

ISOTOPIC COMPOSITION OF LATE JURASSIC AND EARLY CRETACEOUS MAFIC IGNEOUS ROCKS FROM THE SOUTHERNMOST ANDES: IMPLICATIONS FOR SUB-ANDEAN MANTLE

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ABSTRACT

A basaltic dike and minerals within a gabbro from the ophiolitic Tortuga Complex, a portion of the mafic floor of the Late Jurassic Rocas Verdes back-arc basin in southernmost South America, have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.70323 to 0.70429. This range is due to variations in the amount of seawater which interacted with different pseudostratigraphic levels of the Tortuga Complex during the 'ocean floor' hydrothermal metamorphism that affected the Rocas Verdes. An original magmatic $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7031 is estimated for the mafic igneous rocks of the Tortuga Complex, which along with ϵNd_i values of +6.8 to +7.6, is within the range of Late Jurassic depleted asthenospheric mantle. This is consistent with the previous documented oceanic petrochemical and structural character of the Tortuga Complex. Early Cretaceous Barros Arana basalts, which were erupted on the continental platform along the eastern edge of the Rocas Verdes Basin, have similar initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7030, but lower ϵNd_i value of +5.0 to +5.2. This is interpreted as reflecting a contribution from the Mesozoic subcontinental lithospheric mantle, which like the current lithospheric mantle below southernmost South America, has isotopic characteristics indicating time-integrated depletion of large-ion-lithophile elements. The data support the suggestion that, by contrast, even the most mafic gabbros of the Patagonian batholith have incorporated crustal components.

Key words: Ophiolites, Rocas Verdes, Tortuga Complex, Barros Arana Formation, Isotopic composition, Ocean floor metamorphism, Mantle, Southernmost Andes, Chile.

RESUMEN

Un dique basáltico y minerales de un gabro del Complejo ofiolítico Tortuga, pertenecientes al suelo máfico ígneo de la cuenca trasarco Rocas Verdes del Jurásico Superior en el extremo sur de Sudamérica, tienen razones iniciales de $^{87}\text{Sr}/^{86}\text{Sr}$ desde 0,70323 hasta 0,70429. Este intervalo se debió a las variaciones en la cantidad de agua oceánica que interactuó con los diferentes niveles pseudoestratigráficos del Complejo Tortuga, durante el episodio de metamorfismo hidrotermal de 'fondo oceánico', que afectó a las Rocas Verdes. Se ha estimado una razón magmática original de $^{87}\text{Sr}/^{86}\text{Sr}$ de 0,7031 para las rocas ígneas máficas del Complejo Tortuga, la cual, junto a su ϵNd_i de +6,8 a +7,6, se encuentra dentro del intervalo de valores del manto astenosférico empobrecido del Jurásico Superior. Esto es consistente con el carácter oceánico, petroquímico y estructural, previamente documentado para el Complejo Tortuga. Los basaltos de la Formación Barros Arana (Cretácico Inferior), productos de erupción en la plataforma continental, a lo largo del borde oriental de la Cuenca Rocas Verdes, tienen una razón inicial $^{87}\text{Sr}/^{86}\text{Sr}$ similar (0,7030), pero ϵNd_i más bajo (+5,0 a +5,2). Esto se interpreta como un reflejo de la contribución del manto litosférico subcontinental, mesozoico, que, como el actual manto litosférico bajo el extremo sur de Sudamérica, tiene características isotópicas indicativas de un empobrecimiento integrado a través del tiempo por elementos litófilos de iones grandes. La información disponible apoya la idea de que, por el contrario, hasta los gabros más máficos del Batolito Patagónico han incorporado componentes corticales.

Palabras claves: Ofiolitas, Rocas Verdes, Complejo Tortuga, Formación Barros Arana, Composición isotópica, Metamorfismo de fondo oceánico, Manto, Andes Australes, Chile.

INTRODUCTION

This paper presents isotopic data for the Late Jurassic ophiolitic Tortuga Complex, which formed a portion of the mafic igneous floor of the Rocas Verdes back-arc basin of southernmost South America (Fig. 1; Dalziel *et al.*, 1974), and Early Cretaceous Barros Arana Formation basalts, which were erupted within the eastern extension of the Rocas Verdes Basin onto the continental platform (Soffia⁽¹⁾; Stern *et al.*, in press). The isotopic data indicate that, consistent with their emplacement within the extensional tec-

tonic environment associated with the development of the Rocas Verdes Basin, the petrogenesis of these mafic igneous rocks did not involve extensive interaction with the continental crust, as did the petrogenesis of the Patagonian Batholith (Halpern, 1973; Hervé *et al.*, 1981; Weaver *et al.*, 1990). Thus, these data provide information about the subcontinental mantle below southernmost South America during Mesozoic times.

SAMPLE DESCRIPTION

TORTUGA OPHIOLITE COMPLEX

The ophiolitic Tortuga Complex represents an exposed portion of the floor of the Late Jurassic to Early Cretaceous Rocas Verdes marginal basin (Fig. 1; Elthon and Ridley, 1980). The age of the Tortuga Complex has not been determined directly, but U-Pb age determinations on zircons from Rocas Verdes mafic complexes on South Georgia to the southeast, and from the Sarmiento Ophiolite to the northwest, yield ages of 150 ± 2 and 138 ± 2 Ma, respectively (Stern *et al.*, 1991). An age of 150 Ma has been employed here to calculate, from the measured values, the initial isotopic composition of the Tortuga Complex samples.

De Wit (1977) and De Wit and Stern (1981) suggested that the Rocas Verdes marginal basin widened towards the southeast, and that the Tortuga Complex represents a section of the mafic floor of the basin where it was widest and most similar in character to oceanic crust. This is consistent with rare earth chemistry of the Tortuga basaltic dikes and lavas, which are similar to mid-ocean ridge basalts (MORB) (Stern, 1980).

The pillow basalts and dikes that form the upper pseudostratigraphic units of the Tortuga Complex have undergone 'ocean floor'-type hydrothermal metamorphism involving interaction with seawater at elevated temperature (Stern *et al.*, 1976; Stern and Elthon, 1979). This has resulted in extensive development of secondary zeolite, prehnite-pumpellyite, and greenschist facies minerals and the redistribution of mobile minor and trace elements, although

relict igneous textures are often preserved. Gabbros were altered much less extensively, although at higher temperature, to greenschist and amphibolite facies minerals. Fresh relict pyroxenes, plagioclase, and olivine are present in many gabbros, and at the deepest levels of exposure, where the original igneous mineral grain size is the largest, optically observable alteration effects are restricted to grain boundaries. The difference in the extent of metamorphic replacement within the gabbros compared to the pillow lavas has been interpreted to reflect a decrease in the volume of seawater penetrating into the deeper levels of the ophiolite complex. Elthon *et al.* (1982) estimated that the alteration of the Sarmiento Complex, another Rocas Verdes ophiolites involved seawater/rock ratios that decreased from 15-90 within the pillow lavas to less than 1 within the gabbros.

In this study, measurements were made of the Sr and Nd isotopic composition of augite-clinopyroxene and Ca-plagioclase (An_{79}) separated from a gabbro collected at the deepest exposed pseudostratigraphic level of the Tortuga Complex on Isla Milne Edwards (sample H57; Stern, 1979), and for a dike cross-cutting pillow lavas from above the sheeted dike level of the complex on the west flank of Cerro Tortuga at the southwest extreme of Isla Navarino (sample NB93-1; Stern, 1980). The coarse clinopyroxene and plagioclase grains in the gabbro are optically fresh, although alteration effects occur along their grain boundaries and fractures within these grains. In contrast, the dike is extensively altered to a greenschist facies mineral assemblage (Stern and Elthon, 1979) and the only primary igneous mineral-

⁽¹⁾1988. Evaluación geológica y petrolera del sector sur de la Provincia Última Esperanza. Empresa Nacional del Petróleo, Magallanes (Unpublished internal report No. 1.0100.0252), 82 p.

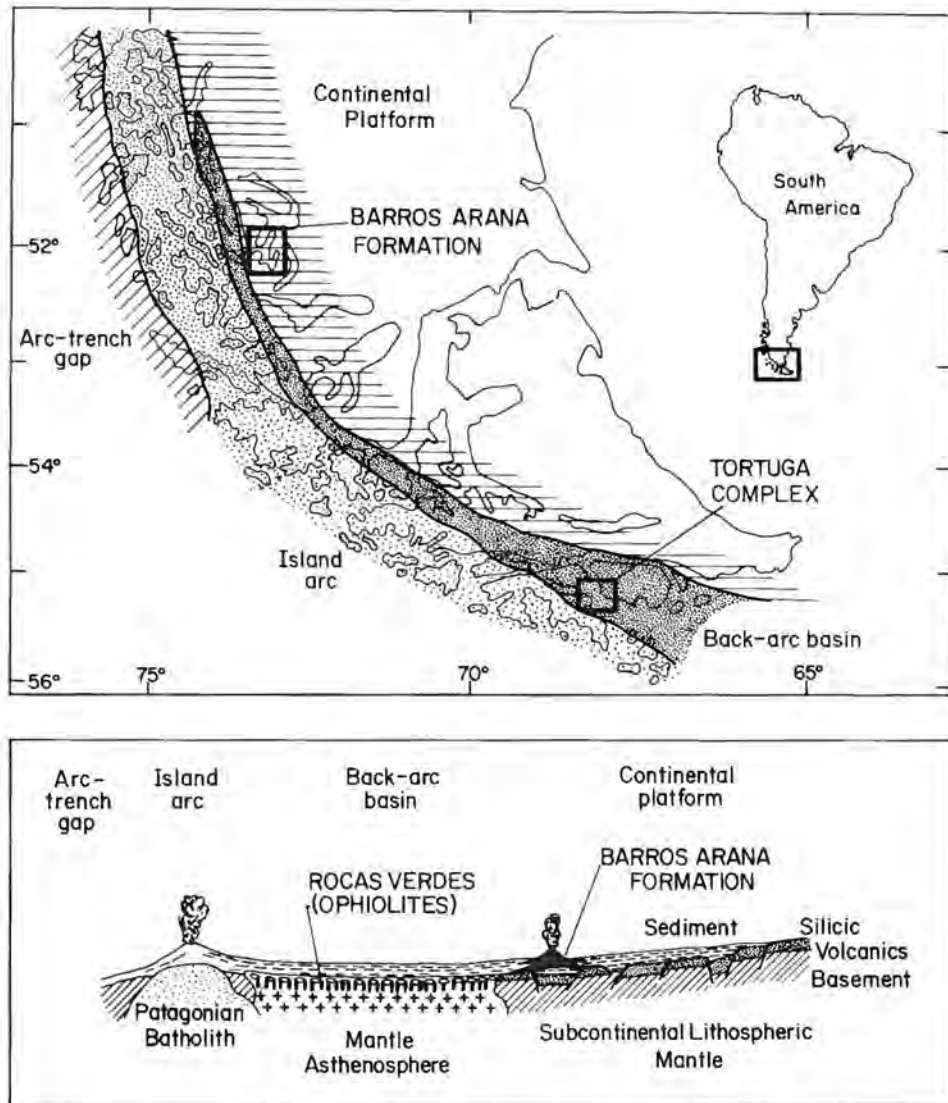


FIG. 1. Map and cross-section showing the location of Barros Arana Formation and Tortuga Complex within the context of the major litho-tectonic units of the southernmost Andes during the late Mesozoic (Dalziel *et al.*, 1974; De Wit and Stern, 1981; Stern *et al.*, in press).

ogy preserved is in some relict cores of clinopyroxene phenocrysts.

BARROS ARANA FORMATION

The Barros Arana Formation consists of mafic dikes, lavas, and volcanoclastic breccias and sediments which outcrop on Peninsula Barros Arana, southwest of Puerto Natales in Ultima Esperanza, Magallanes (Fig. 1; Soffia¹¹). These igneous rocks

were emplaced within the sedimentary infill of the eastward extension of the Rocas Verdes marginal basin onto the continental platform (Stern *et al.*, in press). They interfinger with the uppermost portions of Early Cretaceous sedimentary rocks of the Erezcano Formation. Stern *et al.* (in press) concluded that the Barros Arana basalts are absarokites, the mafic member of the mildly alkaline shoshonite rock suite of subduction-related arcs, which were generated in the Southern Andes when subduction

geometry began to undergo the changes (flattening) that led to the initiation of the closure, uplift and deformation of the Rocas Verdes marginal basin in the late Albian.

As with the Rocas Verdes pillow lavas, the Barros Arana basalts are spilitized and metasomatized. However, megacrysts of amphiboles, and plutonic xenoliths up to 30 cm in diameter consisting of amphibole + clinopyroxene + apatite, which occur within the Barros Arana basalts, are essentially fresh and unaltered, except, as in the case of the Rocas Verdes gabbros, along mineral grain boundaries. The pargasitic amphibole and augitic clinopyroxene in these megacrysts and xenoliths are compositionally similar to the relict igneous phenocrysts observed in the Barros Arana lavas (Stern *et al.*, in press). This suggests that these mafic plutonic phases are

co-genetic with the Barros Arana basalts. Presumably they formed by crystallization in the same magma chambers and conduits through which their host basalts rose to the surface. This conclusion is consistent with the K-Ar age of 104 ± 3 Ma obtained on one of these amphibole megacrysts, which agrees with the Albian stratigraphic age of the Barros Arana basalts (Fuenzalida and Covacevich, 1988; Stern *et al.*, in press).

For this study, measurements of the Sr and Nd isotopic composition were made on an amphibole megacryst (sample 11B-X; Stern *et al.*, in press), a clinopyroxene-rich portion of an 80% clinopyroxene + 20% amphibole xenolith (sample 11B-W; Stern *et al.*, in press), and an apatite separate from the same xenolith.

SAMPLE PREPARATION, ANALYTICAL TECHNIQUES AND RESULTS

In order to remove optically observable alteration effects from the grain boundaries and fractures of the minerals analyzed, hand picked mineral separates were first crushed and sieved to obtain a 60-120 mesh-size fraction. These were then ultrasonically cleaned in dilute HCl for 15-30 minutes. The silicate phases were further washed in HF for 15 minutes, after which they were again ultrasonically cleaned, this time in distilled water, for another 15-30 minutes. Optical examination indicated that these steps, which dissolved approximately 20 weight percent of the original sample, removed all grain boundary alteration phases.

Samples were crushed to a fine powder and dissolved in HF and HClO₄. Rb, Sr, and bulk rare earth elements were separated according to established cation exchange techniques. The bulk rare earth fraction was subsequently injected into a 30 cm by 2 mm quartz glass column filled with Bio-Rad Aminex cation exchange resin, and Sm and Nd separates were eluted with 0.32 N methylactic acid. Both the Sm and Nd separates were then cleaned by electrodeposition onto high purity Pt cathodes from a weak HCl solution. Sample Rb, Sr, Nb, and Sm concentrations were determined by isotope dilution, with analytical precision and accuracy, as determined by repeated analyses of standards, estimated at 0.5% or better. The Sr and Nd isotopic analyses were performed on a Finnigan-MAT 6-collector solid

source mass spectrometer. The Sr isotopic analyses were 4 collector static mode measurements. Replicate analyses of the SRM-987 standard yielded a mean $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.71025 ± 2 (2σ). The Nd isotopic compositions were performed in a triple collector dynamic mode and normalized for mass fractionation effects on the basis of a value of $^{146}\text{Nd}/^{144}\text{Nd}$ equal to 0.7219. Repeated measurements of the La Jolla Nd standard in this mode yielded a mean $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.511840 ± 3 (2σ). ϵNd_i were calculated using a present day reference value of 0.512638.

Results are presented in Table 1. The Nd and Sm concentrations of Tortuga dike NB93-1 are within 7% and 2%, respectively, of previously determined values (Stern, 1980). The small differences in the initial Nd-isotopic composition, with ϵNd_i within analytical error, of the Barros Arana apatite compared to the associated silicate phases suggests that the HF washing of the latter did not produce any undesirable preferentially leaching effects. The small differences in the initial Sr isotopic composition of these phases, and the larger differences among the initial Sr isotopic composition measured for the Tortuga Complex, are attributed to post-crystallization seawater alteration effects, while differences in the initial Nd-isotopic composition between the Tortuga and Barros Arana basalts are attributed to differences in the isotopic composition of their mantle sources, as discussed below.

TABLE 1. Rb, Sr, Nd, AND Sm CONTENTS IN ppm, AND $^{87}\text{Sr}/^{86}\text{Sr}$ AND $^{143}\text{Nd}/^{144}\text{Nd}$ RATIOS FOR SAMPLES FROM THE TORTUGA COMPLEX AND BARROS ARANA FORMATION OF SOUTHERNMOST SOUTH AMERICA

	Rb	Sr	$^{87}\text{Rb}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_M$	$(^{87}\text{Sr}/^{86}\text{Sr})_i$	
Barros Arana Formation (104 Ma)						
Amp 11B-X	11.8	730	0.047	0.70320	0.70313	
Amp + Cpx 11B-W	2.3	204	0.032	0.70334	0.70329	
Apatite 11B-W	0.9	2305	0.001	0.70302	0.70302	
Tortuga Complex (150 Ma)						
Gabbro Plag	0.5	108	0.135	0.70326	0.70323	
Gabbro Cpx	0.1	7.6	0.045	0.70405	0.70395	
Dike NB93-1	42.5	145	0.848	0.70610	0.70429	
	Sm	Nd	$^{147}\text{Sm}/^{144}\text{Nd}$	$(^{143}\text{Nd}/^{144}\text{Nd})_M$	$(^{143}\text{Nd}/^{144}\text{Nd})_i$	ϵNd_i
Barros Arana Formation (104 Ma)						
Amp 11B-X	7.68	27.3	0.170	0.512889	0.512773	+5.2
Amp + Cpx 11B-W	3.54	13.3	0.162	0.512871	0.512761	+5.0
Apatite 11B-W	77.1	371.2	0.125	0.512850	0.512765	+5.1
Tortuga Complex (150 Ma)						
Gabbro Plag	0.32	0.71	0.276	0.513090	0.512819	+7.3
Gabbro Cpx	1.12	2.02	0.334	0.513160	0.512832	+7.6
Dike NB93-1	2.64	7.94	0.201	0.512992	0.512794	+6.8

M. Measures ratio; i. Initial ratio.

DISCUSSION

SEAWATER ALTERATION

The plagioclase and clinopyroxene from the Tortuga gabbro, as well as the dike, have nearly identical ϵNd_i , but, distinctly different initial $^{87}\text{Sr}/^{86}\text{Sr}$ (Table 1, Fig. 2). This may be explained by differences in the extent to which interaction with seawater, during the hydrothermal metamorphism of the Tortuga Complex, affected the Sr-isotopic composition of each of these phases. Because seawater has significant Sr content, approximately 8 ppm, but essentially negligible Nd content, interaction with seawater modifies the Sr-isotopic composition of a rock or mineral, but not its Nd-isotopic composition (Spooner, 1976; O'Nions *et al.*, 1977; Hawkesworth *et al.*, 1977). The clinopyroxene from the Tortuga gabbro, with only 7.6 ppm Sr, would be relatively sensitive to interaction and exchange with even a small volume of seawater, while the plagioclase in the gabbro, and the dike, both with more than 100 ppm Sr, would be less sensitive to such interaction.

For the clinopyroxene and plagioclase from the

Tortuga complex gabbro, both their original initial magmatic $^{87}\text{Sr}/^{86}\text{Sr}$ and the minimum amount of seawater with which they interacted may be calculated, as illustrated by Spooner (1976), assuming that: 1. These minerals were originally in isotopic equilibrium; 2. The same amount of seawater interacted with each phase; 3. Exchange of seawater was 100% efficient so that for a seawater/rock ratio of $X/1$, $8X$ ppm of Sr would be exchanged; and 4. The Sr-isotopic composition of seawater in the Late Jurassic was 0.707 (Burke *et al.*, 1982). For the minerals from the Tortuga gabbro, these conditions are satisfied by an original initial magmatic $^{87}\text{Sr}/^{86}\text{Sr}$ equal to 0.7031 and seawater/rock ratio of 1/4, which is less than the ratio of 1/2 suggested by Elthon *et al.* (1982) as an upper limit within the gabbros of the ophiolitic Sarmiento Complex. A larger volume of seawater may have passed through the gabbro if: 1. Exchange was less than 100% efficient; 2. It did so along grain boundaries and fractures, where secondary phases formed, but did not react with the optically fresh cores of the minerals of the gabbro; and/or 3. The Sr content

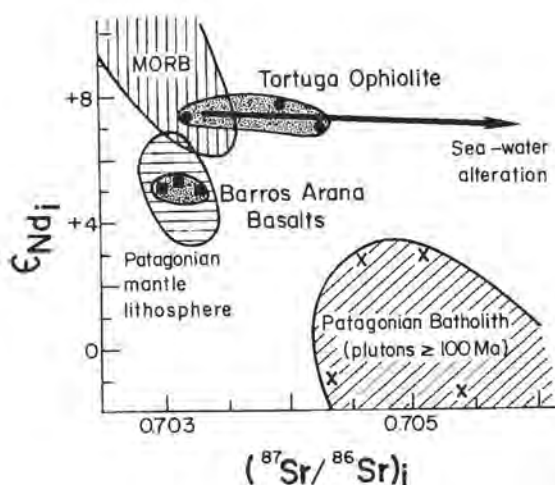


FIG. 2. ϵNd_i versus $(^{87}\text{Sr}/^{86}\text{Sr})_i$ of the samples from the Barros Arana Formation and Tortuga Complex compared to MORB basalts (DePaolo, 1988), the sub-continental lithospheric mantle below southernmost South America as defined by the Pali-Aike basalts and associated ultramafic xenoliths (Stern *et al.*, 1989 and 1990), and >100 Ma plutons of the Patagonian Batholith (Weaver *et al.*, 1990). The heavy arrow indicates the trend towards increasing $^{87}\text{Sr}/^{86}\text{Sr}$ at near constant ϵNd produced by seawater alteration (Spooner, 1976; O'Nions *et al.*, 1977; Hawkesworth *et al.*, 1977).

and isotopic composition of this water had already been extensively modified by interaction with the overlying lithologies prior to penetrating to the pseudostratigraphic level of the gabbros.

In contrast, to explain the initial $^{87}\text{Sr}/^{86}\text{Sr}$, equal to 0.70429, of the Tortuga dike, assuming that it was also originally in isotopic equilibrium with the gabbro as suggested by its ϵNd_i , and thus had an original initial magmatic $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7031, requires that almost 30% of its Sr be replaced by Sr derived from seawater. This implies an exchange of 40 ppm of Sr, or a seawater/rock ratio of 5/1. This ratio falls between the maximum values of 3 and 15-90 estimated by Elthon *et al.* (1982) for seawater/rock ratios within the sheeted dike complex and extrusive pillow lavas, respectively, of the Sarmiento ophiolite, and is consistent with the pseudostratigraphic position of this dike between these two levels.

Similar calculations can be made for the minerals analyzed from the Barros Arana Formation, which also have nearly identical ϵNd_i , but for which small differences in initial $^{87}\text{Sr}/^{86}\text{Sr}$ exist (Table 1, Fig. 2). Taking the $^{87}\text{Sr}/^{86}\text{Sr}$ of Early Cretaceous seawater to

be 0.7072 (Burke *et al.*, 1982), an original magmatic initial $^{87}\text{Sr}/^{86}\text{Sr}$ equal to 0.7030, essentially the same as determined for the apatite, and a seawater/mineral ratio of 2/1 could explain the Sr-isotopic differences among these mineral phases. Some of the Barros Arana lavas are extensively spilitized, suggesting higher seawater/rock ratios, possibly in the range estimated for the extrusive units of the Rocas Verdes ophiolites complexes. However, although greater amounts of seawater may have interacted with the vesiculated fine-grained lavas that host the coarse-grained megacrysts and mafic plutonic xenoliths, interaction and exchange of this water with the cores of the coarse-grained minerals in these mafic plutonic phases was apparently more limited, as suggested also by the restriction of optically observable alteration effects to their grain boundaries.

INITIAL MAGMATIC ISOTOPIC COMPOSITION : TORTUGA COMPLEX

Taking into account the effects of seawater alteration, the original magmatic isotopic composition of the three samples from the Tortuga Complex is estimated to have been $(^{87}\text{Sr}/^{86}\text{Sr})_i$ equal to 0.7031 and ϵNd_i equal to +6.8 to +7.6. These values fall within the range of modern MORB (Fig. 2). According to studies of other ophiolite sections, the ϵNd_i of MORB has not changed significantly since the Jurassic (DePaolo, 1988). As it has previously been demonstrated that Tortuga Complex basalts have MORB-type petrochemistry, in particular light rare earth element depletion (Stern, 1980), it can be concluded that the parental magmas of the mafic igneous rocks of the Tortuga Complex were derived from a MORB-type source mantle, presumably upwelling asthenosphere (Fig. 1). This supports the conclusion that at the latitude of the Tortuga Complex, the mafic floor of the Rocas Verdes marginal basin was oceanic in character (De Wit and Stern, 1981).

It has been suggested that MORB source asthenosphere forms a global reservoir which potentially may be tapped in both oceanic and continental regions (Perry *et al.*, 1987). However, few MORB-type basalts have been documented to have erupted through continental lithosphere (Kay and Hubbard, 1978). The combined isotopic and trace-element data for the Tortuga Complex basalts confirm the presence of MORB-type source mantle below the Late Jurassic continental crust of southernmost South America.

INITIAL MAGMATIC ISOTOPIC COMPOSITION: BARROS ARANA FORMATION

The original isotopic composition of the amphibole megacryst and mineral phases of the mafic plutonic xenolith found within the Early Cretaceous Barros Arana basalts is estimated to be $(^{87}\text{Sr}/^{86}\text{Sr})_i$ equal to 0.7030 and ϵNd_i equal to +5.0 to +5.2. Since the phases are interpreted as co-genetic with the host Barros Arana basalts, their isotopic composition is taken to be the isotopic composition of these basalts as well.

The ϵNd_i values of the Barros Arana basalts are lower than those of either MORB or the Tortuga Complex mafic igneous rocks. Instead they fall within the field for the subcontinental lithospheric mantle as defined by alkali basalts and ultramafic xenoliths from the Quaternary Pali-Aike volcanic field of southernmost Chile (Fig. 2; Stern *et al.*, 1989, 1990). The presence of a subcontinental lithospheric mantle component in the Barros Arana basalts is consistent with their eruption on the continental platform along the eastern edge of the Rocas Verdes Basin (Fig. 1; Stern *et al.*, in press). The composition of many other continental alkali basalts, including those erupted above active subduction zones such as the Barros Arana basalts, have also been shown to reflect an important contribution from the subcontinental lithospheric mantle (Perry *et al.*, 1987; Muñoz and Stern, 1989; Rogers and Hawkesworth, 1989; Stern *et al.*, 1990).

IMPLICATONS FOR ANDEAN MAGMATISM

The mafic igneous rocks of the late Jurassic Tortuga Ophiolite Complex and the Early Cretaceous Barros Arana Formation presumably did not incorporate significant proportions of continental crust because of their emplacement within the generally extensional tectonic environment of the Rocas Verdes marginal basin. Thus their initial magmatic isotopic compositions may be considered representative of the Mesozoic subcontinental mantle below southernmost South America, although they might not reflect the complete isotopic variability within this mantle. The isotopic data for the Tortuga Complex and Barros Arana basalts, combined with published data from the Quaternary Patagonian plateau lavas and associated ultramafic mantle-derived xenoliths (Figs. 2, 3), indicate that since the Jurassic, asthenospheric and lithospheric mantle magma source regions with

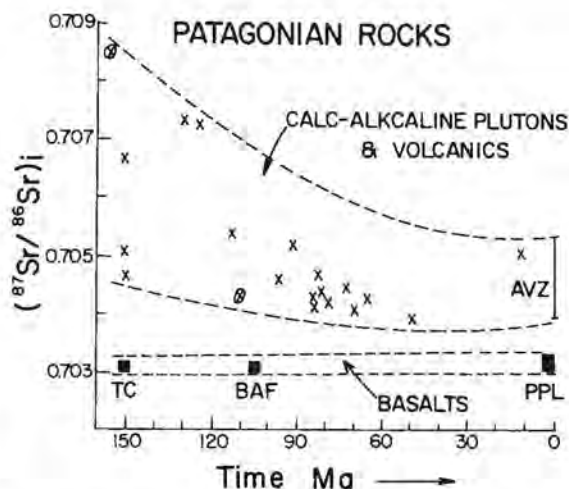


Fig. 3. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ versus age in Ma for igneous rocks of Patagonia, including mantle-derived mafic igneous rocks of the Tortuga Ophiolite Complex (TC), Barros Arana Formation (BAF) and Patagonian plateau lavas (PPL) (Stern *et al.*, 1990), calc-alkaline I- and S-type (circled) plutons of the Patagonian Batholith (Halpern, 1973; Hervé *et al.*, 1981; Weaver *et al.*, 1990), and orogenic volcanics of the active Austral Volcanic Zone (AVZ; Futa and Stern, 1988).

isotopic composition reflecting time-integrated depletion of large-ion-lithophile-elements have existed below southernmost South America.

By comparison, plutons of the Patagonian Batholith have lower ϵNd and higher $(^{87}\text{Sr}/^{86}\text{Sr})_i$ than either the Tortuga ophiolite or Barros Arana basalts (Figs. 2, 3). This may reflect mantle isotopic heterogeneity, but it has been suggested independently that the plutons of the batholith have incorporated continental crust during their petrogenesis (Halpern, 1973; Hervé *et al.*, 1981; Weaver *et al.*, 1990). This suggestion is consistent with the more radiogenic isotopic compositions of the Patagonian Batholith compared to the mafic rocks from the Tortuga Complex, Barros Arana Formation, and Patagonian plateau basalts.

Weaver *et al.* (1990) suggested that decreasing $(^{87}\text{Sr}/^{86}\text{Sr})_i$ with time (Fig. 3) indicates that the amount of crust incorporated during the petrogenesis of plutons of the Patagonian Batholith decreased progressively. When the initial Sr-isotopic composition of the 12 Ma Torres del Paine Pluton (Halpern, 1973) and recent orogenic arc volcanoes from the Austral volcanic Zone (Futa and Stern, 1988) are added to their data base (Fig. 3), it is clear that the trend to lower $(^{87}\text{Sr}/^{86}\text{Sr})_i$ with time is not completely regular, al-

though the plutons with the highest initial Sr-isotopic ratios are of Late Jurassic and Early Cretaceous age. However, even the most primitive gabbro pluton identified by Weaver *et al.* (1990; sample G58, 46 Ma, $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7037$, $\epsilon\text{Nd}_i = +6.4$) has higher initial Sr-isotopic ratio than the mantle-derived mafic magmas of the Tortuga Complex, Barros Arana basalts, and

Pali-Aike basalt field (Fig. 3). This suggests that crustal components were involved in the petrogenesis of even this most primitive mafic pluton of the Patagonian Batholith, either by assimilation within the crust itself, or tectonically added to its mantle-source region by subduction-related processes.

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REFERENCES

- Burke, W.H.; Denison, R.E.; Hetherington, E.A.; Koepnick, R.B.; Nelson, H.F.; Otto, J.B. 1982. Variations of seawater $^{87}\text{Sr}/^{86}\text{Sr}$ throughout Phanerozoic time. *Geology*, Vol. 10, p. 516-519.
- Dalziel, I.W.D.; De Wit, M.J.; Maarten, J.; Palmer, K.F. 1974. Fossil marginal basin in the southern Andes. *Nature*, Vol. 250, No. 5464, p. 291-294.
- DePaolo, D.J. 1988. Neodymium isotope geochemistry. *Minerals and Rocks*. Springer Verlag, Vol. 20, 187 p.
- De Wit, M.J. 1977. The evolution of the Scotia Arc as a key to the reconstruction of Gondwanaland. *Tectonophysics*, Vol. 37, p. 53-81.
- De Wit, M.J.; Stern, C.R. 1981. Variations in the degree of crustal extension during formation of a back-arc basin. *Tectonophysics*, Vol. 72, p. 229-260.
- Elthon, D.; Ridley, W.I. 1980. The petrology of the Tortuga ophiolite complex. In *Ophiolites, International Ophiolite Symposium, Proceedings*, p. 507-514. Cyprus 1979.
- Elthon, D.; Lawrence, J.R.; Hanson, R.E.; Stern, C.R. 1982. Modelling of oxygen-isotope data from the Sarmiento ophiolite complex, Chile. In *Ophiolites and Oceanic Lithosphere* (Gass, I.G.; Lippard, S.J.; Shelton, A.W.; editors). Blackwell Scientific Publishing Co., p. 185-197. London.
- Fuenzalida, R.; Covacevich, V. 1988. Volcanismo y bioestratigrafía del Jurásico Superior y Cretácico Inferior en la Cordillera Patagónica, Región de Magallanes, Chile. In *Congreso Geológico Chileno, No. 5, Actas*, Vol. 3, p. H159-H183. Santiago.
- Futa, K.; Stern, C.R. 1988. Sr and Nd isotopic and trace element compositions of Quaternary volcanic centers of the Southern Andes. *Earth and Planetary Science Letters*, Vol. 88, p. 253-262.
- Halpern, M. 1973. Regional geochronology of Chile south of 50° latitude. *Geological Society of America Bulletin*, Vol. 84, p. 2407-2422.
- Hawkesworth, C.J.; O'Nions, R.K.; Pankhurst, R.J.; Hamilton, P.J.; Evensen, N.M. 1977. A geochemical study of island-arc and back-arc tholeiites from the Scotia Sea. *Earth and Planetary Science Letters*, Vol. 36, p. 253-262.
- Hervé, F.; Nelson, E.; Kawashita, K.; Suárez, M. 1981. New isotopic ages and timing of orogenic events in the Cordillera Darwin, southernmost Chilean Andes. *Earth and Planetary Science Letters*, Vol. 55, p. 523-548.
- Kay, R.W.; Hubbard, N.J. 1978. Trace elements in ocean ridge basalts. *Earth and Planetary Science Letters*, Vol. 38, p. 95-116.
- Muñoz, J.; Stern, C.R. 1989. Alkaline magmatism within the segment 38-39°S of the Plio-Quaternary volcanic belt on the southern South American continental margin. *Journal of Geophysical Research*, Vol. 94, p. 4545-4560.
- O'Nions, R.K.; Hamilton, P.J.; Evensen, N.M. 1977. Variations in $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in oceanic basalts. *Earth and Planetary Science Letters*, Vol. 34, p. 13-22.
- Perry, F.V.; Baldrige, W.S.; De Paolo, D.J. 1987. Role of asthenosphere and lithosphere in the genesis of late Cenozoic basaltic rocks from the Río Grande Rift and adjacent regions of the southwestern United States. *Journal of Geophysical Research*, Vol. 92, p. 9193-9213.
- Rogers, G.; Hawkesworth, C.J. 1989. A geochemical trav-

- erse across the northern Chilean Andes: evidence for crust generation from the mantle wedge. *Earth and Planetary Science Letters*, Vol. 91, p. 271-285.
- Spooner, E.T.C. 1976. The strontium isotopic composition of seawater, and seawater-oceanic crust interaction. *Earth and Planetary Science Letters*, Vol. 31, p. 165-174.
- Stern, C.R. 1979. Open and closed system igneous fractionation within two Chilean ophiolites and the tectonic implications. *Contributions to Mineralogy and Petrology*, Vol. 68, p. 243-258.
- Stern, C.R. 1980. Geochemistry of Chilean ophiolites: evidence for the compositional evolution of the source of back-arc basin basalts. *Journal of Geophysical Research*, Vol. 85, p. 955-966.
- Stern, C.R.; Elthon, D. 1979. Vertical variations in the effects of hydrothermal metamorphism in Chilean ophiolites: their implications for ocean floor metamorphism. *Tectonophysics*, Vol. 55, p. 179-213.
- Stern, C.R.; De Wit, M.J.; Lawrence, J.R. 1976. Igneous and metamorphic processes associated with the formation of Chilean ophiolites and their implications for ocean floor metamorphism, seismic layering, and magnetism. *Journal of Geophysical Research*, Vol. 81, p. 4370-4380.
- Stern, C.R.; Saul, S.; Skewes, M.A.; Futa, K. 1989. Garnet peridotite xenoliths from the Pali-Aike basalts of southernmost South America. In *Kimberlites and related rocks. Geological Society of Australia, Special Publication, No. 14, Blackwell*, Vol. 2, p. 735-744. Carlton, Australia.
- Stern, C.R.; Frey, F.A.; Futa, K.; Zartman, R.E.; Peng, Z.; Kyser, T.K. 1990. Trace-element and Sr, Nd, Pb, and O isotopic composition of Pliocene and Quaternary alkali basalts of the Patagonian plateau lavas of southernmost South America. *Contributions to Mineralogy and Petrology*, Vol. 104, p. 294-308.
- Stern, C.R.; Mukasa, S.B.; Fuenzalida, R. 1991. Age of the Sarmiento ophiolite complex and the Rocas Verdes marginal basin, Magallanes, Chile. In *Congreso Geológico Chileno, No. 6, Actas*. Viña del Mar.
- Stern, C.R.; Mohseni, P.; Fuenzalida, R. (in press). Petrochemistry and tectonic significance of Early Cretaceous Barros Arana Formation basalts, southernmost Chilean Andes. *Journal of South American Earth Sciences*.
- Weaver, S.G.; Bruce, R.; Nelson, E.P.; Brueckner, H.K.; LeHuray, A.P. 1990. The Patagonian Batholith at 48°S latitude, Chile; geochemical and isotopic variations. In *Plutonism from Antarctica to Alaska. Geological Society of America, Special Paper*, No. 241, p. 33-50