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NEW GEOCHRONOLOGICAL DATA ON VOLCANIC ROCKS FROM NORTHEAST SUDAN AND THEIR IMPLICATION FOR CRUSTAL EVOLUTION

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ABSTRACT

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The basement volcano-sedimentary rocks of northeast Sudan form part of the Nubian Shield of northeast Africa. Volcanic rocks from the Kadawēb area yield Rb—Sr whole-rock isochron ages of 718 and 722 Ma and initial $^{87}Sr/^{86}Sr$ ratios of 0.7027 and 0.7029. In the Homogar area, 150 km to the south, volcanic rocks yield a Rb—Sr whole-rock isochron age of 671 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7034. Although all of these lavas have been altered by a low-grade greenschist facies event, isotopic and geochemical evidence indicates limited open system behaviour. Thus these dates most probably represent extrusive ages indicating two episodes of volcanic activity during the evolution of the Nubian Shield. These results place some important constraints on the nature of crustal evolution in northeast Africa.

INTRODUCTION

The Red Sea Hills of northeast Sudan form a marked topographic feature up to 120 km wide, bounded to the west by the Nubian Desert and to the east by the coastal plains of the Red Sea. The highlands continue north into the Eastern Desert of Egypt and extend southwards into Ethiopia. The basement complex of the Red Sea Hills comprises mixed sequences of volcanic, volcaniclastic and sedimentary rocks which have been intruded by numerous batholithic granitoids and high-level, largely sub-volcanic igneous complexes. The basement rocks have been deformed and metamorphosed and are unconformably overlain by undeformed sediments of the Nubian Sandstone Formation.

The Pre-Nubian basement rocks of northeast Sudan are lithologically and structurally similar to rocks occurring in the western shield of Saudi Arabia (Jackson, 1980) and, together with lateral equivalents in Egypt

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and northern Ethiopia, they form the Arabian—Nubian Shield (Brown and Jackson, 1960). Considerable debate has taken place concerning the age and evolution of these basement rocks. In particular discussion has concentrated on two models. The first maintains that the basement rocks of the Arabian—Nubian Shield include early Proterozoic or Archaean continental crust (Kazmin, 1975; Hepworth, 1979; Almond, 1982) while the second considers that these rocks evolved entirely within the upper Proterozoic (Gass, 1981). A considerable hindrance to this debate has been the reliance on a lithostratigraphic basis to the stratigraphy of the area and the lack of reliable geochronological data.

Recently, considerable geochronological work based on the Rb—Sr whole-rock method has shown that the basement lavas of western Saudi Arabia were formed over a period ranging from c. 1000 to 500 Ma ago (Greenwood et al., 1976; Darbyshire et al., 1983; Roobol et al., 1983). Isotopic evidence also indicates that these lavas have low $^{87}Sr/^{86}Sr$ initial ratios, generally falling within the range 0.702—0.706 (Gass, 1981). The restricted range of $^{87}Sr/^{86}Sr$ initial ratios, together with the upper Proterozoic age of these lavas, place some constraints on the nature of crustal evolution in the Arabian portion of the Shield. In particular these data raise some problems for those models which imply that the basement rocks of the Arabian—Nubian Shield include early Proterozoic or Archaean continental crust. However, these data generally support those models which suggest that the basement rocks of the Arabian—Nubian Shield evolved within the upper Proterozoic and were largely uncontaminated by ancient crustal material.

Geochronological data for the lavas of the Sudanese portion of the Nubian Shield are limited (Cavanagh, 1979; Fitches et al., 1983), but are compatible with those from the western shield of Saudi Arabia. The present work extends the range of geochronological data available from northeast Sudan and shows that the lavas studied have a similar range of $^{87}Sr/^{86}Sr$ initial ratios and that they are temporally related to the volcanic rocks occurring in western Saudi Arabia (Darbyshire et al., 1983).

REGIONAL GEOLOGY AND PREVIOUS STUDIES

Although published geochronological data on the basement rocks of northeast Sudan were scarce prior to the 1970's the rocks were generally defined as Precambrian (Whiteman, 1971). The volcano-sedimentary rocks of the basement complex have been divided into two important groups based on lithology and metamorphic grade (Ruxton, 1956; Gabert et al., 1960; Kabesh, 1962). The older Nafirdeib Series comprises andesites, tuffs and agglomerates which have been deformed and affected by greenschist-facies alteration (Ruxton, 1956). In contrast the younger Awat Series includes dacites and rhyolitic lavas which are characterised, according to Ruxton (1956), by their undeformed structure and fresh appearance. The

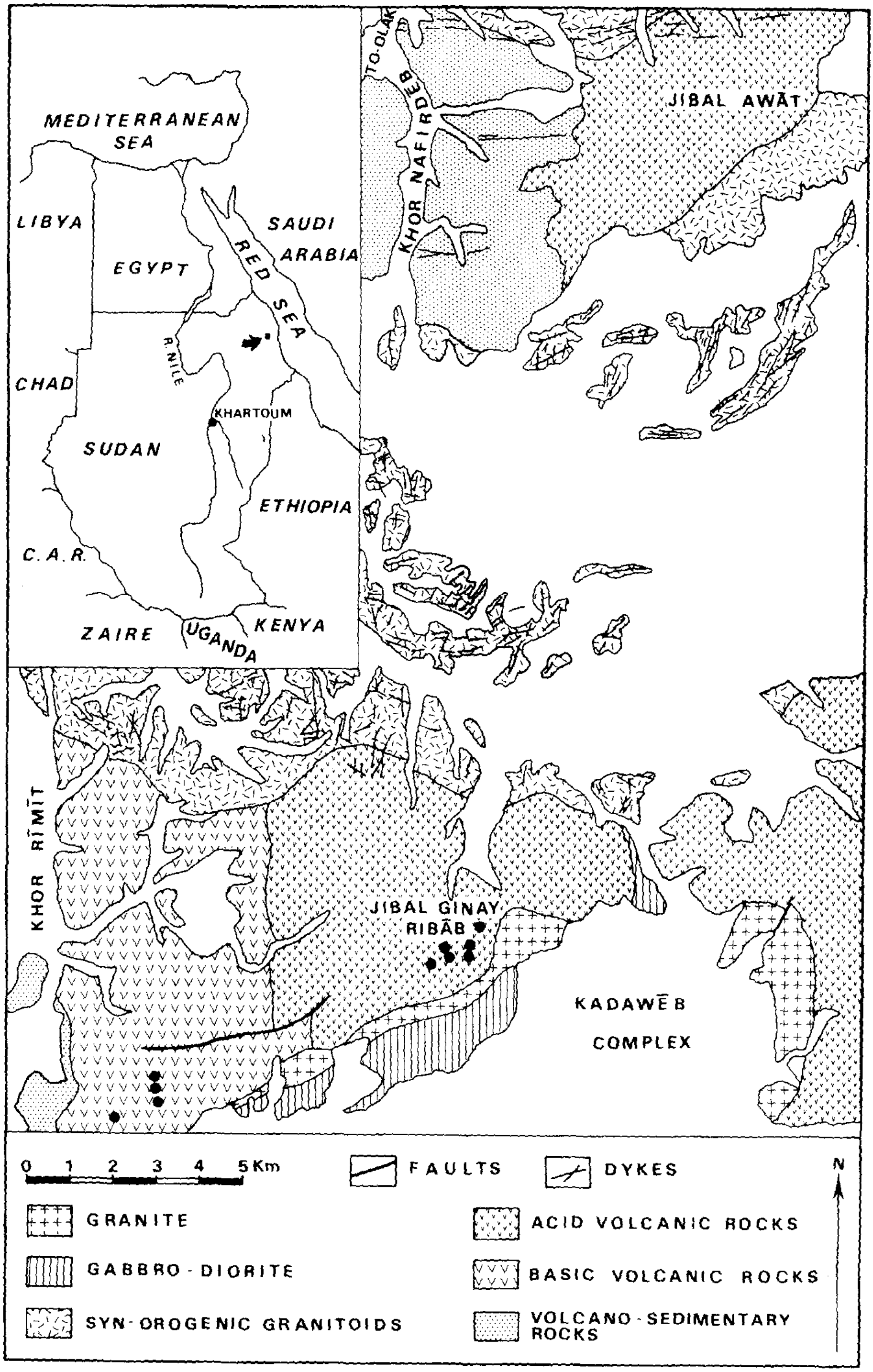
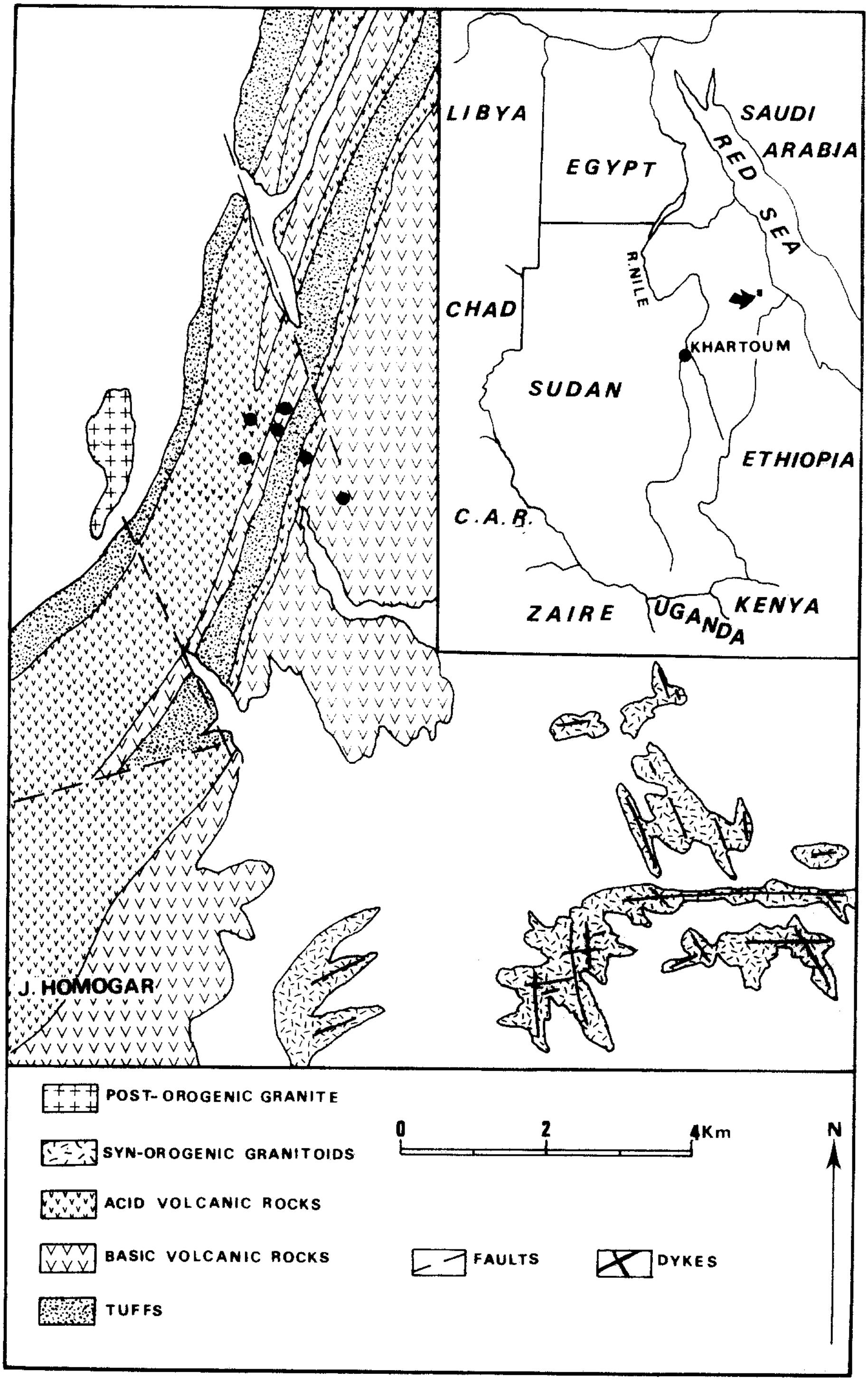


Fig. 1. Geological map of the Kadawēb Volcanic Group (modified after Klemenic and Poole, 1982; Vail et al., 1984). Closed circles show the location of samples used in this study, and the inset map indicates the location of the Kadawēb area.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basis for the identification and separation of these two series has largely remained unchanged since then, although the name given to the lithological groups may vary locally (Ali, 1979; Vail, 1979). However, many problems are encountered when attempting to recognise relative temporal variation between these complex volcanic rocks, and it is probably more realistic to restrict the lithostratigraphic divisions of the earlier workers to their type area alone (Embleton et al., 1982).

The first wide-scale geochronological study of the basement rocks of the Red Sea Hills was made during the Soviet—Sudanese project by Technoexport (1974). However, this project largely concentrated on the intrusive material and determined the relative age of the volcanic rocks on the basis of contact relationships (Ahmed, 1979). A further drawback to this study was its predominant reliance on the K—Ar whole-rock method since Vail and Rex (1970) demonstrated the likely mobility of ^{40}Ar due to a series of regional metamorphic events which affected these rocks between c. 650 and 450 Ma ago. Two recent studies have used the Rb—Sr whole-rock method, which is generally considered to be less susceptible to the effect of low-grade metamorphic overprinting (Faure, 1977). These studies have shown that the basement lavas from two volcanic groups occurring in the northern part of the Red Sea Hills are 649 and 712 Ma old, respectively (Cavanagh, 1979, Fitches et al., 1983).

During the present study basement volcanic rocks were examined in the Kadawēb and Homogar areas (Figs. 1 and 2). In the Kadawēb area a good exposure of Awat-type acid lavas had been described by Kabesh (1962), unconformably overlying Nafirdeib-type basalts and andesites. However, a recent study has shown that all of these rocks have been deformed and that greenschist facies minerals are common within both Nafirdeib and Awat type rocks (Klemenic and Poole, 1982). Consequently no clear and incontrovertible field evidence could be found to support an unconformity, although a lithological variation does occur (Fig. 1). In the Homogar area (Fig. 2) volcanic rocks occur which have been compared with the Awat Series by Ali (1979) on a regional scale but renamed the Homogar Volcanic Group locally. However, the Homogar lavas have been deformed and metamorphosed at the greenschist grade, hence it is unlikely that a regional correlation can be made between the Homogar Volcanic Group and the Awat Series of Ruxton (1956).

GEOCHRONOLOGY

Sampling and analytical procedure

Although the rocks collected from the Kadawēb and Homogar areas

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Fig. 2. Geological map of the Homogar Volcanic Group (modified after Ali, 1979). Closed circles show the location of samples used in this study, and the inset map indicates the location of the Homogar area.

have been affected by low-grade greenschist facies alteration, original minerals can be recognised (eg., olivine, augite, hypersthene and calcic plagioclase) together with primary volcanic textures and features (eg., clinkery surfaces, vesicles and phenocrysts). Thus, careful selection of samples in the field and later microscopic examination resulted in a suite of volcanic rocks which, although not pristine, represent the least altered material available for study. Variation diagrams of major elements plotted against SiO_2 do not show excessive scatter (Fig. 3) and, with the exception of P_2O_5, both the Kadawēb and Homogar lavas display broadly similar trends. Despite the alteration it is suggested that element mobility is not great and that metamorphism has not disguised the original chemical character of these lavas. The isotopic data tend to confirm this view since well fitted Rb—Sr whole-rock isochrons can be obtained with low MSWD's and low errors on the slope and intercept (Fig. 4), implying limited open system behaviour of Rb and Sr.

Lavas sensu stricto were collected (volcaniclastic and ash material was rejected), and 2—5 kg samples were considered suitable for this study. The samples were crushed to <200 mesh powder using a mechanical jaw crusher and a tungsten carbide Tema disc mill. The concentrations of Rb and Sr and the Rb/Sr ratios were determined using a Philips 1450 automatic X-ray fluorescence spectrometer after the method of Pankhurst

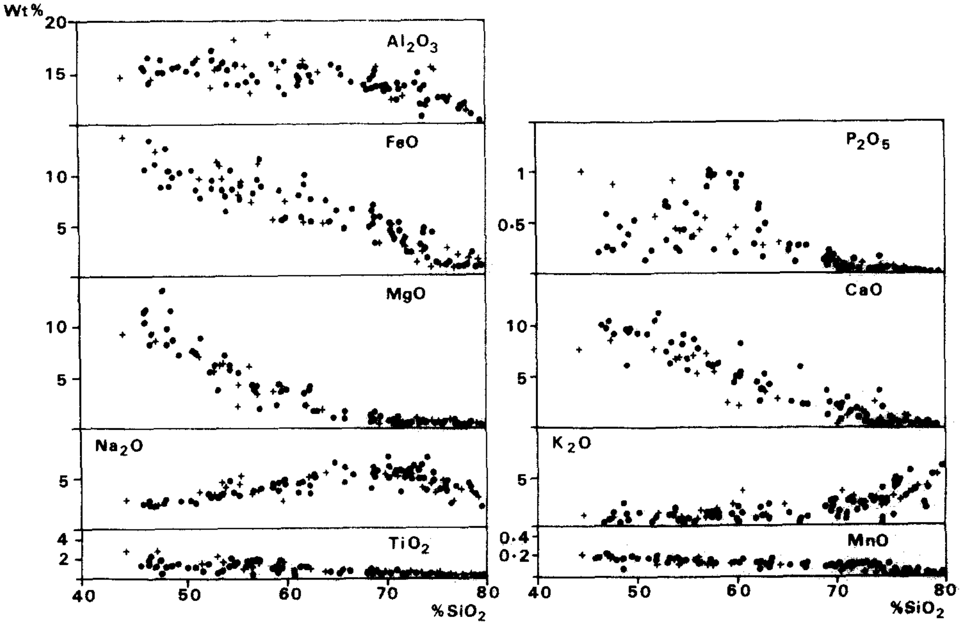

Fig. 3. Variation diagrams of the major elements plotted against SiO_2 for the Kadawēb (•) and Homogar (+) lavas. (Data from Ali, 1979; Klemenic, 1984; Klemenic and Poole, 1982).

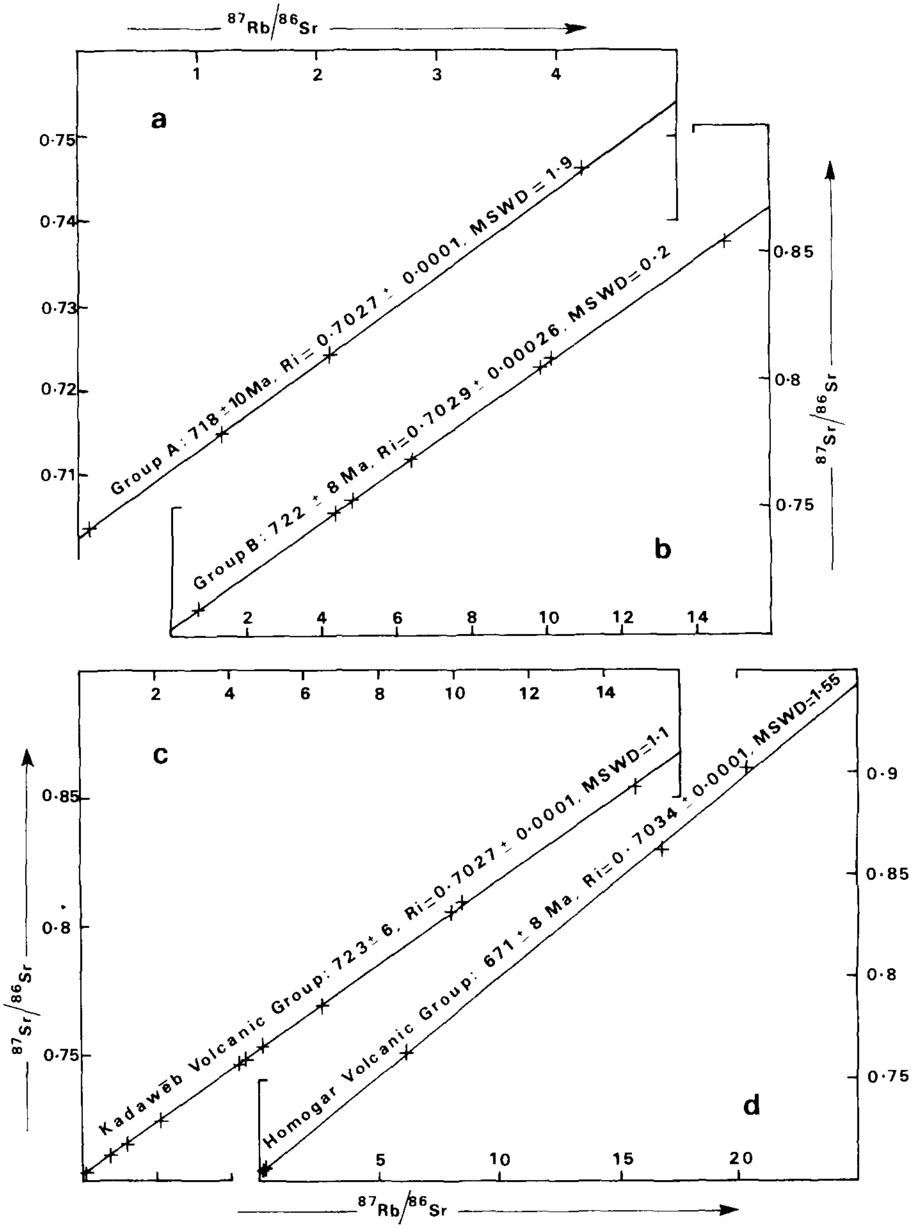

Fig. 4. Rb—Sr whole-rock isochrons of the Kadawēb lavas (a—c), and the Homogar lavas (d). Ri means initial $^{87}Sr/^{86}Sr$ ratio. Data from Table I.

and O'Nions (1973). Strontium was separated using standard dissolution methods and ion exchange procedures. Strontium was loaded onto single tantalum filaments prepared with phosphoric acid, and the isotopic composition was determined using an automatic VG Micro Mass 30 mass spectrometer. Errors are quoted throughout as 2 standard deviations, and the analytical uncertainties are given in Tables I and II. The decay constant used in the age calculation was ^{87}Rb = 1.42 × 10^{-11} a^{-1} (Steiger and Jäger, 1977). During the course of this study the average ^{87}Sr/^{86}Sr ratio determined for the standards NBS 987 and Eimer and Amend $SrCO_3$ was 0.71028 ± 0.00002 (45 analyses) and 0.70805 ± 0.00002 (21 analyses), respectively. Isochrons were fitted to the data using a least squares regression method based on York (1969). All analytical work was undertaken in the laboratories of the Isotope Geology Unit (British Geological Survey) London.

TABLE I

Rb—Sr isotope data for the Kadawēb and Homogar Volcanic Groups. Analytical uncertainties on the Rb/Sr and ^{87}Sr/^{86}Sr ratios are given in parentheses

Kadawēb Volcanic Group

Sample	Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
Group B				
32	65.0	12.9	14.802 (1.7)	0.85420 (0.03)
33	55.6	16.0	10.164 (1.3)	0.80860 (0.03)
35	34.3	135.2	0.734 (0.8)	0.71045 (0.013)
36	45.0	29.9	4.372 (0.9)	0.74785 (0.02)
37	54.2	24.6	6.423 (1.0)	0.76876 (0.03)
45	55.5	16.4	9.873 (1.3)	0.80496 (0.03)
46	44.9	27.0	4.825 (1.0)	0.75276 (0.02)
Group A				
162	19.4	606.6	0.093 (1.0)	0.70369 (0.01)
165	40.7	98.8	1.194 (1.0)	0.71473 (0.01)
166	30.4	42.0	2.097 (1.0)	0.72419 (0.01)
167	68.4	47.3	4.196 (1.0)	0.74622 (0.01)

Groups A + B Rb/Sr error = 1.0, ^{87}Sr/^{86}Sr = 0.01

Homogar Volcanic Group

Sample	Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
2	28.5	512.7	0.161 (1.0)	0.70498 (0.01)
3	133.6	19.3	20.396 (1.0)	0.90137 (0.01)
5	150.1	26.2	16.843 (1.0)	0.86180 (0.01)
6	28.0	607.3	0.133 (1.0)	0.70476 (0.01)
7	123.2	58.5	6.132 (1.0)	0.76256 (0.01)
8	14.6	211.8	0.199 (1.0)	0.70530 (0.01)

TABLE II

Rb—Sr isotope data for the Kadawēb complex and Kadawēb dykes. Analytical uncertainties on the Rb/Sr and ^{87}Sr/^{86}Sr ratios are given in parentheses

Kadawēb Complex

Sample	Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
15	78.0	26.9	8.428 (1.0)	0.78845 (0.03)
16	82.3	25.2	9.520 (1.0)	0.80040 (0.03)
17	72.3	26.3	8.017 (1.0)	0.78500 (0.03)
30	81.0	24.3	9.757 (1.0)	0.80231 (0.03)
31	77.9	26.4	8.621 (1.0)	0.79043 (0.03)
156	43.2	163.1	0.767 (0.5)	0.71036 (0.013)
47	34.1	92.4	1.069 (0.5)	0.71365 (0.013)
49	36.9	89.0	1.200 (0.5)	0.71493 (0.013)
50	39.6	110.1	1.042 (0.5)	0.71339 (0.013)
52	39.0	93.9	1.200 (0.5)	0.71509 (0.013)
155	0.9	455.3	0.006 (1.5)	0.70264 (0.01)
157	29.7	451.2	0.190 (1.5)	0.70458 (0.01)
158	36.5	477.5	0.221 (1.5)	0.70492 (0.01)
159	12.3	409.1	0.087 (1.5)	0.70351 (0.01)

Kadawēb Dykes

Sample	Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
198	11.2	332.6	0.098 (0.5)	0.70378 (0.01)
200	5.1	194.6	0.076 (0.5)	0.70356 (0.01)
201	8.8	298.3	0.086 (0.5)	0.70356 (0.01)
202	27.2	396.0	0.199 (0.5)	0.70472 (0.01)
203	17.2	524.6	0.095 (0.5)	0.70391 (0.01)
205	55.1	297.6	0.571 (0.5)	0.70869 (0.01)

Whole-rock isochrons

Two suites of samples were collected from the Kadawēb area, one from the predominantly acid lavas occurring at Jibal Ginay Ribāb and another from the more basic lavas occurring to the east of Khor Rimit (Fig. 1). Although these lavas were described as typical Nafirdeib and Awat type by Kabesh (1962) they have simply been named group A and B, respectively, during the present work (Table I). Group A rocks (the so-called Nafirdeib Series) consist of basalts, basaltic andesites and andesites from which a four-point Rb—Sr whole-rock isochron was obtained yielding an age of 718 ± 10 Ma, Ri = 0.7027 ± 0.0001 and MSWD = 1.90 (Fig. 4a). From the dacites and rhyolites of group B (the so-called Awat Series) a seven-point Rb—Sr whole-rock isochron was obtained yielding an age of

722 ± 8 Ma, Ri = 0.7029 ± 0.00026 and MSWD = 0.2 (Fig. 4b). Within the errors, the ages and intercepts (Ri) of the two isochrons are similar and the two suites can therefore be considered to belong to a single group. Field evidence supports this conclusion and the two groups have been named the Kadawēb Volcanic Group (Klemenic and Poole, 1982; Klemenic, 1984). The combined isotopic data produce an isochron yielding an age of 723 ± 6 Ma, Ri = 0.7027 ± 0.00012 and MSWD = 1.1 (Fig. 4c).

The lavas of groups A and B have been affected by a regional metamorphic event and it may be suggested that the date obtained from the combined isochron (Fig. 4c) represents the age of metamorphism. However, primary minerals and textures can still be recognised and the alteration that is evident has not resulted in any significant data point scatter in terms of major elements (Fig. 3) or isotopic ratios (Fig. 4c). A further complication to the interpretation of the isotopic data may be the intrusion of a gabbro—granite complex (the Kadawēb complex) into the lavas (Fig. 1). Again it may be argued that this intrusion has reset the isochron through the effect of thermal and/or hydrothermal activity. However, there is no evidence of thermal metamorphism, at least not where the volcanic rocks were collected (c. 500 m from the contact). Further, evidence for hydrothermal activity within the basement lavas is not obvious, and the intrusive complex contains unaltered gabbro with fresh olivine. The field evidence together with the low $^{87}Sr/^{86}Sr$ ratio and restricted scatter of the isotopic data (Fig. 4a—c) is not consistent with that of rocks which have been affected by hydrothermal activity (Zartman and Marvin, 1971).

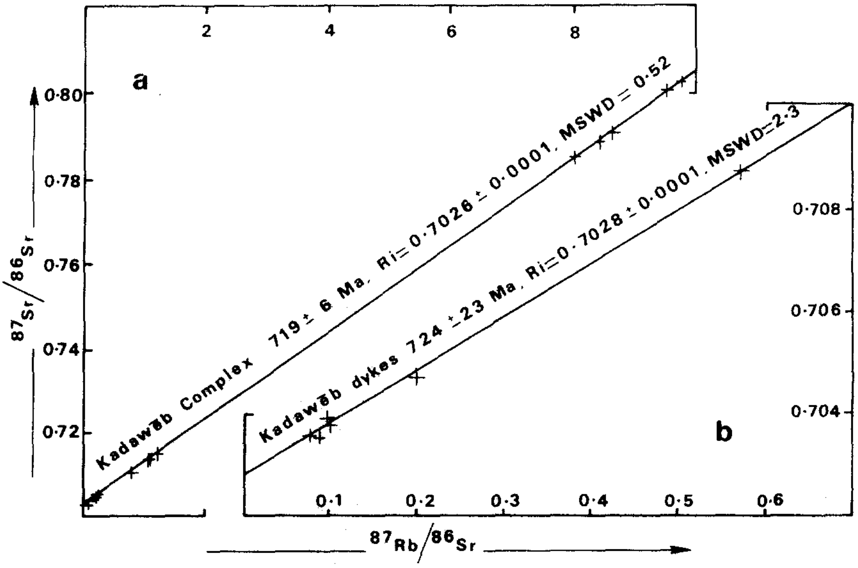

Fig. 5. Rb—Sr whole-rock isochrons of the Kadawēb complex (a) and the Kadawēb dykes (b). Ri means initial $^{87}Sr/^{86}Sr$ ratio. Data from Table II.

Significantly, the age and $^{87}Sr/^{86}Sr$ initial ratio of the Kadawēb complex (719 ± 6 Ma, Ri = 0.7026 MSWD = 0.52; Fig. 5a) is not different from that of the Kadawēb lavas, and it has been suggested that the high-level igneous complex is genetically related to the lavas (Klemenic, 1974; Klemenic and Poole, 1982). Similar temporal and genetic relationships between high-level igneous complexes and overlying volcanic rocks have been described from northeastern Sudan by Neary et al. (1976). It is suggested that the Rb—Sr whole-rock isochrons presented here (Fig. 4a—c) have not been reset by later regional metamorphic or intrusive activity and that the date of the combined isochron (Fig. 4c) most probably represents the age of eruption. Although no independent isotopic data are available to support this conclusion, the result is consistent with that obtained from Nafirdeib type lavas occurring 180 km to the north of the Kadawēb area (Fitches et al., 1983). On a wider scale the age of the Kadawēb lavas is similar to that recorded from the Idsas and Ishmas lavas of western Saudi Arabia, the Series B lavas of Roobol et al. (1983).

The Homogar Volcanic Group occurs about 150 km to the south of the Kadawēb Volcanic Group and have been compared with the Awat Series of Ruxton (1956) by Ali (1979). A suite of basalts, andesites and rhyolites were collected across the Homogar ridge (Fig. 2) and a Rb—Sr whole-rock isochron was produced from the data which yield an age of 671 ± 8 Ma, Ri = 0.7034 ± 0.0001 and MSWD = 1.55 (Fig. 4d).

The rocks occurring at Jibal Homogar have been deformed and metamorphosed at the greenschist facies. Ali (1979) described subspherical masses within the basic lavas which he suggested to represent deformed pillow structures, and hence reflect subaqueous conditions. This palaeoenvironmental evidence has been used by Ali (1979) to suggest that the basic lavas were contaminated by sea water producing a "spilitic" appearance. However, no pillows were observed by the present author, and the ubiquity of feldspar phenocrysts and vesicles within the basic lavas suggest subaerial eruption. The metamorphic mineralogy of the Homogar lavas could have simply resulted from a regional low-grade event, similar to that which affected the Kadawēb rocks. This conclusion is supported by geochemical evidence as the bulk trends of the data from the Homogar and Kadawēb lavas (particularly Na_2O) are similar (Fig. 3). Thus, despite the altered appearance of the Homogar lavas, the major element character of these rocks is not significantly different from those rocks of the Kadawēb Group. Isotopic evidence also suggests limited open system behaviour as, within the errors applied, the isochron is well fitted to the data and a low MSWD is obtained together with low errors on the slope and intercept (Fig. 4d).

The recognition of primary minerals and volcanic textures, together with the limited scatter of geochemical and isotopic data suggest that the age obtained from the Homogar Volcanic rocks (Fig. 4d) represents an original extrusive age. No independent isotopic data are available for the Homogar lavas. However, a suite of local gabbroic dykes has yielded ages of between 654 and 633 Ma by the K—Ar whole-rock method (Vail and Hughes, 1977). The relationship between these dykes and the Homogar lavas is uncertain, but it may be significant that, whereas the dykes are frequent within the syn-orogenic granitoids, they are noticeably absent from the lavas of the Homogar ridge (Fig. 2). This is a common feature throughout the basement complex of northeast Sudan and may simply reflect the control of jointing within the granitoids (Nour, 1983). Nevertheless, Nour (1983) showed a close chemical link between doleritic dykes, which intrude syn-orogenic granitoids in the Kadawēb area (Fig. 1), and the Kadawēb Volcanic Group (Fig. 1). Isotopic studies on the Kadawēb dykes yield a Rb—Sr whole-rock isochron age of 724 ± 23 Ma and Ri = 0.7028 (Fig. 5b) and a genetic link has been suggested (Vail et al., 1984). On a regional scale the age for the Homogar lavas reported here is close to that of the Asoteriba lavas (649 ± 18), which occur 375 km to the north of the Homogar area (Cavanagh, 1979) and, providing that these dates represent original extrusive ages, they tend to confirm the correlation made by Jackson (1980). On a wider scale the age and the intercept of the Homogar lavas fall within the range for the latest Proterozoic lavas from the western shield of Saudi Arabia, such as the Fatimah suite (Darbyshire et al., 1983).

If the dates for the Kadawēb and Homogar Volcanic Groups represent original extrusive ages then there is a significant temporal difference of some 50 Ma between them. The difference between the two groups is further emphasised by the initial $^{87}Sr/^{86}Sr$ ratio, because the intercept of the isochron of the Kadawēb Group is 0.7027 while the intercept defined by the Homogar isochron is significantly higher at 0.7034.

DISCUSSION AND CONCLUSIONS

The results presented here suggest that the Kadawēb and Homogar lavas represent two volcanic episodes in the evolution of the Nubian Shield of northeast Africa at c. 720 and 670 Ma ago, respectively. However, despite the recognition of primary minerals and textures and the apparent original chemical character of these lavas, the possibility that these ages are reset cannot be unequivocally rejected. However, the results of this study are compatible with those reported from the northern Red Sea Hills of Sudan (Fitches et al., 1983). They are also within the range of Rb—Sr whole-rock ages and initial $^{87}Sr/^{86}Sr$ ratios reported from the western shield of Saudi Arabia (Greenwood et al., 1976; Darbyshire et al., 1983; Roobol et al., 1983). Further, the initial $^{87}Sr/^{86}Sr$ ratios of the Kadawēb and Homogar Groups are low and lie, within the errors quoted, on the strontium evolution curve of mantle-derived basalts (Klemenic, 1984). Thus, it is unlikely that these lavas had any significant crustal history prior to the ages calculated from the regression lines presented here.

Geochronological studies suggest that the basement lavas of the Arabian—

Nubian Shield are no older than c. 1000 Ma. Further, the isotopic data indicate that the basement lavas have a limited range of initial $^{87}Sr/^{86}Sr$ ratios which are generally <0.706 (Gass, 1981). These data place some constraints on the nature of crustal evolution in the Arabian—Nubian Shield. In particular, the isotopic data are inconsistent with those models which suggest that the basement rocks of the Arabian—Nubian Shield include early Proterozoic or Archaean continental crust (Kazmin, 1975; Hepworth, 1979; Almond, 1982). However, the data do support those models which limit the growth of these basement rocks to the upper Proterozoic, predominantly from a source with low Rb/Sr ratios such as the mantle (Gass, 1981).

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