Pergamon

Journal of African Earth Sciences, Vol. 19, No. 1/2, pp. 3-15, 1994

0899-5362/94 $7.00 + 0.00

0899-5362(95)00003-8

Geochronology of anorogenic igneous complexes in the Sudan: isotopic investigations in North Kordofan, the Nubian Desert and the Red Sea Hills

A. HÖHNDORF[1], K-D. MEINHOLD[1], and J. R. VAIL[2]

[1]Bundesanstalt für Geowissenschaft und Rohstoffe, Hannover, Germany
[2]Department of Geology, University of Portsmouth, England

(Received 22 August 1994 : accepted 16 November 1994)

Abstract - Rb-Sr isotopic analyses have been made on 14 selected anorogenic alkaline igneous complexes, composed mainly of quartz syenites and granites, which have been intruded through gneissic continental crust, and Neoproterozoic greenschists of the oceanic Nubian Shield. The complexes form three distinct provinces, two of which are aligned in narrow ENE bands across several hundreds of kilometres.

In North Kordofan three groups of ages of emplacement have been delineated at 441 Ma, 280-270 Ma and 206-163 Ma. In the Nubian Desert, east of the Nile river, a group of four complexes has been dated at 297 Ma, 265 Ma, 257 Ma and 250 Ma; they form the western extremity of a WSW belt of intrusions in southern Egypt whose published ages date from 229 to 140 Ma. A pair of igneous complexes in the central Red Sea Hills of eastern Sudan has yielded ages of 480 Ma and 466 Ma. These results confirm the episodic nature of the igneous activity from the Ordovician to the Jurassic. The location of the centres and the similar low Sr initial ratios for all age groups testify to the deep seated influence of the crustal fractures, which enabled the mantle magmas to penetrate close to the surface.

Résumé - Des mesures isotopiques Rb-Sr ont été réalisées sur 14 complexes ignés anorogéniques alcalins. Ces derniers sont composés principalement de syénites quartziques et de granites intrusifs dans une croûte continentale gneissique ainsi que dans les roches vertes néoprotérozoïques du bouclier nubien océanique. Les complexes constituent trois provinces distinctes dont deux forment des alignements étroits orientés à l'ENE sur des centaines de kilomètres.

Dans le Kordofan septentrional, trois groupes d'âges de mise en place sont démontrés à 441 Ma, 280-270 Ma et 206-163 Ma. Dans le désert nubien, à l'est du Nil, un groupe de quatre complexes a été daté à 297 Ma, 265 Ma, 257 Ma et 250 Ma; ils forment l'extrémité occidentale d'une bande orientée WSW d'intrusions d'Egypte méridionale dont les âges publiés s'échelonnent de 229 Ma à 140 Ma. Deux complexes ignés du centre des Red Sea Hills de l'est Soudan ont fourni des âges de 480 Ma et 466 Ma. Ces résultats confirment la nature épisodique de cette activité ignée de l'Ordovicien au Jurassique. La localisation de ces centres et les rapports isotopiques du Sr toujours bas quelque soient les âges, démontrent l'influence des fractures crustales profondes qui ont permis à ces magmas de pénétrer près de la surface.

INTRODUCTION

The Sudan and Nubian Shields of NE Africa are well known for the abundant occurrences of post-orogneic and anorogenic plutonic complexes, many in the form of well developed ring structures, which penetrate the Proterozoic basement and, in places, the Palaeozoic cover rocks as well.

Petrological studies, geochemical investigations and the examination of the structure and mode of emplacement have been carried out on many of the complexes, from which a classification by petrology and mineralogy is developing. In addition, completion of the pattern of distribution is being achieved as more complexes are being discovered and described. However, before the regional implications can be fully considered, the age of the magmatic activity must be known and this has necessitated the dating of each complex.

From previous geochronological studies of the complexes in the area under review (summarized by El Ramly and Hussein 1985 and by Vail 1990) it is evident that some complexes show more than one apparent age, that there is a spread of ages from Early Palaeozoic to Cretaceous and that progressive emplacements are restricted to local areas, such as the Bayuda Desert (Almond *et al.*, 1983). Furthermore, there are two regions of recently recognized abundant intrusions that have lacked isotopic information. These are in the North Kordofan Province and in the Nubian Desert, east of the Nile river. The present study has therefore been directed towards providing age data by Rb-Sr analyses for selected complexes in those areas, and also in the Red Sea Hills further to the east, in order to cover magmatism emplaced through both continental and oceanic crust. A recent K-Ar study has now been published (Schandelmeier and Richter 1991; Müller-Sohnius and Horn 1994) for some of the Kordofan complexes, those results can be compared with these and other age determinations reported in the literature (Vail 1989).

GEOLOGY OF THE NORTH KORDOFAN ANOROGENIC COMPLEXES

Ten igneous centres have been recognized in North Kordofan (Elnetaifa and Vail 1989, Elnetaifa 1990) of which eight have been sampled and isotopically dated (Fig. 1). They are all petrographically rather similar, composed of mainly quartz syenite or granite intrusives, with corresponding rhyolitic and ignimbritic extrusive phases preserved in some places. At three of the complexes (Katul, Nus, Haraza) small outcrops of gabbro are present, for which the precise relation to the major acid phases can only be surmised. Country rocks are not well exposed but are generally known to consist of rare metasediments in the form of gneisses and schists, with occasional marble bands, and granitoid gneisses, generally considered to be Paleoproterozoic in age, in which mylonitic shear zones form prominent siliceous ridges.

The complexes are distributed along a band over 250 km in length trending approximately N 60°E from south of the village of Umm Badri to the village of Hamrat el Wuz and Jebel Haraza in the east (Fig. 1). This includes the following complexes: Qeili el Humeira, an unnamed body, Abu Asal, Katul, Abu Hadid, Umm Durag, Nahd er Rihani, Nahd es Sidani, Nus and Haraza (with satellite Karos in the north, Sania in the west and Kalengei in the east). This line, if extended, would pass near the southern Bayuda Desert and through the Sabaloka basement inlier on the Nile (Fig. 6), adjacent to the Silietat es Sufr, Abu Tuleih and Sabaloka igneous intrusions (Almond 1977). Eighty kilometres to the north of the band of intrusive centres in North Kordofan lies the igneous body of Jebel El Hursh. It is located across the Sodiri Shear Zone, which, although a Neoproterozoic (Pan African) phenomenon, shows a rejuvenation during Permian times. The shearing of the igneous rocks of Jebel El Hursh is considered to be an independant event in the Triassic or younger times (Müller-Sohnius and Horn 1994).

Petrologically, the complexes are composed of medium- to coarse-grained quartz and K-feldspar with small amounts of alkali pyroxenes or amphiboles, some mica and accessories such as zircon, apatite and, more rarely, calcite. Although unmetamorphosed, the plutons are well jointed with displacements on some of the

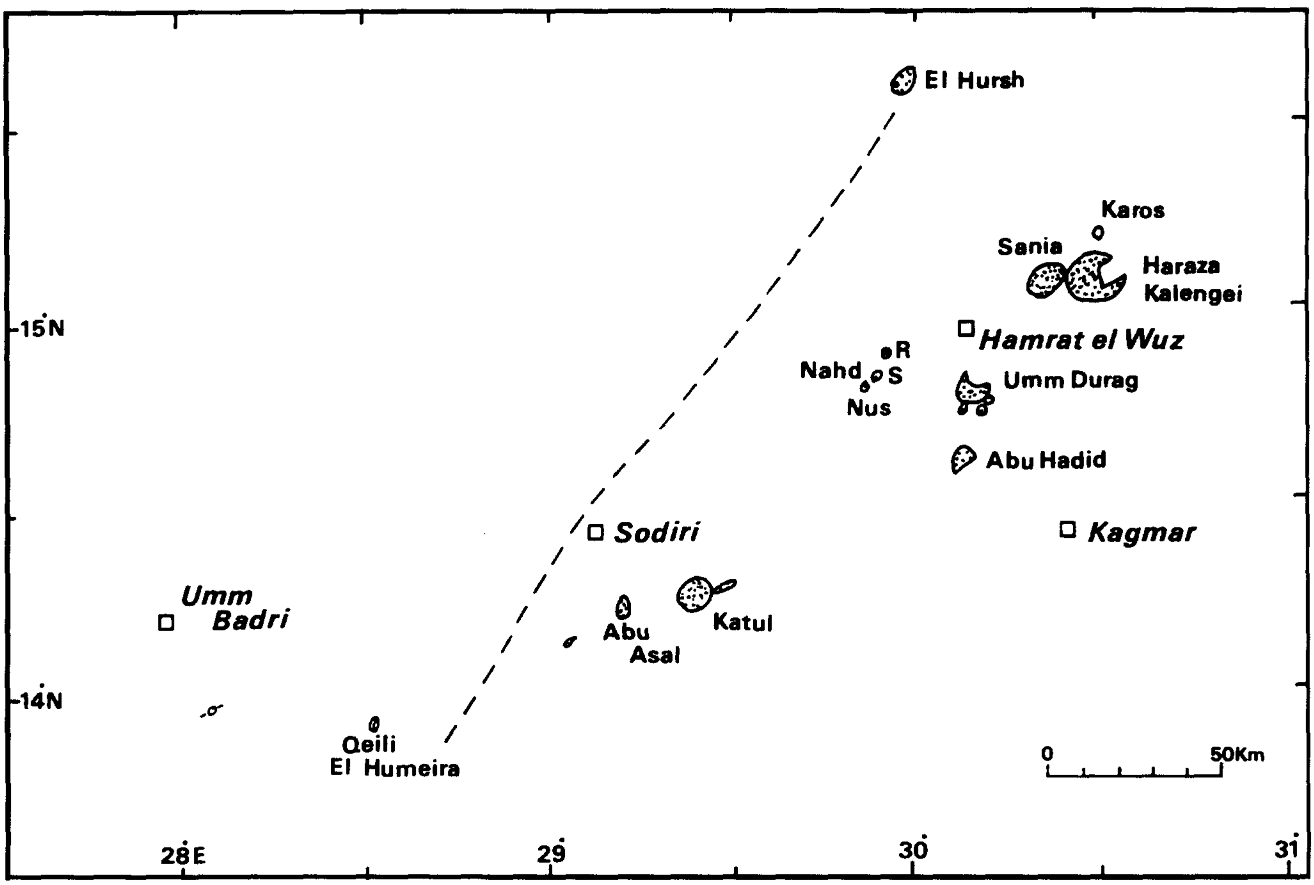

Figure 1. Location of the North Kordofan igneous complexes, Sudan, discussed in the text. Symbols: dashed line-Sodiri Shear zone; squares-villages; stippled circles-igneous centres.

major fractures. Weathering affects surface exposures to a greater or lesser extent, the current climate regime being one of dry, hot conditions with seasonal rainfall and extreme diurnal temperature variations.

The chemistry of the sampled complexes shows no anomalies - most are silica saturated and quartz normative. The different complexes do show individual trends, and slight variations enable a distinction to be recognized, which is reflected in the isotopic chemistry. The trace and minor elements vary more dramatically, especially Zr, which reflects the variable presence of accessory minerals.

GEOLOGY OF THE NUBIAN DESERT COMPLEXES

The Nubian Desert can be considered to cover the area east of the Nile River valley from about 20° N extending northwards across the Egyptian border and eastwards to the Red Sea Hills and the coast. This is a poorly mapped area containing many igneous complexes, few of which have been studied (Fig. 2). This area is fringed by a cover of Mesozoic sediments of the Nubian Supergroup, the underlying basement being dominantly made up of granitic gneisses and metasediments in the west and low grade volcano-sedimentary sequences with syntectonic granitoid batholiths of the Nubian Shield in the east. The contact between these two terranes probably lies along the drainage system of Wadi Gabgaba, approximately 33°30' E. Additionally, there is an isolated outlier of greenschist, volcanic and metasedimentary rocks extending along the Nile for about 200 km south of Wadi Halfa.

Four complexes have been sampled for the present study. They are the Kuror, Tarag, Ataliya and Ago intrusions. The first two form part of a line of centres trending NNW over 140 km, although across the Nubian Desert as a whole the igneous complexes form a band aligned approximately N 55° E, the direction which is emphasized by the ENE line of eight alkali anorogenic centres in southern Egypt described and dated by Hashad and El Reedy (1979), Serencsits *et al.* (1981) and El Ramley and Hussein (1985).

Petrologically the complexes are quartz syenites and alkali granites. They are medium- to coarse-grained and contain variable amounts of quartz and large perthitic K-feldspars, many of which are highly altered. The dark minerals form clusters of opaque iron ores, aegirine augite, riebeckite-arfvedsonite alkali amphiboles, brown biotite and rare muscovite. Apatite, zircon and calcite are accessory minerals. In one of the intrusive centres at Jebel Ago, serpentinized and remnant olivine is present, together with brown hornblende and

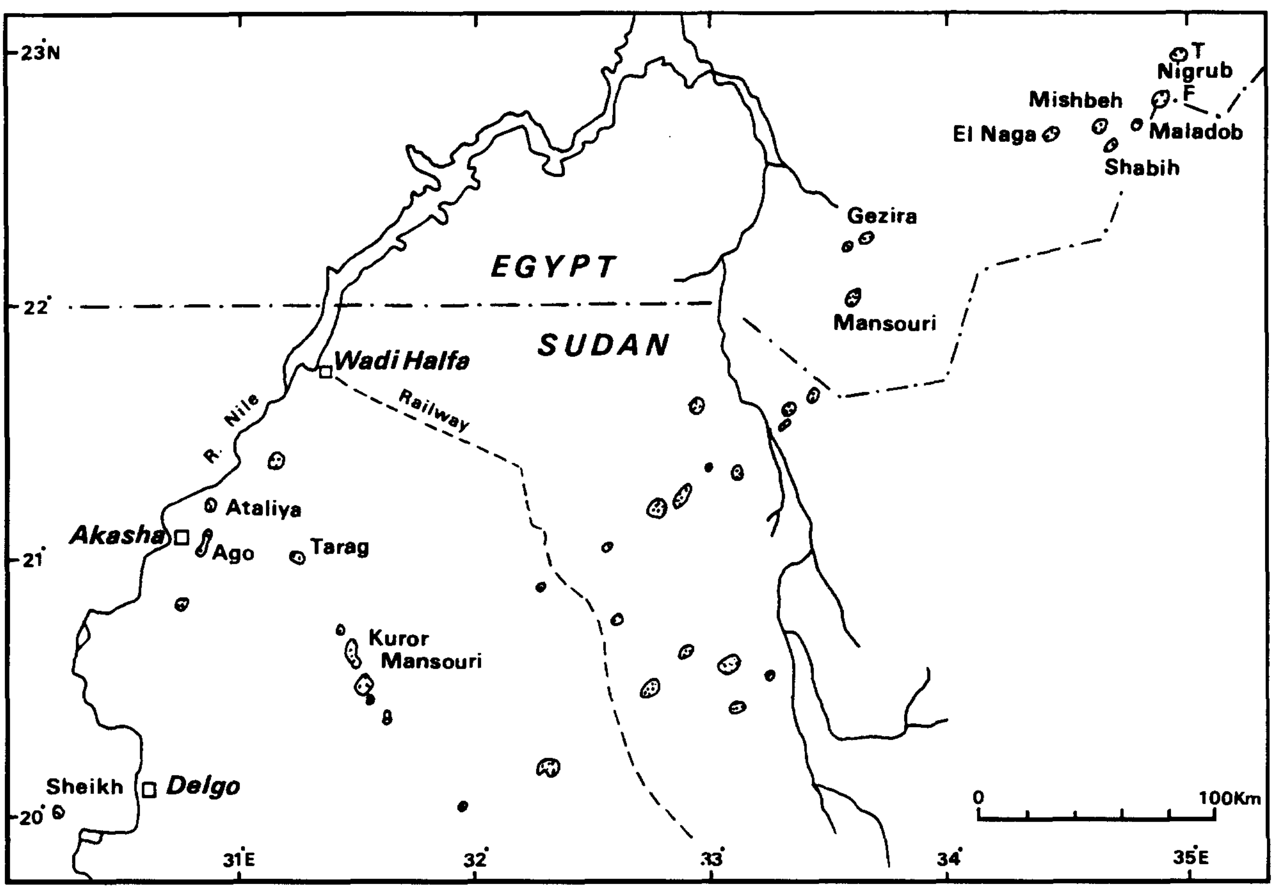

Figure 2. Location of the Nubian Desert igneous complexes, Sudan. Symbols-squares, villages; stippled circles-igneous complexes; broken line-international administrative boundary; pecked line-railway; solid lines-rivers.

brownish augite. As in the North Kordofan complexes, the rocks vary widely in the proportion of minerals present, in the type of ferromagnesian minerals and in the distribution of accessories. This mineralogical variability is reflected in the chemistry, but no great differences are evident in the suites as a whole.

GEOLOGY OF THE RED SEA HILLS COMPLEXES

The Red Sea Hills of Egypt and the Sudan extend parallel to the coast for several hundreds of kilometres and are made up of volcano-sedimentary-ophiolite sequences intruded by synorogenic batholithic granitoids, which together form the Neoproterozoic Nubian Shield (Vail 1988). Intruded into these rocks are numerous post- and anorogenic complexes, several of which have been studied in detail (Klemenic 1987) and some of which have been isotopically dated (Vail 1990).

For the present study a newly investigated complex, which occurs on the western side of the main Red Sea Hills and on the eastwards extension of the North Kordofan-Bayuda Desert line of complexes, has been selected for analysis. This is the Erba Ring complex (Elnour 1991) (Fig 6). It comprises two distinct centres - the southern Erbab structure of diorite and arfvedsonite granite intruded by biotite granite and the smaller northern Saluweb intrusion of aegirine-augite granite, biotite granite and trachytic and rhyolitic dykes. Chemically they both show within-plate alkaline characteristics. Mineralogically the rocks are composed of variable amounts of quartz, K-feldspar much of which is perthitic, sodic pyroxene and arfvedsonitic amphibole. Iron ores and minor amounts of calcite, fluorite, sphene, apatite and zircon are accessories. Biotite and plagioclase may be more dominant in some rocks, whereas in contaminated varieties near the contact with the diorites, andesitic plagioclase, biotite and hornblende are well developed.

RB-SR ISOTOPIC ANALYSES AND AGE DETERMINATIONS

Whole rock analyses by the Rb-Sr method have been made on 98 samples from 13 anorogenic complexes using standard isotopic techniques and the results presented in a number of tables and figures. For details of the analytical procedure see Einfalt *et al.* (1993). The blanks for the procedure as a whole typically yielded values of 0.6 ng Sr and 0.4 ng Rb. Experimental errors of ±2% for the ^{87}Rb/^{86}Sr ratio and ±0.06% for the ^{87}Sr/^{86}Sr isotopic ratio at the 95% confidence level were estimated from the standard deviation of replicate analyses on samples and on the K-feldspar standard NBS 607, which was measured to 147.7±1.5 ppm ^{87}Rb, 6.025±0.015 ppm ^{86}Sr and ^{87}Sr/^{86}Sr=1.2010±0.0005. The IUGS recommended constants (Steiger and Jäger 1977) were used for calculations involving the measured isotopic data. Isochron calculations were carried out using the ISOPLOT program of Ludwig (1992). In cases where the data sets define errorchrons, *i.e.* MSWD >2, model 3 of the ISOPLOT program was used for the calculation of the isochron data. This model assumes that the scatter of the data points is due to a combination of the analytical errors plus an unknown normally-distributed variation in the initial Sr ratios (R_i). All errors are given as 95% confidence-limit errors.

To demonstrate the scatter of the sample points around the regression line, in the sub diagrams below the isochron plots (Figs. 3, 4 and 5) the weighted deviations of the sample points from the isochron (CHI) are plotted versus the ^{87}Rb/^{86}Sr ratio. CHI is defined by the formula:

CHI=$(y_i-a*x_i-b)/SQRT(\sigma y_i^2+a^{2}*\sigma x_i^2)$,where y_i=^{87}Sr/^{86}Sr, x_i=^{87}Rb/^{86}Sr, σy_i, σx_i are the measured ratios and errors of the i-th sample and y=a*x+b is the equation of the isochron.

Northern Kordofan Province

Five groups of samples have been analysed (Table 1). The westernmost two complexes, Abu Asal and Katul, are similar in composition. If the eight samples are combined they yield a Middle Jurassic age of 162.7±3.7 Ma, R_i=0.7035±0.0006, MSWD=4.1 (Fig. 3a). Umm Durag has provided a six-point regression line indicating an Early Jurassic age of 193.9±9.2 Ma with R_i=0.7082±0.0021 and MSWD=20 (Fig. 3b). Haraza is a heterogeneous complex made up of several distinct parts, which might in themselves be separate and different complexes. However, of necessity the eleven samples have been combined with consequential scatter about the regression line to yield an errorchron showing 205.5±5.2 Ma and R_i=0.7125±0.0039, MSWD=8.8 (Fig. 3c). The high Sr initial ratios for Haraza and Umm Durag suggest that the regression lines are rotated and therefore the isochron dates should be interpreted as giving minimum ages for the intrusion. For Haraza this is supported by somewhat higher K/Ar dates for feldspars and sericite of 221 Ma (Müller-Sohnius and Horn 1994).

The three complexes that make up the Nahd (Nehud) group have yielded similar Early Permian ages in the range 270-280 Ma, which is significantly older than the previously mentioned complexes. The regression lines (Fig. 3d-f) yielded 268.7±6.5 Ma, R_i=0.7064±0.0024, with MSWD=17 for En Nahd er Rihani, 270.3±3.5 Ma, R_i=0.70488±0.00041, MSWD=0.2 for En Nahd es Sidani, and an apparent age of 280±14 Ma, R_i=0.7039±0.0036, MSWD=14.4 for the syenites and gabbros of Jebel Nus. The gabbros (MK 42, JVK 14) fit the regression line of the syenites, indicating that the gabbros belong to the intrusive suite of the complex (Fig. 3f). If all the syenite samples from the three complexes are regressed together in one errorchron the resulting age is 270±5 Ma, R_i=0.7060±0.0017 (MSWD=12.4).

Of the seven North Kordofan complexes analysed, Abu Hadid stands out as conspicuously older. Eight samples have yielded a regression line age of 441±10

Table 1. Rb-Sr isotopic data for North Kordofan anorogenic complexes, Sudan.

Sample No.	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$ [a]	$^{87}Sr/^{86}Sr$ [a]
J. Katul				
JVK 1	1.228	326.52	0.011	0.70282
JVK 2	81.01	56.670	4.143	0.71337
JVK 3	76.11	50.052	4.406	0.71421
JVK 5	136.33	15.937	24.907	0.76176
JVK 6	169.19	119.61	4.098	0.71333
JVK 8	192.17	8.322	67.896	0.85877
Abu Asal				
JVK 11	44.44	132.65	0.9702	0.70534
JVK 12	59.02	69.976	2.442	0.70883
J. Umm Durag				
MK 46	181.23	126.27	4.162	0.72107
MK 48B*	201.53	59.131	9.899	0.73827
MK 50A	101.45	111.06	2.647	0.71416
MK 53	242.76	17.812	37.876	0.81206
MK 114	179.99	84.872	6.151	0.72418
MK 115	195.24	53.127	10.696	0.73851
MK 117	150.10	20.801	21.012	0.76639
J. Haraza				
Sania				
JVK 42	186.84	9.603	57.316	0.88480
JVK 45	155.77	8.212	55.802	0.87051
MK 139*	262.70	17.539	43.873	0.82563
	262.38	17.539	43.823	0.82511
MK 140	207.60	9.988	61.288	0.89503
MK 141	211.62	40.422	15.235	0.75727
MK 143C	149.14	46.865	9.244	0.73926
Karos				
JVK 48	285.19	6.665	128.56	1.09140
Kalengei				
JVK 51	196.94	18.945	30.368	0.79779
JVK 52	217.73	14.916	42.831	0.83951
Haraza				
JVK 47	189.77	6.114	92.292	0.98110
JVK 50	231.71	10.142	67.435	0.90498
J. En Nahd er Rihani				
MK 14	137.42	100.91	3.948	0.71923
	129.37	100.61	4.033	0.71938
MK 16	137.63	6.711	60.737	0.93930
	1137.95	6.737	60.635	0.93824
MK 17	120.37	27.655	12.666	0.75877
	122.53	27.521	12.959	0.75901
MK 18B	104.06	14.084	21.567	0.79075
	104.56	14.053	21.722	0.79089
MK 19A	76.50	46.051	4.818	0.72435
	77.48	45.937	4.892	0.72413
JVK 21	199.02	16.023	36.453	0.84419
	201.46	15.949	37.060	0.84414
J. En Nahd es Sidani				
MK 20A	81.37	56.681	4.162	0.72095
MK 29	97.78	4.541	63.775	0.94865
MK 30	125.88	7.902	46.921	0.88610
MK 31	114.23	16.459	20.255	0.78290
MK 32	73.14	96.339	2.200	0.71329
J. Nus				
MK 38	56.09	250.46	0.6483	0.70747
MK 39B	91.22	8.783	29.576	0.82120
	87.69	8.762	29.304	0.82133
MK 40	98.77	13.586	21.223	0.79223
	99.97	13.524	21.578	0.79246
JVK 15	101.41	12.729	23.266	0.79079
JVK 17	75.64	20.653	10.644	0.74446
gabbro				
MK 42	21.60	540.13	0.1157	0.70414
JVK 14	18.00	528.76	0.09864	0.70416
J. Abu Hadid				
MK 66	51.18	70.37	2.1085	0.71793
MK 70	179.0	9.947	53.797	1.03531
MK 83B	108.7	14.870	21.431	0.83723
MK 83C	71.27	181.04	1.1406	0.71113
MK 86	116.0	3.720	95.466	1.29524
MK 87A	68.76	14.747	13.617	0.79288
MK 87B	126.3	3.548	110.05	1.40071
MK 88	124.3	5.127	73.464	1.17695

[a] Analytical precision at the 95% confidence level: d($^{87}Rb/^{86}Sr$) = ±2% and d($^{87}Sr/^{86}Sr$) = ±0.06%
Samples marked with an asterisk are not included in the calculation of the isochron parameters.

Ma, with R_i=0.7043±0.0069, MSWD=4.9 (Fig. 3g). The initial ratio is not significantly different from the most reliable values for the other North Kordofan complexes, 0.704 compared to 0.704-0.706, nor does it stand out for its mineralogy or geochemistry. However, in its Late Ordovician age and isotopic character Abu Hadid is comparable with the Abu Tuleih Complex in the Sabaloka inlier on the Nile (Klemenic 1983; Harris *et al.*, 1983) which lies north-eastwards of the Kordofan line (Fig. 6).

Recently an investigation by K-Ar analyses has been made of several of the Kordofan complexes (Müller-

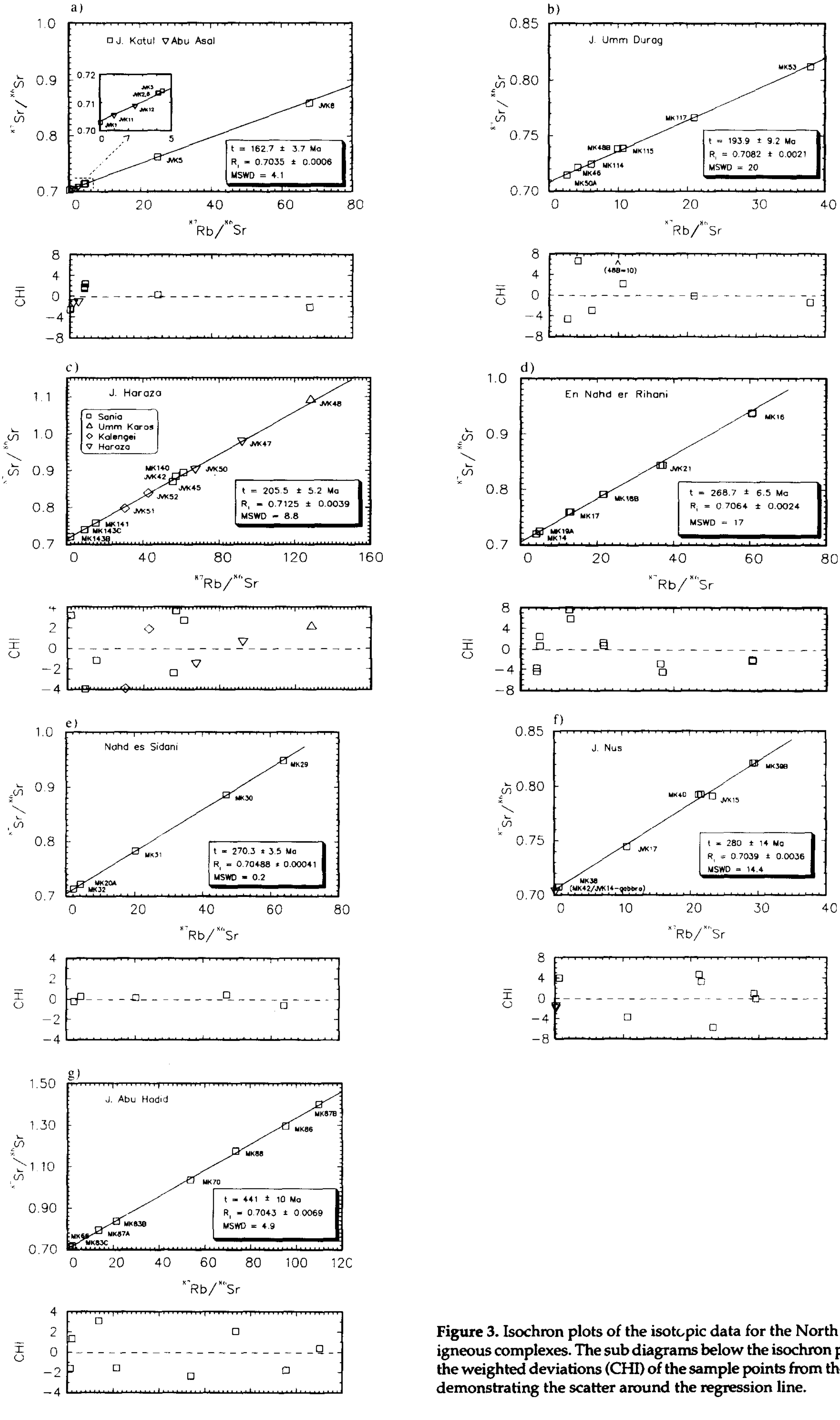

Figure 3. Isochron plots of the isotopic data for the North Kordofan igneous complexes. The sub diagrams below the isochron plots show the weighted deviations (CHI) of the sample points from the isochron demonstrating the scatter around the regression line.

Sohnius and Horn 1994) and the preliminary results have been published (Schandelmeier and Richter 1991). The measured Mesozoic ages compare well with those reported here. Alkali granite from Katul gave an average age of 168±6 Ma; Haraza 221 Ma (feldspar), Nahd er Rihani: 278±9 Ma (hornblende and biotite), Nahd es Sidani: 281±12 Ma (hornblende) and J. Nus: 280±9 Ma (biotite and plagioclase). In addition, a rhyolite and a trachyte from south of Umm Badri in the extreme west of the belt gave a whole rock K-Ar apparent age of 206±8 Ma and 214±8 Ma respectively, while the El Hursh complex north of the alignment gave a hornblende age of 221±8 Ma. It is also noted that the other nearest complex to the east, Silietat es Sufr, in the Sabaloka inlier, has been dated at 165±4 Ma by K-Ar (reported in Vail 1990) and at 169±2 Ma, R_i=0.7091±0.0025, MSWD=4.5 (2 σ) by Klemenic (1983).

Nubian Desert complexes

Four complexes have been dated in this programme from the east side of the Nile valley, and the results presented in Table 2. They generally have yielded lower MSWD values than the Kordofan analyses and the regression lines can mostly be accepted as isochrons. The Kuror complex, if the Sample ZVH 1 is omitted, provides a six point isochron age of 250.1±5.2 Ma, R_i=0.7043±0.0020, MSWD=3.1 (Fig. 4a).

The next dated complex to the north is Tarag, the regression of all samples for which yielded 260.7±7.6 Ma, R_i=0.70321±0.00026, MSWD=3.3. However, because three samples have nearly the same Rb/Sr ratios the age is derived from a virtual four point regression line. The slope of the regression line changes significantly if one or the other of the samples with higher Rb/Sr ratios (ZVH 11, ZVH 12) is omitted, yielding 257±8 Ma, MSWD 0.14 (omitting ZVH 11) and 289±18 Ma, MSWD=0.70 (omitting ZVH 12), (Fig. 4b). Both samples are medium to coarse-grained alkali syenites consisting of perthitic feldspar laths, large, bright green aegirine augite, brown hornblende, bluish amphibole, apatite and iron ore. ZVH 11 shows some signs of alteration and may represent a somewhat disturbed Rb-Sr system. Therefore, we consider the lower date as a better estimate for the age of the Tarag complex.

The samples from the Ago complex in the Nile valley have produced a good six point isochron with a Permian age of 265±12 Ma, R_i=0.7032±0.0011, MSWD=1.8 (Fig. 4c). A few kilometres to the north the Ataliya ring complex has provided a nine point isochron indicating 297.0±6.1 Ma, R_i=0.7029±0.0004, MSWD=1.8, which is

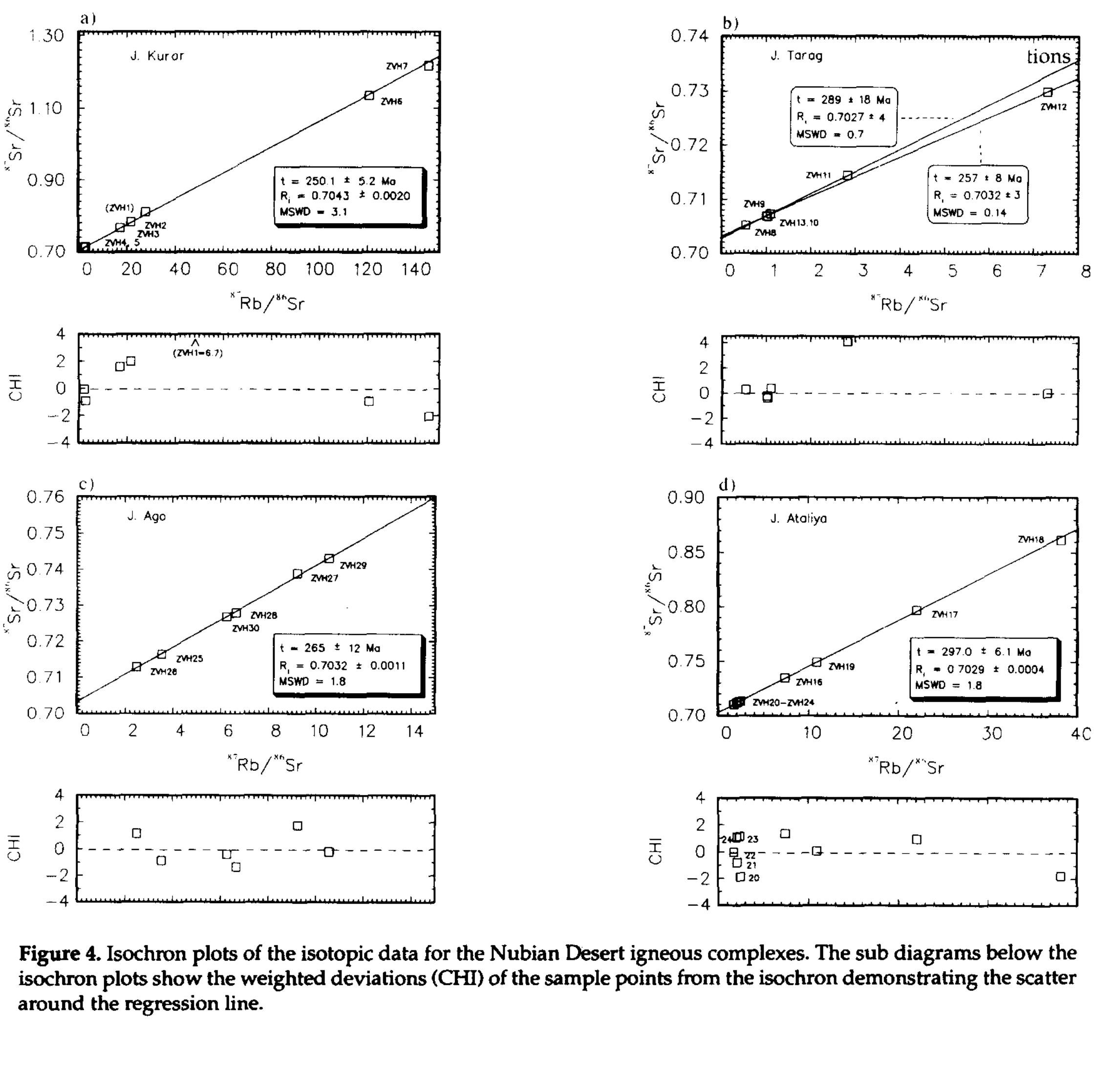

Figure 4. Isochron plots of the isotopic data for the Nubian Desert igneous complexes. The sub diagrams below the isochron plots show the weighted deviations (CHI) of the sample points from the isochron demonstrating the scatter around the regression line.

Table 2. Rb-Sr isotopic data for the Nubian Desert - Nile Valley anorogenic complexes, Sudan.

Sample No.	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr^{a}$	$^{87}Sr/^{86}Sr^{a}$
J. Kuror				
ZVH 1*	120.29	12.605	27.916	0.81100
ZVH 2	53.70	7.228	21.674	0.78310
ZVH 3	103.27	17.563	17.125	0.76614
ZVH 4	93.08	130.68	2.063	0.71083
ZVH 5	87.38	95.285	2.657	0.71277
ZVH 6	115.33	2.883	120.67	1.13392
ZVH 7	107.16	2.237	145.61	1.21708
J. Tarag				
ZVH 8	40.67	221.37	0.5319	0.70515
ZVH 9	43.09	113.08	1.1034	0.70726
ZVH 10	37.84	106.48	1.0290	0.70682
ZVH 11*	42.70	43.792	2.8257	0.71444
ZVH 12	46.86	18.606	7.3101	0.72985
ZVH 13	56.58	161.64	1.0136	0.70680
J. Ago				
ZVH 25	68.91	56.492	3.5354	0.71641
ZVH 26	65.83	76.796	2.4834	0.71293
ZVH 27	69.62	21.889	9.2387	0.73888
ZVH 28	78.51	34.252	6.6505	0.72794
ZVH 29	85.58	23.531	10.569	0.74308
ZVH 30	77.65	35.970	6.2629	0.72680
J. Ataliya				
ZVH 16	103.31	40.368	7.4304	0.73478
ZVH 17	115.70	15.311	22.074	0.79712
ZVH 18	178.96	13.759	38.233	0.86159
ZVH 19	149.49	39.693	10.950	0.74918
ZVH 20	85.65	99.313	2.4987	0.71297
ZVH 21	57.58	80.106	2.0822	0.71147
ZVH 22	80.95	136.44	1.7184	0.71011
ZVH 23	60.14	74.168	2.3496	0.71305
ZVH 24	56.34	80.189	2.0355	0.71170

[a] Analytical precision at the 95% confidence level: $d(^{87}Rb/^{86}Sr) = \pm 2\%$ and $d(^{87}Sr/^{86}Sr) = \pm 0.06\%$
Samples marked with an asterisk are not included in the calculation of the isochron parameters.

Late Carboniferous (Fig. 4d). These data can therefore be compared with the North Kordofan ages reported above. On the other hand the only other isotopically dated complex in the vicinity is the small syenite intrusion west of the Nile near the Third Cataract, named the Sheikh ring complex, which yielded a Rb-Sr errorchron with an age of 103±14 Ma (Franz *et al.*, 1993). Recent K-Ar analysis of syenites and trachytic dykes here have yielded ages of 87±2 Ma and 86±1 Ma (Müller-Sohnius and Horn 1994). The K-Ar and Rb-Sr ages obtained from complexes in the south-eastern part of the Egyptian Eastern Desert (summarized by Serencsits *et al.*, 1981) will be considered later.

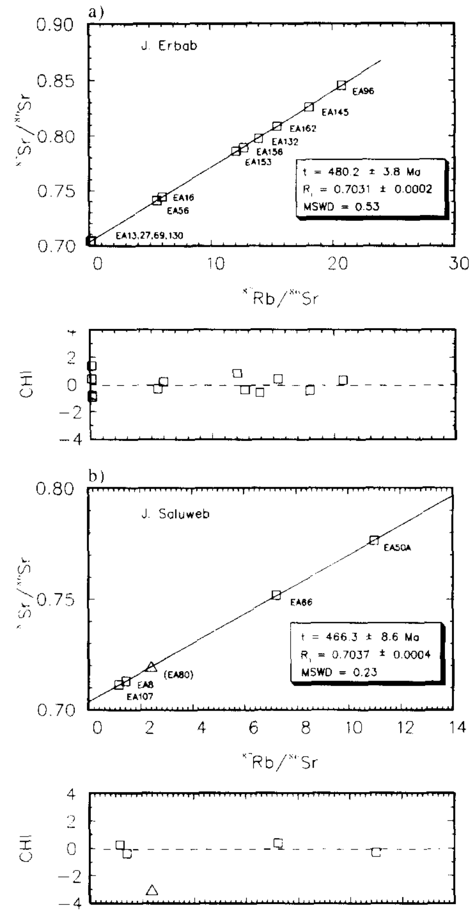

Figure 5. Isochron plots of the isotopic data for the Erba igneous complex, Red Sea Hills. The sub diagrams below the isochron plots show the wieghted deviations (CHI) of the sample points from the isochron demonstrating the scatter around the regression line.

The Red Sea Hills igneous complexes

The Erba complex in the Red Sea Hills has been studied in some detail (Elnour 1991) and a number of samples analysed isotopically (Table 3). The larger of the two centres, Jebel Erbab, comprising fine and coarse-grained granites and older diorites, has provided a twelve point isochron giving an Early Ordovician age of 480.2±3.8 Ma, R_i=0.7031±0.0002, and MSWD=0.53 (Fig. 5a). The smaller, northern Jebel Saluweb ring has yielded a four point isochron indicating a Middle Ordovician age of 466.3±8.6 Ma, R_i=0.7037±0.0004, MSWD=0.23 (Fig. 5b). These dates are more nearly comparable with Abu Hadid in Kordofan and with other intrusions in the Red Sea Hills than with the Nubian desert complexes.

Age results from SE Egypt

Seven of the igneous complexes aligned ENE along the Egyptian border with the Sudan have been analysed by various methods and reported in the literature (Lutz *et al.*, 1978; Hashad and El Reedy 1979; Serencsits *et al.*, 1981; de Gruyter and Vogel 1981; Omar *et al.*, 1987). Since they are a direct continuation of the Nubian Desert province of the Sudan, the results are worth repeating here. They range from the Middle Carboniferous to the

Early Cretaceous, from west to east as follows: Mansouri 132±10 Ma (Rb-Sr); El Gezira 229±5 Ma (K-Ar); El Naga 146±4 Ma (K-Ar), 146±6 Ma (Rb-Sr); Mishbeh 142±3 Ma (K-Ar), 145±12 Ma (Rb-Sr); Shabih 191±7 Ma (fission track); Nigrub el Fogani 139±3 Ma (K-Ar), 141 Ma (Rb-Sr); Nigrub el Tahtani 140 Ma (K-Ar), 140±9 Ma (Rb-Sr). All the complexes are supposed to lie along a lineament, which is the landward extension of a transform fault in the Red Sea (Garson and Krys 1976).

DISCUSSION

The results of the present investigation have shown a number of age groups for the various igneous provinces studied. In keeping with other known and dated complexes in the Sudan and neighbouring areas, it has been found that there is a wide range of ages of emplacement, not only within one province, but between adjacent complexes and even within a single complex. This is most likely accounted for by repeated injections of magma, but in some instances it may be due to contamination or geochemical/isotopic irregularities. In all cases where the initial Sr ratios of the alkaline ring complexes are precisely defined the values lie in a remarkable narrow range from 0.703 to 0.706 independently of the intrusion age of the complexes (Barth *et al.*, 1983; Curtis and Lenz 1985; *this paper*). These consistently low initial Sr ratios found for the igneous complexes, intruded from Ordovician to Cretaceous times in a spacial range of *ca* 1600 km from the Nuba Mountains in the south to as far as the Red Sea Hills in the north, testify to the deep seated influence of crustal fractures which enabled mantle magmas, without significant contamination by much older continental crust, to penetrate close to the surface.

Table 3. Rb-Sr isotopic data for the Erba anorogenic complex, Red Sea Hills, Sudan.

Sample No.	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr^{a}$	$^{87}Sr/^{86}Sr^{a}$
J. Erbab				
fine grained granites				
EA 16	167.43	81.177	5.9946	0.74420
EA 56	138.27	72.622	5.5318	0.74080
EA 96	181.90	25.733	20.746	0.84548
EA 156	169.66	39.054	12.681	0.78950
EA 162	154.63	29.371	15.397	0.80888
coarse grained granites				
EA 132	120.94	25.390	13.916	0.79771
EA 145	78.05	12.681	18.028	0.82588
EA 153	122.75	29.702	12.059	0.78631
gabbros and monzonites				
EA 13	23.25	447.75	0.1470	0.70393
EA 27	29.76	571.43	0.1508	0.70393
EA 130	33.14	593.09	0.1618	0.70449
EA 69	21.78	613.40	0.1028	0.70388
J. Saluweb				
quartz syenites				
EA 8	46.75	95.294	1.4215	0.71304
EA 50A	57.50	15.240	10.999	0.77651
EA 66	87.91	35.409	7.2203	0.75185
EA 107	39.79	100.02	1.1525	0.71140
trachyte				
EA 80*	47.02	57.156	2.3846	0.71886

[a] Analytical precision at the 95% confidence level: $d(^{87}Rb/^{86}Sr) = \pm 2\%$ and $d(^{87}Sr/^{86}Sr) = \pm 0.06\%$
Samples marked with an asterisk are not included in the calculation of the isochron parameters.

In keeping with other areas, both the North Kordofan and the Nubian Desert complexes show a broad alignment along parallel, ill defined bands trending ENE across several hundreds of kilometres. Within each province there is also a more local yet strongly developed NNW trend and in some cases a migration of centres in this direction. Progressive temporal emplacement is not clearly evident, although there is a tendency for a progression of general location with time, blurred by the heterogeneity of the various provinces.

The ages of emplacement in the North Kordofan province are apparently in three groups, Abu Hadid at around 441 Ma, the Nahd group about 280-270 Ma, and the others between about 220-163 Ma. These events compare with the 478-452 Ma intrusions of Abu Tuleih, the 460-439 Ma age of the Qeili complex, and the 169-164 Ma dates from Sulietat es Sufr in the Sabaloka inlier and Butana of central Sudan (Vail 1990), all of which lie on the eastwards extension of the Kordofan line and all of which are considered to have been emplaced within the continental crust of the Sudan Shield (Fig. 6).

The Nubian Desert province, at least those complexes isotopically dated along the east of the Nile, provided results between 265 and 253 Ma, with the Ataliya complex yielding an age of 297 Ma, while an age of 103-87 Ma has been reported from the Sheikh intrusion. Some of these emplacements must have been contemporary with those in the Nuba Mountains of Southern Kordofan (Curtis and Lenz 1985; Batyrmurzaev *et al.*, 1982). There is also a possibility that the NNW aligned band of complexes in the Bayuda Desert (J. Sultaniyat, J. Ras Ed dom, J. Abu Dom) with ages of 243 to 233 Ma (recalculated from Barth *et al.*, 1983; Almond *et al.*, 1983) may have been an extension along the same trend through the Tarag, Kuror and Mansouri line, at least since 261 Ma or earlier. Of similar interest is whether the intrusions in the east in southern Egypt are an extension of those near the Nile in the western Nubian

Desert. The former show no noticable age progression, although they might range from 229 Ma to 142 Ma from El Gezira to Nigrub el Fogani near the coast 150 km further east (El Ramly and Hussein 1985) and might be considered to reflect a continuation of the age trend of 265 Ma and 253 Ma from the present work.

Attention was drawn to the perceived episodic nature of the igneous activity in Egypt by Lutz (1979), in which a periodicity of 51 Ma was supposed to separate many of the emplacement events. This was further investigated by Serencsits *et al.* (1981) and discussed by El Ramly and Hussein (1985). Missing events from the predicted cycle of multiples of 51.6 Ma plus 38 Ma could now be filled for the 191 Ma event by the Shabieh (191±7 Ma) date (Omar *et al.*, 1987), the 245 Ma event by Kuror (250±5.2 Ma), and the 296 Ma event by Ataliya (297±6 Ma), reported in this paper.

It is clear, however, that the igneous activity in the Sudan appears to be essentially continuous from the Neoproterozoic to the Cenozoic. There are, nevertheless, some periods of increased activity, illustrated by the distribution of available radiogenic ages from the non-orogenic intrusive and extrusive events in the area (Fig. 7). Late to post-orogenic granites were mainly intruded in the period 700 Ma to 500 Ma, with a pronounced peak around 540 Ma. Anorogenic magmatism in the form of alkaline complexes commenced around 580 Ma, with three main periods of activity at 480-350 Ma, 280-220 Ma, and 170-120 Ma. In the Cenozoic, mid-plate basaltic rocks occurred about 90-60 Ma, 26-20 Ma, and 5-0.06 Ma.

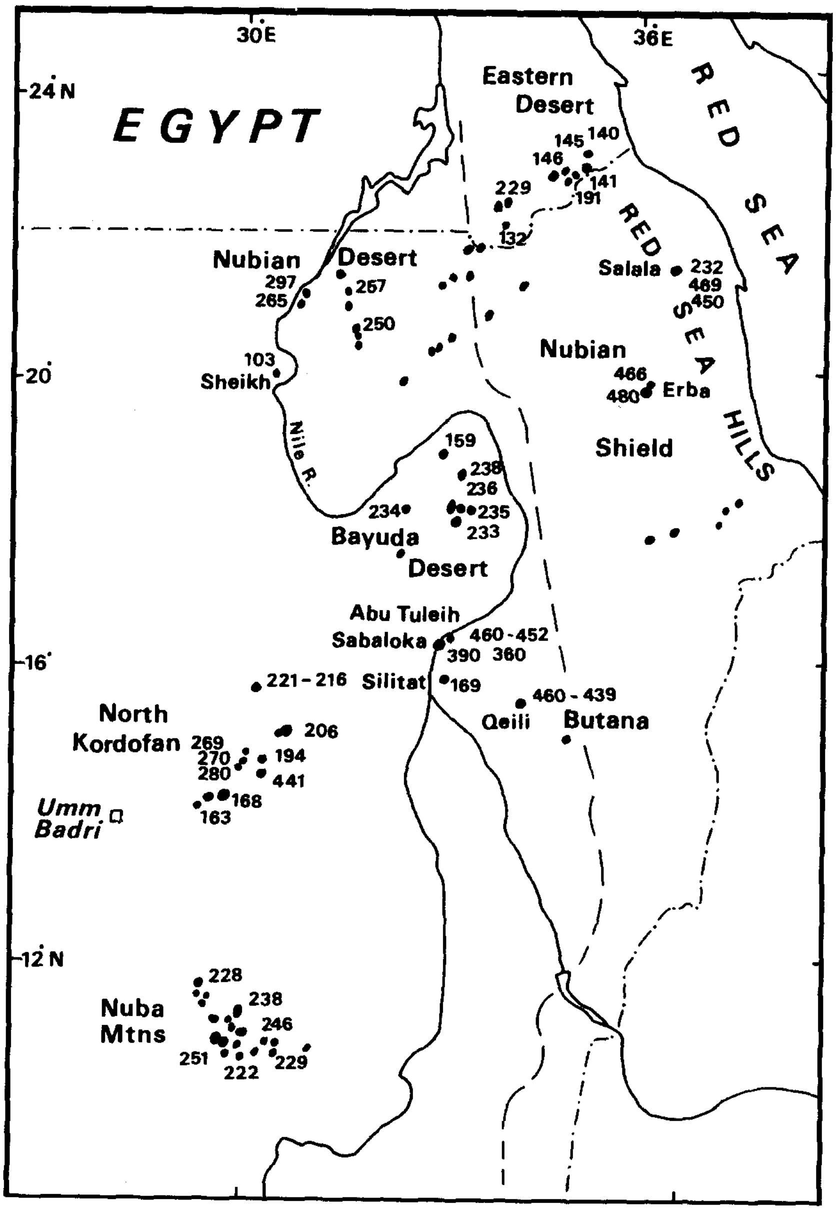

Figure 6. Distribution of selected anorogenic igneous complexes in the Sudan and southern Egypt, showing isotopic age of apparent emplacement. Broken lines indicate W limit of oceanic greenschist terrane; solid lines Nile drainage and Red Sea coast.

The Egyptian complexes have been intruded through the oceanic crust of the Nubian-Arabian shield, but there is uncertainty about whether the Sudanese Nubian Desert complexes are also emplaced in oceanic crust or through continental basement because there is a detached block of volcano-sedimentary greenschists, comprising the Halfa Terrane (Vail 1988), forming a narrow strip along the Nile valley. The tectonic units hereabouts have recently been redesignated by Schandelmeier *et al.* (1993).

There is no such doubt about the tectonic environment of the Red Sea Hills complexes as they were all emplaced into the oceanic volcano-sedimentary-ophiolitic greenschist assemblage of the Nubian Shield. The Erba complex (482-465 Ma) compares, not only in age with the Abu Tuleih results (Harris *et al.*, 1983), but also with some of the late tectonic magmatic events elsewhere in the Red Sea Hills, such as at the Salala ring complex (Vail 1990).

Liegeois *et al.* (1991) and Black and Liegeois (1993) have described somewhat similar anorogenic alkaline magmatism from the eastern margins of the West African Craton, where they concluded that the emplacement of the intrusive centres was influenced by fractures associated with earlier plate tectonic events between oceanic mobile belts and continental crustal cratons. The composition of the magmas was influenced by the underlying lithosphere, a point made also by Klemenic (1987) when he contrasted the Rb-Sr initial ratios of material emplaced through continental crust, in the Sabaloka inlier and, through oceanic crust, in the Red Sea Hills. The location of the igneous complexes in the Sudan has been controlled by two different tectonic lines of weakness. A dominant ENE trend follows fold trends in the basement, e.g. in the Bayuda Desert (Barth and Meinhold 1981; Meinhold 1983), as well as crustal fractures identified from surface features (Schandelmeier and Richter 1991) and by geophysics (Browne *et al.*, 1985), which delineated the rifted basins of southern Sudan from the eastern Sudan Swell in the north. At almost right angles to this is the NNW trend of many igneous centres (Vail 1985), which partly

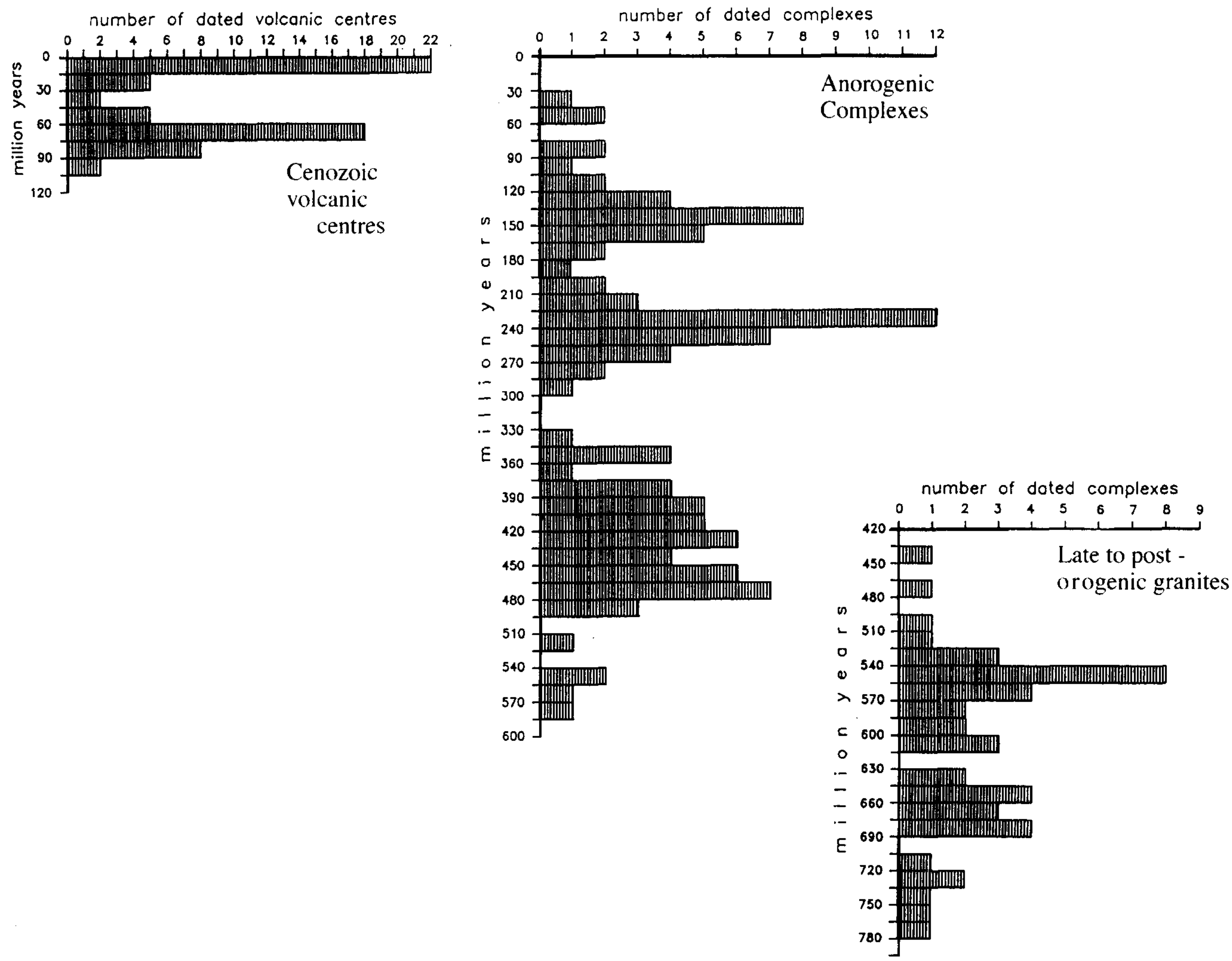

Figure 7. Histogram plot of ages of igneous activity in the Sudan.

parallels the western margin of the oceanic plate of the Nubian-Arabian Shield, which probably in turn influenced the axis of the Red Sea and the NW trending rift basins of the southern Sudan. These conjugate zones of weakness in the crust enabled magmas from the upper mantle to penetrate to the surface where they were emplaced as volcanoes, only the plutonic roots of most of which are preserved today as the igneous complexes sampled here.

Acknowledgements

The authors thank Dr J. Menuge and D. Müller-Sohnius for their critical comments and the Director and staff of the Geological Research Authority of the Sudan for assistance with the collection of the samples in the field.

REFERENCES

Almond, D.C. 1977. The Sabaloka igneous complex, Sudan. *Philosophical Transactions Royal Society* **A287**, 595-633.

Almond, D.C., Curtis, P.A.S., McCormac, M., O'Halloran, D.A. and Vail, J.R. 1983. Migrating Younger Granite ring complexes in the Bayuda desert, northern Sudan. *Bulletin Faculty Earth Science King Abdulaziz University, Jeddah* **6**, 271-276.

Barth, H., Besang, C., Lenz, H. and Meinhold, K.D. 1983. Results of petrological investigations and Rb/Sr age determinations of the non-orogenic igneous ring-complexes in the Bayuda Desert, Sudan. *Geologisches Jahrbuch* **B51**, 3-35.

Batyrmurzayev, A.S., Trofimov, N.N., Shakhpazov, I.M., Ahmed, F., Khalil, B.E., Zakieva, F.S., Gadzhiyev, S.V. and Slyunyaev, A.A. 1982. The absolute age of minerals in certain Sudanese petrographic provinces (in Russian). In: *Mobile Belts and Deposits: A collection of scientific papers*. Academy of Sciences, pp30-36. Patrice Lumumba University, Moscow.

Black, R. and Liegeois, J-P. 1993. Cratons, mobile belts, alkaline rocks and continental lithospheric mantle: the Pan-African testimony. *Journal Geological Society* **150**, 89-98.

Browne, S.E., Fairhead, J.D. and Mohamed, I.I. 1985. Gravity study of the White Nile Rift, Sudan, and its regional tectonic setting. *Tectonophysics* **113**, 123-137.

Curtis, P.A.S. and Lenz, H. 1985. Geological and geochronological investigations of selected alkali igneous complexes in the Nuba Mountains, Southern Kordofan, Sudan. *Geologisches Jahrbuch* **D69**, 3-24.

De Gruyter, P. and Vogel, T.A. 1981. A model for the origin of the alkaline complexes of Egypt. *Nature* **291**, 571-574.

Einfalt, H.C., Hoehndorf, A. and Kaphle, K.P. 1993. Radiometric age determination of the Dadeldhura Granite, Lesser Himalaya, Far Western Nepal. *Schweizerische Mineralogische Petrographische Mitteilungen* **73**, 97-106.

Elnetaifa, M.A.M. 1990. Anorogenic magmatism in the Sudan; petrology and petrogenesis of some alkaline complexes from Northern Kordofan Province, Sudan. *M. Phil. thesis* 160p. University of Portsmouth, U.K.

Elnetaifa M.A.M. and Vail, J.R. 1989. Progress of work on alkaline orogenic complexes, Northern Kordofan Province, Sudan. *Report on Activities, Geology Department, Portsmouth Polytechnic* **13**, 31-32.

Elnour, A.B.E. 1991. The geology of the Jabal Erba ring complex, Red Sea Hills, N.E. Sudan. *M. Phil. thesis* 202p. University of Portsmouth, U.K.

El Ramly, M.F. and Hussein, A.A.A. 1985. The ring complexes of the Eastern Desert of Egypt. *Journal African Earth Sciences* **3**, 77-82.

Franz, G., Harms, U., Denkler, T. and Pasteels, P. 1993. Late Cretaceous igneous activity in the Delgo uplift (Northern Province, Sudan). In: *Geoscientific research in north-eastern Africa* (Edited by Thorweihe,U. and Schandelmeier,H.) pp227-230. Balkema, Rotterdam.

Garson, M.S. and Krys, M. 1976. Geophysical and geological evidence of the relationship of Red Sea transverse tectonics to ancient fractures. *Bulletin Geological Society of America* **87**, 169-181.

Harris, N.B.W., Duyverman, H.J. and Almond, D.C. 1983. The trace element and isotope geochemistry of the Sabaloka Igneous complex, Sudan. *Journal Geological Society* **140**, 245-256.

Hashad, A.H. and El Reedy, M.W.M. 1979. Geochronology of the anorogenic alkaline rocks, south Eastern Desert, Egypt. *Annals Geological Survey of Egypt* **9**, 81-101.

Klemenic, P.M. 1983. Isotope geology and geochemistry of selected igneous complexes and basement rocks of eastern Sudan. *Ph.D thesis* 385p. University of Portsmouth, U.K.

Klemenic, P.M. 1987. Variable intra-plate igneous activity in central and north-east Sudan. *Journal African Earth Sciences* **6**, 465-474.

Liegeois, J-P., Sauvage, J.F. and Black, R. 1991. The Permo-Jurassic alkaline province of Tadhak, Mali: geology, geochronology and tectonic significance. *Lithos* **27**, 95-105.

Ludwig, K.R. 1992. ISOPLOT - A Plotting and Regression Program for Radiogenic Isotope Data. *Open File Report* **91-445**, U.S. Geological Survey.

Lutz, T.M. 1979. Strontium and Oxygen isotope relations and geochemistry of the Abu Khruq complex, Egypt. Implications for the petrogenesis of the alkaline rocks of the eastern Desert, Egypt. *Ph.D thesis*, University of Pennsylvania, U.S.A.

Lutz, T.M., Foland, K.A., Faul, H., Friedman, I. and Serencsits, C.M. 1978. Ages of Egyptian alkaline complexes and Sr and O isotope relations at the Abu Khruq Complex. *4th International Conference on Geochronology, Cosmochronology and Isotope Geology. Open File Report* **78-701**, pp265-267. U.S. Geological Survey, Denver.

Meinhold, K.D. 1983. Summary of the regional and economic geology of the Bayuda Desert, Sudan. *Bulletin Geology and Mineral Resources Department* **33**, 45p. Geology and Mineralogy Resources Department, Ministry of Energy and Mining, Khartoum.

Müller-Sohnius, D. and Horn, P. 1994. K-Ar dating of ring complexes and fault systems on Northern Kordofan, Sudan: evidence for independent magmatic and tctonic activity. *Geologische Rundschau* **83**, 604-613

Omar, G.I., Kohn, B.P., Lutz, T.M. and Faul, H. 1987. The cooling history of Silurian to Cretaceous alkaline ring complexes, south Eastern Desert, Egypt, as revealed by fission track analysis. *Earth Planetary Science Letters* **83**, 94-108.

Schandelmeier, H., Kuster, D., Wipfler, E., Abdel Rahman, E.M., Stern, R.J. Abdelraman, M.G. and Sultan, M. 1993. Evidence for a new Late Proterozoic suture in Northern Sudan. In: *Geoscientific research in north-east Africa*. (Edited by Thorweihe,U. and Schandelmeier,H.) pp83-85. Balkema, Rotterdam.

Schandelmeier, H. and Richter, A. 1991. Brittle shear deformation in Northern Kordofan, Sudan: Late Carboniferous to Jurassic reactivation of Precambrian fault systems. *Journal Structural Geology* **13**, 711-720.

Serencsits, C.M., Faul, H., Foland, K.A., Hussein, A.A. and Lutz, T.M. 1981. Alkaline ring complexes in Egypt: their age and relationship in time. *Journal Geophysical Research* **86**, 3009-3013.

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

Vail, J.R. 1985. Alkaline ring complexes in Sudan. *Journal African Earth Sciences* **3**, 51-59.

Vail, J.R. 1988. Tectonics and evolution of the Proterozoic basement of north-eastern Africa. In: *The Pan-African belt of north-east Africa and adjacent areas* (Edited by El-Gaby,S. and Greiling,R.O.) pp195-226. Vieweg, Braunschweig.

Vail, J.R. 1989. Ring complexes and related rocks in Africa. *Journal African Earth Sciences* **8**, 19-40.

Vail, J.R. 1990. Geochronology of the Sudan. *Overseas Geology and Mineral Resources*, **66**, 58p. British Geological Survey, H.M.S.O., London.

Geological Maps

Geological map of the Bayuda Desert 1:250 000. 1982. Complied by Barth,H. and Meinhold,K.D. *B.G.R.*, Hannover and *Geological Mineralogical Resources Department*, Khartoum.