New U-Pb zircon ages of the Nückopf Formation and their significance for the Mesoproterozoic event in Namibia

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U-Pb single and multi-grain zircon ages have been obtained for volcanic and subvolcanic rocks from three isolated outcrops of the Nückopf Formation in the Rehoboth Basement Inlier of central Namibia. One concordant U-Pb age of 1226.4 ± 10.1 Ma from abraded zircons from the type locality (Farm Nauzerus 111) coincides with U-Pb zircon upper discordia intercepts of 1221 $^{+36}/_{-29}$ Ma and 1222 ± 46 Ma from quartz-feldspar porphyries of Farms Alberta 176 and Jan Swart 326, respectively and is interpreted as the time of magmatic emplacement. In contrast, $^{207}Pb/^{206}Pb$ model ages from non-abraded and successively abraded zircons range unsystematically between 1219 and 1614 Ma. These surprisingly old ages are best explained by inherited Paleoproterozoic zircon xenocrysts from the assimilation of surrounding country rocks. In a regional context, the results of this study are compatible with those undertaken elsewhere along the western and northern margin of the Kalahari Craton.

Introduction

In an attempt to improve the understanding of the assembly of the supercontinent of Rodinia, the geology and evolution of Mesoproterozoic terranes worldwide has been the focus of recent multi-disciplinary research (see Precambrian research, volumes 111, 112 and references therein). In southern and central Africa, tectonic processes linked to this assembly are often separated into an early event between 1400-1200 Ma and a later event between 1100-1000 Ma. The early event is referred to as the Kibaran I (e.g. Goodwin, 1996) and has been linked to both intracontinental rifting and continental margin terrane accretion. The later event involved collisional orogeny and is usually referred to as the Namaquan (e.g. Robb *et al.*, 1999) or Kibaran II.

Research on the Mesoproterozoic geology of southern Namibia, has been dominated by studies of a group of elongate fault-bounded volcano-sedimentary basins associated with the Awasib Mountains and Rehoboth basement inlier (Figure 1 inset map). One aspect of this research has focused on the tectonic significance of these basins and their relationship to a contamporaneous active continental margin that produced the high-grade rocks of the adjacent Namaqua metamorphic terrane (Blignault *et al.*, 1983; Colliston and Schoch, 2000) the following scenarios have been proposed for the basins:

- active continental margin (Watters, 1976),
- anorogenic continental rift (Kröner, 1977; Brown and Wilson, 1986; Borg, 1988),
- back-arc basin and/or subduction-induced pull-apart basin (Hoal, 1990; Pfurr *et al.*, 1991; Hoal and Heaman, 1995),
- collison-induced pull-apart basin (Jacobs *et al.*, 1993), and a
- basin-and-range environment, caused by late orogenic collision-related extensional collapse (Kampunzu *et al.*, 1998).

Of critical importance to all of these models is the timing of basin evolution and subsequent evolution as constrained by the age of the felsic volcanic rocks forming part of the basin-fill. Models based on back-arc extension at an active continental margin (e.g. Hoal, 1990, Hoal and Heaman, 1995) ideally require the magmatism to be older but certainly not younger than the orogenic event resulting from the subduction process (i.e. minimum age of 1100 Ma). Models linked to collisional or post-collisional tectonics (e.g. Jacobs *et al.*, 1993; Kampunzu *et al.*, 1998) imply that the extension and related magmatism should be synchronous with or younger than the orogenic event (i.e. a maximum age of 1100 Ma). The available geochronological data base (e.g. Hugo and Schalk, 1974; Watters, 1974; Burger and Coertze, 1975, 1978; Hegenberger and Burger, 1985; Pfurr *et al.*, 1991; Ziegler and Stoessel, 1993; Hoal and Heaman, 1995, Kampunzu *et al.*, 1998; Nagel, 1999; Steven *et al.*, 2000) does not unequivocally support either of these alternatives but does suggest that isotopic ages of approximately 1200 Ma are characteristic of rocks from the Awasib Mountains and Sinclair basin (Figure 1) in the west whereas ages of 1100 Ma and younger are as-sociated with outcrops in eastern Namibia (Hegenberger and Burger, 1985; Steven *et al.*, 2000) and adjacent parts of Botswana (Kampunzu *et al.*, 1998). However, to complicate the picture rocks with ages belonging to both groups have been reported from parts of the Rehoboth Basement Inlier (Figure 1).

We address this problem by reporting new U-Pb zircon ages of felsic volcanic rocks from several outcrops of the Nückopf Formation, which is considered to be related to the end of Mesoproterozoic volcanic activity in this part of Namibia (SACS, 1980). We also report the results of successively abraded zircons, which were analysed in order to investigate the possibility that inherited components were responsible for the previously reported spread in age of both volcanic rocks and their intrusive equivalents.

Regional Geology

The Rehoboth Basement Inlier of central Namibia is a belt of igneous and metasedimentary rocks exposed over an area of 200.000 km^2 along the southwestern, western, and northwestern margins of the Kalahari Craton (Fig. 1) probably deposited in fault-bounded grabens or half-grabens. Two main occurrences, the Sinclair and the Rehoboth areas (Fig. 1), each of which covers approximately 10.000 km^2, can be distinguished. Further to the NE, isolated inliers within the savannah of the Kalahari link the Rehoboth area with the Mesoproterozoic Ngamiland belt in Botswana (Kampunzu *et al.*, 2000a, b).

In the Sinclair area, Mesoproterozoic low-grade metamorphic supracrustal rocks have been grouped into the Sinclair Sequence (SACS, 1980). These rest unconformably on medium-grade metamorphic rocks of the Early to Middle Mesoproterozoic Kumbis and Kairab Complexes (Watters, 1974; Hoal, 1990). Three cycles of deposition can be distinguished, which took place in elongated, almost N-S-trending sub-basins (Hoal, 1990). Each cycle is characterised by basal clastic sediments and an overlying succession of bimodal to calcalkaline volcanic rocks, all of which have been intruded by Mesoproterozoic calcalkaline and minor alkaline magmas (von Brunn, 1967; Watters, 1974; Hoal, 1990). Further to the north, the outcrops of these rocks are separated from the Rehoboth area by the NNW-SSE striking Nam Shear belt, which forms the northernmost part of a regional shear system that was generated and active during the circa 1.1-1.0 Ga Namaqua Orogeny (Watters, 1974, Toogood, 1976, Robb *et al.*, 1999; Colliston and Schoch, 2000).

In the Rehoboth area, a large basement inlier is preserved between the Southern Margin Zone and the Southern Foreland of the Neoproterozoic Damara Orogenic Belt (Fig. 1). The so-called Rehoboth Basement Inlier (RBI) is bounded to the north by overthrust metasediments of the Nosib and Swakop Groups, and is unconformably overlain by sedimentary rocks of the Tsumis Group (Hoffmann, 1989) in the south, all of which belong to the Neoproterozoic Damara belt. To the east and west, much of the area is covered by poorly consolidated Subrecent to Recent sand dunes of the Kalahari Desert. The RBI is composed of (1) a late Paleoproterozoic greenstone belt (1800-1700 Ma; Becker *et al.*, 1998; Ledru *et al.*, subm.), (2) the Mesoproterozoic metasedimentary and metavolcanic rocks, which are pre-sently correlated with the third cycle of the Sinclair Sequence (Guperas Formation) and (3) the Mesoproterozoic Gamsberg Granite Suite (SACS, 1980). An early tectono-metamorphic-E-W trending gneissic fabric is restricted to the Paleoproterozoic domain. It developed under low pressure and medium to high temperatures (De Thierry, 1987).

The reconstruction of the Mesoproterozoic stratigraphy in the RBI is hampered by the generally isolated nature of individual outcrops and/or occurrences, which result from subsequent batholitic intrusions and extensive younger cover rocks. Additionally, reliable correlations are complicated by folding and thrusting resulting from the Damara Orogeny and thus, previous models for the evolution of the Mesoproterozoic rocks of the RBI basin have been of a more general nature (Borg and Maiden, 1986, Borg, 1988).

The subdivision of Mesoproterozoic rocks in the RBI as correlatives of the Sinclair Sequence (Table 1, SACS, 1980) is based on relationships recognised in the western part of the RBI. This model has been challenged by Hoffmann (1989), who regarded the regional unconformity at the base of the Doornpoort Formation as the boundary between the Meso- and Neoproterozoic eras. Recently, the combination of high-resolution airborne geophysics, structural analysis, and petrography to-gether with geochemical and isotopic age data has allowed the establishment of a three stage model for the Mesoproterozoic history in the RBI (Fig. 2; Ledru *et al.*, subm.; Becker *et al.*, subm.). This model also takes into account the eastern part of the RBI, where isolated outcrops can now be linked using new geophysical data. As part of this model, the low-grade metamorphic rocks of the Billstein Formation, which previously has been interpreted as Paleoproterozoic in age, are regarded as part of the Mesoproterozoic Sequence.

The initiation of the basin (stage 1) is recorded in widespread epicontinental detrital sedimentary rocks of the Billstein Formation (Fig. 2), which comprise basal quartzite, metapsammite and metaconglomerate. Several hundred metres of red manganese-rich metapelites with minor intercalated mafic schist bands at the base overlie these metapsammites. Stratigraphy related to stage 1 also includes quartzite and schist successions, previ-ously placed stratigraphically into the underlying Marienhof Formation. Although there is no detrital zircon data from the Billstein Formation, the minimum age of deposition can be constrained from cross-cutting porphyries, which have a multi-grain zircon age of

Table 1: Lithostratigraphic subdivision of 'Correlates of the Sinclair Sequence' in the Rehoboth area (SACS, 1980)

Formation	lithology	intrusion
Klein Aub	Fine-grained purplish quartzite, rare gritty layers Shale, shaly quartzite, calcareous shale, lenses of limestone, breccia Conglomerate interfingering with quartzite Reddish and brownish quartzite and basal conglomerate	
	unconformity	
Doornpoort	Red quartzite and minor red shale, amygdaloidal lava, layers of felsic tuff and pyroclastics together with coarse conglomerate in lower part of succession	
Eskadron	Red quartzite and shale, interbedded layers of calcareous shale and lenses of limestone, conglomerate and sedimentary breccias	
	unconformity	
Grauwater	Purplish-grey and brown quartzite, minor mafic lava and rhyolitic tuff, locally coarse basal conglomerate	- Dykes of porphyry and diabas -in few places Gamsberg Suite
Nuckopf	Mainly felsic volcanic rocks (rhyolite, ignimbrite, ash-flow tuff, qtz-fsp porphyry), subordinate mafic lava and pyroclastics; quartzite and conglomerate	- Dykes of porphyry and diabas - Gamsberg Suite (various granites, granophyr, aplite and pegmatite)

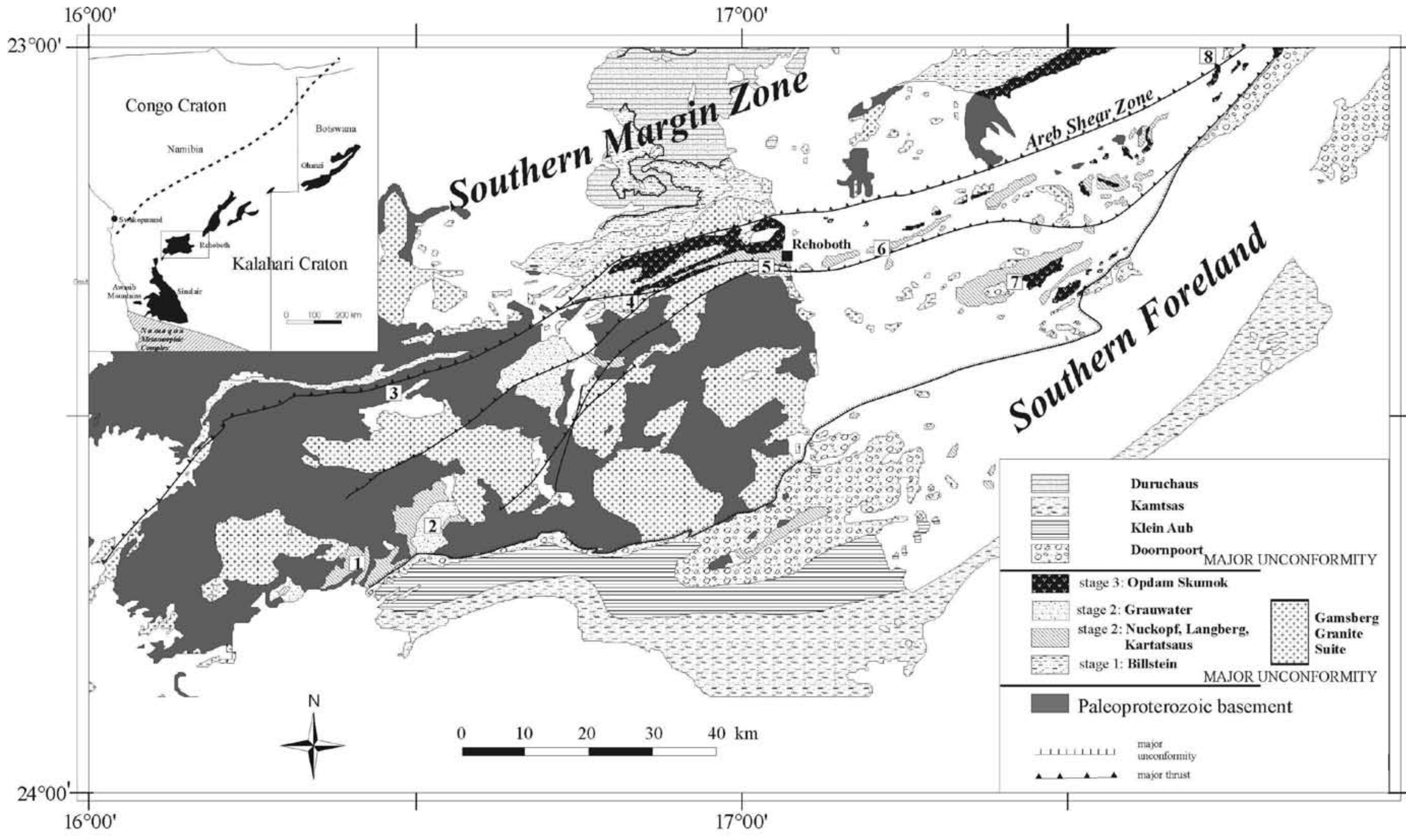

Figure 1: Simplified geological map of the Rehoboth Basement Inlier (RBI). The inset map shows the regional distribution of Mesoproterozoic basins and the position of the map. Numbers indicate type localities which are referred to in the text: (1) Nauzerus 111 / Kabiras 343, (2) Grauwater 341, (3) Alberta 176, (4) Jan Swart 326, (5) Rehoboth, (6) Langberg, (7) Kartatsaus 293, and (8) Opdam

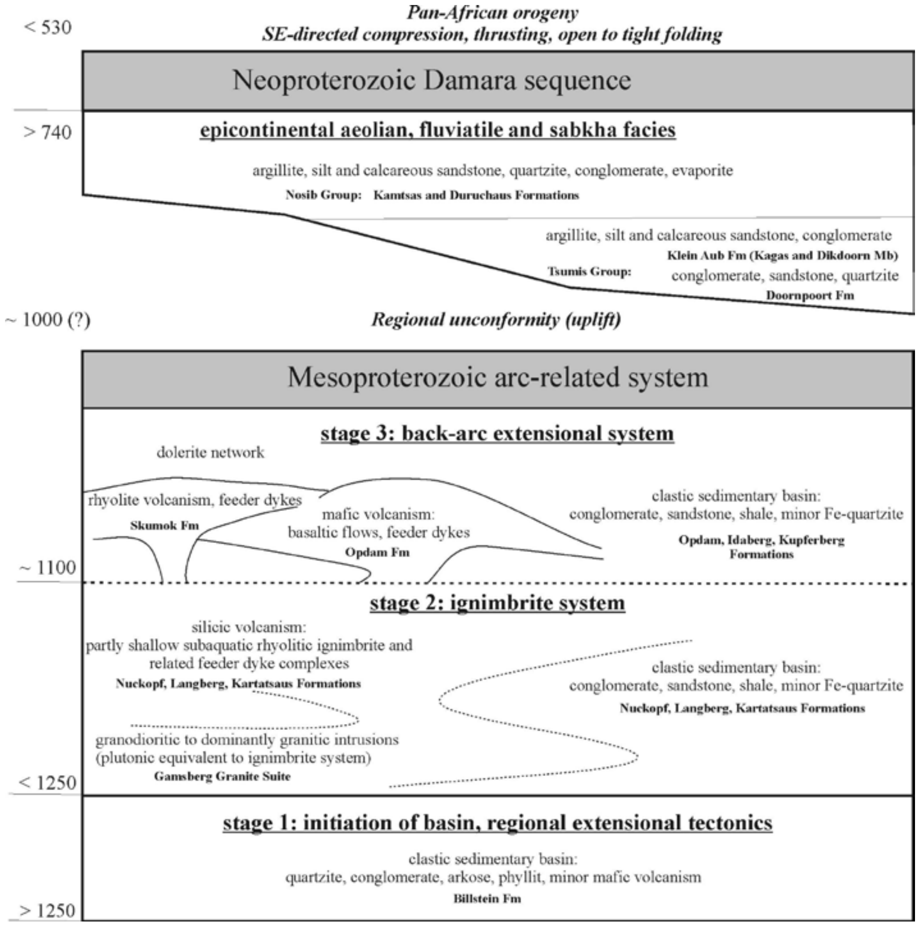

Figure 2: Revised event-stratigraphic concept for the Mesoproterozoic domain of the Rehoboth Inlier, based on igneous and sedimentary processes.

1210±7 Ma (Ziegler and Stoessel, 1993).

The second stage is characterised by a major rhyolitic ignimbrite system and its plutonic equivalents, the age of which is bracketed between approximately 1230 Ma and 1090 Ma (Hugo and Schalk, 1974; Burger and Coertze, 1975, 1978). Strong syn-depositional tectonics movements have been documented by poorly-sorted sediments underlying and interfingering with the metavolcanic rocks. Deposition took place in a shallow water environment as shown by the textures of both metavolcanic and metasedimentary rocks. The Nückopf, Langberg, and Kartatsaus Formations, as well as parts of the Grauwater Formation, as defined by Schalk (1988), are considered to be lateral equivalents of this ignimbritic system. The lithological and petrological variations within the metarhyolitic complex are mainly a function of the distance to volcanic centres and local active fault scarps.

The second stage was terminated by the emplacement of granite bodies of up to batholitic dimensions, which are grouped into the Gamsberg Granite Suite (SACS, 1980) Rhyolitic and microgranite enclaves are common and in some areas rhyolitic dykes are intrusive into the granite. Diffuse contacts are also found between coarse-grained granite and aplitic veins. These observations favour the concept of contemporaneous volcanism and plutonism during Mesoproterozoic times.

The third stage is marked by major basaltic flow volcanism, intercalated with the shallow water sediments of the Opdam Formation, for which the type locality is lo-cated NE of Rehoboth (Fig. 1). Numerous mafic dykes, ranging form coarse-grained gabbro to dolerite, have been emplaced along a dense network of fractures and are interpreted as feeders to the basaltic flows. Minor rhyolitic volcanism and immature meta-arenite, displaying planar bedding (Skumok Formation) characterises the end of stage 3.

Analytical Methods

U-Pb isotope analyses of zircons were carried out at the University of Göttingen (samples TBE-300396 and UHI-030896, multi-grain method) and at the Rheinisch- Westfälische Technische Hochschule (RWTH) Aachen (samples N86, N99, N100, N123, N124; single grain, partly abrasion method). Sampling and analytical procedures at the laboratory of the University of Göttingen have been described by Becker *et al.* (1996). At the RWTH Aachen, abrasion of the zircons followed the procedures as outlined by Krogh (1982). U-Pb isotopes of both non-abraded and abraded fractions have been analysed, with abraded fractions being further subdivided according to the degree of abrasion. Uranium and lead measurements were carried out at both institutes using a multichannel TIMS (Finnigan MAT 262 RPQ+ and Finnigan MAT 261, respectively).

Age calculations are based on the constants recommended by IUGS (Steiger and Jaeger, 1977). Initial lead ratios for the correction of common lead 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). The initial lead ratios 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 its concentration (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 2 σ 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 diagram (York, 1969). Regression errors are two σ 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 alpha level. In addition, concordia averages were calculated for single grain samples (i.e. N86-N124). The software GEODATE for Windows (Eglington & Harmer, 1993) was applied for presentation of the data in conventional concordia diagrams (Wetherill, 1956). In cases where common lead was very high (i.e. sample TBE-300396) the calculation of the age and errors followed the method outlined by Wendt (1982, 1984).

Analytical Results

The Nückopf Formation

The Nückopf Formation is considered to be the oldest Mesoproterozoic unit within the RBI by SACS (1980). Several isolated outliers are grouped into this unit due to their alignment along strike and their compositional similarity. Samples were collected from various localities in the western RBI and these are described in more detail below.

Farms Nauzerus 111 and Kabiras 343

The most complete lithostratigraphic section of the Nückopf Formation occurs on the Farms Nauzerus 111 and Kabiras 343, where the rocks are exposed over an area of approximately 100 km^2 (Figs. 1 and 3). Generally, the rocks have been only weakly affected by deformation and the metamorphic overprint is low to very low grade. Basal, predominantly siliciclastic rocks, up to 400 m thick, comprise interbedded phyllitic shale, phyllite, metapelite, gritty meta-arenite (with cross-bedding), and a poorly sorted polymictic metaconglom-

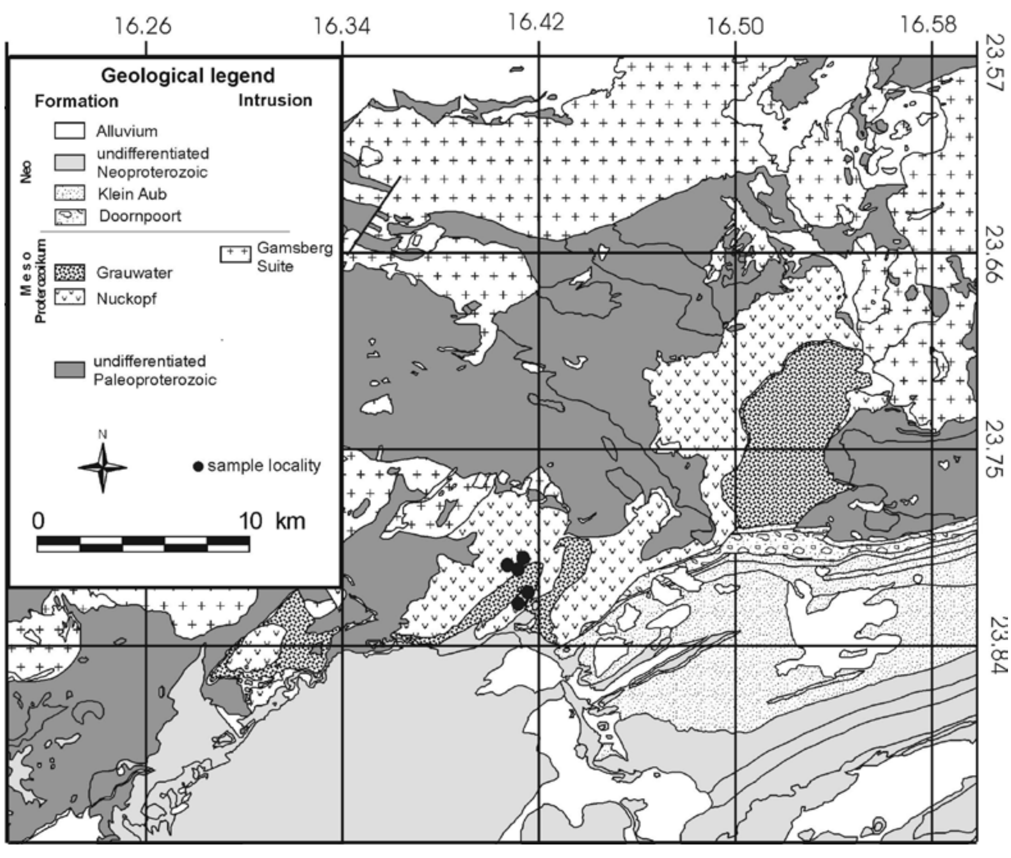

Figure 3: Geological map of the Nauzerus area and sample localities

erate. All rest unconformably on the Paleoproterozoic basement. Intercalated distal hyaloclastic to epiclastic rocks attest to contemporaneous felsic volcanic activity. Two distinct horizons of amygdaloidal metabasalts have been recognised, which each attain a thickness of up to 35 m (De Waal, 1966, Borg and Maiden, 1987, Borg, 1988).

Felsic volcanic rocks, with a maximum thickness of 300 m, overlie this basal unit and, towards the north, transgress unconformably onto the Paleoproterozic basement, thus marking a progressive widening of the basin and an overstepping of the shoulders of the (initial rift) graben. In the lower portion, the felsic unit includes abundant basement fragments, whereas in higher parts of the succession, the dominant lithotype is a finely flow-banded quartz-feldspar porphyry containing locally lithophysae up to 3 cm in diameter but which is generally devoid of basement xenoliths. Various pyroclastic rock fragments ranging from tuff to agglomerate and pyroclastic breccias can be distinguished (De Waal, 1966). At the top of the succession, the metavolcanic rocks interfinger with progressively increasing clastic metasedimentary rocks, which are regarded as part of the Grauwater Formation. The subdivison of the Nückopf into a lower and upper volcanic and a central clastic unit has been proposed by De Waal (1966). However, the structural map of the same author reveals, that the upper and lower volcanic units appear to be identical. The petrographic differences described by Schneider (in prep.), may be due to lateral facies changes away from a volcanic centre and/or the influence of syndepositional faulting.

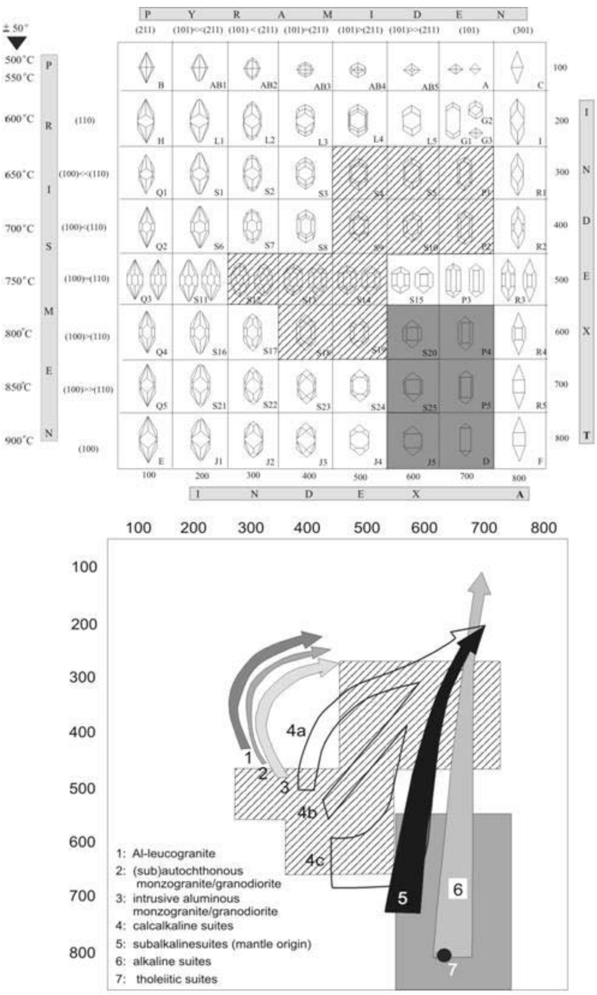

Figure 4: Classification diagram for zircons after Pupin (1980). The zircons from all samples cover fields of subalkaline, alkaline, and tholeiitic suites

Five metarhyolite samples from various stratigraphic levels within the Nückopf Formation were selected for the present isotope studies. Samples N86 and N100 are from welded and flow-type pyroclastic rocks in the lower portion of the stratigraphic column. Samples N99, N123 and N124 from the upper part of the profile consist of homogeneous metarhyolite (porphyritc quartz - K-feldspar) and have been interpreted as flows or shallow subvolcanic intrusions. All samples show only minor alteration.

Zircon separates from all samples are homogeneous in typology and composition. Euhedral, prismatic to long prismatic, clear and transparent crystals with simple crystal (100) > (110) and (101) > (211) faces are dominant and no indication of magmatic corrosion or post-magmatic alteration was recognised. On a standard classification diagram (e.g. Pupin, 1980, the analysed grains plot in fields, that are typical for alkaline, subalkaline, and tholeiitic magma series with incipient crystallisation temperatures between 800-900°C (Fig 4). The application of cathodoluminescence was not possible at RWTH Aachen; hence, no information on the internal structure of the zircons is available. The results of the isotope analyses are shown in Table 2 and Figure 5.

Zircons from all samples from the Nauzerus area are characterised by low U concentrations (55-323 ppm) and low to medium proportions of common lead (2 - 14.3 %). Conventional concordia diagrams (Fig. 5) yield upper intercept ages between 1228 $^{+21}/_{-32}$ Ma and 1442 $^{+770}/_{-174}$ Ma. The same holds true for lower intercepts of 1015 $^{+150}/_{-583}$ Ma (sample N86) and 395 $^{+533}/_{-626}$ Ma (sample N100) for two samples and no lower intercept for the other samples. Calculated $^{207}Pb/^{206}Pb$ model ages of all samples vary between 1219 and 1614 Ma (Table 2). Generally, no correlation is evident between the degree of abrasion and the position of the fraction on the discordia. In sample N86, non-abraded crystals are marked by the highest apparent ages close to the upper intersection of the discordia (Fig. 5a); little abrasion results in a strong shift of the isotope system to its lower end, which is again reversed in more abraded crystals. In contrast, in sample N100 the more abraded crystals are increasingly discordant. This is at variance with a model assuming old cores and younger, overgrown rims. In sample N123 and N124, abrasion results in a shift of the data points towards the concordia, with one, action yielding a concordant age of 1219 Ma (N124/1); is interpreted as the crystallisation age of the

Table 2: Results of the U-Pb single and multi-grain zircon analyses

Locality	sample	Lithotype	Analysis No.	size [µm]	weight (mg)	abr.	No of crystals	U ppm	Pb-t ppm	Pb-r ppm	Pb-c ppm	Pb-c %	$^{206}Pb/^{238}U$	error [%]	age [Ma]	$^{207}Pb/^{235}U$	error [%]	age [Ma]	$^{207}Pb/^{206}Pb$	error [%]	age [Ma]
		welded	N86-I	125-180	0.056	N	6	220.4	80.3	69.3	11.0	13.7	0.2461	1.02	1419	3.3085	5.48	1483	0.0975	4.84	1577
S 23°49'29"	N86	ignimbrite	N86-I-1/1		0.039	Y	5	158.2	41.2	39.7	1.5	3.6	0.2025	0.21	1189	2.2804	0.34	1206	0.0817	0.25	1238
E 16°22'46"		KPQ-phyric	N86-I-1/2		0.012	Y	9	323.6	94.2	87.7	6.5	6.9	0.2046	0.43	1200	2.3494	0.65	1227	0.0833	0.46	1276
Nauzerus 111		rhyolite	N86-I-1/3		0.021	Y	2	96.5	36.0	33.1	2.9	8.1	0.2100	0.42	1229	2.4068	0.60	1245	0.0831	0.41	1272
		KQ-phyric	N100-I	125-180	0.059	N	5	131.5	36.6	34.1	2.5	6.8	0.1983	0.34	1166	2.4740	2.91	1265	0.0905	2.62	1436
S 23°48'7"	N100	rhyolite	N100-I/1-1		0.015	Y	3	113.8	32.7	31.4	1.3	4.0	0.2061	0.56	1208	2.3628	0.80	1231	0.0831	0.57	1272
E 16°24'9"		lava	N100-I/1-2		0.015	Y	3	141.9	40.2	36.7	3.5	8.7	0.2031	0.55	1192	2.3011	0.65	1213	0.0822	0.34	1250
Kabiras 343			N100-I/1-3		0.017	Y	3	238.0	61.1	56.7	4.4	7.2	0.1925	0.32	1135	2.1746	0.40	1173	0.0819	0.24	1243
S 23°49'2"	N99	lava or sub-	N99-II	125-180	0.097	N	10	85.3	29.6	23.4	6.2	21.0	0.1998	1.05	1174	2.7407	9.50	1340	0.0995	8.48	1614
E 16°22'41"		volcanic																			
S 23°49'55"	N123	lava or sub-	N123-II	125-180	0.011	N	5	173.9	49.3	46.6	2.7	5.5	0.2020	0.52	1186	2.4684	3.21	1263	0.0886	2.92	1396
E 16°23'31"		volcanic	N123-II/1		0.010	Y	4	37.6	12.1	10.4	1.7	14.0	0.2099	1.95	1228	2.4983	3.55	1272	0.0863	2.87	1345
S 23°49'48"	N124	lava or sub-	N124II	62-80	0.465	N	50	102.5	27.1	24.6	2.5	9.2	0.1806	0.55	1070	2.2326	3.87	1191	0.0897	3.48	1418
E 16°23'28"		volcanic	N124II/1		0.013	Y	4	94.5	26.0	25.5	0.5	1.9	0.2099	0.80	1228	2.3412	0.93	1225	0.0809	0.46	1219
Nauzerus 111		rhyolite	N124II/2		0.006	Y	4	55.1	17.2	15.6	1.6	9.3	0.2092	2.46	1224	2.5480	6.58	1286	0.0884	5.87	1390
			536	>125	1.51	N	P	267	56.7	51.8	4.91	8.66	0.1616		966	1.7463		1026	0.0784		1157
S23°32'38"	UHI-030896	qtz-fsp	535	100-125	0.73	N	P	273	58	55.3	2.66	4.59	0.1699		1012	1.8528		1064	0.0791		1174
E16°24'19"		porphyry	534	80-100	1.34	N	P	231	48.9	46.3	2.63	5.38	0.1665		993	1.8353		1058	0.08		1196
Areb 176			533	60-80	0.33	N	P	480	88.8	79.8	8.97	10.11	0.1376		831	1.475		920	0.0777		1140
			532	45-60	0.37	N	P	215	40	36.7	3.34	8.35	0.1418		855	1.548		950	0.0792		1177
			485	<45	2.17	N	P	575	290	107	183	172	0.1411	0.7228	907	1.5251	7.47	983	0.0784		1156
S23°32'38"	TBE-300396	qtz-fsp	486	45-60	4.2	N	P	573	319	113	206	182	0.1599	0.6878	956	1.7712	7.23	1034	0.0803		1205
E16°24'19"		porphyry	487	60-80	3.69	N	P	529	308	87	221	254	0.1398	0.9086	843	1.5194	9.29	938	0.0788		1168
Jan Swart 326		dyke	488	80-100	2.74	N	P	445	272	77	195	252	0.1609	0.7355	961	1.7546	8.34	1029	0.0791		1175
			489	100-125	2.82	N	P	407	243	81	162	201	0.1619	0.7291	966	1.7638	7.99	1032	0.0791		1175

rhyolite. The best results in the geochronological analysis are achieved by calculating the average position of the fractions in the concordia diagram. This results for two samples (N123 and N124) in meaningful, nearly or completely concordant ages of 1230.8 ± 23.7 Ma and 1226.4 ± 10.1 Ma, respectively (Fig. 5c and 5d).

Farm Areb 176

Low-grade metamorphic and typically highly sheared rocks of the Nückopf Formation are exposed on Farm

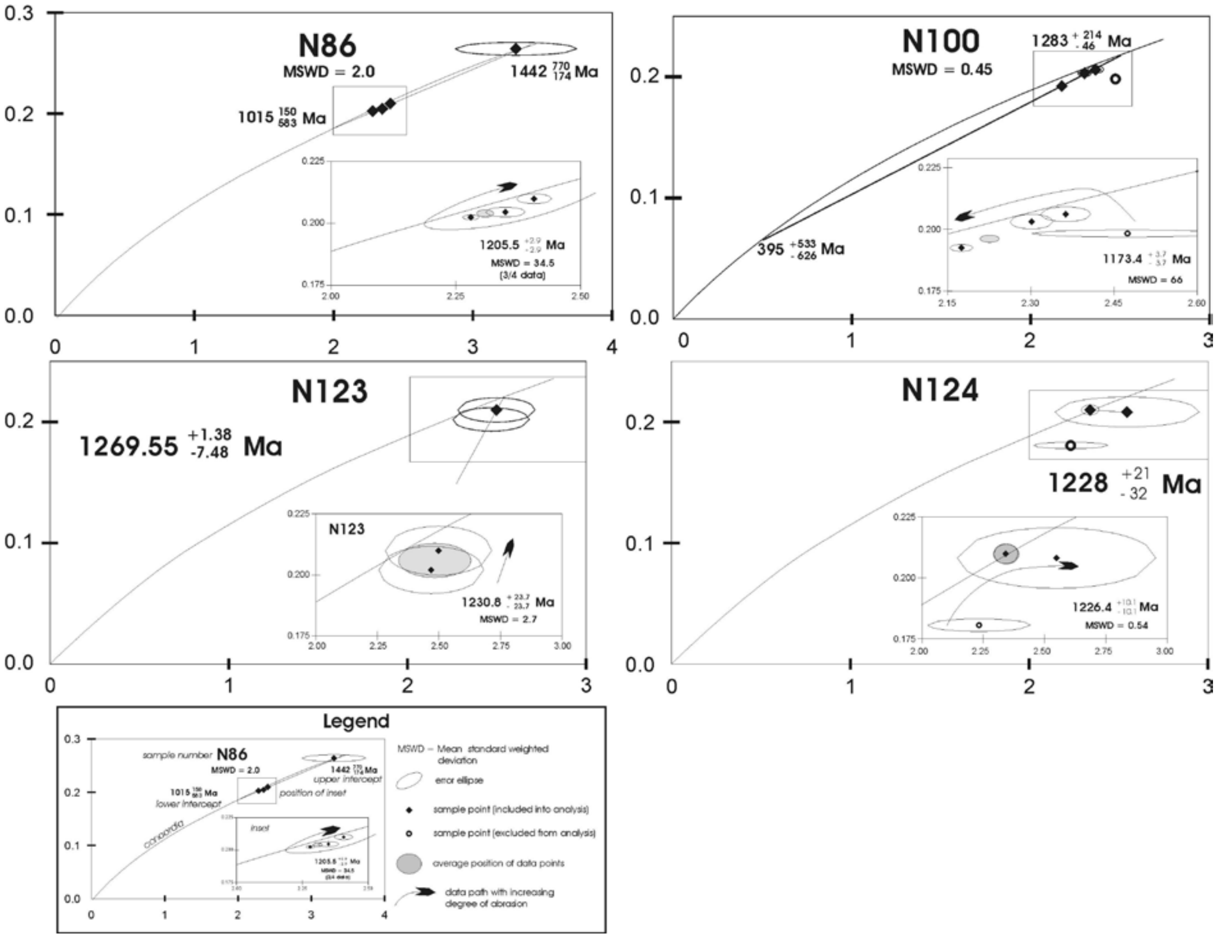

Figure 5: Plot of U-Pb single grain zircon analyses of samples from Farm Nauzerus 111 in conventional concordia diagrams (after Wetherill, 1956)

Areb 176 over an area of approximately six km^2 (Figs. 1, 6). Here, a basal conglomerate of 30m thickness overlies the Paleoproterozoic Elim Formation. This conglomerate is characterised by poorly sorted and sub-rounded to angular clasts of local provenance within a schistose matrix. Intercalations of schist and phyllite are locally developed within the conglomerate. Amygdaloidal mafic flows (20m) and rhyolitic porphyry (10m) follow higher up in the sequence. An intercalated volcanic breccia has been interpreted as a diatreme (De Waal, 1966).

Sample UHI-030896 was collected from the rhyolitic porphyry. It is characterised by a fine-grained to aphanitic glassy matrix and phenocrysts up to 3mm in size comprise quartz, K-feldspar and plagioclase. The latter are commonly altered to secondary muscovite and epidote.

Zircons from this sample show the same variation in colour and transparency, which changes from clear colourless to metamict brownish. Two groups of zircons are distinguished with respect to their crystal shapes: elongated crystals are marked by a dominance of simple (101) pyramidal and prismatic (110) facets, whereas short crystals generally show more complex pyramidal (101) and (211) as well as both (100) and (110) prismatic facets. This is typical for zircons of calcalkaline magmatic suites (Fig. 4, Pupin, 1980). Rare inclusions of small biotite flakes have also been found. In most grains, cathodoluminescence imaging revealed oscillatory zoning oriented parallel to the c-axis. These features were interpreted to reflect a change in magma composition during the growth of the magmatic zircons.

The results of the isotope analyses are presented in Table 2 and in the conventional $^{206}Pb/^{238}U$-$^{207}Pb/^{235}U$ concordia diagram (Fig. 7a). The individual fractions are characterised by medium uranium concentrations (215-480 ppm) a medium proportion of common lead (5-10%), and a considerable degree of discordance. An upper discordia intercept age has been determined at 1221 $^{+36}/_{-29}$ Ma (MSWD = 2.5), interpreted as minimum age of crystallisation and a lower intercept age at 174 $^{+112}/_{-116}$ Ma.

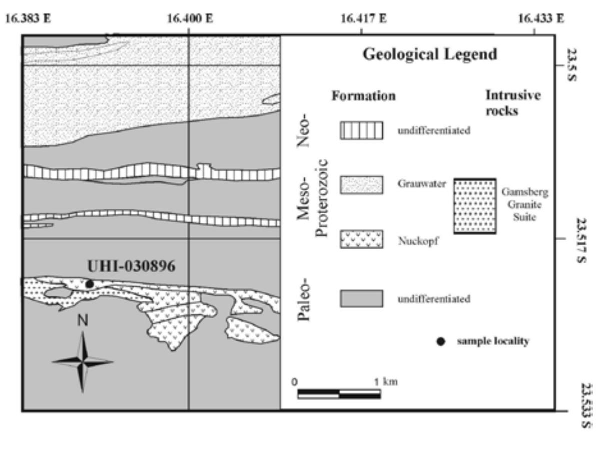

Figure 6: Geological map of Farm Alberta 176 (modified from De Waal, 1966) with sample locality.

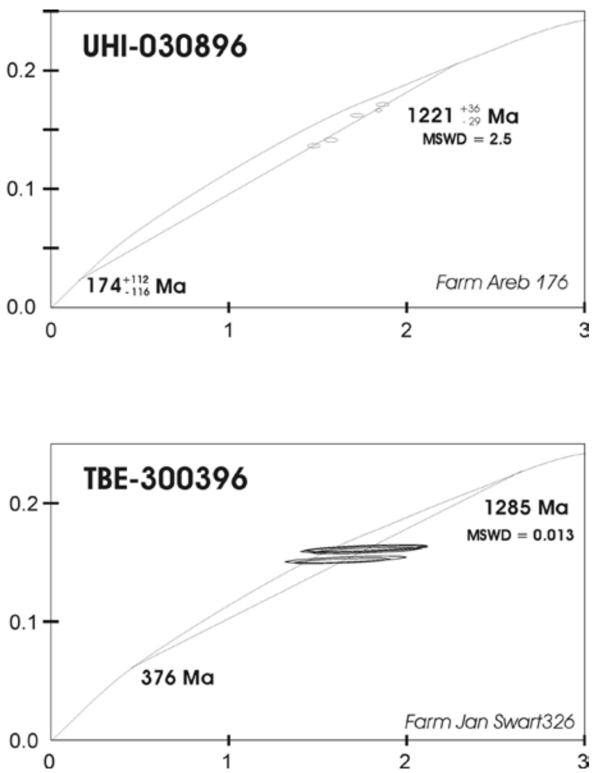

Figure 7: Plot of U-Pb multi-grain zircon analyses of samples from Farms Areb 176 (UHI 030896) and Jan Swart (TBE 300396) in conventional concordia diagrams (after Wetherill, 1956)

Farm Jan Swart 326

On Farm Jan Swart 326, situated some 30 km southwest of Rehoboth, a quartz-feldspar porphyry of volcanic or intrusive origin with intercalated mafic sills or flows overlies the Paleoproterozoic Elim Formation (Figs. 1, 8). It is in turn overthrusted by quartzites of

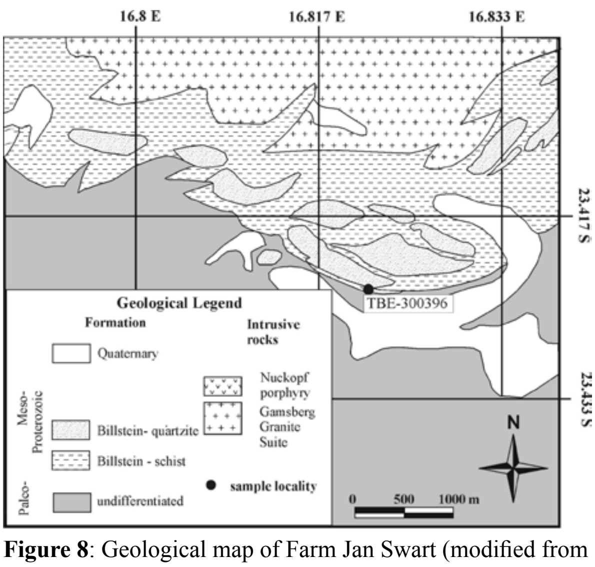

Figure 8: Geological map of Farm Jan Swart (modified from Schulze-Hulbe, 1976) with sample locality.

the Marienhof Formation from the north. The porphyry is marked by K-feldspar and quartz phenocrysts up to 5 mm in diameter whereas the schistose matrix consists mainly of quartz, feldspar and biotite with accessory zircon and opaque minerals as well as secondary muscovite and epidote. Sample TBE-300396 was taken from that rock. No study of the zircon morphology has been carried out to date. The results of the isotope analyses (Table 2, Fig. 7b) show that zircons from this sample are marked by high uranium contents and very high proportions of common lead (162-221%), which results in an upper discordia intercept of 1285 Ma with unacceptably high errors of more than 300 Ma. Thus, the calculation of the age and errors followed the method outlined by Wendt (1982, 1984). Here, under the assumption that the isotopic composition of common lead is identical in all fractions, no knowledge of the Pbcom isotopic ratios (e.g. $^{208}Pb/^{204}Pb_{com}$; $^{207}Pb/^{204}Pb_{com}$; $^{206}Pb/^{204}Pb_{com}$) is required and hence, errors can be considerably reduced. The application of this method constrains an upper discordia intercept age of the porphyry at 1222 ± 46 Ma and a lower intercept age at 114 ± 29 Ma.

Discussion

U-Pb zircon analyses

The present U-Pb single zircon study from rhyolitic rocks of the Nückopf formation shows, that the determined discordia intercepts represent a complex mixture of heterogeneous domains with very distinct isotope characteristics. Generally, older cores (of inherited zircon xenocrysts) and younger rims of magmatic overgrowth are to be expected. However, the abrasion of some of the zircons has revealed no systematic relationship between the apparent age of the fraction and their degree of abrasion:

- in sample N100, the discordance increased in more strongly abraded crystals,
- in sample N86, the discordance decreased after an initial strong shift,
- in sample N123, the abrasion resulted in a more concordant age, and
- in sample N124, abrasion led to an initially concordant and subsequently a discordant age.

This apparently unsystematic behaviour probably reflects an inherent problem of the single grain method: only a few crystals have been used for each analysis and abrasion is done on different zircon batches. Hence, the heterogeneity of individual crystals can influence the results of the analyses quite markedly.

The conventional multigrain method omits this statistical problem with the arrangement of the data points being a function of the grain size and the lead-loss related to it. In a two-stage history, this method works very reliably and constrains both the time of magmatism and a second geologic event (Fig 9a). However, many zircons feature a more complex composition: older xenocrystic cores from assimilated country rocks have become overgrown during subsequent magmatic and metamorphic events and/or affected by subsequent episodic lead-loss during uplift or hydrothermal alteration (Fig 9b). Hence, the upper intercept age from the resulting discordias can theoretically be both younger and older than the actual geologic events (Fig. 9c). How-ever, surprisingly, the multigrain analyses from UHI-030896 and TBE-300396 yield very similar results of 1221 $^{+36}/_{-29}$ Ma and 1222 ± 46 Ma respectively, which are within the error of the concordant age of sample N124/1 of 1226.4 ± 10.1 Ma. Therefore, the influence of any inherited components in those samples appears to have been very small and episodic lead-loss affected the grains systematically. In conclusion, these data constrain a minimum age of primary zircon crystallisation, which is indistin-guishable from the concordant age obtained from sample N124/1. In contrast, a wide range of $^{207}Pb/^{206}Pb$ single zircon ages up to 1614 Ma in the more abraded fractions documents a strong influence of inherited, probably Paleoproterozoic cores and al-

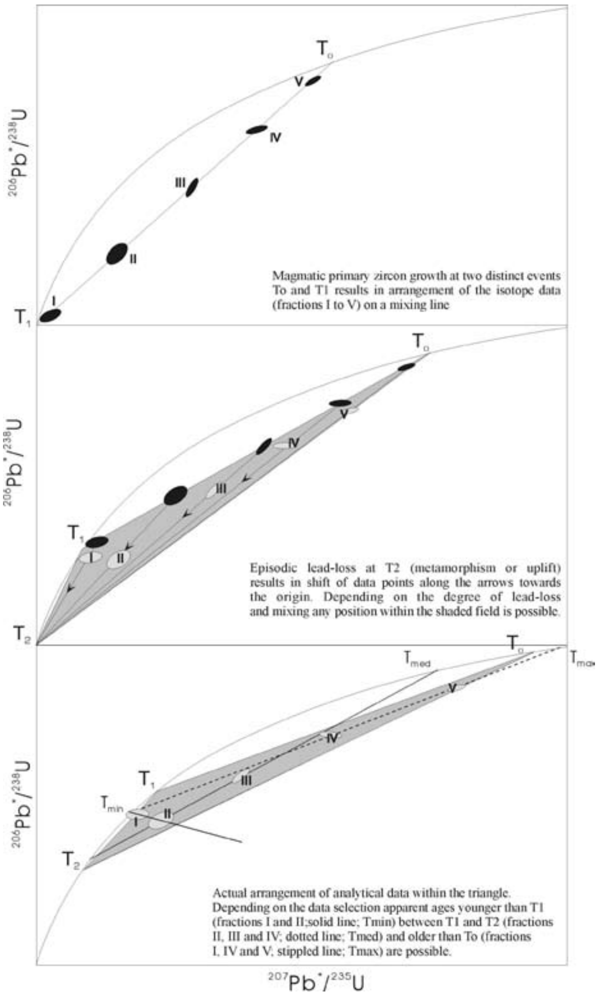

Figure 9: The effects of a polyphase history on the U-Pb isotope system, assuming magnetic crystallisation and assimilation of TO and T1 followed by partial metamorphic reset at T2. All data positions are possible in the shaded areas.

tered rims on the isotope composition of these samples. A wide range of U-Pb zircon ages between 1095 and 1441 Ma reported from granites of the Gamsberg Suite (Nagel, 1999), which have locally intruded the Nückopf metavolcanic rocks, can be explained in a similar way by the assimilation of country rocks.

Regional geological and plate tectonic implications

The present study constrains a concordant U-Pb single zircon grain age at of 1226.4 ± 10.1 Ma for the felsic metavolcanic rocks of the Nückopf Formation on Farm Nauzerus 111. This age is within error of conventional multigrain U-Pb zircon ages of 1222 ± 46 Ma and 1221 $^{+36}/_{-29}$ Ma for metarhyolites from two other isolated occurrences of the RBI on Farms Areb 176 and Jan Swart 326.

In contrast, the emplacement age of the Gamsberg Suite and a felsic porphyry dyke swarm in the same area is constrained at 1210±7 and 1210±3 Ma, respectively (Pfurr *et al.*, 1991, Ziegler and Stoessel, 1993). Therefore, a cogenetic relationship between the Nückopf Formation and the Gamsberg Suite cannot be supported by the present geochronological data. However, the Gamsberg Suite remains geochronologically poorly-defined and comprises a wide range of Mesoproterozoic granitoids, probably with a considerable spread in emplacement ages.

On a regional scale, a similar situation has been described from the Sinclair and Awasib Mountain areas further south (Fig. 1). Here, the age of the Awasib granite has been determined by the single zircon method at 1216 $^{+1.6}/_{-1.8}$ Ma (Hoal and Heaman, 1995). This granite has intruded the Haiber Flats Formation, which is considered as a western correlative of the Barby Formation from the second cycle of the Sinclair Sequence (Hoal, 1990). Field observations suggest a cogentic relationship between the Awasib granite and the Haiber Flats Formation (Hoal, 1990) and hence, imply a similar age for the Barby Formation. This implies that the Nückopf Formation is older than the Barby Formation and should be considered as a northern correlative of the Nagatis Formation from the first volcano-clastic cycle of the Sinclair Sequence. Thus, the SACS (1980) correlation of the Nückopf Formation with the Guperas Formation of the third cycle is no longer valid.

In general, it appears from the present geochronological data set, that igneous activity in the western RBI and the Sinclair area occurred within a rather limited period of time, i.e., from approximately 1230 Ma to 1200 Ma. This igneous event pre-dates the Namaquan (Grenvillan) orogenic episode (1060-1030 Ma), as defined by Robb *et al.* (1999), by more than 100 Ma. This excludes earlier models of both collision-induced pull-apart basins and collision-associated extensional collapse (Jacobs *et al.*, 1993, Kampunzu *et al.*, 1998) for the formation of the Sinclair type basins in Namibia. However, in the Awasib Mountain Terrane, a regional gneissic fabric in syn- to late-kinematic granitoids dated at 1370 Ma (Hoal, 1990; Hoal and Heaman, 1995) points to an extended polyphase tectono-metamorphic history of a long-lived active continental margin setting. The geometry of that hypothetical margin within Namibia remains obscure, although, windows of basement rocks within the Central Zone and Southern Margin Zone of the Pan-African Damara Orogen comprise Mesoproterozoic igneous rocks and may represent the continuation of such a margin (Kröner *et al.*, 1991; Steven *et al.*, 2000; Kampunzu *et al.*, 2000a, b).

Alternatively, a back-arc basin or basin and range environment (Hoal 1990; Becker *et al.*, in prep.) for the Sinclair type basins is supported by the batholithic calcalkaline plutonism within the Rehoboth and Sinclair areas, the partly calkalkaline intermediate nature of the metavolcanic rocks, especially from the Barby Formation of the Sinclair Sequence (Watters, 1974), the apparent absence of any alkaline igneous activity in the RBI and areas further northeast, and the long-lived nature of that event between at least 1234 and 1019 Ma (Kampunzu *et al.*, 2000).

The composition of shallow water non-marine metasediments and dominantly bimodal metavolcanic rocks make a continental rift setting (Kröner, 1977; Brown and Wilson, 1986; Borg, 1988) possible, too. However, this model is considered less likely due to the huge volumes of granitic magmas that were produced. An overall younging direction of the magmatic activity along the craton margin towards the northeast, as interpreted from older age data by Borg (1988), must also be discarded due to new high-precision U-Pb zircon SHRIMP data from rocks of northwestern Botswana (Kampunzu *et al.*, 2000a, b) as well as from central and northeastern Namibia (Becker *et al.*, in prep.).

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