Isotope geology and geochemistry of the Rehoboth Basement Inlier, Namibia/S.W. Africa : a multimethod case history

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Isotope Geology and Geochemistry of the Rehoboth Basement Inlier, Namibia/S.W. Africa; a Multimethod Case History

with 13 Figures

by

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Abstract

The application of various geochemical (XRF-analyses, neutron activation) and dating techniques (Sm-Nd, U-Pb, Rb-Sr and K-Ar methods of dating) have permitted a better understanding of the history of the Precambrian Rehoboth Basement Inlier (RBI) within the pan-African Damara Orogen in central Namibia. Sm-Nd analyses enabled a position of theRBI in the regional framework of the crustal evolution of southern Africa. U-Pb analyses have in spite of partial lead loss indicated some minimum formation ages of granitoid intrusions and volcanics in the area while the Rb-Sr method of dating only could provide formation ages of post-Gamsberg lithologies as the Rb-Sr systems of all the older lithologies were disturbed by the Gamsberg magmatism. The K-Ar method allowed to outline the influence of the Damara Orogeny and of later tectonic processes on the RBI.

Zusammenfassung

Die Anwendung verschiedener geochemischer Untersuchungsmethoden (Röntgenfluoreszenz, Neutronenaktivierung) und Datierungstechniken (Sm-Nd, U-Pb, Rb-Sr und K-Ar) ermöglichte ein besseres Verständnis des präkambrischen Rehobother Basement Inliers (RBI) im pan-afrikanischen Damara Orogen Zentral-Namibias. Sm-Nd Studien ermöglichten es die Stellung des RBI in der geologischen Entwicklung des südlichen Afrikas festzulegen. U-Pb Analysen konnten trotz teilweise aufgetretenem Bleiverlust Minimalalter für verschiedene Granitintrusionen und Vulkanite aufzeigen während die Rb-Sr Methode nur Bildungsalter von post-Gamsberg Gesteinen aufzeigen konnte, da die Rb-Sr Systeme der älteren Gesteine durch den Gamsberg Magmatismus gestört wurden. K-Ar-Datierungen erlaubten es, den Einfluss der Damara Orogenese und späterer tektonischer Prozesse auf den RBI zu bestimmen.

1. Introduction

This article represents a summary of the results obtained by the authors during their doctoral thesis at the University of Berne in cooperation with the Geological Survey of Namibia (STOESSEL and ZIEGLER, 1989). Most of the analytical results discussed and interpreted below were presented to the Geological Survey in Windhoek as annual reports on the progress of the project and have already been or will shortly be published in the Communications of the Geological Survey of Namibia (Volume 4, 5 and 6). Here we try to summarise all the results and to place them into a regional context which

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should help to elucidate parts of the geological history of the Rehoboth Basement Inlier of central Namibia. Moreover it is attempted to give criteria on the capacities and limitations of the utilized K-Ar, Rb-Sr, U-Pb and Sm-Nd methods of dating in a Precambrian cratonic area which has been affected by a multitude of geologic processes during its evolution.

2. Area of Investigation

The area of investigation is situated about 80 km south of Windhoek between 23°S and 25°S and between 16°E and 18°E in the central part of Namibia where it forms the southernmost inlier of pre-Namibian basement rocks in the Damara Sequence (Fig. 1). This Rehoboth Basement Inlier, which was named after the capital of the Rehoboth District, forms an elongate SW-NE trending body with a maximum width of approximately 50 km. Towards the southwest of the area the inlier changes its trend to a more southerly direction, continuing into the Sinclair area as far south as 26°S along the big escarpment separating the Namib desert from the fertile central parts of the country.

Towards the north the Rehoboth Basement Inlier is limited by the Southern Marginal Zone of the Damara Orogen while its southern border is indicated by the occurrence of the platform sediments of the Nama Group (Fig. 1). The Naukluft Nappe

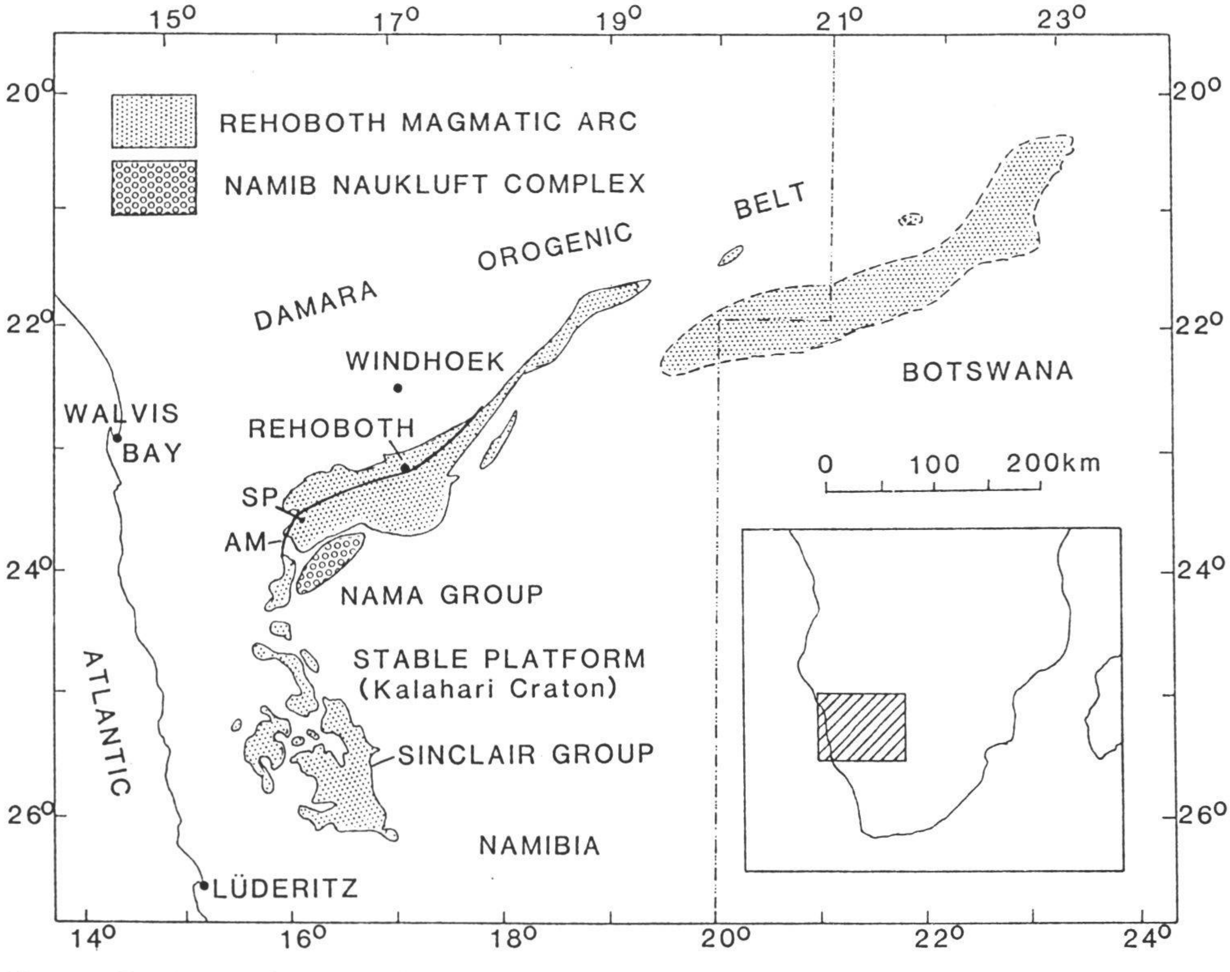

Fig. 1 Sketch map of the area of investigation. (AM = Areb Mylonite; SP = Spreetshoogte Pass).

Complex composed of sediments of the Damara Sequence (Fig. 1), today rests on the Nama sediments with a tectonic contact, thus indicating a partial override of the Rehoboth Inlier by derivates of the southern zones of the Damara Orogen during orogenesis. The inlier is crosscut by a major shear zone, the so-called Areb mylonite or Areb shear zone (AM on Fig. 1), which, according to SCHULZE-HULBE (1979), possibly formed during the early Proterozoic and was probably reactivated during the pan-African movements of the south African crust.

The outcrops of basement rocks to the east and south of the Rehoboth Basement Inlier in western Botswana and in the Sinclair area, respectively (Fig. 1), are often grouped together with the rocks of the Rehoboth area in the so-called Rehoboth Magmatic Arc (WATTERS, 1978). This arc, which possibly forms an extension of the Irumide Belt and/or the Eburnian event of the Limpopo Belt, has an extension of about 1200 km and a maximum width of about 150 km.

According to the 1:1'000'000 Geological map of SWA/Namibia (1980 edition, Fig. 2) and SACS (1980) the lithology of the Rehoboth area is subdivided, from top to bottom, into the following units whose classification partly needs further verification:

— The Klein Aub Formation, regarded as the uppermost formation of the Rehoboth Inlier, consists of quartzites, slates, conglomerates and some limestone (SCHALK, 1970).

— It is underlain by the volcano-sedimentary Doornpoort- and Grauwater Formations with felsic basaltic volcanics interlayered with quartzites, conglomerates and slates (SCHALK, 1970). The Nueckopf porphyries and ignimbrites form the lower part of the Grauwater Formation. According to SCHALK (1970) all these formations, including the Nueckopf volcanics, are believed to be equivalents of the Sinclair Sequence of the southern continuation of the Rehoboth Basement Inlier.

— The underlying Rehoboth Sequence is divided into the Gaub Valley-, Billstein-, and Marienhof Formations which largely consist of low to medium grade metamorphosed quartzites, mica-schists, some phyllites and minor amounts of conglomerates and of acid to basic volcanics. The base of the Rehoboth Sequence is formed by the low to medium grade metamorphosed Elim Formation, composed of quartzites, mica-schists, greenschists and minor amounts of amphibolites, calc-silicates and meta-rhyolites.

— The oldest parts of the inlier belong to the Neuhof Formation and to the underlying Mooirivier Complex, both of which were metamorphosed under medium to high grade metamorphic conditions. The Mooirivier Complex consists of migmatitic gneisses, amphibolites, quartzites and schists while the Neuhof Formation is composed of metamorphosed acid and basic volcanic rocks, mica-schists, greenschists, conglomerates and impure marbles.

The Rehoboth Inlier as a whole is intruded by diverse kinds of acid and basic magmas such as the Weener Quartz Diorite, the Piksteel Intrusive Suite, the Gamsberg Granite Suite and a variety of acid and basic dykes (Fig. 2). Depending on their local position these intrusives have partly been altered and in various cases even been metamorphosed under low grade metamorphic conditions, due to events such as the intrusion of younger magmas, the Damara Orogeny and the tectonic activities along the Areb shear zone. The dating of these intrusives of the different magmatic suites by means of radiometric age determinations by BURGER et al. (1973, 1973-74, 1975-76a & b, 1977-78, 1980), MALLING (1978), Seifert (1986), REID et al. (1988). In this study a framework for the cognition of the evolution of the Rehoboth Basement Inlier through the Precambrian and the Paleozoic is provided. Prior to this study the age of the

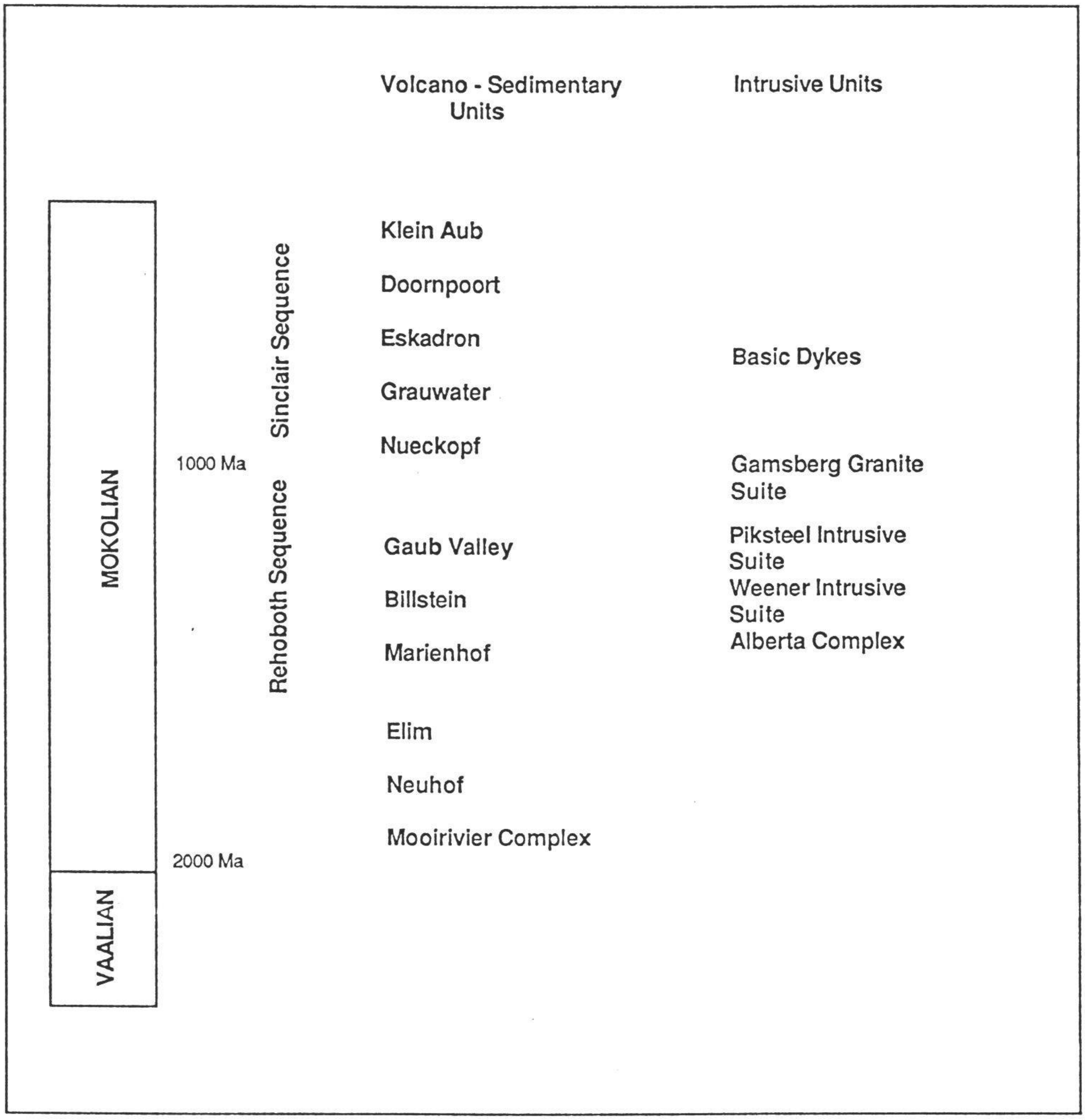

Fig. 2 Pre-Damaran stratigraphy of the Rehoboth area slightly modified after the geological map of SWA/Namibia 1:1'000'000, 1980 edition.

Weener Intrusives was assumed to be about 1870 Ma (SEIFERT, 1986), although REID et al. (1988) proposed an age of approximately 1200 Ma, while the age of the Piksteel Intrusive Suite was estimated to range between 1050 and 1750 Ma (REID et al., 1988; BURGER et al., 1975-76). The age of the Alberta Complex was assumed to be about 1440 Ma (REID et al., 1988) while the age of the Gamsberg Granite Suite is estimated to range between 950 and 1200 Ma (SEIFERT, 1986; REID et al., 1988; BURGER et al., 1973-74, 1974-75, 1975-76a & b). The age of the basic dykes occurring throughout the Rehoboth area was indicated to be approximately 1030 Ma (REID et al., 1988).

3. Sample Condition

Thin section analyses of the samples collected throughout the Rehoboth Basement Inlier have shown that most of them were affected by alteration processes. This may be deduced from the saussuritisation of plagioclase, the partial chloritisation of biotite, the formation of chlorite and epidote minerals from original amphiboles, the widespread strong fracturing and partial mylonitisation of many rocks and the subsequent formation of veinlets consisting, to a large degree, of quartz, calcite and epidote minerals. For these reasons great care had to be taken for the interpretation of the results furnished by the geochemical and isotopic analyses (often not readily interpretable due to the occurrence of alteration phenomena).

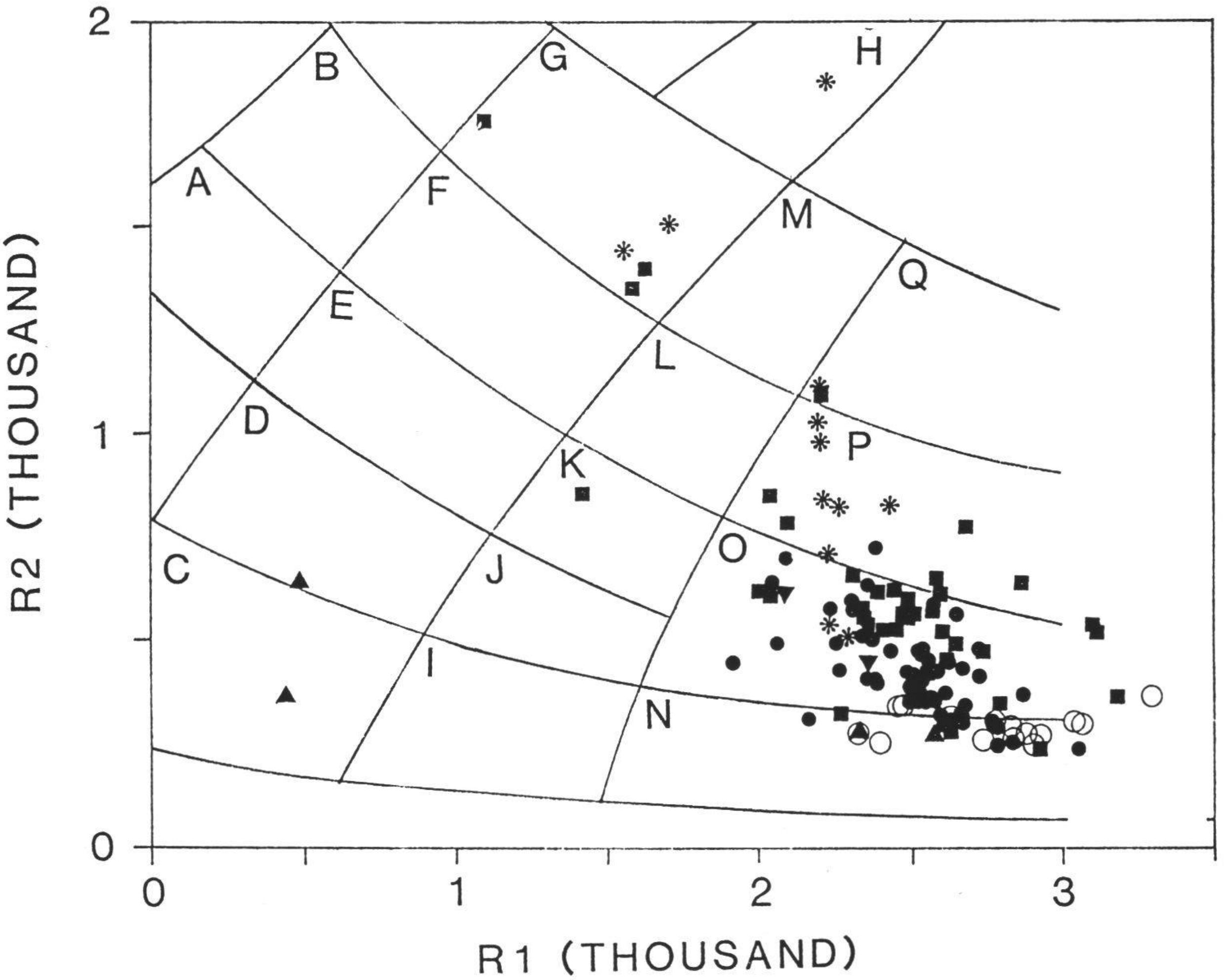

Fig. 3 Classification diagram of De La Roche et al. (1980) modified by Streckeisen (1981) for all the analysed plutonic rocks and the analysed acid volcanic rocks of the Rehoboth Basement Inlier. (R1 = 6Ca+2Mg+Al; R2 = 4Si-11(Na+K)-2(Fe+Ti); A and B: Essexite, C: Alk. Syenite, D: Syenite, E: Monzonite, F: Monzodiorite, G: Diorite, H: Gabbro, I: Q. Alk. Syenite, J: Q. Syenite, K: Q. Monzonite, L: Q. Monzodiorite, M: Q. Diorite, N: Alkali Granite (Alkali Rhyolite, respectively), O: Granite (Rhyolite, respectively), P: Granodiorite, Q: Tonalite; Solid Circles: Gamsberg Granite Suite, Squares: Piksteel Intrusive Suite, Asterisks: Weener Intrusive Suite, Upright Triangles: Granitoids mapped as Neuhof Granitoids, Downward Pointing Triangles: Granitoids mapped as Moorivier Granitoids, Open Circles: Acid Volcanics).

4. Results

4.1 Geochemistry

4.1.1 Granitoids

Major and trace element whole rock geochemistry has permitted a classification of the analysed granitoids of the Weener- and Piksteel Intrusive Suites, the Gamsberg Granite Suite, the Neuhof Formation and the Mooirivier Complex according to the classification scheme of DE LA ROCHE (1980) and STRECKEISEN (1981), in which a wide compositional range from alkaline granites through granites, syenites, alkali syenites, diorites, quartz monzonites, tonalites and granodiorites to gabbros can be observed (Fig. 3). This large scatter already indicates a certain mobility of the alkalis during the widespread alteration of the granitoids as is best seen according to the analyses of the Neuhof granitoids, where two samples even plot in the fields of syenites and alkali syenites. According to the index of SHAND (1927) most of the analysed granitoids can be classified as peraluminous intrusives, while only few exceptions have to be classified as metaluminous granitoids (Fig. 4). The A/CNK ratios (Mol.%

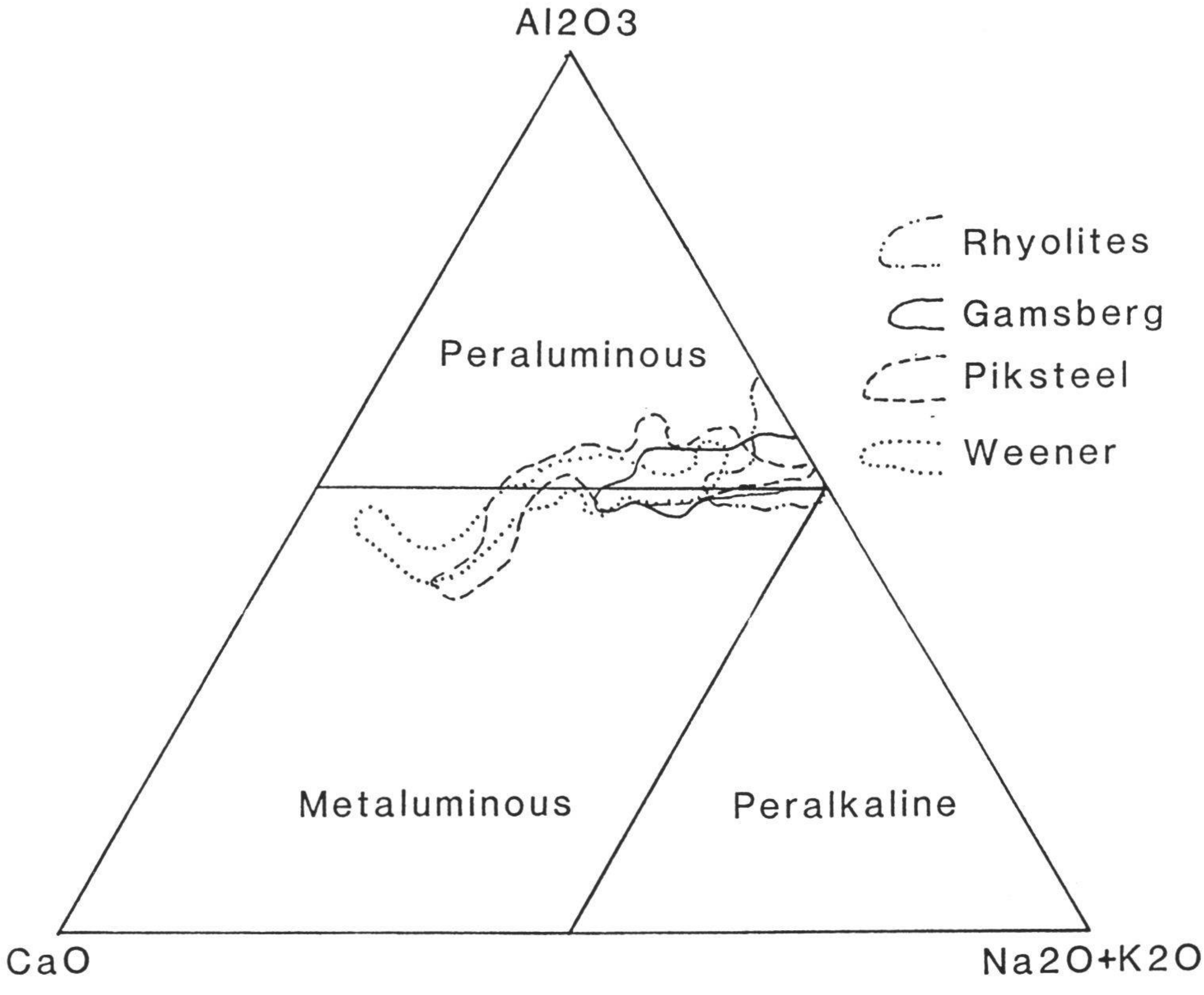

Fig. 4 Mol. % Al_2O_3-CaO-($Na_2O + K_2O$) ternary diagram after SHAND (1927 and 1951) for all the analysed plutonic rocks and the analysed acid volcanic rocks of the Rehoboth Basement Inlier.

$Al_2O_3/CaO+Na_2O+K_2O$) of the analysed granitoids range between 0.65 and 1.3 with the majority of samples plotting between values of 0.9 and 1.3. The Weener granitoids show a strong tendency towards lower values (0.65-1.13), while the Gamsberg and Piksteel samples plot in a range of values between 0.87 and 1.26. As most of the data from all the analysed plutons scatter slightly below a ratio of 1.1, which, according to CHAPPELL and WHITE (1974), separates S-type granites (>1.1) from I-type granites (<1.1), it can not be decided, based on this criteria, whether most of the granitic crust of the Rehoboth Basement Inlier has been generated from either S- or I-type magmatism although a tendency towards I-type magmatism is evident. Nevertheless it can be stated that the overall degree of alumina saturation generally is high, and thus would indicate upper crustal origin for most of the analysed plutons. All the analysed granitoids plot on a calc-alkaline trend in the AFM ternary diagram after KUNO (1968, Fig. 5). As calc-alkaline magmas are predominantly produced in continental-collision and in continental- and island arc tectonic settings, as well as during post orogenic mag-

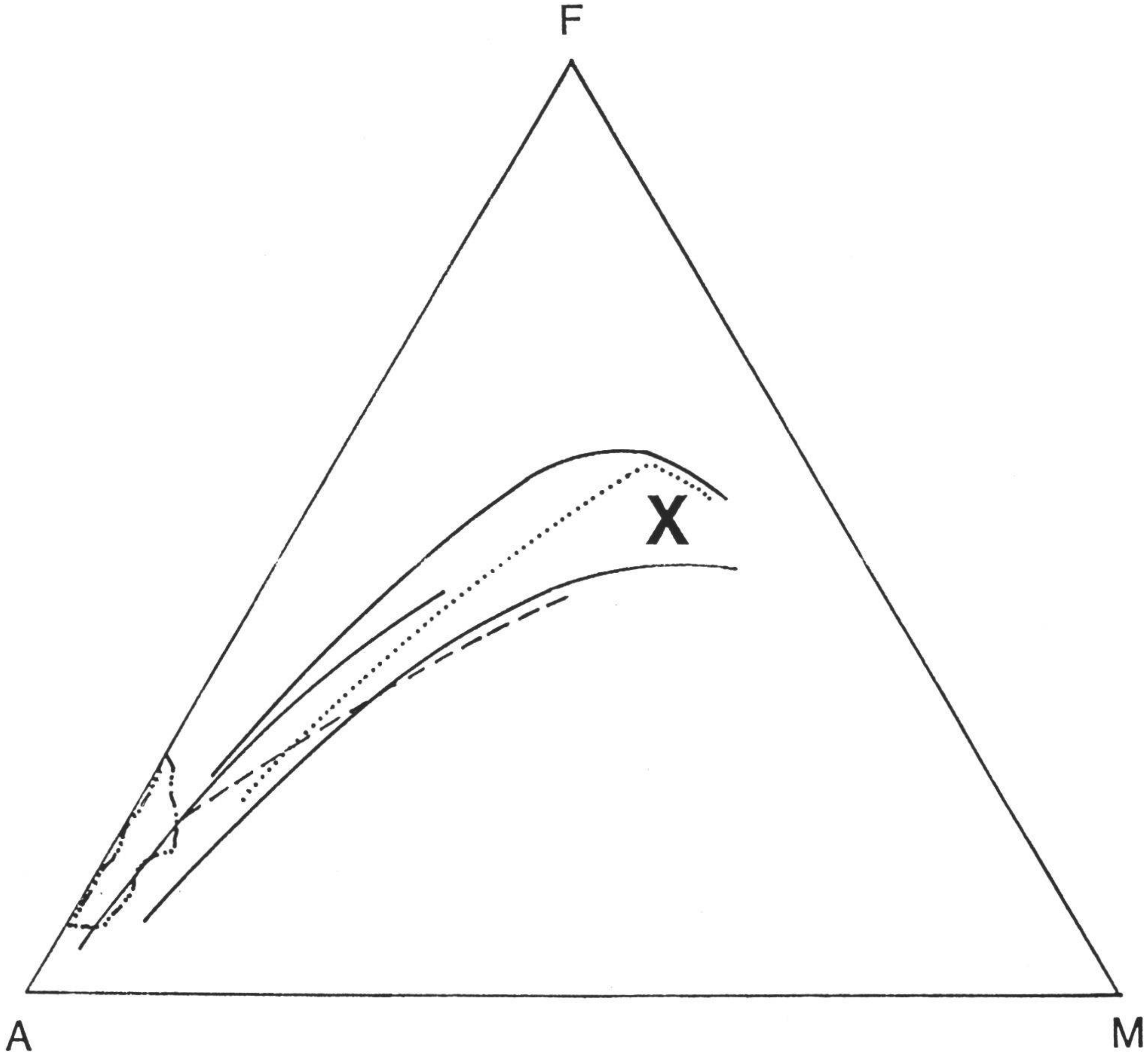

Fig. 5 Trends for all analysed Rehoboth granitoids on an AFM diagram after KUNO (1968). (Same symbols as in Fig. 4., the area X denotes the position of typical calc-alkaline series according to KUNO (1968).

matism, this may indicate a formation of the Rehoboth granitoids during various stages of the development of tectonic settings along active plate margins. This is confirmed to a certain degree by the tectonic discriminant Nb+Y versus Rb diagram of PEARCE et al. (1984), whose significance is frequently dubious according to the considerations of WILCOX, (1979). In this diagram the majority of the analyses plot in the field for volcanic arc granites and only a few exceptions plot in the fields for syn-collision granites and within plate granites (Fig. 6). It is of interest to note that most of the few data points plotting into the fields within plate Granites are samples which, according to their age, have to be assigned to the Gamsberg Granite Suite, the youngest large-scale magmatic event in the Rehoboth Basement Inlier. Consequently, they might indicate a change of the plate tectonic setting of the area during Gamsberg magmatism from a collisional to a more extensional tectonic regime.

The indication of possibly mainly I-type origins for the analysed Rehoboth granitoids is to some extent supported by the study of the Rb-Sr and Sm-Nd isotope systematics of the Rehoboth granitoids by various authors (REID et al., 1988; SEIFERT, 1986; this study). The initial $^{87}Sr/^{86}Sr$ ratios of the Weener intrusives range between 0.700 and 0.705 (SEIFERT, 1986; REID et al., 1988) while those of the granitoids of the Mooirivier Complex and the Neuhof Formation are approximately 0.704 (Fig. 13). The intrusives of the Gamsberg Granite Suite and the Piksteel Intrusive Suite cover a wide range of initial $^{87}Sr/^{86}Sr$ ratios from 0.700 to 0.708 and 0.702 to 0.709, respectively (SEIFERT, 1986; REID et al., 1988; this study). These generally quite low to very low initial ratios are generally even below the $^{87}Sr/^{86}Sr$ ratio of today's uniform reservoir of

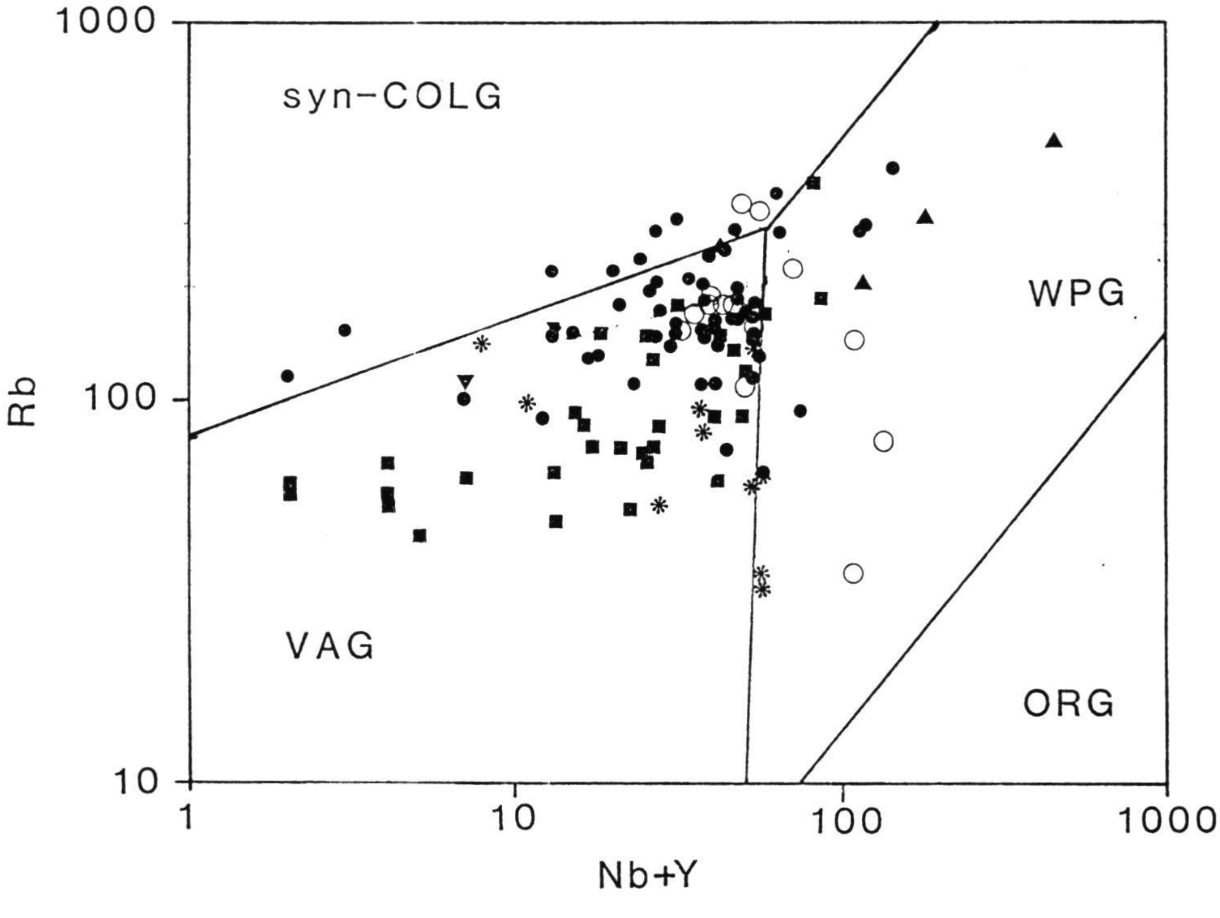

Fig. 6 Rb versus Nb+Y diagram after PEARCE et al. (1984) for all the analysed Rehoboth granitoids and associated acid volcanics. (Same symbols as in Fig. 3).

0.7045 (DE PAOLO, 1988). They indicate that in spite of post-formation alteration and at least partial resetting of the Rb-Sr system of many of the analysed plutons, the major part of the material forming the Rehoboth granitoids originally derives from a primitive source in the upper mantle or in the lower crust. It can thus be said that the source material of the analysed granitoids consisted of material with primitive Sr composition (low $^{87}Sr/^{86}Sr$ ratios), low Rb-Sr ratios, and that no significant amounts of material with $^{87}Sr/^{86}Sr$ and high Rb-Sr ratios was admixed to this source material during later processes of crustal reworking and alteration. This view is conditionally supported by the εSr and εNd characteristics of some granitoids of the Piksteel Intrusive Suite, which clearly confirm a Rb depleted source in the upper mantle for these granitoids (Fig. 11). The analyses of the Rare Earth Element (REE) composition of several Piksteel- and Gamsberg granitoids have shown quite flat chondrite normalised patterns in a range which is typical for granitoid rocks (Fig. 7). The patterns decrease from chondrite normalized La values of approximately 100, to chondrite normalised Yb values of about 10. Several samples showed slightly concave-up REE patterns similar to those described for the Namaqualand by MCCARTHY and KABLE (1978).

4.1.2 Amphibolites

The analyses of amphibolites from the meta volcanosedimentary Neuhof- and Elim Formations and the Moorivier Complex have shown that most of the specimens are of orthogenic origin and that the vast majority of the samples reflect tholeiitic magmatism. No general plate tectonic environment could be assigned to the analysed amphibolites according to the classification schemes of PEARCE et al. (1973), as they were found to plot in all the fields assigned to various plate tectonic settings. It is not clear whether this variation indicates the occurrence of diverse plate tectonic settings in one single formation or whether it represents the effects of post-formation alteration of the analysed specimens. The initial $^{87}Sr/^{86}Sr$ ratios of all the analysed sets of amphibolitic samples range between 0.702 and 0.706 (Fig. 13). These quite low values and the corresponding low Rb-Sr fractionation factors confirm the magmatic origin of these rocks

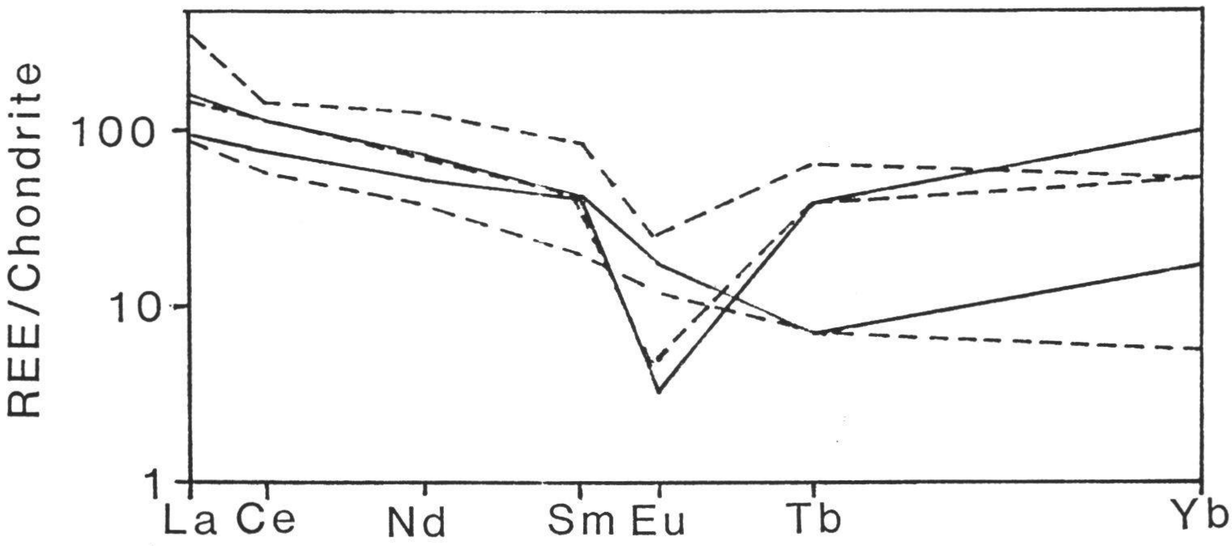

Fig. 7 Generalised REE patterns for members of the Gamsberg Granite Suite (solid lines) and the Piksteel Intrusive Suite (dashed lines).

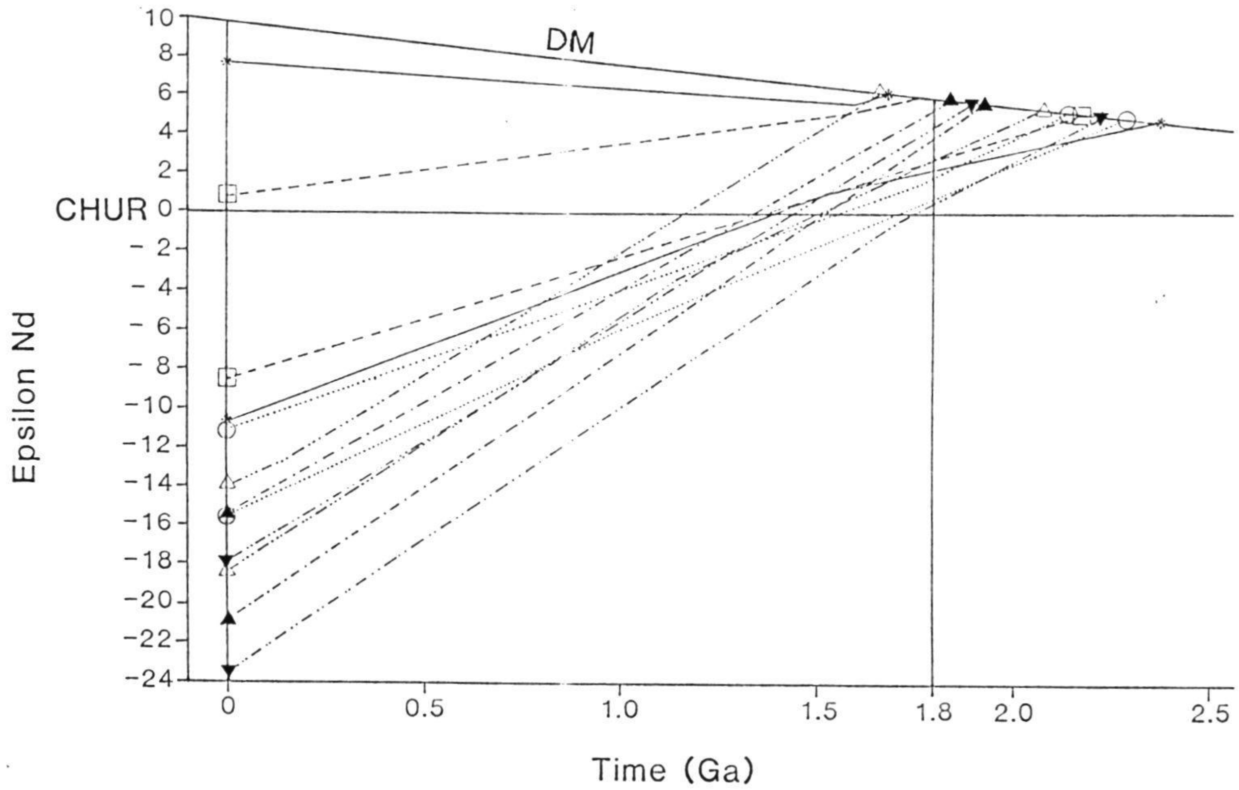

Fig. 8 Model age versus Epsilon Nd evolution diagram for all the analysed specimens from the Rehoboth Basement Inlier (only maximum and minimum lines are displayed for the individual formations; Symbols: Asterisks: Amphibolites of the Elim Formation, Circles: Amphibolites of the Neuhof Formation, Squares: Basic dykes, Upright Triangles: Borodino pluton of the Piksteel Intrusive Suite (PIS), Downward Pointing Triangles: Opetjie pluton of the PIS, Open Triangles: Piksteel pluton of the PIS).

and also show that alteration of the Rb-Sr systems through metamorphism did not admix large amounts of highly radiogenic common Sr. Also the εSm and εNd studies of some amphibolites of the Elim- and Neuhof Formations suggest that these specimens derive from magmatic sources which probably lie in the depleted upper mantle (Fig. 10).

4.1.3 Acid Volcanics

The comparison of acid volcanic dykes crosscutting the Marienhof Formation, the Weener- and Piksteel Intrusive Suites and the Gamsberg Granite Suite with those of the post-Gamsberg Nueckopf Formation, representing the largest mass of volcanic rocks occurring in the Rehoboth Basement Inlier, has shown that all the analysed acid volcanics are high-K rhyolites of mainly peraluminous nature (Fig. 3). The analysed volcanics may be regarded as more evolved Gamsberg, Piksteel and Weener type magmas according to their element distribution patterns and their position in the AFM ternary diagram (Fig. 5). The A/CNK ratios are mainly below 1.1 and plot well within the fields for Gamsberg and Piksteel intrusives, thus indicating I-type sources for the analysed volcanics similarly to the analysed Piksteel and Gamsberg rocks. The observed

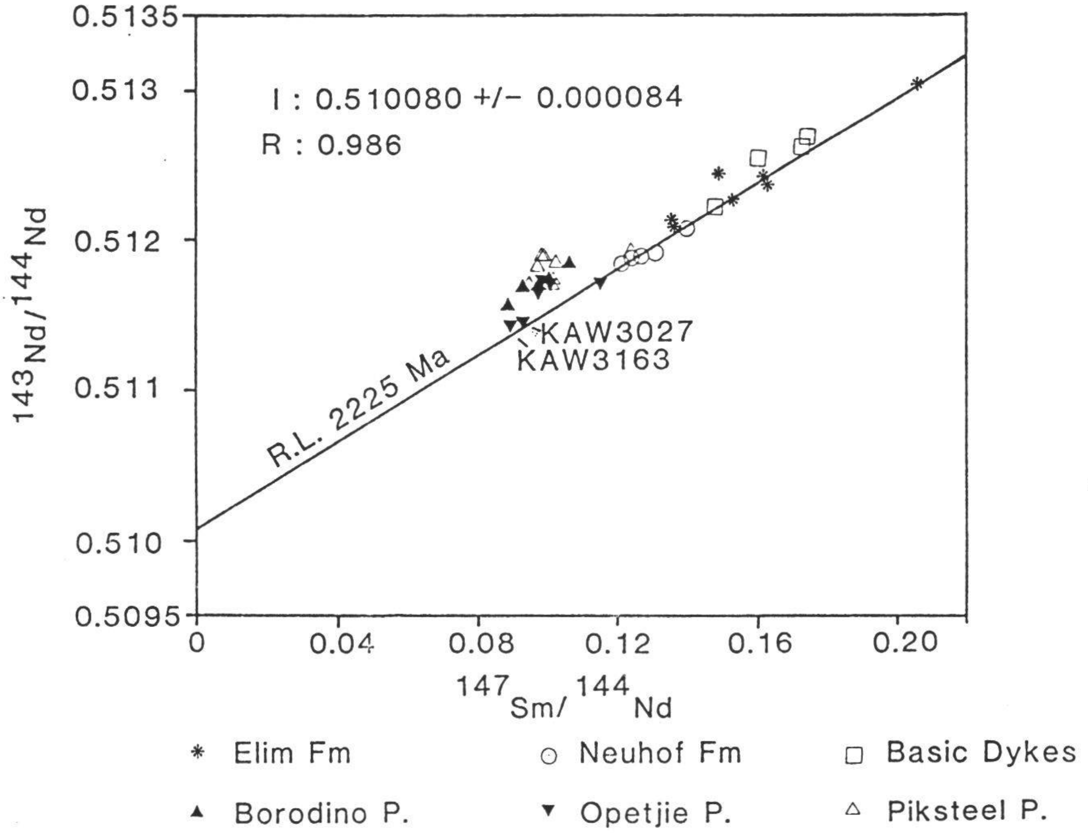

Fig. 9 $^{147}Sm/^{144}Nd$ versus $^{143}Nd/^{144}Nd$ isochron diagram for all the analysed specimens from the Rehoboth Basement Inlier. (Same symbols as in Fig. 8).

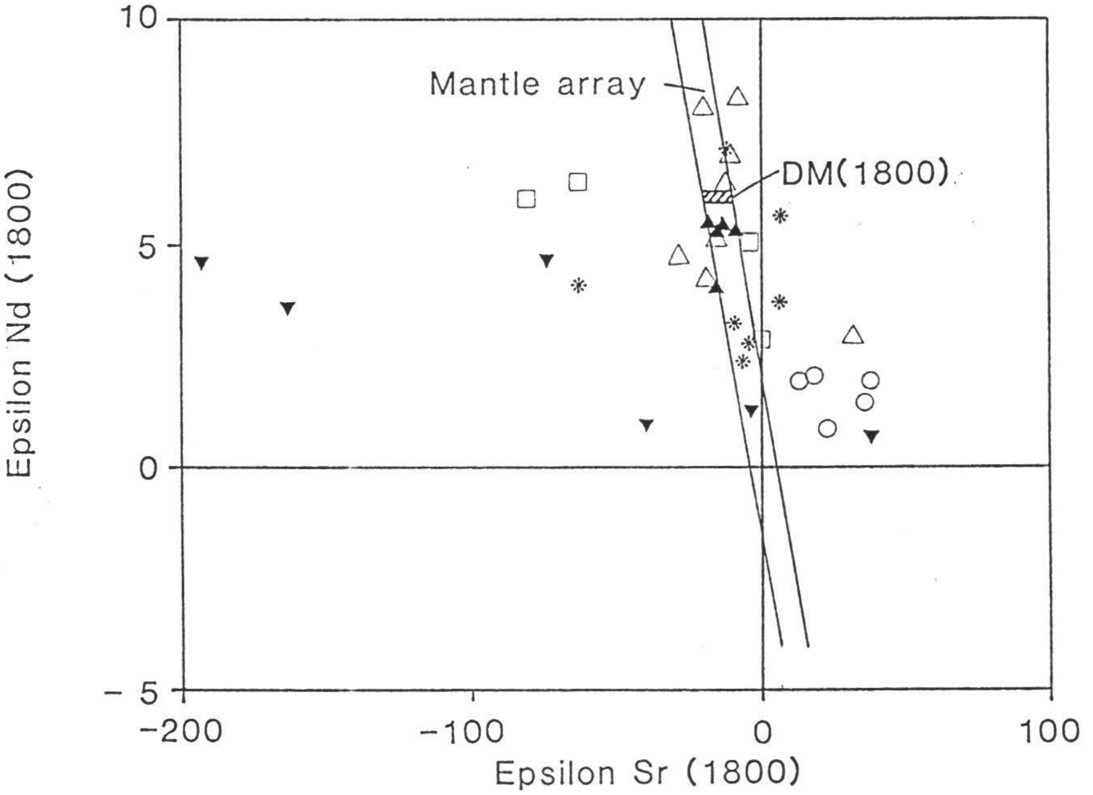

Fig. 10 Epsilon $Sr_{(1800)}$ versus Epsilon $Nd_{(1800)}$ diagram for the analysed samples of the Rehoboth Basement Inlier. (Same symbols as in Fig. 8).

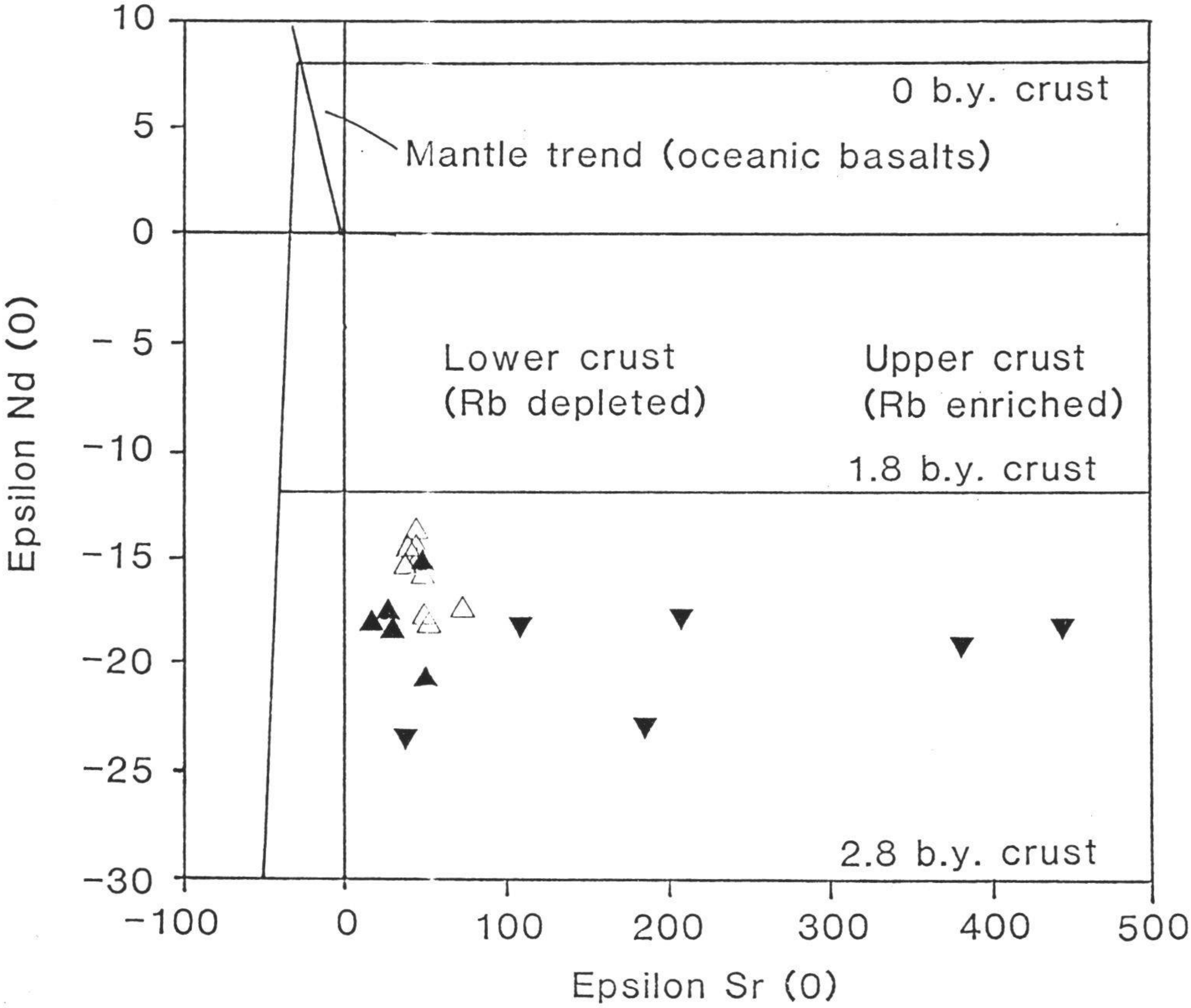

Fig. 11 Epsilon $Sr_{(O)}$ versus Epsilon $Nd_{O)}$ diagram for the analysed specimens of the Rehoboth Basement Inlier.

initial $^{87}Sr/^{86}Sr$ ratio of 0.708 lies at the upper end of the range observed for magmas of the Gamsberg Granite Suite and for the Piksteel Intrusive Suite and thus might also corroborate a continuation of the trends observed for these suites. In the tectonic discriminant Nb+Y versus Rb diagram of PEARCE et al. (1984, Fig. 6.) most of the volcanics plot into the areas for volcanic arc granites and plate granites, which are also covered by the Gamsberg and Piksteel Intrusive Suites.

4.1.4 Basic Dykes

The analysed five post-Gamsberg basic dykes crosscutting the Rehoboth Basement Inlier are all of basaltic tholeiitic origin. According to the classification of PEARCE et al. (1973) they probably derive from a continental plate tectonic environment. Their low initial $^{87}Sr/^{86}Sr$ ratios (Fig. 13) and their εNd values (Fig. 10) suggest an origin in the lower crust or in the upper mantle where their melts were generated from much older source material (see below) due to post-Mokolian dilatational processes in the Rehoboth inlier.

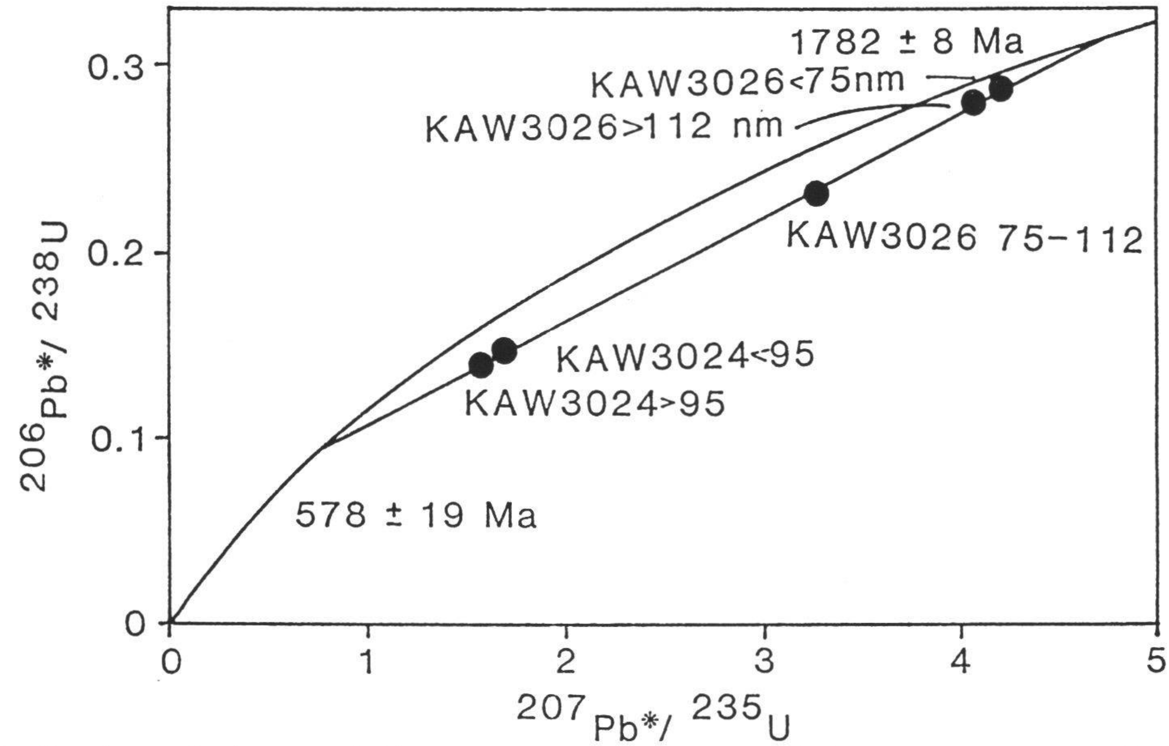

Fig. 12 Concordia diagram of WETHERILL (1956) for the analysed zircon separates from a diorite (KAW3026) and a granite (KAW3024) of the Opetjie pluton of the Piksteel Intrusive Suite. Note the high percentage of loss of radiogenic lead of KAW3024 (>50%).

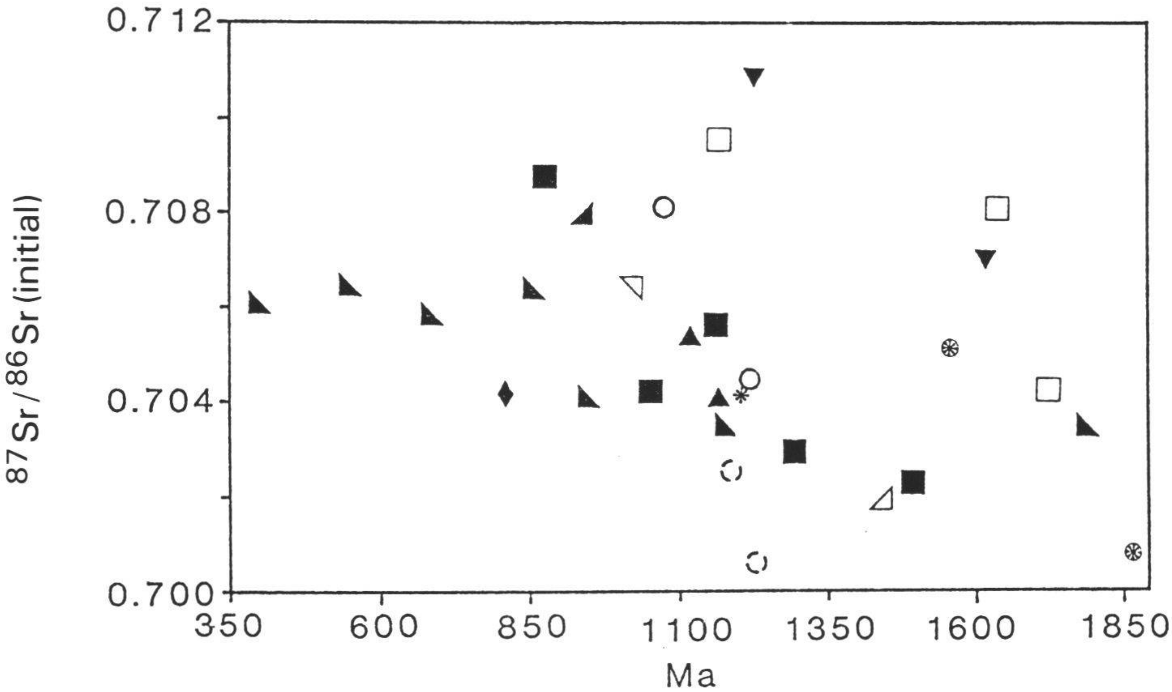

Fig. 13 Age versus initial $^{87}Sr/^{86}Sr$ diagram for all known Rb-Sr data of the Rehoboth Basement Inlier. (Open Circles: Gamsberg data of REID et al., 1988; Open Squares: Piksteel data of REID et al., 1988; Left Skew Open Triangles: Alberta Complex data of REID et al., 1988; Right Skew Open Triangles: Dyke data of REID et al., 1988; Asterisks: Weener data of REID et al., 1988; Encircled Asterisks: Weener data of SEIFERT, 1986; Broken Circles: Gamsberg data of SEIFERT, 1986; Solid Squares: Piksteel data, this study; Diamond: Basic dykes, this study; Left Skew Solid Triangle: Nueckopf Rhyolites, this study; Right Skew Solid Triangles: Elim Formation, this study; Upright Triangle: Amphibolites of the Neuhof Formation; Downward Pointing Triangles: Metasediments of the Mooirivier Complex).

4.1.5 Metasediments

The analyses of the partly garnetiferous biotite schists of the Mooirivier Complex have shown a slight enrichment of incompatible elements such as Rb, Ba, K, La, Nd and Zr, while compatible elements such as Al, Ca, Sc, Fe, Mg and Ni are slightly depleted. The initial $^{87}Sr/^{86}Sr$ ratios of a fan of isochrons calculated trough the Rb-Sr results of the Mooirivier schists yielded crustal upper and lower limits of 0.711 and 0.707, respectively, while a small scale isochron indicates the addition of Sr with an initial ratio exceeding 0.766 (Fig. 13).

The analysed mica schists and marbles of the Elim Formation were found by geochemical means to be typical representatives of their species. The initial $^{87}Sr/^{86}Sr$ ratios of two Elim marbles are 0.707 and 0.714, respectively, clearly indicating the admixture of highly radiogenic Sr to the analysed samples by metamorphic fluids, as according to FAURE (1986), the composition of Sr in seawater before 1000 Ma ago never exceeded a value of 0.707.

4.2 Age Determinations

4.2.1 Sm - Nd Dating

The analyses of 35 whole rock samples of the Piksteel Intrusive Suite, the Elim and Neuhof Formations and of basic dykes by the Sm-Nd method have provided a sound insight into the age of the crust of the Rehoboth Basement Inlier. The T(Depleted Mantle) model ages of all the samples range between 1.6 Ga and 2.4 Ga (Fig. 8). A reference line fitted through 20 of the 35 data points yielded an age of 2.23 Ga while reference lines calculated through the individual sets of samples from different localities yielded ages between 1655 Ma and 2574 Ma (Fig. 9). The fact that only 20 out of 35 analysed specimens plot on a reference line, while the rest plot above this line, indicates the occurrence of either post-separation alteration processes (such as the reworking of crustal material), and/or primary inhomogeneities of the source regions in the upper mantle. The $T_{(DM)}$ model ages of the basic dykes which did not intrude before 850 Ma (see Rb-Sr data below) and thus are much younger than the minimum age of the other analysed specimens of approximately 1.8 Ga (see U-Pb data below), range between 1.77 Ga and 2.10 Ga, while a reference line calculated through their data points shows an age of approximately 2.6 Ga. Four out of eight samples from the Piksteel pluton of the Piksteel Intrusive Suite, an amphibolite of the Elim Formation and a basic dyke have shown $T_{(DM)}$ model ages between 1.66 Ga and 1.79 Ga; in the case of the Piksteel- and Elim samples, these $T_{(DM)}$ model ages are below the assumed minimum formation age of these formations of 1.8 Ga and thus indicate the occurrence of post-formation (hydrothermal ?) alteration processes disturbing some of the analysed Sm-Nd systems.

In spite of the occurrence of a diversity of alteration processes it can be proposed that the Rehoboth crust formed during the early Proterozoic between 1.8 Ga and 2.6 Ga by the separation of material from a source in the depleted mantle and by subsequent reworking of this material under the possible addition of new source material. Therefore it must be assumed that the Rehoboth Basement Inlier is part of an accretionary belt coeval to the younger events of the Limpopo Province connecting the Archean nucleii of the Kalahari craton of South Africa and Zimbabwe. The comparison of the results of this study with Sm-Nd data for the Damara Orogen of other workers (MCDERMOTT, 1986; Hawkesworth et al., 1983) strongly suggests that the Damara

Orogen is primarily composed of crustal material derived from sources which formed contemporaneously with the Rehoboth Basement Inlier, but it also shows that possibly crustal material older than the material of the Rehoboth Basement Inlier existed in the area of the Damara Orogen.

4.2.2 U-Pb Dating

A total of 20 zircon fractions from 11 samples of the Piksteel-, Borodino- and Opetjie plutons of the Piksteel Intrusive Suite, of two rhyolite dykes crosscutting the Marienhof Formation and of one sample obtained from the Weener Intrusive Suite were analysed by the U-Pb population method. All the analysed zircon fractions are characterized by loss of between 10% and more than 60% of radiogenic lead (Fig. 12). This indicates the occurrence of post-formation processes capable of affecting the analysed zircons. The zircon fractions of the rhyolite dykes showed a discordant age of 1210 Ma +/- 7 Ma which probably represents the age of intrusion of the analysed dykes crosscutting the Marienhof Formation, and which thus indicates that these dykes probably belong to the Gamsberg related magmatism of the Rehoboth area.

The single sample of the Weener Intrusive Suite yielded a discordant $^{207}Pb/^{206}Pb$ minimum formation age of 1723 Ma. This lends some confirmation to the data of SEIFERT (1986) who obtained a Rb-Sr reference age of 1871 Ma +/- 143 Ma for the Weener Suite. The Rb-Sr age of 1207 Ma +/- 170 Ma obtained by REID et al. (1988) possibly reflects rejuvenating processes partially affecting the Rb-Sr systems of the Weener Suite by Gamsberg magmatism or later events.

The discordias which were calculated through the zircon data of the analysed plutons of the Piksteel Intrusive Suite yielded minimum ages of 1786 Ma +/- 11 Ma for the Opetjie pluton (Fig. 12), 1506 Ma +/- 69 Ma for the Piksteel pluton and 1369 Ma +/- 8 Ma for the Borodino pluton. The minimum age of the Opetjie pluton which intrudes the Elim Formation thus gives a good minimum age for the Elim- and older Formations of the Rehoboth Basement Inlier. Moreover, such a minimum can also be assumed for the members of the Rehoboth Sequence, which is intruded by several members of the Piksteel Intrusive Suite. This Opetjie minimum age of approximately 1800 Ma thus also served as lower limit for the considerations based on Sm-Nd dating (see above). The highly discordant minimum ages of the Piksteel- and Borodino plutons of 1506 Ma and 1369 Ma, respectively, in the view of the authors do not represent more than minimum ages reflecting a severe loss of lead from the analysed zircons. These ages clearly separate the members of the Piksteel Intrusive Suite from the members of the Gamsberg Granite Suite which intruded the Rehoboth area between 1.0 Ga and 1.2 Ga ago.

4.2.3 Rb-Sr Dating

Whole rock Rb-Sr analyses were carried out on five biotite schists, four amphibolites and two granitoids of the Mooirivier Complex, on six amphibolites and four granitoids of the Neuhof Formation, on 21 amphibolites and two marbles of the Elim Formation, on 21 granitoids of the Piksteel Intrusive Suite, on seven Nueckopf volcanics, on two acid rhyolitic dykes and on five basic dykes. The results of the Rb-Sr analyses are summarized in Fig. 13.

It has been shown that the southern part of the Mooirivier Complex was intruded by late Mokolian granites with a «Gamsberg» age of 1100 Ma, which were able to reset and homogenize the whole rock Rb-Sr systems of the analysed specimens. The Rb-Sr systems of the analysed specimens from the Spreetshoogte Pass area in the northern outcrop area of the Mooirivier Complex were affected even after the intrusion of such late Mokolian Gamsberg type granites by processes probably related to the Damara Orogeny. This can be shown by the occurrence of a small scale reference line yielding an age of 634 Ma.

The analyses of the Neuhof samples showed an age pattern which is quite similar to that of the Moorivier Complex. The southern outcrops of the Neuhof Formation were also intruded by Mokolian Gamsberg type granitoids which were capable of resetting the whole rock Rb-Sr systems of the analysed amphibolites and granitoids to an age of about 1167 Ma +/- 9 Ma. The samples from the northern outcrops of the Neuhof Formation yielded a certain scatter of data corresponding to reference lines of 1122 Ma and 2569 Ma. The younger reference line might again be related to the intrusion of late Mokolian Gamsberg type granitoids in the area, while the older line, whose age even exceeds the Sm-Nd crustal age of the Neuhof Formation (see above), certainly represents alteration processes affecting the analyzed Rb-Sr systems.

None of the analysed sets of amphibolitic and greenschist samples from various localities of the Elim Formation showed satisfactory results in terms of Rb-Sr isochrons. The obtained ages for reference lines calculated through various sections of the analyzed sets of samples range between 396 Ma and 1174 Ma and thus indicate the occurrence of post-Gamsberg and at least partly also post-Damaran alteration processes affecting the Rb-Sr systems of the analysed specimens. It is of interest, however, that the samples from the farm Naub plot quite well on a reference line corresponding to an age of 1788 Ma with an intercept at $^{87}Sr/^{86}Sr$ = 0.7022 calculated through the data of the Naub diorite intruding the Elim Formation on the same farm (with a Rb-Sr age of 1725 Ma +/- 74 Ma; REID et al., 1988) and through the samples collected during this study. This lends confirmation to the minimum age of the Elim Formation being approximately 1780 Ma as deduced from the U-Pb analyses of the Opetjie pluton and it also shows that a certain homogenisation between rocks of the Elim Formation and the intruding Naub diorite has conceivably taken place.

Rb-Sr dating of several plutons of the Piksteel Intrusive Suite has shown reference ages of 1298 Ma and 1057 Ma for the Piksteel type locality, 1164 Ma and 878 Ma for the Opetjie pluton and 1489 Ma for the Borodino pluton. All these reference ages are well below the assumed minimum age for the members of the Piksteel Intrusive Suite of about 1.8 Ga and thus clearly indicate the occurrence of rejuvenation processes affecting these granitoids. The obtained reference ages might be explained by the occurrence of Gamsberg-related alteration and homogenisation processes while those of the Opetjie pluton also indicate a later phase of alteration which could possibly be related to the Damara Orogeny. The reference age of the Borodino pluton of 1489 Ma, higher than the U-Pb zircon age of 1369 Ma of the same samples, probably reflects a partial reset of the analyzed Rb-Sr system of this pluton in combination with a steepening of its isochron due to alteration processes taking place after 1369 Ma.

The analyses of seven Nueckopf rhyolites yielded a reference age of 948 Ma +/- 25 Ma which might very well represent the formation age of these volcanics which partly overlie members of the Gamsberg Granite Suite and thus could not be affected by Gamsberg related alteration. A two point isochron calculated through the data of two rhyolitic dykes crosscutting the Marienhof Formation yielded an age of 813 Ma with an intercept at a high $^{87}Sr/^{86}Sr$ ratio of 0.717. This age, which is in conflict with the U-Pb age of the samples of 1210 Ma and the comparatively high initial ratio, indicate that the Rb-Sr system of these two samples must have been disturbed after their formation.

The analyses of 5 basic dykes crosscutting the whole sequence of the Rehoboth

Basement Inlier have yielded a reference age of 821 Ma +/- 33 Ma for four of the five analyzed specimens. This age probably represents late to post-Mokolian dilatational tectonic processes in relation with the early rifting stages of the Damara system.

4.2.4 K-Ar Dating

K-Ar age determinations were carried out on five biotite separates from samples of the Mooirivier Complex collected in the Spreetshoogte Pass area, on two biotite separates and nine muscovite/sericite separates from various outcrops of the Elim Formation, on one biotite and 11 white mica/phyllite concentrates and on seven phyllite whole rock aliquots from samples collected within outcrops of the Marienhof Formation, on five white mica separates from the Billstein Formation, on six biotite concentrates of members of the Piksteel Intrusive Suite and on five whole rock aliquots of basic dykes crosscutting the Rehoboth Basement Inlier.

The obtained results have shown that formation ages are no longer recorded by the analyzed K-Ar systems and that some radiogenic argon was lost from most of the separates due to alteration processes occurring after the closure of the K-Ar systems. This method has proved to be very successful in analysing the younger history of the Rehoboth Basement Inlier.

The analyses of the Marienhof and Billstein samples, which partly were collected in the northern central part of the Rehoboth Basement Inlier and along the central section of the Areb shear zone, have all yielded individual apparent ages between 490 Ma and 529 Ma, thus indicating that the K-Ar systems of biotites and white micas of the northern part of the Rehoboth Basement Inlier have been reset by the Damaran Orogeny. The biotite separates of the Mooirivier samples, which were collected in the vicinity of the western branch of the Areb shear zone in the Spreetshoogte pass area, yielded ages ranging between 404 Ma and 545 Ma, thus indicating the occurrence of Damaran as well as post-Damaran alteration processes affecting the analysed biotites. Samples collected further towards the east yielded higher ages compared to those collected further west. This might indicate an alteration influence by the opening of the South Atlantic. The apparent individual ages of biotites and white micas of Elim samples collected on the farm Areb, directly along the central part of the Areb shear zone, yielded individual apparent ages between 315 Ma and 397 Ma, while individual ages between 728 Ma and 782 Ma were observed for white mica concentrates collected a few hundred meters away from the shear zone. This indicates that the Areb shear zone must have been active after the Damaran Orogeny until at least 315 Ma ago, and that these activities were restricted to the close vicinity of the shear zone, as the ages of the white micas collected at a further distance were not even completely reset by the Damaran Orogeny. A decrease of the influence of the Damaran Orogeny could also be shown with the analyses of biotite separates from Piksteel granitoids which yielded ages between 647 Ma and 955 Ma, thus showing that post-Gamsberg rejuvenation processes must have occurred, probably in connection with the Damara Orogeny, and at the same time indicating that the Damara related metamorphism did not reach the biotite K-Ar reset temperature of 300°C further south than 23°55'S. This in turn indicates that Damara K-Ar ages of 478 Ma to 547 Ma which are reported for the Namib Naukluf Nappe Complex to the south of the Rehoboth Basement Inlier by AHRENDT et al. (1977) must represent transported ages. The whole rock K-Ar dating of the basic dykes did not show results which are consistent with the knowledge on the geology of the area due to the occurrence of argon exchange processes such as loss and/or inheritance of argon of the analysed K-Ar systems.

5. Discussion of the Significance and Limitations of the Applied Isotopic Dating Techniques

With the exception of SEIFERT (1986), who was working in a narrowly limited area, all the earlier workers who carried out radiometric age determinations in the Rehoboth area, such as CLIFFORD (1967), BURGER et al. (1973, 1973-74, 1975-76 a & b, 1977-78 and 1980), AHRENDT et al. (1977) and REID et al. (1988), always used only one method of dating for their respective studies on relatively isolated areas within the Rehoboth Basement Inlier. This prevented the recognition of the continuity of the multitude of tectonic stages affecting the Rehoboth area but nonetheless led to the construction of a general framework for the geological history of the Rehoboth Inlier. For the present study, more age determinations were carried out than had ever previously been done. The application of various methods of dating and geochemical investigations on the same rock samples now enables us to provide a better insight into the history of the Rehoboth Basement Inlier.

The combination of Sm-Nd and REE studies on various granitoids and amphibolites has shown that the respective systems have been relatively unaffected by the observed hydrothermal and up to low grade metamorphic alteration of the analysed specimens. The Sm-Nd method of dating was thus capable of providing the oldest ages. These first Sm-Nd ages of the Rehoboth area are considered to represent formation ages for the Rehoboth crust. The use of the U-Pb method of dating on zircon populations of members of the Piksteel Intrusive Suite has shown that the late Mokolian intrusion of the Gamsberg Granite Suite and the Damara Orogeny led to a severe loss of lead from the analyzed zircons. As the zircon populations of rhyolitic dykes assigned to the Gamsberg Granite Suite and crosscutting the Marienhof Formation have preserved a «Gamsberg age» of 1210 Ma, it can be assumed that the alteration processes leading to the observed lead loss from the zircons of samples of the Piksteel Instrusive Suite occurred in relation to the intrusion of the Gamsberg Granite Suite, which also led to the occurrence of a major hydrothermal alteration phase in the Rehoboth Basement Inlier. The existence of such a hydrothermal alteration phase in relation to the intrusion of the Gamsberg Granite Suite can, on one hand, be deduced from thin section investigations showing, for example, saussuritisation of plagioclase and partial chloritisation of biotite of pre-Gamsberg lithologies throughout the Rehoboth Basement Inlier; on the other hand it is shown by the Rb-Sr results. None of the pre-Gamsberg formations were datable by the Rb-Sr method. Almost all the attempts of dating pre-Gamsberg amphibolitic to granitoid lithologies by the Rb-Sr method resulted either in «Gamsberg ages» ranging between 1000 and 1250 Ma, or in ages ranging between the age of the Gamsberg intrusive cycle and the assumed age of the Piksteel Intrusive Suite. The fact that the Gamsberg plutons themselves and the younger basic dykes are reproducibly datable by the Rb-Sr method (SEIFERT, 1986; REID, 1988; this study) shows that the Rb-Sr whole rock systems of the rocks of Rehoboth Basement Inlier were virtually unaffected in post-Gamsberg times, although further alteration processes must have affected the entire area as is shown by the K-Ar data of this study. The K-Ar method of dating was a good tool to investigate the influence of the Damara Orogeny on the Rehoboth Basement Inlier by showing a complete reset of the K-Ar systems of biotite and white micas in the northern part of the inlier, while in the southern part of the inlier only a rejuvenation but not a complete reset of the K-Ar systems was detectable, thus indicating a decreasing influence of the pan-African Damara Orogeny towards the south. A rejuvenation of the K-Ar ages of biotites and white mica/sericite to values below 400 Ma could be observed along zones of major tectonic lineaments, thus indicating tectonic activity in the area after the end of the Damara Orogeny. It can thus be concluded that the K-Ar systems of biotites and white micas were much more sensitive to the alteration processes occurring in the Rehoboth Basement Inlier compared to whole rock Rb-Sr systems and to U-Pb zircon systems, which were indeed affected by post-formation alteration processes in relation to the Gamsberg magmatism but which have not, in any of the investigated areas, been reset by the Damaran Orogeny. The whole rock Sm-Nd systems of the analysed specimens therefore represent the only isotopic systems which remained virtually closed to the multitude of alteration processes occurring in the Rehoboth area.

6. Geological History of the Rehoboth Basement Inlier based on the Results of this Study

A combination of the results of the Sm-Nd and U-Pb analyses has shown that the major part of the Rehoboth crust must have formed during the early Proterozoic between 2.6 and 1.8 Ga as accretionary belt extending the Archean nucleii of the Kalahari craton in a northwestern direction, as an equivalent of the younger parts of the South African and Zimbabwean Limpopo Province. During the early stages of this crustal evolution the freshly formed crust must also have been readily reworked by various stages of erosional, metamorphic and anatectical processes in order to be present today as metamorphosed volcano-sedimentary sequence including the lithologies from the Moorivier Complex at its base to the Billstein Formation at its top. The theory of an early reworking of the originally formed crust is supported by the occurrence of granitic pebbles and boulders in various formations of the Rehoboth Sequence. In this place it is worth noting that the majority of the formations from the Mooirivier Complex to the Billstein Formation originally had most similar lithological compositions, thus leaving doubts about the present stratigraphic classification according to SACS (1980), which is primarily based on tectonic and metamorphic considerations. During the Eburnian Orogeny, between about 2.0 Ga and 1.8 Ga, the Rehoboth area was intruded by the calc alkaline members of the Weener- and Piksteel Intrusive Suites, most likely generated in a collisional tectonic environment. At about 1.4 Ga before today the Alberta Mafic Complex and related intrusives were emplaced in the northern parts of the Rehoboth Basement Inlier. This was followed, between 1.25 and 1.0 Ga, by the intrusion of the members for the Gamsberg Granite Suite and related rhyolitic dykes whose related hydrothermal activities led to a strong alteration of the major part of the intruded rock sequence. At about 950 Ma the final stages of the Gamsberg magmatism led to the extrusion of the high potassium rhyolites of the Nueckopf Formation. About 130 Ma later, at approximately 820 Ma, the whole area of the Rehoboth Basement Inlier was then intruded by swarms of basic dykes in a diverging tectonic regime in directions parallel to the direction of the Areb shear zone.

The compressional phase of the Damaran Orogeny to the north of the Rehoboth Basement Inlier led to metamorphic conditions ($>300°C$) in the northern part of the inlier capable of resetting the K-Ar systems of biotites and white micas, while south of 23°55'S they were not strong enough to completely reset the K-Ar systems of biotites. The Rehoboth Basement Inlier must therefore have been overridden by nappes of the Damara Orogen as may be deduced from the Damara ages of micas from the Namib Naukluft Nappe Complex. After the Damaran Orogeny the Rehoboth Inlier was affected by the break-up of Gondwana, resulting in the opening of the South Atlantic and the reactivation of the Areb shear zone, as evidenced by the partial rejuvenation of biotite and white mica separates from samples of the Mooirivier Complex and the Elim Formation collected along the Areb shear zone, which currently yield apparent ages of 315 Ma to 427 Ma.

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Buchbesprechung

The German Continental Deep Drilling Program (KTB) (1989)

Site-selection Studies in the Oberpfalz and Schwarzwald

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Ende 1986 wurde beschlossen, dass der Beitrag der BRD für das Super-Tiefbohr-Projekt in der Oberpfalz in Nordbayern durchgeführt werden soll. Anlässlich einer Konferenz wurde vom 19.-21. September 1986 die in diesem Buch enthaltenen Unterlagen, die zu diesem Beschluss führten, präsentiert und diskutiert.

Das Buch fasst die Resultate der verschiedenen Untersuchungsprojekte aus beiden Arealen zusammen und stellt die Interpretationen und Modelle die zur endgültigen Wahl der Test-Lokation führten vor. Die ersten Resultate der Pilotbohrungen sind zum Schluss kurz erwähnt.

Die beinahe 70 Mitarbeiter haben ein riesiges Vorbereitungsmaterial für das wohl bisher grösste Bohrprojekt der Erde präsentiert, deshalb ist das Buch als Arbeitsunterlage und nicht als Übersicht zu verstehen.

GABRIEL WIENER