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Significance of high-grade metasediments from the Neoproterozoic basement of Eritrea

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Abstract

High grade orthogneiss, amphibolitic dykes and paraschist to migmatites were studied in the Red Sea Lowlands of eastern Eritrea. Chemical data and a mineral assemblage of kyanite, staurolite, almandine garnet, biotite and quartz indicate that the schists were formed by metamorphism of pelitic metasediments derived by subaerial weathering, deposited in a marine environment. Thermobarometry based on element partitioning between coexisting minerals of schist, orthogneiss and amphibolite shows that peak metamorphic conditions were ca 700°C and 8–10 kbar. An overall clockwise P–T loop is suggested by the thermobarometry results, and is consistent with a collision setting. The Eritrean high-grade metasediments can be correlated with similar rocks between Arabia and this defines a sedimentary basin that was at least 400 km from north to south. Low initial $^{87}Sr/^{86}Sr$ (0.7014–0.7028) and $\epsilon Nd_{(800\ Ma)}$ of +2.5 to +4.7 along with a mean T_{DM} model age of 1.05 Ga indicates that juvenile Neoproterozoic crustal sources controlled the sedimentation of the pelites, and permits negligible involvement of older crustal sources. Rb/Sr geochronology suggests an age of ca 650 Ma for thermal resetting, consistent with a model whereby plate collision between east and west Gondwanaland was responsible for the metamorphism and exhumation. These metasediments reflect the transition between the northern and southern sectors of the East African Orogen, containing the juvenile isotopic signature similar to rocks of the Arabian–Nubian Shield but a chemical composition and metamorphic grade that are indistinguishable from assemblages characteristic of the Mozambique Belt. © 1997 Elsevier Science B.V.

Keywords: Arabian–Nubian Shield; Eritrea metasedimentary rocks; Geochemistry; High grade metamorphism; Neoproterozoic

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1. Introduction

The Neoproterozoic evolution of the Arabian–Nubian Shield (ANS) continues to be a topic of active research interest. This is partly because formation of this continental crust can be clearly linked to plate tectonic processes, including terrane accretion (Stoeser and Camp, 1985), formation and emplacement of ophiolites (Pallister et al., 1988), widespread generation of granitic intrusions (Harris et al., 1993), and fractionation into mafic lower crust and intermediate upper crust (McGuire and Stern, 1993). The deformation of the ANS is linked to continental collision in the

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Mozambique Belt to the south (Berhe, 1990). Stern (1994) infers a Wilson Cycle, beginning with the breakup of the supercontinent Rodinia, ending with the formation of a new supercontinent, and lasting most of Neoproterozoic time. These are the events that formed the East African Orogen (EAO, Stern, 1994), as East and West Gondwanaland collided to form the supercontinent 'Greater Gondwanaland' or 'Pannotia' and led to the dramatic climatic and biological changes marking the transition to Phanerozoic time.

We have much to learn about the geologic history of this region. One set of problems concerns how the transition is accomplished between juvenile crust in the ANS and reworked older crust of the Mozambique Belt. Studying this transition is complicated by the Red Sea, which cuts obliquely across the Neoproterozoic structural grain, and by young flood basalts burying most of the Ethiopian basement. Nevertheless we must first be able to trace basement structures from Arabia into Africa before we can understand how the EAO changes southward. Understanding the Neoproterozoic geology of the Horn of Africa is critical for this effort.

The purpose of this contribution is to present data for distinctive high-grade metasedimentary units of eastern Eritrea. We show that these metasediments were derived from erosion and weathering of juvenile Neoproterozoic crust, then buried >20 km deep in the crust and almost melted. These distinctive rocks can be correlated across the Red Sea with similar distinctive metasediments of the southern Arabian Shield, providing one of the few firm links that we have between Neoproterozoic units across the Red Sea (Fig. 1A).

2. Geologic setting

The Precambrian basement of Eritrea and eastern Sudan is subdivided into three terranes, separated by major shear zones (Drury and Berhe, 1993; Kröner et al., 1987). These include (from west to east):

(1) Barka-Haya Terrane (upper amphibolite facies felsic gneisses and supracrustal rocks);
(2) Hagar Terrane (greenschist-facies deformed intermediate, mafic and ultramafic igneous rocks; and
(3) Nacfa-Tokar Terrane (greenschist-facies metavolcanics, diorites and granodiorites.

We have a reasonable understanding of the age of the metavolcanics of the Nacfa-Tokar Terrane [Tsaliet Group of Beyth (1973)]. Felsic volcanic rocks in the Sudan yield evaporation ages of 840±16 Ma and 854±18 Ma (Kröner et al., 1991). A zircon evaporation age of 811±3 Ma was obtained from a syntectonic diorite intruding the Nacfa metavolcanic rocks (Teklay et al., 1996).

A distinctly different metamorphic facies from the Nacfa-Tokar greenschists is observed along the Red Sea escarpment, extending almost from the border with Sudan south of Massawa. Garnet-staurolite schists and gneisses dominate exposures along the Red Sea lowlands, defining a belt that is ca 25 km wide at the margins of the Eastern Escarpment and the Ghedem Range before it passes beneath younger rocks to the east. This belt is covered by Plateau basalts to the north but is discontinuously exposed along the base of the escarpment for ca 300 km from ca 14°30′ to 17°20′ N. The relationship between the metasedimentary amphibolites to the east and the Tsaliet metavolcanics to the west is poorly understood; a tectonic contact is inferred (Mohr, 1979). The restricted occurrence of deformed mafic dykes in the higher grade rocks led Drury et al. (1994) to suggest that the high grade rocks 'could indicate a pre-Pan-African component'. The relationship between the Nacfa greenschists to the west and the amphibolite-facies rocks in the Red Sea lowlands is similar to the relationship between Baish greenschists and Bahah metasedimentary amphibolites of the southern Arabian Shield, and these have been correlated across the Red Sea (Mohr, 1979; Ramsay et al., 1979). This interpretation is supported by similar ages of Baish metavolcanics [ca 820 to 840 Ma; Kröner et al. (1992)], which are indistinguishable from Tsaliet metavolcanics of the Tokar–Nacfa Terrane, as well as the fact that the location of the Eritrean paraschists to the east of the Tsaliet metavolcanics could be correlated with the ca 810–850 Ma Bahah–Ablah metasediments of the Al Lith area in southern Arabia (Kröner and Basahel, 1984; Kröner et al., 1992). This interpretation is shown in Fig. 1B.

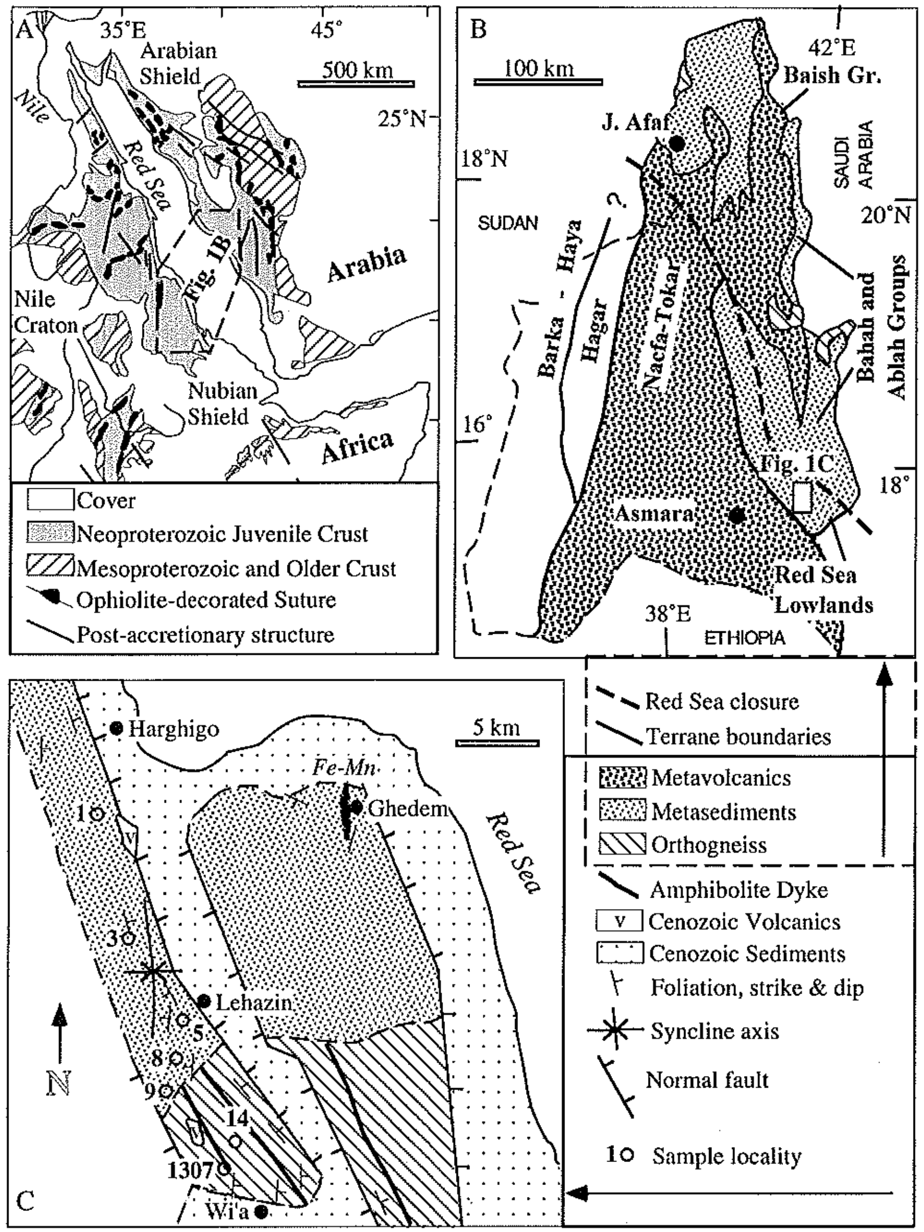


Fig. 1. Locality map of the study area. (A) Map of Neoproterozoic basement exposures around the Red Sea, modified after Worku and Schandelmeier (1996). The location of the Arabian and African areas combined in Fig. 1B are shown. (B) Generalized basement map of northern Eritrea and portions of Arabia in pre-Red Sea configuration, after Brown et al. (1989); Drury and Berhe (1993). Red Sea is closed coastline-to-coastline (Sultan et al., 1993). Units mapped as metasediments include the Bahah and Ablah Groups in Saudi Arabia and high-grade gneisses and metasediments in Eritrea (Drury et al., 1994; Merla et al., 1979). Units mapped as metavolcanics include 820–860 Ma Baish Group in Saudi Arabia and similar aged metavolcanics exposed in the Nacfa–Tokar Terrane of Eritrea and Sudan. Names of terranes in Eritrea and Sudan combine terminologies of Kröner et al. (1987) and Drury and Berhe (1993).

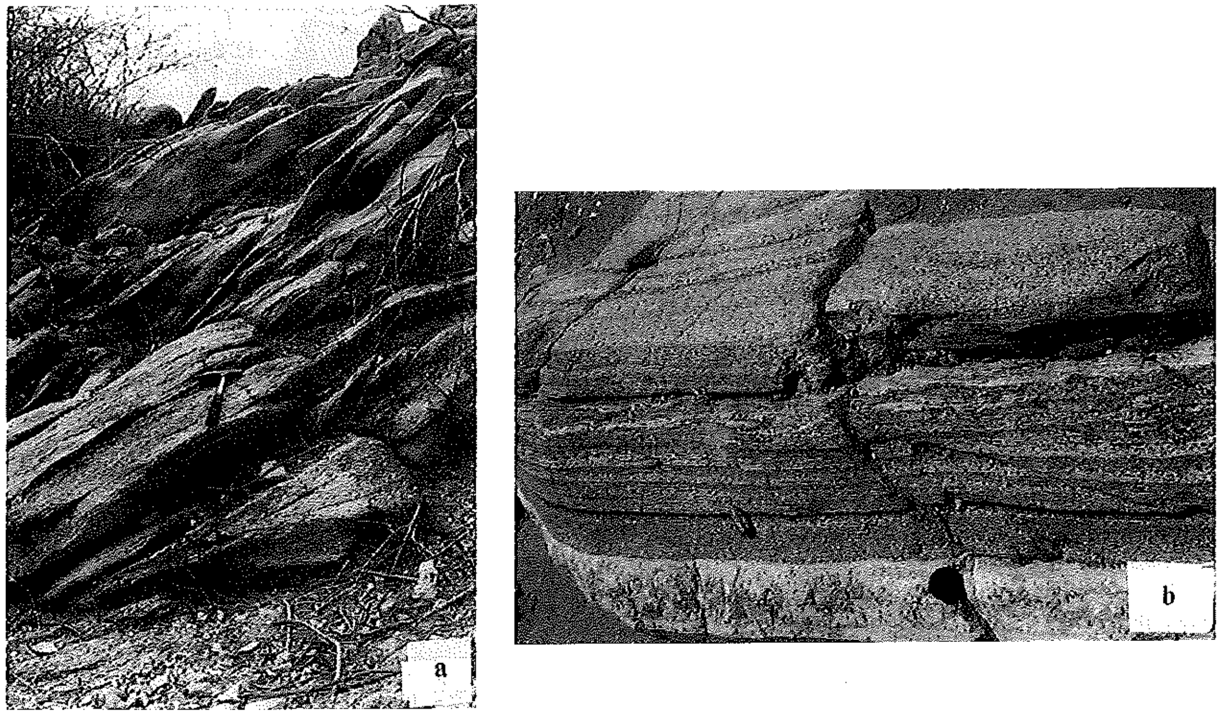
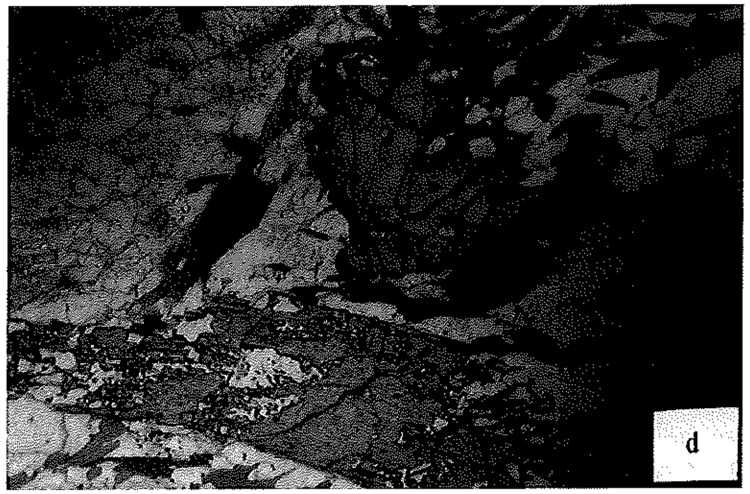


Fig. 2. Field photos and photomicrographs: a, orthogneiss; b, well-bedded paraschist; c, cross-bedding in staurolite–garnet paraschist; d, photomicrograph of kyanite, staurolite, biotite schist (field of view ~8 mm.)

We studied amphibolite-facies paraschists and related rocks from exposures in the rift mountains south of Massawa between Wi'a in the south and Hirghigo in the north (Fig. 1C). The general geology of the region was presented by Merla et al. (1979), Kazmin (1973), and Beyth (1995). The study area is dominated by a large body of garnet–biotite–muscovite gneiss in the south and amphibolite–facies paraschist and migmatites in the north. The gneiss probably intruded the metasediments, and these two were deformed and metamorphosed together. Mafic amphibolite dykes or sills (up to 20 m thick) intrude mainly the gneiss, and were deformed with it. More than one deformation episode may exist, but the dominant foliation strikes ca NNW. The paraschists are tightly folded eastwards and westwards while the foliation in the gneiss dips 30–55° eastwards only. Large veins (up to 50 m thick) of coarse perthite–quartz–muscovite pegmatite cross-cut the paraschists close to the contact with the gneiss; thinner pegmatites invade the gneiss and the paraschist elsewhere. Pegmatite veins are unfoliated and trend N20°E to N40°E oblique to foliation, clearly indicating that pegmatite generation and emplacement postdates deformation of the metamorphic rocks. Excellent access to the paraschist sequence is obtained from a small wadi west of Lehazin. An identical paraschist sequence was briefly studied at the Eritrean escarpment ca 80 km south of Lehazin in the Boya River.

We interpret the paraschists to represent a thick sequence of dominantly pelitic metasediments. The sequence is well-bedded, and primary sedimentary structures such as graded bedding and cross-bedding are well-preserved (Fig. 2). The sedimentary sequence is interpreted to have formed in a sedimentary basin at some distance from the source of the sediments. A tectonic setting such as distal parts of a passive continental margin is consistent with the large-scale features of the sedimentary sequence.

In this study, we report the field relations, metamorphic grade and chemical and isotopic compositions based on a reconnaissance field and



laboratory study of 30 samples collected in the field and examined in thin section. Based on results of petrographic studies, six paraschists, two amphibolites and an orthogneiss were subjected to chemical and isotopic studies, the results of which are reported here. Although brief, this is the first study of its kind for these rocks in Eritrea. Sample localities are shown in Fig. 1C.

3. Analytical techniques

Petrographic thin section studies and XRD analyses were used to define the metamorphic mineral assemblages. Mineral chemistries for thermobarometry were determined using a Jeol JXA 8600 Electron Microprobe. Formula reduction was made using the program AX95 (Holland, personal communication). Of the minerals studied only garnets showed distinct compositional differences between cores and rims.

Samples for whole rock analytical studies, including major and trace element concentrations and Sm/Nd and Rb/Sr isotopic compositions, were pulverized in a tungsten–carbide ball mill. Major elements were analyzed by ICP–AES after fusion with a lithium-metaborate flux and decomposition of the melt in nitric acid. Trace elements Zr, Ni, Cr, Pb, U and rare earth elements (REE) except Sm and Nd were determined by ICP–MS after

Table 1
Rb and Sr concentration and ^{87}Sr/^{86}Sr data

Sample	Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
1–1[a]	60.0	86.2	2.01	0.72350
3–1[a]	46.9	241.0	0.563	0.71000
3–2[a]	50.5	184.1	0.798	0.71282
5–1[a]	50.9	130.3	1.13	0.71492
8–1[a]	55.9	249.3	0.649	0.71028
9–3[a]	40.6	179.2	0.655	0.71158
9–2[b]	2.35	129.8	0.0523	0.70405
1307[b]	4.15	785	0.0153	0.70307
14–3[c]	28.0	434	0.186	0.70464

[a] Paraschist.
[b] Amphibolite dyke.
[c] Gneiss.

Na_2O_2 sintering at the Geological Survey of Israel. Rb, Sr, Sm and Nd concentrations in whole-rock powders were determined by isotope dilution at University of Texas at Dallas, following dissolution in Krogh-type bombs and other procedures outlined in Stern and Kröner (1993). Procedures for the analysis of Sr and Nd isotopic compositions of whole rock powders are also presented in Stern and Kröner (1993). Data are adjusted to a value for E and A $SrCO_3$ $^{87}Sr/^{86}Sr = 0.70800$. Accuracy on ^{87}Sr/^{86}Sr for these is better than ± 0.00004, and data in Table 1 are accepted to have this uncertainty. Rb/Sr ages are calculated using the York II approach (York, 1969); for the Eritrean samples MSWD > F-variate, so the York II age uncertainty and initial ratio are multiplied by $MSWD^{1/2}$. Analyses of Nd standards yielded a mean ^{143}Nd/^{144}Nd of 0.511859 ± 13 (total range for seven analyses) and 0.512630 (one analysis) for the UCSD and BCR-1 standards, respectively. Calculation of initial Nd isotopic compositions as $\epsilon Nd_{(t)}$ is based on Sm/Nd data from Table 1, and assumes an age of 800 Ma. Nd model ages are calculated after the algorithm of Nelson and DePaolo (1985).

4. Results

4.1. Metamorphic conditions

The paraschists (samples 1–1, 3–1, 3–2, 5–1, 8–1 and 9–3) are composed of kyanite, staurolite, almandine garnet, amphibole, biotite, quartz and feldspar, with occasional muscovite. Garnet and kyanite crystals are as large as several centimeters in their greatest dimension. The amphibolite dykes are composed of plagioclase and hornblende (1307), sometimes with very large crystals of garnet (9–2). This hornblende-plagioclase assemblage and the staurolite–kyanite–garnet assemblage of the paraschists indicate conditions in the amphibolite facies. The presence of garnet–amphibolite (9–2) with large garnet porphyroblasts (~1 cm), partly rotated with isoclinally folded internal foliation (Fig. 2), also indicates high grade conditions. Insignificant retrograde metamorphism was identified; except for chlorite in sample 9–3, the high grade metamorphic minerals are mostly unaltered. Metamorphic P–T conditions were determined from the chemical compositions of coexisting minerals using the following methods: amphibolites–hornblende–plagioclase (hb–pl) thermometer of Holland and Blundy (1994); paraschists–garnet–biotite (gt–bi) thermometer (Ferry and Spear, 1978) and garnet–Al–silicate–plagioclase–quartz (gt–ky–pl–q) barometer (Ghent, 1976). The gt–bi and gt–ky–pl–q calculations were made using the updated thermodynamic data set of Holland and Powell (1990) (Thermocalc 2.5, generated August 1996) with end-member activities calculated by the program AX95 (Holland, personal communication). The hb–pl procedure gives two independent temperature estimates according to the edenite–tremolite (ed–tr) and edenite–richterite (ed–ri) components. Estimated errors on individual determinations are ±50°C and ±1 kbar.

The results are shown in Fig. 3 and are plotted against the background of the Al_2SiO_5 phase diagram. At pressures within the kyanite field (> 8 kbar) both the ed–tr and ed–ri thermometers give very consistent temperature estimates of ca 700°C. The thermobarometry associated with paraschists is more complicated. The highest P–T estimates are given by sample 9–3 from which rim analyses of minerals give temperatures of 650–680°C and pressures of 9.5–10 kbar. Other paraschist samples give lower rim temperatures and pressures of ca 600°C and 6.5 kbar down to ca 500°C and 5 kbar. Garnet core analyses in these

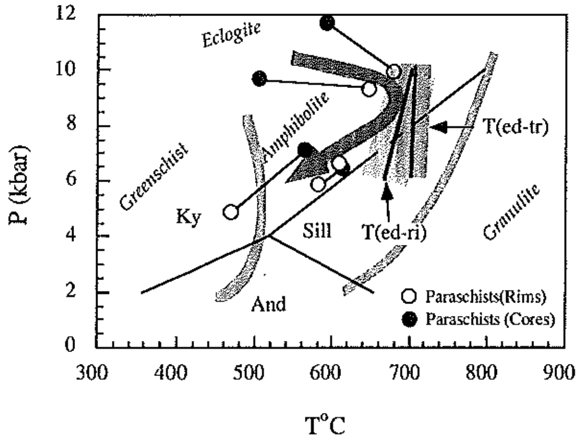


Fig. 3. *P–T* diagram for Eritrean metamorphics deduced from mineral thermobarometric studies. Lines and shading give mean values and standard deviation of the ed–tr and ed–ri results. The Al_2SiO_5 phase diagram is calculated using Thermocalc 2.5 code. Metamorphic facies according to Percival (1994). The arrow indicates a possible *P–T* path indicated by geothermobarometry estimates.

samples give higher *P–T* estimates than the rims, but still lower values than the *P–T* conditions deduced from the amphibolites and garnet rims of sample 9–3. Most remarkable is that *P–T* estimates for 9–3 based on the composition of garnet cores (the only mineral to show significant zoning) give lower temperatures but slightly higher pressures (10–12 kbar) than given by the rims. Given that 700°C temperatures are also deduced for the amphibolites, it is suggested that the estimates for sample 9–3 define part of a *P–T* path involving isobaric or slight decompressional heating from pressure of 10–12 kbar and $T = 500°C$ to peak temperature conditions of 700°C at 10 kbar (Fig. 3). The lower temperatures and pressures in other paraschists represent subsequent retrograde cooling and decompression (Fig. 3). It can be noted that such an overall clockwise *P–T* path (indicated by the arrow in Fig. 3) is consistent with a model of thermal relaxation (heating) and decompression following a collision event (e.g. England and Thompson, 1984), that is, peak metamorphism at 700°C was preceded by collision and was followed by decompression and cooling (exhumation).

4.2. Chemical composition

Samples of paraschist are compositionally similar, with 63–68% SiO_2, 14–19% Al_2O_3, 3.2–3.7% MgO, <3% CaO, <3% Na_2O, and 1.9–2.8% K_2O (Table 2). The paraschists contain 25–36% normative quartz and 4.5–13.2% normative corundum. These compositions are similar to typical shales, and the excess alumina responsible for the formation of the aluminosilicates is apparent from these data. K/Rb ranges from 300 to 400, with no evidence for depletion of Rb and the high K/Rb ratios (<1000) associated with depleted, high grade rocks. The paraschists are moderately to strongly enriched in the LREE (Fig. 4). $(La/Yb)_n$ ranges between 2.5 and 4.6, and the paraschists are not depleted in HREE $(Yb)_n = 12–18$. The paraschists have moderate to negligible Eu anomalies. The paraschists are moderately enriched in refractory trace elements Cr (91–224 ppm) and Ni (40–56 ppm).

Paraschist compositions are similar to, if less evolved, than shales such as the North American Shale Composite (NASC) and metamorphosed equivalents (Gromet et al., 1984). Major element compositions of Eritrean paraschists are similar in most regards to NASC (Table 3), except for lower CaO and K_2O and higher Na_2O. The trace element signature of Eritrean paraschists also similar if less evolved. The high Ni and Cr contents in the Eritrean paraschists could point to a mafic volcanogenic source for the shale protolith. That the shale protoliths for Eritrean paraschists were less evolved than NASC or metamorphosed equivalents is further demonstrated by the lower K_2O/Na_2O, Rb/Sr and $(La/Yb)_n$ and higher K/Rb and Eu/Eu* of the Eritrean paraschists.

The two samples of amphibolite dyke are both mafic but are otherwise distinct. Both are depleted in LIL elements, but one (9–2) is a ferro-amphibolite enriched in HFSC such as Ti, Y, Zr and REE where as the other (1307) is relatively depleted in High Field Strength Cations. Sample 1307 contains 24% Al_2O_3, 77% normative plagioclase and no normative corundum. The orthogneiss has a trondhjemitic composition and is very depleted in trace elements, including REE (Fig. 4).

Table 2
Major and trace element compositions

	Paraschists						Amphibolite		
	1–1	3–1	3–2	5–1	8–1	9–3	Dykes		
							9–2	1307	14–3
Gneiss									
SiO_2	63.0	67.2	64.1	64.1	63.4	68.0	47.5	49.5	73.6
TiO_2	0.9	0.6	0.8	0.9	0.7	0.7	2.4	0.7	<0.1
Al_2O_3	19.2	14.4	16.3	18.1	15.9	15.8	13.7	23.7	15.4
Fe_2O_3	6.5	4.8	6.7	7.7	7.2	4.6	16.2	6.2	1.0
MgO	3.5	3.3	3.7	3.1	3.2	2.6	6.2	3.5	0.4
MnO	<0.05	0.06	0.08	0.15	0.14	<0.05	0.21	0.12	0.06
CaO	0.4	2.1	1.2	1.5	2.5	1.2	9.3	10.9	2.3
Na_2O	2.0	2.7	2.8	1.2	2.8	3.3	3.6	4.0	4.5
K_2O	2.5	2.1	2.4	1.9	2.4	1.5	0.3	0.4	1.5
P_20_5	0.2	0.2	0.3	0.3	0.3	0.2	0.3	0.2	0.1
LOI	1.5	2.2	0.8	1.5	1.0	1.8	0.4	0.8	0.6
Total	99.7	99.7	99.2	100.5	99.5	99.7	100.1	100.0	99.5
Trace elements (ppm)									
Rb^{a}	60	46.9	50.5	50.9	55.9	40.6	2.35	4.15	28.0
Sr^{a}	86	241	184	130	249	179	130	785	434
Y	36	26	29	37	35	29	40	11	9
Zr	180	140	180	150	130	180	100	<50	<50
La	—	9.7	16.4	14.4	14.3	19.7	9.2	3.7	4.7
Ce	—	27.5	38.0	33.0	31.3	48.0	23.7	8.8	9.6
Nd	52.4^{a}	14.2^{a}	22.6	18.4^{a}	14.5^{a}	26.6^{a}	17.7^{a}	7.0^{a}	5.4
Sm	11.3^{a}	3.36^{a}	5.0	4.53^{a}	3.61^{a}	6.07^{a}	5.23^{a}	1.87^{a}	1.2
Eu	—	1.1	1.4	1.2	1.4	1.7	1.1	0.6	0.4
Gd	—	3.7	5.1	5.3	5.1	6.2	6.7	1.8	1.2
Dy	—	4.1	4.9	6.1	5.5	5.3	7.2	1.7	1.3
Er	—	2.8	3.0	4.0	3.7	3.2	4.3	1.0	0.9
Yb	—	2.7	3.0	3.8	3.7	2.9	3.9	1.2	1.0
Ni	40	42	56	49	44	35	45	30	8
Cr	224	136	115	131	91	67	64	38	5
Pb	19.5	11.6	13.3	9.6	13.7	7.0	5.0	6.1	4.8
U	1.9	1.0	1.3	1.1	1.2	1.6	0.3	0.2	0.2
K/Rb	346	372	394	310	356	307	1060	400	445

[a] Data by isotope dilution.

4.3. *Isotopic data*

Rb/Sr and Sm/Nd isotopic data are reported in Tables 1 and 4, respectively, and plotted in Figs. 5 and 6. Rb/Sr data define an errorchron with an age of ca 666 Ma, which we interpret as a reset age occurring at peak metamorphic temperature. This is consistent with evidence for resetting observed from the northernmost Nacfa–Tokar Terrane in Sudan. Rb/Sr whole rock isochrons for metavolcanic rocks in Sudan are ca 150 Ma younger than the 840–854 Ma zircon ages yielding 666 ± 16, 702 ± 57 and 684 ± 16 Ma. A post-tectonic granite yields a zircon evaporation age of 652 ± 14 Ma (Kröner et al., 1991) suggesting thermal resetting about the time that post-tectonic granites were emplaced (Kröner et al., 1991).

Initial $^{87}Sr/^{86}Sr$ for the paraschists are moderately low, ca 0.705. Assuming the 650 Ma age approximates peak metamorphism and that the

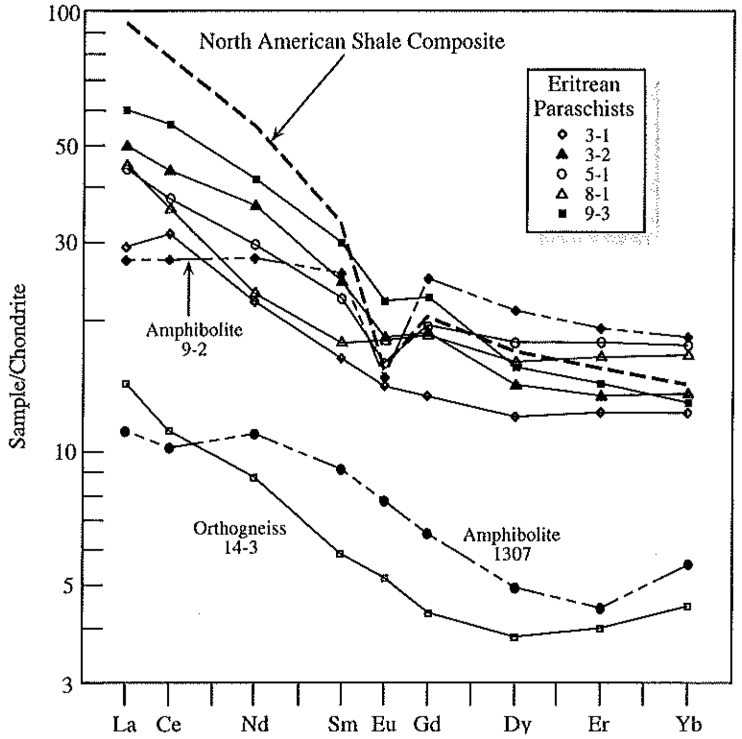


Fig. 4. REE patterns for Eritrean paraschists and related rocks (normalized to chondritic abundances).

Eritrean paraschists can be correlated with ca 800 Ma Bahah–Ablah metasediments of Arabia, the $^{87}Sr/^{86}Sr$ of the Eritrean sediments at the time of deposition must have been lower. Using the paraschist mean $^{87}Rb/^{86}Sr$ (0.97), mean $^{87}Sr/^{86}Sr$ (0.7138) and an age range of 800–900 Ma, a range of initial $^{87}Sr/^{86}Sr = 0.7014–0.7028$ is obtained. Initial $^{87}Sr/^{86}Sr$ assuming an age of 800 Ma can also be calculated for the amphibolites 9–2 (0.70345) and 1307 (0.7029) and the orthogneiss 14-3 (0.7025). These data show no evidence for involvement of older crustal components in sediments, dykes and gneiss.

The Nd isotopic data give further indication of the age of the crust that was eroded to produce the Eritrean paraschists. Because sedimentary rocks are mechanical mixtures from broad expanses of the crust, interpreting the significance of Nd model ages can be difficult. Interpretation of the significance of Nd model ages of shales is even more difficult because of added problems to Sm/Nd fractionation and the isotopic composition Nd as igneous minerals are reconstituted to clays. In spite of this, Nd model age studies of sediments and shales are accepted to yield first-order insights into the mean age of the crustal block from which these are derived (Goldstein et al., 1984; Li and McCulloch, 1996). No systematic difference is observed for Nd model ages determined between shales and arkosic sediments (Frost and Winston, 1987), and we infer that the Nd model ages calculated for Eritrean paraschists contain significant information about the age of the crust from which the protolith shale was derived.

The Nd isotopic composition of the Eritrean paraschists are presented in Fig. 6 and listed in Table 4. The paraschists have a mean $^{147}Sm/^{144}Nd = 0.142$, significantly higher (less LREE-enriched) than NASC and present day river and aeolian particles, which have $^{147}Sm/^{144}Nd \sim 0.11$ (Goldstein et al., 1984). The Eritrean paraschists have low enough $^{147}Sm/^{144}Nd$ so that their Nd isotopic trajectories intersect the depleted mantle growth curve at a high angle and yield a

Table 3
Comparison between mean Eritrean paraschist and NASC

	Mean Eritrean paraschist	NASC[a]	Metamorphosed[a] NA shales
SiO_2	66.6	64.8	60.48
TiO_2	0.78	0.78	0.91
Al_2O_3	17.0	16.9	16.6
FeO	5.77	5.70	8.10
MgO	3.31	2.85	6.35
MnO	—	0.06	0.13
CaO	1.52	3.56	2.31
Na_2O	2.53	1.15	1.80
K_2O	2.19	3.99	3.17
P_20_5	0.26	0.11	0.17
Trace elements (ppm)			
Rb	51	125	129
Sr	178	142	192
Y	32	—	—
Zr	140	200	165
La	14.9	31.1	32.6
Ce	35.6	67.8	72.7
Nd	24.8	34.4	31.3
Sm	5.6	6.69	6.16
Eu	1.4	1.18	1.27
Gd	5.1	5.6	—
Dy	5.2	5.75	—
Er	3.3	3.34	—
Yb	3.2	3.06	2.8
Ni	44	58	227
Cr	127	125	417
Pb	12.5	—	—
U	1.4	2.66	2.48
K_2O/Na_2O	0.87	3.47	1.76
K/Rb	356	265	204
Rb/Sr	0.29	0.88	0.67
$(La/Yb)_n$	3.2	7.0	8.0
Eu/Eu[a]	0.79	0.64	—

[a] Data from Gromet et al. (1984).

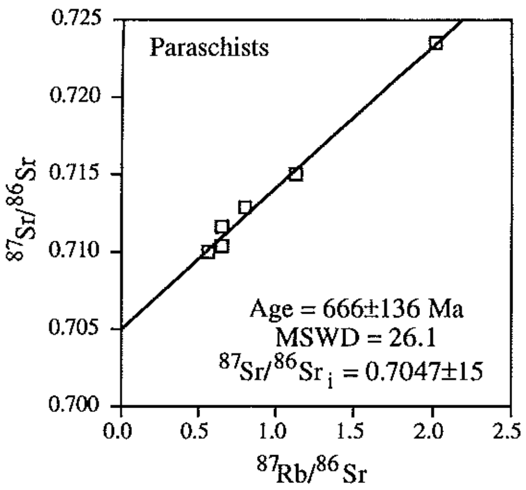


Fig. 5. Rb/Sr errorchron for Eritrean paraschists.

meaningful Nd model age (T_{DM}). These range in age from 0.97 to 1.26 Ga, with a mean of 1.05 Ga–ca 200–300 million years older than the expected stratigraphic age. Initial isotopic compositions at the time of sedimentation 800 Ma ago are reported as $\epsilon Nd_{(800)}$ and range from +4.7 to +2.5, with a mean of +4.0. This is slightly lower than the $\epsilon Nd_{(800)} = +5.9$ calculated for the depleted mantle model of Nelson and DePaolo (1985). It is difficult to determine what part of this difference is due to the presence of pre-Neoproterozoic crustal components and what part is due to the contribution of juvenile Neoproterozoic contributions reflecting an isotopically heterogeneous mantle. The likelihood that heterogeneous crustal isotopic signatures where $\epsilon Nd_{(t)} > 0$ mostly reflects heterogeneous mantle is acknowledged in the plot of age versus T_{DM} of (Harris et al., 1990), where divergences of

Table 4
Sm and Nd concentration and $^{143}Nd/^{144}Nd$ data

Sample (Ga)	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\epsilon_{Nd(800)}$	T_{DM}
1–1	52.4	11.32	0.131	0.512520±26	+4.5	0.97
3–1	14.17	3.36	0.143	0.512585±18	+4.5	0.99
5–1	18.37	4.53	0.149	0.512629±15	+4.7	0.98
8–1	14.52	3.61	0.150	0.512515±13	+2.5	1.26
9–3	26.55	6.07	0.138	0.512525±36	+3.9	1.04
9–2	17.70	5.23	0.179	0.512778±7	+4.6	1.14
1307	7.03	1.87	0.161	0.512764±12	+6.1	0.83

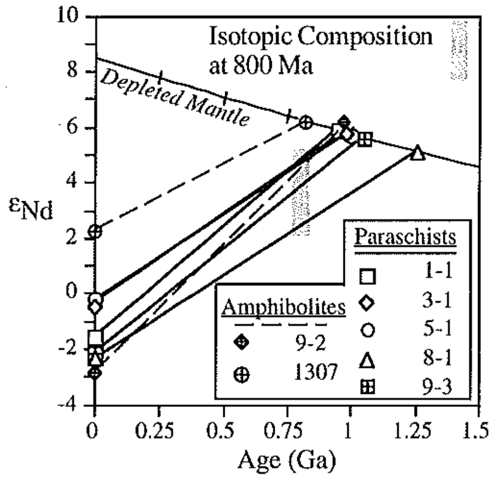


Fig. 6. Nd isotopic systematics for Eritrean paraschists (———) and amphibolite dykes (- - -). Field for NE Sudan juvenile crust is from Stern and Kröner (1993). Model for the evolution of depleted mantle is from Nelson and DePaolo (1985).

T_{DM} from the formation age as great as 300 Ma are nevertheless accepted as 'oceanic', that is, juvenile. For example, 740 Ma igneous rocks of Jebel Moya, Sudan [U/Pb zircon; Stern and Dawoud (1991)] have $\epsilon Nd_{(740)} \sim +3.0$, and $T_{DM} =$ (crystallization age +230 Ma); this is argued to reflect mantle heterogeneity, not participation of older crust (Stern and Dawoud, 1991). Such an explanation is also consistent with the range in $\epsilon Nd_{(800)}$ found for the amphibolite dykes (+4.6 to +6.1; Table 4). Simple calculations limit the participation of older crust to a few percent. Paleoproterozoic and Archean crustal protoliths in Yemen had $\epsilon Nd_{(800)} \sim -20$ (Windley et al., 1996); the Nd isotopic composition of Eritrean paraschists can be explained by adding as little as 5% or as much as 13% of sediment derived from such ancient crustal sources to sediment derived from juvenile crust with the Nd isotopic composition of model depleted mantle.

5. Discussion

The data which we have presented allows insights into a number of interesting problems concerning crustal evolution in the ANS. Considered together, the isotopic composition of Sr and Nd in the Eritrean paraschists at the time these sediments were deposited indicates limited to negligible involvement of older crustal sources. The isotopic data are consistent with models for the deposition of the sediments in back-arc basins or other oceanic domains. The data are inconsistent with any hypothesis that the high-grade rocks of Eastern Eritrea are remnants of pre-Neoproterozoic crust (Drury et al., 1994).

Our results provide paleogeographic constraints for the ANS at ca 800 Ma. Because aluminous clays form by weathering above sea level, the chemical data indicate erosion and extensive chemical weathering of a sustantial landmass to form clays, followed by transport of these mature sediments to and deposition in a shallow marine setting. The dimensions of this landmass can be inferred from the length of the metasedimentary belt defined in Fig. 1B to be at least 400 km from north to south. If our correlation is correct, the dimensions of the landmass may have approached subcontinental dimensions. This landmass nevertheless was overwhelmingly composed of juvenile continental crust, a result that is consistent with the conclusion of Kröner et al. (1992), that correlative sediments in Arabia were derived from juvenile sources in the southern Arabian Shield.

The geographic distribution of the Arabian and Eritrean high-grade metasediments offers insights into the suture formed by collapse of the Mozambique Ocean by closure of West and East Gondwanaland (Stern, 1994). The belt of Arabian and Eritrean high grade metasediments extends ca 300 km west of and parallel to the western flank of older continental fragments associated with the NW flank of East Gondwana (Fig. 7), including Mesoproterozoic crust of the Afif Terrane, Saudi Arabia, Paleoproterozoic and Archean crust in eastern Yemen. The fact that the metasedimentary belt now lies nearer to pre-Neoproterozoic crustal fragments of East Gondwanaland than the belt is to West Gondwanaland suggests that it lay on the eastern side of the Mozambique Ocean. These metasediments have been correlated with the Hafafit gneisses of Egypt by Kröner and Basahel (1984). The Hafafit gneisses lie close to pre-Neoproterozoic crust of West Gondwanaland, and if the correlation were correct, it would have

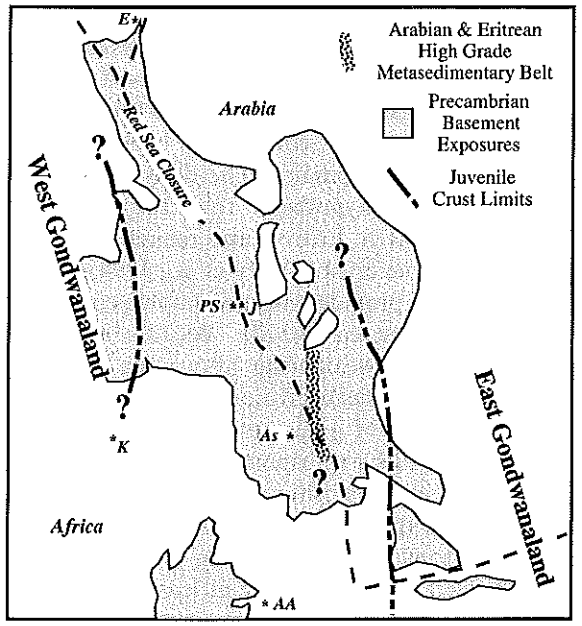


Fig. 7. Regional setting of the Arabian and Eritrean High Grade Metasedimentary Belt in the ANS, showing the inferred eastern limits of West Gondwanaland [after Stern (1994)] and western limits of East Gondwanaland (Kröner and Sacci, 1996; Stern, 1994; Windley et al., 1996). Note that the metasedimentary belt is closer to the margin of East Gondwanaland. Approximate locations of cities are shown: E, Elat; K, Khartoum; PS, Port Sudan; J, Jeddah; As, Asmara; and AA, Addis Ababa. Question marks indicate that further work is needed to trace the distribution of pre-Neoproterozoic crust and southern extension of the Arabian and Eritrean High Grade Metasedimentary Belt.

important paleogeographic constraints. We do not accept this correlation because the Eritrean and Arabian high-grade metasediments are part of the ca 800–850 Ma Barca/Haya–Asir terrane, which cannot be correlated with the ca 700–750 Ma crust in the SE Desert of Egypt. We conclude that sediments equivalent to Eritrean and high-grade metasediments do not extend very far west of the region shown in Figs. 1B and 7.

Finally, one of the most interesting questions concerns the timing and tectonic cause of the metamorphism. Our geochronologic results suggests that the timing of high-grade metamorphism was ca 650 Ma, but further work is needed to confirm or refute this result. This is about the time of intense collision between East and West Gondwanaland, thought to be most intense in the southern part of the EAO (Stern, 1994), and a plausible if tentative model would relate the intense metamorphism and rapid subsequent exhumation to this collision. The clockwise *P–T* path deduced by mineral thermobarometry is consistent with a collision process. In any case—and although it is lost beneath rift structures and flood basalts to the south—the high-grade metasedimentary belt appears to continue south, marking a structural and metamorphic transition within the EAO between the high-grade metamorphic rocks to the south and the low grade juvenile crust to the north.

6. Conclusions

At ca 800–850 Ma ago, a large marine basin in the Mozambique Ocean adjacent to east Gondwanaland began receiving pelitic sediments from a nearby low landmass, composed of juvenile crust. An unknown thickness of well-bedded pelitic sediments was deposited in a non-volcanic basin, perhaps in association with a passive margin. These sediments were heated and deeply buried. Peak metamorphic conditions were 700°C and 8–10 kbar and followed a period of isobaric or decompressional heating. The peak of metamorphism occurred ca 650 Ma ago; deformation, metamorphism and rapid exhumation accompanied collision between East and West Gondwanaland to form the EAO.

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