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LATE PRECAMBRIAN (740 MA) CHARNOCKITE, ENDERBITE, AND GRANITE FROM JEBEL MOYA, SUDAN: A LINK BETWEEN THE MOZAMBIQUE BELT AND THE ARABIAN-NUBIAN SHIELD?[1]

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ABSTRACT

New Rb-Sr and whole rock and U-Pb zircon data are reported for deep-seated igneous rocks from Jebel Moya in east-central Sudan. This exposure is important because it may link the high-grade metamorphic and deep-seated igneous rocks of the Mozambique Belt with the greenschist-facies and ophiolitic assemblages of the Arabian-Nubian Shield, both of Pan-African (ca. 900–550 Ma) age. The rocks of Jebel Moya consist of pink granite, green charnockite, and dark enderbite. A twelve-point Rb-Sr whole rock isochron for all three lithologies yields an age of 730 ± 31 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7031 ± 1. Nearly concordant zircon ages for granite, charnockite, and enderbite are 744 ± 2,742 ± 2, and 739 ± 2 Ma, respectively. Initial ε-Nd for these rocks are indistinguishable at +3.0 ± 0.4. The data suggest that the charnockite, enderbite, and granite are all part of a deep-seated igneous complex. No evidence was found for the involvement of pre-Late Precambrian crust. Instead, the initial isotopic compositions of Sr and Nd indicate that Jebel Moya melts were derived from a mantle source that experienced significantly less time-integrated depletion of LRE and LIL elements than the source of Arabian-Nubian Shield melts. The ages for Jebel Moya deep-seated igneous rocks are in accord with data from elsewhere in the Mozambique Belt indicating that peak metamorphism occurred about 700–750 Ma. The northward extension of the Mozambique Belt to the Arabian-Nubian Shield defines a single east Pan-African orogen. The principal difference between the northern and southern sectors of this orogen may be the greater degree of thickening and subsequent erosion experienced in the south during the late Precambrian, perhaps a result of continental collision between East (Australia-India) and West Gondwanaland (S. America-Africa) about 750 Ma.

INTRODUCTION

Much of East Africa was formed or severely disturbed during the late Precambrian Pan-African orogeny, about 950–550 Ma (Kröner 1984). As might be expected for an orogen that is 5000 km long, many aspects of this belt change dramatically along strike (fig. 1*A*). The northern part of the orogen is called the Arabian-Nubian Shield. It is comprised of juvenile crust formed by the consolidation of several arc/back-arc basin systems, involving abundant ophiolites, arc volcanic and plutonic sequences, and immature sediments, generally metamorphosed to greenschist facies (Stoeser and Camp 1985; Vail 1985; Kröner et al. 1987*a*). At the same time, early Proterozoic and Archean crust to the west was thermotectonically reworked (Harms et al. 1990). From eastern Uganda and Kenya southward, the exposed extent of the orogen—known as the Mozambique Belt—narrows and is separated by metamorphic and deformational fronts from undisturbed Archean and Early Proterozoic cratons to the west. The rocks of the Mozambique Belt are generally of a higher metamorphic grade than those of the Arabian-Nubian Shield and are dominated by biotite gneisses and migmatites but with characteristic occurrences of ophiolitic fragments and granulites (Holmes 1951; Berhe 1990).

The Mozambique Belt is more enigmatic than the Arabian-Nubian Shield (Shackleton 1986). This results from more severe deformation and metamorphism in the Mozambique Belt, rendering the interpretation or even the identification of supracrustal sequences a formidable task. Questions as fundamental as whether the Mozambique Belt is predominantly juvenile or reworked Archean crust remain unanswered.

Another important question concerns the relationship between the Arabian-Nubian Shield and the Mozambique Belt. Disagreement continues between those who argue that Mozambique-like "fundamental basement" underlies the lower-grade assemblages in the north (e.g., Vail 1976; Hepworth 1979) and those who argue that the latitudinal variations

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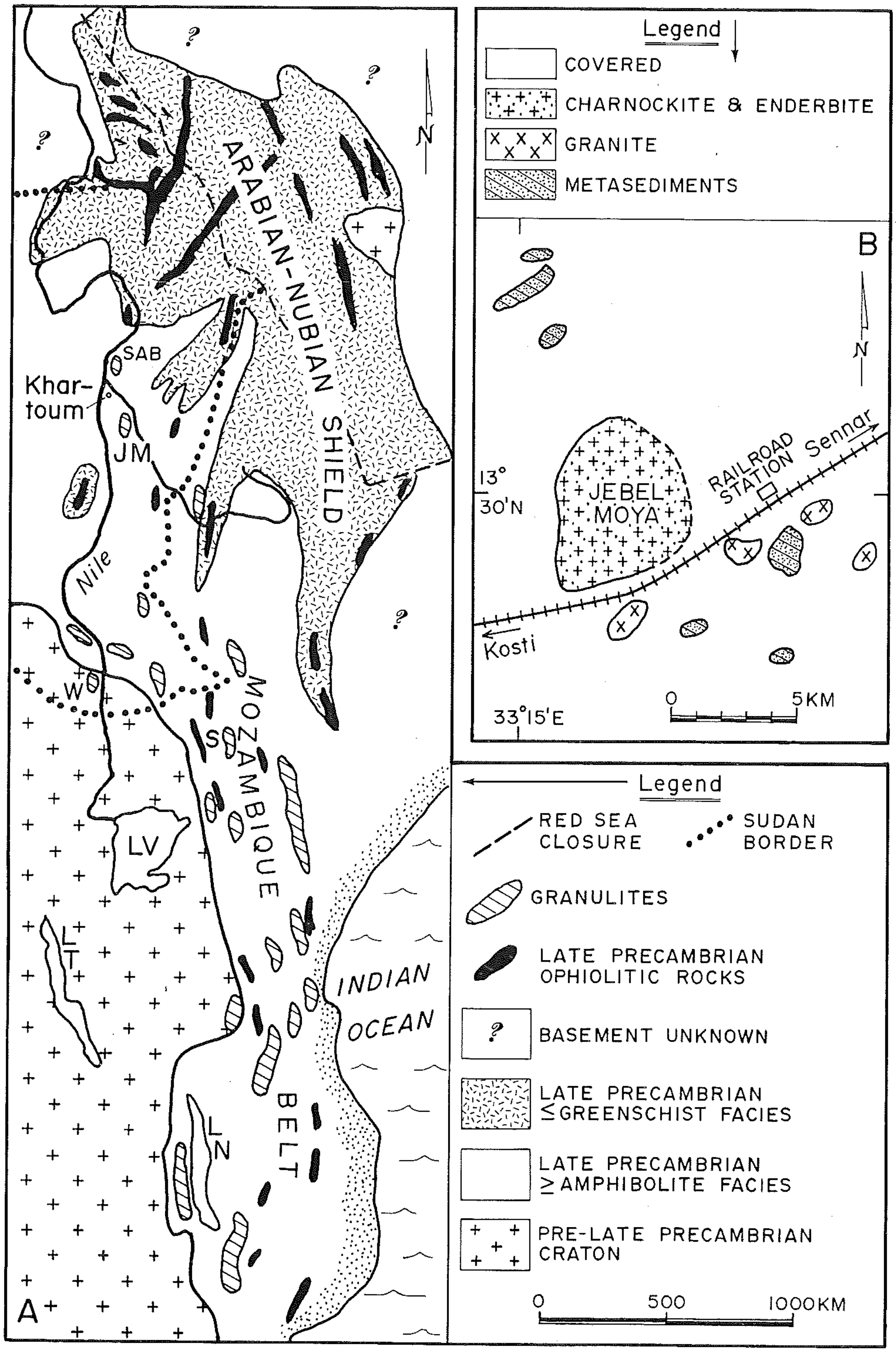

FIG. 1.—Location maps. (*A*): Distribution of characteristic lithologies in the Mozambique Belt–Arabian-Nubian Shield orogenic belt, modified after Berhe (1990), Vail (1976), Cahen et al. (1984), and Stoeser and Camp (1985). The Nile, several lakes (LV = Lake Victoria, LT = Lake Tanganyika, LN = Lake Nyasa) and the closure line of the Red Sea are shown for reference purposes. The location of Phanerozoic cover has been deleted where the basement relations can be inferred; question marks in the north reflect the fact that the lateral extent of the Arabian-Nubian Shield is unconstrained. Granulite locality labeled "Sab" is the Sabaloka occurrence; Jebel Moya is labeled "JM"; Watian granulites of Uganda are labelled "W"; Samburan-Sabachian granulites of Kenya are labeled "S." (*B*): Outcrop map of the area around Jebel Moya (mapping by A.S.D.).

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in metamorphism and deformation reflect a more intense (continent-continent) collision in the south compared to less severe, arc-arc collisions in the north (e.g. Shackleton 1986; Burke and Sengor 1986). The interpretation that highly dismembered ophiolites define suture zones that can be traced southward from the Arabian-Nubian Shield into the Mozambique Belt supports the idea that collision tectonics is the dominant orogenic mechanism. For this reason there has been a recent concentration of effort on documenting ophiolite occurrences within the Arabian-Nubian Shield/Mozambique Belt (hereafter referred to as the "East Pan-African Orogen").

Granulitic and charnockitic rocks are another diagnostic association that vary along strike within the East Pan-African Orogen. Such occurrences are generally interpreted as being formed during collision-related crustal thickening and exhumed by deep erosion of high mountains. The concentration of granulitic rocks in the Mozambique Belt and their absence from the Arabian-Nubian Shield supports the interpretation that crustal thickening, erosion, and intensity of deformation increased to the south (Berhe 1990). Furthermore, the distribution and age of granulites and intrusive charnockites constrains the timing of tectonism within the East Pan-African Orogen. For this reason, we report and interpret new geochronologic and isotopic data on granites, charnockites, and enderbites from Jebel Moya in east-central Sudan, a region at the junction between the Mozambique Belt and the Arabian-Nubian Shield (fig. 1).

GEOLOGIC SETTING AND PETROGRAPHY

As noted above, the nature of the transition between the greenschist-facies assemblages in the Arabian-Nubian Shield and the higher-grade metamorphic terranes to the west and south is poorly understood. Vail (1976) outlined the distribution of "greenschist assemblage" rocks (fig. 1*A*), distinguishing these from higher-grade rocks, which he interpreted to be older. Jebel Moya lies just west of this boundary, in an area whose basement evolution is poorly constrained. Understanding of this basement block is complicated by poor exposure, intense deformation and metamorphism, and Phanerozoic rifting. The basement between the Blue and White Niles may constitute a terrane bounded to the west by the Kabus suture (Hirdes and Brinkmann 1985; Abdelsalam and Dawoud 1991) and to the east by the Qala En Nahl-Ingessana Hills suture (Vail 1985; Berhe 1990). Alternatively, it may be an extension of one of the terranes identified in the Arabian-Nubian Shield (Vail 1985; Kröner et al. 1987*a*).

Vail (1976) showed the distribution of granulite-facies rocks in Sudan. With the exception of granulites at Sabaloka (fig. 1*A*), no detailed studies have been reported. Almond (1980) noted that the Sabaloka granulites were derived from both igneous and sedimentary protoliths. He concluded that these were metamorphosed at 600–700°C and 18–23 km depth. On the basis of isotopic studies, Kröner et al. (1987*b*) concluded that the metamorphism of the Sabaloka granulites culminated about 700 Ma, although both juvenile and pre-late Precambrian components were identified in the protoliths.

Granulite occurrences adjacent to the Sudan indicate at least two episodes of granulite-facies metamorphism, Archean and late Precambrian. Charnockitic gneiss from extreme southeast Egypt yields a Rb-Sr whole rock age of 2656 ± 71 Ma, while Watian granulites in northwest Uganda (fig. 1) yield Rb-Sr whole rock and U-Pb zircon ages of 2748 ± 47 Ma and ca. 2910 Ma, respectively (Cahen et al. 1984); these ages are interpreted to date the time of granulite-facies metamorphism. Granulites in northernmost Kenya are inferred from Rb-Sr whole rock data to have formed at ~820 Ma (Key et al. 1989). These data suggest that there may be a N-S zone in northeast Africa, separating Archean granulitic rocks in the west from late Precambrian granulitic rocks to the east.

Whiteman (1971) noted the occurrence of charnockitic rocks and granite at Jebel Moya, about 250 km SSE of Khartoum. The rocks of interest here include pink granites, green charnockites, and dark green enderbites. Poor exposure prohibits resolution of the relations between these rocks with surrounding amphibolite-facies metasediments (marbles, quartzites, and schists; fig. 1*B*) and hinders our understanding of the relationship between the granite and the granulites. Whiteman (1971) concluded that the granites intrude the charnockites, but our field studies do not compel agreement.

Detailed petrographic, mineral chemistry, and geochemical studies are in progress and will be reported elsewhere (Dawoud unpub. data), but a summary of our present understanding is given here. The charnockites are green, coarse-grained rocks dominated by orthopyroxene, megacrysts (1–4 cm) of green K-feldspar and blue quartz, accompanied by minor plagioclase, biotite, and hornblende, and contain 66–69% SiO_2. The enderbites contain abundant orthopyroxene, clinopyroxene, and plagioclase, along with minor K-feldspar and quartz, and contain 56–63% SiO_2. Two varieties of enderbite are observed: one has a well-developed layering while the other is massive. Both are found as inclusions in the charnockite, demonstrating that the charnockite is intrusive and that the enderbite is older. Amphibolites are interpreted as retrogressed enderbites and show various stages of assimilation by the granite and charnockite. In some places almost completely assimilated portions appear as dark streaks in the charnockite. The granites consist of pink K-feldspar megacrysts (1–4 cm) set in a dark matrix of quartz, biotite, and plagioclase, and contain 67–70% SiO_2.

The following are important observations regarding the relationship between the granite and the charnockite: (1) granite and charnockite are similar in texture, grain size, and—excepting orthopyroxene instead of biotite in the charnockite—similar in mineralogy; (2) there are shear zones within the charnockite that are lighter in color, contain pinkish feldspar, and so appear to be granite; (3) some outcrops between the charnockite and the granite are intermediate in color, indicating a gradational contact; and (4) in one locality a xenolith of charnockite was observed in the granite; in the same area, the contact between charnockite and granite is gradational. Our preliminary conclusions based on our field observations is that the granite and charnockite are transitional facies of a single pluton or plutonic episode that intruded into enderbites and related amphibolites.

ANALYTICAL TECHNIQUES

Four samples each of charnockite, enderbite, and granite were analyzed to obtain Rb-Sr whole rock isochrons (table 1). Rb and Sr concentrations were determined by isotope dilution using the 12 inch radius thermal ionization mass spectrometer at UTD; uncertainties on Rb/Sr are estimated at 1.5%. $^{87}Sr/^{86}Sr$ was determined using the Finnigan MAT 261 thermal ionization mass spectrometer at UTD using procedures outlined by Stern et al. (1990). All ratios were corrected for fractionation to $^{86}Sr/^{88}Sr = 0.1194$ and normalized to $^{87}Sr/^{86}Sr$ for the E&A $SrCO_3$ $= 0.70800$; uncertainties based on replicate analyses of the E&A standard are ±0.00004. Total processing blanks for Rb and Sr are <0.1 ng and <3.0 ng, respectively, and are negligible for the purposes of this study. Age regression was carried out using the York II treatment of data (York 1969), and age uncertainties are reported at the 2-sigma level.

One sample each of charnockite, enderbite, and granite was processed for U-Pb zircon dating (table 2). An excellent yield of zircons was obtained; these are elongate, prismatic, and euhedral, with no evidence of metamict cores or overgrowths. Two nonmagnetic size fractions (2–16 mg) for each lithology were spiked with ^{235}U and dissolved in HF in Mattinson-type bombs (Mattinson 1987), placed in an oven at 190°C for three weeks, followed by drying and redissolution of the residue in 6N HCl overnight at 100°C. One aliquot of this liquid was spiked with ^{208}Pb for determining Pb concentration by isotope dilution. U was separated by conventional anion exchange techniques, and Pb was isolated by the single-bead technique (Manton 1988). Total processing blanks for Pb are dominated by Pb released from the Teflon bomb and are about 500 pg. Isotopic analyses for Pb and U were corrected for fractionation by 0.15% and 0.4% per amu, respectively. Analyses were corrected for common Pb using the growth curve for Pb of Stacey and Kramers (1975) at 750 Ma. Ages and uncertainties (2-sigma level) were determined using the approach of Lidwig (1980) but with the lower intercept forced through zero. This approach has been found to be valid for most dated rocks in the Arabian-Nubian Shield (Cooper et al. 1979) and is consistent with the low MSWD obtained for these regressions.

One sample each of charnockite, enderbite, and granite was analyzed for Sm and Nd concentrations and $^{143}Nd/^{144}Nd$ (table 3). Spiked and unspiked aliquots of powder were dissolved for one week in Krogh bombs

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JM-5
JM-9
JM-10
JM-11
JM-12
JM-23
JM-27
JM-29
JM-32
JM-33

[a] C = Charnoc

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JM-14
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JM-33
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JM-33

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TABLE 1

RB-SR CONCENTRATION AND ISOTOPIC DATA, JEBEL MOYA WHOLE ROCK SAMPLES

Sample	Lithology[a]	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
JM-1	C	72.3	1019	.205	.70518
JM-2	E	55.1	382	.417	.70736
JM-5	E	18.5	485	.110	.70421
JM-9	G	55.8	806	.200	.70522
JM-10	G	62.8	817	.222	.70550
JM-11	G	57.6	788	.211	.70526
JM-12	G	55.1	766	.208	.70529
JM-23	E	65.0	506	.372	.70708
JM-27	C	42.6	762	.162	.70486
JM-29	C	41.8	932	.130	.70450
JM-32	C	45.2	775	.169	.70494
JM-33	E	32.7	601	.157	.70475

[a] C = Charnockite; E = Enderbite; G = Granite.

TABLE 2

U-PB CONCENTRATION AND PB-ISOTOPIC DATA, JEBEL MOYA ZIRCONS

	Measured				Corrected[a]			
Sample (Mesh)	U (ppm)	Pb (ppm)	$\frac{^{204}Pb}{^{206}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{206}Pb}$ age[b]
JM-10								
−140+200	1654	179.3	.000042	.064692	.06409	1.013	.1146	745
−270	1817	194.1	.000050	.064849	.06406	.9968	.1129	744
JM-14								
−200+270	1759	192.8	.000036	.064565	.06403	1.019	.1155	742
−270	1723	188.1	.000041	.064620	.06400	1.024	.1161	741
JM-33								
+140	744	84.6	.000077	.065056	.06394	1.038	.1177	740
−200+270	772	82.4	.000027	.064275	.06389	.9426	.1070	738

[a] Corrected for common Pb at 750 Ma (Stacey and Kramers 1975).
[b] In Ma.

TABLE 3

SM-ND CONCENTRATION AND ISOTOPIC DATA, JEBEL MOYA WHOLE ROCK SAMPLES

Sample	Lithology[a]	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\epsilon_{Nd}(740)$	T_{DM} (Ga)
JM-1	C	27.4	4.39	.0969	.512289	+2.9 ± .5	.97 ± .04
JM-11	G	26.4	4.16	.0953	.512269	+2.7 ± .5	.98 ± .03
JM-33	E	135	25.0	.112	.512387	+3.4 ± .5	.96 ± .03

[a] C = Charnockite; E = Enderbite; G = Granite.

(Krogh 1973). Chemical procedures follow those of Lin et al. (1989, 1990), and determinations were made using the UTD Finnigan MAT 261. Uncertainties on Sm/Nd are about 1%. Analytical details of the $^{143}Nd/^{144}Nd$ determinations including normalization procedures and processing blanks are reported by Stern et al. (1990). ϵ-Nd calculations were made assuming Bulk Earth $^{147}Sm/^{144}Nd$ = 0.1967 and using the determinations of ϵ-Nd for the UCSD Nd standard (−15.2) and BCR (−0.16) reported by Pier et al. (1989) to calculate a Bulk Earth $^{143}Nd/^{144}Nd$ evolution appropriate for the standards analyzed at UTD

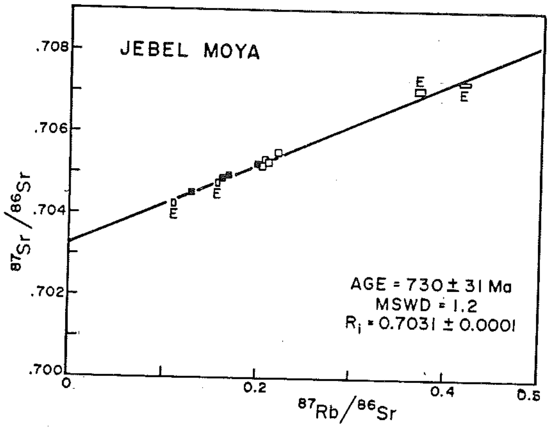

FIG. 2.—Rb-Sr isochron diagram for 12 whole rock samples reported in table 1. Enderbites are shown as open rectangles labeled "E." Charnockites are shown as filled rectangles. Granites are shown as open, unlabeled rectangles.

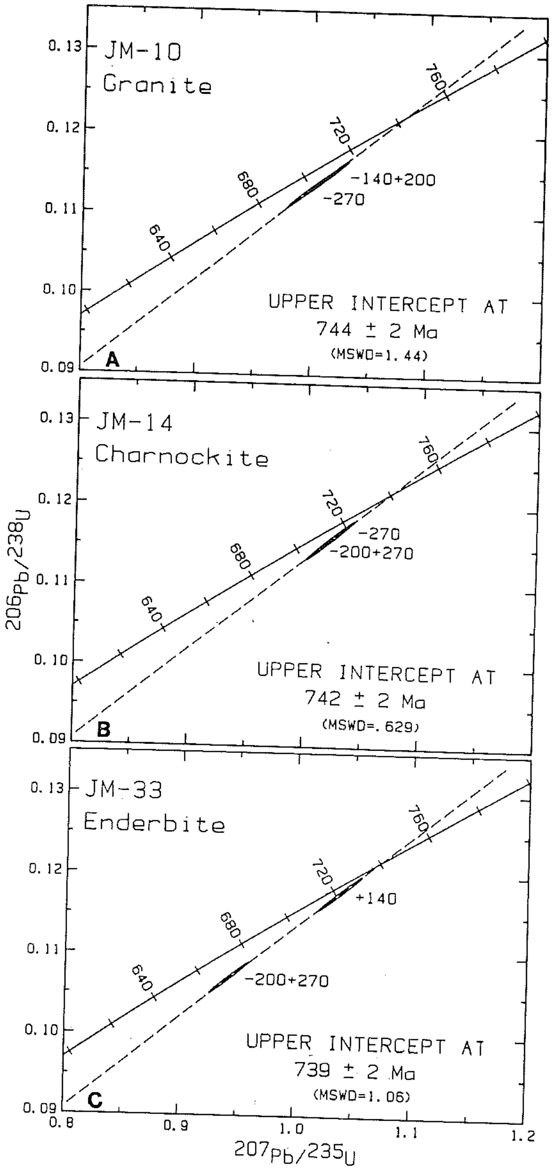

FIG. 3.—U-Pb concordia diagrams for J. Moya granite (*A*), charnockite (*B*), and enderbite (*C*). Mesh sizes of fractions are labelled next to each fraction. Upper intercept ages and MSWD are calculated assuming a zero-age lower intercept.

(UCSD Nd ^{143}Nd/^{144}Nd = 0.511847 ± 10; BCR ^{143}Nd/^{144}Nd = 0.512612 ± 20; errors reported as total range). We take the total range of ±0.000020 reported for BCR as the uncertainty for ^{143}Nd/^{144}Nd where the in-run precision is better than this. Depleted mantle or crust formation model ages (T_{DM}) were calculated using the quadratic expression for the evolution of depleted mantle (Nelson and DePaolo 1985).

RESULTS

The results of the Rb-Sr whole rock analyses are plotted as an isochron diagram (fig. 2). Very little spread in Rb/Sr was obtained, but the data define an isochron with an age of 730 ± 31 Ma and an initial ^{87}Sr/^{86}Sr (R_i) = 0.7031 ± 0.0001. The fact that all three lithologies plot on one isochron means that there is no discernible difference between the ages or R_i of granite, enderbite, or charnockite.

The results of the U-Pb zircon analyses are plotted as three concordia diagrams (fig. 3). All fractions are nearly concordant. This means that our assumption of zero-age lead loss is unimportant for calculating the upper intercept, a conclusion supported by agreement between ^{207}Pb/^{206}Pb ages for individual fractions and the upper intercept ages (compare ages listed in table 2 and fig. 3). There is a very close correspondence in age: the granite (744 ± 2 Ma) has an analytically indistinguishable age from the charnockite (742 ± 2 Ma), and the charnockite is indistinguishable in age from the enderbite (739 ± 2 Ma). Only the ages of the granite and the enderbite are analytically distinguishable, and the older isotopic age of the granite is in conflict with the field observations. The common lead correction is by far the greatest source of error in U-Pb zircon dating (Mattinson 1987), and all of the fractions dated here have extremely low proportions of common lead. Nevertheless, the correction on ^{207}Pb/^{206}Pb ranges from 0.6 to 1.7% (table 2) and could be partly responsible for the discrepancy. We interpret

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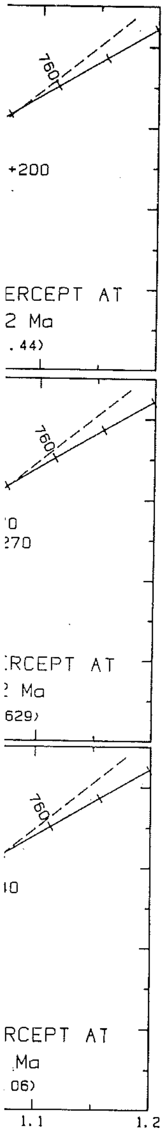

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the conflict between the U-Pb zircon data and the field data as indicating that all three lithologies were emplaced within a very short period of time, and may be comagmatic.

The neodymium isotopic data (table 3) indicate that granite, charnockite, and enderbite had indistinguishable ϵ-Nd (+3) at 740 Ma, and that they also have an identical T_{DM} (0.97 Ga).

The similarity of Rb, Sr, Sm, and Nd contents of the charnockite and granite and the similar U and Pb contents of their zircons is noteworthy. Along with the isotopic data, this indicates a strong relationship between the two rock types.

DISCUSSION

The geochronologic and isotopic data presented here allow us to examine the following problems: (1) the relationships between granite, charnockite, and enderbite; (2) the source of these magmas; and (3) the relationship between the Mozambique Belt and the Arabian-Nubian Shield.

Relationship between Granite, Charnockite, and Enderbite.—We take the 744 ± 2 Ma age of the granite as approximating the time of its intrusion. The close similarity in age of the charnockite, its chemical, mineralogic, and initial isotopic similarity, and the field relations strongly suggest that the charnockite magma was the same as or very similar to that of the granite. The question that we cannot resolve with the present data set is whether the charnockite formed as an igneous rock or represents a later metamorphic recrystallization of the granite. All we know is that *P-T* conditions appropriate for the formation of charnockite occurred at or after 742 ± 2 Ma. Similarly, the conflicting conclusions resulting from field and zircon age data for the enderbite and the felsic intrusive rocks, coupled with the fact that all three rock types had indistinguishable initial Sr and Nd isotopic compositions, leads us to hypothesize that these are all components of a single deep-seated igneous complex, with the enderbites comprising deeper levels than the granite and the charnockite. This hypothesis will be tested by further field and geochemical studies, now in progress.

Source of Granite-Charnockite-Enderbite Magmas.—The initial Sr and Nd isotopic data provide insights into the sources responsible for the generation of the Moya charnockite-enderbite-granite magmas. The initial isotopic compositions of Sr and Nd were significantly more and less radiogenic, respectively, than coeval magmas generated in the Arabian-Nubian Shield (figs. 4, 5). Figure 4 shows the field defined by initial $^{87}Sr/^{86}Sr$ for the J. Moya samples calculated at 740 Ma. Note that the J. Moya samples have significantly higher initial $^{87}Sr/^{86}Sr$ than do samples from the N. Red Sea Hills, Sudan, and E. Desert, Egypt. Figure 5 shows the isotopic evolution of neodymium in the J. Moya samples and compares these with coeval and well-dated samples from the Arabian-Nubian Shield. It is clear that the Moya samples had significantly less radiogenic neodymium at the time of their crystallization than did similar-aged igneous rocks to the east.

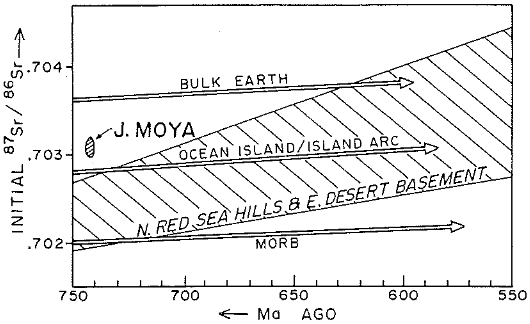

FIG. 4.—$^{87}Sr/^{86}Sr$ evolution diagram for Jebel Moya samples and likely mantle reservoirs (MORB, Ocean Island/Island Arc, Bulk Earth). Field for Red Sea Hills and Eastern Desert basement is principally from Stern et al. (1989), with additional data from Klemenic (1985), and Klemenic and Poole (1988).

There are three ways to interpret the isotopic data for the J. Moya samples, as illustrated in Figure 5: (1) these are melts of 1 Ga old crust; (2) these are hybrids between 740 Ma old melts from "Depleted Mantle I" and anatectic melts of much older crust; and (3) these are juvenile melts derived from a mantle which, although depleted in Rb/Sr and Sm/Nd relative to the "Bulk Earth," was significantly less depleted than "Depleted Mantle I."

The data presented here lead us to prefer the third hypothesis, for the following reasons: First, if older crust was significantly involved in the evolution of J. Moya charnockite-enderbite-granite melts, we might expect this to be reflected as some proportion

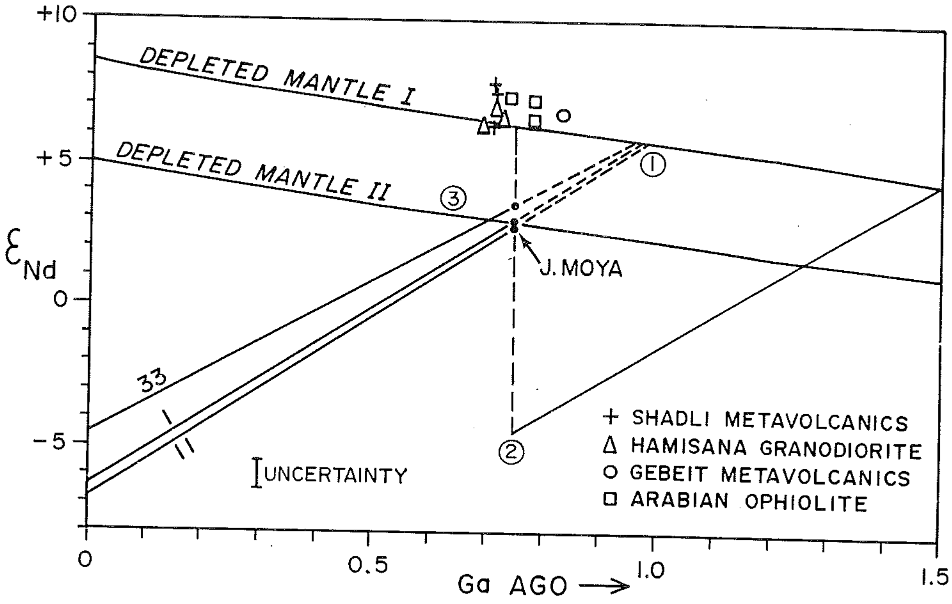

FIG. 5.—Neodymium isotopic evolution for Jebel Moya samples and similar aged samples from the Arabian-Nubian Shield, including the Red Sea Hills of Sudan (Gebeit Metavolcanics: Reischmann 1986; Hamisana granodiorites: Stern unpub. data), Southeastern Desert, Egypt (Shadli metavolcanics, Stern et al. 1991), and Arabia (Ess and Al Wask ophiolites, Claesson et al. 1984). The model growth curves for Depleted Mantle I is that of Nelson and DePaolo (1985), while the Chondritic Uniform Reservoir (CHUR) always has ε-Nd = 0. Note that samples from the Arabian-Nubian Shield have T_{DM} that match their crystallization ages, indicating that these were derived from mantle similar to Depleted Mantle I. The circled numbers correspond to the three hypotheses for the origin of the Jebel Moya suite, as discussed in the text: (1) anatexis of crust which formed about 1 Ga; (2) hybridization of mantle-derived melts having the isotopic composition of Depleted Mantle I with much older crust; and (3) derivation of Jebel Moya melts from a mantle (Depleted Mantle II) that was less severely depleted in Nd/Sm (and Rb/Sr) than that of Depleted Mantle I.

of older zircons among those separated. Evidence for older zircons, such as cores or abundant metamict grains, is not observed. Furthermore, all fractions from all three lithologies give nearly the same age, an age that agrees with the Rb-Sr whole rock age. This agreement among suites and between dating techniques indicates that older grains are an insignificant part of the zircon population. Second, the fact that the initial isotopic composition of Nd is so similar between granite-charnockite, with about 70% SiO_2 and 27 ppm Nd, and enderbite, with about 60% SiO_2 and 135 ppm Nd, is inconsistent with Hypothesis 2, which predicts that the more felsic rocks should have a greater component of any older crust. If this were the case, we expect that the higher proportion of older crust in the felsic rocks would be manifested by significantly older T_{DM} ages. The similar age and initial isotopic composition of enderbite and charnockite-granite makes it more likely that these share a fractionation relationship, with the ca. 60% SiO_2 enderbites being parental.

The conclusion that J. Moya magmas tapped a source that was less depleted than that responsible for magmas in the Arabian-Nubian Shield is noteworthy, because neodymium isotopic data are often reported as T_{DM} ages in the region and play an especially important role in interpreting crustal evolution in the region west of the Nile (Harris et al. 1984; Schandelmeier et al. 1988; Harms et al. 1990). In this region there are as yet no U-Pb zircon ages, and existing Rb-Sr ages are often interpreted as being reset during the late Precambrian. Because there is generally good agreement between T_{DM} model ages and Rb-Sr whole rock and U-Pb zircon ages for rocks of the Arabian-Nubian Shield there is a tacit assumption that mantle sources for all of the late Precambrian rocks of North Africa were similarly depleted. With the evidence from J. Moya that less-depleted mantle reservoirs may have existed, it is clear that T_{DM}

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ages for rocks west of the Arabian-Nubian Shield should be viewed with more caution.

Relationship between the Mozambique Belt and the Arabian-Nubian Shield.—Because of Jebel Moya's location close to the boundary between the Mozambique Belt and the Arabian-Nubian Shield, the data presented here provide an excellent perspective on the nature of this boundary. The data demonstrate that an important part of the boundary between the two is defined by a difference in metamorphic grade. While the Arabian-Nubian Shield exposes greenschist-facies supracrustal rocks and epi- to mesozonal intrusions, coeval igneous suites exposed to the west and south consist of a much higher proportion of amphibolite- or granulite-facies supracrustal rocks and catazonal intrusions. This is not the only change that occurs across the boundary: the Jebel Moya suite manifests derivation from a mantle source significantly less depleted than that which produced the Arabian-Nubian Shield. Nevertheless, we conclude that the differences reflect a much greater amount of uplift and erosion in the Mozambique Belt than in the Arabian-Nubian Shield. There is as yet little information on the uplift history of the Mozambique Belt. Maboko et al. (1989) used results of their $^{40}Ar/^{39}Ar$ study of Tanzanian granulites to conclude that these experienced a long period of cooling, consistent with erosion and isostatic readjustment of thickened crust. This suggests that the most important reason for the differences in metamorphism between the Mozambique Belt and the Arabian-Nubian Shield is that the former experienced much greater thickening about 700–750 Ma relative to the latter.

CONCLUSIONS

The association of granite, charnockite, and enderbite dated at ~740 Ma indicates that an episode of deep-seated igneous activity occurred in northeast Africa about that time. The data indicate that the granulitic conditions typical of the Mozambique Belt can be traced into SE Sudan close to the southern margin of the Arabian-Nubian Shield. Our study further indicates that the first-order difference between the two sectors of the East Pan-African Orogen is a difference in metamorphic grade of rocks now exposed at the surface. This implies that erosion has been much more severe in the Mozambique Belt than to the north, and therefore further suggests that maximum crustal thicknesses were also much greater to the south. The initial isotopic data suggest an additional difference, that the source of Arabian-Nubian Shield melts was significantly more depleted than was that of some igneous rocks in the Mozambique Belt.

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