Contribution of pre Pan-African crust to formation of the Arabian Nubian Shield: New secondary ionization mass spectrometry U-Pb and O studies of zircon

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ABSTRACT

New secondary ionization mass spectrometry U-Pb and O isotope analyses of detrital zircons from the Sa'al schist in Sinai coupled with whole-rock Nd isotopic analyses provide new evidence of pre-Neoproterozoic crust in the northernmost Arabian-Nubian Shield (ANS). The detrital zircon age population is bimodal, with concordia ages of 1029 ± 7 Ma and 1110 ± 8 Ma. The whole-rock ε_{Nd}(t = 1.0 Ga) value of +2 is significantly lower than found for juvenile Neoproterozoic rocks in the region. Thus, the Sa'al schist is interpreted to represent Kibaran (Grenville) age crust incorporated into the northernmost ANS. The $\delta^{18}O$ (zircon) values (6.1‰–9.4‰) imply that supracrustal recycling was involved in the formation of this ca. 1.0–1.1 Ga crust. A compilation of reported xenocrystic and detrital pre-ANS zircons and the variability of Nd, Sr, Pb, and O isotopic compositions within the shield suggests that its northernmost and eastern margins were more strongly contaminated by older crust ca. 0.9–3.0 Ga old. The distribution of 0.9–1.1 Ga xenocrystic and detrital zircons mainly in the east and north of the ANS suggests that such crust characterized parts of the northeastern margin of western Gondwana prior to ANS formation, and that 0.9–1.1 Ga old zircons detected in lower Paleozoic sandstone cover may have a proximal provenance.

INTRODUCTION

The Arabian-Nubian Shield (ANS) forms one of the largest exposures of juvenile continental crust on Earth. The ANS evolved during the Neoproterozoic East African orogeny (870–550 Ma ago), and is generally viewed as a collage of juvenile volcanic arc terranes and ophiolite remnants amalgamated during the assembly of the eastern part of Gondwana (Bentor, 1985; Stern, 1994, 2002; Stein and Goldstein, 1996). Some reworked older crust flanks the ANS margins (Stacey and Hedge, 1984; Whitehouse et al., 2001; Abdelsalam et al., 2002), but radiogenic isotope ratios (Nd-Sr-Pb) from the ANS core region (Fig. 1) have traditionally been interpreted to show a lack of involvement of pre-Neoproterozoic crust in its formation (Stein and Goldstein 1996; Stern, 1994, 2002). Nevertheless, a large number of pre–870 Ma inherited zircons (0.9–3.0 Ga) within the ANS core magmas (Sultan et al., 1990; Kröner et al., 1992; Kennedy et al., 2004; Hargrove et al., 2006; Ali et al., 2009) and sediments (Dixon, 1981; Wilde and Youssef, 2002; Avigad et al., 2007) has been reported. Hargrove et al. (2006) defined a "contaminated shield" region (Fig. 1) that encompasses a third of the ANS by including localities where such pre-ANS zircons have been detected.

Evaluating the extent of pre-ANS crustal input into the shield's core region carries important implications for the ongoing debate regarding its origin and evolution, because this affects critically models of crustal accretion rates and the interpretation of the Nd, Sr, Pb, and O isotope compositions of ANS rocks. Of similar importance is identifying the age of such pre-ANS crustal components and trying to correlate these with known exposures of cratonic material at its flanks. Among the pre-ANS zircons, those of Kibaran (Grenvillian, ca. 1.0–1.4 Ga) and early Neoproterozoic (0.9–1.0 Ga) ages are of particular interest. While older zircons could be derived from the ANS flanks, the nearest Kibaran crust is exposed ~3000–2000 km to the south and 0.9–1.0 Ga crust is also not known in the vicinity of the shield.

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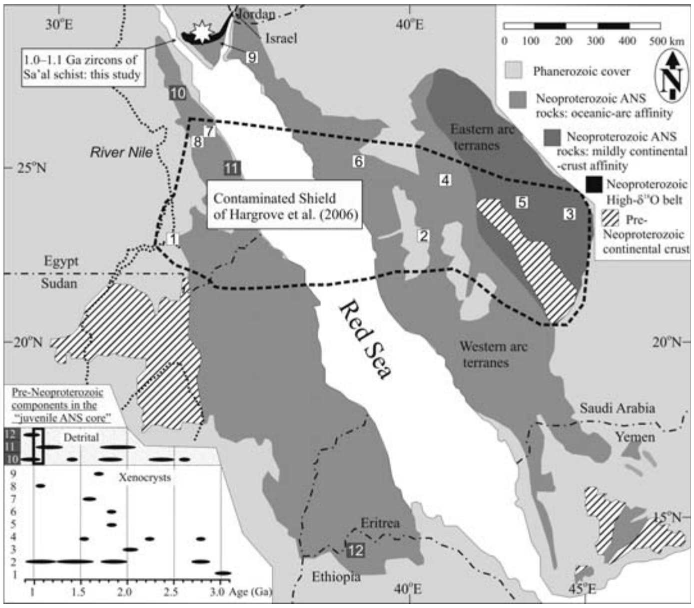

Figure 1. Map of Arabian-Nubian Shield (ANS) modified after Hargrove et al. (2006) and Stoeser and Frost (2006) showing location of Sa'al schist, and "contaminated shield" region of Hargrove et al. (2006). ANS core division into oceanic arc versus mildly continental crust affinity regions follows Hargrove et al. (2006, and references therein). High $\delta^{18}O$ belt is from Be'eri-Shlevin et al. (2009). Data for inset: 1—Kröner et al. (1992); 2—Hargrove et al. (2006); 3—Calvez et al. (1985); 4, 5, and 6—Kennedy et al. (2004); 7—Sultan et al. (1990); 8—Loizenbauer et al. (2001); 9—Ali et al. (2009); 10—Wilde and Youssef (2002); 11—Dixon (1981); 12—Avigad et al. (2007).

In this work, we present new ion-microprobe U-Pb and $\delta^{18}O$ analyses of zircons accompanied by a whole-rock Nd isotope analysis from an andalusite-bearing schist (ca. 740 Ma old) of the northernmost ANS. The results of this work reveal a tract of Kibaran age crust that was incorporated into the northernmost ANS during middle Neoproterozoic time. The compilation of xenocrystic and detrital zircon ages reported from the ANS and the associated isotope ratios along with the new evidence presented here enable a reassessment of the extent of the "contaminated shield" of Hargrove et al. (2006).

GEOLOGICAL SETTING AND SAMPLE DESCRIPTION

The Sa'al complex of Sinai (Figs. 1 and 2) forms one of several ca. 820–740 Ma old metamorphic complexes exposed in the northernmost part of the ANS (Kröner et al., 1990; Kolodner et al., 2006). These include greenschist to amphibolite facies metasedimentary to metavolcanic sequences, gneisses, and locally migmatites, that were later intruded by

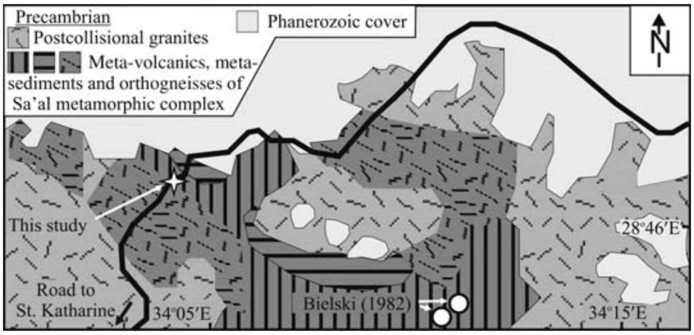

Figure 2. Simplified geological map of Sa'al metamorphic complex (modified after Eyal et al., 1980) showing location of samples from Bielski (1982) and this study.

several episodes of granitoid and dike magmatism, prior to continental-scale uplift, erosion, and deposition of a thick Paleozoic sedimentary cover (Bentor, 1985; Garfunkel, 1999). Four metavolcanic samples from the Sa'al metamorphic complex yielded an imprecise Rb-Sr age of 732 ± 120 Ma with Sr_i = 0.7033 ± 0.0028 (mean square of weighted deviates, MSWD = 3.1; recalculated from Bielski, 1982).

Sample YBS-401 is a metapelitic siltstone from the northernmost part of the Sa'al complex in southern Sinai collected at a road cut at 28°46′10″N, 34°04′17″E (Fig. 2). The rock comprises fine-grained quartz, feldspar, mica, and opaques that define fine-scale foliation with minor folding. Large andalusite (centimeter size) pseudomorphs are abundant.

RESULTS

Analytical methods along with U-Pb, $\delta^{18}O$, and Sm-Nd data are presented in the GSA Data Repository[1].

U-Pb Dating

Detrital zircons from sample YS-401 vary in size from 60 to 150 µm and are euhedral to slightly rounded. The majority of zircons exhibit bright oscillatory zoning under cathodoluminescence (CL), but some sector zoning was also observed. The CL responses, U contents (50–370 ppm), and Th/U ratios of 0.3–1.2 (0.7 on average) indicate that these are magmatic, nonmetamorphic zircons in origin. The $^{207}Pb/^{206}Pb$ ages span the range 930–1130 Ma, but a bimodal age distribution on the concordia diagram (Fig. 3A) is interpreted in terms of two magmatic events. Of 14 common Pb corrected analyses, three zircon cores yielded a concordia age of 1110 ± 8 Ma (MSWD = 2.2). Another seven analyses of cores and rims from other grains yielded a concordia age of 1029 ± 7 Ma (MSWD = 1.9); of the remaining four analyses, two are normally discordant and are interpreted to represent zircons that have undergone minor lead loss, and two are reversely discordant analyses that are probably slightly overcorrected for common Pb (Fig. 3A). Both age populations include euhedral grains as well as slightly rounded ones.

Nd Isotope Data

A single whole-rock Sm-Nd analysis of the Sa'al schist yielded a $^{143}Nd/^{144}Nd$ value of 0.512267 ± 15 and a $^{147}Sm/^{144}Nd$ value of 0.1223 ± 6. The maximum constraint for the deposition of the Sa'al schist sediment protolith is given by the age of the youngest magmatic event determined by U-Pb zircon dating in this study (i.e., 1029 ± 7 Ma). Figure 3B shows

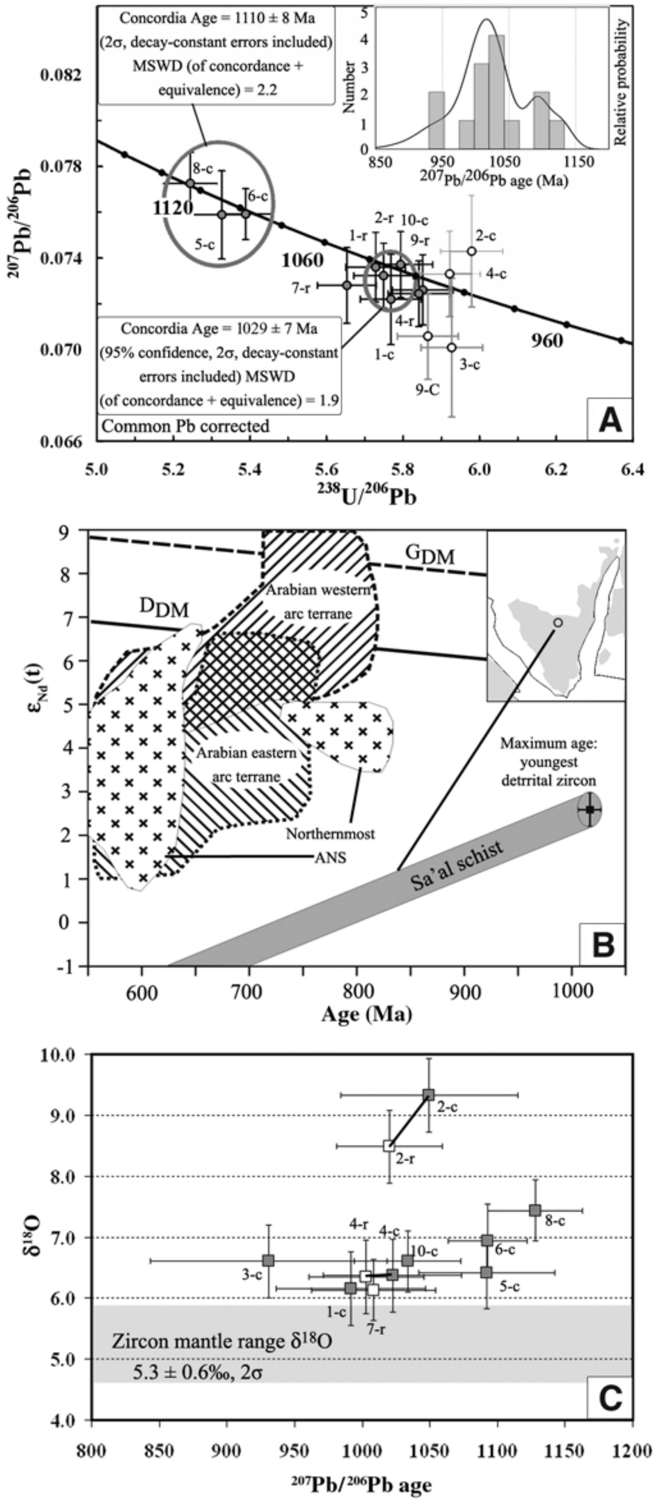

Figure 3. A: Tera-Wasserburg concordia diagram showing dated zircons of Sa'al schist. Inset shows relative probability of $^{207}Pb/^{206}Pb$ ages. B: $\varepsilon_{Nd}(t)$ versus age for Arabian-Nubian Shield (ANS) rocks and the Sa'al schist. C: $\delta^{18}O$ versus $^{207}Pb/^{206}Pb$ age for Sa'al schist zircons. MSWD—mean square of weighted deviates.

the evolution of $\varepsilon_{Nd}(t)$ versus age for the Sa'al schist from ca. 1.03 Ga ago, along with fields for the Arabian Shield (Stoeser and Frost, 2006) and for the northernmost ANS (Stein and Goldstein, 1996; Stern, 2002; Moussa et al., 2008). The $\varepsilon_{Nd}(t)$ range for the Sa'al schist plots significantly lower than the two ANS fields, defining a different crustal evolution for this rock unit.

[1]GSA Data Repository item 2009226, methods, Table DR1 (U-Th-Pb and O analytical data for zircons of sample YBS-401), Table DR2 (whole rock Sm-Nd data for sample YBS-401), and Figure DR1 (CL images of zircons from sample YBS-401), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

O Isotope Data

The $\delta^{18}O$ values of 11 U-Pb dated core and rim zones of zircons range from 6.1‰ to 9.4‰ (associated with 0.6‰–0.8‰ errors, 2σ; Fig. 3C). While three analyses from both age populations plot significantly above the mantle range for zircon [$\delta^{18}O$ (Zrn) = 5.3‰ ± 0.6‰, 2σ; Valley et al., 1998], the rest plot above this range with slight overlap (Fig. 3C). Two analyzed core-rim pairs show distinctly different characteristics. The core-rim pair of grain 4 have virtually the same $\delta^{18}O$ (Zrn) value, which is similar to all younger age (i.e., ca. 1.0 Ga) zircons. In contrast, the $\delta^{18}O$ (Zrn) values of the core-rim pair of grain 2 are higher than all other zircon domains and thus may correspond to a high $\delta^{18}O$ magmatic source.

EXTANT TRACT OF KIBARAN AGE CRUST IN THE NORTHERNMOST ANS

Two important features characterize the dated zircons of the Sa'al schist: (1) the dominance of 1.0–1.1 Ga old sources is established, although cores and rims of only 11 grains were dated in this study; (2) the zircons are euhedral to subrounded regardless of age. Kibaran age crust typifies an orogenic belt in central Africa, and crust of this age is generally not known north of Tanzania, apparently requiring a very distal provenance for the Sa'al schist zircons. However, in this case we would expect to find other pre-Neoproterozoic zircons within this population. The occurrence of clearly euhedral grains within the older (ca. 1.1 Ga) and younger (ca. 1.0 Ga) populations also argues against a distal source. The exclusively 1.0–1.1 Ga zircon ages as well as the low $\varepsilon_{Nd}(t)$ of the Sa'al schist suggest that this unit represents a tract of Kibaran age crust or sediments dominated by detritus shed from it. The high $\delta^{18}O$ (Zrn) values measured for some of these originally magmatic (i.e., nonmetamorphic) zircons implies that supracrustal material was recycled into to the magmas that generated this Kibaran age crust.

KIBARAN AGE CRUST IN THE JUVENILE ANS CORE AND FLANKS

Kibaran age zircons have been reported in several localities within the shield (Dixon, 1981; Teklay et al., 1998; Loizenbauer et al., 2001; Hargrove et al., 2006; Avigad et al., 2007; Fig. 1 inset). Generally, where found, Kibaran and early Neoproterozoic (0.9–1.0 Ga) age zircons form <15% of the detrital and xenocrystic population; other components are in the age range of 1.5–2.2 Ga and more rarely 2.6–3.0 Ga. The dominance of the Kibaran age zircons and specifically the lack of other pre-Neoproterozoic ages in the Sa'al schist are taken as evidence for the existence of such crust in close proximity to the ANS. Similar conclusions were reached by Avigad et al. (2007), who studied the Negash and Shiraro sedimentary sequences from northern Ethiopia at the other end of the ANS. However, the latter are dominated by detrital zircons younger than ca. 0.95 Ga old, and contain only a small fraction (2.5%–15%) of the ca. 0.95–1.1 Ga zircons.

Xenocrystic and detrital zircons of Paleoproterozoic–Archean age detected in the ANS core may have been derived from cratonic segments located at the ANS flanks (i.e., parts of Yemen, the Khida terrane, and the Saharan metacraton; Whitehouse et al., 1998, 2001; Abdelsalam et al., 2002), but 0.9–1.4 Ga zircons are more difficult to explain since no in situ crust within the 0.9–1.1 Ga range has yet been reported in the vicinity of the ANS.

Nevertheless, the proximal provenance assigned for the zircons from the Negash-Shiraro and the Sa'al sedimentary protoliths as well as the other occurrences of Kibaran age zircons in xenocryst and detrital populations all attest to crust of this age having existed very close to the ANS. Such crust could have characterized parts of the northeastern flank of western Gondwana prior to ANS formation. The occurrence of ca. 1 Ga old zircons in peri-Gondwanan terranes of the Eastern Mediterranean (Keay and Lister, 2002; Zulauf et al., 2007) is in accord with such an interpretation. Kibaran age zircons form a pattern of decreasing abundance to the east; thus, such sediments were probably shed into the forming ANS from the south, west, and northwest.

IMPLICATIONS FOR ANS FORMATION MODELS

Several authors suggested that the ANS core may be more contaminated with pre-Neoproterozoic crust than previously thought (Sultan et al., 1990; Hargrove et al., 2006; Stoeser and Frost, 2006). The detection of pre-Neoproterozoic zircons in the Sa'al schist expands the "contaminated shield" region defined by Hargrove et al. (2006), and with the evidence from northern Ethiopia (Teklay et al., 1998; Avigad et al., 2007) it now encompasses most of the ANS. However, in Arabia the "contaminated shield" covers parts of both the western and eastern arc terranes, which are characterized by Pb, Sr, Nd, and O isotope compositions of oceanic arc versus more continental-crust–like affinity, respectively (Stoeser and Frost, 2006). In a study of the Bi'r Umq suture of the western arc terrane, Hargrove et al. (2006) could find little correlation between pre-Neoproterozoic inheritance and lower $\varepsilon_{Nd}(t)$ values, but such correlation does exist in the part of the "contaminated shield" that overlaps the eastern arc terrane. The $\varepsilon_{Nd}(t)$ values of the northernmost ANS are comparable with those of the eastern arc terrane of Arabia (Fig. 3B) and correlate with high $\delta^{18}O$ values (Be'eri-Shlevin et al., 2009; Fig. 1) and with the finding of extant Kibaran age crust in this region. Mixing of Neoproterozoic oceanic crust with older cratonic material has been suggested as a possible mechanism to explain the isotopic compositions of the eastern arc terrane (Stoeser and Frost, 2006), thus it is not surprising that pre-Neoproterozoic zircons ca. 1.8–3.0 Ga old were found there. The Nd and O isotopic compositions of the northernmost ANS probably also reflect significant contribution from pre-Neoproterozoic components. Mixing with a crustal component such as the Kibaran crust represented by the Sa'al schist could explain the mildly enriched $\varepsilon_{Nd}(t)$ and high $\delta^{18}O$ values of the northernmost ANS rocks. The lack of correlation between the occurrence of pre-ANS zircons and isotopic composition of oceanic-arc affinity in the Arabian western arc terrane and in parts of the Nubian Shield (Sultan et al., 1990) probably reflects the fact that only minor amounts of pre-ANS material contaminated this region, enough to be traced by zircon U-Pb dating but hardly sufficient to affect the Nd isotopic composition (Hargrove et al., 2006).

As concluded by Hargrove et al. (2006), the ANS core is less juvenile than previously thought, and estimation of the ANS crustal accretion rates should be revised. However, the division between juvenile versus contaminated regions as defined here is significantly different from that suggested by Hargrove et al. (2006). The association of pre-Neoproterozoic tracts with mildly enriched $\varepsilon_{Nd}(t)$, high $\delta^{18}O$ values, and pre-ANS zircon inheritance in the Arabian eastern arc terrane and the northernmost ANS defines a more strongly contaminated shield. In the rest of the ANS only minor contamination occurred. One important implication from this division is that smaller parts of the ANS incorporated significant amounts of older material than considered by Hargrove et al. (2006), and these parts are located at its margins in association with pre-Neoproterozoic crustal tracts. Another important implication is that the above division correlates pre-Neoproterozoic inheritance with the composition of isotopic tracers such as Nd.

PROVENANCE OF THE ANS PALEOZOIC COVER SEDIMENTS

Recent studies of the Cambrian–Ordovician sandstones blanketing the northern Arabian–Nubian Shield have shown that 0.9–3.0 Ga old zircons are a prominent component of the detrital zircon age spectra of this terrane (Avigad et al., 2003; Kolodner et al., 2006). Avigad et al. (2003) suggested that the enigmatic 0.9–1.1 Ga zircons in this population may represent zircons reworked from far-traveled ice-rafted material, but considered the possibility of hidden sources from within the shield. The data presented in this work clearly identify a possible proximal source for such zircons. Moreover, the growing evidence for 0.9–3.0 Ga zircons within Neoproterozoic ANS magmas and sediments implies that the shield is a plausible source terrane for all the material within the cover sandstones, and that there is no need to evoke distal provenance.

CONCLUSIONS

The detection of 1.0–1.1 Ga old zircons in the Sa'al schist along with the low $\varepsilon_{Nd}(t)$ of this rock provides new evidence that pre-Neoproterozoic crustal terranes were involved in the generation of the northernmost ANS. The $\delta^{18}O$ (Zrn) values imply that the 1.0–1.1 Ga magmatic events involved supracrustal recycling, and thus this is not a juvenile terrane.

The distribution of pre-ANS xenocrystic and detrital zircons found within the shield points to an important crustal component ca. 0.9–1.1 Ga, that probably occupied parts of the northeastern margin of western Gondwana prior to the ANS formation. Compilation of reported data for pre-ANS zircons and Nd, Sr, Pb, and O isotope ratios of ANS rocks redefines the "contaminated shield" area of Hargrove et al. (2006). A strongly contaminated shield occupies less than one-third of the ANS. Because pre-ANS zircons are abundant throughout the shield, there is no need to evoke distal provenance for pre-ANS zircons in the Paleozoic sandstone cover.

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