Journal of African Earth Sciences 34 (2002) 109–117

Journal of African Earth Sciences

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Crustal evolution in the East African Orogen: a neodymium isotopic perspective

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Received 15 December 2000; accepted 30 October 2001

Abstract

The East African Orogen (EAO) is one of Earth's great collision zones, where East and West Gondwana collided to form the supercontinent 'Greater Gondwana' or 'Pannotia' at the end of Neoproterozoic time. There is now sufficient Nd isotopic data for basement rocks of the EAO to yield a useful summary. A total of 449 samples were gleaned from the literature, recalculated to a common value for the La Jolla Nd standard, and entered in Excel spreadsheets. This data set was filtered to exclude samples with $^{147}Sm/^{144}Nd > 0.165$, considered to yield unreliable model ages, leaving 413 suitable data. The crust of the Arabian–Nubian Shield, including Egypt east of the Nile, Sudan east of the Keraf suture, Sinai, Israel, Jordan, most of Arabia, Eritrea, and northern Ethiopia yields overwhelmingly Neoproterozoic model ages. Crust to the east, in the Afif terrane of Arabia, Yemen, Somalia, and Eastern Ethiopia yields much older model ages, averaging 2.1 Ga, demonstrating an abundance of reworked ancient crust. This provides an isotopic link with Madagascar (mean age of 2.4 Ga), which in pre-Jurassic reconstructions lies on the southern extension of this older, remobilized tract. Crust in the far southern extreme of the EAO in Tanzania also yields ancient model ages, averaging 2.3 Ga. The central EAO, in southern Ethiopia and Kenya, yields intermediate ages (mean 1.1–1.2 Ga), interpreted to indicate extensive mixing between Neoproterozoic mantle-derived melts and ancient crust. The Nd isotope data indicate that the northern EAO is composed of juvenile Neoproterozoic crust sandwiched between reworked older crust, whereas the EAO farther south is progressively dominated by ancient crust reworked during Neoproterozoic time. The distribution of juvenile and reworked ancient crust suggests that the most intense collision between East and West Gondwana occurred in the southern part of the EAO.

Keywords: East African Orogen; Nd isotopes; Neoproterozoic; Crustal evolution

1. Introduction

The East African Orogen (EAO) marks one of earth's greatest collision zones, a global feature in space (about 6000 km long where it is preserved in Africa and Antarctica and in time (350 million years of evolution; Stern, 1994; Jacobs et al., 1998; Kröner et al., 2000a,b). The EAO marks the disappearance of a major ocean basin (the Mozambique Ocean), the formation of a vast tract of juvenile Neoproterozoic continental crust (Vervoort and Blichert-Toft, 1999), and where East and West Gondwana joined (Rogers et al., 1995). The great rifts of Africa, the Red Sea, and the Indian Ocean itself were spawned along the EAO. The EAO is hemispheric in scale, and understanding a feature of this magnitude is a tremendous challenge.

Work in the EAO over the past quarter century has leapfrogged from country to country, with major advances in understanding which began 25 years ago in the north (Saudi Arabia, Egypt, and Sudan). Efforts to understand the EAO are returning to focus on the areas where Holmes' (Holmes, 1951) original study was concentrated, and results are now coming out of Ethiopia, Eritrea, Tanzania, and Madagascar. In addition, new insights are resulting from studies in the Egyptian basement, and new initiatives are expected from the newly formed Saudi Geologic Survey. The geographic separation of nations where EAO studies are now more vigorously advancing stimulates healthy competition and dialog. The hemispheric scale of the EAO challenge indicates that leading 'Pan-African' geologists will be those who are most knowledgeable of the geology of neighboring nations as well as their own.

In this spirit, the present review focuses on the growing body of Neodymium isotopic data for the EAO.

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PII: S0899-5362(02)00012-X

This is one of the most promising and rapidly evolving fields of inquiry for understanding the entire EAO. Most of this data has been presented in the six years since my previous review (Stern, 1994). The database has grown to the point where such a review would be useful and of interest to a broader scientific audience, including those interested in the global problem of crustal evolution as well as how the EAO formed. This approach also has the advantage of presenting the EAO in its entirety.

2. Nd isotopic mapping and the identification of juvenile and remobilized crust

Although the technique has existed for a quarter of a century, it is useful to review some fundamentals of Nd isotopic applications. More detailed presentations can be found in DePaolo (1988) and Dickin (1995). Samarium-147 undergoes alpha-decay to Neodymium-143, with an accepted decay constant of 6.54×10^{-12} year^{-1}. Neodymium isotopic data are reported relative to Neodymium-144, which is a stable isotope. Rocks or minerals which have had high Sm/Nd (approximately proportional to $^{147}\text{Sm}/^{144}\text{Nd}$) for long periods of time will have higher, more radiogenic $^{143}\text{Nd}/^{144}\text{Nd}$ than rocks or minerals with low Sm/Nd. The Sm/Nd ratio varies inversely with enrichment of the light rare earth elements (LREE), so that LREE-enriched samples have relatively low Sm/Nd. A sample with a chondritic REE pattern corresponds to $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$, values which are also taken to be those of the bulk earth.

The REE are strongly fractionated during formation of juvenile crust, either directly upon melting of the mantle to form mafic crust or by two stage melting or melting and fractionation to form felsic crust (Ben Othman et al., 1984). This results in strong enrichment of LREE in the crust, which greatly slows the growth of radiogenic Nd. It is a simple matter to calculate the Nd isotopic composition of an igneous rock whose age is known. This initial isotopic composition can be compared with the isotopic composition of the mantle at the same time, using the epsilon (ε_{Nd}) notation. The ε_{Nd} of a sample at the time of its formation—denoted $\varepsilon_{\text{Nd}}(t)$, where t is the age of the sample—is calculated by comparing the initial $^{143}\text{Nd}/^{144}\text{Nd}$ of the rock with the isotopic composition of a chondritic bulk earth at that time ($\varepsilon_{\text{Nd}}(t) = [^{143}\text{Nd}/^{144}\text{Nd}_{\text{sample}}(t) - {}^{143}\text{Nd}/^{144}\text{Nd}_{\text{BE}}(t)] \times 10^4$). Nd 'model ages' can also be calculated to estimate when important fractionations of Sm and Nd due to mantle melting occurred; these calculations are discussed further below. All the data that is needed to obtain the $\varepsilon_{\text{Nd}}(t)$ of a sample is the age of the rock, its contents of Sm and Nd, and its present Nd isotopic composition; only the last two are needed to calculate a Nd model age.

It has been observed that the isotopic composition of the upper mantle as inferred from modern volcanic rocks derived from asthenospheric sources has been depleted in LREE relative to the bulk earth for a long time and thus has evolved strongly positive ε_{Nd}. For example, mid-ocean ridge basalts typically have $\varepsilon_{\text{Nd}} = +8$ to $+12$, whereas lavas erupted from juvenile island arcs average about $+8.5$. Oceanic within-plate basalts have a wide range of Nd isotopic compositions but the largest volumes cluster about $+8$. The formation of juvenile continental crust today is concentrated at island arcs, with a subordinate proportion being added from accreted oceanic plateaus, and so has a $\varepsilon_{\text{Nd}} \sim +8$. This is also thought to be the origin of the juvenile terranes of the EAO.

3. Compilation of neodymium isotopic data for the EAO

Data necessary to calculate Nd model ages were compiled from the literature, dissertations, and a few unpublished results. All data that could be found for Precambrian basement rocks from Jordan, Israel, Arabia, Yemen, Madagascar, Eritrea, Ethiopia, Somalia, Kenya, and Tanzania were included (Fig. 1). Data for Egypt are limited to outcrops east of the Nile, while samples from Sudan are limited to those from east of the Keraf zone (Abdelsalam et al., 1998). Data for the crustal tract west of the Arabian–Nubian shield are specifically excluded from this compilation but are discussed in a companion paper (Abdelsalam et al., 2002). A total of 449 samples were entered into a spreadsheet database (Excel) [1], which include other information as well, such as $\varepsilon_{\text{Nd}}(t)$ and $^{147}\text{Sm}/^{144}\text{Nd}$.

Nd model ages—sometimes referred to as 'crust formation ages'—should be calculated assuming derivation of juvenile crust from depleted, asthenospheric mantle. The model age is the time when the initial $^{143}\text{Nd}/^{144}\text{Nd}$ of the sample equalled that of its depleted mantle source (Fig. 2). These model ages are also known as depleted mantle model ages, denoted T_{DM}. Nd model age calculations thus depend on the model for the depleted mantle, and there are several of these published in the literature (see Dickin (1995) for a discussion). Important models are those of DePaolo and co-workers (Nelson and DePaolo, 1984; DePaolo, 1988) and that of Goldstein et al. (1984). The DePaolo and Goldstein models differ in that the Goldstein model is linear between $\varepsilon_{\text{Nd}} \sim +10$ today and $\varepsilon_{\text{Nd}} \sim 0$ at 4.6 Ga, whereas the DePaolo model is a quadratic expression ($\varepsilon_{\text{Nd}}(t) = 0.25t^2 - 3t + 8.5$). Using these different algorithms yields different model ages, with the Goldstein model ages being 100–200 million years older than DePaolo model ages for Neoproterozoic rocks. Clearly, any compilation of Nd

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[1] Electronic copies of these spreadsheets can be obtained from the author upon request (rjstern@utdallas.edu).

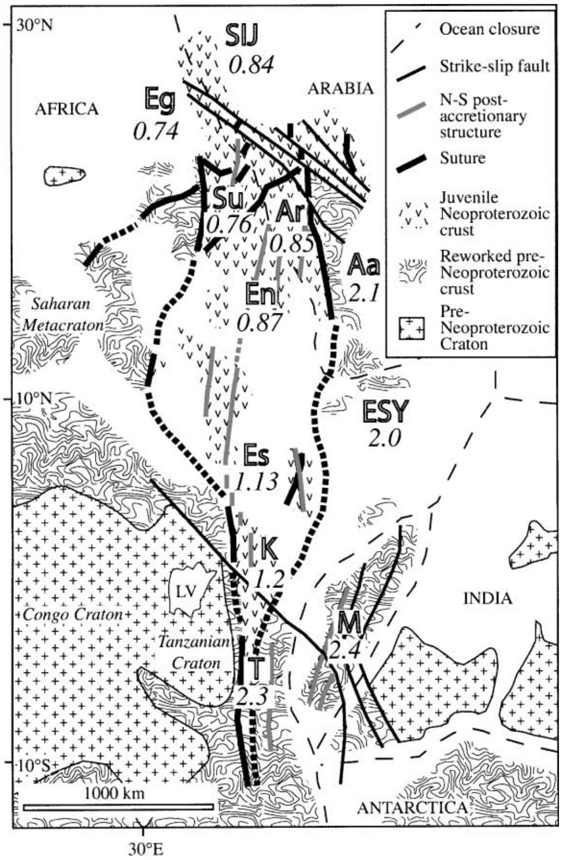

Fig. 1. Pre-Jurassic configuration of the EAO in Africa and surrounding regions, modified from Abdelsalam and Stern (1996). Regions referred to in text and data sets shown on corresponding figures: Egypt (Eg, Fig. 3a); Sinai–Israel–Jordan (SIJ; Fig. 3b); Afif terrane, Arabia (Aa, Fig. 4); Rest of Arabian Shield (Ar, Fig. 4); Sudan (Su, Fig. 5a); Eritrea and northern Ethiopia (En, Fig. 5b); Eastern Ethiopia, Somalia, and Yemen (ESY, Fig. 6); Southern Ethiopia (Es, Fig. 7a); Kenya (K, Fig. 7b); Madagascar (M, Fig. 8); Tanzania (T, Fig. 9). Numbers in italics beneath each region letter are the mean Nd-model ages shown in Figs. 3–9.

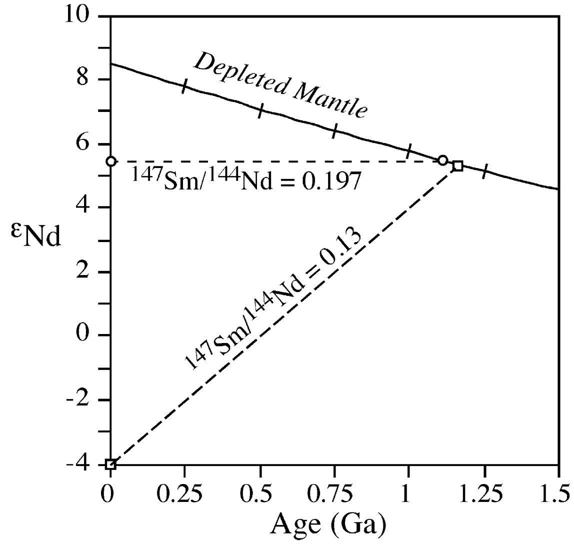

Fig. 2. Illustration of how Nd model ages are calculated. The depleted mantle evolution curve is that of Nelson and DePaolo (1984). The intersection of the sample evolution line (dashed) and the mantle evolution line (solid) yields the model age. Two examples with different $^{147}Sm/^{144}Nd$ are shown to highlight uncertainties attendant the calculation of model ages for samples with high Sm/Nd. The sample with lower $^{147}Sm/^{144}Nd$ intercepts the mantle evolution curve at a high angle, so uncertainties in the real isotopic composition of the mantle source translate into relatively small differences in model ages. The sample with the high $^{147}Sm/^{144}Nd$ intercepts the mantle curve at a low angle, so that uncertainties in the composition of the mantle source translate into relatively large differences in model ages. In general, the lower the $^{147}Sm/^{144}Nd$, the more robust the model age.

model ages must recalculate all data using the same model. The DePaolo model is selected here, for two reasons. First, it assumes a more realistic ε_{Nd} of the source of arc and oceanic plateau basalts (+8.5 vs. +10), so that extrapolation back in time can also be expected to be more realistic. Second, a wide range of well-dated, non-ophiolitic rocks from the Arabian–Nubian Shield which are thought to be juvenile, plot within ±1 epsilon unit of the DePaolo curve—that is, their crystallization ages are very close to their model ages, as expected for juvenile rocks, whereas Goldstein model ages are 100–200 million years older than the crystallization ages of magmatic rocks thought to be juvenile additions to the crust.

Isotopic data should be adjusted to a common value for the laboratory standard so that interlaboratory bias can be overcome. Most labs report values for the La Jolla standard, and with this information we have adjusted the value for the 'chondritic uniform reservoir' needed to calculate ε_{Nd}, using values for the La Jolla Nd Standard ($\varepsilon_{Nd} = -15.2$) reported by Pier et al. (1989) which is then used to calculate a Bulk Earth $^{143}Nd/^{144}Nd$ appropriate for the sample. In a few cases, only values for the Merck standard are reported. For these, we take a value of La Jolla $^{143}Nd/^{144}Nd = 0.511863$ as equivalent to $^{143}Nd/^{144}Nd = 0.511735$ for the Merck standard, by adjusting the results of Wasserburg et al. (1981) to a value of 0.7219 for $^{146}Nd/^{144}Nd$.

Another important point in this compilation is that samples with high Sm/Nd give unreliable Nd model ages and should be excluded. Nd model ages are most robust when the $^{147}Sm/^{144}Nd$ is low, as discussed in the figure caption of Fig. 2. At what Sm/Nd data should be excluded is difficult to decide; samples with $^{147}Sm/^{144}Nd > 0.165$ have been excluded from this compilation reported. A total of 415 samples pass this filter, or about 90% of the data. Excluded samples mostly come from the Arabian–Nubian Shield. Another two samples, from the southern EAO, gave unrealistic model ages and so were also excluded, leaving a total of 413 samples on which the compilation is based.

A final note: Nd model ages should never be confused with crystallization age as inferred from geochronology, or for that matter the actual time that the crust separated from the mantle. It is an estimate that should be taken with caution, especially considering the uncertainties in

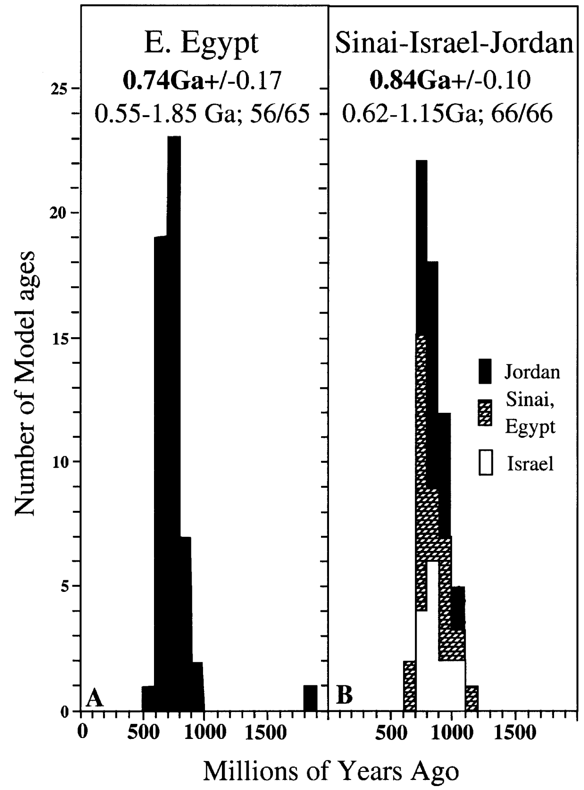

Fig. 3. Histograms of Nd model ages for E. Egypt, Sinai, Israel, and Jordan. (a) Egypt east of the Nile, excluding Sinai (Eg in Fig. 1). Data sources: (Furnes et al., 1996; Harris et al., 1984; Sultan et al., 1990; Stern et al., 1991; Landoll and Foland, 1994; Brueckner et al., 1995; Zimmer et al., 1995; Moghazi, 1999). (b) Sinai–Israel–Jordan (SIJ in Fig. 1). Data sources: (Brook et al., 1990; Beyth et al., 1994; Stein and Goldstein, 1996; Moghazi et al., 1998; Jarrar et al., submitted for publication; Stern, unpublished data). Bold numbers are means for the population, ±1 standard deviation. Range of model ages for the population is also given. Numbers separated by '/' denote samples with $^{147}Sm/^{144}Nd < 0.165$ used in calculating the mean and 1 standard deviation and the total number of samples.

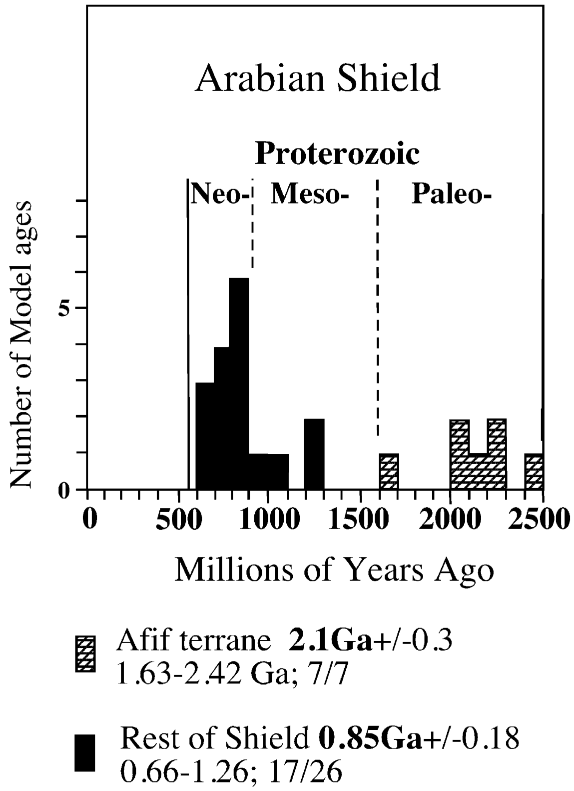

Fig. 4. Histogram of Nd model ages for the Arabian Shield. Data sources: (Bokhari and Kramers, 1981; Duyverman et al., 1982; Stacey and Hedge, 1984; Agar et al., 1992). Mean ages for Afif terrane (Aa in Fig. 1) and the rest of the Shield (Ar in Fig. 1) are also shown. Bold numbers are means for the population, ±1 standard deviation. Range of model ages for the population is also given. Numbers separated by '/' denote samples with $^{147}Sm/^{144}Nd < 0.165$ used in calculating the mean and 1 standard deviation and the total number of samples.

what the composition of the mantle was at the time of interest, which we know to be very heterogeneous. Furthermore, the simplifying assumption of a single stage extraction of the crust from the mantle is inconsistent with multi-stage processes known to be important in generating granitic rocks, which dominate the data set. Nevertheless, if the composition of the mantle is reasonably well known and if the time between extraction of the primitive (mafic) crust and development of evolved granitic melts is relatively short, the Nd model age data set can provide useful insights into how the crust of a region formed. Histograms of Nd model ages are shown in Figs. 3–9 and form the basis for the following discussion.

4. Variations in neodymium model ages for the EAO

It has been known for some time that the Arabian–Nubian Shield is made up of juvenile crust, mostly from the abundance of non-radiogenic initial Sr isotopic compositions. The juvenile nature of the crust is confirmed by the Nd model ages from this region, which show a tight clustering of crust formation ages which are very close to the crystallization ages of the same rocks (Figs. 3–5). Data for Egypt (Fig. 3a) and Sudan (Fig. 5b) cluster tightly about 750 million years, and convincingly demonstrate that these crusts are dominated by juvenile additions from the mantle during Neoproterozoic time. Note that one sample from Egypt has a Nd model age of almost 2.0 Ga; this is a metasediment from near the Nile in southern Egypt, probably shed from pre-Neoproterozoic crust to the west. Crust in the northernmost EAO (Sinai, Israel, and Jordan; Fig. 3b) yields a similarly tight but slightly older cluster of Nd model ages. The significance of the slightly older Nd model ages of the Sinai–Israel–Jordan basement compared to that of E. Egypt and Sudan is not clear, but it is consistent with earlier inferences of a major Neoproterozoic crustal boundary approximating the present Gulf of Suez (Stern and Manton, 1987). Regardless of these differences, the crust of the E. Egypt–Sinai–Israel–Jordan region must

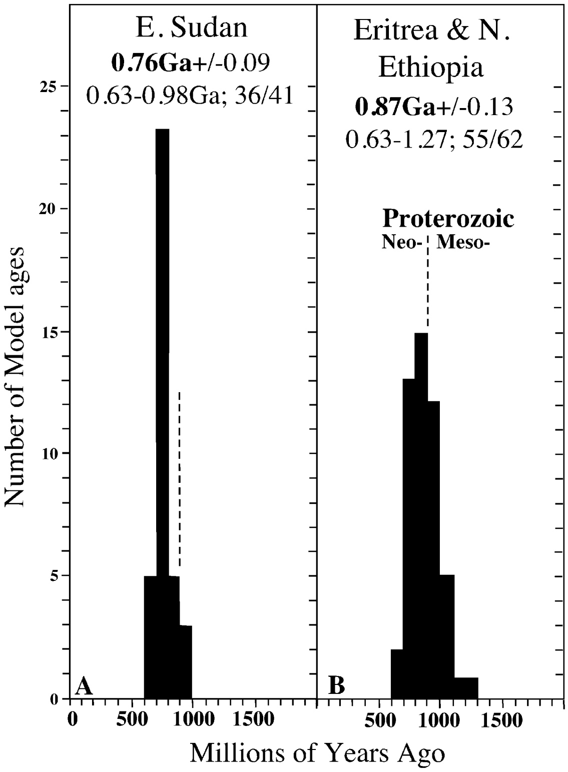

Fig. 5. Histogram of Nd model ages for Sudan, Eritrea, and N. and S. Ethiopia. (a) Sudan, east of the Keraf suture (Su in Fig. 1). Data sources: (Kröner et al., 1991; Stern and Dawoud, 1991; Stern and Kröner, 1993; Reischmann and Kröner, 1994; Stern and Abdelsalam, 1998). Dashed vertical line marks the Neoproterozoic–Mesoproterozoic boundary. (b) Eritrea and N. Ethiopia (En in Fig. 1). Data sources: (Beyth et al., 1997; Teklay, 1997; Tadesse et al., 2000). Bold numbers are means for the population, ±1 standard deviation. Range of model ages for the population is also given. Numbers separated by '/' denote samples with $^{147}Sm/^{144}Nd < 0.165$ used in calculating the mean and 1 standard deviation and the total number of samples.

be regarded as juvenile additions to the crust from the mantle in mid-Neoproterozoic time.

The Arabian Shield (Fig. 4) can be subdivided into older crust of the Afif terrane and juvenile Neoproterozoic crust of the rest of the Arabian Shield. The Nd-model ages for the Afif terrane cluster around 2.1 Ga, with no Archean model ages. This is consistent with zircon geochronological results indicating that Paleoproterozoic basement (1.6–1.8 Ga) underlies the Afif Terrane (Stacey and Hedge, 1984; Agar et al., 1992). The rest of the Arabian Shield yields mostly Neoproterozoic model ages but includes a few of Mesoproterozoic age. The significance of these older ages is not known, and in spite of this, the mean age of the Arabian Shield other than the Afif terrane is 0.85 Ga, similar to adjacent juvenile terranes in Jordan, E. Egypt, E. Sudan, Eritrea, and N. Ethiopia (Figs. 3 and 5a,b).

The status of Nd isotopic data from Arabia warrants comment. In spite of the fact that applications of modern isotopic techniques to the EAO began here, progress

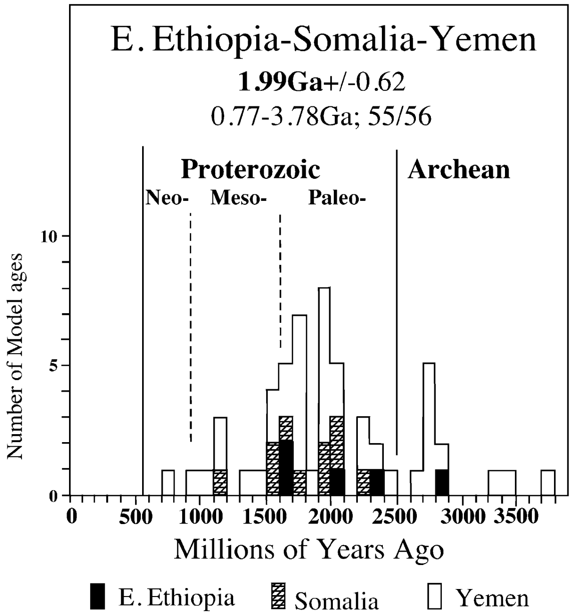

Fig. 6. Histogram of Nd model ages for E. Ethiopia, Somalia, and Yemen (ESY in Fig. 1). Data sources: (Lenoir et al., 1994; Windley et al., 1996; Whitehouse et al., 2001; Teklay et al., 1998). Bold numbers are means for the population, ±1 standard deviation. Range of model ages for the population is also given. Numbers separated by '/' denote samples with $^{147}Sm/^{144}Nd < 0.165$ used in calculating the mean and 1 standard deviation and the total number of samples.

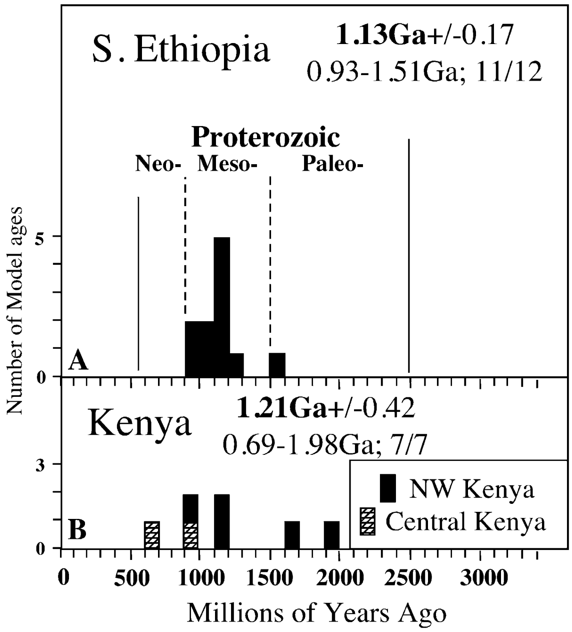

Fig. 7. Histogram of Nd model ages for S. Ethiopia and Kenya. (a) S. Ethiopia (Es in Fig. 1). Data sources: (Worku, 1996; Teklay et al., 1998). (b) Kenya (K in Fig. 1). Data sources: (Harris et al., 1984; Key et al., 1989). Bold numbers are means for the population, ±1 standard deviation. Range of model ages for the population is also given. Numbers separated by '/' denote samples with $^{147}Sm/^{144}Nd < 0.165$ used in calculating the mean and 1 standard deviation and the total number of samples.

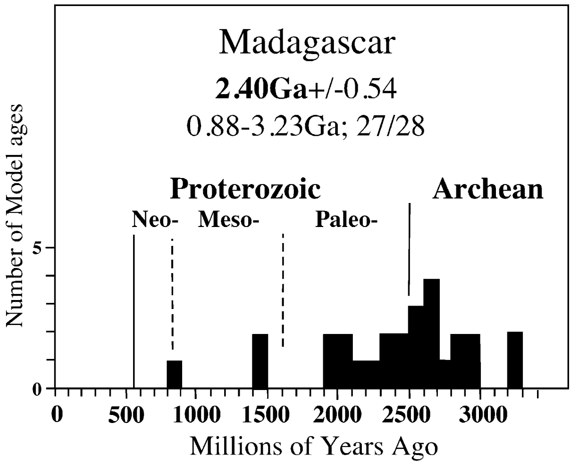

Fig. 8. Histogram of Nd model ages for Madagascar (M in Fig. 1). Data sources: (Paquette et al., 1994; Tucker et al., 1999; Kröner et al., 2000a,b). Bold numbers are means for the population, ±1 standard deviation. Range of model ages for the population is also given. All 28 samples have $^{147}Sm/^{144}Nd < 0.165$, but one sample (with $^{147}Sm/^{144}Nd < 0.1648$) gives an unrealistic Nd-model age of 4.38 Ga and so 27 are plotted and used for calculating the mean and 1 standard deviation.

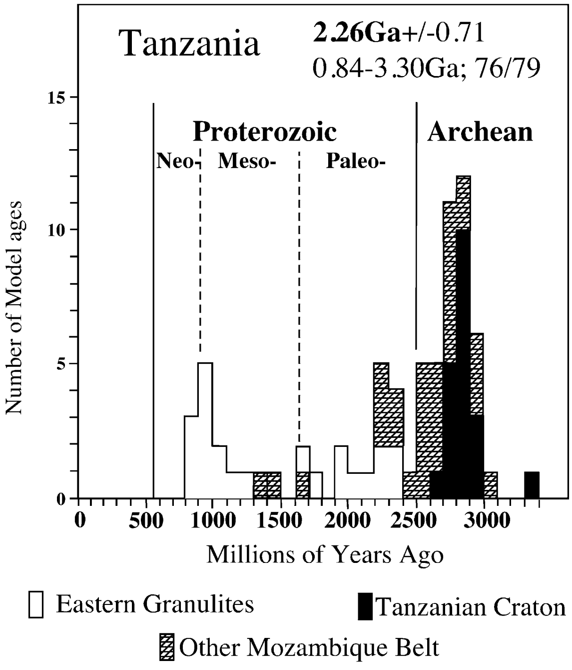

Fig. 9. Histogram of Nd model ages for Tanzania (T in Fig. 1). Data sources: (Maboko, 1995; Maboko and Nakamura, 1996; Möller et al., 1998; Maboko, 2000). Bold numbers are means for the population, ±1 standard deviation. Range of model ages for the population is also given. 77 samples out of a total of 79 have $^{147}Sm/^{144}Nd < 0.165$, but one sample gives an unrealistic Nd-model age of 4.92 Ga and so 76 are plotted and used for calculating the mean and 1 standard deviation.

since then has lagged to the point that there is a noticeable deficiency in data from this area compared to other parts of the EAO. Most of the Nd isotopic work done on the juvenile parts of the Arabian Shield was conducted in the mid-1980s. Much of the Nd data shown on Fig. 4 was obtained in order to better define the extent of the pre-Neoproterozoic Afif terrane in the eastern part of the Shield, so the spread of ages probably underemphasizes the abundance of juvenile crust. There is a need for a dedicated effort of Nd-isotopic mapping in the Arabian Shield to identify the regions underlain by pre-Neoproterozoic crust.

There has been a great increase in the Sm–Nd isotopic database for the EAO in Sudan, Ethiopia, Somalia, and Yemen. All of the data plotted in Figs. 5 and 6 were published in the last 10 years, and there are now over 170 basement samples from this region for which Nd isotopic data has been reported. Samples from E. Sudan define a tight cluster of Neoproterozoic model ages, with a mean of 0.76 Ga (Fig. 5b). Eritrea and northern Ethiopia define a similar tight cluster, with a mean of 0.87 Ga (Fig. 5b). This region is clearly underlain by juvenile Neoproterozoic crust and on this basis should be considered part of the Arabian–Nubian shield. There are no model ages from W. Ethiopia yet, but this is likely to change in the near future.

Samples from E. Ethiopia, Somalia, and Yemen give mostly older ages, with a mean of 2.0 Ga (Fig. 6), similar to the mean for the Afif terrane in Arabia and only slightly younger than the means for Tanzania and Madagascar. The distribution of these ages is similar to the data for Tanzania and Madagascar in having Archean and Paleoproterozoic peaks. Mesoproterozoic ages can be found for a few xenocrystic zircons from much younger igneous bodies from E. Ethiopia and N.Somalia dated with evaporation techniques (Kröner and Sassi, 1996; Teklay, 1997), but these ages could simply be strongly discordant Archean or Paleoproterozoic zircons which have a non-zero lower intercept. An ion-probe study for samples from Yemen found mixed zircon populations of Neoproterozoic and Archean age (Whitehouse et al., 1998). Clearly, a major crustal boundary exists in Ethiopia which separates juvenile crust in the north and west from reworked Paleoproterozoic and Archean crust to the east. The nature of this boundary will be difficult to delimit further because of the extensive cover of Tertiary basalts forming the Ethiopian Plateau.

Sparse data from Southern Ethiopia show a cluster of late Mesoproterozoic ages (1.13 Ga; Fig. 7b). This indicates that the crust of S. Ethiopia contains a significant proportion of remobilized older crust, and differs in this regard from juvenile crust to the north. Zircon ages for rocks from this region provide little evidence for the presence of Mesoproterozoic crust (Worku, 1996; Teklay et al., 1998). An ion-probe study found mixed zircon populations of Neoproterozoic and Archean age (Yibbas, 1999). Because there is no evidence for igneous or high-grade metamorphic activity in S. Ethiopia during Mesoproterozoic time, the abundance of such Nd model ages is interpreted to reflect mixing of dominantly Neoproterozoic mantle-derived melts with pre-Mesoproterozoic crust. Certainly further geochronologic and isotopic work is needed to verify or refute this inference.

The Nd data set for Kenya is also scant, with only 7 Nd model ages (Fig. 7b). These are quite variable but are like those of southern Ethiopia in having a Mesoproterozoic mean Nd model age (1.21 Ga). At present no zircon ages exist for basement rocks from Kenya, complicating interpretations of the Nd data, but it is reasonable to tentatively adopt an interpretation similar to that for the basement of southern Ethiopia. Such an interpretation is consistent with Rb–Sr whole rock ages for Kenya, which also show no evidence of Mesoproterozoic crust (Key et al., 1989).

Although Madagascar today lies southeast of Tanzania, its position up to Jurassic time was much farther north, adjacent to Kenya (Fig. 1). Reconstructed, Madagascar lay south of the E. Ethiopia–Somalia–Yemen region, where the basement is dominated by pre-Neoproterozoic crust that was remobilized during Neoproterozoic time. The paleogeographic reconstructions are consistent with the isotopic data. The basement of Madagascar yields mostly Paleoproterozoic and Archean Nd model ages, with a mean age of 2.40 ± 0.54 Ga (Fig. 8). These old Nd model ages contrast with the abundance of Neoproterozoic zircon ages obtained from the basement of Madagascar. Combined Nd isotopic and zircon age data suggest that Neoproterozoic igneous rocks of Madagascar largely result from remelting Archean crust during Neoproterozoic time.

In contrast to the abundance of juvenile crust in the northern EAO, crust in the southern EAO is mostly remobilized older material. This is clear from the data for Tanzania (Fig. 7), which yield a mean of 2.26 Ga but with a lot of variability (1 standard deviation = 0.71 Ga). The Tanzanian data can be further subdivided into three groups. Samples from the Tanzanian craton cluster tightly around a mean Nd model age of 2.82 ± 0.08 Ga. Gneisses and amphibolites from the EAO to the east of the craton yield a younger but still Archean mean model age of 2.54 Ga, which is also variable (1 standard deviation = 0.42 Ga). These rocks are mostly reworked Archean igneous rocks or sediments derived almost entirely therefrom. Rocks from the Eastern Granulites are the youngest and most variable, with a mean model age of 1.44 ± 0.57 Ga. Because most of these rocks are Neoproterozoic igneous rocks, this should also be interpreted as mostly due to mixing between juvenile Neoproterozoic melts and Archean crust and sediments.

5. Discussion and conclusions

The data set reviewed above demonstrates striking and systematic variations in Nd model ages along and across the EAO. The region to the west of the Nile in Egypt and to the west of the Keraf Suture in Sudan is known to contain pre-Neoproterozoic crust that was reworked during the Neoproterozoic, and such crust can be traced southward towards the Congo and Tanzanian cratons (Sultan et al., 1990; Stern, 1994; Harms et al., 1994). Abdelsalam et al. (2002) argue that the enigmatic crustal tract west of the Nile should be referred to as the 'Saharan Metacraton'. The Saharan Metacraton is flanked to the east by a vast region on both sides of the Red Sea, stretching in the north from Jordan and Israel to northern Ethiopia in the south. The tight clustering of Neoproterozoic Nd model ages demonstrates that this region is overwhelmingly composed of crust that was extracted from depleted mantle during Neoproterozoic time. Details of the extraction process remain to be elucidated, particularly those which occured over timespans shorter than the ~100–200 Ma resolution of Nd-model ages. This includes the important issue of whether granitic rocks are the result of fractionation of more mafic melts or anatectic melts of juvenile lower crust, mafic volcanics, or sediments.

The region defined by Neoproterozoic Nd model ages approximates the traditional outlines of the Arabian–Nubian Shield. There appear to be subtle variations within the region identified as juvenile crust, with Neoproterozoic ages >0.8 Ga characterizing Sinai, Israel, Jordan, Eritrea, northern Ethiopia and the juvenile part of the Arabian Shield, whereas Neoproterozoic ages ~0.75 Ga characterize Egypt and Sudan. The significance of these second-order variations is not understood but worthy of further investigation. It would be useful in particular to undertake regional Nd isotopic mapping in Arabia, especially to see if there is any correspondence between well-defined terrane boundaries (Stoeser and Camp, 1985) and Nd model ages. Nevertheless, the correspondence of the traditional limits of the Arabian–Nubian Shield with distribution of Neoproterozoic Nd model ages (using the DePaolo model) suggests a new way to define the Arabian–Nubian Shield and to subdivide the EAO.

An extensive tract of ancient crust defines the eastern flank of the EAO, from the Afif Terrane in south-central Arabia as far south as Tanzania and Madagascar. Along this stretch, mean model ages are commonly 2.1–2.4 Ga. It is not yet clear whether this indicates remobilized Paleoproterozoic crust or mixing between Archean crust and subordinate Neoproterozoic mantle-derived melts (Maboko and Nakamura, 1996; Maboko, 2000). In spite of these uncertainties, it seems likely that the boundary between the juvenile crust in the northern part of the EAO and the much older tract to the east marks the western margin of East Gondwana. The pre-Jurassic position of Madagascar, on the eastern side of Kenya, and its isotopic similarity with crustal tracts on the eastern flank of EAO juvenile crust, indicates that Madagascar was part of East Gondwana.

A final, very interesting point emerges from the Nd model age data set. That is the enigmatic nature of the crust in the transition between the juvenile crust in the northern EAO and the Archean-Paleoproterozoic crust in the southern EAO. This is the region of southern Ethiopia and Kenya, where a limited database is dominated by Mesoproterozoic model ages. This scarcity of data makes it difficult to evaluate with any confidence the possibility that the region may be dominated by Mesoproterozoic Nd model ages, and a related problem is that there is very little zircon geochronological data to constrain interpretations.

Note added in Proof

Granitic rocks of apparent Cambro-Ordovician age (541–490 Ma) in the Central Eastern Desert of Egypt are reported by Hassanen and Harraz (1996, Precambrian Research 80, 1–22) to yield Nd model ages of 0.97–1.7 Ga. Although younger than the rocks of interest here, this suggests that some pre-Neoproterozoic crust may be preserved in the northernmost EAO.

Acknowledgements

The author wishes to thank the conveners of the 18th Colloquium on African Geology, Eckhart Wallbrecher and Sospeter Muhongo, for inviting me to deliver this keynote address. Thanks also to U.B. Andersson and Andreas Möller for thoughtful reviews. I apologize for inadvertently overlooking any pertinent dataset and encourage those who generate future Nd data in the EAO to send me a copy for inclusion in updated datasets. This is UTD Geosciences contribution #955.

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