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GEOCHRONOLOGIC AND ISOTOPIC CONSTRAINTS ON LATE PRECAMBRIAN CRUSTAL EVOLUTION IN THE EASTERN DESERT OF EGYPT

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ABSTRACT. Ages for twenty-four units from the Eastern Desert of Egypt were determined using combined Rb-Sr and U-Pb zircon techniques. These results, coupled with a threefold subdivision of this basement based on the distribution of diagnostic lithologies, lead to the following conclusions: (1) igneous (and tectonic?) activity in the Eastern Desert began sometime prior to 765 Ma and ended by 540 Ma; (2) within this time frame, the oldest rocks are found in the South Eastern Desert and the youngest rocks are found in the North Eastern Desert; (3) the mean age of the basement decreases from south to north; (4) five or six igneous pulses, separated by 40 ± 10 Ma can be tentatively identified within this interval; (5) a fundamental transition in tectonic and magmatic style, from compressional to extensional, occurred about 600 Ma and was especially important in the development of crust in the North Eastern Desert; and (6) all igneous rocks in the Eastern Desert have low initial $^{87}Sr/^{86}Sr$ (0.702-0.704), such that reworking of older continental crust is precluded. Instead, the basement of the Eastern Desert of Egypt must have evolved via melting of metasomatically enriched mantle and/or remelting of immature geosynclinal materials over 230 × 10^6 yrs at the end of the Precambrian.

INTRODUCTION

The Late Precambrian to Early Paleozoic orogenic event which Kennedy (1964) termed the "Pan-African Thermo-Tectonic Episode" represents an intense period of crustal formation and remobilization throughout Gondwanaland. Although this event was especially important in the structural differentiation of Africa, all continents were affected at this time (~ 450-900 Ma). Yet in spite of its ubiquity, the Pan-African event is in many ways still an enigma. For example, it is not clear whether orogenic models based on our understanding of post-Permian plate tectonics apply to this event (Hurley, 1972). While some investigators argue that Pan-African belts in many cases reflect continent-continent collisions (Dewey and Burke, 1973; Rogers and others, 1978; Fleck and others, 1980) or arc-continent sutures (Gass, 1977; Bakor, Gass, and Neary, 1976), these arguments are not yet compelling. Alternate models calling for Pan-African belts to represent sites of mantle upwelling and crustal distension

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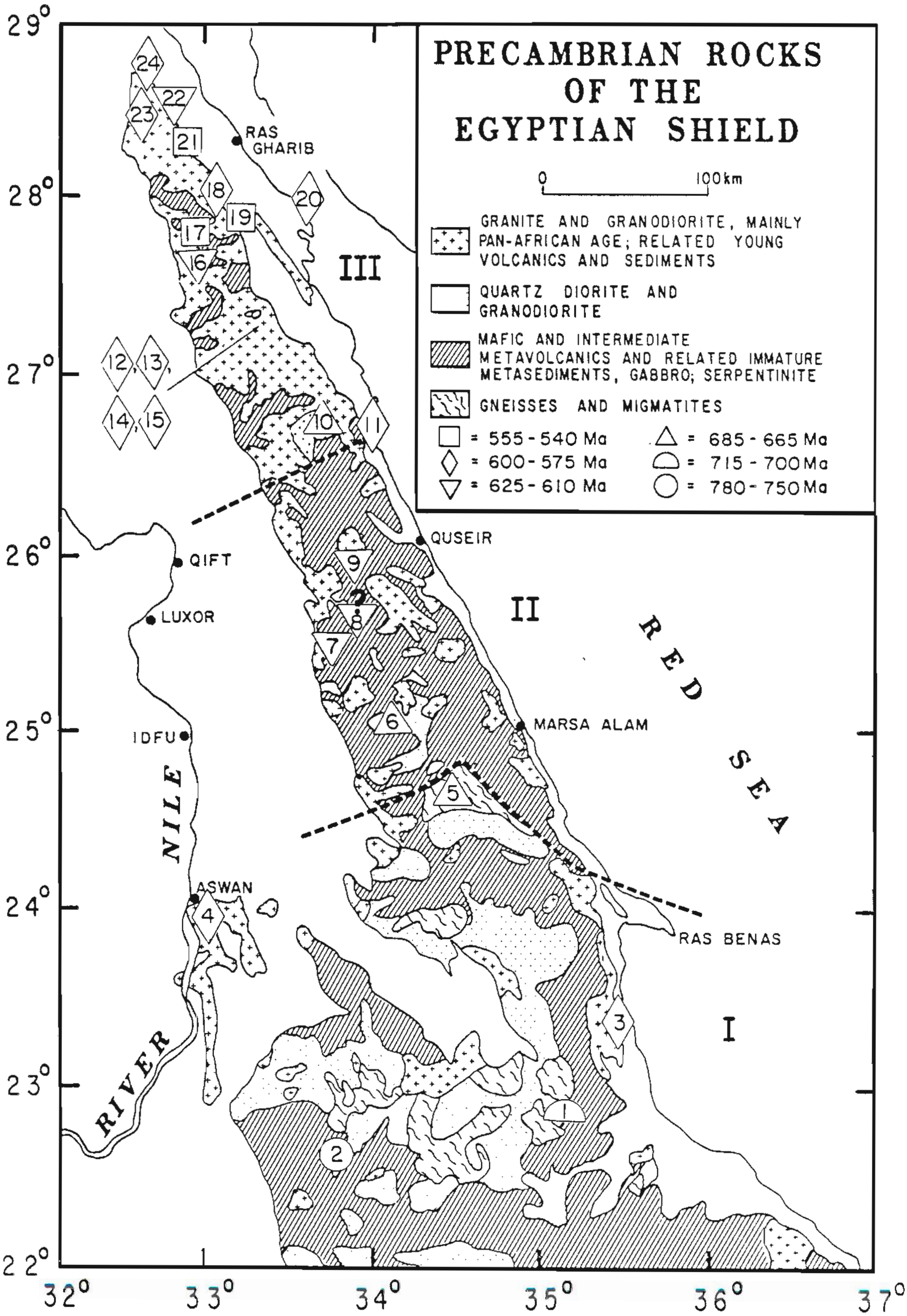
(Kazmin, Shifferaw, and Balcha, 1978; Kröner, 1979; Shimron, 1980; Engel, Dixon, and Stern, 1980) are supported by numerous observations: (1) the absence of the paired metamorphic belts, linear batholiths, and blueschists characteristic of Mesozoic and younger circum-Pacific orogenic belts; (2) paleomagnetic evidence indicating African cratons were in their present relative positions as early as the Early Proterozoic (Piper, Briden, and Lomax, 1973); (3) the apparent lack of high mountains (Gaudette and Hurley, 1979); and (4) the merging of more primitive, ophiolite-rich terranes in northeast Africa southward into the gneissic, reworked crustal orogens of the Mozambique belt (Kazmin, 1972).

It is becoming increasingly apparent that studies of the Pan-African event in northeast Africa and Arabia must be placed in a secure geochronologic framework. In the past, such studies have been largely concentrated in basement terranes in Arabia (that is, Fleck and others, 1980; Cooper and others, 1979; Fleck and Hadley, 1982). Similar terranes on the west flank of the Red Sea have received less attention. Very little is known about the geochronology of vast tracts of Precambrian crust in the Sudan, Ethiopia, and Somalia. In this paper we present the results of our efforts to date the Egyptian basement between the Red Sea and the Nile (fig. 1). These consist of U-Pb zircon and Rb-Sr ages for twenty-four distinct plutons, dikes, and volcanic successions selected from $\sim 8 \times 10^4$ km^2 of the Precambrian in the Eastern Desert. We use these data further to constrain models of the crustal evolution in this region.

REGIONAL SUBDIVISION OF THE PRECAMBRIAN OF THE EASTERN DESERT

We recognize three distinctive basement terranes in the Eastern Desert of Egypt: North Eastern Desert, Central Eastern Desert, and South Eastern Desert. Inspection of the geologic map of the Eastern Desert (El-Ramly, 1972) shows the following features in the basement: (1) there is a much higher concentration of granitic rocks to the north and south than in the Central Eastern Desert; (2) serpentinites are extremely rare in the north; (3) gneisses are much more common in the south than elsewhere; and (4) the central part exposes by far the greatest concentration of rocks with strong oceanic affinities ("Ensimatic Complex" of Stern, 1981). The nature and origin of this lithologic heterogeneity has been

Fig. 1. Generalized geologic map of the Eastern Desert of Egypt, showing the distribution of lithologies and sample localities discussed in the text. Numbers 1 through 24 correspond to the following samples: 1 = Wadi Kreiga tonalite; 2 = Abu Swayel rhyodacite: 3 = Gebel Farid granite; 4 = Aswan granite; 5 = Hafafit tonalite; 6 = Wadi Mia granodiorite; 7 = Wadi El Mahdaf metavolcanics; 8 = Wadis Arak and Massar metavolcanics; 9 = Abu Ziran granodiorite; 10 = Mons Claudianus granodiorite: 11 = Gebel Nuqrah volcanics; 12 = Gebel Qattar granite; 13 = Salah El Belih granodiorite; 14 = Gebel Dokhan volcanics; 15 = Qattar-Dokhan Area dikes; 16 = Wadi Dib granodiorite; 17 = Wadi Dib bostonite dike; 18 = Gebel Dara granite; 19 = Gebel Dara felsic dike; 20 = Gebel Zeit granite; 21 = Gebel Gharib granite; 22 = Wadi Hawashiya granodiorite; 23 = Wadi Hawashiya granite; 24 = Um Tennasib granite dikes. Shapes enclosing the locality numbers indicate the approximate age of the basement sampled as in the legend. Also shown is the subdivision of the basement into the South Eastern Desert (I), Central Eastern Desert (II), and North Eastern Desert (III) as discussed in the text. Map modified after that of Gillespie and Dixon (1983).


PRECAMBRIAN ROCKS
OF THE
EGYPTIAN SHIELD
0
100km
GRANITE AND GRANODIORITE, MAINLY PAN-AFRICAN AGE; RELATED YOUNG VOLCANICS AND SEDIMENTS
QUARTZ DIORITE AND GRANODIORITE
MAFIC AND INTERMEDIATE METAVOLCANICS AND RELATED IMMATURE METASEDIMENTS, GABBRO; SERPENTINITE
GNEISSES AND MIGMATITES
= 555-540 Ma
= 600-575 Ma
= 625-610 Ma
= 685-665 Ma
= 715-700 Ma
= 780-750 Ma
RAS GHARIB
QUSEIR
QIFT
LUXOR
IDFU
MARSA ALAM
ASWAN
RAS BENAS
RIVER NILE
RED SEA
I
II
III
29°
28°
27°
26°
25°
24°
23°
22°
32°
33°
34°
35°
36°
37°

commented on in the past (Barron and Hume, 1902; Barthoux, 1922; Schürmann, 1966).

One major discontinuity occurs across a N 60° E line extending approximately between the great bend of the Nile (26°10′ N, 32°44′ E) and Safaga, on the Red Sea coast (26°47′ N, 33°56′ E). This is the division used for the purpose of discussing the litho-tectonic domains of the North Eastern Desert and the Central Eastern Desert.

The general lithologic characteristics of the South Eastern Desert are discussed by Andrew (1939) and Akaad and El Ramly (1960). Metasedimentary gneisses occur mainly in this area, and the low grade metagraywackes, pillowed basalts, and iron formation typical of the Central Eastern Desert are generally missing. The geologic map of the Eastern Desert (El-Ramly, 1972) shows that a profound discontinuity occurs south of 25° N. South of a line trending about N 60° E on the northwest flank of G. Migif corresponding to Wadi Shait is a terrane of highly metamorphosed and migmatized gneisses and syntectonic granitic intrusions. North of this, the basement is dominated by the lower grade metavolcanics and metasediments, serpentinites, et cetera, typical of the Central Eastern Desert. To the east, this discontinuity turns S 45 E and follows Wadi Nugrus to the Red Sea. El-Ramly and others (in press) call this the "Migif-Hafafit culmination" and identify it as a shear zone developed during a major event of south-directed overthrusting. We accept the trace of this shear zone as the boundary between the Central Eastern Desert and the South Eastern Desert.

We point-counted lithologies shown on the 1:1,000,000 scale geologic map of the Eastern Desert (El-Ramly, 1972) and Sinai (El Shazly and others, 1974) with the aid of a 1/16″ grid. A total of 40085 points were counted. The data were grouped into three categories: (1) granite and gneiss (continental affinities); (2) volcanics and sediments (ensimatic affinities); and (3) serpentinites (ophiolite?) and plotted in figure 2. The data further emphasize the different distribution of lithologic associations among the four crustal provinces.

ANALYTICAL PROCEDURES AND DATA REDUCTION

Analytical work was largely carried out at the U.S. Geol. Survey laboratory in Denver. Additional Rb-Sr whole rock studies were conducted at The University of Texas at Dallas. The latter may be distinguished in table 1 by the individual assignment of errors to $^{87}Sr/^{86}Sr$. Three other analyses in table 1 were conducted at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington.

Rb, Sr, U, and Pb concentrations were determined by isotope dilution using ^{87}Rb, ^{84}Sr, ^{235}U, and ^{208}Pb as tracers and have a precision of ± 1 percent ($2\ \sigma_{\bar{x}}$). The isotopic composition determined at the USGS are precise to ± 0.01 percent for Sr and ± 0.1 percent for Pb. Common lead corrections were carried out using the technique of Cooper and others (1979). The mass spectrometers used for strontium determinations yielded an average $^{87}Sr/^{86}Sr$ for the E and A standard of 0.7080 at the

USGS, 0.70792 at UTD, and 0.70790 at DTM. All $^{87}Sr/^{86}Sr$ have been normalized to E and A $SrCO_3 = 0.70800$. Blanks were in all cases negligible. Ages were calculated using the decay constants recommended by the International Subcommission on Geochronology (Steiger and Jager, 1977).

Rb-Sr isochron age calculations were carried out with a computer program written by J. C. Roddick (Univ. Leeds) that combines York's (1969) regression and McIntyre and others' (1966) statistical assessment of variances of $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$. Analytical uncertainties were taken at 1 percent for $^{87}Rb/^{86}Sr$ and 0.01 percent for $^{87}Sr/^{86}Sr$. Isochrons were identified when the mean square of weighted deviates (MSWD) was less than the F-variate for the number of points regressed. When MSWD was greater than the F-variate, the data defined an errorchron. Unless otherwise noted, isochron ages and initial values are those of McIntyre Model I. Uncertainties are quoted at the 1σ level for the York II treatment of error.

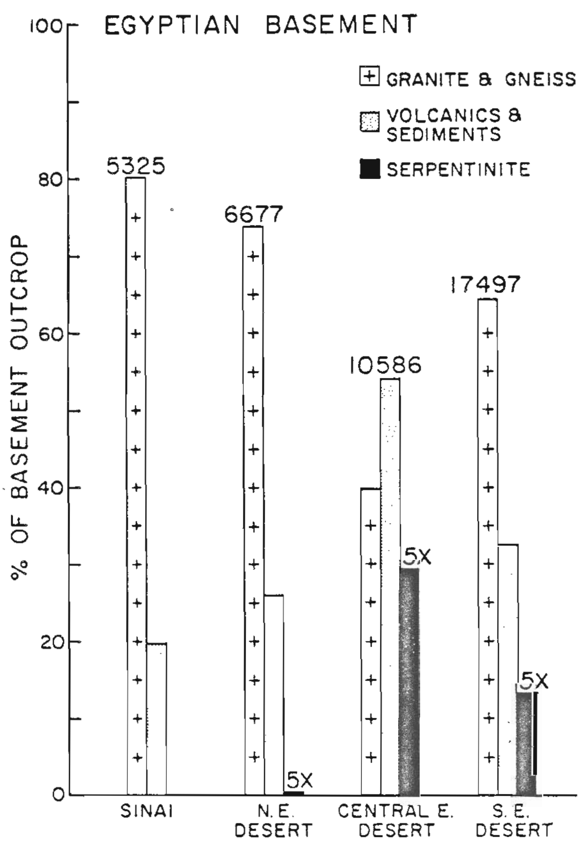


Fig. 2. Composition of the Egyptian basement as determined by point counting of Egyptian geologic maps (El Ramly, 1972; El Shazly and others, 1974). Numbers at the top of each set of histograms refer to the number of points counted. Note that the percentage abundance of serpentinites is shown with a fivefold exaggeration.

TABLE 1

Rb, Sr, and $^{87}Sr/^{86}Sr$ isochron data

Locality no.	Field no.	Lithology	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
2.	*Abu Swayel:*					
	74A	rhyodacite	14.2	54.3	0.7574	0.7104
	74B	rhyodacite	18.4	89.3	0.5961	0.7083
	74C	rhyodacite	15.1	93.3	0.4694	0.7070
	74E	rhyodacite	16.3	44.1	1.072	0.7135
3.	*Gebel Farid:*					
	GF-1	pink granite	90.6	192	1.368	0.7152
	GF-1	K-feldspar	201	155	3.751	0.7346
	GF-1	plagioclase	19.4	327	0.1715	0.7049
6.	*Wadi Mia:*					
	63-A	granodiorite	81.3	107	2.209	0.7239
	63-B	granodiorite	64.5	185	1.009	0.7124
	63-C	granodiorite	69.8	264	0.7667	0.7100
	63-D	granodiorite	73.2	231	0.9170	0.7115
7.	*Wadi El Mahdaf:*					
	106E	dacite	19.1	388	0.1426	0.7041
	107L	rhyolite	72.5	110	1.909	0.7197
	109R	rhyolite	78.2	50.2	4.524	0.7422
	109W	rhyolite	79.6	44.7	5.174	0.7493
	109X	andesite	27.7	466	0.1757	0.7042
8.	*Wadis Arak and Masser:*					
	13	rhyolite	34.3	107	0.9257	0.7122
	14	basalt	5.1	299	0.0496	0.7027
	15	andesite	16.6	578	0.0833	0.7035
	41	rhyolite	130	36.6	10.39	0.7932
	79C	andesite	19.0	109	0.5030	0.7075
	79E	rhyolite	21.2	88.9	0.6902	0.7110
	79F	rhyolite	77.2	37.0	6.060	0.7551
	190D	rhyolite	46.5	81.0	1.661	0.7168
	190E	dacite	38.1	580	0.1897	0.7042
	190F	andesite	5.4	247	0.0635	0.7034
10.	*Mons Claudianus:*					
	113	granodiorite	29.3	524	0.1617	0.7040
	MC-1	granodiorite	32.3	564	0.1655	0.7042
	MC-2	granodiorite	28.6	601	0.1378	0.7038
	MC-2	K-feldspar	93.3	781	0.3457	0.7059
	MC-2	plagioclase	3.6	932	0.0112	0.7026
	MC-2	biotite	269	11.5	71.98	1.3279
11.	*Gebel Nuqrah felsics:*					
	22	rhyolite	74.7	70.8	3.059	0.7290
	23	rhyolite	111	150	2.157	0.7215
	25	rhyolite	110	110	2.889	0.7276
	181E	rhyolite	104	113	2.678	0.72535 ± 17
	181F	rhyolite	91.8	41.4	6.415	0.75506 ± 9
	185	rhyolite porphyry	120	11.7	30.34	0.9568
	186C	rhyolite	113.8	146	2.249	0.72168 ± 9
	192B	rhyolite dike	137	224	1.764	0.71773 ± 11
	194	granite	127	194	1.895	0.7191

TABLE 1 (continued)

Locality no.	Field no.	Lithology	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
11.	*Gebel Nuqrah andesites:*					
	4A	andesite flow	47.4	714	0.1919	0.7045
	26	andesite flow	19.2	588	0.0944	0.7034
	178E	andesite dike	25.4	629	0.1167	0.70376 ± 9
	179E	andesite flow	41.4	793	0.1509	0.70410 ± 9
	180C	andesite flow	50.6	639	0.2292	0.70498 ± 9
	182C	andesite flow	31.6	956	0.0957	0.70351 ± 4*
	187C	andesite flow	44.9	870	0.1494	0.70398 ± 6*
	191F	andesite dike	76.6	600	0.3696	0.70623 ± 13
	192A	andesite dike	38.0	597	0.1841	0.70431 ± 12
	192C	andesite dike	66.2	620	0.3087	0.70562 ± 6*
	193D	andesite dike	28.3	686	0.1203	0.70399 ± 7
14.	*Gebel Dokhan flows:*					
	163C	andesite	127	626	0.5814	0.70760 ± 10
	163F	andesite	48.2	625	0.2233	0.70476 ± 7
	163I	andesite	47.7	731	0.1888	0.70450 ± 7
	163J	andesite	25.8	772	0.0969	0.70357 ± 7
	163K	andesite	20.4	996	0.0594	0.70354 ± 11
	163L	andesite	40.0	920	0.1258	0.70383 ± 7
	200B	andesite	72.8	958	0.2197	0.70459 ± 9
	200E	andesite	41.0	943	0.1257	0.70386 ± 7
	202D	andesite	14.0	921	0.0439	0.70323 ± 9
	202F	andesite	100	462	0.6278	0.70832 ± 11
15.	*Qattar-Dokhan Area dikes:*					
	195A	andesite	65.0	489	0.3849	0.70655 ± 11
	195B	andesite	22.9	552	0.1200	0.70398 ± 7
	195C	rhyolite	62.0	180	0.9987	0.71139 ± 15
	195D (I)	andesite	61.5	634	0.2809	0.70658 ± 14
	195D (II)	andesite	59.8	628	0.2756	0.70659 ± 7
	195E	andesite	27.3	626	0.1262	0.70396 ± 10
	195F	rhyolite	54.9	183	0.8668	0.71009 ± 9
	195H	andesite	83.2	573	0.4208	0.70639 ± 5
	195I	rhyolite	97.8	70.3	4.024	0.73697 ± 10
	195J	andesite	68.1	527	0.3737	0.70624 ± 6
	196C	rhyolite	223	37.6	17.15	0.84885 ± 11
	197C	rhyolite	240	32.8	21.14	0.87701 ± 9
	198B	rhyolite	82.8	92.5	2.59	0.7248 ± 2
	198C	andesite	14.3	717	0.0577	0.70434 ± 7
	200F	rhyolite	125	122	2.95	0.7281 ± 2
	204F	rhyolite	212	22.0	27.91	0.93769 ± 13
	204I	rhyolite	170	60.3	8.179	0.77041 ± 12
	204J	andesite	17.5	614	0.082	0.70356 ± 10
	E-6-80	rhyolite	141	205	1.997	0.7198
	E-6-80	K-feldspar	240	291	2.394	0.7228
	E-6-80	plagioclase	42.0	217	0.5612	0.7083
23.	*Wadis Hawashiya and Gazalla:*					
	137	granite	64.0	808	0.2292	0.7055
	139	granite	84.1	252	0.9656	0.7115
	141	aplite dike	71.8	41.0	5.095	0.7456
24.	*Um Tennasib:*					
	144A	granite dike	174	74.7	6.792	0.7597
	144B	granite dike	169	51.0	9.660	0.7841
	144C	granite dike	150	28.5	15.41	0.8300

* Analyses performed at Department of Terrestrial Magnetism, Carnegie Institution of Washington.

Many of the late granites and dikes have relatively high $^{87}Rb/^{86}Sr$ ratios (> 9). In such cases a Rb/Sr model age was calculated using an initial $^{87}Sr/^{86}Sr$ of 0.7035. The choice of this initial was made as a result of the observation that initial ratios from well-defined isochrons of 570 to 600 Ma rocks fall in the range 0.7028 to 0.7042 (fig. 6).

U-Pb zircon ages were determined using either of two treatments of the analytical data: (1) regression of chord to the concordia, where two or more fractions were analyzed (fig. 4), or (2) model age determinations where upper intercepts were calculated assuming a lower intercept of 15 Ma. This was done when only one fraction of zircon was analyzed or when two or more fractions gave little spread. The validity of the procedure for similar rocks in Saudi Arabia was demonstrated by Cooper and others (1979). In general, U-Pb zircon results are close enough to concordant that they are largely insensitive to the time of lead loss. The late granites tend to give the most discordant U-Pb zircon ages because of relatively high U contents. We believe the agreement between the U-Pb and Rb-Sr model ages from the same body (G. Qattar, Salah El Belih) supports the validity of this method of treating single fraction zircon data.

Initial $^{87}Sr/^{86}Sr$ were determined either directly, using the Y-intercept of the Rb-Sr isochron regression, or indirectly, correcting the whole-rock or feldspar data for radiogenic growth using the U-Pb zircon age.

SAMPLE LOCALITIES AND LITHOLOGIES

The consecutive numbers below are identical to sample localities in figure 1, analytical data in tables 1 to 3, and the Geochronologic Summary, table 4.

South Eastern Desert

1. *Wadi Kreiga tonalite.*—This sample was collected by T. H. Dixon from outcrops along Wadi Kreiga (22°51′ N, 35°15′ E). The geology of this area is very poorly known; El Ramly (1972) mapped the geology of this region as dominated by gneisses and syntectonic plutonic rocks bounded to the east by a strip of serpentinites and geosynclinal Shadli metavolcanics (ophiolites?) near the coast.

In outcrop the rock appears weathered. In thin section, the rock is identified as an altered tonalite, with abundant cloudy plagioclase, chloritized biotite, and epidote (T. H. Dixon, personal commun., 1983). A single zircon fraction gave a model age of 709 Ma. Using this age and the whole rock Rb-Sr data, an initial $^{87}Sr/^{86}Sr$ of 0.7023 is indicated.

2. *Abu Swayel rhyodacite.*—These samples were collected 10 m apart from an outcrop of massive quartz-feldspar porphyry exposed on the east side of Wadi Murra (22°31′ N, 33°54′ E, fig. 1). These contain 73 to 75 percent SiO_2, 1.7 to 1.9 percent K_2O, and 4.9 to 5.9 percent Na_2O. K/Rb ratios are high, ranging from 870 to 1100 (Stern, unpub. data). Similar rhyodacites have been reported from the Abu Swayel area, 25 km to the north. El Shazly and others (1973) termed the Abu Swayel rhyodacites "Emerging Geosynclinal Volcanics" and reported an Rb/Sr age of 654 to 665 Ma. The latter are associated with older units for which severely disturbed Rb-Sr isochron ages in the range 850 to 1200 Ma were reported.

TABLE 2

Single sample Rb-Sr data

Locality no.	Location	Number	Lithology	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Model Age (Ma)*	Calculated initial**
1.	Wadi Kreiga	WK-1	tonalite	16.0	416	0.1115	0.7034	—	0.7023
3.	Aswan	E-4-81	granite	106	173	1.784	0.7180	—	0.7029
3.	Aswan	E-4-81	k-feldspar	212	255	2.407	0.7234	—	0.7030
4.	Hafafit	E-7-81	tonalite	18.1	198	0.264	0.7049	—	0.7024
9.	Abu Ziran	E-149	granodiorite	35.4	1056	0.0969	0.7037	—	0.70295
12.	Gebel Qattar	E-2-80	granite	238	6.1	123.6	1.7164	575	—
13.	Salah El Belih	E-4-80	granite	187	186	2.91	0.7272	571	0.7030
16.	Wadi Dib	E-8-80	granodiorite	157	372	1.222	0.7133	—	0.7025
17.	Wadi Dib	E-7-80	bostonite dike	196	63.5	8.989	0.7740	550	—
18.	Gebel Dara	E-9-80	granite	116	457	0.7360	0.7093	—	0.7030
19.	Gebel Dara	E-10-80	rhyolite dike	189	18.1	30.82	0.9419	543	—
20.	Gebel Zeit	—	granite	171	19.1	26.54	0.9274	592	—
21.	Gebel Gharib	E-206B	granite	299	19.9	44.96	1.0523	544	—
22.	Wadi Hawashiya	E-138	granodiorite	80.4	644	0.3614	0.7065	—	0.7033

* Initial $^{87}Sr/^{86}Sr$ assumed = 0.7035.

** Corrected for radiogenic growth using zircon data.

Four whole-rock specimens of the Abu Swayel rhyodacite define an isochron of 768 ± 31 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7019 ± 3 (MSWD = 2.23; fig. 3A). This is the oldest age we found in the Eastern Desert, but the arguments of El Shazly and others (1973) suggest that older units may exist in the western part of the South Eastern Desert.

3. *Gebel Farid granite.*—Sample GF-1 was collected by T. H. Dixon from the southernmost part of a large (40 × 15 km) body of pink granite exposed near the Red Sea coast on the southern slopes of Gebel Farid at

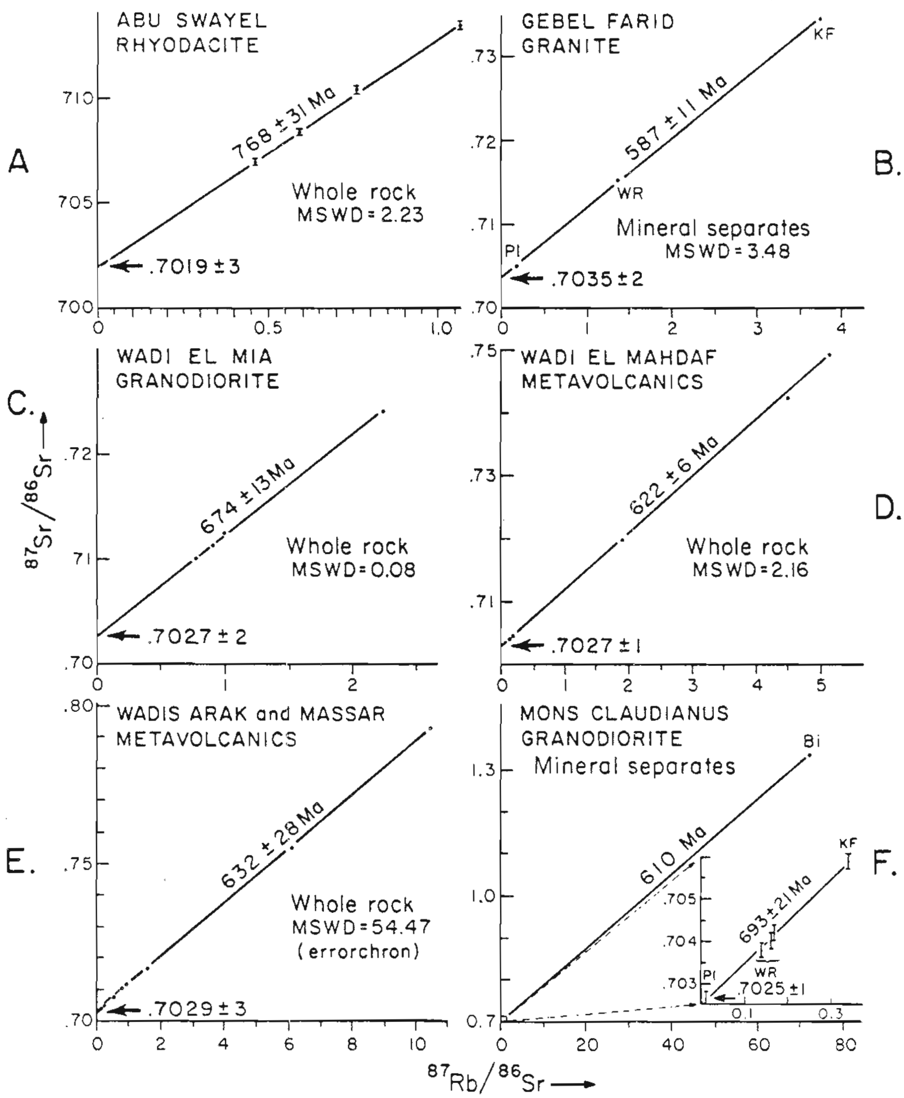
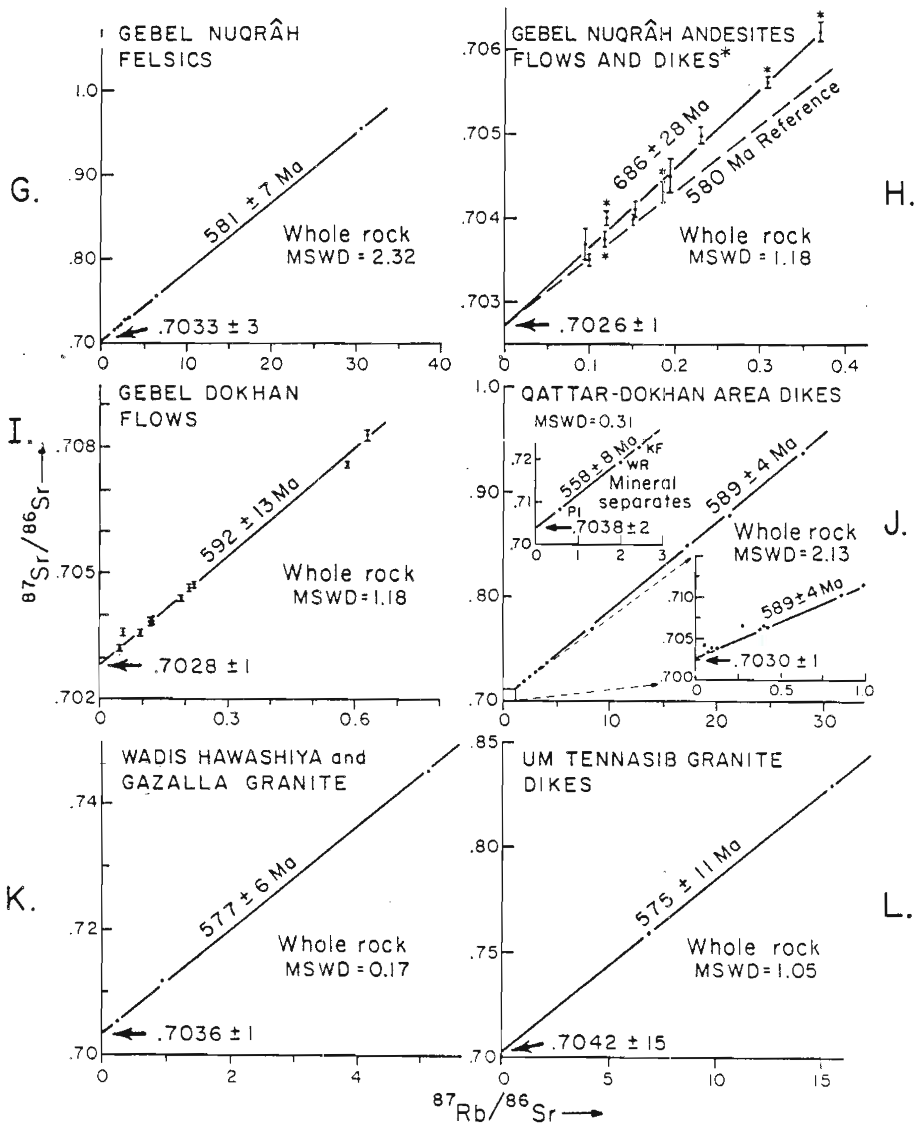


Fig. 3. Rb-Sr isochron diagrams for Egyptian basement units.

23°16′ N, 35°22′ E (Gillespie and Dixon, 1983). Ball (1912) described this body as being composed of porphyritic pink granite. In thin section the analyzed specimen is very fresh, consisting principally of orthoclase and minor microcline, quartz, and fresh biotite. Visible alteration effects are limited to minor sericitization of the feldspars. A three-point internal isochron defines an age of 587 ± 11 Ma (MSWD = 3.48) and an initial $^{87}Sr/^{86}Sr$ of 0.7035 ± 2, isotopically indistinguishable from pink granites studied from farther north in the Eastern Desert (fig. 3B; Fullagar, 1980;



Greenberg, 1981). We note, however, that petrographically similar granites from the southern Arabian Shield may be as old as 650 Ma (Fleck and others, 1980) and recognize the possibility that the Farid granite could be reset.

4. *Aswan granite.*—Pink granite is well-exposed in numerous quarries around the city of Aswan (fig. 1). Studies of the pink granites and the metamorphic basement into which the granites intrude include field geology (El Shazly, 1954), granite petrochemistry (El Gaby, 1975; Greenberg, 1981), and geochronology (Schürmann, 1966; Leggo, 1968; Hashad and others, 1972; Abdel-Monem and Hurley, 1980). The geochronologic investigations have not resulted in complete agreement regarding the age or the initial $^{87}Sr/^{86}Sr$ of these granites. Schürmann (1966) reported 470 and 570 Ma K-Ar ages for feldspar and biotite separates respectively. Based on five whole-rock samples, Leggo (1968) reported an age of 580 ± 20 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.704 ± 1. Based on three whole-rock samples, Hashad and others (1972) reported a Rb/Sr age of 571 ± 37 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7092 ± 9. Abdel-Monem and Hurley (1980) analyzed 6 zircon fractions which did not define a chord.

The sample analyzed here was collected from an abandoned quarry on the southeast edge of Aswan. Two fractions of zircon were analyzed but resulted in little spread (table 3; fig. 4A). An upper intercept of 594 ± 4 Ma is indicated. This is similar to an age of 608 Ma resulting from the line defined by the whole-rock and potassium feldspar separates (table 2). Using the zircon age, the whole rock Rb/Sr data indicate an initial $^{87}Sr/^{86}Sr$ of 0.7029.

5. *Hafafit tonalite.*—Reconstruction of the magmatic and tectonic history of the Migif-Hafafit Gneiss Dome has long been recognized as critical for understanding basement evolution in the Eastern Desert. Hume (1934) argued that this dome represented a "fundamental basement" of possible Archean age that underlay the lower-grade metamorphic succession. The first detailed mapping (El Ramly and Akaad, 1960) indicated that the Migif-Hafafit area consisted of a 4 km-thick succession of gneisses exposed in a doubly plunging anticline with granite gneiss occupying the core. The gneisses are bounded north and east by highly sheared mafic igneous and sedimentary rocks. The latter are interpreted as ophiolitic melange (Ries and others, 1983; El Ramly and others, in press). This break is abrupt and of regional extent. El Ramly and others (in press) identified this boundary as a northeast-dipping thrust fault showing a strong vergence to the south and southwest and also recognized that the core tonalites were intrusive into the enveloping high-grade assemblage.

Previous geochronologic investigations in the area have given inconclusive results. Hashad and others (1972) produced a 3-point whole-rock Rb/Sr isochron of 801 ± 50 Ma from the type locality of the Shaitian Granite. This region is 60 km east-southeast from the Migif-Hafafit Dome but lies along the general trend of the structure. Abdel-Monem and Hurley (1979) attempted to date psammitic gneisses collected about 50 km southeast of the Migif-Hafafit culmination. Twelve zircon aliquots from

TABLE 3

U-Pb zircon data

Locality	Field no. (Mesh)	Lithology	Concentrations U (ppm)	Concentrations Pb (ppm)	Atomic ratios* 206Pb/238U	Atomic ratios* 207Pb/235U	Atomic ratios* 207Pb/206Pb	Ages (Ma) 206Pb/238U	Ages (Ma) 207Pb/235U	Ages (Ma) 207Pb/206Pb
1. *Wadi Kreiga*:										
	WK-1	tonalite	80.9	9.67	0.10261	0.8908	0.06296	630	647	707
4. *Aswan*:										
	4-81 (+100)	granite	630	52.6	0.07688	0.6320	0.05962	477	497	590
	4-81 (−400)	granite	508	50.6	0.08016	0.6597	0.05968	497	514	592
5. *Hafafit*:										
	7-81 (+150)	tonalite	507	52.8	0.10578	0.9067	0.06217	648	655	680
	7-81 (−400)	tonalite	706	83.2	0.10562	0.9066	0.06226	647	655	683
9. *Abu Ziran*:										
	E-149 (100-150)	granodiorite	213.1	20.65	0.09082	0.7556	0.06033	560	571	616
	E-149 (150-250)	granodiorite	226.6	22.06	0.09264	0.7686	0.06017	571	579	601
	E-149 (250-325)	granodiorite	229.1	21.45	0.08917	0.7404	0.06022	551	563	611
10. *Mons Claudianus*:										
	E-113	granodiorite	113.9	13.49	0.10559	0.8989	0.06174	647	651	665
12. *Gebel Qattar*:										
	2-80	granite	4305	464.3	0.07324	0.5980	0.05921	456	476	575
13. *Salah El Belih*:										
	4-80	granodiorite	454.0	31.16	0.06501	0.5314	0.05929	406	433	578
16. *Wadi Dib*:										
	8-80	granodiorite	504.7	48.74	0.09063	0.7551	0.06042	559	571	619
18. *Gebel Dara*:										
	9-80	granite	1177	104.2	0.07501	0.6175	0.05970	466	488	594
22. *Wadi Hawashiya*:										
	136	granodiorite	583.2	55.56	0.08122	0.6742	0.06021	503	523	611

* Corrected for common lead.

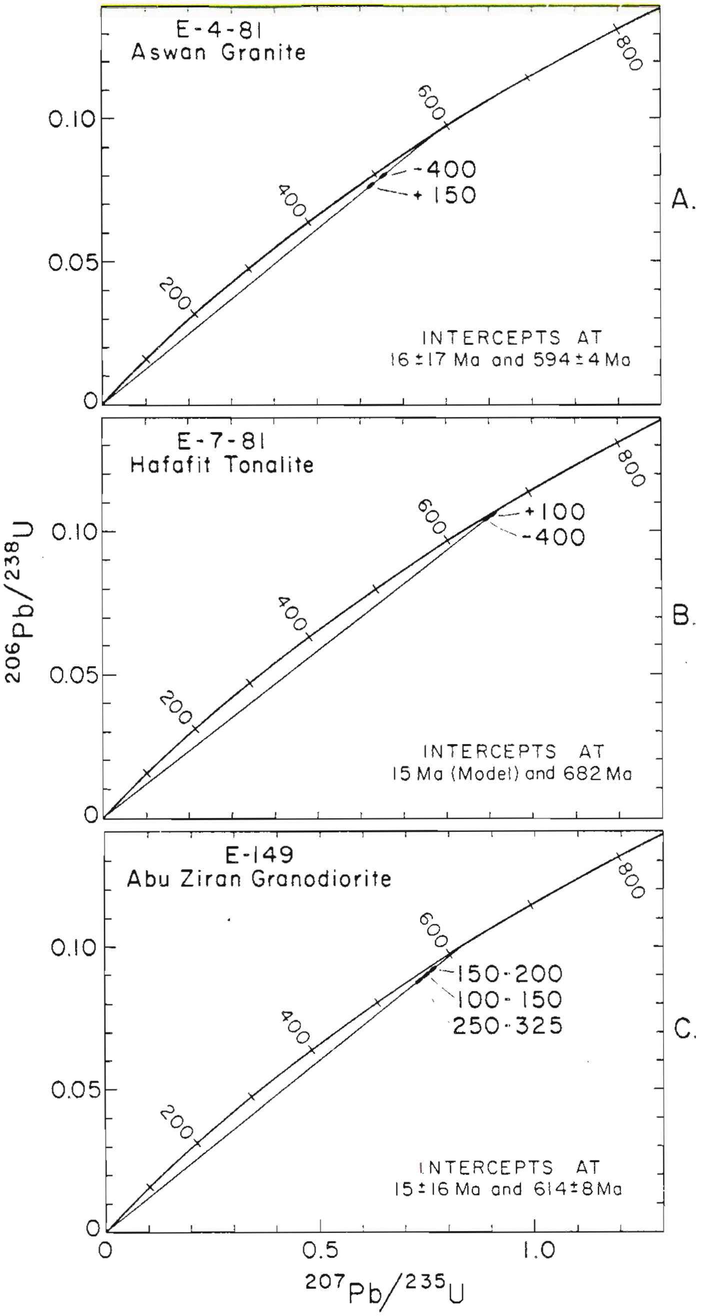


Fig. 4. U-Pb concordia diagrams for zircons from Egyptian basement units.

gneiss collected in Wadi Abu Rosheid clustered around 400 to 450 Ma, but one aliquot from gneiss collected in Wadi Sikait gave a $^{207}Pb/^{206}Pb$ age of 1580 Ma. Abdel-Monem and Hurley (1979) interpreted this point as lying on a chord between a 400 Ma lower intercept and a 1770 Ma intercept. The older age was interpreted as the age of the igneous or metamorphic provenence from which the original sediments were derived. This conclusion is consistent with the results of Dixon (1981) who found that granitic cobbles from the Atud Conglomerate in Wadi Mobarak (about 60 km north-northwest of the Migif-Hafafit Culmination) ranged in age from 1120 Ma to possibly as old as 2060 Ma.

The sample analyzed here was collected from a migmatized and foliated tonalite that occupies the core of the Migif-Hafafit Dome. This pluton is mapped as granite gneiss and was shown to intrude the surrounding hornblende and biotite gneisses (El Ramly and others, in press). The two zircon fractions give little spread but are close to concordant, giving a model age of 682 Ma (fig. 4B). We interpret this as the time of emplacement and cooling of the pluton and believe that this age also dates the tectonic activity/thrusing in the surrounding region. Using this age and the measured whole rock Rb, Sr, and $^{87}Sr/^{86}Sr$ data, the initial $^{87}Sr/^{86}Sr$ was 0.7024 (table 2).

TABLE 4

Geochronologic summary, Eastern Desert of Egypt

Location (fig. 1)	Name	Lithology	Age	Initial $^{87}Sr/^{86}Sr$
1	Wadi Kreiga	tonalite	709	0.7023
2	Abu Swayel	rhyodacite	768 ± 31	0.7019 ± 3
3	Gebel Farid	granite	587 ± 11	0.7035 ± 2
4	Aswan	granite	594 ± 4	0.7030
5	Hafafit	tonalite	682	0.7024
6	Wadi Mia	granodiorite	674 ± 13	0.7027 ± 2
7	Wadi El Mahdaf	metavolcanics	622 ± 6	0.7027 ± 1
8	Wadi Arak and Massar	metavolcanics	errorchron	—
9	Abu Ziran	granodiorite	614 ± 8	0.7030
10	Mons Claudianus	granodiorite	666	0.7025 ± 1
11	Gebel Nuqrah	felsic rocks	581 ± 7	0.7033 ± 3
12	Gebel Qattar	granite	579	—
13	Salah El Belih	granodiorite	583	0.7030
14	Gebel Dokhan	andesites	592 ± 13	0.7028 ± 1
15	Qattar-Dokhan Area	dikes	589 ± 4	0.7030 ± 1
16	Wadi Dib	granodiorite	620	0.7025
17	Wadi Dib	bostonite dike	550	—
18	Gebel Dara	granite	596	0.7030
19	Gebel Dara	felsic dike	543	—
20	Gebel Zeit	granite	592	—
21	Gebel Gharib	granite	544	—
22	Wadi Hawashiya	granodiorite	614	0.7033
23	Wadi Hawashiya	granite	577 ± 6	0.7036 ± 1
24	Um Tennasib	granite dikes	575 ± 11	0.7042 ± 15

Uncertainties in age and initial $^{87}Sr/^{86}Sr$ are quoted at the one sigma level. Ages without uncertainties are model ages. Initial $^{87}Sr/^{86}Sr$ without uncertainties are calculated from whole-rock Rb-Sr data corrected for post-emplacement growth of $^{87}Sr/^{86}Sr$ using the zircon age of that unit.

Central Eastern Desert

6. *Wadi El Mia granodiorite.*—These samples were taken during reconnaissance investigations of the "syntectonic plutonites" in the Baramia district (fig. 1). The granodiorite, exposed at 25°15′ N, 33°45′ E, has been mapped as "grey granite" (Sabet and Z'aatout, 1955). The body is equidimensional, with a mean diameter of 5 km. The granodiorite consists of albite, quartz, and biotite, with minor (< 10 percent) K-feldspar. It is foliated and commonly contains mafic xenoliths. It has experienced post-consolidation retrograde metamorphism to greenschist facies. Samples were collected on a traverse across the pluton.

The data reported in table 1 differ slightly from those in table 4 of Stern (1979) as a result of redissolution and reanalysis of samples 63A-D. Since incomplete dissolution was observed in the first set and dissolution was complete in the second, data from the latter are preferred. These define an isochron (fig. 3C) with an age of 674 ± 13 Ma and an initial $^{87}Sr/^{68}Sr$ of 0.7027 ± 2 (MSWD = 0.08). This is interpreted as the emplacement/cooling age of the pluton.

7. *Wadi El Mahdaf metavolcanics.*—These rocks are part of the Younger Metavolcanic (YMV) succession described by Stern (1981). Five samples were collected from different flows of the YMV at 25°45′ N, 33°39′ E. Those at Wadi El Mahdaf have been slightly metamorphosed, with partial degradation and albitization of plagioclase and introduction of minor amounts of carbonate and silica (< 5 percent). The low intensity of the metamorphism is reflected in the general absence of a penetrative deformation, excellent preservation of original igneous textures, and the pristine appearance of euhedral clinopyroxene and ilmenite phenocrysts in the andesites and quartz phenocrysts in the rhyodacites.

The five specimens analyzed define an isochron with an age of 622 ± 6 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7027 ± 1 (MSWD = 2.16; fig. 3D). We interpret these to be the age and original isotopic composition of the volcanic flows.

8. *Wadis Arak and Massar metavolcanics.*—Seven samples (13-79F) were collected from exposures of the YMV along Wadi Arak (25°46′ N, 33°52′ E), and three samples (190D-F) were collected from similar exposures in Wadi Massar (25°38′ N, 33°47′ E). The samples are clinopyroxene–plagioclase andesites and rhyodacites similar to the YMV of Wadi El Mahdaf. The 10 analyses define a least-squares fit age of 632 ± 28 Ma with an initial $^{87}Sr/^{86}Sr$ of 0.7029 ± 3, very similar to the El Mahdaf YMV (fig. 3E). The MSWD of 54.5 is unacceptably high. Subdividing the data into two subsets ($^{87}Rb/^{86}Sr > 0.6$ and $^{87}Rb^{86}/Sr < 0.6$) suggests that the high Rb/Sr group is younger, with a least-squares fit "age" of 580 ± 29 Ma and initial of 0.7046 ± 7, compared to the low Rb/Sr group, with an "age" of 690 ± 56 Ma and an initial of 0.7025 ± 2. The MSWD for both the high $^{87}Rb/^{86}Sr$ group (42.7) and the low $^{87}Rb/^{86}Sr$ (7.3) are greater than expected from analytical uncertainty alone. We consider three possible explanations for these data: (1) variable initial $^{87}Sr/^{86}Sr$; (2) two or more real ages of magmatic activity; and (3) metamorphic disturbance of

the Rb/Sr system. In the first case, the poor fit of the $0.6 < {}^{87}Rb/{}^{86}Sr$ data to the ${}^{87}Rb/{}^{86}Sr > 0.6$ isochron is due to the lavas being erupted with different ${}^{87}Sr/{}^{86}Sr$, that is, ${}^{87}Sr/{}^{86}Sr$ varies with ${}^{87}Rb/{}^{86}Sr$ at the time of eruption. Initial ${}^{87}Sr/{}^{86}Sr$ would have to vary about 0.001 for this to be effective. This interpretation is supported by the fact that McIntyre Model III (MSWD set at 1.00; variation of initial ratio assumed) is statistically favored over McIntyre Model II (MSWD set at 1.00; variation of age assumed). McIntyre Model III gives an age of 607 ± 8 Ma and an initial of 0.7031 ± 3, similar to the age and initial for the YMV at Wadi El Mahdaf and a similar succession at Wadi Sodmein (age = 616 ± 9 Ma, Ries and Darbyshire, in press).

In the second case (two or more real ages of magmatic activity), we recognize the possibility that the data may reflect the fact that we have sampled two or more volcanic successions of different ages. Samples were collected over a much larger area (15 km distance) than any of our other suites in order to obtain a better spread in Rb/Sr. Whereas our field investigations did not indicate the presence of angular unconformities or structural discordances, the recognition of such breaks in an entirely volcanic pile is difficult. We cannot preclude the possibility that an about 700 Ma low Rb/Sr volcanic succession and an about 600 Ma high Rb/Sr volcanic succession have been sampled in the Wadis Arak-Massar area. Finally, we also recognize the possibility that post-eruption alteration may also have been responsible for the scatter to the Arak-Massar isochron.

9. *Abu Ziran granodiorite.*—Like the Migif-Hafafit Gneiss Dome, there is considerable discussion about the origin of the Meatiq Dome. Hume (1934) and Schürmann (1966) argued that the Meatiq Gneisses represented an ancient fundamental basement. Sturchio, Sultan, and Batiza (1983) reported that the dome consisted of a core of granite gneiss with a mylonitic carapace. The mylonite graded upward into a nonmylonitic cover of low-grade ophiolitic rocks. Sturchio, Sultan, and Batiza (1983) interpreted the mylonites to have formed in a low-angle ductile shear zone during an episode of tectonic compression accompanied by the syntectonic emplacement of tonalites and granodiorite. This structural complex was then domed upward by the intrusion of a pink granite at 579 ± 5 Ma (Sturchio and others, in press).

A sample of the syntectonic tonalite/granodiorite was collected from the westernmost outcrop along the Qena-Quesir road (26° N, 33°45′ E). Here the granodiorite intrudes foliated metaquartzites across a contact that places the granodiorite *over* the quartzites. This contact is parallel to the foliation in both the metaquartzites and the granodiorite. The field relations indicate that the granodiorite was intruded at the same time as the principal tectonic movement around the Meatiq Dome.

Three fractions of zircons were analyzed (table 3; fig. 4C). These lie along a chord with an upper intercept of 614 ± 8 Ma. We interpret this to represent the age of emplacement of the pluton and timing of major crustal movements in this part of the Eastern Desert. Using this age and the whole-rock Rb, Sr, and ${}^{87}Sr/{}^{86}Sr$ data (table 2), the granodiorite had an initial ${}^{87}Sr/{}^{86}Sr$ of 0.7030.

North Eastern Desert

10. *Mons Claudianus granodiorite.*—These samples were collected from the large body mapped as "Old Granitoids and Migmatized Rocks" by Ghanem and others (1973). The rock was quarried by the Romans, providing good access to fresh rock. The analyzed specimens were collected from the ancient quarries at 26°49′ N, 33°29′ E. In thin section the rock is identified as a granodiorite, composed of oligoclase, quartz, and biotite with subordinate K-feldspar and hornblende. Chemical analyses indicate it contains 66 percent SiO_2, 1.9 percent K_2O, and 4.5 percent Na_2O (Greenberg, 1981). All three whole rocks have unfavorable $^{87}Rb/^{86}Sr$ (< 0.2). For this reason, mineral separates of plagioclase, potassium feldspar, and biotite, as well as three independent whole-rock splits, were analyzed.

An age of 610 Ma is defined by the biotite (fig. 3F). The whole rock and feldspar data give an age of about 693 Ma. A single fraction of zircons is nearly concordant, with a model age of 666 Ma. Using either the Rb-Sr isochron age (excluding biotite) or the U-Pb zircon age, the initial $^{87}Sr/^{86}Sr$ was 0.7025 ± 1.

11. *Gegel Nuqrah volcanics: felsic and andesitic.*—A large exposure (10 × 10 km) of Dokhan volcanics has been identified around Gebel Nuqrah, west of Safaga (Ghanem and others, 1973). The area lies between 33°45′ and 33°35′ E and 26°33′ and 26°45′ N. The following discussion is based on our field studies over the past 3 yrs. Six principal lithologies comprise the basement: granodiorite, andesitic dikes, andesitic flows, rhyolitic ignimbrites and associated pyroclastic sediments, rhyolite porphyry hypabyssal intrusions, and pink granite. The granodiorite is petrographically and geochemically similar to the Mons Claudianus granodiorite with which the granodiorite of the Nuqrah area is continuous. Based on field observations and unpublished geochemical data, the andesitic dikes represent feeders for the andesitic flows. The andesitic flows are commonly plagioclase-phyric, occasionally pillowed, and are at least 200 m thick. These are overlain conformably by a thick succession of rhyolitic ignimbrites, pyroclastic rocks, and volcaniclastic sediments. The rhyolite extrusives are intimately related to hypabyssal rhyolite porphyry plugs. These may have served as centers from which the rhyolites were erupted. The rhyolite porphyries grade down into equigranular pink granite. This granite was intruded as a lopolith between the granodiorite and the andesitic flows.

An earlier Rb-Sr geochronologic study of the Dokhan Volcanics in the Nuqrah Area reported an isochron age of 602 ± 13 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7028 ± 2. This was based on five whole rock analyses, three of rhyolites, and two of andesites (Stern, 1979). Subsequent analyses (table 1) indicate this age may be an average and that the data points lie on two distinct isochrons with different slopes (fig. 4, G and H). One, defined by six ignimbrites, one rhyolite dike, one rhyolite porphyry, and one granite, has an age of 581 ± 7 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7033 ± 3 (MSWD = 2.32; fig. 3G). This is consistent with the field observations showing the ignimbrites and rhyolite porphyry to be the extrusive and shallow intrusive equivalents, respectively, of the pink granite, dated everywhere in Egypt at 570 to 600 Ma (Fullagar, 1980; this study).

Data from the andesites are more puzzling. Analyses of six flows and five dikes define a line with an age of 686 ± 28 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7026 ± 1 (MSWD = 1.18; fig. 3H). No significant difference is seen in the age defined solely by flows or dikes. As noted previously, the succession from lower andesites to upper rhyolites appears in the field to be conformable. Several traverses across the andesite–rhyolite contact failed to find evidence of an angular unconformity or basal conglomerate. Instead, primary structures in the andesite appear better preserved as the contact is approached with spectacular pillows and intercalated tuffs preserved just beneath the first ignimbrites. Farther upsection andesites that are chemically indistinguishable from those erupted prior to the rhyolites are interbedded with the rhyolites. For these geologic reasons we interpret these data to indicate that eruption of the andesites (and emplacement of the andesitic dikes) only slightly predated the pulse of felsic magmatism. Although the MSWD here is more than adequate than needed for an isochron, we interpret the age for the Dokhan andesites from this region as corresponding to no geologic event.

It is not evident what mechanism is responsible for this apparently erroneous age. Rocks that have been reset as a result of post emplacement/eruption thermal disturbances typically appear younger than they are. Loss of Rb during such an event could be responsible, but this must have occurred in a much more systematic manner than we are at present willing to accept. Alternatively, the andesites may have been out of isotopic equilibrium at the time of their emplacement such that andesites with a higher Rb/Sr had a slightly higher $^{87}Sr/^{86}Sr$. This could have been accomplished if the total range in $^{87}Sr/^{86}Sr$ at eruption was 0.7025 to 0.7031.

Such variability in $^{87}Sr/^{86}Sr$ is common in younger igneous rocks erupted both on oceanic crust (Brooks and others, 1976) and in continental environments (Brooks, James, and Hart, 1976). The cause of this covariation of $^{87}Sr/^{86}Sr$ with Rb/Sr, whether "mantle isochron" or crustal contamination is not always known, but it is apparent that radiometric dates from Rb/Sr whole-rock analyses of mafic and intermediate igneous rocks should be interpreted with caution.

12. *Gebel Qattar granite.*—The 20 × 30 km pink granite pluton exposed around Gebel Qattar (27°04′ N, 33°22′ E) is one of the biggest such bodies in the Eastern Desert. Schürmann (1966) identified this as the type locality for the "Qattarian Granite" elsewhere referred to as the Pink, Younger, or Post-Tectonic granite. The analyzed specimen is a coarse equigranular granite collected from near the north contact of the pluton along Wadi Belih. Chemical analyses of granites from Gebel Qattar indicate 67 to 74 percent SiO_2, 3.5 to 4.8 percent K_2O, and K_2O/Na_2O = 0.5 to 1.1 (Schürmann, 1966). One fraction of zircons gave a model age of 579 Ma, an age similar to the Rb/Sr model age of 575 Ma. Due to the very high $^{87}Rb/^{86}Sr$ of this sample (~ 124), no initial $^{87}Sr/^{86}Sr$ was calculated.

13. *Salah El Belih granodiorite.*—Plutonic rocks northeast and northwest of Gebel Qattar appear in the field to be older than the granite of Gebel Qattar. Where the latter is seldom cut by dikes, the former commonly are. Since the Hammamat Conglomerates often carry cobbles of pink granite, yet are intruded by pink granite, Schürmann (1966) subdivided the Qattarian granites into the Upper Qattarian and the Lower Qattarian. The former were typified by the granite of Gebel Qattar, while the granites and granodiorites around its base were identified as Lower Qattarian. While Schürmann's (1966) identification of two distinct magmatic pulses separated by an unconformity may not be warranted, it is clear that the intrusive rocks around the margins of the Gebel Qattar pluton are somewhat older than Gebel Qattar itself.

A sample of this Lower Qattarian granodiorite was collected from the foot of Salah El-Belih (27°11′ N, 32°22′ E). The single fraction of zircons analyzed gave a model age of 583 Ma, similar to the Rb/Sr model age of 571 Ma. Using the zircon age and the whole rock Rb, Sr, and $^{87}Sr/^{86}Sr$ data, an initial of 0.7030 is calculated. Thus the granodiorites and granites around Gebel Qattar have analytically indistinguishable ages from that of Gebel Qattar itself.

14. *Gebel Dokhan flows.*—Ten specimens of volcanic flows were collected from along Wadi Umm Sidri and Wadi Abu Maamal (27°15′-27°20′ N, 33°17′-33°22′ E). These specimens are from the type locality of the Dokhan Volcanics (Ghobrial and Lotfi, 1967) and consist of andesites and dacites. The whole rock analyses define an age of 592 ± 13 Ma with an initial $^{87}Sr/^{86}Sr$ of 0.7028 ± 1 (MSWD = 1.18; fig. 3I). We are aware of the problems inherent in dating intermediate volcanic rocks such as these, as we have discussed previously. We believe the age of 592 ± 13 Ma determined on these rocks represents the time of eruption of the rocks for the following reasons: (1) this age is similar to that of 589 ± 4 Ma for dikes in the region which we interpret as shallow feeders for the Dokhan; (2) it is similar to the age of 581 ± 7 Ma for the felsic volcanics from G. Nuqrah which are mapped as Dokhan; and (3) the MSWD is reasonably low.

15. *Qattar-Dokhan Area dikes.*—Numerous east-southeast west-northwest trending dikes cut the granites and granodiorites in the area around Gebels Qattar and Dokhan. These also intrude the Hammamat sediments. These dikes in part represent feeders for the overlying Dokhan Volcanics. The dikes are compositionally bimodal with subequal rhyolite prophyry and andesitic dikes. Composite dikes are common. Eighteen whole-rock samples and mineral separates of potassium feldspar and plagioclase were analyzed for Rb, Sr, and $^{87}Sr/^{86}Sr$. The whole-rock data, with two exceptions, define an isochron with an age of 589 ± 4 Ma and an initial of 0.7030 ± 1 (MSWD = 2.13; fig. 3J). The two exceptions (195D, 198C) lie well above the isochron, possibly indicating derivation from a heterogeneous source or crustal contamination. Mineral separate and host whole-rock analyses define a 558 ± 8 Ma isochron with an initial $^{87}Sr/^{86}Sr$ of 0.7038 ± 2 (MSWD = 0.31), indicating a thermal disturbance of that age.

16. *Wadi Dib granodiorite.*—North of the Qattar-Dokhan Area, the basement is largely made up of pink granite and Dokhan Volcanics. A large

expanse of granodiorite is exposed to the north of this, between 27°30′ and 27°55′ N (Ghanem and others, 1973). A sample of this granodiorite was collected just north of the Wadi Dib Ring Complex, at 27°36′ N, 32°55′ E. Analysis of one fraction of zircons from this granodiorite (E-8-80) yielded a model age of 620 Ma. Using this age and the Rb, Sr, and $^{87}Sr/^{86}Sr$ whole-rock data (table 2) the initial $^{87}Sr/^{86}Sr$ is determined to be 0.7025.

17. *Wadi Dib felsic dike.*—Hammamat-like breccias exposed in the lower stretches of Wadi Dib are intruded by numerous dikes. One of these (E-7-80) was collected at 27°48′ N, 33°02′ E. This sample is brick-red in color with large (~ 1 cm) phenocrysts of orthoclase. Rb-Sr whole-rock analysis indicates a model age of 550 Ma.

18. *Gebel Dara pink granite.*—North of the Wadi Dib granodiorites is another broad expanse of pink granite and Dokhan Volcanics (Ghanem and others, 1973) extending from 27°55′ N to 28°10′ N. A sample of this pink granite (E-9-80) was collected from the foot of Gebel Dara, at 27°55′ N, 33°03′ E. A single fraction of zircon was analyzed and gave a model age of 596 Ma. Using this age and the Rb, Sr, and $^{87}Sr/^{86}Sr$ data listed in table 2, an initial $^{87}Sr/^{86}Sr$ of 0.7030 is indicated.

19. *Gebel Dara Rhyolite dike.*—A sample (E-10-80) of orthoclase–quartz–plagioclase prophyritic rhyolite was collected from dikes that cut the Dara granite. This sample had a very favorable $^{87}Rb/^{86}Sr$ (~ 30) and gave a model age of 543 Ma.

20. *Granite of Gebel Zeit.*—A sample of the riebeckite granite described by Schürmann (1966) was collected from the Ras Zeit range (27°58′ N, 33°29′ E). The whole rock has a very favorable $^{87}Rb/^{86}Sr$ (26.5) and gave a model age of 592 Ma.

21. *Granite of Gebel Gharib.*—The granite pluton (8 × 13 km) of riebeckite alkali granite exposed around Gebel Gharib has long been suspected of being significantly younger than the typical pink granites of the Eastern Desert (Ghanem and others, 1973). A sample from the eastern slope of the mountain (28°08′ N, 32°06′ E) had a very favorable $^{87}Rb/^{86}Sr$ (~ 45) and gave a model age of 544 Ma.

22. *Wadi Hawashiya granodiorite.*—North of the expanse of pink granite that extends from 27°55′ N to 28°10′ N is a tract of granodiorite that continues north until basement exposures disappear (~ 28°42′ N). This granodiorite was sampled at the first basement exposure in Wadi Hawashiya (E-138; 28°24′ N, 32°41′ E). A single fraction of zircon was analyzed, giving a model age of 614 Ma. This age and the whole-rock Rb-Sr data (table 2) indicate an initial $^{87}Sr/^{86}Sr$ of 0.7033.

23. *Wadis Hawashiya and Gazalla granite.*—Two samples of pink granite and one of an aplite dike associated with the pink granite were collected from separate outcrops along Wadis Hawashiya and Gazalla (E-173: 28°25′ N, 32°34′ E; E-139: 28°25′ N, 32°36′ E; E-141: 28°17′ N, 32°37′ E). These samples define an isochron with a whole-rock Rb-Sr age of 577 ± 6 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7036 ± 1 (MSWD = 0.17; fig. 3K).

24. *Um Tennasib Granite dikes.*—Three samples of hypabyssal granitic dikes were collected from the southwest slope of Gebel Um Tennasib

(28°32′ N, 32°35′ E). These define a Rb-Sr whole-rock isochron with an age of 575 ± 11 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7042 ± 15 (MSWD = 1.05; fig. 3L).

DISCUSSION

A summary of the twenty-four age and eighteen initial $^{87}Sr/^{86}Sr$ determinations is presented in table 4. We believe these data contribute to the further understanding of the Late Precambrian crustal evolution in Egypt: (A) Was igneous activity episodic or continuous? (B) Was there a spatial progression of igneous activity with time? (C) What was the relationship between igneous and tectonic activity? and (D) What is the significance of the low initial $^{87}Sr/^{86}Sr$ of Egyptian Precambrian rocks? These questions are discussed below.

Late Precambrian Igneous Activity in Egypt: Continuous or Episodic?

The answer to this question should provide a critical constraint on models of crustal evolution in the region. Of course, we recognize the uncertainties inherent in trying to decide this question on the basis of a limited data base. The question is nevertheless important enough that it is appropriate to begin to address it here. It is in this spirit that we have approached this problem, and we appreciate the validity of alternate interpretations of the data.

The results of the present study are consistent with a model whereby much of the Late Precambrian igneous activity occurred in at least five and perhaps six distinct episodes. These episodes are identified by the existence of at least two reliable dates for rocks of similar or related composition and inferred tectonic setting. They occupy the following approximate intervals: 715 to 700 Ma, 685 to 665 Ma, 625 to 610 Ma, 600 to 575 Ma, and 555 to 540 Ma. A sixth episode is suggested by the date of 768 ± 31 Ma for the Abu Swayel rhyodacite. These appear to have occurred at a frequency of 40 ± 10 Ma.

Spatial Progression of Late Precambrian Igneous Activity

The ages determined in this study indicate a general progression of igneous activity from south to north with time. This is summarized in figure 5, which shows the distribution of episodes within the tectonic domains outlined earlier, along with a qualitative estimate of the intensity of each pulse. Such estimates are based on geochronologic results and field investigations but are necessarily subjective at present. Since the bulk of our geochronologic and field studies has been carried out in the North Eastern Desert, we are most confident about the assignment of episodes in that region.

In spite of these uncertainties, the present data set indicates that the locus of Late Precambrian igneous activity migrated northward with time. This is most evident with regard to the distribution of the youngest (555-540 Ma) and oldest (765 Ma, 715-700 Ma) episodes. Evidence for the latter is found only in the South Eastern Desert. Evidence for yet older rocks is also limited to this region (El Shazly and others, 1973; Hashad and others, 1972; Abdel Monem and Hurley, 1979). Further support for the existence of older crust in the south comes from consideration of the Atud Conglomerate (El-Ramly and Akaad, 1960). These distinctive conglomerate beds contain granitic and arkosic cobbles derived from a 1.1 to 2.3 Ga sialic source (Dixon, 1981). These beds are found in the Central Eastern Desert, where they thicken to the south and are not found north of 26° N.

Evidence for the 555 to 540 Ma event is restricted to the North Eastern Desert. Within this region, it becomes more important to the north. This is shown by the fact that the southernmost manifestation of this event is the resetting of the Qattar-Dokhan dike internal isochrons at 27°10′ N. Igneous rocks of this age are encountered north of 27°30′ N where dikes and at least two alkaline plutons are known (G. Gharib: 544 Ma, 28°10′ N; Wadi Dib Ring Complex: 28° N, 554 ± 12 Ma K-Ar age; Lutz and others, 1978). Igneous rocks and reset biotites of similar age are reported from Sinai (Bielski, Jager, and Steinitz, 1979), Jordan (Lenz and others, 1972), and northern Arabia (Fleck and others, 1976).

In addition to the restricted distribution of the oldest rocks in the south and the youngest rocks to the north, the most intense magmatic episodes also appear to migrate northward with time. For example, the bulk of the South Eastern Desert crust was created prior to 650 Ma, while the

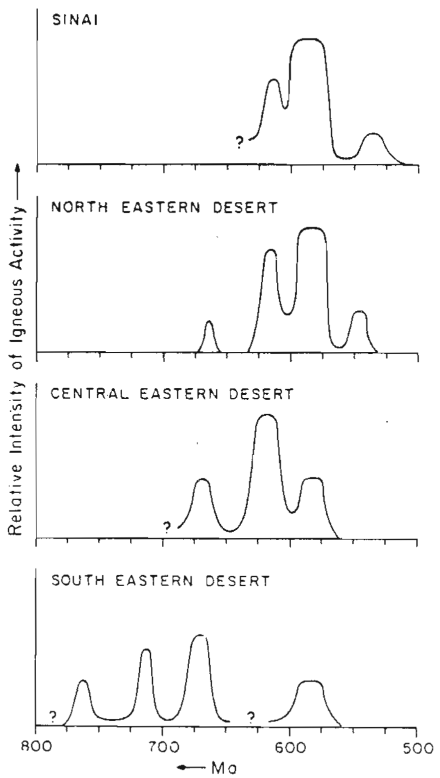


Fig. 5. Distribution, timing, and relative intensity of igneous episodes in the Egyptian basement. Data sources as discussed in the text.

major pulses in the Central Eastern Desert occurred in the interval 685 to 575 Ma. In the North Eastern Desert (and Sinai?) the crust was principally formed in the period 625 to 575 Ma.

Timing and Nature of Major Crust-Forming Events

The geochronologic framework outlined in this paper allows the partial identification of the following crust-forming episodes in the Eastern Desert:

780 to 750 Ma episode (?).—Very little is known about this event except that low-K rhyodacites were erupted. We prefer at present not to speculate on the significance of this age.

715 to 700 Ma episode.—Rocks of this age are known from two localities in the eastern part of the South Eastern Desert south of 24° N, where they are part of a major north-south trending batholith. In a detailed study of intrusive rocks surrounding the Dahanib ultramafic body (23°45′ N, 35°12′ E), Dixon (1981) found these to be dominated by low-K quartz diorite (60 percent SiO_2, 0.6 percent K_2O) with relatively flat REE patterns (Ce = 13x chondritic; Yb = 6x chondritic). The quartz diorite gave a nearly concordant U/Pb zircon age of 711 ± 7 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.70262. Dixon compared the Dahanib quartz diorite with primitive Archean tonalites; although he declined to comment on the specific tectonic setting of the Dahanib tonalite, he argued for a primitive crustal environment.

Rocks of similar age are also reported from the northeastern Sudan. Fitches and others (1983) reported andesites and dacites from the Nafirdeib Series at Sol Hamed (22°15′ N, 36°15′ E) with a whole-rock Rb-Sr age of 712 ± 58 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7023 ± 1. The Nafirdeib Series was interpreted to represent a primitive island arc built over a southeastward dipping Benioff Zone. This is consistent with the data for the Egyptian rocks, although a north-south trending, west-dipping Benioff Zone stretching from at least 24° N to 22° N is needed to explain the present distribution of rocks of this age in Egypt and northeast Sudan.

685 to 665 Ma episode.—Three separate tonalite/granodiorite plutons are known from this period: Hafafit, Wadi Mia, and Mons Claudianus. The first two of these appear to be representatives of numerous granodiorite/tonalite bodies intruded around the Migif-Hafafit culmination between 24°40′ and 25°20′ N (El-Ramly and Akaad, 1960). The Hafafit tonalite is clearly a syntectonic intrusion that was probably emplaced at the same time that major south-directed thrusting of ophiolites was in progress (El-Ramly and others, in press). This appears to be the earliest evidence for the emplacement of the great ophiolitic nappes and melanges of the southern portion of the Central Eastern Desert.

The tectonic setting of the Mons Claudianus granodiorite is not clear. It is compositionally similar to the Hafafit and Mia bodies, and all three are located near the margin of the Central Eastern Desert, but it is different in that the Hafafit and Mia bodies are strongly foliated and syntectonic while the Mons Claudianus body is not. This reflects the fact that where the border between the Central and South Eastern Deserts is a major shear zone, that between the North and the Central Eastern Desert is defined by an intrusive contact. A possible explanation of these observations could include a north-dipping subduction zone at the Central-South Eastern Desert boundary with the active arc astride the Central-North Eastern Desert boundary.

625 to 610 Ma episode.—This is a major event in the evolution of the Central and North Eastern Deserts but seems not to be recorded in the basement to the south. This was a period of strong, largely compressional crustal movements in the northern half of the Central Eastern Desert, as is shown by the eruption of the arc-like Younger Metavolcanics (Stern, 1981) and by the emplacement of the Abu Ziran granodiorite which dates the principal shear deformation around the Meatiq Dome (Sturchio, Sultan, and Batiza, 1983). In contrast, the two granodiorites of this age from the North Eastern Desert record no obvious structural effects of crustal compression.

600 to 575 Ma episode.—It is well known that pink granites of this age are common throughout the Eastern Desert and Sinai (Hashad and others, 1972; Bielski, Jager, and Steinitz, 1979; Fullagar, 1980; Halpern and Tristan, 1981). Our results confirm these results and indicate further that magmatism in this interval involved a number of other types of activity. These include eruption of the Dokhan Volcanics and emplacement of dikes in the North Eastern Desert. We also note that whereas rocks of this age are common throughout the Eastern Desert, this episode is especially important in the crustal evolution of the North Eastern Desert. Stern, Gottfried, and Hedge (1984) reviewed the geology of this region and concluded that the igneous and sedimentary associations indicated a tectonic setting of strong crustal extension directed north-south or northwest-southeast. This appears to have been a major episode of crust formation in the North Eastern Desert, while to the south activity was essentially anorogenic with pink granites being passively emplaced into pre-existing crustal weaknesses.

555 to 540 Ma episode.—Activity during this period reflects a relatively minor episode of crustal rifting. Especially good evidence for this is found on the east side of the Jordan Rift, where rhyolite plugs intrude Cambrian sandstones. Bender (1982) regarded this activity as an early stage of crustal extension. A related tectonic setting is likely for the 540 to 555 Ma igneous rocks of the North Eastern Desert.

Late Precambrian magmatic and tectonic activity in the Eastern Desert can be grossly subdivided into two major cycles having distinct magmatic and tectonic characteristics. The older of these encompasses activity from 765 to 610 Ma. Its igneous products are characterized by strong calc-alkaline and low-K tholeiitic affinities. Although we do not know the precise age of the Egyptian ophiolites, they clearly belong to this or an older interval. Plutonic rocks range from quartz diorites to granodiorites. The igneous rocks of this older cycle bear a marked resemblance to modern island arc, back-arc basin, and/or ocean floor igneous assemblages (Engel, Dixon, and Stern, 1980). Tectonic activity during this episode was strongly compressive with numerous thrust faults and other shear zones

(Stern, 1979; Sturchio, Sultan, and Batiza, 1983; Ries and others, 1983; El Ramly and others, in press). Thus, the earlier cycle exhibits structural and geochemical characteristics similar to those documented from more recent convergent margins.

The younger of the two major cycles lasted from 600 to 540 Ma. Magmatism and tectonic activity during this time are markedly different from that of the earlier cycle. Igneous rocks are typically granites and bimodal hypabyssal intrusives and volcanic flows. All igneous rocks are strongly enriched in the incompatible elements, and mildly alkaline affinities are common. There is no evidence for ophiolitic rocks being emplaced during this interval, and tectonic activity is generally limited to the development of broad open folds. Stern, Gottfried, and Hedge (1984) argued these features are most consistent with an extensional tectonic setting.

Temporal Variations and Implications of Initial $^{87}Sr/^{86}Sr$

All the Late Precambrian igneous rocks from the Eastern Desert that we have analyzed have low initial $^{87}Sr/^{86}Sr$. With the exception of the Um Tennasib initial $^{87}Sr/^{86}Sr$ which has a large uncertainty, 19 initial ratios range between 0.7019 and 0.7036. This is common to most Late Precambrian igneous rocks from around the Red Sea (for example, Fleck and others, 1980; Engel, Dixon, and Stern, 1980; Fleck and Hadley, 1982; Duyverman, Harris, and Hawkesworth, 1982; Fitches and others, 1983). Such low initials constrain petrogenetic models for these igneous rocks and specifically do not allow the participation of significantly older continental crust in the generation of any of the melts.

In spite of remarkably large variations in major and trace element compositions, all Egyptian basement suites appear to have been derived from very similar sources with respect to isotopic composition. These sources show strong long-term depletions in Rb relative to Sr. For example, the initial $^{87}Sr/^{86}Sr$ of the oldest suite, the Abu Swayel rhyodacite, could have evolved in a source with a single stage Rb/Sr of 0.019. At the time of eruption, this source would have had Sr-isotopic characteristics similar to those of MORB. Subsequently, the Rb/Sr of the source regions increased by an order of magnitude to between 0.15 and 0.25 (fig. 6).

The apparent two-stage history of the Eastern Desert magma sources is most consistent with either of two general models: (A) melting of metasomatically enriched mantle or (B) melting of primitive crust. In the first case an event or series of enrichment events occurred in the upper mantle just prior to or during crustal formation. Metasomatic enrichment would result from the upward percolation of LIL-rich fluids into a previously depleted upper mantle. Such a process has been advocated for the evolution of the source for more recent alkaline magmas (for example, Boettcher and O'Neil, 1980; Menzies and Murthy, 1980; Basu and Tatsumoto, 1980). The Late Precambrian event of mantle metasomatism would be required to enrich Rb relative to Sr. Such metasomatism could also have enriched the mantle source region in a variety of other LIL elements, LREE, et cetera and in this fashion been responsible for the observed progression in rock types from depleted (tonalitic) to enriched (granitic, *sensu stricto*) with time.

In the second model, the observed progressive enrichments and increase in initial $^{87}Sr/^{86}Sr$ with time reflect the remelting of first cycle sediments and igneous rocks. The increased Rb/Sr is that of more fractionated tonalites and graywackes that were buried and anatectically reworked. Such a source would have an Rb/Sr of 0.1-0.2 and is thus consistent with the observed increase of initial $^{87}Sr/^{86}Sr$ with time. Melting of such materials in the crust could also produce the observed temporal progression of depleted to enriched melts. This explanation is preferred by a number of investigators (for example, Fleck and others, 1980; Duyverman and Harris, 1982) and is supported by a lead isotope study of the Egyptian Shield (Gillespie and Dixon, 1983). We caution, however, that the geochemical and isotopic data are consistent with either model and do not know of any unequivocal basis with which to choose between them.

CONCLUSIONS

A. Igneous activity responsible for the construction of the crust in the Eastern Desert of Egypt spanned at least 230×10^6 yrs, from 770 to 540 Ma.

B. The distribution of basement ages corresponds with the proposed subdivision of the Eastern Desert into South Eastern, Central Eastern, and

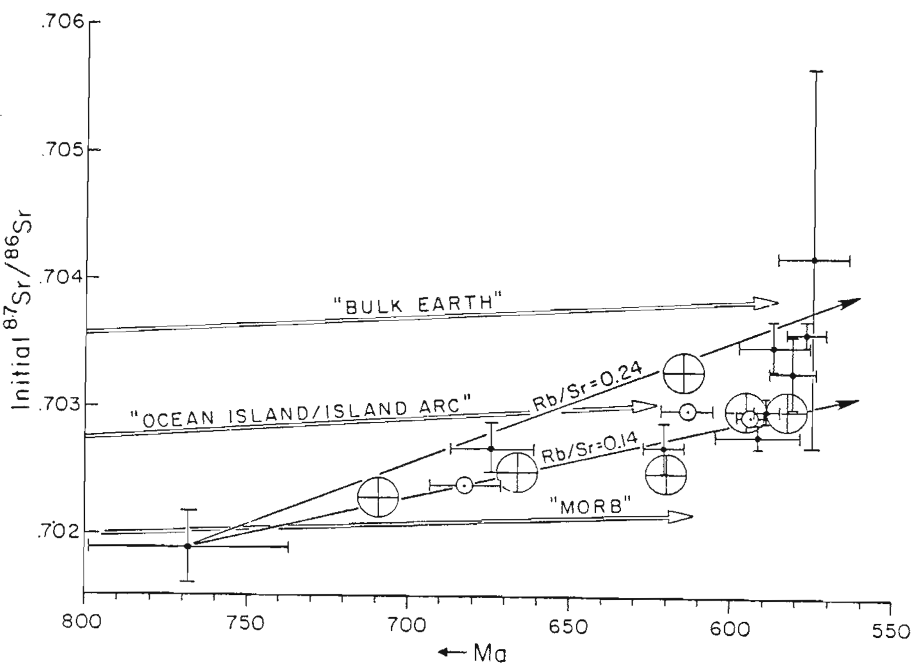


Fig. 6. Variation of initial $^{87}Sr/^{86}Sr$ with age in the Egyptian Shield. All data are as follows: (1) vertical and horizontal error bars represent y-intercepts of Rb-Sr isochrons; (2) small circles with horizontal error bars represent whole-rock Rb-Sr data corrected for radiogenic growth using the upper intercept of U-Pb zircon concordia age; and (3) large circles represent whole-rock Rb-Sr data corrected for radiogenic growth using U-Pb zircon model age.

North Eastern Desert litho-tectonic domains. The oldest rocks are found in the south, and the youngest units are found in the north.

C. To a first approximation, the basement youngs to the north.

D. The present geochronologic data base is consistent with the identification of at least five igneous episodes, separated by 40 ± 10 Ma: (1) 715 to 700 Ma; (2) 685 to 665 Ma; (3) 625 to 610 Ma; (4) 600 to 575 Ma; and (5) 555 to 540 Ma. A sixth pulse is suggested by a single age of 768 ± 31 Ma.

E. Units older than 768 ± 31 Ma probably occur throughout the western and central portions of the South Eastern Desert.

F. A fundamental transition in tectonic setting occurred about 600 ± 10 Ma. At that time the crustal environment changed from one dominated by compression into one dominated by extension.

G. All igneous rocks in the Eastern Desert of Egypt were generated with low initial $^{87}Sr/^{86}Sr$, ranging from 0.702 to 0.704. There is no evidence for the participation of older, more evolved crust in the generation of the basement.

H. The observed increase in initial $^{87}Sr/^{86}Sr$ with time is consistent with a two-stage evolution of the source. The source in the first stage would be very similar to that of modern abyssal tholeiites at 750 Ma. The second stage represents the enrichment of this source in Rb relative to Sr. These observations are consistent with a source of either metasomatically enriched mantle or first-cycle geosynclinal sediments and igneous rocks.

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REFERENCES

Abdel-Monem, A. A., and Hurley, P. M., 1979, U-Pb dating of zircons from psammitic gneisses, Wadi Abu Rosheid-Wadi Sikait Area, Egypt, *in* Tahoun, S. A., ed., Evolution and Mineralization of the Arabian-Nubian Shield, v. 2: New York, Pergamon Press, p. 165-170.

———— 1980, Age of the Aswan Monumental Granite, Egypt, by U-Pb dating of zircons, *in* Al-Shanti, A. M. S., ed., Evolution and Mineralization of the Arabian-Nubian Shield, v. 3: New York, Pergamon Press, p. 141-144.

Akaad, M. K., and El Ramly, M. F., 1960, Geological history and classification of the basement rocks of the central-eastern desert of Egypt: Cairo, Egypt Geol. Survey, 22 p.

Akaad, M. K., and Moustafa, G. A., 1963, The Shait granite, a cataclastic-mylonitic granodiorite: Egypt Geol. Survey Paper 19, 18 p.

Andrew, G., 1939, The greywackes of the Eastern Desert of Egypt: Inst. d'Egypte Bull., v. 21, p. 153-190.

Bakor, A. R., Gass, I. G., and Neary, C. R., 1976, Jabal al Wask, northwest Saudi Arabia: an Eocambrian back-arc ophiolite: Earth Planetary Sci. Letters, v. 30, p. 1-9.

Ball, J., 1912, The Geography and Geology of South-Eastern Egypt: Cairo, Egypt Geol. Survey, 394 p.

Barron, T., and Hume, W. F., 1902, Topography and geology of the Eastern Desert of Egypt, central portion: Cairo, Egypt Geol. Survey, 331 p.

Barthoux, J., 1922, Chronologie et Description des Roches Ignées du Désert Arabique: Inst. d'Egypte Mém., v. 5, 262 p.

Basu, A. R., and Tatsumoto, M., 1980, Nd-isotopes in selected mantle-derived rocks and minerals and their implications for mantle evolution: Contr. Mineralogy Petrology, v. 75, p. 43-54.

Bender, F., 1982, On the evolution of the Wadi Araba-Jordan Rift: Geol. Jahrb., B 45, p. 3-20.

Bielski, M., Jäger, E., and Steinitz, G., 1979, The geochronology of Iqna Granite (Wadi Kid Pluton), Southern Sinai: Contr. Mineralogy Petrology, v. 70, p. 159-165.

Boettcher, A. L., and O'Neil, J. R., 1980, Stable isotope, chemical, and petrographic studies of high-pressure amphiboles and micas: Evidence for metasomatism in the mantle source regions of alkali basalts and kimberlites: Am. Jour. Sci., v. 280-A, p. 594-621.

Brooks, C., James, D. E., and Hart, S. R., 1976, Ancient lithosphere: Its role in young continental volcanism: Science, v. 193, p. 1086-1094.

Brooks, C., Hart, S. R., Hofmann, A., and James, D. E., 1976, Rb-Sr mantle isochrons from oceanic regions: Earth Planetary Sci. Letters, v. 32, p. 51-61.

Cooper, J. A., Stacey, J. S., Stoeser, D. G., and Fleck, R. J., 1979, An evaluation of the zircon method of isotopic dating in the Southern Arabian Craton: Contr. Mineralogy Petrology, v. 68, p. 429-439.

Dewey, J. F., and Burke, K. C. A., 1973, Tibetan, Variscan, and Precambrian basement reactivation: Product of continental collision: Jour. Geology, v. 81, p. 683-692.

Dixon, T. H., ms, 1979, The evolution of continental crust in the Late Precambrian Egyptian Shield: Ph.D. thesis, Univ. California San Diego, 231 p.

———— 1981, Age and chemical characteristics of some pre-Pan-African rocks in the Egyptian Shield: Precambrian Research, v. 14, p. 119-133.

Duyverman, H. J., and Harris, N. B. W., 1982, Late Precambrian evolution of Afro-Arabian crust from ocean arc to craton: Discussion of paper by Engel, Dixon, and Stern: Geol. Soc. America Bull., v. 93, p. 174-176.

Duyverman, H. J., Harris, N. B. W., and Hawkesworth, C. J., 1982, Crustal accretion in the Pan African: Nd and Sr isotope evidence from the Arabian Shield: Earth Planetary Sci. Letters, v. 59, p. 315-326.

El Gaby, S., 1975, Petrochemistry and geochemistry of some granites from Egypt: Neues Jahrb. Mineralogie Abh., v. 124, p. 147-189.

El Ramly, M. F., 1972, A new geological map for the basement rocks in the eastern and southwestern deserts of Egypt: Egypt Geol. Survey Annals, v. 2, p. 1-18.

El Ramly, M. F., and Akaad, M. K., 1960, The basement complex in the Central-Eastern Desert of Egypt: Egypt Geol. Survey Paper 8, 35 p.

El Ramly, M. F., Kröner, A., Greiling, R., and Rashwan, A. A. A., in press, On the tectonic evolution of the Wadi Hafafit area and environs, Eastern Desert of Egypt: Jeddah, Saudi Arabia, King Abdul Aziz Univ., Fac. Sci. Bull.

El Shazly, E. M., 1954, Rocks of the Aswan area, Egypt Geol. Survey, 21 p.

El Shazly, E. M., Abdel Hady, M. A., El Ghawaby, M. A., El Kassas, I. A., and El Shazly, M. M., 1974, Geology of Sinai Peninsula from ERTS-1 satellite images: Remote Sensing Research Project: Cairo, Egypt, Acad. Sci. Research and Technology, 20 p.

El Shazly, E. M., Hashad, A. H., Sayyah, T. A., and Bassyuni, F. A., 1973, Geochronology of Abu Swayel area, South Eastern Desert: Egyptian Jour. Geology, v. 17, p. 1-18.

Engel, A. E. J., Dixon, T. H., and Stern, R. J., 1980, Late Precambrian evolution of Afro-Arabian crust from ocean arc to craton: Geol. Soc. America Bull., v. 91, p. 699-706.

Fitches, W. R., Graham, R. H., Hussein, I. M., Ries, A. C., Shackleton, R. M., and Price, R. C., 1983, The late Proterozoic ophiolite of Sol Hamed, NE Sudan: Precambrian Research, v. 19, p. 385-411.

Fleck, R. J., Coleman, R. G., Cornwall, H. R., Greenwood, W. R., Hadley, D. G., Schmidt, D. L., Prinz, W. C., and Ratte, J. C., 1976, Geochronology of the Arabian Shield, western Saudi Arabia: K-Ar results: Geol. Soc. America Bull., v. 87, p. 9-21.

Fleck, R. J., Greenwood, W. R., Hadley, D. G., Anderson, R. E., and Schmidt, D. L., 1980, Rubidium–Strontium geochronolgy and plate-tectonic evolution of the southern part of the Arabian Shield: U.S. Geol. Survey Prof. Paper 1131, 38 p.

Fleck, R. J., and Hadley, D. G., 1982, Ages and strontium initial ratios of plutonic rocks in a transect of the Arabian Shield: U.S. Geol. Survey Open-file Rept. OF-03-83, 43 p.

Fullagar, P. D., 1980, Pan-African age granites of North Eastern Africa: New or reworked sialic materials?, *in* Salem, M. J., and M. T. Busrewil, eds., Geology of Libya, Second symposium on the Geology of Libya, v. 3: New York, Academic Press, p. 1051-1058.

Gass, I. G., 1977, The evolution of the Pan African crystalline basement in NE Africa and Arabia: Geol. Soc. London Jour., v. 134, p. 129-138.

Gaudette, H. E., and Hurley, P. M., 1979, Where were the Pan-African mountains? No evidence of 500 m.y. detrital zircons: Tectonophysics, v. 54, p. 212-230.

Ghanem, M., Dardir, A. A., Francis, M. H., Zalata, A. A., and Abu Zeid, K. M., 1973, Basement rocks in eastern desert of Egypt north of latitude 26°40′ N: Egypt Geol. Survey Annals, v. 3, p. 33-38.

Ghobrial, M. G., and Lotfi, M., 1967, The geology of Gebel Gattar and Gebel Dokhan areas: Egypt Geol. Survey Paper 40, 26 p.

Gillespie, J. G., and Dixon, T. H., 1983, Pb isotope systematics of some granitic rocks from the Egyptian Shield: Precambrian Research, v. 20, p. 63-77.

Greenberg, J. K., 1981, Characteristics and origin of Egyptian Younger Granites: Summary: Geol. Soc. America Bull. I., v. 92, p. 224-232.

Halpern, M., and Tristan, N., 1981, Geochronology of the Arabian-Nubian Shield in southern Israel and eastern Sinai: Jour. Geology, v. 89, p. 693-648.

Hashad, A. H., Sayyah, T. A., El Kholy, S. B., and Youssef, A., 1972, Rb/Sr isotopic age determination of some basement Egyptian granites: Egyptian Jour. Geology, v. 16, p. 269-281.

Hume, W. F., 1934, Geology of Egypt, v. 2, part 1; The metamorphic rocks: Egypt Geol. Survey, 293 p.

Hurley, P. M., 1972, Can the subduction process of mountain building be extended to Pan-African and similar orogenic belts?: Earth Planetary Sci. Letters, v. 15, p. 305-314.

Kazmin, V., 1972, Some aspects of Precambrian development in East Africa: Nature, v. 237, p. 160.

Kazmin, V., Shifferaw, A., and Balcha, T., 1978, The Ethiopian basement: Stratigraphy and possible manner of emplacement: Geol. Rundschau, v. 67, p. 531-546.

Kennedy, W. Q., 1964, The structural differentiation of Africa in the Pan-African (± 500 m.y.) tectonic episode: Univ. Leeds, Inst. African Goelogy, 8th Rept., p. 48-49.

Kröner, A., 1979, Pan African plate tectonics and its repercussions on the crust of northeast Africa: Geol. Rundschau, v. 68, p. 565-583.

Leggo, P. J., 1968, Some recent isotope investigations: Univ. Leeds, Inst. African Geology and Dept. of Earth Sci., 12th Ann. Rept, p. 45-46.

Lenz, H., Bender, F., Besang, C., Haare, W., Kreuzer, H., Muller, P., and Wendt, I., 1972, The age of early tectonic events in the zone of the Jordan Geosuture, based on radiometric data: Internat. Geol. Cong., 24th, Montreal 1972, sec. 3, p. 371-379.

Lutz, T. M., Foland, K. A., Faul, H., Friedman, I., and Serencsits, C. McM., 1978, Ages of Egyptian alkaline complexes and Sr and O isotope relations at the Abu Khruq Complex: U.S. Geol. Survey Open-file Rept. 78-701, p. 265-267.

McIntyre, G. A., Brooks, C., Compston, A., and Turek, A., 1966, The statistical assessment of Rb-Sr isochrons: Jour. Geophys. Research, v. 71, p. 5459-5468.

Menzies, M., and Murthy, V. R., 1980, Nd and Sr isotope geochemistry of hydrous mantle nodules and their host alkali basalts: Implications for local heterogeneities in metasomatically veined mantle: Earth Planetary Sci. Letters, v. 46, p. 323-334.

Piper, J. D. A., Briden, J. C., and Lomax, K., 1973, Precambrian Africa and South America as a single continent: Nature, v. 245, p. 244-248.

Ries, A. C., and Darbyshire, D. P. F., in press, Rb-Sr whole-rock ages and Pan-African evolution of the Eastern Desert, Egypt: Geol. Soc. London Jour.

Ries, A. C., Shackleton, R. M., Graham, R. H., and Fitches, W. R., 1983, Pan-African structures, ophiolites and melange in the Eastern Desert of Egypt: A traverse at 26° N: Geol. Soc. London Jour., v. 140, p. 75-95.

Rogers, J. J. W., Ghuma, M. A., Nagy, R. M., Greenberg, J. K., and Fullagar, P. D., 1978, Plutonism in Pan-African belts and the geologic evolution of North Eastern Africa: Earth Planetary Sci. Letters, v. 39, p. 109-117.

Sabet, A. H., and Z'aatout, M. A., 1955, Geology of El-Shalul — El-Bakriya district. Barramiya west sheet: Cairo, Egypt Geol. Survey, 75 p.

Schürmann, H. M. E., 1966, The Pre-Cambrian along the Gulf of Suez and the northern part of the Red Sea: Leiden, E. J. Brill, 404 p.

Shimron, A. E., 1980, Proterozoic island arc volcanism and sedimentation in Sinai: Precambrian Research, v. 12, p. 437-458.

Steiger, R. H., and Jäger, E., 1977, Subcommission in geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth Planetary Sci. Letters, v. 36, p. 359-362.

Stern, R. J., ms, 1979, Late Precambrian ensimatic volcanism in the Central Eastern Desert of Egypt: Ph.D. thesis, Univ. California, San Diego, 210 p.

———— 1981, Petrogenesis and tectonic setting of Late Precambrian ensimatic volcanic rocks, Central Eastern Desert of Egypt: Precambrian Research, v. 16, p. 197-232.

Stern, R. J., Gottfried, D. G., and Hedge, C. E., 1984, Late Precambrian rifting and crustal evolution in the North Eastern Desert of Egypt: Geology, v. 12, p. 168-172.

Sturchio, N. C., Sultan, M., and Batiza, R., 1983, Geology and origin of Meatiq Dome, Egypt: A Precambrian metamorphic core complex?: Geology, v. 11, p. 72-76.

Sturchio, N., Sultan, M., Sylvester, P., Batiza, R., Hedge, C., El Shazly, E. M., and Abdel-Meguid, A., in press, Geology, age and origin of Meatiq Dome: Implications for the Precambrian stratigraphy and tectonic evolution of the Eastern Desert of Egypt: Jeddah, Saudi Arabia, King Abdul Aziz Univ., Fac. Sci. Bull.

York, D., 1969, Least-squares fitting of a straight line with correlated errors: Earth Planetary Sci. Letters, v. 5, p. 320-324.

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