Multiple subduction components in the mantle wedge: Evidence from eruptive centers in the Central Southern volcanic zone, Chile

Rosemary Hickey-Vargas
Murong Sun
Department of Earth Sciences, Florida International University, Miami, Florida 33199, USA
Leopoldo López-Escobar Grupo Magmatico, Instituto de Geología Económica Aplicada, Universidad de Concepción, Concepción, Chile
Hugo Moreno-Roa Observatorio Volcanológico de los Andes del Sur, Temuco, Chile
Mark K. Reagan Department of Geology, University of Iowa, Iowa City, Iowa 52242, USA
Julie D. Morris Department of Earth and Planetary Sciences, Washington University, St. Louis, Missouri 63130, USA
Jeff G. Ryan Department of Geology, University of South Florida, Tampa, Florida 33620, USA

ABSTRACT

In the Andean Central Southern volcanic zone, basalts from small eruptive centers near the large composite center Volcan Villarrica are poor in fluid mobile elements, such as B, Cs, Rb, K, Pb, Ba, and U, compared with concurrently erupted Villarrica basalts. New ^{10}Be and U-series isotopic data for these centers show that fluid mobile element–poor small eruptive center basalts have small ^{10}Be/^{9}Be ratios (1.6–1.9 × 10^{-11}) and (^{238}U/^{230}Th) activity ratios near 1.0, whereas basalts from Villarrica show ^{238}U enrichment and larger ^{10}Be/^{9}Be ratios (4.0–6.4 × 10^{-11}). These results suggest that small eruptive center basalts include materials derived from the subducted lithosphere that were stored in the mantle wedge for 350 k.y. to 3 m.y. That these materials are poor in fluid mobile elements may reflect fluid expulsion during solidification or their formation in an initially hotter subduction setting. In contrast, the composite center basalts sample materials rich in fluid mobile elements that were recently transferred into the mantle wedge from the subducted lithosphere. The results confirm that mantle wedges in subduction zones include subducted materials added to the wedge over both long and short time scales.

Keywords: subduction-zone magmatism, Chile, U-series isotopes, ^{10}Be.

INTRODUCTION

The processes that transfer elements from subducted crust to mantle wedge to magma are important because they determine the composition of arc magmas, the composition of the lithosphere that is recycled into the mantle, and, ultimately, the composition of the continental crust. Studies of subduction-related volcanic rocks show that often more than one subduction component can be identified within a suite of rocks or related volcanic centers (Reagan et al., 1994; Hochstaedter et al., 1996; Elliott et al., 1997). This finding means that the sources of materials transferred from slab to mantle to magma and/or the processes that transfer them can vary over small spatial and temporal scales. Small-scale variations must be understood in order to properly construct large-scale mass-balance estimates of elemental cycling in subduction zones, and close examination of such variations can help us understand the nature of the transfer processes.

In this paper we report new U-series isotope and ^{10}Be data for volcanic rocks from a cluster of small eruptive centers closely surrounding a large composite center in the Central Southern volcanic zone of the Andes. The results show that at least two distinct subduction components have been incorporated into these magmas. One is poor in fluid mobile elements and has been stored within the mantle wedge. The second component, which is dominant at the large composite center, is younger and richer in volatile elements.

GEOLOGIC AND GEOCHEMICAL BACKGROUND

The Southern volcanic zone of the Andes (33°–46°S, Fig. 1A) is formed by the convergence of the Nazca and South American plates. The Southern volcanic zone can be subdivided into Northern, Transitional, Central, and Southern segments on the basis of changes in crustal thickness and the petrologic and geochemical features of the volcanic rocks (Tormey et al., 1991). The Central Southern volcanic zone is sited on relatively thin (30 km) continental crust, and most of the active stratovolcanoes in this region erupt basalt. Previous work on volcanic centers in this volcanic zone has shown that crustal influence on the magma chemistry is minor for mafic magmas (Déruelle et al., 1983; Hickey et al., 1986; Hickey-Vargas et al., 1989), but discernible through O isotope and major element changes (McMillan et al., 1989; López-Escobar et al., 1995).

At 39°30′S (Fig. 1B), three large stratovolcanoes, Villarrica, Quetrupillan, and Lanin, are along a northwest-trending lineation that offsets the north-trending Liquiñe-Ofqui fault zone. Small eruptive centers (<1 km^3 per edifice) are found throughout this area, some along well-defined north-trending lineations parallel to the fault zone. Work on Volcan Villarrica (Moreno et al., 1994) showed that the volcano has produced basaltic ignimbritic eruptions of massive extent. Deposits from two of these eruptions, the Lican Ignimbrite (14 ka) and the Pucon Ignimbrite (4 ka), which mark the beginning and end of the Villarrica II eruptive stage, bracket the ages of the small eruptive cen-

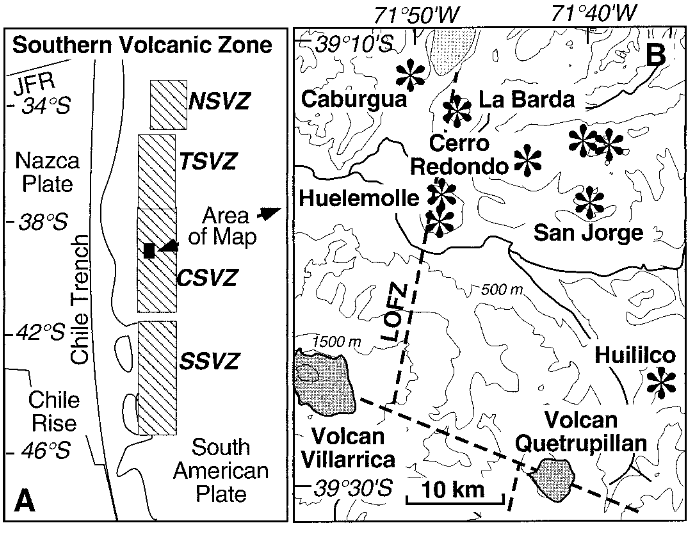

Figure 1. A: Map of Southern volcanic zone (SVZ) of Andes showing Northern (NSVZ), Transitional (TSVZ), Central (CSVZ), and Southern (SSVZ) segments and study area. JFR is Juan Fernandez Ridge. B: Location of small eruptive centers (large asterisks) near Volcan Villarrica. LOFZ is Liquine-Ofqui fault zone.

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TABLE 1. U-SERIES ISOTOPES, $^{10}Be/^{9}Be$, AND OTHER CHEMICAL DATA FOR BASALTS FROM SMALL ERUPTIVE CENTERS AND VOLCAN VILLARRICA

	V. Villarrica	Small Eruptive Centers†					
	1971 flow*	San Jorge	Caburgua	La Barda	Huelemolle	C. Redondo	Huililco
Sample #:	210181-1	140194-1	150194-1	150194-6	110194-3	140194-9	240394-6A
% SiO_2	52.60	50.39	50.91	50.35	50.98	51.55	51.76
% MgO	6.05	10.40	6.45	7.62	5.74	6.49	5.98
$(^{238}U/^{232}Th)$§	1.16	1.27	0.86	0.85	0.82	0.92	0.94
$(^{230}Th/^{232}Th)$	0.77	0.76	0.94	0.89	0.87	0.92	0.87
$(^{238}U/^{230}Th)$	1.51	1.66	0.91	0.95	0.95	1.00	1.08
$(^{210}Po/^{230}Th)$	1.57	1.60	1.01	1.02	1.10	1.13	1.28
$^{10}Be/^{9}Be$§	4.0×10^{-11}	4.6×10^{-11}	1.9×10^{-11}	1.9×10^{-11}	1.6×10^{-11}	—	—
B/Be	39	17.7	5.7	14.3	2.9	9.6	9.0
$^{143}Nd/^{144}Nd$	0.512893	0.512909	0.512852	0.512839	0.512784	0.512835	0.512866

Note: *Major element and Nd isotope data for this sample are from Hickey-Vargas et al. (1989).

†Data from major elements and Nd isotopes for all small eruptive centers are from Sun (2001).

§U-series isotopes were measured by alpha spectrometry at the University of Iowa, using the techniques reported by Reagan et al. (1994). Typical errors for U-series activity ratios are ±5%. ^{10}Be abundances were measured by accelerator mass spectrometry at Lawrence Livermore National Laboratory, using preparation techniques described in Morris and Tera (1989). Typical errors for ^{10}Be measurements are less than ±5%. Samples were leached to monitor in situ–produced ^{10}Be, which was negligible in all cases. Be and B abundances were measured by direct current plasma atomic-emission spectrometry (DCP-AES) at the University of South Florida, following methods outlined in Ryan and Langmuir (1988) and Ryan et al. (1996), respectively.

ters Caburgua, LaBarda, Huelemolle, and Cerro Redondo (Fig. 1B). The ages of the other small eruptive centers are not defined.

Prior work comparing the bulk chemistry of basalts from Villarrica and four small eruptive centers (Hickey-Vargas et al., 1989) showed that, compared to Villarrica, small eruptive center basalts were systematically depleted in alkali elements and Ba relative to rare earth elements (REEs) and that the small eruptive center basalts had higher light REE abundances and light REE/heavy REE ratios. On the basis of their geochemical characteristics, Hickey-Vargas et al. (1989) proposed that the source of the small eruptive center magmas, compared with that for Villarrica, incorporated a smaller amount of a hydrous slab-derived fluid, which then induced a smaller extent of partial melting of the mantle wedge. The lower extent of melting is implied by the higher abundances of light REE and higher light REE/heavy REE ratios.

Comprehensive major and trace element and Sr, Nd, and Pb isotopic study of basalts from seven small eruptive centers by Sun (2001) has confirmed the overall geochemical characteristics delineated earlier, with one exception, the small eruptive center San Jorge (Fig. 1B), which has chemical characteristics similar to those of Villarrica. On the basis of detailed modeling, Sun (2001) concluded that the small eruptive center and Villarrica magmas were formed by different extents of melting, but that they also had incorporated subduction components with differing abundances of fluid mobile elements. Such differences in subduction-zone processes are difficult to reconcile with the concurrent volcanic activity at the large and small centers, and their close spacing of 5–30 km (Fig. 1B).

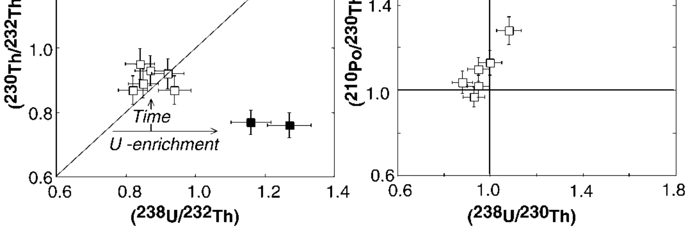

Figure 2. A: Plot of $(^{230}Th/^{232}Th)$ vs. $(^{238}U/^{232}Th)$. B: $(^{210}Po/^{230}Th)$ vs. $(^{238}U/^{230}Th)$. Plots show differing characteristics in basalts from Volcan Villarrica and San Jorge compared to other small eruptive centers (SECs). Arrows in A show differing effects of U enrichment and time.

NEW RESULTS

Short-lived U-series isotopes and $^{10}Be/^{9}Be$ and B/Be ratios are exceptional tools for interpreting the timing and sources of enrichment events during subduction because they are diagnostic for the influence of fluid transport versus melting [B/Be; the activity ratio $(^{238}U/^{232}Th)$] and sediment versus altered-basalt source materials [$(^{230}Th/^{232}Th)$ and $^{10}Be/^{9}Be$], and because they can set limits on the timing of chemical fractionation during subduction processes. Table 1 lists data for these tracers for basalts from the Villarrica and small eruptive center suite[1].

B abundances in the small eruptive centers follow the fluid-depleted trend shown by elements Cs, Rb, K, Pb, Ba, and U. For example, B/Be ratios, used by Morris et al. (1990) to define fluid-enrichment trends in arc lavas worldwide, are lower in the small eruptive centers and higher in lavas from San Jorge and Villarrica (Fig. 1B). $(^{238}U/^{232}Th)$ activity ratios are also lower in the small eruptive centers (0.82–0.94 vs. 1.16–1.27), and $(^{230}Th/^{232}Th)$ are slightly higher (0.87–0.94 vs. 0.76–0.77). On an equiline plot (Fig. 2A), the small eruptive centers plot in a cluster near or on the equiline, indicating that either significant fractionation of Th and U did not occur during the generation of the magma or that it occurred sufficiently long ago for secular equilibrium to be reestablished (ca. 350 k.y.). Villarrica and San Jorge samples plot to the right of the equiline, showing the U enrichment that is characteristic of many arc lavas. Such enrichment is interpreted to indicate the preferential mobility of U over Th in hydrous subduction fluids. The lower $(^{230}Th/^{232}Th)$ activity ratios in Villarrica and San Jorge lavas preclude an interpretation that Th was derived from the same source as the small eruptive center, at the same time.

Because of the short half-life of ^{210}Po and its parent ^{210}Pb, (^{210}Po) can be used as a proxy for (^{226}Ra) (Reagan et al., 1994). The age of the small eruptive center is about three to four times the half-life of ^{226}Ra; therefore, significant $(^{226}Ra/^{230}Th)$ disequilibrium is not expected. High $(^{226}Ra/^{230}Th)$ (Fig. 2B) is observed in a recent lava from Villarrica (the 1971 flow) and in basalt from San Jorge. These data suggest that the small eruptive center San Jorge may be significantly younger than other small eruptive centers, in addition to having a unique geochemical character. These results establish the occurrence of ^{226}Ra excesses in young Central Southern volcanic zone lavas, similar to those observed in other arcs worldwide (Turner et al., 2001). The ^{226}Ra excesses suggest that enrichment of Ra (and probably Ba) rela-

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[1] GSA Data Repository item 2002018, Full chemical analyses of the samples, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

TABLE 2. Nd AND Th CONTRIBUTIONS FROM SUBDUCTED SEDIMENT AND INFERRED SOURCE AGES

	V. Villarrica	San Jorge	Caburgua	La Barda	Huelemolle
	Percentage of element contributed by subducted sediment				
Nd	38	35	44	47	56
Th	68	70	40	48	52
	Source age inferred by assuming percentage of Be contributed by sediment = percentage of Nd contributed by sediment				
Measured $^{10}Be/^{9}Be$	4.0×10^{-11}	4.6×10^{-11}	1.9×10^{-11}	1.9×10^{-11}	1.6×10^{-11}
Inferred $^{10}Be/^{9}Be$ in sediment	10.5×10^{-11}	13.1×10^{-11}			
	(average 11.8×10^{-11})				
Inferred initial $^{10}Be/^{9}Be$ in SEC source			5.2×10^{-11}	5.5×10^{-11}	6.6×10^{-11}
Inferred age of source	0 Ma	0 Ma	2.2 Ma	2.3 Ma	3.1 Ma

Note: The percentage of each element contributed by subducted sediment is calculated from the isotopic data in Table 1 and the following values: $^{143}Nd/^{144}Nd = 0.51315$ and $(^{230}Th/^{232}Th) = 1.0$ for MORB source mantle; $^{143}Nd/^{144}Nd = 0.51310$ and $(^{230}Th/^{232}Th) = 1.2$ for altered Nazca plate MORB; $^{143}Nd/^{144}Nd = 0.5125$ and $(^{230}Th/^{232}Th) = 0.6$ for subducted sediment. The inferred $^{10}Be/^{9}Be$ in sediment is calculated from the measured $^{10}Be/^{9}Be$ for Villarrica and San Jorge basalts and the percentage of Be (= Nd) contributed by sediment to their source, assuming $^{10}Be/^{9}Be = 0$ in the mantle and altered MORB. The inferred initial $^{10}Be/^{9}Be$ in the SEC source is estimated by using the inverse approach, and the age is calculated by using the decay constant for ^{10}Be. The mantle contribution for Villarrica and the SEC estimated by Sun (2001) is 36% for Nd and 10% for Th. MORB is mid-ocean ridge basalt; SEC is small eruptive center.

tive to Th occurs during arc-magma generation within a few thousand years before eruption at the surface.

The $^{10}Be/^{9}Be$ ratios were measured in five samples. Villarrica samples, including three from Morris et al. (1990), have $^{10}Be/^{9}Be$ ratios of 4.0 to 6.4×10^{-11}, which confirm the involvement of subducted pelagic sediment in the origin of these magmas. San Jorge has similar high $^{10}Be/^{9}Be$ ratios of 4.6×10^{-11}, whereas the other small eruptive centers have lower ratios of 1.6 to 1.9×10^{-11}.

DISCUSSION

Evidence for a Stored Subduction Component

Geochemical modeling of small eruptive centers and Villarrica basalts indicates that they incorporated different subduction components, and this conclusion conflicts with the close (<30 km) spacing of these centers and their concurrent volcanic activity. The new ^{10}Be and U-series isotopic results indicate that a likely explanation is that the subduction component for the small eruptive centers is older, that it was stored within the mantle wedge and reactivated at the time of their eruptive activity. To illustrate this idea, Table 2 shows an estimate of the contribution of subducted sediment to the abundances of Nd, Th, and Be in the small eruptive center and Villarrica sources. These percentages are estimated from the isotopic composition of these elements in the lavas (Table 1), estimated isotopic values for subducted mid-ocean ridge basalt (MORB), sediment, and the presubduction mantle source, and the amount of each element contributed by the subduction component (altered MORB plus sediment). The absolute values of the percentages depend on the choice of sediment, and MORB and mantle compositions, but the difference between percentages for the small eruptive centers and Villarrica do not, so long as the same end members are used. The amounts of each element contributed by the subduction component (Table 2, notes) are maxima, calculated assuming that Nb is completely incompatible during mantle melting (Sun, 2001). This assumption also does not strongly affect the results, because the Nd isotope composition of subducted MORB and MORB-source mantle are similar. For example, a 10% change in the amount of subduction component changes the contribution of Nd from sediment in the Villarrica and small eruptive center basalts by <2%, and it produces no change in the estimated storage times discussed in the following.

For Nd, small eruptive center basalts have a higher contribution from subducted sediment than Villarrica and San Jorge lavas (Table 2). This observation conflicts with their lower ^{10}Be values, particularly because the elements Be and Nd behave similarly in geochemical processes (Ryan and Langmuir, 1988). The lower ^{10}Be could result from incorporation of the older, ^{10}Be-poor sections of a sediment column, or from aging of the entire subduction component within the mantle wedge. The former explanation is also difficult to reconcile with the close spatial relationship of the centers. If we use the latter interpretation and assume that the contributions of sediment Be and Nd are the same, we can estimate an initial $^{10}Be/^{9}Be$ ratio for the time at which the subduction component was generated (Table 2). Comparison with present-day values shows that 2.2–3.1 m.y. of aging is required to explain the decrease in $^{10}Be/^{9}Be$. These ages are within the time span of plate convergence at the Central Southern volcanic zone, and the current phase of arc magmatism.

Results for the U-series isotopes are also consistent with aging of the subduction component for the small eruptive centers. Small eruptive center basalts plot along the equiline and have slightly higher $(^{230}Th/^{232}Th)$ activity ratios than those for Villarrica. If it is assumed that both subduction components were enriched in U (Fig. 2A), storage of the small eruptive center component within the mantle wedge for ~350 k.y. would allow it to reach secular equilibrium. If the initial $(^{230}Th/^{232}Th)$ ratios were similar to those for Villarrica and San Jorge (similar contributions from sediment, basalt, and mantle Th), then their higher $(^{230}Th/^{232}Th)$ activity ratios could result from aging of a component less enriched in U (Fig. 2A), consistent with the fluid mobile element depleted character of the small eruptive centers. An alternative interpretation is that the higher $(^{230}Th/^{232}Th)$ activity ratios indicate a smaller contribution of Th from subducted sediment in the small eruptive center source, compared with Villarrica and San Jorge (Table 2), but this also conflicts with the Nd isotope results.

Implications for Magma Generation in the Southern Volcanic Zone

Our interpretation that the subduction component sampled by the small eruptive centers was stored and aged in the mantle wedge makes it easier to explain the concurrent eruption of geochemically distinct magmas at the small eruptive centers and Villarrica. The reason that the small eruptive center component was remobilized at 6–4 ka is not known, but it could reflect unusual heating of the wedge during that time, addition of water or entrainment of the small eruptive center component in the rising melt column, and melting by decompression. It is also unknown whether the small eruptive center component was included in the active melt column tapped at Villarrica. Detailed study of the composition of Villarrica II lavas shows no systematic shift at that time (Hickey-Vargas et al., 1989). Either the component was not included, or its volume was so small that it had little impact on the overall composition of magmas being erupted.

A survey of U-series isotopes, ^{10}Be, and B in the Southern volcanic zone by Sigmarsson et al. (1990) found that volcanic centers exhibited an overall correlation of $(^{238}U/^{230}Th)$ and ^{10}Be enrichment

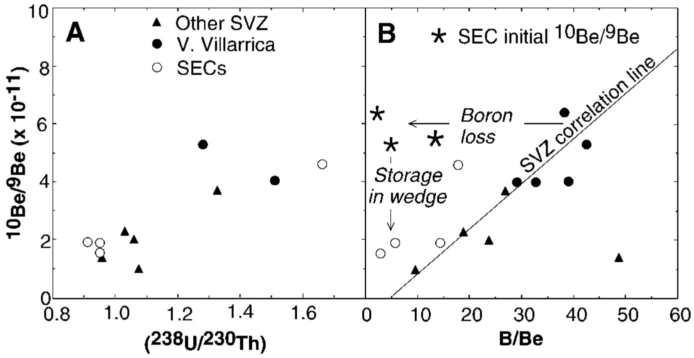

Figure 3. A: Plot of ^{10}Be/^{9}Be vs. (^{238}U/^{230}Th). B: ^{10}Be/^{9}Be vs. B/Be. Plots are for samples from Villarrica region and other centers in Southern volcanic zone (SVZ; Sigmarsson et al., 1990; Morris et al., 1990). Southern volcanic zone correlation line in B is from Morris et al. (1990). Initial ^{10}Be/^{9}Be ratios for small eruptive center (SEC) samples are from Table 2. Arrows showing B loss, followed by decay of ^{10}Be during storage in wedge, illustrate one possible origin for small eruptive center magma sources.

that was interpreted as mixing between mantle and subduction fluid. The results of this study follow that relationship (Fig. 3A); however, our interpretation is that time also plays an important role. The mantle wedge probably contains stored material transferred from the slab at different times. Episodic or continuous sampling of these materials by young magmas, or wholesale remelting of the stored materials, will produce diverse geochemical patterns. The trend shown in Figure 3A probably reflects (1) variable addition of ^{10}Be and ^{238}U-enriched subduction components to the sources of active volcanoes and the wedge, (2) variable sampling of aged material in the wedge, and (3) variable contamination by continental crust for rocks of the Northern Southern volcanic zone.

Morris et al. (1990) noted a linear correlation between ^{10}Be/^{9}Be and B/Be ratios in the Southern volcanic zone, as well as in many other arcs and arc segments worldwide. These correlations were also interpreted as the result of mixing between B and ^{10}Be-rich subduction fluids and the mantle wedge. The linearity indicated a remarkable homogeneity in subduction component along the length of the arc. Data for the Villarrica region also follow this pattern (Fig. 3B), although the small eruptive centers have slightly higher ^{10}Be/^{9}Be ratios at low B/Be ratios.

Melt and Fluid Transfer of Elements from Slab to Wedge

Recent controversy has centered on whether elements are transferred from slab to wedge as melts or hydrous fluids, or both (e.g., Johnson and Plank, 1999). The relationship between small eruptive center and Villarrica-type components, which are, respectively, rich and poor in fluid mobile elements, has bearing on this controversy. Because the small eruptive center component was stored in the mantle wedge, it presumably solidified there either by cooling and crystallization (melt) or by reaction with the surrounding peridotite (hydrous fluid). In either case, it is possible that the low budget of fluid mobile elements resulted from continued migration of these elements in water expelled after solidification. A similar process was proposed by Hochstaedter et al. (1996) to account for unusually B-, Cs-, and U-poor magmas from the Mexican volcanic belt. For the small eruptive centers, B loss through this process could also explain the disparity between initial ^{10}Be/^{9}Be ratios for the small eruptive centers versus B/Be on the Southern volcanic zone correlation plot (Fig. 3B). Scavenging of such fluids by magma rising within the wedge could produce enrichments of water- and fluid-soluble elements that would be difficult to distinguish from direct transport of hydrous fluid from slab to wedge. Alternatively, the two subduction components may have been generated independently at different times under different conditions. For example, low abundances of fluid soluble elements are typical of volcanic-front magmas in unusually hot subduction zones, where the slab has undergone a large extent of early dehydration (e.g., Leeman et al., 1990; Hochstaedter et al., 1996). The small eruptive center component may have formed under these conditions 2–3 m.y. ago, whereas the current subduction component is generated under cooler conditions.

CONCLUSIONS

Basaltic magmas erupted at Villarrica and surrounding small eruptive centers sample two distinct subduction components. The ^{10}Be/^{9}Be and U-series isotope data show that the subduction component sampled by the 6–4 ka small eruptive centers was stored in mantle wedge for 350 k.y. to 3 m.y. and was poor in fluid mobile elements, either as the result of fluid expulsion following solidification in the wedge or by its generation in a hotter subduction setting. Magmas erupted at the large, composite edifice Villarrica, and at one small eruptive center, San Jorge, sample a younger subduction component, rich in fluid mobile elements. In terms of subduction-zone magmatism, the results generally corroborate mounting evidence that the mantle wedge contains elements transferred from the subducted lithosphere over long (10 m.y.–100 k.y.) and short (1 k.y.) time scales.

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