mineral. Petrol., Vol. 80, p. 189-200.

DEDIOS, P. 1967. Cuadrángulo Vicuña, provincia de Coquimbo. Inst. Invest. Geol., Carta Geol. Chile, No. 16, 65 p.

FUJIMAKI, A.; AOKI, K. I. 1980. Quatitative microanalyses of silicates, oxides and sulfides using an energy-dispersive type eletron probe. Tohoku Univ., Sci. Rep., Ser. 3, Vol. 14, No. 3, p. 261-268.

HARRIS, P. G.; KENNEDY, W. Q.; SCARFE, C. M. 1970. Volcanism versus plutonism; the effect of chemical composition. *In* Mechanism of igneous intrusion. (Newall, G.; Rast, N.; eds.) Seel House Press, p. 187-200. Liverpool.

HILDRETH, W. 1981. Gradients in silicic magma chambers; implications for lithospheric magmatism. J. Geophys. Res., Vol. 86, No. B11, p. 10153-10192.

HILLS, E. S. 1936. Reverse and oscillatory zoning in plagioclase feldspar. Geol. Mag., Vol. 73, p. 49-56.

LETELIER, M. 1977. Petrología, ambiente de depositación y estructura de las formaciones Matahuaico, Las Breas, Tres Cruces *sensu lato* e intrusivos hipabisales permotriásicos, en el área de Rivadavia-Alcohuas, valle del Elqui, IV Región, Chile. Memoria de Título, Univ. Chile, Depto. Geol., 131 p. Santiago.

LOOMIS, T. P. 1979. An empirical model for plagioclase equilibrium in hydrous melts. Geochim Cosmochim. Acta, Vol. 43, No. 11, p. 1753-1760.

LOOMIS, T. P.; WELBER, P. 1982. Crystallization processes in the Rocky hill granodiorite pluton, California; An interpretation based on compositional zoning of plagioclase. Contrib. Mineral. Petrol, Vol. 81, p. 230-239.

McDOWELL, S. D. 1978. Little Chief Granite porphyry; feldspar crystallization history. Geol. Soc. Am., Bull., Vol. 89, No. 1, p. 33-49.

PARADA, M. A. (in prep.). Petrology of the Permotriassic anorogenic granitic rocks in the High Andes of central Chile (30° S): an association of S-type granitoids and A-type granites.

PHEMISTER, J. 1934. Zoning in plagioclase feldspar. Mineral. Mag., Vol. 23, p. 541-555.

PRINGLE, G. J.; TREMBATH, L. T.; PAJARI, G. E. Jr. 1974. Crystallization history of a zoned plagioclase. (Microprobe analysis of zoned plagioclase from the Grand Manan tholeiite sheet). Mineral. Mag., Vol. 39, No. 308, p. 867-877.

SHAW, H. R. 1974. Diffusion of H_2O in granitic liquids; Part 1, Experimental Data; Part 2, Mass transfer in magma chambers. Carnegie Inst. Wash., Publ., No. 634, p. 139-170.

SMITH, J. V. 1974. Feldspar Minerals; 2, Chemical and textural properties. Springer-Verlag, 690 p. New York.

STULL, R. J. 1978. Mantled feldspar from the Golden Horn batholith, Washington. Lithos, Vol. 11, p. 243-249.

SWANSON, S. E. 1977. Relation of nucleation and crystal-growth rate to the development of granitic textures. Am. Mineral, Vol. 62, No. 9-10, p. 966-978.

VANCE, J. A. 1962. Zoning in igneous plagioclase: normal and oscillatory zoning. Am. J. Sci., Vol. 260, p. 746-760.

VANCE, J. A. 1965. Zoning in igneous plagioclase: patchy zoning. J. Geol., Vol. 73, p. 636-651.

WHITNEY, J. A. 1975. The effects of pressure, temperature and X_{H_2O} on phase assemblage in four synthetic rock compositions. J. Geol., Vol. 83, No. 1, p. 1-31.

WIEBE, R. A. 1968. Plagioclase stratigraphy; a record of magmatic conditions and events in a granitic stock. Am. J. Sci., Vol. 266, p. 690-703.

WILLIAMS, H.; McBIRNEY, A. 1979. Volcanology, Freeman, Cooper & Co., 397 p. San Francisco.