

Origin of Late Precambrian Intrusive Carbonates, Eastern Desert of Egypt and Sudan: C, O and Sr Isotopic Evidence

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Abstract

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The problem of the origin of northeast African basement carbonates is approached using a regional study of C, O and Sr isotopic compositions in whole-rock samples of late Precambrian carbonate rocks of the Egyptian and Sudanese shields (ESS), from the Eastern Desert of Egypt and Sudan. The isotopic data indicate that three distinct reservoirs were available for generation of ESS intrusive carbonates: (1) sedimentary carbonates, with moderately high $^{87}\text{Sr}/^{86}\text{Sr}$ and heavy C and O; (2) depleted mantle, with low $^{87}\text{Sr}/^{86}\text{Sr}$ and light C and O; and (3) enriched mantle or lower crust, with high $^{87}\text{Sr}/^{86}\text{Sr}$ and light C and O. Isotopic data indicate that the intrusive carbonates of the North Eastern Desert were derived from reservoir (2), and a sample from the interior of Sudan was derived from reservoir (3). The origin of the remaining intrusive carbonates of the Central Eastern Desert and Sudan is best explained as mixing between remobilized sedimentary carbonates and mantle fluids, i.e. reservoirs (1) and (2). The source of the sedimentary carbonates may have been carbonate bank sediments deposited during Pan-African rifting and evolution of a passive continental margin on the north flank of the South Eastern Desert, now structurally buried under the Central Eastern Desert melange.

Introduction

Basement rocks exposed along the western flank of the Red Sea in Egypt and Sudan formed between 900 and 550 Ma as the result of accretionary tectonics followed by post-collisional extension and shearing (Gass, 1977; Stern et al., 1984; Kröner, 1985). Thickening of the early arc and back-arc basin crust was accomplished

by stacking of nappes composed of ophiolites, intermediate volcanics, and associated wackes (Ries et al., 1983). Thrusting was accompanied by low-grade metamorphism, generally in the greenschist facies (Stern, 1981). This preliminary thickening of the crust represents the accretion of several terranes and was completed by ~670 Ma (Stoeser and Camp, 1985). Further intense deformation accompanied large-scale shearing along the Najd Fault System (Stern, 1985; Sultan et al., 1988).

Deformation and metamorphism were com-

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TABLE 1

Location and field description of northeast African basement carbonates

Sample	Location	Outcrop description
<i>Intrusive carbonates</i>		
<i>North Eastern Desert</i>		
E-175B	Wadi Abu Nakhra 26°25.5'N, 33°48'E	White carbonate veins intruded into quartz-rich tuffaceous metasediments
E-183D	Wadi Nuqara 26°39'N, 33°52'E	White carbonate segregation in Dokhan andesite
E-187A	Wadi Nuqara 26°39'N, 33°50'E	Gray carbonate vein in Dokhan andesite
E-193A	Wadi Umm Tagher 26°44'N, 33°50'E	White carbonate vein in amphibolite migmatite
E-220D,E	Wadi El Atrash 27°08'N, 33°13'E	White carbonate veins in Hammamat sediments (Willis et al., 1988)
<i>Central Eastern Desert</i>		
E-64H	Wadi Arak 25°44.5'N, 33°43.5'E	Orange carbonate dike, trend 090/40°N, intruding younger metavolcanics (Stern, 1981)
E-89; E-90F	Wadi El Gord 25°45'N, 33°42'E	Red carbonate vein, trend 330/60°S, intruding sheared older metavolcanics (Stern, 1981)
E-104A	Wadi Umm Seleimat 25°58'N, 33°41'E	Orange and white carbonate vein intruding older metavolcanics
E-104B	Wadi Umm Seleimat 25°58'N, 33°41'E	White carbonate vein intruding older metavolcanics
E-105B	Wadi El Gord 25°47'N, 33°42'E	Orange carbonate dike, trend 045, V, intruding older metavolcanics
E-223D,E	Wadi Mia Mine 25°18'N, 33°57'E	Massive white carbonate associated with sheared serpentized ultramafics
<i>Sudan</i>		
S-11	Bangadeed Village, Sabaloka ~16°10'N, 32°52'E	White carbonate vein in granite
GE-112, 113, 114	5 km south of Gebeit Mine 21°00'N, 36°20'E	Sheared gray carbonate intrusive (?) into Nafirdeib metavolcanics
<i>Sediments</i>		
TD-3B	NE Sudan 21°05'N, 33°10'E	White marble bed, 100 m thick and traceable for > 5 km
S-16	Sasa Plain (east side) ~20°50'N, 36°20'E	White marble interbedded with quartzite
E-78	Wadi Allaqi ~22°23'N, 33°48'E	Gray, laminated marbles. 3 beds each 1-2 m thick
D-96B	Wadi Allaqi ~22°30'N, 33°50'E	Gray marble
E-109I	Wadi El Mahdaf 25°46.5'N, 33°39'E	Brown and gray laminated marl

monly accompanied by the migration of carbonate-rich solutions, which are preserved as veins and dikes of calcite and dolomite, less typically ankerite, magnesite and breunnerite. The migration of these solutions also resulted in the diffuse and pervasive carbonation of a wide range of basement units. One such mani-

festation is the 'Baramia Rock' of Hume (1934), whereby ultramafics have been altered to a fine admixture of talc, serpentine, magnesite and dolomite. In other instances, entire exposures with well-preserved structures, such as pillowed basalts, have been almost completely replaced by carbonate. Although we are not yet

able to quantify the volume of carbonate added to the crust of this region, it is clear that vast amounts of such fluids accompanied the greenschist-facies metamorphism of a large portion of the Arabian–Nubian Shield.

The timing of carbonate alteration is not readily determined directly. Relationships with radiometrically dated volcanic and plutonic units in the North Eastern Desert (Stern and Hedge, 1985) indicate that carbonates were intruded there during the interval 600–580 Ma. Similar arguments indicate that carbonation in the Central Eastern Desert occurred during the interval 700–600 Ma. The Sabaloka carbonate vein (Table 1, sample S11) is associated with a granite body intruded at 540 Ma (Kröner et al., 1987). This is a location where detrital zircons and elevated initial $^{87}\text{Sr}/^{86}\text{Sr}$ suggest the proximity of a pre-Pan-African continental margin (Kröner et al., 1987). The other intrusive carbonates of northeast Sudan were emplaced sometime between the eruption of the 830 Ma Gebeit volcanics (Reischmann, 1986) and the intrusion of the ~680 Ma 'Batholithic Granites' (Cavanagh, 1979).

The source of fluids responsible for the carbonation has long been sought. Suggestions include: (1) exsolution of carbonate fluids from cooling granite intrusions (Wilcockson and Tyler, 1933); (2) submarine metamorphism at great depth, where H_2O and CO_2 were forced into slowly cooling lavas as a result of great hydrostatic pressure (Rittmann, 1958); (3) release of CO_2 from calcareous sediments during metamorphism (Shukri and Lotfi, 1959; Bogoch and Magaritz, 1983); and (4) degassing of a mantle source similar to that of carbonatites (Shimron et al., 1973). Although all who have looked at the problem have appreciated the importance of carbonate alteration in the late Precambrian basement of northeast Africa, none have presented compelling arguments regarding the origin of these fluids. This is a topic of interest not only to students of northeast African basement evolution, but also to economic geologists, as carbonate alteration is important

in the localization of gold deposits both within the region (Almond et al, 1984) and globally (Cameron, 1988). Furthermore, recognition of major carbonation events affecting large crustal tracts is a key to reconstructing terrestrial degassing history.

The purpose of this paper is to contribute to our understanding of the origin of northeast African basement carbonates. We report the results of the first regional study of the isotopic compositions of C, O and Sr in late Precambrian carbonate rocks of the Egyptian and Sudanese shields (ESS): similar studies have already been carried out on Precambrian carbonates in Sinai (Shimron et al., 1973; Bogoch and Magaritz, 1983; Bogoch et al., 1986).

Field occurrence

The ESS 'intrusive' carbonates manifest several different emplacement styles (Table 1), in part reflecting the different deformation styles and modes of crust formation in the region. The North Eastern Desert of Egypt (III in Fig. 1) differs from the rest of the ESS in its relative youth (670–580 Ma; Stern and Hedge, 1985), absence of ophiolites, and extensional mode of origin (Stern et al., 1984). Carbonates occur here principally as small veins (<1 m thick) and segregations in greenschist-facies metavolcanic rocks. The degree of carbonation is minor, affecting less than about 5% of the basement, with progressively less carbonation occurring from south to north. In addition, sedimentary marbles are known only from Wadi Dib (27°40'N, 32°54'E; Schürmann, 1966) in this part of the study area.

In contrast to the North Eastern Desert, extensive carbonation affected the Central Eastern Desert of Egypt (II in Fig. 1). This basement province is distinguished by its greater age (>670–570 Ma; Stern and Hedge, 1985), abundance of ophiolites, and compressional mode of formation (Ries et al, 1983). Carbonation is most commonly associated with greenschist-

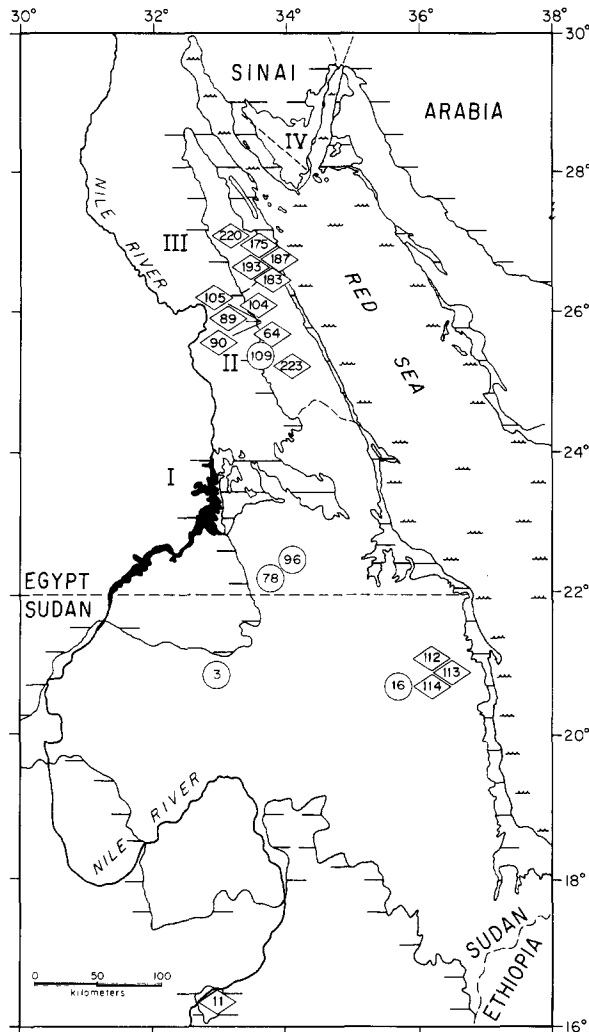


Fig. 1. Locality map for late Precambrian carbonate samples. Exposed Precambrian basement is shown in white, with the limit of Phanerozoic cover shown with horizontal lines. Diamonds correspond to intrusive carbonates; circles represent sedimentary carbonates. For simplicity, only the main sample identification number is shown, with sample prefixes and secondary descriptors omitted. The principal subdivisions of the Egyptian basement are indicated with Roman numerals: I. South Eastern Desert; II. Central Eastern Desert; III. North Eastern Desert; IV. Sinai.

facies metamorphism and pervasive shearing, particularly where dismembered ophiolites are involved. Generally the carbonate makes up 5–30% of the resulting alteration products, but occasionally much more. Large, relatively un-sheared dikes (1–2 m thick) and veins of car-

bonate are also common; these typically exploit faults and shear zones. Occasionally, large un-sheared exposures may be almost completely replaced by metasomatic carbonate: in one instance, an otherwise well-preserved exposure of pillowed basalt was so affected. It is difficult to determine the amount of carbonate that has been added to the crust of the Central Eastern Desert, but based on five field seasons of regional studies, we estimate that 5–10% of the basement is composed of non-sedimentary carbonate material, and that less than 2% of the exposed Central Eastern Desert basement is composed of layered, sedimentary carbonate rocks.

The situation in northeast Sudan is similar to that in the Central Eastern Desert, with large amounts of carbonate having been added to the basement during deformation and metamorphism. However, there is considerably more carbonate of sedimentary origin; perhaps 5% of the basement. At present no samples of intrusive carbonates from the South Eastern Desert of Egypt are available. Sedimentary carbonates occur in proportions similar to northeast Sudan.

Sample locations and mineralogy

Twenty-three samples were collected from over 11° of latitude during the course of several field seasons (Fig. 1; Table I). Five samples are from bedded sedimentary limestone, marble, or marl; these are mostly from southeast Egypt or northeast Sudan. X-ray diffraction (XRD) studies show that these consist of calcite (D96B, S16) or dolomite (E78) or both (TD3B) with minor (<5%) quartz, chlorite or kaolinite. One sample of marly limestone (E109I) consists of a mixture of calcite, feldspar and quartz, and was used only for the purpose of determining the $^{87}\text{Sr}/^{86}\text{Sr}$ of the leachate. The rest of the samples are from carbonates that are not of obvious sedimentary origin, generally dikes and thick veins where large, pure rhombs could be

extracted. Six samples are from the North Eastern Desert of Egypt; XRD studies show these to be pure calcite. The eight samples from the Central Eastern Desert of Egypt manifest a diverse mineralogy; XRD studies indicate that these samples consist of calcite (E104A,B), dolomite + calcite (E64H), calcite + ankerite (E223E), calcite + brucite (E223D), calcite, hematite and minor enstatite (E89, E90F), or ankerite (E105B). Four non-sedimentary samples are from the Sudan. Three are from the region around the Gebeit gold mine. The Gebeit carbonates consist of either calcite + quartz (GE113) or calcite + minor dolomite and quartz (GE112, GE114). The Sabaloka sample (S11) consists of calcite + minor dolomite.

Analytical techniques

All of the samples analyzed were whole-rock powders. Analyses for K, Rb and Sr concentration and Sr isotopic composition were performed using the chemical and instrumental facilities at The University of Texas at Dallas. Procedures have been outlined by Stern and Hedge (1985), with the exception that samples (except E-109I) were dissolved in 2.5 N HCl, and both 6-in-radius and 12-in-radius mass spectrometers were used. All Sr isotope data have been normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $\text{E} \& \text{A SrCO}_3$ $^{87}\text{Sr}/^{86}\text{Sr} = 0.70800$. Errors listed in Table 2 are $2\sigma_x$. Total blanks for K, Rb and Sr are about 55 ng, 0.1 ng and 3 ng, respectively.

XRD and stable isotope analyses were completed at the ARCO Oil and Gas Exploration Research laboratories in Plano, Texas. XRD analyses were done on a Scintag X-ray diffractometer at 45 kV and 35 mA, using Cu $K\alpha$ radiation and a solid-state detector. Powdered samples were analyzed while spinning, over a 2θ range of $2-70^\circ$, at a rate of 2° min^{-1} . Scanning electron microscope and energy dispersive X-ray fluorescence studies were used to augment XRD data for solid-solution-series minerals not readily identifiable by XRD analysis.

Analyses for O and C stable isotope compo-

sition were done on a VG Micromass 602E mass spectrometer having a 90° sector fixed magnet of 6 cm radius, with dual collectors. Powdered samples were prepared for analysis by reaction with 100% phosphoric acid (density = 1.86 g cm^{-3}) at 25°C (McCrea, 1950; Walters et al., 1972; Wachter and Hayes, 1985). Samples containing a single carbonate mineral were reacted for 1 day (calcite) or 3 days (ankerite). Although complete reaction ($>99\%$) of the ankerite would have required much longer (cf. Rosenbaum and Sheppard, 1986), the sample is likely to be sufficiently homogeneous isotopically that CO_2 from the small unreacted fraction would not be different enough from the CO_2 evolved after 3 days to change the isotopic value significantly. Further, as reaction rate is known to be a function of grain size (Walters et al., 1972), this sample (E105B) was ground to $\sim 2 \mu\text{m}$ in a mortar and pestle to maximize both reaction rate and homogeneity. For samples with multiple carbonate minerals (calcite and dolomite), the timed extraction method of Epstein et al. (1964) was used. For samples E64H, TD3B, and GE114, CO_2 gas collected after 1 h of reaction was taken to represent the isotopic composition of calcite; gas evolved between 1 h and 5 days represents dolomite. The amounts of dolomite in samples GE112 and S11 were insufficient to be distinguishable from the calcite remaining after 1 h of reaction time by this technique. Similarly, it was not possible to separate the small amount of ankerite ($<5\%$) from the calcite in sample E223E using this technique, and the gas collected after 2.5 h of reaction time represents only calcite. Carbon isotope values are reported relative to VPDB, and O isotope values are reported relative to VSMOW (Hut, 1987). $\delta^{18}\text{O}$ values were calculated using $10^3 \ln a$ fractionations for H_3PO_4 -liberated CO_2 of 10.20 for calcite and 11.03 for dolomite (Friedman and O'Neil, 1977); the fractionation value for dolomite was also used for ankerite. Higher values of $10^3 \ln a$ published recently by Rosenbaum and Sheppard (1986)

TABLE II

Geochemical and isotopic data for northeast African basement carbonates

Sample	Concentrations (ppm) ¹			Ratios		$(^{87}\text{Sr}/^{86}\text{Sr})_{\text{m}}^2$	$(^{87}\text{Sr}/^{86}\text{Sr})_{650}^3$	$\delta^{18}\text{O}$ SMOW	$\delta^{13}\text{C}$ PDB
	K	Rb	Sr	K/Rb	Rb/Sr				
<i>Intrusive carbonates</i>									
<i>North Eastern Desert</i>									
E-175B	5.1	0.017	140	300	0.00012	0.70315 ± 4	0.70315	+6.8	-5.1
E-183D	22.2	0.047	78.3	472	0.00060	0.70294 ± 9	0.70292	+7.0	-7.7
E-187A	20.9	0.044	815	475	0.00005	0.70288 ± 6	0.70288	+7.0	-3.9
E-193A	0.5	0.002	215	250	0.000009	0.70315 ± 6	0.70315	+10.1	-5.5
E-220D	113	0.269	347	420	0.00078	0.70327 ± 15	0.70325	+9.3	-6.1
E-220E	-	0.62	438	-	0.0014	0.70334 ± 7	0.70330	+8.5	-6.2
<i>Central Eastern Desert</i>									
E-64H	19.7	0.028	246	704	0.00011	0.70430 ± 6	0.70430	{ +23.1 cc -7.4 cc +27.4 dol -7.5 dol	
E-89	215	0.618	130	348	0.0048	0.70351 ± 10	0.70338		+12.1
E-90F	20.4	0.082	123	249	0.00067	0.70350 ± 10	0.70348	+14.6	-5.1
E-104A	6.8	0.015	1676	453	0.000009	0.70354 ± 4	0.70354	+11.9	-6.9
E-104B	3.9	0.017	35.0	229	0.00049	0.70393 ± 4	0.70392	+10.5	-7.8
E-105B	14.8	0.028	43.1	529	0.00065	0.70483 ± 7	0.70481	+21.6	-3.6
E-223D	4.4	0.018	82.7	244	0.00022	0.70610 ± 8	0.70609	+20.2	+3.5
E-223E	254	1.29	123	197	0.010	0.70504 ± 7	0.70477	+19.6	-2.2
<i>Sudan</i>									
S-11	1.7	0.009	1033	189	0.000009	0.70968 ± 11	0.70968	+5.9	-5.9
GE-112	193	0.529	601	365	0.00088	0.70421 ± 9	0.70419	+13.3	-2.2
GE-113	64.6	0.169	437	382	0.00039	0.70451 ± 5	0.70450	+9.5	-0.3
GE-114	840	2.24	322	375	0.0070	0.70442 ± 5	0.70423	{ +14.7 cc -3.5 cc +15.3 dol -4.9 dol	
<i>Sediments</i>									
TD-3B	8.8	0.015	1266	587	0.000012	0.70621 ± 8	0.70621	{ +16.3 cc -1.2 cc +14.7 dol -0.7 dol	
S-16	12.8	0.057	612	225	0.000093	0.70595 ± 6	0.70595		+21.1
E-78	31.0	0.078	75.7	397	0.0010	0.70527 ± 10	0.70524	+23.2	+3.4
D-96B	36.7	0.052	161	706	0.00032	0.70434 ± 6	0.70433	+15.6	+4.0
E-109I	-	-	-	-	-	0.70475 ± 9	(0.70475)	-	-

¹Blank-corrected concentrations.²Present-day isotopic composition, adjusted to E & A SrCO_3 $^{87}\text{Sr}/^{86}\text{Sr}=0.70800$.³Isotopic composition at 650 Ma.

for ankerite and dolomite are also nearly identical (11.70 and 11.71 at 25°C, respectively).

Results

Analytical data are listed in Table 2 and plotted in Fig. 2a-c. The data span a wide range, with $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.70288 to 0.70968, $\delta^{18}\text{O}$

from +5.9 to +27.4‰, and $\delta^{13}\text{C}$ from -7.8 to +4.0‰. Three samples have data for calcite-dolomite pairs. These pairs give no consistent results, with dolomite-calcite fractionation ranging from +4.3 to -1.6‰ for $\delta^{18}\text{O}$ and from +0.5 to -1.4‰ for $\delta^{13}\text{C}$. These variations can be largely explained as resulting from more than a single episode of carbonate alteration. Such

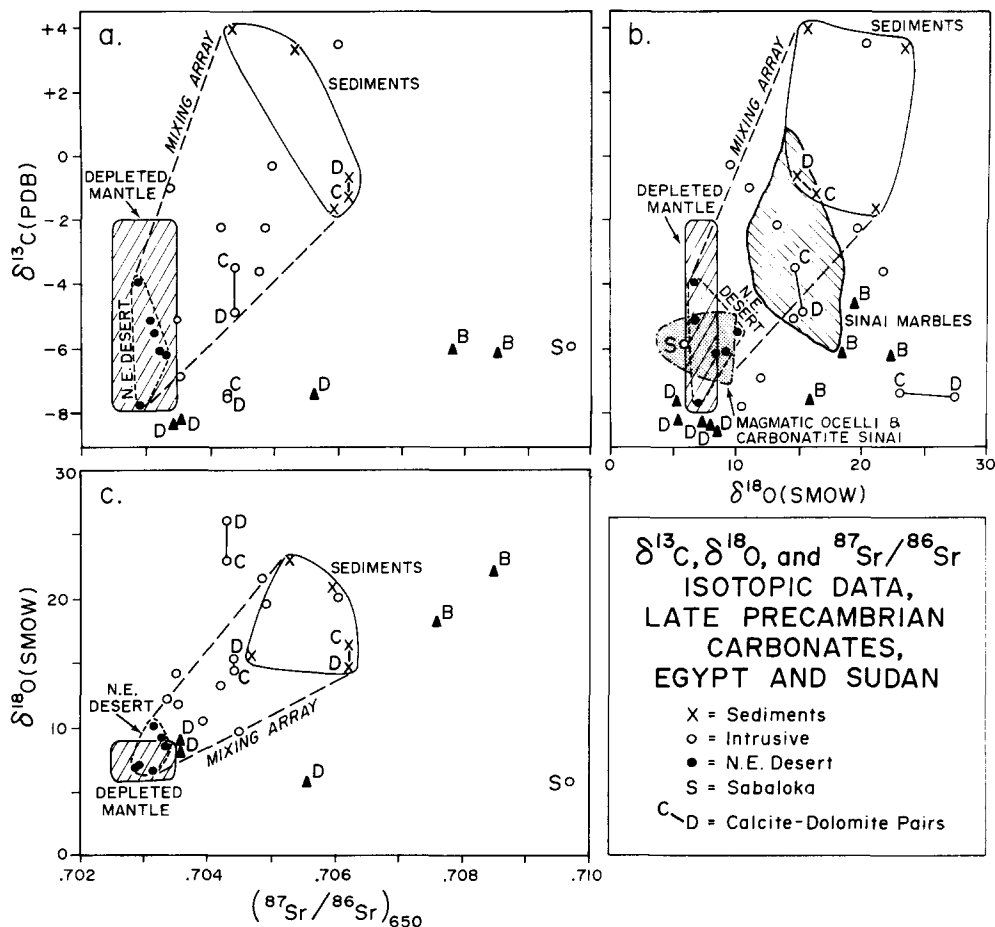


Fig. 2. Plots of O, C and Sr isotope data for northeast African carbonates. (a) $\delta^{13}\text{C}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ at 650 Ma, with fields for North Eastern Desert intrusive carbonates, sediments, and bulk mixing array as discussed in text. Data for Sinai carbonates are shown as filled triangles, marked 'D' (dolomite) or 'B' (breunnerite) (Bogoch et al., 1986). Field for late Precambrian mantle-derived carbonates is taken from C-isotopic data of Taylor et al. (1967) and Deines (1980), and Sr-isotopic data for Egyptian basement rocks are from Stern and Hedge (1985). (b) $\delta^{13}\text{C}$ vs. $\delta^{18}\text{O}$ for the same samples, with similar reference fields outlined. The fields occupied by magmatic ocelli and carbonatite from Sinai (Bogoch and Magaritz, 1983) and Sinai marbles of sedimentary origin (Bogoch et al., 1986) are also shown for reference. (c) $\delta^{18}\text{O}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ at 650 Ma, again with similar reference fields displayed.

an interpretation is supported by textural evidence for multiple episodes of carbonate addition and replacement. In spite of this, the variations observed for the calcite-dolomite pairs are small compared with the variations observed between individual samples.

The intrusive carbonates contain extremely low concentrations of K and Rb (Table II), with a mean of 106 ppm K and 0.34 ppm Rb. K/Rb ranges from 189 to 707, with a mean of 364 (Fig. 3). Sr contents vary widely, from 35 to 1676

ppm, with a mean of 383 ppm (Fig. 4). Rb/Sr ratios are uniformly low, invariably less than 0.01, with a mean of 0.0016. Contents of K and Rb in the sedimentary carbonates are also very low, averaging 13 ppm K and 0.05 ppm Rb; Sr has a wide range of concentrations, from 76 to 1266 ppm for four samples.

The five samples of sedimentary carbonate are generally distinct isotopically from the carbonate dikes and veins, with generally higher $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$. The field defined by

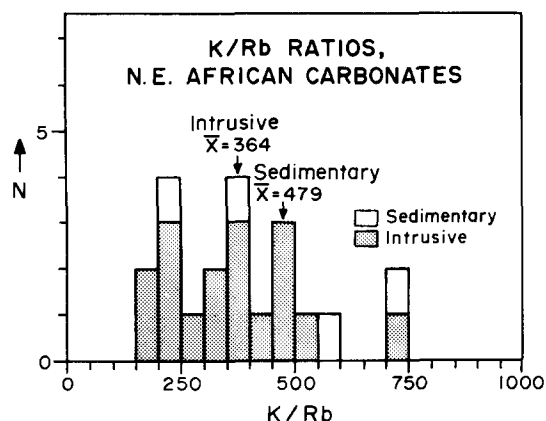


Fig. 3. K/Rb ratios for late Precambrian carbonates from northeast Africa. Mean values are given for intrusive and sedimentary samples.

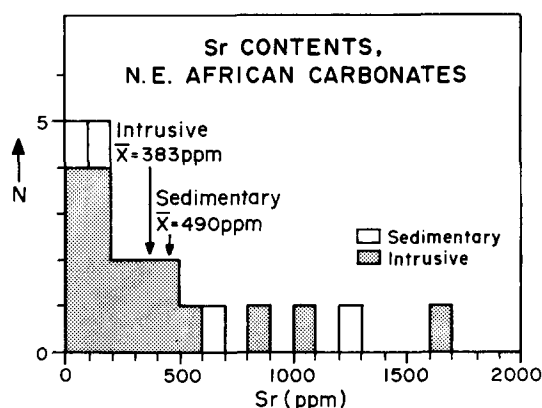


Fig. 4. Sr contents for late Precambrian carbonates from northeast Africa. Mean values are given for intrusive and sedimentary samples.

the sediments is consistent with the composition expected for late Precambrian marine carbonates, although the $^{87}\text{Sr}/^{86}\text{Sr}$ is somewhat lower in the present data set (Veizer et al., 1983; Holland, 1984).

The sedimentary carbonates are most readily distinguished from the intrusive carbonates by $\delta^{13}\text{C}$ in conjunction with either $^{87}\text{Sr}/^{86}\text{Sr}$ or $\delta^{18}\text{O}$. The heavier nature of the sedimentary carbon, coupled with their generally more radiogenic Sr ($^{87}\text{Sr}/^{86}\text{Sr}$ from 0.7043 to 0.7062) and heavier O ($\delta^{18}\text{O}$ from +15.6 to +23.2‰) best resolves the sediments from the intrusive ESS carbonates. There is nevertheless signifi-

cant overlap among the sedimentary and non-sedimentary carbonates.

Samples from the North Eastern Desert of Egypt constitute another distinctive group, containing the lightest C and O and the least radiogenic Sr. The six samples analyzed define a tight cluster, with $\delta^{13}\text{C} = -7.7$ to -3.9 ‰, $\delta^{18}\text{O} = +6.8$ to $+10$ ‰, and $^{87}\text{Sr}/^{86}\text{Sr} = 0.70288$ – 0.70330 . These samples have $\delta^{18}\text{O}$ values similar to that of mantle-derived carbonates (Taylor et al., 1967). The $\delta^{13}\text{C}$ value for the North Eastern Desert samples is similar to a wide range of mantle-derived rocks, including diamonds (-5 to -6 ‰; Pineau et al., 1976; Deines, 1980; Exley et al., 1986). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in these samples is indistinguishable from initial ratios for mantle-derived volcanics from the North Eastern Desert (0.7029–0.7031; Stern and Hedge, 1985) and falls within the range expected for the upper mantle at the end of the Precambrian. The North Eastern Desert carbonates are dominated by mantle components and manifest no discernible interaction with crustal Sr or surficial O or C.

Non-sedimentary carbonates from the Central Eastern Desert and northeast Sudan lie between the extremes of the North Eastern Desert mantle-derived carbonates and the sedimentary carbonates. With the exception of S11, these samples range in $\delta^{13}\text{C}$ from -7.8 to -0.3 ‰, in $\delta^{18}\text{O}$ from $+9.5$ to $+27.4$ ‰, and in $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.70338 to 0.70609. A few have compositions that are close to that expected for mantle-derived carbonates (D27; E104A,B), but most have Sr and O isotopic compositions that are similar to those of the sedimentary carbonates. Sample S11 is a special case, with mantle-like O and C but very radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$. This sample most probably manifests the role of enriched mantle or lower crust underlying the pre-Pan African crust of central Sudan.

Origin of northeast African intrusive carbonates

Because carbonate rocks recrystallize easily, so obscuring mineralogic and chemical indica-

tions of alteration, it is necessary to have other means of assessing the extent to which secondary alteration has changed the isotopic composition of the original rock. This is fairly easy where surficial waters were important alteration agents. These fluids have very low C/O and the carbonate rock being altered will show major shifts in $\delta^{18}\text{O}$ before $\delta^{13}\text{C}$ changes appreciably. Thus, low- T alteration of mantle-derived carbonates by low- T meteoric water would be expected to result in rocks with mantle-like $\delta^{13}\text{C}$ (from about -8 to -2‰) but relatively heavy $\delta^{18}\text{O}$ (from about $+10$ to $+30\text{‰}$). These changes have been documented for the alteration of mantle-derived carbonates of the Tarr Complex, Sinai, where alteration of mantle-derived dolomites ($\delta^{18}\text{O}$ from $+5$ to $+8\text{‰}$) resulted in breunnerites with very heavy O ($\delta^{18}\text{O}$ from $+16$ to $+22\text{‰}$) but little change in C ($\delta^{13}\text{C}$ from -5 to -8‰ ; Bogoch et al., 1986). This behavior suggests that carbonate alteration in equilibrium with surficial water should define a trend toward heavy O at a relatively constant $\delta^{13}\text{C}$. Such a trend is very different from that defined by mixing between mantle-derived and sedimentary carbonates and allows us to distinguish altered from fresh carbonates.

Examination of the data in Table II and Fig. 2 indicates that only sample E-64H falls consistently outside the mantle-sediment mixing array in $\delta^{18}\text{O}$ - $\delta^{13}\text{C}$ -($^{87}\text{Sr}/^{86}\text{Sr}$)₆₅₀ space. This deviation is to the high $\delta^{18}\text{O}$ side of the mixing array, which was also found for the Sinai breunnerites. The other samples fall within or close to the mixing array for all three diagrams in Fig. 2 and we interpret all except E-64H to approximate the isotopic composition of the original rock. The following discussion builds on this conclusion.

Three distinct reservoirs of Sr, O and C were available for the generation of the ESS intrusive carbonates: (1) sedimentary carbonates (moderately high $^{87}\text{Sr}/^{86}\text{Sr}$, heavy O and C); (2) depleted mantle (low $^{87}\text{Sr}/^{86}\text{Sr}$, light O and C); and (3) enriched mantle or lower crust (high $^{87}\text{Sr}/^{86}\text{Sr}$, light O and C). The intrusive

carbonates from the North Eastern Desert clearly tapped reservoir (2), a conclusion that is consistent with observations based on sedimentologic studies (Stern et al., 1984; Willis et al., 1988) and combined geochronologic and initial $^{87}\text{Sr}/^{86}\text{Sr}$ data for igneous silicate rocks (Stern and Hedge, 1985), that no crust older than about 670 Ma exists in the region. In this case, there would be no aged enriched subcontinental mantle available beneath the North Eastern Desert at the end of the Precambrian, so that any mantle source would have non-radiogenic Sr. This contrasts with the situation for Sinai, where somewhat older (>780 Ma; Stern and Manton, 1987) lithosphere yielded mantle-derived carbonates with significantly more radiogenic Sr ($^{87}\text{Sr}/^{86}\text{Sr}=0.7036\text{--}0.7060$; Bogoch et al., 1986). Details regarding the generation of the North Eastern Desert carbonates await further resolution; these fluids could have formed as a distinct carbonate 'melt' in the upper mantle or could have been exsolved from fractionating mantle-derived silicate melts. In a similar study of basement carbonates in Sinai, Shimron et al. (1973) suggested that bodies with low $^{87}\text{Sr}/^{86}\text{Sr}$ and narrow ranges of both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ were derived from a carbonatitic source in the mantle. This interpretation is difficult to reconcile with the low Sr contents of the North Eastern Desert carbonates; the mean of 339 ± 268 ppm Sr is in marked contrast with typical concentrations of 3000–8000 ppm Sr in unequivocal carbonatites (Higazy, 1954; Bowden, 1962). Low Sr contents are also characteristic of the Sinai mantle-derived dolomites (Bogoch et al., 1986). Nevertheless, the isotopic signature of the North Eastern Desert carbonates indicates mantle derivation. We thus prefer to interpret these as having exsolved from cooling silicate melts of mantle origin, rather than being derived directly from a carbonatitic source.

The specimen from Sabaloka (S11) was clearly derived from enriched upper mantle or aged lower crust. The O and C data fall in the field for the mantle (Fig. 2b) whereas the $^{87}\text{Sr}/$

^{86}Sr is more radiogenic than is typical for the mantle (Fig. 2a,c). An attractive explanation of the Sabaloka data involves the lower crust as the source for most of the Sr, with the O and C evolving from the mantle or from a lower crust that had re-equilibrated with mantle O and C. The granites that host the Sabaloka carbonate veins also contain large blocks of lower crustal granulites, some of which are metasediments containing Archean and lower Proterozoic zircons (Kröner et al., 1987). These data have been interpreted to indicate the proximity of pre-Pan-African crust in the region, an interpretation that is also consistent with elevated initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.710) for 540 Ma granite at Sabaloka (Kröner et al., 1987). If these granites are melts of the lower crust (Jackson et al., 1984), the similarity of initial $^{87}\text{Sr}/^{86}\text{Sr}$ for granite and carbonate is a strong argument that at least the Sr in the carbonate originated in aged lower crust. An origin for the carbonate by exsolution from cooling silicate melts is thus also preferred here (cf. Wilcockson and Tyler, 1933).

The origin of the remaining intrusive carbonates is not obvious. Their isotopic characteristics fall between those having depleted upper mantle and sedimentary characteristics. In Fig. 2a–c, the intrusive carbonates of the Central Eastern Desert and northeast Sudan fall within fields defined by bulk mixing between the North Eastern Desert intrusive carbonates and sedimentary carbonates. Three samples fall outside this field, samples E64H, E104B and E105B. E105B falls in the mixing field defined by $\delta^{13}\text{C}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$, but has slightly heavier O relative to C than would be predicted from bulk mixing alone. E104B falls within the mixing fields for $\delta^{18}\text{O}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$, but also has lighter C than would be expected from mixing alone. Sample E64H falls far outside mixing fields on all three projections, with much lighter C and/or heavier O than would be predicted for mixing alone. The latter especially may result from partial re-equilibration with groundwater, as previously discussed.

With the exception of sample E64H, we believe that the compositional and isotopic features of the intrusive carbonates of the Central Eastern Desert and northeast Sudan are very similar to those at the time of emplacement. If this is correct, then a significant fraction of these bodies must be composed of remobilized sedimentary carbonate. This is especially clear for the Wadi Mia body (E223D,E), which has Sr-, O-, and C-isotopic features indistinguishable from the late Precambrian sedimentary carbonates analyzed here (Fig. 2a–c). In fact, it is not possible to identify any non-sedimentary isotopic component in the intrusive composition of this carbonate body. Sample E105B and the intrusive carbonates from northeast Sudan also have isotopic compositions approaching those of sedimentary carbonates. Other samples, such as E89, E90F, E104A and E104B manifest a strong mantle component, with relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ and moderately light C and O. These samples nevertheless appear to represent a mixture of mantle and sedimentary carbonate components.

Consideration of $^{87}\text{Sr}/^{86}\text{Sr}$ alone for the intrusive carbonates also indicates that those from the Central Eastern Desert and northeast Sudan have a significant non-mantle component. Figure 5 plots the fields occupied by the intrusive carbonates, late Precambrian seawater and silicate rocks of the Egyptian basement. The field for the Egyptian basement provides a *maximum* value for the upper mantle beneath this region during the time that the carbonates were being emplaced, as much of the increasing $^{87}\text{Sr}/^{86}\text{Sr}$ ratio with time resulted from remelted juvenile crust (Stern and Hedge, 1985). Note that the data for the North Eastern Desert fall well within the field for the Egyptian basement, a result that is consistent with the combined O–C–Sr isotopic arguments indicating mantle derivation. Data for the Central Eastern Desert and northeast Sudan define fields that are largely or entirely more radiogenic than the Egyptian basement, strengthening the argument that these cannot have been

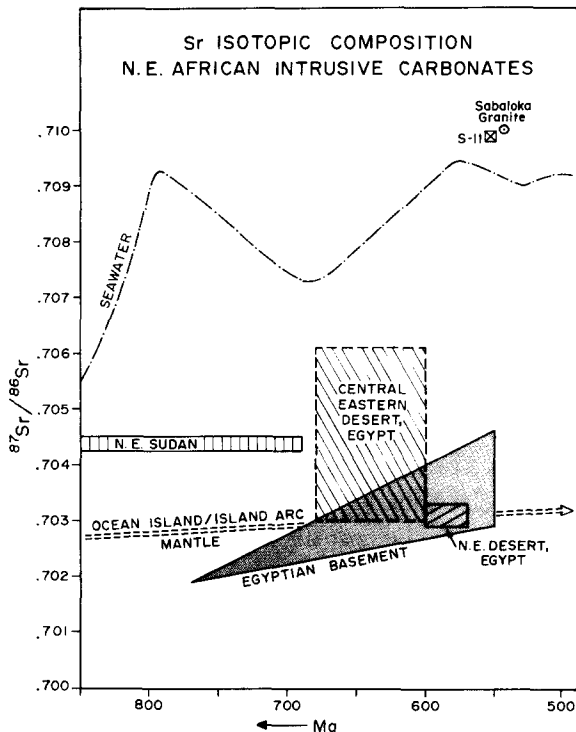


Fig. 5. Isotopic evolution of Sr in late Precambrian intrusive carbonates from northeast Africa. The ages of emplacement for the intrusive carbonates are estimated from the age of the surrounding basement units (Cavanagh, 1979; Stern and Hedge, 1985; Reischmann, 1986; Kröner et al., 1987). Field of initial $^{87}\text{Sr}/^{86}\text{Sr}$ for the Egyptian basement is also shown (Stern and Hedge, 1985); this field represents an upper limit for the isotopic composition of Sr in the depleted mantle beneath northeast Africa at that time. Isotopic composition of late Precambrian seawater is also shown, after Veizer et al. (1983). Note that the fields for the Central Eastern Desert and northeast Sudan intrusive carbonates are displaced from the field for the Egyptian basement towards late Precambrian seawater. Note also that the close correspondence of initial $^{87}\text{Sr}/^{86}\text{Sr}$ for the Sabaloka granite and sample S11 suggest that both may originate in the lower crust.

generated from depleted mantle alone.

The wide range of intrusive compositions, especially of the sedimentary carbonates, as well as uncertainties regarding the conditions of extraction and mixing of mantle and sedimentary sources, precludes a serious attempt at quantitative modelling of this mixing. Inspection of Fig. 2a indicates that the intrusive carbonates in the Central Eastern Desert of Egypt and

northeast Sudan are best explained as a result of bulk mixing of variable amounts of sedimentary and mantle-derived carbonate material, in proportions ranging approximately from 100:0 to 30:70.

Mixing mechanics are enigmatic. The intrusive carbonate bodies were emplaced at relatively low temperatures ($< 300^\circ\text{C}$), as demonstrated by their ubiquitous association with sheared greenschist-facies rocks and serpentinites. This inference is also consistent with the lack of any evidence for chilled margins on any of the carbonate dikes. Given the high geothermal gradients reported for the Pan-African of this region ($> 50^\circ\text{C km}^{-1}$; Reymer et al., 1984), this would indicate that mixing occurred in the upper crust.

The constraints and inferences outlined above suggest that the intrusive carbonates of the Central Eastern Desert of Egypt and northeast Sudan can best be explained as resulting from the large-scale remobilization of carbonate sediments and mixing with mantle fluids. Extensive bodies of sedimentary carbonate are not encountered in the Central Eastern Desert, although they are known from northeast Sudan (Fitches et al., 1983). Nevertheless, large volumes of intrusive carbonates exist in the Central Eastern Desert that were substantially to overwhelmingly derived from sedimentary carbonates. What evidence is there that large volumes of sedimentary carbonate once existed in the region now occupied by the Central Eastern Desert?

There is a significant body of evidence that the South Eastern Desert existed as juvenile continental crust at the same time that a basin, floored by oceanic crust, existed to the north. Stern and Hedge (1985) drew on a variety of lithologic data to substantiate their differentiation of the Eastern Desert of Egypt into Northern, Central and Southern sub-provinces. Critical to this assessment was the observation by Stern (1979) that ferruginous sediments, including hematitic iron-formation and related jaspers, outlined a basin that corresponded pre-

cisely to the outlines of the Central Eastern Desert as deduced from other lines of evidence. Shackleton et al. (1980) noted that the melange of the Central Eastern Desert rests on pelitic shelf sediments. El Ramley et al. (1984) noted that the basement sequence exposed in the Hafafit Culmination, at the boundary between the Central Eastern and South Eastern Deserts, begins with shallow-water sediments deposited between 1120 and 720 Ma. Cobbles in these sediments include granodiorite, quartzite, arkose, marble and felsic volcanics; these comprise the 'Atud Conglomerate' (El Ramley and Akaad, 1960), which is most common in the southern part of the Central Eastern Desert. The Atud Conglomerate and related fine-grained sediments are most simply explained as having been shed during the early stages of rifting and evolution of a passive continental margin on the north flank of the South Eastern Desert. This passive margin would be a likely setting for large deposits of sedimentary carbonates. Southward-directed thrusting, now manifested by the nappes of the Hafafit Culmination (El Ramley et al., 1984), accompanied by the intrusion of large volumes of granodiorite, would provide a natural mechanism for mixing and remobilizing the sedimentary carbonates as intrusive carbonates. The sedimentary carbonate component in the Central Eastern Desert intrusive carbonates would thus largely represent the remobilized components of a Pan-African carbonate bank that is otherwise not exposed, being either buried under the Central Eastern Desert melange and/or largely remobilized as intrusive carbonates.

This hypothesis finds some support in the gross geographic variation of the isotopic characteristics of the Central Eastern Desert intrusive carbonates. The samples collected closest to the inferred continental margin (E223D,E) manifest an overwhelming sedimentary component, whereas the remaining samples, taken from farther north, reflect a substantial mantle contribution. This variation may reflect the large volume of sedimentary carbonate that was

available to be remobilized in the south, whereas carbonates to the north reflect proximity to the unequivocally mantle-derived carbonates of the North Eastern Desert. Further sampling and isotopic studies are, of course, required to test the validity of this hypothesis.

Conclusions

Late Precambrian carbonate intrusions and alteration products in eastern Egypt and Sudan are derived from three reservoirs. That of carbonates in the northernmost ESS predominantly lies in the mantle. Relatively minor carbonate veins in the North Eastern Desert of Egypt exhibit the isotopic composition of depleted mantle, and probably exsolved from mantle-derived silicate melts. Much larger volumes of carbonate intrusive and alteration material in the Central Eastern Desert show a strong latitudinal variation, with strong mantle affinities in the north and an increasing sedimentary component towards the south. This variation is consistent with an increasing involvement of late Precambrian carbonate bank deposits, inferred to have existed on the northern margin of the South Eastern Desert. Intrusive carbonates from northeast Sudan also have a predominantly crustal origin. A carbonate vein from the interior of Sudan indicates that Sr was largely derived from the lower crust but O and C were derived from the mantle. The interaction of these three reservoirs has resulted in a wide range of isotopic compositions of carbonate alteration products and intrusions. The complex origins of late Precambrian carbonate intrusions and alteration products indicates that it will be difficult to resolve the amount and relative proportions of volatiles degassed from the mantle or recycled from the crust. Further and increasingly detailed studies of the sort initiated here will be required before this issue can be resolved.

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