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STRONTIUM ISOTOPIC GEOCHEMISTRY OF INTRUSIVE ROCKS, PUERTO RICO, GREATER ANTILLES

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The strontium isotopic geochemistry is given for three Puerto Rican intrusive rocks: the granodioritic Morovis and San Lorenzo plutons and the Rio Blanco stock of quartz dioritic composition. The average calculated initial $^{87}Sr/^{86}Sr$ ratios are 0.70370, 0.70355 and 0.70408, respectively. In addition, the San Lorenzo data establish a whole-rock isochron of 71 ± 2 m.y., which agrees with the previously reported K-Ar age of 73 m.y. Similarity of most of the intrusive rocks in the Greater Antilles with respect to their strontium isotopic geochemistry regardless of their major element composition indicates that intrusive magmas with a wide range of composition can be derived from a single source material. The most likely source material, in view of the available isotopic data, is the mantle wedge overlying the subduction zone.

1. Introduction

Considerable attention has been given to spatial and temporal variations in the composition of igneous rock in oceanic island arc areas and the insights into magma origin that can be gained from these variations [1,2]. Most such attention has focused on the relatively abundant volcanic rocks in these arcs, although in almost all oceanic arcs, the most acidic rock units are the intrusive bodies [3].

Puerto Rico, along with the Virgin Islands, form the eastern end of the Greater Antilles, an inactive oceanic island arc. The geologic development of Puerto Rico began with pre-Albian deep-water submarine volcanism, followed in turn by more explosive, shallower-water submarine and terrestrial volcanism [4,5]. This volcanic sequence has been divided by Donnelly et al. [4] into an earlier "chemically primitive" group of middle Cretaceous age and a later "chemically more evolved" group that formed from middle Cretaceous to Eocene time. The large intrusive units are associated with the later group. By late Oligocene time volcanism and intrusive activity ceased and the area was partly covered by volcaniclastic and then carbonate sediments.

In a study of the compositional evolution of intrusive rocks in the eastern Greater Antilles, Kesler and Sutter [6] showed that there had been a decrease in K_2O in the intrusive magmas during approximately the last half of arc evolution from 88 to 38 m.y. ago. The average rate of change of K_2O content with time was approximately –0.06% per million years. In this study, we have obtained high-precision strontium isotopic analyses for three intrusive rocks that represent almost this entire span of time in order to determine whether similar isotopic changes can be observed in this genetically important parameter.

Two of the intrusive rock units tested in this study

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are compositionally anomalous with respect to the most common volcanic and intrusive rocks in an island arc. Whereas the volcanic rocks in the eastern Greater Antilles are largely andesitic [7] and the intrusive rocks are largely quartz dioritic, the Morovis and San Lorenzo units included here are granodioritic. Thus, our data also provide information on whether these more potassic magmas were derived from essentially the same source as the more abundant, less potassic magmas.

2. Geological setting and characteristics of the intrusive rocks

Puerto Rico is at the eastern end of the Greater Antilles island arc, which was active volcanically from late Jurassic or early Cretaceous until Eocene time. This end of the Greater Antilles arc, including the Virgin Islands, Puerto Rico and Hispaniola (Fig. 1), appears to have been built on metamorphosed oceanic crust that yields K-Ar ages of about 125 m.y. [8,9]. Early volcanism in the eastern Greater Antilles was largely deep submarine [4,5] whereas later volcanism took place in a shallow water or terrestrial environment [5]. Intrusive rocks of significant size developed during the later phases of volcanic activity in late Cretaceous and early Cenozoic time and it is these rocks that are included in this study.

Kesler and Sutter [6] have reviewed the distribution, age and major element chemical compositions of intrusive rocks in Puerto Rico and the adjacent Virgin Islands. Of these intrusions, the oldest is the Morovis stock ("MV", Fig. 1), which has a K-Ar age of 88 m.y. [8]. This stock has a relatively small outcrop area of about 25 km^2. It is very homogeneous texturally, exhibits no major element compositional variation, and is a medium-grained, hornblende-biotite monzonite to quartz monzonite. It appears to be coeval with K-rich basaltic rocks of the Rio Orocovis Formation and related volcanic units in central Puerto Rico [10].

The San Lorenzo batholith ("SL", Fig. 1) is the largest intrusive unit in the eastern Greater Antilles, with an outcrop area of about 500 km^2. It has been divided into three facies, the oldest of which is thought to be a small diorite-gabbro unit with a K-Ar age of 78 m.y. As noted by Kesler and Sutter [6], parts of this unit appear to be older than 78 m.y. and little information is available at present on the exact distribution and ages of various mafic rock units in and near the San Lorenzo batholith. For this reason, we have not included these mafic rocks in this study. The bulk of the batholith consists of an extensive granodiorite-quartz diorite unit with a K-Ar age of 73 m.y., and a smaller quartz diorite unit with a K-Ar

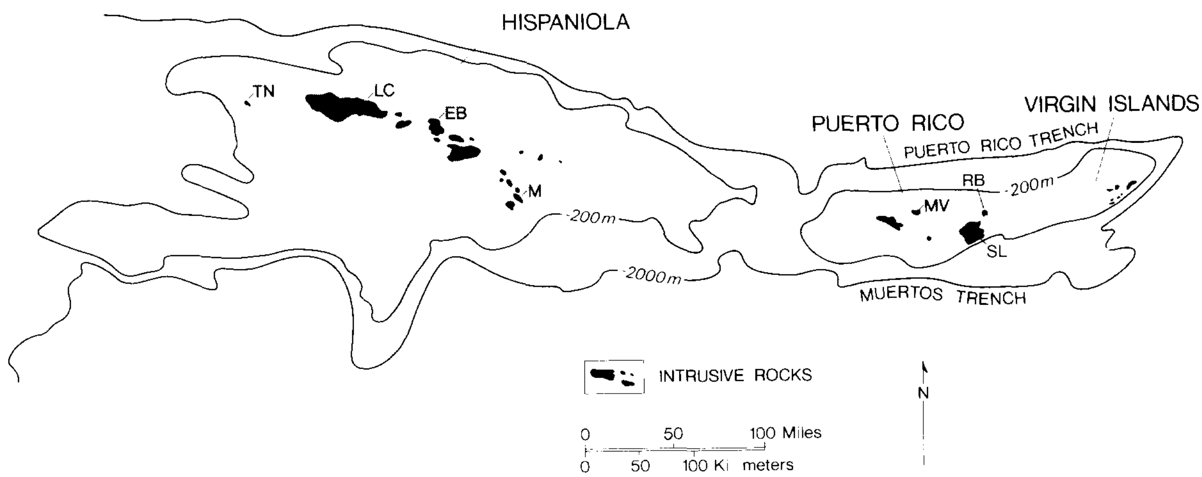

Fig. 1. Schematic geologic and bathymetric map of the eastern Greater Antilles showing the 200- and 2000-m isobaths and the location of intrusive rocks discussed in the text. Puerto Rico: MV = Morovis stock; RB = Rio Blanco stock; Sl = San Lorenzo batholith. Hispaniola: EB = El Bao batholith; LC = Loma de Cabrera batholith; M = Medina stock; TN = Terre Neuve stock.

age of 66 m.y. [8]. Although we can observe textural and major element differences between these two units [6], their Rb/Sr characteristics are similar, as is noted in later section. Thus, we have considered the granodiorite-quartz monzonite facies as a single unit here.

The Rio Blanco stock ("RB", Fig. 1) is also a small intrusion, with an outcrop area of about 25 km^2. It is largely a hornblende-biotite quartz diorite in composition and has a relatively homogeneous, medium-to coarse-grained texture [11]. The Rio Blanco stock is associated with small, contact-localized copper deposits, although the stock itself is relatively unaltered.

The exact tectonic configuration of the eastern Greater Antilles during the development of these intrusive rocks is not known. Subduction could have taken place from either the Puerto Rico trench on the north or from the Muertos trench on the south (Fig. 1) or both [12,13].

In comparison of the Puerto Rican intrusive rocks to those previously described elsewhere in the Greater Antilles, the Morovis stock has no counterpart; the San Lorenzo batholith is slightly more granodioritic than the El Bao batholith in Hispaniola [9]. The Rio Blanco stock, though much smaller, is similar in composition to the Medina and El Bao quartz diorites in Hispaniola ("M" and "EB", Fig. 1). Comparison of the data of Kesler et al. [9] and Kesler and Sutter [6] demonstrate that, in general, the intrusive rocks of Puerto Rico are more granodioritic than those to the west in Hispaniola.

3. Experimental procedures

Collection procedures used to obtain samples and analytical methods used in the major element chemical analyses reported previously are outlined by Kesler and Sutter [6]. The strontium isotopic geochemistry was determined on rock powders originally prepared for the major element chemical work. These powders were dissolved in an HF-HNO_3-$HClO_4$ mixture and the strontium separated by cation exchange using a standard procedure. The purified strontium was placed on a rhenium ribbon and the isotopic composition measured using a Varian MAT 260 thermal ionization mass spectrometer. A double filament arrangement was used for the evaporation-ionization of the sample. A routine analysis consisted of five sets of ten runs, each run consisting of 100 measurements. The standard deviation of the $^{87}Sr/^{86}Sr$ ratio is generally $<\pm 0.00003$ (2σ). The rubidium and strontium concentrations were determined by X-ray fluorescence using an ORTEC TEFA system. Replicate analyses indicate a precision of the Rb/Sr ratio of ~1%.

4. Strontium isotopic data for the Puerto Rican intrusive rocks

Strontium isotopic and related chemical data on the Morovis, San Lorenzo and Rio Blanco intrusive rocks are given in Table 1. Note that the Morovis stock exhibits an isotopic homogeneity similar to its textural and major element chemical homogeneity. This lack of chemical variation precluded the delineation of a whole-rock isochron for the Morovis data (Fig. 2). Initial $^{87}Sr/^{86}Sr$ ratio calculated for the Morovis stock data using an age of 88 m.y. are very similar, ranging from 0.70361 to 0.70380 and averaging 0.70370 ± 0.00006 (6 samples, Table 1). In comparison to other intrusive rocks with relatively high K_2O abundances, the strontium content of the Morovis stock appears to be somewhat high. However, K/Rb ratios average 365 and are well within the expected range for rocks of this type.

The data for the San Lorenzo batholith exhibit a relatively large compositional variation and yield a whole-rock Rb-Sr isochron (Fig. 2) with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70355 ± 0.00002. The age of this isochron is 71 ± 2 m.y., which is very close to the K-Ar age of 73 m.y. obtained for the dominant granodiorite-quartz diorite facies of the batholith [6]. Samples PR-71-67A and -67B, which are part of this isochron, were collected from an area mapped as 66-m.y.-old quartz monzonite facies. A two-point isochron of these samples gives a data of 70 ± 3 m.y. and an initial ratio of 0.70358 ± 0.00004 which is identical to the initial ratio of the first isochron. The average calculated initial ratio for the San Lorenzo batholith samples is 0.70355. In view of the similarity between the Rb/Sr geochemistry of these two units, we interpret our data to represent a composite isochron for both the granodiorite-quartz diorite facies of the batholith.

TABLE 1

Strontium isotopic and related chemical data for the Morovis, San Lorenzo, and Rio Blanco intrusive units, Puerto Rico. The symbols G and Q after the San Lorenzo sample numbers refer to the granodiorite-quartz diorite and quartz monzonite phases of the batholith, respectively

Sample No.	K_2O [a] (wt.%)	K/Rb	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr$ [b]	$^{87}Rb/^{86}Sr$	Age (m.y.)	$(^{87}Sr/^{86}Sr)_0$ [c]
Morovis Stock								
PR-72-115	3.7	330	104	756	0.70412 ± 2	0.398	88	0.70362 ± 3
PR-72-117	3.8	370	95	751	0.70413 ± 3	0.366	88	0.70367 ± 3
PR-72-119	3.7	390	88	753	0.70422 ± 3	0.338	88	0.70380 ± 3
PR-72-121	3.9	380	95	812	0.70418 ± 3	0.338	88	0.70376 ± 3
PR-72-123	3.9	360	101	737	0.70424 ± 2	0.396	88	0.70375 ± 3
PR-72-125	4.2	360	107	731	0.70414 ± 2	0.423	88	0.70361 ± 3
San Lorenzo Batholith								
PR-71-61-G	1.8	430	39	433	0.70377 ± 2	0.26	73	0.70350 ± 3
PR-71-67A-Q	3.6	480	69	446	0.70402 ± 2	0.45	66	0.70360 ± 3
PR-71-67B-Q	NA		88	98	0.70615 ± 3	2.60	66	0.70372 ± 11
PR-71-71B-G	4.5	480	86	80	0.70664 ± 2	3.11	73	0.70342 ± 11
PR-71-90-G [d]	2.0	540	34	363	0.70383 ± 5	0.27	(70)	0.70355 ± 5
PR-72-100-G	2.8	550	47	376	0.70393 ± 2	0.36	73	0.70356 ± 3
Rio Blanco Stock								
PR-71-83	1.2	330	34	229	0.70435 ± 2	0.43	45	0.70407 ± 3
PR-71-87	1.3	370	33	232	0.70438 ± 2	0.41	45	0.70411 ± 3
PR-72-109	0.8	340	22	262	0.70410 ± 3	0.24	45	0.70394 ± 3
PR-72-111	2.4	620	36	242	0.70447 ± 2	0.43	45	0.70419 ± 2

[a] K_2O values from S.E. Kesler, XRF total-rock analyses.
[b] Normalized to $^{86}Sr/^{88}Sr = 0.11940$; NBS 987 $SrCO_3$ standard, $^{87}Sr/^{86}Sr = 0.71037 \pm 0.00002$ (2σ), $N = 9$; Eimer and Amend $SrCO_3$ standard, $^{87}Sr/^{86}Sr = 0.70820 \pm 0.00002$ (2σ), $N = 2$; all uncertainties are 2σ.
[c] Initial $^{87}Sr/^{86}Sr$ ratio calculated assuming $\lambda(^{87}Rb) = 1.42 \times 10^{-11}\ yr^{-1}$.
[d] There is some uncertainty concerning the phase to which this sample belongs.

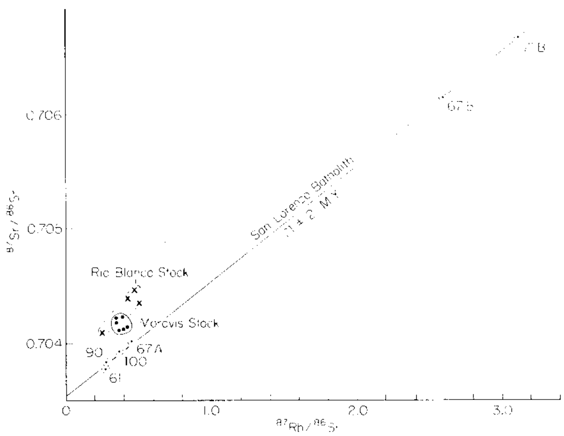

Fig. 2. $^{87}Sr/^{86}Sr$ vs. $^{87}Rb/^{86}Sr$ for the Morovis, San Lorenzo and Rio Blanco intrusive rocks. Note that the San Lorenzo data form a isochron whereas the other two units form clusters.

The four available samples from the Rio Blanco stock exhibit relatively small variation in their present-day isotopic composition of strontium (0.70384–0.70419). A suggestion of a linear trend is generated by these samples on an isochron plot, yielding a slope equivalent to approximately 300 m.y. Analysis of additional samples with a greater spread in the Rb/Sr ratio is necessary as an age of this magnitude is markedly different from the K-Ar age of 45 m.y. obtained for the stock [8] as well as being incompatible with geologic evidence [11]. The average calculated initial $^{87}Sr/^{86}Sr$ ratio for the four Rio Blanco samples is 0.70408 ± 0.00009.

The data summarized here indicate that, as a function of time, the initial $^{87}Sr/^{86}Sr$ ratios for these magmas (San Lorenzo, 0.70355 ± 0.00002; Morovis, 0.70370 ± 0.00006) remained nearly the same or, at most, increased slightly during the generation of the Eocene Rio Blanco magma (0.70408 ± 0.00009). In contrast, average K_2O and Rb contents of the three intrusions decreased steadily with time (Table 1). The Sr content is highest for the Morovis stock, which is the oldest; the two younger intrusive units have similar Sr concentrations. If the parental magmas for these intrusive magmas had been similar in bulk composition, crystal fractionation would have yielded generally similar increases in K_2O and Rb contents and a decrease in Sr content with time. The fact that the K_2O, Rb and Sr contents of the three intrusive magmas are so different suggests that their parental magma compositions were also different. In contrast, the general similarity of initial $^{87}Sr/^{86}Sr$ ratios in the three intrusions indicates that all three may have been derived from similar source materials but by different conditions of partial melting and/or fractional crystallization.

5. Comparison with other oceanic and continental margin arc systems

The similarity of strontium isotopic and major element data for the Puerto Rican intrusions and other intrusive rocks in the Greater Antilles supports the conclusion that intrusive rocks ranging from monzonite to quartz diorite were derived from sources with similar $^{87}Sr/^{86}Sr$ ratios. Kesler et al. [9] obtained calculated initial ratios of 0.7030–0.7037 for the Loma de Cabrera granodioritic and El Bao quartz dioritic batholiths in Hispaniola ("LC" and "EB", Fig. 1). Feigenson [14] subsequently reported that the Loma de Cabrera batholith yields an isochron with an initial ratio of 0.7036. Results for the Medina quartz diorite stock ("M", Fig. 1) were more variable but suggest a similarly low initial ratio. Jones et al. [15] reported an average calculated initial ratio of 0.7036 for the granodioritic Terre Neuve stock in Hispaniola ("TN", Fig. 1) and similar results (0.7033, 0.7034) for the Above Rocks granodioritic stock in Jamaica. Thus, for the Greater Antilles, intrusive rocks ranging from quartz diorite to granodiorite have initial $^{87}Sr/^{86}Sr$ ratios of 0.7035 to about 0.7040.

Comparison of the results from the Greater Antilles with results obtained from other island arcs and continental margin areas (see table 1 in Kay et al. [16]) shows that: (1) most oceanic island arc volcanic rocks have initial $^{87}Sr/^{86}Sr$ ratios very similar to those observed for the intrusive rocks in the Greater Antilles, whereas (2) intrusive and volcanic rocks from continental margin areas exhibit higher initial $^{87}Sr/^{86}Sr$ ratio. The magmas at the continental margins contain a greater proportion of intermediate to granitic compositions than do the island arc magmas. Thus, although derivation of large volumes of granodioritic intrusive rocks at continental margins involves sources that contribute significant amounts of radiogenic strontium, no such source is necessary to generate the granodioritic intrusions of oceanic island arc areas.

6. Source of the intrusive magmas

The Puerto Rico intrusive magmas could have been derived from: (1) subducted oceanic or continental sediments; (2) subducted ocean floor basalt with or without seawater contamination; (3) the mantle wedge above the subduction zone with or without additions from the subduction zone; or (4) some combination of these sources. As noted by Kay et al. [16] and Hawkesworth et al. [17], sedimentary contributions to magma systems are best detected with Pb isotope data. Although no such data are presently available for the Puerto Rican intrusive rocks, Pb isotopic data for mineral deposits derived from these rocks (Cumming and Kesler [18] and unpublished data) do not indicate a recognizable and thus significant sedimentary contribution. Selection between the remaining two sources, oceanic crust or the mantle wedge, is hampered by the absence of Nd isotopic data, although we favor the mantle wedge as the principal magma source for the following reasons. The pattern of decreasing K_2O and Rb with time would be expected for episodic partial melting of a single source but it is more difficult to account for if the subducted slab was undergoing melting. The slight increase in $^{87}Sr/^{86}Sr$ ratio for the Rio Blanco magma could reflect additions of ^{87}Sr to the mantle wedge from volatiles rising from the subducted slab or from minor contamination by crustal melting. If this line of reasoning is correct, the principal reason for the compositional evolution of the Puerto Rican intrusive rocks was the gradual depletion of K and Rb from the partial melting zone in the mantle wedge.

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