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U–Pb geochronology of Seychelles granitoids: a Neoproterozoic continental arc fragment

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Abstract

New high-precision U–Pb zircon ages for 14 granitoid rocks of the Seychelles, including samples from Mahé, Praslin, La Digue, Ste. Anne, Marianne, Fregate and Recifs Islands, yield dates between 748.4 ± 1.2 Ma and 808.8 ± 1.9 Ma, interpreted as representing magmatic crystallization ages. U–Pb zircon ages as young as 703 Ma have been reported by other workers, and the time span of Seychelles magmatic activity, therefore, is ~100 Myr. The vast majority of ages, however, fall in the period 748–755 Ma, suggesting a major period of granite plutonism at this time. At least some Seychelles dolerite dikes have equivalent ages, indicating the contemporaneity of granitic and basaltic magmas, and supporting field and chemical evidence for the production of minor quartz dioritic rocks by hybridization and magma mingling. Possible correlatives of the late Neoproterozoic (~700–800 Ma) granitoids and dolerites of the Seychelles include volcanic and plutonic rocks in Madagascar and northwestern India (Malani Igneous Suite, Rajasthan), which may have formed in a continuous continental (Andean-type) arc located at the western margin of the Rodinia supercontinent. This idea is more consistent with the time span of magmatism, petrologic character of the igneous rocks, and paleomagnetically determined reconstructions, than the commonly held view of an intra-plate extensional setting for the Seychelles and Malani Igneous Suite.

Keywords: U/Pb; geochronology; Neoproterozoic; magmatism; Rodinia; reconstruction; Seychelles

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1. Introduction

The Seychelles Islands (Fig. 1) have been recognized as being composed of granitic rocks since the late 19th century [1], but it was not until the early 1960s that the Late Precambrian age of these rocks was first established [2–4]. Since then, numerous geochronological studies of Seychelles granitoids and crosscutting dolerite dikes (summarized below), using K–Ar, Rb–Sr, Pb–Pb and U–Pb methods, have resulted in a variety of ages, but generally of relatively poor precision. Consequently, some confusion has arisen with regard to the relative ages between granitoid varieties, and to the actual time span of Seychelles magmatism. We present here the results of a com-

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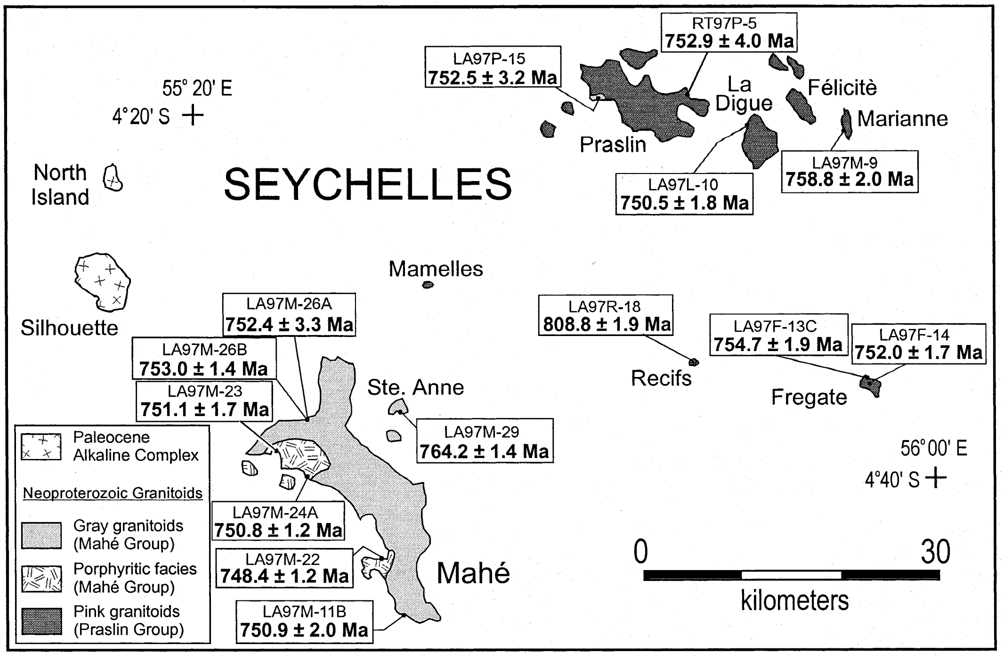

Fig. 1. Map of Seychelles geology (modified from [5,17,20]) showing locations of sampled granitoids, and resulting U–Pb zircon ages.

prehensive geochronological study of Precambrian magmatism in the Seychelles, using precise U–Pb single zircon methods. The geochronological work reported here complements our petrologic, geochemical and paleomagnetic work on the Seychelles [5,6].

Our interest in the Seychelles was inspired by our ongoing project on the geology and geochronology of Madagascar (e.g. [7]), where we have identified a 450 km long belt of Mid-Neoproterozoic (804–776 Ma) granitoid and gabbroic rocks. These rocks are interpreted as the roots of a continental magmatic arc [8] that was active during or slightly preceding the break-up of the Rodinia supercontinent. Conventional reconstructions (e.g. [9–11]) place Madagascar, the Seychelles and northwestern India (Rajasthan) at the margin of Rodinia, facing the Mozambique Ocean; it was logical, therefore, to seek a possible extension of the purported magmatic arc in both the Seychelles and Rajasthan [6,12–14]. Others, however, have proposed an intra-plate extensional setting for Seychelles magmatism [15,16].

2. Seychelles geology and petrology

Of the > 100 islands in the Seychelles Archipelago, most consist of coral atolls and reefs, but about 25 islands, including the principal Mahé–Praslin group (Fig. 1), are composed of undeformed, Late Precambrian granitoid rocks, crosscut by dolerite dikes [17,18]. Alkaline plutonic rocks of Mid-Paleocene age (63.2 ± 1 Ma, Rb–Sr [19]; 63.3 ± 0.2 Ma, unpublished data of the authors) are restricted to Silhouette and North Islands (Fig. 1). The Precambrian granitoids have been variously divided on the basis of color and texture into ‘red’, ‘gray’, ‘porphyritic’ and ‘gneissose’ varieties [17,18,20], but poor exposures preclude detailed correlations, and contact relations are generally not visible [5].

Granitoid rocks of the Seychelles have commonly been described as chemically alkaline (e.g. [21–23]), but nearly all analyzed samples are metaluminous granites and granodiorites with higher normative plagioclase than K-feldspar [5]. Both subsolvus and hypersolvus granitoids are present, although their relative abundances are difficult to determine. Most specimens contain biotite and/or hornblende; alkali amphiboles (e.g. ferrorichterite, riebeckite) are present in some samples [22]. The depleted oxygen isotope signature of Seychelles granitoids ($\delta^{18}O = 3.3 \pm 0.3$‰ [24,25]), indicating interaction with hydrothermal fluids and/or assimilants, has been taken as evidence supporting an extensional or hot-spot origin [16,26]; this was questioned by Ashwal et al. [5]. Weis and Deutsch [21] divided the Seychelles granitoids into two groups on the basis of chemical and isotopic signatures: Mahé granites have relatively primitive Sr, Nd and Pb isotopic signatures, whereas those from Praslin, La Digue and other islands are isotopically more evolved. Our larger database of chemical and isotopic measurements confirms this division [5]. Mahé group granitoids have ε_{Nd} (calculated at 750 Ma) of +2.85 ± 0.17, and initial I_{Sr} of 0.7031 ± 8, indicating a dominantly juvenile source. Praslin group granitoids have lower $\varepsilon_{Nd,750}$ values (−1.1 to −3.8), higher I_{Sr} values of 0.7070–0.7163, and enrichments in LILE relative to Mahé group samples (Rb > 180 ppm, Th > 20 ppm, Pb > 30 ppm, U > 4.2 ppm), suggesting the involvement of an evolved ancient crustal component [5,21]. In this paper we report U–Pb zircon age data for granitoid samples from both Mahé and Praslin groups; the known distribution of the two groups is shown in Fig. 1. A summary of age data obtained previously for Seychelles Precambrian igneous rocks is given in the next section.

Crosscutting dolerite dikes (up to 80 m thick, average = 0.5–2 m) are mainly olivine tholeiites, although some are slightly nepheline normative [5,15]. Dolerite dikes on most Seychelles Islands have been variably altered to fine-grained assemblages of amphibole, chlorite, epidote and sericite, although primary plagioclase and clinopyroxene are present in some specimens. The olivine-bearing dolerites of Praslin are chemically, isotopically and petrographically distinct; evidence is accumulating that these are Late Cretaceous in age ([3,5,27], and see below). Most Seychelles dolerites, however, are probably coeval with the Precambrian granitoids, as shown by field and chemical evidence for magma mixing and mingling, resulting in hybrid rocks of intermediate composition [5]. This interpretation is supported by isotopic data reported in this paper.

3. Previous geochronology of Seychelles granitoids and dolerites

Most of the early isotopic age determinations for both Late Precambrian and Cretaceous igneous rocks from the Seychelles were compiled by Plummer [28]. We summarize here in somewhat more detail the previous geochronological results for the Late Precambrian rocks.

The Late Precambrian age of Seychelles granitoids was first established by Miller and Mudie [2], who obtained K–Ar ages between 503 ± 22 and 544 ± 23 Ma (simple mean of five replicate samples = 527 ± 39 Ma) for a Mahé gray granite, and between 505 ± 22 and 538 ± 22 Ma (simple mean of three replicate samples = 519 ± 34 Ma) for a Mahé pink granite, using the total volume whole-rock method (all cited K–Ar ages obtained prior to 1976 were recalculated using new decay constants [29]). Separates of altered biotite from the pink granite yielded a K–Ar age of 663 ± 17 Ma, using isotope dilution. These ages were considered as minimum crystallization ages because of the likelihood of Ar-loss, especially for the whole-rock analyses. These age results were confirmed by Baker and Miller [3], who determined K–Ar ages between 540 ± 46 Ma and 589 ± 50 Ma on hornblende separates from Mahé granite and alaskite; hornblende in granite from central Praslin yielded an age of 656 ± 55 Ma, and Mahé doleritic rocks (variable states of alteration) gave ages between 558 ± 48 Ma and 654 ± 55 Ma. Almost concurrently, Wasserburg et al. [4] reported Rb–Sr ages for K-feldspar (625 ± 25 Ma) and whole-rock (667 ± 34 Ma) for a Mahé alaskite (Rb–Sr ages recalculated using the decay constants recommended by Steiger and Jager [30]).

Michot and Deutsch [31] published a six-point Rb–Sr whole-rock regression of 710 ± 9 Ma, with $I_{Sr} = 0.7046 \pm 3$ for Seychelles granites of unspecified location. These authors also reported a U–Pb age of ca. 800 Ma obtained from five multi-grain zircon fractions separated from three granites. These U–Pb data were re-interpreted by Weis

Table 1
U–Pb isotope dilution analyses, Seychelles granitoids

	Zircon properties[a]	Concentrations					Atomic ratios				Age
		Wt.[b] (µg)	Pb rad[b] (ppm)	U[b] (ppm)	Pb com[c] (pg)	Th/U[d]	^{206}Pb/^{204}Pb[e]	^{207}Pb/^{206}Pb[f]	^{207}Pb/^{235}U[f]	^{206}Pb/^{238}U[f]	^{207}Pb/^{206}Pb[f] (Ma)
Mahé Island											
Hypersolvus amphibole granite (LA97M-11B)											
1	25 gr, cl, c	33	20.6	152	3.9	0.647	10 138	0.06427 ± 3	1.0936 ± 15	0.12342 ± 17	750.5 ± 1.1
2	52 gr, cl, c	72	11.1	82.3	8.7	0.641	1 796	0.06438 ± 9	1.0984 ± 21	0.12375 ± 18	754.1 ± 3.1
Porphyritic hornblende-biotite granite (LA97M-22)											
3	33 gr, cl, c, s-p	43	14.4	109	3.2	0.640	11 369	0.06421 ± 4	1.0764 ± 22	0.12159 ± 25	748.5 ± 1.2
Porphyritic hornblende-biotite granite (LA97M-23)											
4	44 gr, cl, c, s-p	52	12.6	94.9	3.1	0.644	12 469	0.06426 ± 4	1.0818 ± 15	0.12211 ± 17	750.1 ± 1.3
5	10 gr, cl, c, s-p	21	25.2	190	4.4	0.620	7 198	0.06431 ± 4	1.0820 ± 13	0.12202 ± 13	751.9 ± 1.2
6	24 gr, cl, c, s-p	36	16.4	122	5.3	0.648	6 514	0.06429 ± 4	1.0830 ± 12	0.12218 ± 13	751.2 ± 1.2
Porphyritic hornblende-biotite granite (LA97M-24A)											
7	22 gr, cl, c, s-p	30	21.4	160	5.3	0.652	7 094	0.06426 ± 4	1.0894 ± 15	0.12295 ± 17	750.1 ± 1.3
8	31 gr, cl, c, s-p	43	19.4	144	4.3	0.650	11 357	0.06430 ± 3	1.0897 ± 15	0.12291 ± 17	751.6 ± 1.0
9	19 gr, cl, c, s-p	32	26.8	201	4.0	0.651	12 586	0.06426 ± 3	1.0841 ± 13	0.12235 ± 14	750.3 ± 1.0
10	18 gr, cl, c, s-p	29	18.9	142	2.9	0.640	11 265	0.06429 ± 4	1.0823 ± 15	0.12211 ± 16	751.0 ± 1.5
Porphyritic hornblende quartz diorite (LA97M-26A)											
11	30 gr, cl, c, t-p	42	8.20	55.1	2.7	1.06	6 521	0.06431 ± 6	1.0945 ± 17	0.12344 ± 16	751.8 ± 2.0
12	12 gr, cl, c, t-p	21	9.91	64.8	3.6	1.16	2.981	0.06437 ± 10	1.1005 ± 49	0.12398 ± 53	753.9 ± 3.1
Mafic hornblende quartz diorite (LA97M-26B)											
13	18 gr, cl, c	34	21.4	133	1.9	1.39	18 739	0.06432 ± 4	1.0927 ± 13	0.12322 ± 14	752.1 ± 1.2
14	39 gr, cl, c	52	35.2	231	4.4	1.13	21 647	0.06436 ± 3	1.0991 ± 16	0.12386 ± 14	753.4 ± 0.9
15	5 gr, cl, c	11	24.9	166	8.5	0.981	1 728	0.06507 ± 8	1.1341 ± 19	0.12640 ± 15	776.7 ± 2.7
St. Anne Island											
Hypersolvus amphibole granite (LA97A-29)											
16	44 gr, cl, c	61	27.5	208	3.6	0.507	27 599	0.06469 ± 3	1.1203 ± 16	0.12560 ± 17	764.3 ± 0.8
17	10 gr, cl, c	21	16.4	123	6.3	0.548	3 318	0.06470 ± 6	1.1163 ± 17	0.12514 ± 16	764.5 ± 1.8
18	5 gr, cl, c	10	4.52	36.5	4.4	0.619	623.2	0.06456 ± 12	1.0158 ± 22	0.11412 ± 17	759.9 ± 3.8
19	29 gr, cl, c	54	26.9	201	49	0.518	1 798	0.06514 ± 5	1.1393 ± 21	0.12686 ± 21	778.8 ± 1.7
20	32 gr, cl, c	45	16.9	124	10	0.550	4 464	0.06528 ± 4	1.1507 ± 25	0.12785 ± 27	783.4 ± 1.2
21	17 gr, cl, c	26	21.8	156	4.9	0.568	6 859	0.06263 ± 4	1.1855 ± 81	0.13101 ± 90	794.7 ± 1.3
Praslin Island											
Hornblende-biotite granite (RT97P-5)											
22	28 gr, cl, c	49	4.38	30.4	5.3	0.951	2 226	0.06435 ± 9	1.0997 ± 19	0.12394 ± 14	753.2 ± 3.0
23	27 gr, cl, c	45	4.90	33.2	5.8	0.979	2 072	0.06440 ± 10	1.1086 ± 22	0.12485 ± 18	754.9 ± 3.3
24	25 gr, cl, c	44	2.32	16.5	3.2	0.833	1 817	0.06416 ± 16	1.0864 ± 30	0.12280 ± 18	747.1 ± 5.2
25	22 gr, cl, c	43	4.68	32.7	8.6	0.977	1 282	0.06505 ± 30	1.0845 ± 72	0.12091 ± 77	775.9 ± 9.6
Amphibole granite (LA97P-15)											
26	12 gr, cl, c	16	9.27	66.1	3.2	0.796	2 643	0.06422 ± 12	1.0975 ± 24	0.12395 ± 17	748.9 ± 4.0
27	16 gr, cl, c	19	18.4	134	4.8	0.732	4 173	0.06435 ± 5	1.0959 ± 15	0.12351 ± 14	753.3 ± 1.8

Table 1 (*continued*)

	Zircon properties[a]	Concentrations					Atomic ratios				Age
		Wt.[b] (µg)	Pb rad[b] (ppm)	U[b] (ppm)	Pb com[c] (pg)	Th/U[d]	^{206}Pb/^{204}Pb[e]	^{207}Pb/^{206}Pb[f]	^{207}Pb/^{235}U[f]	^{206}Pb/^{238}U[f]	^{207}Pb/^{206}Pb[f] (Ma)
La Digue Island											
Hornblende-biotite granite (LA97L-10)											
28	18 gr, cl, c	25	24.9	183	4.7	0.760	7430	0.06427 ± 5	1.0755 ± 14	0.12136 ± 15	750.5 ± 1.5
29	15 gr, cl, c	26	198	26.2	8.8	0.722	4494	0.06428 ± 4	1.0516 ± 13	0.11866 ± 14	750.7 ± 1.3
30	11 gr, cl, c	22	12.3	93.2	4.2	0.784	3663	0.06425 ± 7	1.0384 ± 52	0.11722 ± 58	749.9 ± 2.2
Marianne Island											
Amphibole granite (LA97M-9)											
31	14 gr, cl, c	19	13.1	90.4	2.3	0.893	5695	0.06447 ± 7	1.1092 ± 17	0.12477 ± 14	757.1 ± 2.4
32	9 gr, cl, c	14	14.0	99.2	4.2	0.792	2764	0.06452 ± 4	1.1095 ± 13	0.12472 ± 14	758.7 ± 1.2
33	8 gr, cl, c	14	8.66	58.6	5.2	0.922	1337	0.06461 ± 10	1.1117 ± 24	0.12480 ± 24	761.7 ± 3.1
34	24 gr, cl, c	35	4.67	31.9	5.5	0.905	1636	0.06432 ± 13	1.1185 ± 40	0.12612 ± 38	752.1 ± 4.3
Fregate Island											
Porphyritic aplitic amphibole granite (LA97F-13C)											
35	18 gr, cl, c	23	21.2	151	5.9	0.797	4715	0.06445 ± 5	1.0972 ± 16	0.12346 ± 16	756.5 ± 1.5
36	4 gr, cl, c	7	12.3	89.0	1.6	0.753	3307	0.06435 ± 6	1.0983 ± 15	0.12379 ± 14	753.2 ± 1.8
37	9 gr, cl, c	20	21.4	158	12.3	0.661	2041	0.06436 ± 6	1.0981 ± 17	0.12374 ± 16	753.6 ± 1.9
Biotite granite (LA97M-14)											
38	11 gr, cl, c	21	19.2	143	5.7	0.632	4160	0.06429 ± 4	1.0992 ± 13	0.12400 ± 12	751.2 ± 1.2
39	29 gr, cl, c	55	22.2	156	17.1	0.896	3991	0.06434 ± 4	1.0897 ± 15	0.12284 ± 15	752.9 ± 1.2
Recifs Island											
Biotite granophyre (LA97R-16)											
40	7 gr, cl, c	13	25.4	169	4.6	0.805	3934	0.06605 ± 7	1.2096 ± 19	0.13281 ± 18	808.1 ± 2.0
41	24 gr, cl, c	42	17.3	115	4.0	0.794	9938	0.06607 ± 4	1.2083 ± 15	0.13264 ± 17	808.5 ± 1.4
42	10 gr, cl, c	16	24.6	164	1.8	0.783	11973	0.06611 ± 6	1.2104 ± 17	0.13279 ± 16	809.8 ± 1.9

[a] The first column denotes the number of the analysis. The cardinal number in the second column indicates the number of zircon grains analyzed (e.g. 2 gr = two grains). All zircon grains were selected from non-paramagnetic separates at 0° tilt at full magnetic field in a Frantz magnetic separator; c = colorless; cl = clear; s-p = short-prismatic; t-p = tips from prisms. All grains were air-abraded following [35].

[b] Concentrations are known to ±30% for sample weights of about 30 µg and ±15% for samples > 50 µg.

[c] Corrected for 0.0125 mol fraction common-Pb in the ^{205}Pb–^{235}U spike.

[d] Th concentration is calculated ($\lambda^{232}\text{Th} = 4.9475 \times 10^{-11}$ yr^{-1}) from the excess ^{208}Pb after correction for introduced blank, common-Pb, and tracer solution.

[e] Measured, uncorrected ratio.

[f] Ratio corrected for fractionation, spike, blank, and initial common-Pb (at the determined age from Stacey and Kramers, 1975). Pb fractionation correction = 0.094%/amu (±0.025%, 1σ); U fractionation correction = 0.111%/amu (±0.02%, 1σ). U blank = 0.2 pg; Pb blank ≤ 10 pg. Absolute uncertainties (1σ) in the Pb/U and ^{207}Pb/^{206}Pb ratios calculated following [39]. U and Pb half-lives and isotopic abundance ratios from [40].

and Deutsch [21] as defining two subparallel discordia chords corresponding to upper-intercept intersection values of 786 ± 120 Ma and 845 Ma. In a 1982 abstract, Demaiffe et al. [32] reported a Rb–Sr whole-rock age of 710 ± 8 Ma for Seychelles granitoids. Rb–Sr whole-rock isotopic analyses of granitic rocks from Mahé were also determined by Yanagi et al. [33]; these results yielded ages, interpreted as representing magmatic crystallization, of 713 ± 19 Ma with $I_{\text{Sr}} = 0.70419 \pm 32$ (five-point regression for gneissose granites) and 683 ± 16 Ma with $I_{\text{Sr}} = 0.70592 \pm 75$ (eight-point regression for porphyritic granites). Weis and Deutsch [21] determined Pb–Pb whole-rock ages between 917 ± 74 Ma (17 granitic whole-rocks from Mahé) and 1320 ± 220 Ma (seven granitic whole-rocks from Praslin, La Digue and Felicité); these ages were considered to have no time significance because of perturbations in the Pb–Pb system or incorporation of isotopically heterogeneous initial Pb. These authors also re-interpreted unpublished Rb–Sr whole-rock data of Demaiffe et al. [32] as representing different crystallization ages for the granitoids of Mahé (706 ± 12 Ma, $I_{\mathrm{Sr}} = 0.70406 \pm 22$) and Praslin, La Digue and Felicité (667 ± 19 Ma, $I_{\mathrm{Sr}} = 0.7152 \pm 48$). High-precision U–Pb zircon ages for Seychelles rocks were mentioned in an abstract by Stephens et al. [16]. In this study, samples of four granites from Mahé, Praslin and Mammelles, and a single amphibolite inclusion from Mahé yield a tight cluster of concordant ages in the range 750–755 Ma; one younger granite has an age of 703 ± 3 Ma. Two samples show evidence for a ca. 2700 Ma inherited component.

Ages of Seychelles dolerite dikes are sparse, but both Late Precambrian and Cretaceous dikes have been identified. K–Ar results for Mahé dikes yield ages between 312 ± 6 Ma and 654 ± 55 Ma [3,19,27], although most of these ages are considered disturbed due to Ar-loss. Hargraves and Duncan [27] estimated an emplacement age of 620 ± 20 Ma based on combined K–Ar and ^{40}Ar/^{39}Ar measurements for Mahé dolerites. Zircons extracted from a granophyric segregation in a 10 m thick dolerite dike from southwestern Mahé yield a U–Pb age of 750.2 ± 2.5 Ma [6].

4. Sampling and analytical methods

A total of 37 specimens of granitoids and cross-cutting dolerites were collected in January, 1997 from the Seychelles Islands of Mahé, Ste. Anne, Praslin, La Digue, Marianne, Fregate and Recifs. A subset of 14 specimens, mainly granitoids, was selected for U–Pb isotopic age determinations; data for these samples are reported in this paper. Sample selections were made to be representative of the major identified granitoid types and to cover a wide geographic region. Locations are given in Fig. 1. Detailed locations (including GPS coordinates), descriptions, and petrologic, geochemical and isotopic data for the entire sample suite are reported in [5].

U–Pb zircon ages were determined using the methods developed by Krogh [34,35], with modifications described in [36] and [37]. Lead and uranium were loaded on single, outgassed Re filaments and analyzed in a VG Sector-54 mass spectrometer using a single-collector procedure with a Daly photomultiplier detector operating in ion counting mode. In general, an ion beam between 0.5×10^{-14} and 1.5×10^{-13} A was maintained for ^{206}Pb during data acquisition and between 0.5 and 1.5×10^{-13} for U. Average total procedural blanks of 2 pg Pb and 0.2 pg U were maintained during the period of analysis; total common-Pb concentrations for all analyses are reported in Table 1. Initial Pb corrections utilized the Pb isotopic composition estimated by Stacey and Kramers [38] at the indicated age of the rock. In nearly all cases, the uncertainty in the amount of and composition of common-Pb calculated in this manner represents an insignificant contribution to the error of the calculated ages. Error propagation is similar to that developed by Ludwig [39], and age errors are reported at 95% confidence limits. Analytical reproducibility at 1σ confidence levels of replicate samples confirms that the parameters used in data reduction (laboratory blank, fractionation, and Daly mass discrimination) and their errors have been evaluated correctly.

5. Results

All zircons analyzed from Seychelles granitoid rocks are optically clear, colorless and free of inclusions. U–Pb isotopic data (Table 1) are plotted in a series of Concordia diagrams in Figs. 2 and 3. Most analyses are concordant, or less than a few percent discordant and, except for analyses 15 and 19–21 (Table 1), we see little evidence in our data for the presence of inherited components as was also reported by Stephens et al. [16]. Our U–Pb dates are reported at 95% confidence limits and are best interpreted as representing the time of magmatic crystallization.

Ages of granitoids from Mahé are all equivalent within analytical uncertainty, at 751.1 ± 3.3 Ma (simple mean of six samples, with 2σ uncertainty). This includes both subsolvus and hyper-

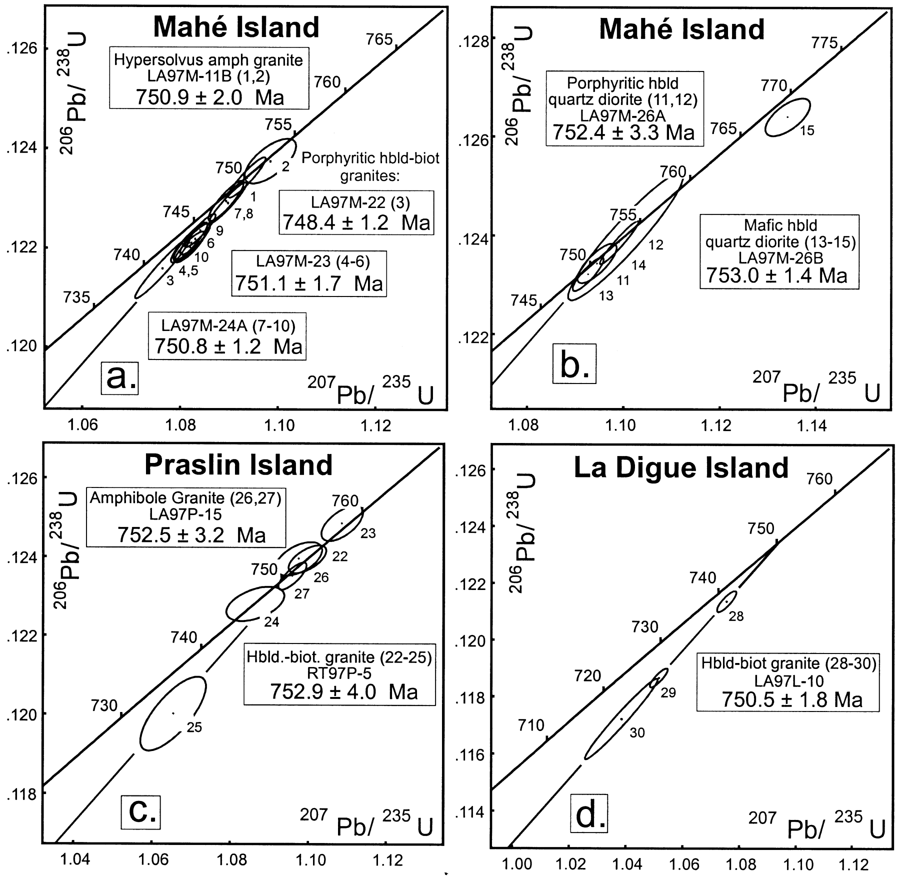

Fig. 2. Concordia diagrams showing U–Pb zircon analyses for granitoid samples from Mahé (a,b), Praslin (c) and La Digue (d) Islands. The crystallization age for each sample (given in the box) is defined by the weighted mean ^{207}Pb/^{206}Pb age of inheritance-free analyses. Ages are cited at 95% confidence limits and error ellipses are plotted at 2σ confidence levels. Numbers refer to individual analyses given in Table 1.

solvus granites, as well as the less abundant intermediate rocks such as the quartz diorites (samples LA97M-26A and -26B). Granitic rocks from Praslin, La Digue and Fregate (five individual samples) are also temporally equivalent, as is the U–Pb zircon age of a 10 m thick dolerite dike from southwestern Mahé (750.2 ± 2.5 Ma [6]). The simple mean of ages from these 12 samples is 751.6 ± 3.3 Ma, indicating that the majority of igneous rocks in the Seychelles were emplaced between 748 and 755 Ma. Similar U–Pb zircon ages were obtained by Stephens et al. [16] for four granitoids from Mahé, Praslin and Mammelles, and an amphibolite inclusion from Mahé.

Three samples in our collection yield older dates. These include an amphibole granite from Marianne (758.8 ± 2.0 Ma), a hypersolvus amphibole granite from Ste. Anne (764.2 ± 1.4 Ma), and a biotite granophyre from Recifs (808.8 ± 1.9 Ma). Stephens et al. [16] also reported a younger age of 703 ± 3 Ma for a granite from Mahé. Neoproterozoic igneous activity in the Seychelles, therefore, ranges between 703 and 808 Ma, or just over 100 Myr, but with a large concentration of ages at about 750–755 Ma (Fig. 4).

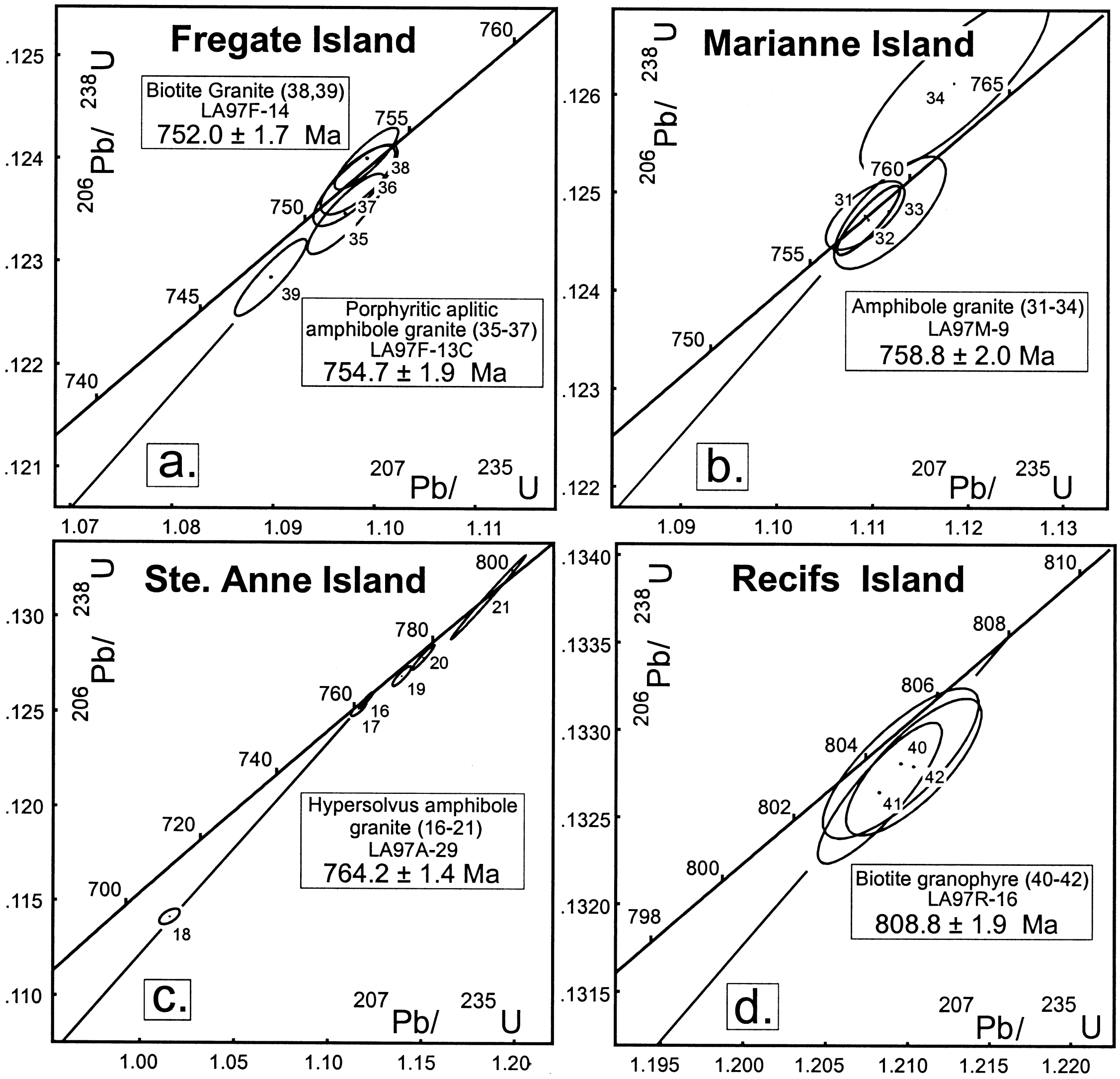

Fig. 3. Concordia diagrams showing U–Pb zircon analyses for granitoid samples from Fregate (a), Marianne (b), Ste. Anne (c) and Recifs (d) Islands. The crystallization age for each sample (given in the box) is defined by the weighted mean ^{207}Pb/^{206}Pb age of inheritance-free analyses. Ages are cited at 95% confidence limits and error ellipses are plotted at 2σ confidence levels. Numbers refer to individual analyses given in Table 1.

6. Discussion

The dominant period of igneous activity in the Seychelles, at 748–755 Ma, is represented over nearly the entire areal extent of principal islands, from Mahé in the southwest, to Praslin and La Digue in the northeast, to Fregate in the east (Fig. 1). There is no indication of any age difference between granitoid magmatism at Mahé and Praslin+La Digue, despite the distinct differences in geochemical and isotopic signatures reported by Weis and Deutsch [21] and confirmed by our research team [5]. This suggests that coeval granitic magmas were produced from different sources, or more likely, have assimilated variable amounts of ancient crustal components [5].

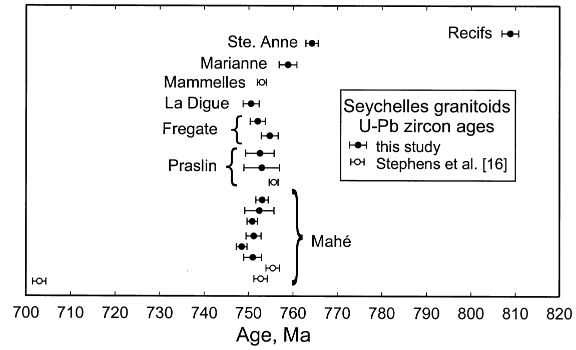

Fig. 4. Histogram of all available U–Pb zircon ages for Seychelles granitoids, including data from this study ($n = 14$) and Stephens et al. [16] ($n = 5$).

A smaller volume of granitoid rocks, both older and younger than the main magmatic episode of 752 ± 3 Ma, is present in the Seychelles. These include samples taken at Ste. Anne, Recifs and Marianne (759–808 Ma), and at eastern Mahé (703 Ma [16]). No relationship is apparent between age and geographic position within the Seychelles (Fig. 1), and the boundaries between chronologically distinct granitoid intrusives are either unexposed or have yet to be identified. We believe that the ~100 Myr time span of igneous activity in the Seychelles is real, and that this is more consistent with a magmatic arc setting than an extensional environment involving plume- or rift-generated magmatism. Chemical and petrological arguments supporting this interpretation have been presented by Ashwal et al. [5], and paleomagnetic data indicate a position for the Seychelles at ~750 Ma at or near the continental margin of Rodinia (Fig. 5) [6]. Therefore, the age data given here could support a link between Seychelles magmatism and the proposed Andean-type arc identified in north–central Madagascar [8,13,14].

The temporal equivalence of Seychelles granitic rocks with at least some of the crosscutting dolerite dikes is an important finding because it implies the coexistence of basaltic and granitic magmas. This is consistent with field observations of complex mingling of mafic and silicic magmas, resulting in hybrid rocks of dioritic to quartz dioritic compositions, which are exposed in a few localities in northern Mahé [5]. Although not diagnostic of tectonic setting, coeval basaltic and granitic magmatism is commonly present in Andean-type arcs (e.g. [41]).

Correlation of the late Neoproterozoic magmatism of the Seychelles with that of possibly contiguous continental fragments of Gondwana is important not only for precise Gondwana reconstructions, but also for the understanding of the development and break-up history of the pre-existing Rodinia supercontinent (Fig. 5). Possible age correlatives of Seychelles magmatism include the 450 km long belt of granitic to gabbroic plutons in north–central Madagascar [8], and also the silicic to intermediate metavolcanic and metaplutonic rocks of extreme northeastern Madagascar, which yield ages of 700–750 Ma ([13,14] and unpublished data of the authors). Likewise, the Malani Igneous Suite of Rajasthan in northwestern India includes voluminous silicic to intermediate volcanic and plutonic rocks, which yield Rb–Sr whole-rock ages between 779 ± 10 and 681 ± 20 Ma [42,43]. Isotopic, petrologic, and geochemical work on the late Neoproterozoic igneous rocks of northern Madagascar and Rajasthan is in progress by our group. Our preliminary and published work, coupled with paleomagnetic reconstructions that place the Seychelles at the margins rather than in the interior of the Rodinian supercontinent, represent a compelling case that the Neoproterozoic granitoids of the Seychelles formed in an Andean-type continental arc setting. The extent and significance of this Neoproterozoic arc system are just beginning to be realized.

7. Conclusions

1. U–Pb zircon geochronology demonstrates that the vast majority of late Neoproterozoic plutonic rocks in the Seychelles were emplaced in the period 748–755 Ma. Reliable ages, however, as old as 808 Ma and as young as 703 Ma indicate a time span of Seychelles magmatism in excess of 100 Myr.
2. The magmatic peak at 748–755 Ma produced granitoid rocks including subsolvus and hypersolvus granites, intermediate quartz dioritic rocks, and dolerites throughout the principal

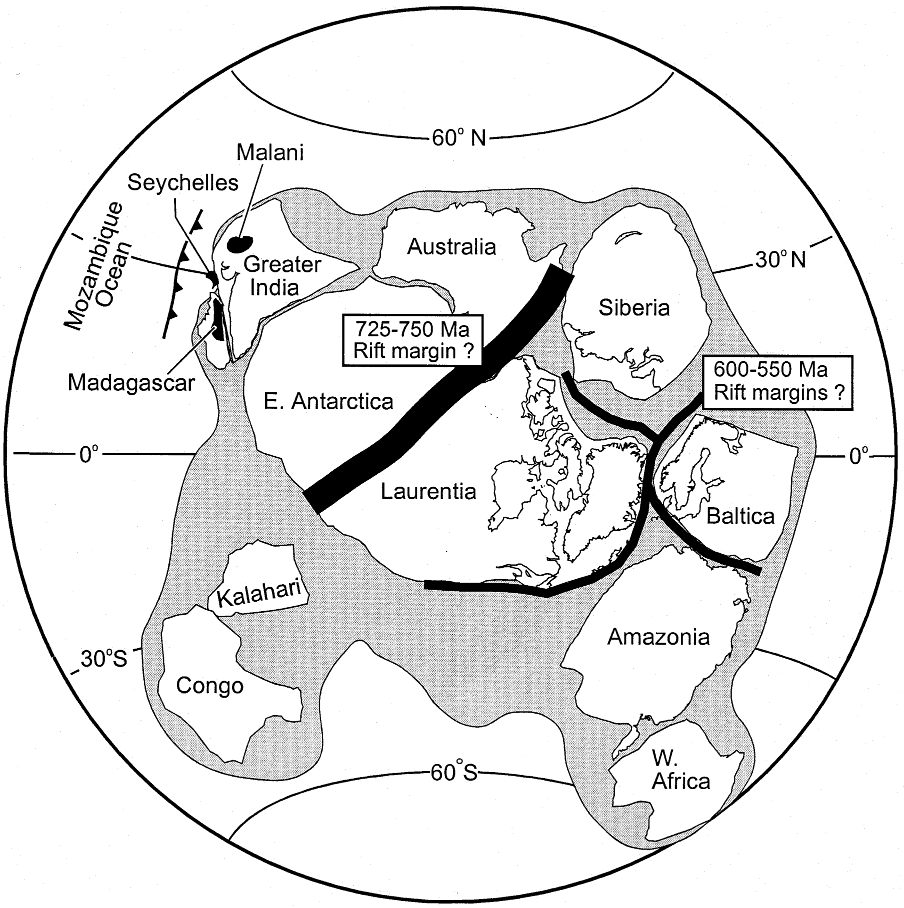

Fig. 5. Reconstruction of the Rodinia supercontinent at ca. 750 Ma [6,9]. Rodinia is reconstructed with a paleomagnetic pole of Lat. = 80.4°N, Long. = 46.7° (A95 = 3.3; Indian coordinates). A new Seychelles–India fit (Euler pole: Lat. = 25.8°, Long. = 330° and rotation angle = 28° [6]) produces a good match of paleomagnetic poles from ca. 750 Ma igneous rocks in the Seychelles and Rajasthan, India (Malani Igneous Suite). Together with Madagascar, we propose that this tectonic trio formed an outboard continental terrane of the Rodinia supercontinent during the Neoproterozoic. The Seychelles formed at ca. 30°N and most likely as part of an Andean-type magmatic arc along the western margin of Rodinia. Location of Neoproterozoic igneous rocks in Madagascar, Seychelles and Rajasthan, India, is indicated in black.

islands of the Seychelles. There is no age difference between granitoids of Mahé and Praslin+La Digue, despite their different chemical and isotopic signatures suggesting multiple sources and/or contaminants.

3. The contemporaneity of granitoid and doleritic magmas supports an origin for intermediate plutonic rocks (e.g. quartz dioritic rocks of Mahé) by hybridization of granite and basalt magmas.
4. The ~100 Myr time span for Seychelles magmatism is more consistent with a continental arc setting than one involving active intra-plate extension.
5. The age and geochemistry of Seychelles igneous rocks can be correlated with those of volcanic and plutonic rocks in northern and north–central Madagascar, and northwest Rajasthan (Malani Igneous Suite), supporting the existence of an active Andean-type margin on the edge of the Rodinia supercontinent between 700 and 800 Ma.

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