Geochronologic and isotopic evidence for involvement of pre-Pan-African crust in the Nubian shield, Egypt

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ABSTRACT

Two Late Proterozoic granitic bodies from the Eastern Desert of Egypt, the ca. 578 Ma Nakhil and the ca. 595 Ma Aswan granites, provide insights into processes of crust formation in the Arabian-Nubian shield. Evidence for involvement of an older crustal component in the formation of the Nakhil granite includes (1) U/Pb zircon data that establish a crystallization age of 578 ±15 Ma and indicate the presence of inherited zircons possibly as old as 1.6 Ga; (2) an elevated model initial $^{87}Sr/^{86}Sr$ (0.7136); and (3) an elevated initial $^{207}Pb/^{204}Pb$ (15.561) relative to model mantle compositions at 578 Ma. Evidence for involvement of an older crustal component in the Aswan granite comes from the elevated initial $^{207}Pb/^{204}Pb$ (15.611). In contrast, extensive crustal contamination is not reflected in the high initial ϵ_{Nd} (+5.7) for the Nakhil and the low initial $^{87}Sr/^{86}Sr$ (0.7029) for the Aswan granite. The contrasting inferences from the different isotopic systems can be explained by the high whole-rock Nd and Sr concentration for the Nakhil (87 ppm Nd) and the Aswan (173 ppm Sr) granites, respectively, that suggest that the Nd and Sr isotopic composition of the older component has been overshadowed by the more primitive material. Similar contrasts in Pb, Sr, and Nd isotopic data from the eastern and western shield margins can be interpreted in the same manner and might suggest widespread involvement of older crustal components in the formation of the Late Proterozoic Arabian-Nubian shield.

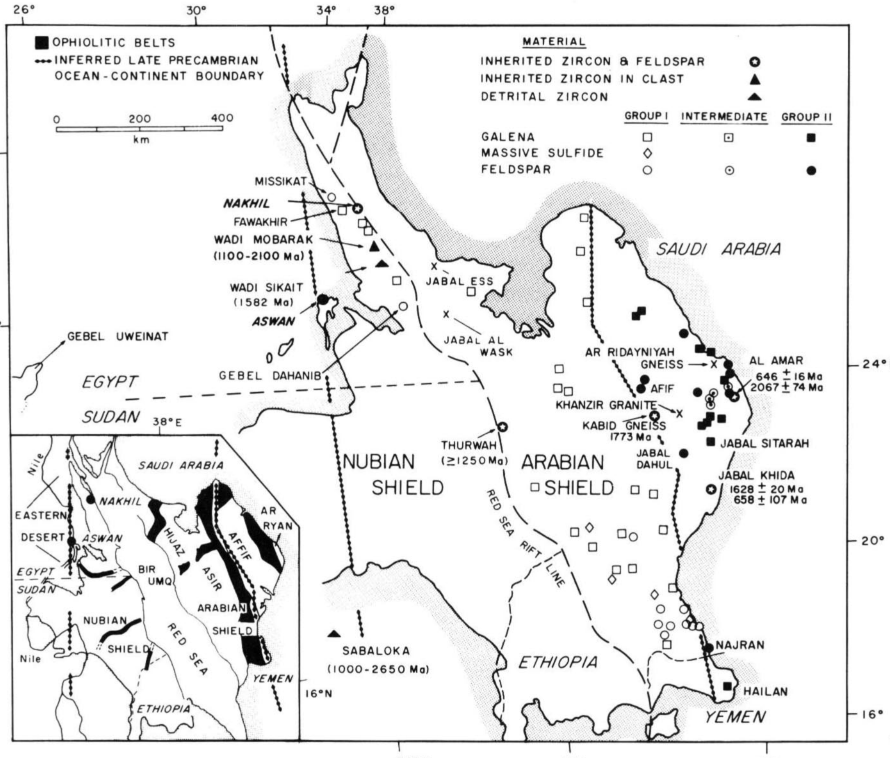

Figure 1. Location map showing outcrops of Arabian-Nubian shield in their relative pre–Red Sea locations. Inset is sketch map of Arabian and Nubian shields in their current locations, showing constituent microplates and interleaving suture zones. Location and sketch maps were modified from Stoeser and Camp (1985) and Vail (1985). Sample locations for Nakhil and Aswan granites and common Pb data for feldspar, galena, and massive sulfides (Stacey et al., 1980; Gillespie and Dixon, 1983; Stacey and Stoeser, 1983; Stacey and Hedge, 1984; Stacey and Agar, 1985; Pallister et al., 1988) are shown. Common Pb data were classified using criteria of Stacey et al. (1980): Group I leads are derived from primitive oceanic sources, whereas group II incorporate older continental crustal component. Zircon U/Pb zircon ages are given for samples that show evidence for inherited zircon component predating Late Proterozoic shield assembly (Abdel Monem and Hurley, 1980; Dixon, 1981; Stern and Hedge, 1985; Calvez et al., 1985; Stacey and Agar, 1985; Kröner et al., 1987b; Pallister et al., 1988). Locations of inferred boundaries between domains with oceanic and others with continental affinities (Dixon and Golombek, 1988) are shown.

INTRODUCTION

The Arabian-Nubian shield is composed largely of Late Proterozoic volcano-sedimentary arc assemblages separated by linear belts of ophiolitic sequences that were assembled and accreted onto the older African craton 600–950 Ma (Stoeser and Camp, 1985; Vail, 1985; Kröner et al., 1987a) (Fig. 1, lower left). The extent of involvement of the older African craton in the formation of the shield is a subject of debate. Reymer and Schubert (1984) modeled crustal growth in the shield using arc addition rates as high as 310 $km^3 \cdot km^{-1} \cdot m.y.^{-1}$, about ten times the average rates calculated for Mesozoic and Cenozoic arcs. Alternatively, Dixon and Golombek (1988) appealed to the presence of large amounts of undetected preexisting sialic basement and favored normal growth rates. They interpreted existing radiometric data to indicate that the central part of the exposed Arabian-Nubian shield consists mainly of juvenile, mantle-derived oceanic and intra-oceanic island-arc Precambrian crust, whereas the eastern and western margins consist mainly of older continental crust (Fig. 1).

It has become clear that some areas in the Arabian shield previously identified as juvenile show evidence for involvement of crustal components predating the Pan-African (550–950 Ma) event. For example, common Pb and U/Pb zircon data from Jabal Khida, Zalm region (Kabid gneiss), Jabal al Wask, and the Bir Umq suture and areas to its southwest indicate that the Affif and Ar Rayn terranes (hereafter referred to as eastern Arabia), the northernmost part of the Asir terrane, and the western part of the Hijaz microplate, contain fragments and/or detritus from pre–Pan-African continental crust

(Stacey et al., 1980; Stern et al., 1982; Stacey and Stoeser, 1983; Stacey and Hedge, 1984; Calvez et al., 1985; Stacey and Agar, 1985; Pallister et al., 1988) (Fig. 1). Although the isotopic systematics of the Nubian shield are less well studied, U/Pb zircon evidence for the existence of older detritus has been presented locally from the Wadi Sikait, Sabaloka, and Wadi Mobarek areas (Abdel Monem and Hurley, 1980; Dixon, 1981; Kröner et al., 1987b) (Fig. 1). In a deviation from widely accepted models that consider the Eastern Desert as being formed of juvenile oceanic crust, Bickford et al. (1989) interpreted common Pb data for 35 alkali-feldspar samples from the Precambrian of the Eastern Desert to indicate widespread involvement of an older crustal component in the formation of the Late Proterozoic rocks of the Eastern Desert.

The Nakhil granite comes from the "oceanic" central part and the Aswan granite comes from the western margin, as defined by Dixon and Golombek (1988) (Fig. 1). The involvement of older crustal components in the formation of both the eastern and western margins is controversial. For example, elevated initial ^{207}Pb/^{204}Pb (15.609–15.65) for the Aswan granite (Gillespie and Dixon, 1983; Stacey and Stoeser, 1983) contrasts with the low model initial ^{87}Sr/^{86}Sr (0.7029) (Stern and Hedge, 1985) and initial ϵ_{Nd} (+2.3) (Harris et al., 1984). Compelling evidence for involvement of older crustal components in the eastern margin comes from (1) U/Pb zircon ages for Jabal Khida (1628 Ma; Stacey and Hedge, 1984), Kabid gneiss (1773 Ma; Stacey and Agar, 1985), and Al Amar region (2067 Ma; Calvez et al., 1985); (2) relatively high initial ^{207}Pb/^{204}Pb values for feldspar, whole-rock, and galena samples (Stacey and Stoeser, 1983) (Fig. 1), and (3) the relatively high initial ^{87}Sr/^{86}Sr (>0.7036; C. E. Hedge, 1982, written commun., cited in Stacey and Stoeser, 1983). However, Duyverman et al. (1982) interpreted Sm-Nd isotopic data from seven granitic and granodioritic samples from eastern Arabia (initial ϵ_{Nd} ranging from +1.6 to +6.9) as indicative of an upper mantle source. Our results bear on the extent of involvement of the old African craton in the formation of the Arabian-Nubian shield, rates of crustal growth, and the apparent discrepancy between inferences made from the Sm/Nd, Rb/Sr, and U/Pb isotopic systems.

FIELD RELATIONS AND PETROGRAPHIC AND GEOCHEMICAL DATA

The Nakhil granite sample (85-1; lat 26°12′N; long 34°3′E) comes from a northwest elongate medium- to coarse-grained, leucocratic, gneissic body that crops out over ~30 km^2 in the central part of the Eastern Desert (Fig. 1). Field relations, petrography, and geochemistry have been described by Abuzied (1984) and are supplemented by our observations. The intrusion contains numerous xenoliths from the surrounding country rocks and has a mylonitic fabric along its northeast contact with metavolcanic and metasedimentary country rocks. The mylonitic zone is about 50 m wide. Penetrative fabrics in the gneiss and country rock are a subhorizontal northwest-trending mineral lineation and a subvertical gneissic foliation. The shear zone appears to represent one of many brittle and/or ductile shear zones belonging to the sinistral Najd transcurrent shear system of the Arabian shield that extends into the central Eastern Desert (Abuzied, 1984; Sultan et al., 1988).

Landsat thematic mapper images processed as described in Sultan et al. (1987) were used to delineate the shear zone and to select the least deformed areas in the pluton for sample collection. Samples from the Nakhil granite show evidence for both cataclastic and ductile deformation. The grain size is bimodal, consisting mostly of porphyroclasts (1.5–5.0 mm) of perthitic alkali-feldspar, less commonly albite (1–3 mm), and recrystallized quartz aggregates (~0.5 mm) included in a finer grained groundmass (<0.5 mm) of quartz, alkali-feldspar, and albite. Accessory phases include zircons and iron oxides. Quartz grains show undulatory extinction and form band and ribbon structures around porphyroclasts. Analysis of our sample and two from Abuzied (1984; samples M30 and N15) show that the Nakhil granite is silica rich (73–77 wt% SiO_2), metaluminous to marginally peraluminous and contains 3.4–4.2 wt% Na_2O, 4.7–4.9 wt% K_2O, 0.06–0.31 wt% CaO, 10.9–13.8 wt% Al_2O_3, and <1 wt% of MgO, MnO, and P_2O_5. The Nakhil granite contains 685 ppm Zr.

The Aswan sample (F-27; lat 24°7′N, long 32°55′E) comes from one of the post-tectonic intrusions known as Pink or Younger Granites that pervasively intruded the Arabian-Nubian shield between 575 and 600 Ma (Stern and Hedge, 1985). Field relations and petrographic and geochemical characteristics of the Younger Granites have been summarized by Greenberg (1981).

ISOTOPIC AND GEOCHRONOLOGIC DATA

The U/Pb zircon data from the Nakhil granite are listed in Table 1 and plotted in Figure 2. Table 2 presents Rb/Sr data for the Nakhil granite and Sm/Nd and common Pb data for the Nakhil and Aswan granites. For comparison, published feldspar common Pb and Sm/Nd data for the Aswan granite are also given in Table 2. Our common Pb data are in Figures 1 and 3 along with published common lead analyses from the shield.

The analyzed zircon fractions from the Nakhil granite ranged from clear, crack-free grains to dark anhedral fragments. There are no apparent relations between morphology, physical characteristics, and discordance. No distinct cores were observed, and the abraded grains do not show an enhanced inherited component. Most of the data cluster together. Two analyses fall off the cluster; one is nearly concordant with a ^{207}Pb/^{207}Pb age of 578 ±15 Ma and the other has a Pb/Pb age of 829 Ma. We interpret this complex array as reflecting a mixture of a very small amount of older, inherited, zircons within younger magmatic ones. In this interpretation, a minimum crystallization age can be estimated from the nearly concordant point, which has a

TABLE 1. U-Pb ZIRCON DATA FOR THE NAKHIL GRANITE

Fractions*		Sample weight (mg)	U (ppm)	Pb (ppm)	Measured ^{206}Pb/^{204}Pb	Atomic Ratios †			Apparent ages (Ma)		
						^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb
(1) NM 0&1	c	0.32	175	19.2	1097	0.10379	0.95499	0.06673	637	681	829
(2) M 0.2&3	A.c	0.95	165	17.3	2424	0.10058	0.85233	0.06146	618	626	655
(3) NM 1	A.d	1.09	198	19.8	3008	0.09860	0.83275	0.06125	606	615	648
(4) M 5&6	A.c	0.73	147	15.5	1316	0.09878	0.83761	0.06150	607	618	657
(5) D -1	A.d	1.41	227	24.5	1325	0.09657	0.80959	0.06080	594	602	632
(6) D -1	c	0.80	262	27.0	1585	0.09529	0.80446	0.06123	587	599	647
(7) NM10-M3	A.d	1.06	357	36.0	1958	0.09444	0.79130	0.06077	582	592	631
(8) NM3-M1	c	1.17	246	24.0	1651	0.09354	0.76465	0.05929	576	577	578

Note: Analytical procedures are in Chamberlain and Bowring (1990).

* NM = nonmagnetic; D = diamagnetic; M = magnetic; A = abraded; c = clear; d = dark; numbers refer to side slopes of magnetic separator.

† Corrected for blank (100 pg) and initial Pb using feldspar Pb values; uncertainties (2σ) for Pb/U ratios range from 0.5 to 1.5%.

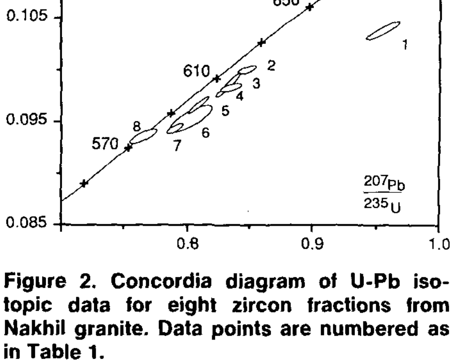

Figure 2. Concordia diagram of U-Pb isotopic data for eight zircon fractions from Nakhil granite. Data points are numbered as in Table 1.

Pb/Pb age of 578 ±15 Ma. The inherited component has a minimum age of 829 Ma, corresponding to the oldest Pb/Pb age. Linear extrapolation through the youngest and oldest points yields an upper intercept of about 1.6 Ga, which could be interpreted as the approximate age of the inherited component, assuming simple two-component mixing. The cluster of the other six data points suggests inheritance of a slightly older components with variable amounts of lead loss. The U-Pb zircon data are consistent with, but do not require, involvement of a pre–Pan-African crustal component.

The crystallization age of the Nakhil granite at 578 ±15 Ma suggests that the subhorizontal northwest-trending stretching lineation in the Hamrawin area and its surroundings developed later than the accretion of the terrain bracketed between 600 and 950 Ma (Kröner et al., 1987a). The stretching lineations observed in the Hamrawin area and over large segments of the Eastern Desert are more likely related to deformation associated with the Najd System, bracketed between 530 and 630 Ma in Arabia (Stacey and Agar, 1985).

The Nakhil granite has a model initial $^{87}Sr/^{86}Sr$ of 0.7136, calculated from whole-rock Rb/Sr data and an age of 578 Ma. The high initial $^{87}Sr/^{86}Sr$ is consistent with involvement of a crustal component in the formation of the Nakhil granite. Data from an alkali-feldspar separate and the whole rock define a line with an initial $^{87}Sr/^{86}Sr$ value of 0.7204 and a slope corresponding to an age of 530 Ma. Feldspar common Pb data from the Nakhil granite straddle the orogene model curve on a common Pb diagram, in contrast to the more primitive samples, such as Dahanib, Missikat, and galenas of field A that are below the average orogene curve (Fig. 3). The simplest interpretation for elevated $^{207}Pb/^{204}Pb$ in the Nakhil granite compared to the more primitive rocks of the same age is the incorporation of older crustal components. Rocks with similar isotopic characteristics from eastern Arabia (e.g., field B galenas) are also interpreted to show evidence for contamination with continental crustal components of at least Early Proterozoic age (Stacey et al., 1980).

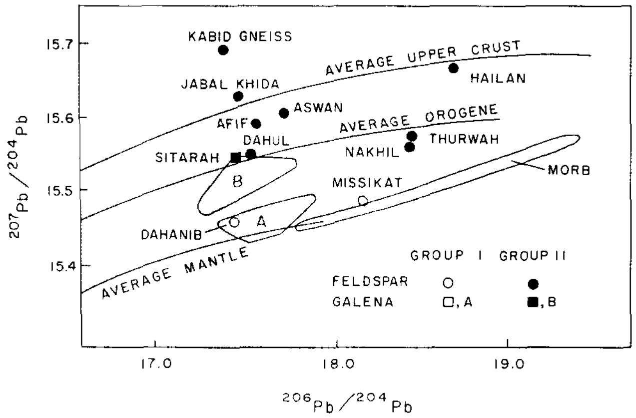

Figure 3. Common lead isotopic data for Nakhil and Aswan granites and other published data plotted in Figure 1. Nakhil and Aswan granites are similar to Group II samples plotting above mantle growth curves, in contrast to Group I samples that straddle mantle curve. Examples of Group I samples include Dahanib and Missikat (Gillespie and Dixon, 1983) and galena field A (Stacey et al., 1980). Examples of Group II samples include Thurwah (Pallister et al., 1988), Sitarah, Hailan, and galena field B (Stacey et al., 1980), and Dahul (Stacey and Stoeser, 1983). Average growth curves are from Zartman and Doe (1981), and field for mid-ocean ridge basalt (MORB) is from Tatsumoto (1978).

TABLE 2. COMMON Pb, Rb/Sr, and Sm/Nd DATA FOR NAKHIL AND ASWAN GRANITES

	Pb	Rb	Sr	Sm	Nd	Atomic ratios* $^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}(T)$†
Aswan granite													
K-feldspar	30.7					17.704	15.611	37.675					
K-feldspar§						17.717	15.609	37.807					
Whole rock				11.7	72.3						0.0981	0.51230	+1
Whole rock**				11.2	68.9						0.098	0.51232	+1.3
Nakhil granite													
K-feldspar		166	11.8			18.392	15.561	38.006	40.59	1.02833			
Whole rock		53.8	15.0	19.6	87.0				10.35	0.79892	0.1361	0.51270	+5.7
Model parameters††						Initial atomic ratios and $\varepsilon_{Nd}(T)$ values at 578 Ma							
Crustal component	10		220		23.8		15.69			0.72038		0.51146	-8.5
Primitive melt	2		210		45		15.42			0.7028		0.51224	+6.8
Model values	4.7		27		87		15.565			0.7137		0.51217	+5.7

Note: Pb, Rb, Sr, Sm, Nd in ppm. Uncertainties at 2σ level are less than 1%.

* Common Pb fractionation determined from replicate analyses of NBS SRM-981. Sr ratio adjusted to 0.71014 for NBS-987. Sm/Nd ratios corrected for instrumental discrimination based on $^{146}Nd/^{144}Nd=0.7219$. Analytical procedures for common Pb from Housh et al. (1989); for Rb/Sr from Popp et al. (1986); for Sm/Nd from Pier et al. (1989). Uncertainties for analyses at 2σ level are less than: 0.1, 0.01, and .03% for Pb/Pb, $^{87}Sr/^{86}Sr$, and $^{143}Nd/^{144}Nd$, respectively.

† $\varepsilon_{Nd}(T)$ is the deviation from the value expected in a chondritic reservoir (CHUR) at time T.

§ After Stacey and Stoeser (1983).

** After Harris et al. (1984). $\varepsilon_{Nd}(T)$ recalculated for the age of 594 +/- 4 Ma measured by Stern and Hedge (1985).

†† Crustal component has the Sr and Pb isotopic composition of the Kabid gneiss (Stacey and Agar, 1985), Sr concentration of the Kabid gneiss, 10 ppm Pb, and the Nd isotopic composition and concentration of Jabal Khida (Stacey and Hedge, 1984). Primitive melt has the Pb, Sr, and Nd isotopic composition of average mantle (DePaolo, 1981; Zartman and Doe, 1981; Faure, 1986). Pb, Sr, and Nd concentrations of the primitive melt are assumed. Bulk solid/liquid partition coefficients for the element between fractionating phases and magma (D_{Sr}, D_{Nd}, and D_{Pb}) are assumed to be 2.7, 0.5, and 0.8, respectively. r (rate of assimilation to rate at which fractionating phases are being removed) is 0.15. F (relative mass of magma remaining) is 0.25.

The initial ϵ_{Nd} for the Nakhil granite is +5.7 at 578 Ma; the depleted mantle model age (T_{DM}) (Nelson and DePaolo, 1985) is 690 Ma. The high initial ϵ_{Nd} would commonly be interpreted as indicating derivation from a depleted mantle source (e.g., Harris et al., 1984). Initial common Pb data for the Aswan granite are extremely radiogenic, plotting significantly above the mantle growth curves (Fig. 3). The Aswan granite has an initial ϵ_{Nd} of +1, distinctly lower than the Nakhil granite, and a T_{DM} of 984 Ma.

DISCUSSION

The use of Pb, Sr, and Nd isotopes provides valuable insights into the role of preexisting crust in the formation of the Arabian-Nubian shield. However, the independent use of these isotopic systems has led to some disagreement over the extent of involvement of preexisting continental crust in the formation of the juvenile assemblages of the shield. We view the origin of many granitic intrusions in the shield as resulting from interaction of primitive mafic melts with older crustal components. These melts probably resulted from partial melting of mantle-derived material that had a short residence time in the lower crust or the mantle itself. The crustal components could have been derived from an underlying pre–Pan-African basement or from detritus introduced from an adjacent continent. Thus, the signature for a given isotopic system will depend at least in part on the relative abundances of a daughter isotope both in the crust and in the primitive melt, and on the age of the crust. In general, the Pb isotopic system is the most sensitive to crustal interaction because of the large differences in Pb concentrations between primitive melts and older continental material. Lead contents of ensimatic rocks are commonly 1 ppm or less, whereas the lead contents of sialic continental crust are usually greater than 10 ppm (Stacey and Stoeser, 1983). In many cases, the Rb/Sr and Sm/Nd isotopic systems are less sensitive to crustal interaction than the U-Pb system because of the smaller differences in Sr and Nd concentrations between mantle and crustal components. Thus, by utilizing all three systems, one can gain insights into the amount and age of crustal components involved in the formation of granitic magmas.

Harris et al. (1984) noted that the Aswan granite had a "high" initial ϵ_{Nd} (+2.3) and a "low" initial $^{87}Sr/^{86}Sr$ (0.7033), which they stated were similar to recent mantle-derived rocks. Similarly, Stern and Hedge (1985) reported low initial $^{87}Sr/^{86}Sr$ of 0.7029 for the Aswan granite. Harris et al. (1984) noted that their conclusion was at odds with the radiogenic Pb signature of the Aswan granite and appealed to subduction processes or sample heterogeneity to explain the isotopic constrasts. Alternatively, the high Nd concentrations in the Aswan (68.9–72.2 ppm) and Nakhil (87 ppm) granites may reflect elevated concentrations in parental magmas that render them relatively insensitive to upper crustal interaction. The observed Nd concentrations are much higher than that reported for average granites (43.5 ppm; Faure, 1986). Likewise the elevated initial $^{87}Sr/^{86}Sr$ ratios for the Nakhil granite is best explained by its low content of Sr (15 ppm), which is much less than average values for granites (100–400 ppm; Faure, 1986). The Aswan granite has a higher concentration of Sr (173 ppm; Stern and Hedge, 1985), which is reflected in its lower initial $^{87}Sr/^{86}Sr$ values. The Nakhil granite has a relatively low whole-rock Pb concentration of 2.79 ppm, consistent with its radiogenic initial $^{207}Pb/^{204}Pb$ value. The Pb, Sr, and Nd concentrations and isotopic composition of the Nakhil granite can be modeled to a first order, as the product of simultaneous fractional crystallization of mafic to intermediate magmas and assimilation of crustal components, using equations described in DePaolo (1981) involving assimilation of approximately 20% of preexisting older crustal material (Table 2). Contrasting isotopic signatures reported from eastern Arabia might be accounted for in a similar manner, suggesting widespread involvement of older crustal components in the formation of the Arabian-Nubian shield. Rb/Sr, Sm/Nd, and common Pb data measured for the same samples will be required to better evaluate crustal contamination across the shield. Large variations in Nd, Sr, and Pb abundances may hold clues to the nature of the source regions and processes involved in granite formation in the shield.

CONCLUSIONS

1. Zircon U/Pb, feldspar common Pb, and Rb/Sr data indicate that a Middle to Early Proterozoic crustal component was involved in the formation of the ca. 578 Ma Nakhil gneissic granite. Common Pb data suggest a similar origin for the ca. 595 Ma Aswan granite. In contrast, extensive crustal contamination is not reflected in the high initial ϵ_{Nd} (+5.7) for the Nakhil and the low initial $^{87}Sr/^{86}Sr$ (0.7029) for the Aswan granite.

2. The high whole-rock Nd and Sr concentration for the Nakhil (87 ppm Nd) and Aswan (173 ppm Sr) suggest that the Nd and Sr isotopic composition of the older component may have been overshadowed by the more primitive material. Contrasting interpretations of common Pb and Sm/Nd data addressing the involvement of older crustal material in eastern Arabia could be explained in the same manner. Thus, the independent use of Sm/Nd or Rb/Sr systematics as indicators of contamination with older crustal components in the Arabian-Nubian shield should be considered with caution.

3. Our results for the Nakhil and Aswan granite, together with published isotopic data, indicate that (1) ensimatic models that envision the Arabian-Nubian shield or large domains within it as entirely formed of juvenile oceanic material are oversimplified; (2) an accurate assessment of the extent of involvement of older crustal components in the formation of the shield is needed to arrive at realistic arc addition rates; and (3) if an important process in assembly of continents is thrusting of juvenile assemblages onto older cratons, then crustal growth rates based on exposed outcrops in these areas will be overestimated.

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