Sm/-Nd, Rb/-Sr and U/-Pb data from the Rehoboth Basement Inlier, Namibia: Evidence of a Paleoproterozoic magmatic arc

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Various Paleoproterozoic igneous rocks from the Rehoboth Basement Inlier of central Namibia have been analysed using the Sm-Nd-, Rb-Sr (whole rock), and U-Pb methods (on separated sphene). The samples belong to the mafic to ultramafic Alberta Complex (AC), the tonalitic to granodioritic Weener Igneous Complex (WIC), the Naub Diorite, as well as mafic metavolcanic rocks and calcsilicate rocks of the Elim Formation (EF).

The Rb-Sr isotope system appears to be strongly disturbed in the intrusive rocks, and a complete reset is evident by subsequent tectono-metamorphic events in the metavolcanic rocks.

In contrast, the Sm-Nd isotope system has been less affected by alteration in both metavolcanic and intrusive rocks. Regression analysis of the Sm-Nd data yielded errorchrons for the investigated meta-igneous rocks between 1750 to 1900 Ma, with a best estimate at 1780 ± 80 Ma. $\varepsilon_{Nd\ (t=1800\ Ma)}$ values vary between -2 and 4 and point to slightly depleted to slightly enriched mantle as a magma source, with only little crustal contamination.

Well-constrained Sm-Nd model ages between 1965 and 2091 Ma of igneous rocks from the WIC and the EF suggest a similar source composition. However, spider diagrams of medium to highly incompatible elements show that the parental magma of the WIC has been hydrothermally overprinted by subduction, whereas the younger mafic rocks of the AC and the EF are unaffected by this process. Progressive opening of a back-arc best explains this change in geochemistry.

The U-Pb sphene (population) analyses of rare calcsilicate rocks within the Elim Formation suggest a first metamorphic event at 1777 +25/-10 Ma coinciding with the emplacement ages of Palaeoproterozoic igneous rocks in this region. It is therefore assumed that juvenile crust of the Rehoboth Basement Inlier was generated within a rather short period between approximately 1900 to about 1750 Ma within an arc to back arc system. Deformation and metamorphism occurred during or shortly after sedimentation and magmatism, and may be linked to arc accretion.

Introduction

The Rehoboth Basement Inlier in central Namibia comprises low- to medium-grade metamorphic rocks of volcanic, sedimentary, and intrusive origin (Fig. 1). According to the current lithostratigraphy (SACS, 1980) these units belong to high-grade metamorphic rocks of pre-Rehoboth age (Elim and Neuhof Formations, Mooirivier Complex), to the Paleoproterozoic Rehoboth Sequence (Marienhof, Billstein and Gaub Valley Formations), and to the Mesoproterozoic Sinclair Sequence (Nückopf, Grauwater, Dornpoort and Klein Aub Formations). In contrast, detailed mapping of the area by the first author showed, that (1) the Gaub Valley Formation grades into and is overlain by the Elim Formation, with the original contact being overprinted by later shearing; (2) there is no difference in regional metamorphic grade between the Elim and Gaub Valley Formations (both are marked by prograde amphibolite facies overprinted by retrograde greenschist metamorphism (3) the Mooirivier Complex largely consists of granodioritic orthogneiss, and the observed higher metamorphic grade and feldspar blastesis of large xenoliths within this gneiss results from contact metamorphism and injection migmatism; (4) the Marienhof Formation must be split into a low-grade domain which comprises the same lithotypes as the Billstein Formation (e.g. quartzite, conglomerate and schist) and a amphibolite facies domain comprising schist and mafic metavolcanic rocks, which is overprinted by retrograde greenschist metamorphism. Consequently, the low-grade domain of the Marienhof Formation has been merged with the Billstein Formation (Becker *et al.*, 1998). The Billstein Formation unconformably overlies the Elim and Marienhof Formations and is succeeded by the approximately 1230 Ma old Nuckopf Formation (Schneider *et al.*, this vol.). A maximum age is constrained for the deposition of the Billstein Formation by the circa 1700 Ma old Piksteel granodiorite, which does not intrude this unit (Becker, 1995; Becker and Brandenburg, 2000; Becker *et al.*, 2003).

Major plutonism occurred during both deposition of the Rehoboth and Sinclair Sequences. The composition of the igneous rocks varies from mafic/ultramafic (AC) to dioritic and tonalitic (WIC and Naub diorite) and granodioritic/granitic (Piksteel and Gamsberg Suites). Field observations as well as geochronological, isotopic and geochemical data all support a cogenetic relationship between the WIC and metavolcanic rocks of the Gaub Valley Formation (Becker, 1995, 1996; Nagel *et al.*, 1996). Similarly, mafic metavolcanic rocks of the Elim Formation show strong affinity to gabbroic rocks from the Marginal Zone of the AC (Becker and Brandenburg, 2000). The emplacement ages of the latter two units are poorly constrained. One Rb-Sr whole rock age from the Alberta Complex of 1442 ± 32 Ma (Reid *et al.*, 1988) is rather ambiguous, due to a possible metamorphic overprint during the Pan-African Orogeny. The age of the Elim Formation has been determined by Sm-Nd whole rock analysis as 1820 ± 185 Ma (five out of six data points) and ε_{Nd} = 3.87±3.44 (Ziegler and Stoessel, 1993). However, the significantly disturbed Rb-Sr isotope system indicates post-magmatic alteration within this unit, which also may have affected the Sm-Nd isotope system (Ziegler and Stoessel, 1993).

This paper presents new Rb-Sr, Sm-Nd and U-Pb isotope analyses from selected Paleoproterozoic units of the Rehoboth Basement Inlier as well as a comparison with existing data in order to test possible genetic relationships between the intrusive and extrusive igneous rocks of this period, and to propose an overall plate tectonic setting.

Analytical techniques

U-Pb sphene (population) method

The sampling and analytical procedures applied during this study are described by Becker *et al.* (1996). Sample preparation and isotope analysis was performed at the Universität of Göttingen/Germany. Uranium and lead measurements were carried out on a multi-channel TIMS (Finnigan MAT 262 RPQ+). Age calculations are based on the constants recommended by IUGS (Steiger and Jaeger, 1977). Initial lead isotope ratios for the correction of Pb_{com} were calculated using the two stage model of Stacey and Kramers (1975) corresponding to an age of 1770 Ma, and errors and error calculations in the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ data were calculated according to Ludwig (1980). These errors are based on assigned errors of the U-Pb ratio in the spike (0.15%), in the initial ratios $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ (1%), in the blank lead (1%) and the concentration of the blank lead (50%). Initial and blank lead has been assigned a correlation factor of 0.7. The error ellipses for the data points were calculated at a confidence level of two sigma on the concordia diagrams. A York II regression calculation was used to obtain the ages and errors of intercepts of the best-fit line with the concordia (York, 1969). Regression errors are two sigma where the MSWD < F and augmented by SQRT (MSWD-F) when MSWD > F, the critical value, which is a function of the replicate analyses, the number of data points and the x-level.

Rb-Sr and Sm-Nd whole rock method

Whole-rock aliquots (100 mg) were spiked with double spikes composed of ^{87}Rb, ^{84}Sr, ^{149}Sm and ^{150}Nd before being dissolved overnight (12h) in superclean teflon autoclaves in a 1:1 mixture of 3 ml HF (4*) and $HClO_4$ (4*) at 180°C. The solutions were evaporated at 150°C and the residue dissolved overnight (12h) in 6 N HCl (4*), thus being transferred into chloridic form. The obtained solutions were again evaporated at 150°C and dissolved within 2 hours in 3 ml 2.6 N HCl (4*) at 80°C. Subsequently, insoluble residues were removed from the solution by centrifuge. Separation of Rb, Sr, Sm, and Nd was carried out by column chemistry using quartz columns filled with cation exchange resin (Dowex Ag 50Wx8). Finally, Sr was purified a second time in order to remove all Rb, while Sm and Nd were purified by means of HDEP-teflon columns (4* = distilled 4 times). Errors based on replicate analyses using standard procedures are 1% for $^{87}Rb/^{86}Sr$, 0.01% for $^{87}Sr/^{86}Sr$, 0.5 % for $^{147}Sm/^{144}Nd$ and 0.003% for $^{143}Nd/^{144}Nd$. For age calculations the constants recommended by IUGS (Steiger and Jaeger, 1977) were used, with statistical regression calculated according to the method of York (1969). Regression errors were calculated as described above. Calculation of model ages (i.e. T_{CHUR} and T_{DM}) is based on the constants of Wasserburg *et al.* (1981) and Michard *et al.* (1985).

Results

Sm-Nd and Rb-Sr whole rock isotope systematics

Sm-Nd and Rb-Sr analyses were carried out on samples from the AC, the Elim Formation, the WIC and the Naub diorite. In addition, one international reference standard (AN-G) was analysed. Sample localities are shown in Fig. 1, and the analytical results are given in Table 1.

Table 1: Results of Sm/Nd, Rb/Sr isotope analysis (whole rock)

Sample No.	Farm	87Rb/86Sr	87Sr/86Sr	εSr (1800 Ma)	147Sm/144Nd	143Nd/144Nd	T_{DM}	T_{CHUR}	εNd (1800 Ma)
Alberta Complex									
PXD1		0.011	0.70411	19.0	0.1545	0.51237	1678	972	4.52
CZ01		0.017	0.70285	-1.4	0.1660	0.51228	2246	1748	0.21
CZ06	Alberta	0.011	0.70373	13.4	0.2196	0.51294		2015	0.64
BZ01		0.42	0.70407	6.7	0.2695	0.51361	1587	2027	2.14
BZ05		0.061	0.70409	0.2	0.1525	0.51227	1842	1261	3.08
UZ02	Nauams	0.051	0.70442	8.6	0.1837	0.51238	2884	2951	-1.95
UZ04		0.271	0.70878	-10.6	0.2616	0.51350	1489	2021	1.86
Elim Formation									
EF01		0.048	0.70478	14.7	0.1577	0.51227	1984	1420	1.92
EF02	Kobos	0.042	0.70382	3.3	0.1591	0.51230	1964	1366	2.11
EF03		0.041	0.70419	8.8	0.1612	0.51233	1952	1308	2.26
Weener-Naub Intrusions									
PR01		0.692	0.72334	41.5	0.1436	0.51204	2085	1719	0.55
PR18	Weener	0.443	0.71696	42.6	0.1123	0.51170	1965	1699	1.11
PR24		0.364	0.71277	12.1	0.1538	0.51222	1991	1481	1.77
RD07		0.737	0.72626	66.5	0.1256	0.51179	2091	1820	-0.18
280396-1	Naub	0.203	0.70785	1.5	0.1163	0.51174	1969	1691	1.14
XE01	Weener	0.015	0.70978	98.3	0.2113	0.51297	2031	3451	3.13
XE01*		0.014	0.70980	98.7	0.2113	0.51296	2231	3305	2.86
Standard									
AN-G		0.033	0.70249	-12.1	0.1774	0.51232	2702	2509	-1.78

Elim Formation

The Elim Formation is exposed in many isolated outcrops within the Rehoboth Basement Inlier over an area of approximately 500 km^2. On Farm Areb North 202 the Elim Formation rests with a sheared contact on the Gaub Valley Formation, whereas on Farm Alberta 175, a transitional contact over 50 m has been observed between the two units. The lower portion of the Elim Formation comprises mainly metapelite and meta-arenite, which were deposited under shallow water conditions. They grade into and are overlain by dominantly mafic and subordinate felsic metavolcanic rocks, the former attaining a maximum thickness of several 100 metres. The original sedimentary and volcanic rocks were hydrothermally affected during or immediately after deposition. This hydrothermal event is evident in Mn-rich magne-tite-quartzite, epidotised metabasalt, muscovite schist, and quartz-magnetite stockwork mineralisation. Detailed descriptions of individual rock types are given by Brewitz (1974), Schalk (1988) and Becker and Brandenburg (2000). Geochemically the mafic metavolcanic rocks show affinity to subalkaline, tholeiitic E-MORB basalts with various element ratios pointing to an island arc or back arc-related environment (Ziegler & Stoessel, 1993; Becker and Brandenburg, 2000). The first metamorphic event occurred under amphibolite facies conditions (sillimanite in) and pre-dates the deposition of the Billstein Formation. Subsequent retrograde greenschist metamorphism is related to the Pan-African orogenic event.

Three samples for isotope analyses were taken from mafic metavolcanic rocks on Farm Kobos 321. High CaO and increased Ni and Cr concentrations were found in these rocks, whereas Al, Mg and Cu are relatively low (Becker and Brandenburg, 2000). Muscovite schist intercalated with the metabasaltic rocks is interpreted as metatuffite which has been affected by potassic metasomatism. Both the geochemical characteristics and the presence of muscovite schist suggest strong hydrothermal alteration in this area caused by convection of seawater close to a spreading centre. Therefore, the Rb-Sr ratio as well as the $^{87}Sr/^{86}Sr$ isotope system have probably been already disturbed at an early stage. As variation of the Rb-Sr-ratio within the present data set is low, literature data from the same area and from the neighbouring Farm Samkubis 516 (Ziegler and Stoessel, 1993) have been included into a regression analysis. Two samples were excluded from the analysis, because they deviate significantly from the regression line (KAW3009, KAW3005). The remaining eight samples poorly define an errorchron (MSWD = 24.5) with an age of 1375 ± 155 Ma and an initial ε_{Sr} of 4.8 ± 4.4 (Fig. 2).

However, the REE-pattern of the analysed samples appear to be almost unaffected by the hydrothermal overprint (Fig. 3). Unfortunately, the Sm-Nd ratios of these samples vary only slightly, which results *a priori* in large regression errors. Therefore, literature Sm-Nd

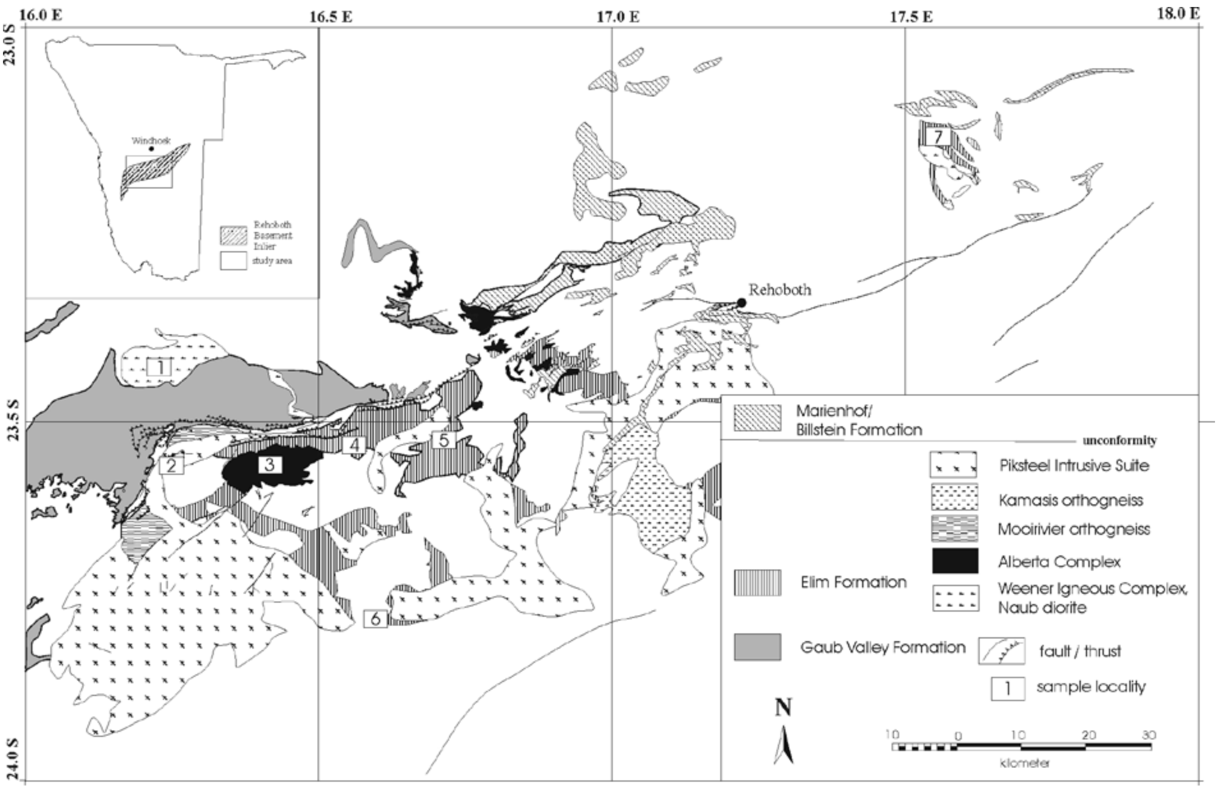


Figure 1: Simplified geological map of the Rehoboth area - Paleoproterozoic units and sample localities (Farm names and numbers): (1) Weener 193 , (2) Namibgrens 154, (3) Alberta 175, (4) Elim 214, (5) Kobos 321, (6) Grauwater 341, (7) Naub 274

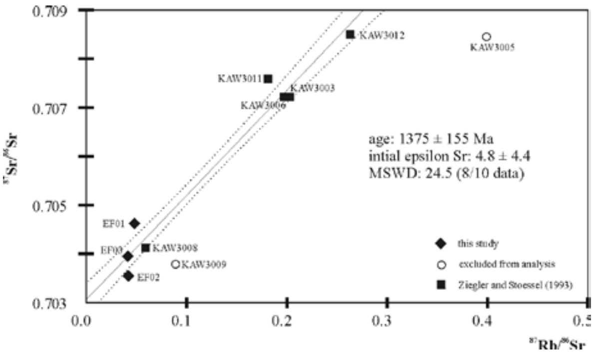


Figure 2: Rb-Sr errorchron diagram for samples from of the Elim Formation (stippled lines mark error envelope)

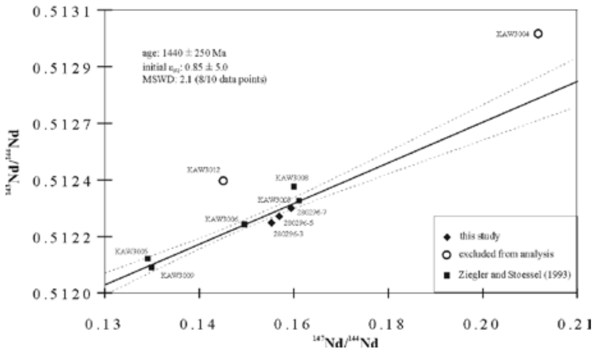


Figure 4: Sm-Nd errorchron diagram of samples from the Elim Formation (stippled lines mark error envelope)

have also been included into the regression analysis, which yields an errorchron (MSWD = 2.1, 8/10 data) of 1440 ± 250 Ma with an initial ε_{Nd} of 0.85 ± 5.0 (Fig. 4). Model ages are well constrained, with T_{DM} varying between 1952 and 1984 Ma and T_{CHUR} between 1308 and 1420 Ma, respectively.

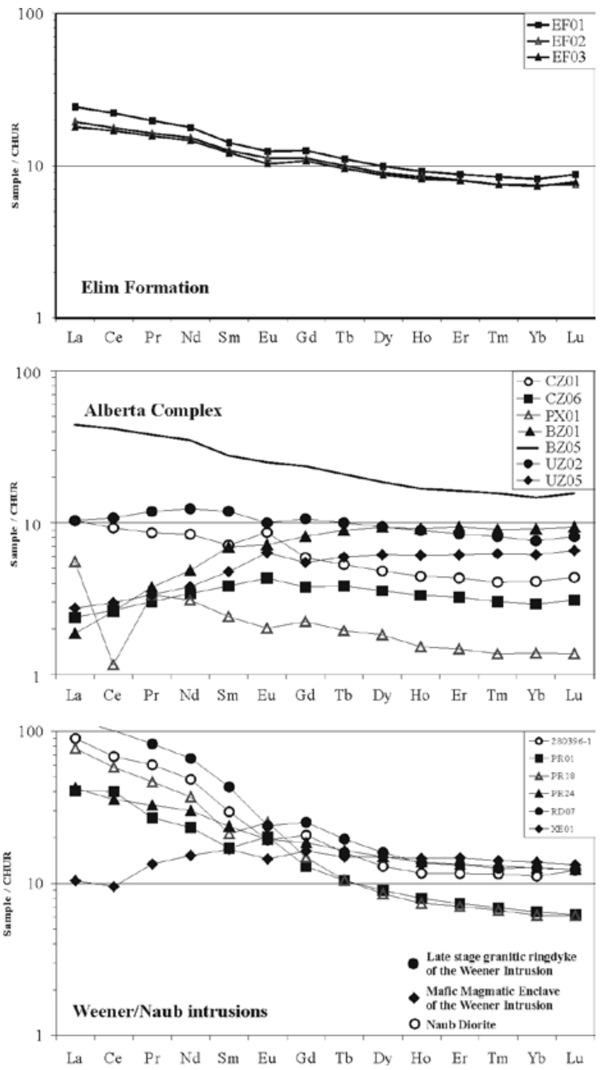


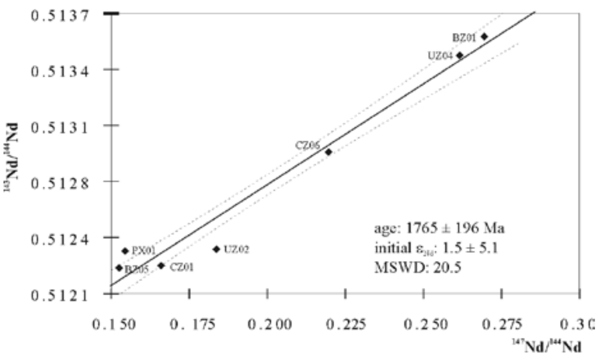
Figure 3: CHUR-normalised REE-distribution patterns of analysed samples. Normalising values for REE from Preston, 2003.

Alberta Complex (AC)

The AC is situated some 140 km southwest of Windhoek, immediately to the south of the Areb Shear Zone, a prominent shear belt that defines the boundary between the Southern Margin Zone and the Southern Foreland of the Pan-African Damara Orogen (Fig. 1). The intensely faulted complex, which encompasses an area of approximately 100 km^2, forms an oval-shaped body, some 16 km in length and 6.5 km in width, and intruded the metasedimentary rocks of the Elim Formation. The AC is essentially composed of a thick succession of cumulate gabbroic rocks, the Layered Sequence, which was intruded at a later stage by a pegmatoid phase and ultramafic rocks (De Waal, 1966). Based on field observations, the Layered Sequence has been subdivided into the Marginal, Basal, Central, and Upper Zones. Geochemical data document the high affinity of gabbros from the Marginal Zone to mafic metavolcanic rocks of the Elim Formation (Becker and Brandenburg, 2000).

The distribution of rare earth elements (REE) within the AC has been mainly controlled by the crystallisation of pyroxene and plagioclase within a local magma chamber (Becker and Brandenburg, 2002). Figure 3 shows the spider diagrams of samples from the AC, which are marked by positive Eu-anomalies (plagioclase cumulate), by variable enrichment of heavy REE relatively to light REE (pyroxene cumulate) or mild enrichment of light REE relatively to heavy REE (original or slightly fractionated melt). Therefore, the Sm-Nd ratio between these samples varies considerable. The seven analysed samples cover the whole range of the observed Sm/Nd ratios. Regression analysis yielded an errorchron (MSWD=20.5) with an age of 1765 ± 196 Ma and an initial ε_{Nd} of 1.5 ± 5.1 (Fig. 5). T_{DM} model ages vary be-tween 1489 and 2884 Ma and T_{CHUR} between 972 and 2951 Ma, respectively. It is remarkable that several T_{CHUR} model ages are older than the T_{DM} age of the respective samples, which might result from the extreme fractionation of the REEs (Fig. 3).

The results of the Rb-Sr isotope analyses are presented in Fig. 6. The data points for these samples define an errorchron (MSWD = 6.98; 5/7 data) with an age of 1402 ± 117 Ma and an initial ε_{Sr} of 3.7 ± 3.0, which



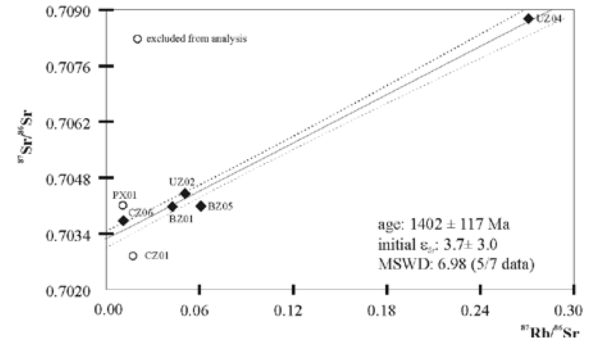


Figure 5: Sm-Nd errorchron diagram for samples from of the AC (stippled lines mark error envelope)

Figure 6: Rb-Sr errorchron diagram for samples from of the AC (stippled lines mark error envelope)

is in agreement with the results obtained by Reid *et al.* (1988). However, the regression line is mainly defined by one sample only, which shows an increased Rb/Sr ratio (UZ04).

Weener Igneous Complex (WIC) - Naub diorite

The WIC and Naub diorite are the most prominent members of a magmatic suite, which is intrusive into the Elim and Gaub Valley Formations. The type areas of these intrusions are located in the extreme western (Weener) and eastern (Naub) parts of the Rehoboth Basement Inlier. The rocks range from gabbro and diorite to tonalite and granodiorite.

Field observations show that the WIC probably represents the volcanic centre from which the pyroclastic rocks of the Gaub Valley Formation have been deposited (Becker *et al.*, 1994). Such a model is supported by geochemical data that document a strong affinity be-tween both units (Becker, 1995). In addition, similar ages for the WIC and the Gaub Valley Formation have been determined with the conventional U-Pb zircon population method at 1768 ± 10 Ma and 1782 ± 10 Ma, respectively (Becker *et al.*, 1996; Nagel *et al.*, 1996). Rb-Sr whole rock analyses yielded data of 1655 ± 123 Ma and 1752 ± 121 Ma; initial ^{87}Sr-^{86}Sr isotope ratios were determined at 0.7041 ± 13 and 0.7033 ± 13, respectively.

The Naub diorite has intruded metasedimentary rocks and mafic volcanic rocks of the Elim Formation, as well as quartzite and migmatised schist of supposed pre-Elim age (Schalk, 1988). The main body, with an outcrop area of approximately 10 km^2, is marked by a strong gneissic fabric. Minor pyroxenite occurs at the centre of the intrusion as an up to 5 m thick layer. Rb-Sr whole rock analyses yielded an age of 1752 ± 52 Ma, with an initial $^{87}Sr/^{86}Sr$ isotope ratio of 0.7041 ± 3 (Reid *et al.*, 1988). Geochemical analyses document the calc-alkaline character of the Naub diorite and its strong affinity to the WIC (Becker and Brandenburg, 2000).

The results of Rb-Sr isotope analyses are presented in figure 7. The combination of our own and published data from the WIC yields an errorchron age (MSWD = 63.8; 7/8 data) of 1714 ± 282 Ma, with an initial ε_{Sr} value of 29 ± 27. Similarly, five samples from the Naub diorite define an errorchron age (MSWD=18.6) of 1839 ± 132 Ma, with an initial ε_{Sr} of 11 ± 16.

For Sm-Nd regression analysis, we combined the samples from the WIC and Naub diorite and the resulting errorchron (MSWD = 2.58) yields an age of 1889 ± 222 Ma and an initial ε_{Nd} of 1.6 ± 3.7 (Fig. 8). T_{DM} ages are well-defined and vary between 1965 and 2091 Ma, whereas T_{CHUR} ranges from 1481 to 1820 Ma (Table 1).

U-Pb sphene analyses

U-Pb sphene analyses were carried out on sphenes from calcsilicate rocks of the Elim Formation, which have been interpreted as metavolcanic rocks (Schalk,

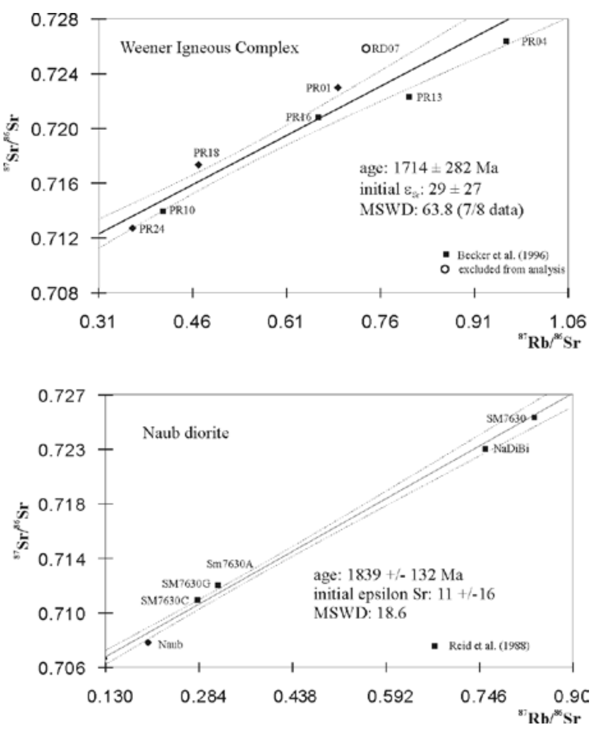


Figure 7: Rb-Sr errorchron diagram of samples from of the WIC and Naub diorite (stippled lines mark error envelope)

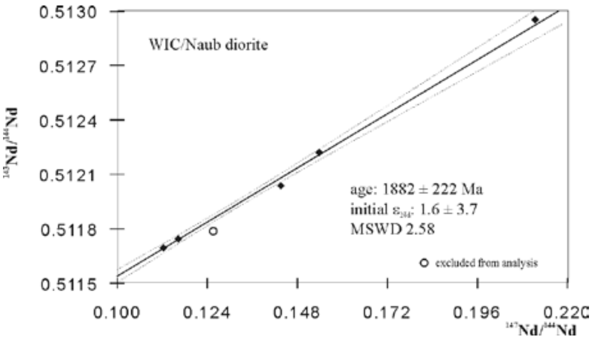


Figure 8: Sm-Nd errorchron diagram of samples from of the WIC and Naub diorite (stippled lines mark error envelope)

1988). On Farm Grauwater 341, these rocks rest on underlying amygdaloidal metabasalt with a tectonic contact and interfinger with overlying dolomitic to calcitic marble. Quartz, biotite, feldspar, tremolite and epidote are the major phases, while secondary calcite occurs in thin veinlets.

Results of the isotopic analyses are shown in figure 9 and table 2. All fractions are characterised by similar concentrations of uranium (65-68 ppm), radiogenic lead (28-31 ppm) and low Pb_{com} (1-2 ppm). Five size fractions cluster closely at the upper intercept of the resulting discordia. No correlation exists between the grain size, position on the discordia and uranium concentrations cluster closely at the upper intercept of the resulting Discordia. No correlation exists between the grain size, position on the discordia and uranium concentration. The best-fit chord (four out of five data points) defines a geochron (MSWD = 2.5) with an upper intercept of 1788 +49/-14 Ma and a lower ill-defined intercept of 1375 ± 230 Ma. Regional igneous activity between 1250-1100 Ma (Schneider *et al.*, this vol.) may have caused partial reset of the U-Pb isotope system. Therefore, constraining the lower intercept at 1250 Ma yields an upper intercept of 1777 +25/-10 Ma (MSWD = 3.0). ^{206}Pb-^{238}U, ^{207}Pb-^{235}U and ^{207}Pb-^{206}Pb model ages scatter in a narrow range between 1724 and 1775 Ma, which is due to the low discordance of the data.

In addition, U-Pb analyses were performed on sphene from orthogneiss (Farm Naub 274), migmatite (Farm Namibgrens 154), and meta-arenite of the Elim Formation (Farm Elim 214) (Table 2, Fig. 1). In contrast to the calcsilicate rocks, concentrations of Pb_{com} are high in these samples, as compared to U and Pb_{rad}. Hence, the regression analysis resulted in very large errors. It is noticeable, however, that the oldest ^{207}Pb-^{206}Pb ages have been determined for sphene of the Mooirivier Complex, whereas the youngest ages, determined for sphene from orthogneiss on Farm Naub 274, coincide with the general time of Mesozoic magmatism in this area.

Discussion

Sm-Nd and Rb-Sr whole rock data

The considerable disturbance of the Rb-Sr isotope system is shown by both data from literature (Ziegler and Stoessel, 1993) and our data presented here. Thus, all regression lines are classified as errorchrons. A partial or complete reset of the Rb-Sr system at some stage after emplacement of the igneous rocks is documented in the mafic metavolcanic rocks of the Elim Formation, which yielded a date of 1375 ± 155 Ma (regression analysis). However, field observations and geochemical analyses clearly indicate considerable alteration of these rocks. The determined age broadly coincides with

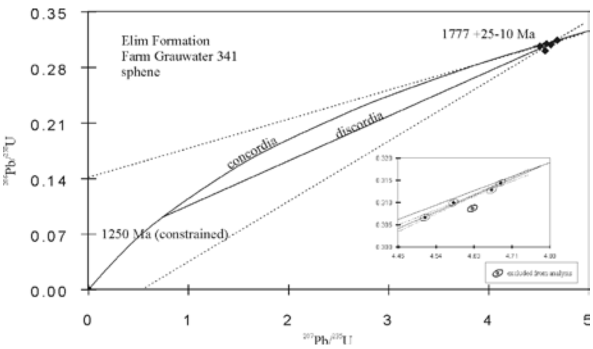


Figure 9: Concordia diagram for sphene from of calcsilicate rocks of the Elim Formation - Farm Grauwater 341

Table 2: Results of U/Pb-isotope analyses from sphene (population method)

sample		fraction	concentration				measured ratios			calculated ratios			calculated ages [Ma]		
Locality / Sample No	Lithological Unit/ rock type		U [ppm]	Pb_{ges} [ppm]	Pb_{rad} [ppm]	Pb_{com} [ppm]	206Pb/ 204Pb	207Pb/ 206Pb	208Pb/ 206Pb	206Pb/ 238U	207Pb/ 235U	207Pb/ 206Pb	(two-stage model, Stacey & Kramers, 1975)		
Farm Grau- water 060396-2	Elim Formation calcsilicate	100-125μ	65.1	30.35	28.64	1.71	669	0.1285	0.5644	0.3128	4.665	0.1082	1755	1761	1769
		80-100μ	65.1	29.93	28.75	1.18	883	0.1225	0.5759	0.3100	4.578	0.1071	1741	1745	1751
		60-80μ	68.1	31.39	30.25	1.14	929	0.1232	0.5889	0.3087	4.621	0.1086	1734	1753	1776
		45-60μ	66.6	31.64	30.52	1.12	948	0.1225	0.6094	0.3144	4.686	0.1081	1762	1765	1768
		<45μ	66.5	30.78	29.84	0.94	1007	0.1202	0.6167	0.3067	4.512	0.1067	1724	1733	1744
Farm Naub 220396-2	Kamasis orthogneiss	80-100 μ	0.745	1.451	0.205	1.25	21.7	0.7297	1.803	0.1876	2.204	0.0852	1108	1182	1320
		125-160 μ	0.873	1.385	0.168	1.22	21.1	0.7458	1.825	0.1358	1.393	0.0744	821	886	1052
Farm Na- mibgrens 260396-2	Mooirivier Complex Migmatitic quartz mica schist	80-100 μ	3.66	15.41	1.795	9.72	19.6	0.8097	2.011	0.2601	5.216	0.1455	1490	1855	2293
		>100 μ	7.22	23.47	2.459	21.0	19.1	0.8218	2.049	0.1775	2.790	0.1140	1053	1352	1864
Farm Elim 030396-7	Elim Formation metapsammite	100-120 μ	25.3	123.1	9.721	113	19.3	0.8110	1.910	0.2887	3.932	0.0987	1635	1620	1601

a period of major Mesoproterozoic bimodal magmatism and hydrothermal activity in this region.

In contrast to the Elim metavolcanic rocks, the calc-alkaline WIC and Naub diorite have been less affected by alteration. As a result, more reliable and similar ages between 1700 and 1900 Ma were obtained by both the Sm-Nd and Rb-Sr methods, with initial ε_{Sr} between 11 ± 16 and 29 ± 27. These data coincide with a U-Pb zircon (population) date of 1768 ± 10 Ma for the WIC, which has been interpreted as time of crystallisation (Becker *et al.*, 1996). The maximum age of crustal components involved in the generation of these magmas is constrained by T_{DM} model ages between 1965 and 2090 Ma.

Therefore, isotopic data constrain the origin of the magma despite of some post-emplacement alteration. Recalculation of ε_{Nd}- and ε_{Sr}-initials values at 1800 Ma yield means of 0.55 ± 0.94 and 19.6 ± 8.3, respectively. Data from the WIC and the Naub diorite plot in the first quadrant of the Nd-Sr correlation diagram (Fig. 10). All data define a curved trajectory suggesting binary mixing of two homogeneous end members. Average N-MORB (at 1800 Ma) has been included into the diagram and plots in the continuation of the trajectory. A decrease of ε_{Nd} and an increase of eSr is evident relative to the inferred degree of fractionation in samples PR24 to RD07, and this might indicate that the degree of mixing correlates with the degree of fractionation. Case studies of recent magmas revealed that such systematic isotopic variations are typical of the contamination of mantle-derived magma by some 20% of an upper crustal component (McCulloch and Chappell, 1982). Comparison with these modern magmas classifies both units as calcalkaline I-type granitoids. In contrast, one analysed ma-fic magmatic enclave (XE01) from within the WIC is offset from the trajectory by the very high ε_{Sr}, whereas ε_{Nd} of XE01 is between the values of PR24 and N-MORB. This pattern suggests complete overprint of the Rb-Sr isotope system. However, the Sm-Nd isotope system remained closed and shows affinity to N-MORB isotopic composition. This affinity is supported by flat CHUR-normalised REE patterns of sample XEO1 and element/MORB ratios of the medium to highly incompatible elements close to unity (Becker and Branderburg, 2000).

The isotopic systems from the AC and Elim Formation are difficult to interpret. As Rb/Sr ratios are very low, gain of radiogenic ^{87}Sr through time was insignificant. Subsequent alteration of the Rb/Sr ratio should not affect the recalculation of the initial $^{87}Sr/^{86}Sr$ ratios. Any variation of the $^{87}Sr/^{86}Sr$ ratios would be due to magmatic mixing processes. However, calculation of ε_{Sr} vs. ε_{Nd} at different times shows that the data never plot on a mixing line or converge at an initial value. This indi-cates again post-magmatic alteration of the Rb-Sr isotope system. Consequently, the mixing hypothesis cannot be tested by the combination of both isotope systems.

Mixing has been also tested with the Sm-Nd isotope system, which generally is less affected by alteration. Here, presentation of the Nd-isotope data in a $\varepsilon_{Nd\ (t=1800\ Ma)}$ versus $^{147}Sm/^{144}Nd$ diagram reveals two trends (Fig. 11): samples UZ02 to PX01 show significant variation of the ε_{Nd} and minor variation of the Sm/Nd ratio; the resulting regression line is marked by a negative slope. In contrast, samples UZ02 to BZ01 display major variation in both ε_{Nd} and Sm/Nd, thus defining a regression line with a positive slope. This arrangement of the data probably reflects processes during emplacement of the AC, because the relative abundance of the REE changes generally little during metamorphism. Therefore, the regression curve between samples UZ02 to PX01 is interpreted as a mixing line. Samples PX01 and UZ01 are thought to approximate the composition of the end members of a binary system, which are slightly depleted mantle (PX01) and lower continental crust or enriched mantle (UZ02), respectively. In contrast, REE patterns of samples UZ02 to BZ01 show that they form clinopyroxene cumulates (Fig. 3), which are related to samples PX01 to UZ02 by magmatic fractionation. Hence, mixing (including assimilation of country rock) and magmatic fractionation occurred simultaneously.

Based on this consideration, a reduced data set has been subjected to regression analysis. Samples PX01

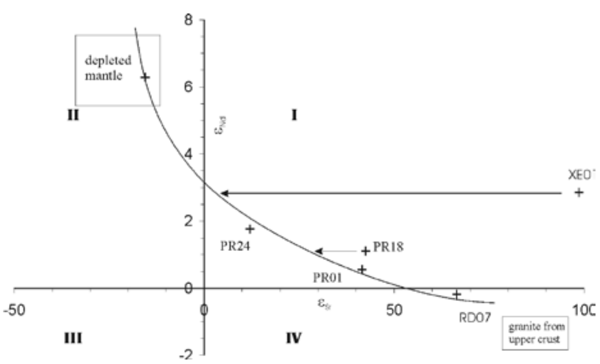


Figure 10: Nd and Sr isotopic compositions of samples from the WIC (at 1800 Ma). Note negative correlation of ε_{Sr} and ε_{Nd}

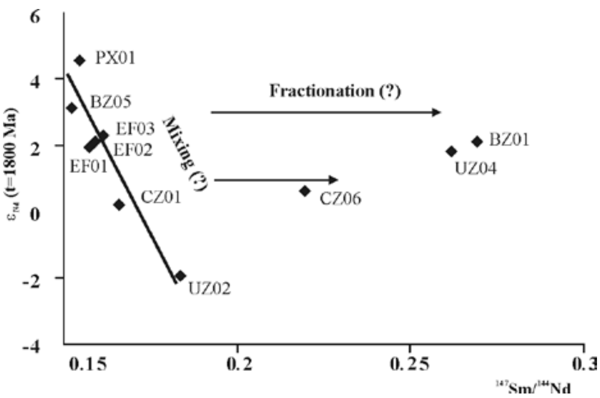


Figure 11: $\varepsilon_{Nd\ (t=1800\ Ma)}$ values of samples from the AC and the Elim Fformation versus ratios of incompatible elements (Sm/Nd)

and UZ02, which both plot on the extremes of the mixing line, have been excluded from the analysis in order to minimise the effects of such mixing processes. The resulting errorchron age of 1780 ± 80 Ma (MSWD = 3.7), with an initial ε_{Nd} of 1.7 ± 2.0, is considered as the best estimate for the time of crystallisation of the Elim igneous rocks and the AC. This age coincides with the formation age of the Paleoproterozoic Rehoboth Sequence (Becker *et al.*, 1997). The initial ε_{Nd} of 1.7 ± 2.0 suggests an origin from almost undepleted or slightly depleted mantle. Sm-Nd model T_{DM} ages of the mafic metavolcanic rocks of the Elim Formation between 1952 and 1984 Ma are considered maximum ages of the oldest juvenile crust in the Rehoboth area. They coincide with Sm-Nd model T_{DM} ages from the WIC and suggest a similar mantle source for both units. However, spider diagrams of medium to highly incompatible elements show that the parental magma of the WIC has been hydrothermally overprinted by subduction, whereas the younger mafic rocks of the AC and the EF are unaffected by this process (Becker and Brandenburg, 2000; 2002). A change in plate tectonic environment from a subduction zone (documented by the WIC) to a progressively opening backarc, with magma derived from normal astenospheric mantle (EF), best explains this change in geochemistry.

U-Pb sphene analyses

The U-Pb multigrain sphene date of 1777 +25/-10 Ma from calcsilicate rocks of the Elim Formation is interpreted as a metamorphic age. Sphene generally forms in calcsilicate rocks during contact metamorphism or regionally under greenschist to lower amphibolite facies conditions (Tröger, 1967). Similar $^{207}Pb/^{206}Pb$ ages have been obtained from two other samples in the eastern and central RBI. Unfortunately, high ratios of Pb_{com}/Pb_{rad} in these samples yield high errors and, therefore, only loosely constrain the time of regional metamorphism. Nevertheless, it may be noted that the metamorphic ages coincide with U-Pb-zircon crystallisation ages of most Paleoproterozoic igneous rocks from this region. Our data therefore suggest that the first metamorphic event of the RBI was coeval with the time of magmatism, which is best explained by arc accretion.

Conclusions

The results of this study imply that the first formation of igneous rocks in the Rehoboth Basement Inlier occurred during the period between 1950 and 1750 Ma. A distinction between the depositional age of the metavolcanic and metasedimentary rocks, the emplacement of various magmatic intrusive suites and subsequent metamorphism is not possible with the present set of geochronological data. Similar ages have been obtained in crustal segments which extend from southern Brasil through southern Africa to equatorial Africa and constitute a major crust-forming event during Paleoproterozoic times (Eburnian-Ubendian cycle). A plate tectonic model for the evolution of this belt was first proposed by Master (1993). According to this model (Fig. 12), convergence of two late Archean continents and subduction of oceanic crust towards the southeast occurred between 2.2 and 2.0 Ga and resulted in the for-mation of a magmatic arc and backarc on the leading plate in the south. At ca. 1.8 Ga ocean closure and collision ended in major orogenic deformation, high-grade metamorphism and collision related magmatism. A separate evolution is assumed for the northern part of this magmatic belt, with a second stage of backarc opening and the formation of a magmatic arc, which overprints the earlier ca. 2.0 Ga magmatic arc. Similarly, geochemical data suggest the origin of the WIC and Naub diorite in an island arc, whereas the Elim Formation evolved in a backarc setting (Becker, 1995; Becker and Brandenburg, 2000). This would be indicative of a similar history of the RBI, with prolonged or renewed ocean opening and subduction related magmatism. However, so far no U-Pb zircon ages older than 1784 Ma have been determined in the RBI and existing geochronological data rather point to the first collision of the Congo and Kalahari Cratons during the Mesoproterozoic Kibaran event (Becker *et al.*, 2003): Ages around 1300-1100 Ma are missing completely in the pre-Damaran crust of northern Namibia believed to be part of the Congo craton, whereas they define a major crustal province at the margins of the Kalahari Craton in southern and central Namibia (Namaqua and Sinclair provinces; Hoal, 1990, Becker *et al.*, 2003). In contrast, magmatic crystallisation and metamorphic ages between 1650 and 1400 Ma have been determined only in the Epupa Metamorphic Complex and Western Kaoko Belt of the Congo Craton (Kröner, 2003; Seth *et al.*, 2004, 2003). Therefore, a conservative reconstruction of any Paleoproterozoic plate tectonic configuration will be possible only once a better understanding of the Mesoproterozoic history of Namibia is achieved.

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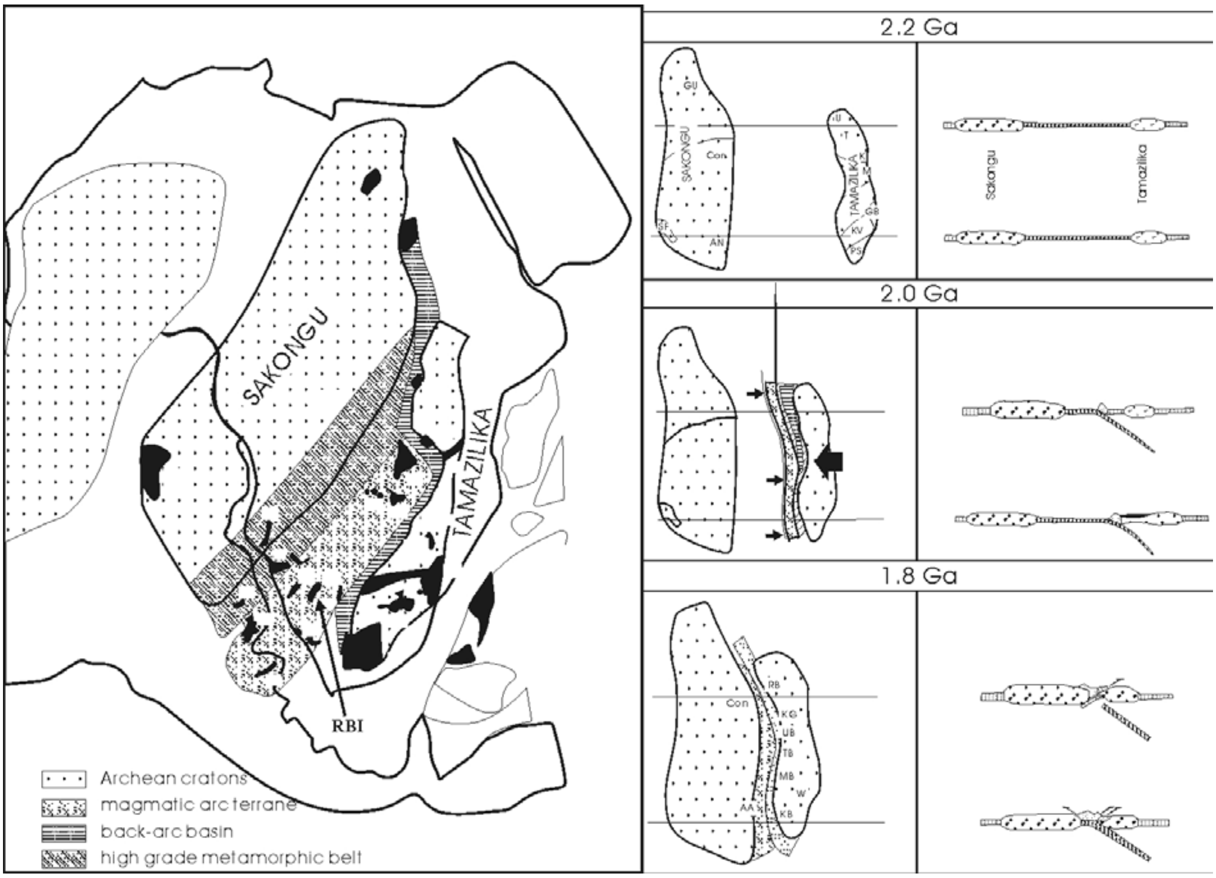

Figure 12: Reconstruction of the proposed Paleoproterozoic magmatic arc and the position of the Rehoboth Basement Inlier (RBI) therein (from Master, 1993).

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