

Insights on the genesis of the Cretaceous Damaraland igneous complexes in Namibia from a Nd- and Sr-isotopic perspective

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This study presents new Sr and Nd isotopic and major and trace element data from seven Cretaceous igneous complexes in the Damaraland, NW Namibia (Erongo, Brandberg, Paresis, Messum, Etaneno, Kalkfeld, Ondurakorume). The samples analysed represent the full range of compositions present in the province, including felsic magmas whose compositions reflect in large part crustal sources and silica-undersaturated alkaline magmas whose composition gives insight to the mantle component involved. Malic and alkaline rocks (lamprophyres, phonolite, alkaline basalt and nepheline syenite) and carbonatites yield a surprisingly narrow cluster of values for ϵNd and Sr_i (at 132 Ma) of -2 to +1 and 0.7040 to 0.7050, respectively, which represent a near bulk-earth isotopic composition similar to that of the present-day Tristan plume. Other studies of the Damaraland complexes have reported similar findings and it can now be suggested that the dominant mantle component represented in the complexes is plume-derived. There is no evidence in any of the rocks studied for involvement of an old, isotopically enriched subcontinental lithospheric mantle. The felsic complexes differ greatly in their Nd isotopic compositions. This can be related to different proportions of mantle to crustal material in the source and the type of crust involved. The peraluminous Erongo granites ($\epsilon\text{Nd} = -7$ to -9) overlap in isotopic composition with Damara Belt metasediments and granites and are considered to represent crustal melts. In contrast, mantle-derived material dominates the source of metaluminous to peralkaline Brandberg granites ($\epsilon\text{Nd} = -1$ to -3). Extremely low ϵNd values and moderate Sr initial ratios of rhyolites from Paresis are unique to that complex (-21 at $\text{Sr}_i = 0.71170$) and indicate an important contribution of pre-Damara basement in the source.

Introduction

The South Atlantic region provides one of the world's best examples of a large igneous province produced at a volcanic rifted margin associated with a mantle plume. The record of igneous activity comprises continental flood basalts (CFB) with associated felsic volcanics and a large number of subvolcanic intrusive complexes, the Damaraland complexes. The intrusive complexes are particularly well preserved and exposed in central Namibia, where they extend in a NE-trending zone from the Atlantic coast at Cape Cross, across the Damara Belt to the margin of the Congo craton some 350 km inland (Fig. 1).

The volcanic rocks of the Parana-Etendeka CFB province in Namibia and Brazil have been extensively studied geochemically (see review by Peate, 1997) but uncertainty remains as to the role of the Tristan da Cunha mantle plume in their origin since the isotopic and chemical characteristics of the basalts are inconsistent with a plume source (e.g., Erlank *et al.*, 1984; Peate, 1997). It has been suggested that the influence of the plume is mostly thermal (Gallagher and Hawkesworth, 1992; Turner *et al.*, 1996). Controversy also prevails as to the origin of felsic units associated with the flood basalts (rhyodacites, quartz latites), debate being centered around the relative importance of crustal melting vs. fractionation of basaltic magma (Garland *et al.*, 1995;

Harris and Milner 1997; Ewart *et al.*, 1998b).

The Damaraland intrusive complexes offer a different perspective on the problem of magma genesis in this setting. This is so because the compositional spectrum of rocks in the complexes is much greater than that of the CFB province, ranging from carbonatite to peraluminous granite, and this offers a chance of finding units where one or another source component can be isolated. Also, the eruptive centers of the flood basalts are rarely

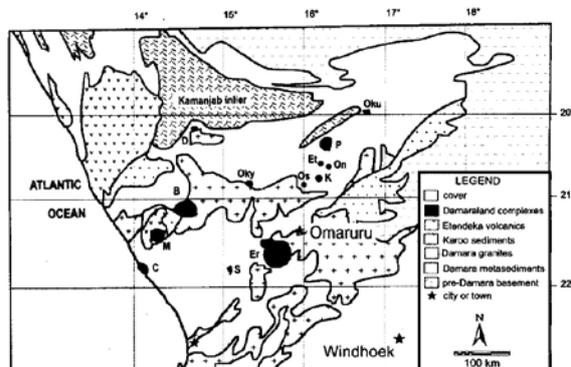


Figure 1: Simplified geologic map of north-central Namibia. The Cretaceous Damaraland igneous complexes are designated as follows: C - Cape Cross, M - Messum, B - Brandberg, S - Spitzkoppe, Er - Erongo, D - Doros, Oky - Okenyena, Os - Osongombe, K - Kalkfeld, Et - Etaneno, On - Ondurakorume, P - Paresis, Oku - Okurusu.

known but there is no ambiguity about where the intrusive complexes were emplaced. This allows a better assessment of compositional differences of the magmas in relation to location within the Damara belt (e.g. distance from the continental margin or the craton edge) and to local basement geology.

Thus, Martin *et al.* (1960) suggested a spatial pattern in the distribution of rock types within the Damaraland complexes and noted that granitic and differentiated basic complexes occur near the Atlantic coast whereas peralkaline and carbonatitic magmatism is concentrated farther inland, the first large carbonatite complex being encountered some 250 km from the coast.

Nd isotope data of igneous rocks can be particularly valuable in mapping basement age and compositional provinces (Bennet and DePaolo, 1987). This paper summarizes Sr and Nd isotopic data from seven of the Damaraland complexes which represent the full range of compositions present in the province: alkaline olivine basalts, phonolite and lamprophyres (*Paresis*); nepheline syenites and carbonatites (*Kalkfeld*, *Ondurakorum*, *Etaneno*), gabbros and syenites (*Messum*, *Paresis*), metaluminous and peralkaline rhyolites (*Paresis*), metaluminous and peralkaline granites (*Brandberg*) and peraluminous granodiorites and granites (*Erongo*).

The radiogenic isotope compositions of most of the granitic units from these complexes have not been studied before, apart from some Rb-Sr age dating, and the data presented here provide important new constraints on their origin. Several studies previously addressed the petrogenesis of the mantle-derived basic alkaline units and carbonatites in Damaraland, and evidence has been found for direct involvement of Tristan plume mantle in their formation. Harris *et al.* (1999) queried how widespread the plume involvement in the Damaraland complexes might be. One conclusion of this work is that the isotopic signature of plume mantle is present in all of the complexes studied so far.

Geologic setting

The Damaraland intrusive complexes in Namibia were emplaced in the Damara Belt, the NE-SW trending inland arm of a late Precambrian (Pan-African) mobile belt, which is bounded by the Congo craton on the north and the Kalahari craton on the south. The Damara belt proper consists of tightly folded platformal and geosynclinal metasediments which are extensively intruded by syn- and post-kinematic granites. Reviews of the regional geology of the Damara Belt can be found in Tankard *et al.* (1982) and Miller (1983). Depositional ages of the metasediments are late Proterozoic to early Cambrian. Metamorphic grades in the deepest exposures, the central zone of the Damara belt, reach the upper amphibolite to granulite facies. The emplacement of post-kinematic granites, mostly of S-type, dates from 560 Ma to 460 Ma (Miller, 1983) and marks the end of the Damara orogeny in this region. The trace element

and isotopic composition of representative Damara metasedimentary units and of several examples of post-kinematic granites have been reported by McDermott and Hawkesworth (1990), McDermott *et al.* (1996) and Jung *et al.* (1998).

Pre-Damara felsic gneisses and granitoids occur in tectonic inliers at the edge of the northern platform zone of the Damara Belt, the largest of which is the Kammanjab inlier (Fig. 1). These rocks in northern Namibia and southern Angola have yielded Proterozoic and late Archean ages and are thought to represent remnants of the southern Congo Craton (Jacob *et al.*, 1978; Tegtmeier and Kröner, 1985; Toteu *et al.*, 1994; Seth *et al.*, 1998).

During the Cretaceous breakup of western Gondwana, the Damara Belt and once adjacent regions of the conjugate South American margin were the site of flood basalts, mafic dike swarms and subvolcanic intrusive complexes which make up the South Atlantic Large Igneous Province. Because of its proximity to the submarine Walvis Ridge as an oceanic hotspot track, this igneous province has generally been attributed to the action of a mantle plume. The volcanic rocks in the province are strictly bimodal, with tholeiitic basalts interlayered with felsic volcanics. Both the basalts and felsic units can be divided into two compositional groups, one relatively rich in Ti and HFS elements (high-Ti group) and the other, low-Ti group, with lower concentrations of those elements (see review by Peate, 1997).

Marine seismic reflection surveys have revealed seaward-dipping reflector sequences on both sides of the south Atlantic which are interpreted as the submerged equivalents of flood basalts on the continental shelf (Gladczenko *et al.*, 1997). The total volume of basaltic magma extruded on both conjugate margins, including the volumes estimated from marine geophysics, is some 2.4 million cubic kilometers (Gladczenko *et al.*, 1997). Additional major volumes of mafic magma are represented by the high-velocity, overthickened oceanic crust at the continent-ocean boundary which has been revealed in the wide-angle seismic study of Bauer *et al.* (2000).

Martin *et al.* (1960) and later Harris (1995) suggested a subdivision of the Damaraland intrusive complexes into three compositional groups: granitic (Brandberg, Erongo, Spitzkoppe), differentiated basic (Cape Cross, Doros, Okenyenya, Messum) and peralkaline basaltic to carbonatitic complexes (Etaneno, Paresis, Kalkfeld, Okurusu and several smaller carbonatites). Some complexes are nearly mono lithologic (e.g., Spitzkoppe granite, Etaneno nepheline syenite) but it is more common to find a variety of rock types erupted or intruded in close proximity. The total range of radiometric dates published from the Damaraland complexes is 137 to 124 Ma (Milner *et al.*, 1995; Renne *et al.*, 1996). Recent $^{40}\text{Ar}/^{39}\text{Ar}$ dates show that many of the flood basalts and silicic volcanic sequences of the Etendeka Group and the Parana Province formed in a narrow age range

of 130 to 135 Ma (Renne *et al.*, 1992; Turner *et al.*, 1994; Renne *et al.*, 1996). There is no apparent pattern of age variation with location within the Damaraland complexes. The age for the onset of seafloor spreading in the South Atlantic is not precisely known but the oldest seafloor magnetic anomaly recognized offshore the Etendeka region is M4, representing an age of 125-127 Ma (Gladchenko *et al.*, 1997). Therefore, it seems that the entire cycle of breakup-related igneous activity took place in a short time period, similar to the situation in other CFB provinces such as the Deccan (Allègre *et al.*, 1999).

Analytical methods

Major and trace elements were analysed at the GFZ Potsdam and in Giessen by X-ray fluorescence using fused and pressed powder discs and a Rh tube (Phillips PW 2400 in Potsdam and PX 1400 in Giessen). H₂O was determined by Karl-Fischer-reaction in both laboratories. CO₂ was measured coulometrically (Giessen) and by infrared spectrometry (Potsdam) using a LECO RC412 instrument.

Analyses of rare earth elements and isotopes were performed at the GFZ Potsdam. The rare earths were determined by ICP-AES using the method described by Zuleger and Erzinger (1988). Sr and Nd isotopic analyses followed standard cation exchange techniques (Biorad AG50Wx12 for Sr, HDEHP-coated teflon powder for Nd) after sample digestion in pressurized teflon vessels in 5:1 HF-HNO₃. Strontium was measured on single Ta filament with a VG Sector 54-30 mass spectrometer operated in the dynamic mode and Nd was measured on a Finnigan MAT 262 mass spectrometer operated in the static mode and using a double-filament procedure (Ta evaporation filament, Re ionization filament). Mass fractionation was corrected using ratios of ⁸⁶Sr/⁸⁸Sr = 0.1194 and ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219. The NBS 987 standard gave ⁸⁷Sr/⁸⁶Sr values of 0.710246 ± 5 (1σ) during the period of this study and the La Jolla Nd standard yielded a value of ¹⁴³Nd/¹⁴⁴Nd = 0.511855 ± 4 (1σ). Total procedural blanks were 100-200 pg for Sr and <50 pg for Nd. Calculation of initial isotopic ratios was made using Rb/Sr and Sm/Nd ratios from ICP-MS and ICP-AES chemical analyses, respectively. All initial ratios were calculated for a common age of 132 Ma. Uncertainties of ± 5 Ma in age and 5% on Sm/Nd ratios correspond to a variation of less than 0.3 units in εNd. Corresponding errors on the Sr initial ratio depend on Rb/Sr and are about 0.2% for samples with Rb/Sr ratio of 5 and about 1 % for an unusually high Rb/Sr ratio of 20. The εNd values are calculated relative to CHUR (chondrite uniform reservoir) based on assumed ¹⁴⁷Sm/¹⁴⁴Nd and ¹⁴³Nd/¹⁴⁴Nd ratios for present-day CHUR of 0.1967 and 0.512638, respectively. All literature data used have been recalculated using the same age and CHUR constants.

Results

The data set for this study includes 60 isotopic and chemical analyses which cover the main units found in the seven Damaraland igneous complexes described below. Table 1 lists isotopic and chemical data from a subset of 41 samples selected to represent the full range of compositions present in each complex. Figure 2 and subsequent diagrams are based on the full data set which can be obtained from the authors upon request.

Granitic complexes

Brandberg

The Brandberg complex (Cloos and Chobuda, 1931; Hodgson, 1973; Diehl, 1990; Schmitt *et al.*, 2000) is a granitic massif some 25 km in diameter. The dominant rock type of the complex is metaluminous biotite-hornblende granite which intrudes an earlier pyroxene-hornblende monzonite unit and is in turn intruded by dikes of biotite leucogranite. A late intrusive component is a sill- and -dike complex of peralkaline arfvedsonite granite (the Amis complex) which occurs at the SW margin of the main massif. The ⁴⁰Ar/³⁹Ar ages of biotite and amphibole from the main granite and arfvedsonite granite show that these two units are contemporary, within error, at 132±1 Ma (Schmitt *et al.*, 2000). A set of trachydacite dikes intrude the country rocks on the NE margin of the Brandberg. The dikes are considered to be part of the Brandberg complex because of geochemical affinity and their orientation parallel to the bounding ring fault of the main massif. There are no contacts between trachydacite dikes and the Brandberg granite so their relative age is uncertain, nor have they been dated radiometrically.

The Sr and Nd isotopic ratios of the Brandberg samples cover a narrow range despite their differences in chemical composition (Fig. 2b). In detail, the monzonite samples are isotopically the most primitive, with εNd and Sr_i values of -0.5 to -0.8 and 0.70718 - 0.70855, respectively. The biotite-hornblende granite has slightly higher values of Sr_i (0.71218 - 0.71354) and lower εNd (-2.7 to -3.5). The peralkaline granites yielded values of εNd which overlap with the other Brandberg units (-0.7 to -2). Note that only one sample of this group is plotted in Fig. 2b because the others have such elevated Rb/Sr ratios that the calculated initial Sr ratios are imprecise. The two samples of trachydacite dikes have slightly lower εNd values than the main massif granites (-4.9 and -5.1) and overlapping initial ⁸⁷Sr/⁸⁶Sr ratios.

The most striking feature of the isotopic data from the Brandberg granites is the relatively primitive isotopic compositions of all units. The low initial Sr ratios and high εNd values resemble the Etendeka flood basalts and the gabbros and syenites from the Okenyenya and Messum complexes (Fig. 2), which suggests a major contribution of mantle-derived material in the parental magmas.

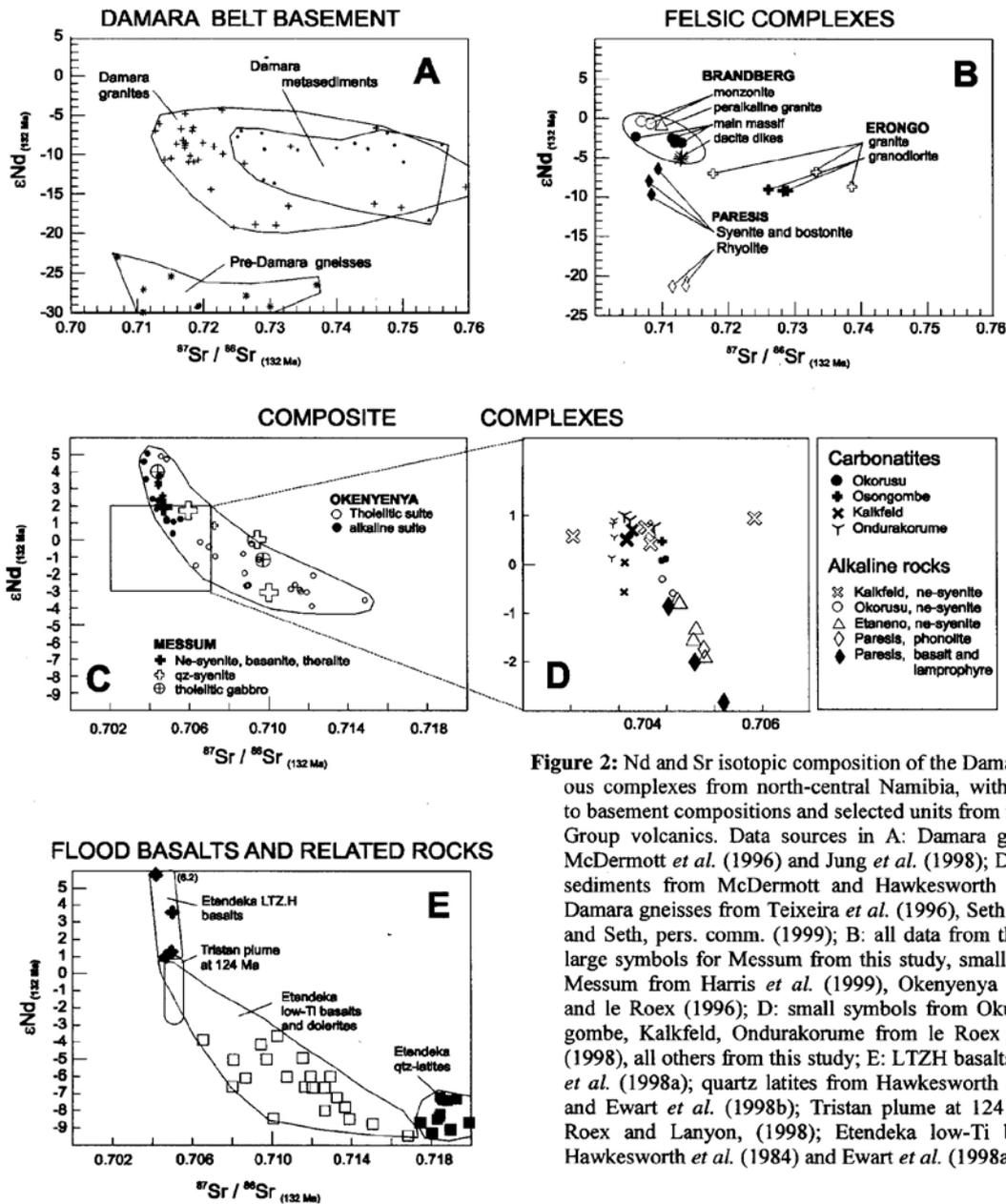


Figure 2: Nd and Sr isotopic composition of the Damaraland igneous complexes from north-central Namibia, with comparison to basement compositions and selected units from the Etendeka Group volcanics. Data sources in A: Damara granites from McDermott *et al.* (1996) and Jung *et al.* (1998); Damara metasediments from McDermott and Hawkesworth (1990); pre-Damara gneisses from Teixeira *et al.* (1996), Seth *et al.* (1998) and Seth, pers. comm. (1999); B: all data from this study; C: large symbols for Messum from Harris *et al.* (1999), Okenyenya from Milner and le Roex (1996); D: small symbols from Okorusu, Osongombe, Kalkfeld, Ondurakorume from le Roex and Lanyon (1998), all others from this study; E: LTZH basalts from Ewart *et al.* (1998a); quartz latites from Hawkesworth *et al.* (1984) and Ewart *et al.* (1998b); Tristan plume at 124 Ma from le Roex and Lanyon, (1998); Etendeka low-Ti basalts from Hawkesworth *et al.* (1984) and Ewart *et al.* (1998a).

Erongo

The Erongo complex (Blümel *et al.*, 1979; Pirajno, 1990; Pirajno *et al.*, 2000) is the largest of the Damaraland complexes, with a diameter of 35 km. The complex consists mainly of two series of ash-flow tuffs with a total exposed thickness up to 800 m. Intrusive into the tuffs at the center of the complex is a peraluminous, cordierite-bearing granodiorite (Ombu granodiorite) which is chemically equivalent to the upper tuffs and thought to represent magma resurgence in the vent area (Pirajno, 1990). A second plutonic phase involved peripheral intrusions of peraluminous, tourmaline-bearing biotite granite (Erongo granite). The granodiorite and associated tuffs carry abundant cm-sized and larger enclaves of Damara granite and schist from the local basement. These enclaves are lacking in the Erongo

granite.

Mafic igneous units associated with the Erongo complex include a sequence of tholeiitic basalt lavas at the base of the tuff sequence and a very prominent ring dike of diabase which half encircles the complex with a diameter of about 50 km. Also present are a number of small basanite and nephelinite plugs intruding tuffs near the NW margin of the complex (Patel, 1988), and rare alkali basaltic dikes which cut the Erongo granite (Blümel *et al.*, 1979).

Isotopic study of the mafic and alkaline units from Erongo is ongoing and we report here only the Sr and Nd isotopic compositions of the felsic units. The granite and granodiorite together cover a range in εNd from -7 to -9 and Sr_i from 0.7263 to 0.7399 which corresponds well with the field for the Damara metasediments and S-

type granites on Fig. 2a. The initial Sr ratios of the highly-evolved Erongo granite are imprecise because of the high Rb/Sr ratios of the samples. This may explain the spread of points in Figure 2b. In terms of ϵ_{Nd} , there appears to be a significant difference between the Erongo granite and the Ombu granodiorite which may relate to differences in the magma source or in the degree of upper crustal contamination. This is supported by the observation that the upper crustal enclaves (Kuiseb schist) are common in the granodiorite but entirely lacking in the granite, and that tourmaline is common in the granite and absent from the granodiorite.

The composite complexes

Messum

The Messum complex (Korn and Martin, 1954; Harris *et al.*, 1999) is a deeply-eroded subvolcanic ring complex about 18 km in diameter which consists of an outer series of cone sheets and an inner core. These rocks intrude a basalt and quartz latite volcanic sequence of the Goboboseb Mountains described by Ewart *et al.* (1998 a, b). The outer cone sheets are composed of a series of tholeiitic gabbros, diorites, norites and anorthosites, which are divided into a western and an eastern set on structural and petrographic grounds (Ewart *et al.*, 1998b). The eastern set is intruded by enclave-rich granite dikes and sheets which show evidence for magma mingling. The central core of the ring complex is highly varied lithologically and consists of a quartz-saturated suite, undersaturated rocks ranging from basanitic to phonolitic compositions, and a sub-

alkaline volcanic and volcanoclastic series (basaltic to rhyolitic) with sedimentary remnants.

Harris *et al.* (1999) reported Nd, Sr and O isotopic compositions of samples from the Messum core units. Our samples from Messum represent units from the core (nepheline syenites and quartz syenites) as well as the western gabbro cone sheets. The data are shown in Figure 2c along with five samples from Harris *et al.* (1999) for which both Sr and Nd data are available. The cone sheet gabbros are represented by two samples which are chemically and isotopically quite different. Gabbro sample M10 (MgO = 11.1 wt.%) yields Nd and Sr isotopic ratios which fall within the mantle array in the depleted quadrant ($\epsilon_{Nd} = +3.9$ and $Sr_i = 0.70440$) whereas sample M9 is more differentiated (MgO = 5.1 wt. %) and it has higher Sr_i and lower ϵ_{Nd} values (0.70974 and -1.2). It must be noted that both samples have positive Eu anomalies and extremely low incompatible element contents (Table 1) which suggests a cumulate origin. However, the isotopic ratios should not be affected by this process and may still reflect the magma composition.

The nepheline syenite M1 from the Messum core has an isotopic composition ($\epsilon_{Nd} = +1.9$ and $Sr_i = 0.7047$) very similar to that of the undersaturated units (nepheline syenites, basanite and theralite) reported by Harris *et al.* (1999). Our data from three samples of quartz syenite show that group to be isotopically heterogeneous, with relatively high Sr_i (0.7060 to 0.7097) and ϵ_{Nd} values ranging from -3 to +1.7. As suggested by Harris *et al.* (1999) and backed up by their oxygen isotope data, the differences between the quartz syenite and under-

Table 1: Chemical and isotopic composition of representative samples from the investigated Damaraland complexes.

	ERONGO							ETANENO			KALKFELD			
	ER202	ER203 granite	ER211	ER204	granodiorite ER206	ER208	ET1 *	ET2 *	ET167 *	carbonate KF59 *	KF94 *	KF202 *	no-syenite KF211 *	KF212 *
SiO ₂	75.2	75.8	74.7	67.8	67.6	67.6	56.3	50.5	55.6	0.12	3.52	53.4	44.2	53.3
TiO ₂	0.09	0.08	0.19	0.78	0.77	0.77	1.01	0.88	1.00	0.04	0.49	0.86	0.53	0.87
Al ₂ O ₃	12.5	12.3	13.2	14.1	14	14.1	16.8	19	17.9	0.34	0.99	17.7	26.5	22.8
Fe ₂ O ₃	1.75	1.70	1.59	5.11	5.12	5.31	8.93	7.27	7.36	2.59	8.94	7.67	2.98	2.83
MnO	0.03	0.03	0.01	0.07	0.08	0.08	0.32	0.19	0.26	1.67	2.36	0.26	0.07	0.06
MgO	0.05	0.05	0.18	1.20	1.25	1.29	0.97	3.20	0.99	0.76	0.44	0.45	0.23	0.50
CaO	0.40	0.38	0.17	1.99	1.87	1.95	3.37	4.85	4.08	37.4	42.5	1.40	1.41	0.93
Na ₂ O	2.82	2.80	2.69	2.78	2.81	2.80	6.45	8.08	6.49	0.12	0.04	8.11	12.76	8.84
K ₂ O	5.35	5.20	5.25	4.52	4.56	4.53	4.79	3.37	3.91	0.01	0.12	7.33	5.48	7.64
P ₂ O ₅	0.04	0.04	0.37	0.24	0.23	0.24	0.35	0.53	0.34	4.99	3.99	0.06	0.05	0.01
CO ₂	0.06	0.04	0.04	0.06	0.06	0.04	0.07	0.36	0.19	41.7	33.4	0.36	1.76	0.42
H ₂ O	0.51	0.49	0.77	1.05	1.01	0.67	0.43	0.94	0.32	0.6	1.4	0.69	2.66	0.52
Total	98.8	98.9	99.2	99.7	99.4	99.4	99.8	99.2	98.5	90.4	98.2	98.3	98.6	98.7
Cr	10	10	15	35	30	27	10	144	10	29	-	14	10	8
Zn	57	58	52	79	75	82	191	76	126	73	345	120	49	46
Rb	861	845	493	206	206	207	261	77	176	-	5	179	120	175
Ba	30	30	137	708	654	633	978	1621	1336	691	2457	330	449	1093
Sr	20	20	35	151	139	142	280	816	508	4.20%	6182	2782	1134	1458
Ga	24	22	21	21	21	21	22	18	25	-	-	33	32	24
Nb	36	32	16	17	17	17	450	101	295	457	2147	464	145	212
Zr	89	95	96	246	244	252	2500	234	1394	184	9	2376	65	366
Y	93	81	18	38	39	39	152	33	303	738	504	49	4	5
La	30	25	11	48	48	47	324	107	213	3932	4384	187	44	28
Ce	64	58	21	92	96	94	592	185	388	7492	8006	286	68	63
Pr	10	8	3	12	12	13	63	19	42	744	849	22	6	7
Nd	35	29	11	45	45	46	191	60	131	2520	2570	64	18	22
Sm	10	8.4	2.5	8.8	9.1	9.5	30.4	8.87	21.5	369	314	9.7	2.7	3.7
Eu	0.12	0.09	0.15	1.3	1.3	1.3	4.25	2.44	4.92	101	87.3	2.8	0.67	1.1
Gd	11	9.7	2.1	8.1	8.3	8.1	25.8	7.01	17.7	269	205	8.4	1.8	2.7
Tb	2.6	2.3	0.43	1.1	-	1.4	4.23	1.03	2.95	36	25.1	1.3	-	0.39
Dy	17	15	2.8	7	7.4	7.6	26.9	5.95	18.6	188	115.5	7.8	1.1	2
Ho	3.4	2.9	0.57	1.3	1.3	1.3	5.71	1.17	3.92	29	19.2	1.8	0.22	0.35
Er	11	9.3	1.8	3.7	3.9	3.9	17.5	3.34	12.1	60	43.2	5.2	0.57	0.85
Tm	1.7	1.5	0.29	0.55	0.56	0.58	2.87	0.51	1.92	4.91	-	-	-	-
Yb	12	11	1.9	3.6	3.7	3.6	19.6	3.2	13.1	30	23.4	5.3	0.36	0.81
Lu	1.7	1.5	0.29	0.54	0.55	0.57	2.98	0.52	2.05	3.2	3.23	0.83	0.05	0.14
⁸⁷ Sr/ ⁸⁶ Sr _m	1.62148(2)	1.67141(2)	0.816025(9)	0.735843(9)	0.736972(9)	0.734107(8)	0.710138(8)	0.705162(8)	0.706842(8)	0.70376(1)	0.703856(8)	0.704433(8)	0.704757(8)	0.70478(1)
⁸⁷ Sr/ ⁸⁶ Sr _i	1.3669	1.4204	0.7388	0.7284	0.7289	0.7262	0.7049	0.7047	0.7049	0.7038	0.7039	0.7041	0.7042	0.7041
¹⁴³ Nd/ ¹⁴² Nd _m	0.51226(1)	0.51227(1)	0.51214(1)	0.51209(1)	0.51210(1)	0.51211(1)	0.512478(6)	0.512482(6)	0.512482(6)	0.512570(7)	0.512568(5)	0.512586(6)	0.512586(6)	0.512592(5)
¹⁴³ Nd/ ¹⁴² Nd _i	0.51211	0.51212	0.51202	0.51199	0.51199	0.51200	0.51239	0.51243	0.51240	0.51249	0.51250	0.51251	0.51249	0.51250
ϵ_{Nd}	-7.0	-6.9	-8.7	-9.3	-9.3	-9.1	-1.5	-0.8	-1.3	0.5	0.6	0.7	0.4	0.7

Table 1: (cont.)

	BRANDBERG										MESSUM							
	monzonite	trachydacite	leucogranite	bl-hbl granite	peralkaline granite	gabro	ne-syenite	qz-syenite	M3	M4	M9	M10	M1	M6	M3	M4		
SiO ₂	61.5	66.8	76.8	68.0	70.9	72.9	71.7	47.0	46.7	53.4	62.0	61.4	61.0	61.0	61.0	61.0		
TiO ₂	1.46	0.93	0.14	0.62	0.46	0.18	0.23	0.89	0.28	0.51	0.67	0.67	1.11	1.25	1.11	1.25		
Al ₂ O ₃	13.6	13.3	12.3	13.4	13.2	10.95	10.88	21.3	18.0	21.3	16.4	16.4	14.7	14	14.7	14		
Fe ₂ O ₃	9.68	6.69	1.48	5.85	3.52	5.65	6.25	10.20	8.44	5.15	6.67	7.28	7.65	7.28	7.65	7.65		
MnO	0.20	0.11	0.03	0.16	0.10	0.08	0.09	0.12	0.13	0.15	0.21	0.20	0.16	0.20	0.16	0.16		
MgO	1.15	0.75	0.15	0.48	0.30	0.04	0.02	5.10	11.10	1.01	0.57	1.34	1.79	1.34	1.79	1.79		
CaO	3.41	2.70	0.52	1.98	1.47	0.18	0.05	13.20	14.10	2.74	2.52	3.18	3.86	3.18	3.86	3.86		
Na ₂ O	4.32	3.44	3.62	3.78	3.71	5.04	4.94	2.34	1.40	8.63	5.72	5.45	5.01	5.45	5.01	5.01		
K ₂ O	3.64	4.37	5.17	4.79	5.28	4.37	5.05	0.14	0.08	5.38	4.70	4.78	4.48	4.78	4.48	4.48		
P ₂ O ₅	0.46	0.25	0.01	0.13	0.09	0.00	0.00	0.01	0.02	0.33	0.14	0.26	0.31	0.14	0.26	0.31		
CO ₂	0.13	0.17	0.02	0.04	0.04	0.05	0.05	0.32	0.26	0.55	0.03	0.13	0.08	0.03	0.13	0.08		
H ₂ O	0.77	0.29	0.15	0.55	0.31	0.18	0.21	0.34	0.48	0.76	0.29	0.35	0.40	0.29	0.35	0.40		
Total	100.3	99.83	100.4	99.8	99.8	99.6	99.5	101.0	101.0	99.9	99.9	100.2	100.0	100.2	100.0	100.0		
Cr	10	13	10	11	10	11	13	115	320	42	10	10	18	10	10	18		
Zn	156	100	32	109	97	591	778	75	45	58	106	117	109	106	117	109		
Rb	144	146	408	186	206	892	1102	<5	<5	168	162	214	251	162	214	251		
Ba	747	914	129	1017	806	32	15	10	49	10	1353	741	10	1353	741	10		
Sr	225	200	19	147	111	79	6	388	212	526	164	267	207	526	164	267		
Ga	25	23	15	20	24	50	25	25	16	18	22	20	20	18	22	20		
Nb	51	42	50	44	50	92	556	5	5	89	125	282	69	89	125	282		
Zr	373	366	212	396	398	594	610	10	15	238	688	786	358	238	688	786		
Y	67	63	66	60	63	509	395	6	5	15	80	124	81	15	80	124		
La	62	71	67	76	78	219	174	1.0	1.1	47	80	104	67	47	80	104		
Ce	129	145	132	138	178	402	330	2.2	2.4	63	132	174	123	63	132	174		
Pr	16	18	15	20	18	74	56	0.6	0.7	7	19	30	21	7	19	30		
Nd	64	64	47	69	69	304	202	2.5	2.0	25	61	92	68	25	61	92		
Sm	14	13	9.1	14	14	83	50	0.83	0.66	3.8	14.8	20.6	13.7	3.8	14.8	20.6		
Eu	3.4	2.4	0.57	3.1	2.4	2.3	1.05	0.56	0.36	1.3	3.4	2	1.92	1.3	3.4	2		
Gd	11	12	9.3	12.8	12.4	91.1	46.9	1.2	0.95	13.6	18.8	12.3	12.3	13.6	18.8	12.3		
Tb	2.2	2.1	1.8	2.2	2.2	13	6	0.19	0.15	0.24	3.8	1.56	1.56	0.24	3.8	1.56		
Dy	1.6	-	1.2	1.2	1.2	13	6	0.19	0.15	0.24	3.8	1.56	1.56	0.24	3.8	1.56		
Ho	2.6	-	2.3	2.5	2.4	9.6	10.7	0.21	0.18	0.4	2.5	4.2	2.82	0.4	2.5	4.2		
Er	6.1	-	7.6	7.3	6.9	25	31	0.61	0.49	1.5	8.8	12.8	8.5	1.5	8.8	12.8		
Tm	0.9	-	1.2	1	0.9	3	4.5	0.1	0.08	0.22	1.2	0.72	0.72	0.22	1.2	0.72		
Yb	7	6	8.3	6.3	6.5	18	18	0.58	0.51	1.6	8.4	12.2	8.7	1.6	8.4	12.2		
Lu	1.1	0.9	1.3	1	1	2.7	2.8	0.09	0.08	0.22	1.2	1.6	1.2	0.09	0.08	1.2		
⁸⁷ Sr/ ⁸⁶ Sr _{in}	0.71191(2)	0.71709(2)	0.81806(5)	0.71842(2)	0.72195(2)	0.89249(2)	1.50879(3)	0.70981(1)	0.70452(9)	0.70644(5)	0.71133(1)	0.71654(2)	0.71666(2)					
⁸⁷ Sr/ ⁸⁶ Sr _{st}	0.7084	0.7130	0.7061	0.7119	0.7116	0.7340	0.6300	0.7097	0.7044	0.7047	0.7060	0.7096						
¹⁴³ Nd/ ¹⁴² Nd _{in}	0.512546(8)	0.51231(5)	0.512448(5)	0.512426(7)	0.512440(5)	0.512557(5)	0.512557(5)	0.51258(1)	0.51284(1)	0.512648(5)	0.512681(5)	0.512585(6)						
¹⁴³ Nd/ ¹⁴² Nd _{st}	0.51243	0.51220	0.51235	0.51232	0.51233	0.51242	0.51243	0.51241	0.51267	0.51257	0.51255	0.51247						
εNd _t	-0.8	-5.1	-2.4	-2.8	-2.7	-1.1	-0.9	-1.2	3.9	1.9	1.7	0.0						

Table 1: (cont.)

	PAREISIS										ONDURAKORUME					
	rhyolite	comendite	qz-syenite	bostonite	basalt	phonolite	lamprophyre	carbonatite	On64 *	On65 *	On76 *	On77 *	On78 *	On79 *	On80 *	
SiO ₂	71.1	68.6	74.0	75.0	56.1	65.5	43.7	45.1	54.3	39.6	36.4	0.06	0.06	1.23	1.23	
TiO ₂	0.43	0.70	0.31	0.20	1.08	1.28	0.60	1.42	1.37	0.32	2.14	0.05	0.04	0.07	0.07	
Al ₂ O ₃	13.9	13.9	11.4	10.9	16.1	15.8	15.1	13.7	12.9	21.6	13.5	0.41	0.41	0.58	0.58	
Fe ₂ O ₃	3.47	3.81	5.33	5.24	8.28	9.25	5.87	13.62	13.62	4.36	11.88	0.19	0.19	2.34	2.34	
MnO	0.01	0.08	0.10	0.07	0.19	0.19	0.17	0.17	0.18	0.18	0.21	1.57	1.42	1.75	1.75	
MgO	0.16	0.66	0.09	0.07	0.59	0.72	0.34	11.39	13.33	0.66	7.67	0.45	1.81	1.11	1.11	
CaO	0.31	1.83	0.54	0.22	3.86	4.35	1.26	11.37	10.57	1.52	14.08	39.8	41.3	42.1	42.1	
Na ₂ O	3.73	4.02	3.40	4.10	5.05	4.96	6.28	2.31	2.42	9.49	4.21	0.07	-	-	-	
K ₂ O	5.77	5.20	5.16	4.29	4.85	5.09	4.69	0.39	0.65	6.38	1.03	0.01	0.01	0.04	0.04	
P ₂ O ₅	0.11	0.18	0.04	0.01	0.47	0.53	0.11	0.23	0.22	0.12	1.33	5.41	3.16	5.43	5.43	
CO ₂	0.35	0.43	0.09	0.08	1.76	1.77	0.50	0.11	0.10	0.07	1.28	37.6	40.0	35.7	35.7	
H ₂ O	0.99	0.93	1.12	0.99	1.25	0.77	0.72	1.83	2.20	1.16	4.16	1.2	0.5	1.2	1.2	
Total	100.3	100.3	101.5	101.1	101.0	100.8	101.1	100.4	102.7	100.2	101.1	95.4	95.4	95.4	95.4	
Cr	18	19	33	41	14	13	10	675	924	20	139	16	14	18	18	
Zn	111	79	254	307	100	96	133	96	96	76	97	106	64	101	101	
Rb	208	159	382	486	72	79	153	13	23	179	49	-	2.6	-	-	
Ba	799	1886	81	82	1287	1291	575	196	231	635	1914	3546	1167	4621	4621	
Sr	94	169	19	8	212	267	69	306	234	265	1517	1.92%	2.61%	25858	25858	
Ga	15	10	28	16	15	26	18	13	10	8	-	-	-	-	-	
Nb	26	19	146	179	14	14	177	15	14	188	-	-	-	-	-	
Zr	533	521	1457	2477	210	257	973	98	96	345	299	-	-	-	-	
Y	50	50	126	150	32	34	84	18	19	24	100	217	244	244	244	
La	108	93	208	105	80	91	176	16	15	84	162	358	401	440	440	
Ce	219	151	359	188	156	168	309	38	34	136	297	1235	1487	1584	1584	
Pr	27	20	46	26	18	20	34	5	4	12	30	190	240	244	244	
Nd	94	76	166	98	68	77	118	23	19	35	107	1235	1478	1584	1584	
Sm	17	13	32	21	11.6	13	20	5.3	4.6	5.6	17	190	240	244	244	
Eu	1.8	2.45	1	0.59	3.7	3.9	1.7	1.6	1.4	1.1	4.4	14	18	17	17	
Gd	12	11	29	18	9.24	10	17	4.8	4.45	4.3	12.2	58	69	73	73	
Tb	1.99	1.56	4.5	3.3	1.22	1.3	2.6	0.74	0.71	1.43	8.4	9.2	10	10	10	
Dy	11	8.8	25	19	6.9	7.7	1.6	4.2	4.05	4.2	7.38	15	18	18	18	
Ho	2.1	1.8	5.1	3.9	1.2	1.4	3.3	0.79	0.76	0.94	1.25	2.8	3.1	3.1	3.1	

At the other compositional extreme, the Paresis rhyolites have extremely low ϵNd (-20.5 to -21.3) and moderately radiogenic Sr ($\text{Sr}_i = 0.7117$ to 0.71384). As seen by comparing Figures 2a and 2b, these values rule out an origin from Damara Belt granites or metasediments but they overlap with the field of early Precambrian gneisses and granitoids from NW Namibia (Seth *et al.*, 1998) and similar rocks from the Sao Francisco Craton in Brazil (Teixeira *et al.*, 1996). Paresis is located closest to the Congo craton and farthest from the continental margin (Fig. 1) and we interpret the low ϵNd values to indicate an important contribution of pre-Damara crustal material in its source.

The Paresis syenites and bostonite (microsyenite) have isotopic compositions which plot approximately midway between the rhyolites and the undersaturated units ($\epsilon\text{Nd} = -6.5$ to -9.7 , $\text{Sr}_i = 0.70733$ to 0.7095). The comendite samples Pa 49 and Pa 51 are not plotted on Figure 2b because their Sr ratios are poorly defined due to extreme Rb/Sr ratios. They have slightly lower ϵNd values than the syenites (-10.8, -11.3). Mingram *et al.* 2000 show that the isotopic and trace element composition of the syenites and comendite can be explained by contamination of mantle-derived mafic magma by the pre-Damara crust.

Carbonatites and nepheline syenites

Etaneno

Etaneno (Prins, 1981) forms an intrusion of nepheline monzosyenites and nepheline-bearing alkali-feldspar syenites which is circular in plan and about 2 km in diameter. The rocks consist mostly of nepheline, clinopyroxene, olivine, feldspars and amphiboles with minor and variable amounts of sodalite, biotite and fluorite. Four samples from Etaneno are shown in Figure 2d (three are listed in Table 1) and these represent the range of fractionation found in the complex. The most primitive sample, ET2 (3.2 % MgO, 144 ppm Cr, 77 ppm Rb) has Nd and Sr isotopic compositions close to bulk-earth values ($\epsilon\text{Nd} = -0.8$ and $\text{Sr}_i = 0.7047$). The most evolved sample, ET1 (0.97 % MgO, 10 ppm Cr, 261 ppm Rb) has a slightly higher Sr_i of 0.7049 and lower ϵNd value of -1.5. Thus, there is no significant difference in isotopic composition with chemical differentiation, suggesting that magma evolution at Etaneno was a nearly closed-system fractionation.

Kalkfeld

The Kalkfeld ring complex (Van Zijl, 1962; Verwoerd, 1966; Prins, 1981; Bühn and Rankin, 1999; Bühn *et al.*, 2001), about 10 km in diameter, is composed of a central carbonatite plug and an outer suite of alkaline silicate rocks (nephelinites to nepheline syenites) and fenites. The silicate rocks are composed largely of nepheline, feldspars, augitic clinopyroxenes, titanite, sodalite and biotite. The carbonatites are predominantly sovites with low Mg concentrations and highly variable

Fy, P, Sr and F contents.

Table 1 presents isotope data from both the carbonatite and nepheline syenite. The data are shown in Figure 2d. The Nd isotopic composition of the silicate and carbonatite rocks overlap and the alkaline rocks have a much wider range of Sr isotope values ($\epsilon\text{Nd} = 0.4$ to 0.9 and $\text{Sr}_i = 0.70287$ to 0.70593). Also included in Figure 2d are two analyses of carbonatite from Kalkfeld by Le Roex and Lanyon (1998), shown in smaller symbols. These authors did not analyse samples of the alkali silicate rocks. The results from both rock series reveals an overlap in isotopic composition which supports the suggestion of Bühn *et al.* (submitted) that the silicate and carbonatite magmas at Kalkfeld may be cogenetic.

Ondurakorume

The Ondurakorume complex (Van Zijl, 1962; Verwoerd, 1966; Prins, 1981; Bühn *et al.*, submitted) forms a small intrusion about 1.5 km in diameter which is very similar to Kalkfeld in having a central carbonatite plug and outer ring of fenitized syenite rocks. Ondurakorume carbonatites are generally more Mg-rich than at Kalkfeld and the complex is largely composed of beforosite varieties. Individual layers or lenses in the carbonatite are locally strongly enriched in Fe, P, Nb and F.

The alkali-silicate rocks at Ondurakorume are highly altered and therefore only carbonatites were analysed (Table 1). The Nd and Sr isotopic compositions of three samples of carbonatite (Fig. 2d) are the same as those from Kalkfeld ($\epsilon\text{Nd} = +0.8$ to $+1.0$ and $\text{Sr}_i = 0.7037$ to 0.7043). Le Roex and Lanyon (1998) reported very similar values to these from three carbonatite samples and one sample of a lamprophyre dyke at Ondurakorume. Their data are included in the figure and distinguished by smaller symbols.

Discussion

Mantle components and role of the Tristan plume

It has been noted for many years that the majority of flood basalts from the Parana - Etendeka CFB province have isotopic and trace element compositions different from those of oceanic island basalts and therefore appear not to represent melting of mantle plume material (e.g., Erlank *et al.*, 1984; Peate, 1997; Hawkesworth *et al.*, 1999). Exceptions to this are a particular variety of basalts from near Messum (Tafelkop, also called LTZH basalts) reported by Ewart *et al.* (1998a) and picrites from the base of the Etendeka sequence (Gibson *et al.*, 1999).

On the other hand, plume signatures appear to be common in the isotopic composition of alkaline basic and ultrabasic units from the Damaraland intrusive complexes. This was first suggested by Milner and Le Roex (1996) in their study of the Okenyenya complex. The Okenyenya rocks in fact cover a large range in isotopic composition and only the alkaline suite (alkaline

gabbros, essexite, nepheline syenite and lamprophyre) has ϵ_{Nd} and Sr_i values consistent with a plume source. Many of the silica-oversaturated samples (tholeiite suite) from Okenyenyanya have negative values of ϵ_{Nd} and deviate considerably from the mantle array toward higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Fig. 2c). This was attributed by Milner and Le Roex (1996) to crustal contamination. A

similar case seems to prevail at Messum with respect to the quartz-oversaturated and undersaturated units (Harris *et al.*, 1999). Discounting for the moment the oversaturated and crustally contaminated rocks, it can be said that the basic and alkaline units from Messum (Harris *et al.*, 1999; this study), Paresis, Etaneno and Kalkfeld (this study), Okorusu and Ondurakorume (Le Roex and Lanyon, 1998), and Okenyenyanya (Milner and Le Roex, 1996) have the same Bulk Earth isotopic composition as the carbonatites from Kalkfeld, Ondurakorume, Osongombo and Okorusu (Le Roex and Lanyon, 1998; this study). Thus, the mantle-derived units in the Damaraland complexes have a remarkably uniform Sr and Nd isotopic composition. This contrasts strongly with the isotopic composition of most of the Parana-Etendeka flood basalts (cf. Figs. 2c and 2e). A further point to emphasise is that none of the alkaline rocks and carbonatites from Damaraland show evidence for a strongly enriched lithospheric mantle component as was identified by Gibson *et al.* (1996) in mafic potassic complexes in Brazil (ϵ_{Nd} at 130 Ma below -10).

The range of Nd and Sr isotopic values covered by alkaline units and carbonatites from the Damaraland complexes extends from the Bulk Earth composition slightly into both the enriched and depleted quadrants of Figure 2d. This variation probably reflects the involvement of more than one mantle component in the magma source rather than crustal contamination. One argument for this is that the high Nd and Sr concentrations in carbonatites and some of the alkali silicate units make them rather insensitive to crustal contamination. Furthermore, oxygen isotope data from the Okenyenyanya alkaline suite (Martinez *et al.*, 1996), Messum (Harris, 1995; Harris *et al.*, 1999), Etaneno and Okorusu (Harris, 1995) show that crustal contamination of these rocks must be low. There is some consensus in the literature that the range of isotopic compositions in mafic rocks from the Parana-Etendeka province may reflect mixing of subcontinental lithospheric mantle (SCLM) and a plume mantle component but there is no agreement on the composition of these components. For example, Ewart *et al.* (1998a) suggested that the plume component involved in Etendeka LTZH. basalts had an ϵ_{Nd} value (at 132 Ma) of +6. This seems hard to reconcile, however, with the slightly enriched Sr and Nd ratios of modern basaltic rocks from islands above the Tristan hotspot (White and Hofmann, 1982; Le Roex *et al.*, 1990) or the Walvis Ridge (Richardson *et al.*, 1982). Le Roex and Lanyon (1998) estimated that Tristan plume material at 124 Ma had a range of ϵ_{Nd} values from +1 to -3 and Sr_i from 0.7043 to 0.7054 based on the isotop-

ic ratios of modern Tristan da Cunha basanites and the estimated bulk Sm/Nd and Rb/Sr of their source. Milner and Le Roex (1996) also concluded that the plume component involved in the Okenyenyanya complex had essentially the same, mildly enriched composition as the Tristan hotspot today and was likely derived by partial melting of ascending plume material.

Our data from basic alkaline and carbonatite units from the Damaraland complexes, combined with analyses already published, suggest that the dominant mantle source involved had ϵ_{Nd} values of -2 to +2 and Sr_i of 0.7037 to 0.7054. This corresponds closely to the ancestral Tristan mantle plume composition suggested by Le Roex and Lanyon (1998). There are a number of samples from Okenyenyanya, Messum and the Etendeka LTZH basalts which plot in the depleted quadrant of Figure 2 at ϵ_{Nd} values from +3 to +6. We do not consider it likely that these represent the isotopic composition of the plume, as was argued by Ewart *et al.* (1998a), and follow Le Roex and Lanyon (1998) in suggesting that the mantle source is heterogeneous and includes a depleted component. Whether this depleted component resides in the asthenosphere and was entrained in the ascending plume, or whether it is part of the subcontinental lithosphere is not possible to distinguish from the existing data. Le Roex and Lanyon (1998) favoured the subcontinental lithosphere but also cited data from Inaccessible Island in the south Atlantic which gives evidence that depleted mantle material is part of the Tristan plume. In any case, the main mantle component involved in the Damaraland complexes has a near Bulk Earth isotopic signature and whatever its ultimate origin may have been, this composition is appropriate to use in models designed to test the amount of mantle vs. crustal material in the felsic Damaraland complexes as discussed in the next section.

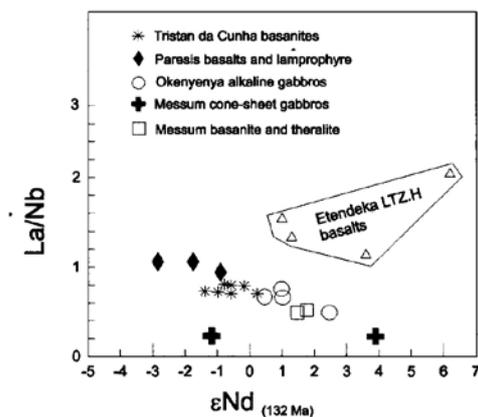


Figure 3: Variation diagram of La/Nb ratio and ϵ_{Nd} (calculated at 132 Ma) for mafic and alkaline samples of the Damaraland complexes, excluding carbonatites and nepheline syenites. Paresis data and Messum cone sheet gabbros from this study, other data from literature as follows: basanites from Tristan da Cunha (Le Roex *et al.*, 1990), Etendeka LTZH basalts (Ewart *et al.*, 1998a), Okenyenyanya alkaline gabbros (Milner and Le Roex, 1996; Le Roex *et al.*, 1996) Messum basanite and theralite (Harris *et al.*, 1999).

Incompatible trace element ratios can give additional constraints on the mantle source because they are relatively unaffected by fractional crystallization but are affected by open-system magma evolution. A number of element ratios are commonly used in this approach and we present in Figure 3 a variation diagram of La/Nb vs. the ϵNd ratio. The diagram shows samples with less than 55 wt.% SiO_2 , and excludes carbonatites and nepheline syenites because these rocks can contain REE- and Nb-bearing accessory phases which violate the condition that the elements considered remain incompatible during magma evolution. Also shown in the diagram are literature data from Tristan da Cunha basanites (le Roex *et al.*, 1990) and from other units in the Damaraland which are thought to have a plume mantle signature. These include the Etendeka LTZH. basalts (Ewart *et al.*, 1998a), Okenyenya alkali gabbros (Milner and Le Roex, 1996; Le Roex *et al.*, 1996) and Messum basanite and theralite (Harris *et al.*, 1999). For comparison, the primitive mantle ratio is thought to be about 1 (Hofmann, 1988), average oceanic plume magmas have 0.7 (Gibson *et al.*, 1996) and estimates for the lower crust and upper crust are 1.6 and 2.1, respectively (Rudnick and Fountain, 1995). The La/Nb ratios of lamprophyre and alkaline olivine basalts from Paresis are similar to mafic alkaline units from Messum and Okenyenya and support the isotopic evidence for derivation from a mantle source of near Bulk Earth composition. The Messum cone sheet gabbros (M9, M10) have the lowest La/Nb ratios on Figure 3 but these values may not reliably reflect magma ratios because the rocks are cumulates (see results section) and have extremely low incompatible trace element abundances generally; Nb in particular is close to the detection limit.

Why the plume signature should be common in the in trusive complexes and rare in the more voluminous flood basalts is a matter for speculation. The mafic alkaline rocks and carbonatites represent relatively low-degree partial melts of the mantle compared with the tholeiitic flood basalts. It may be that during the onset of plume arrival under the continental lithosphere, decompression melting in the plume material was selective and produced only low-degree melts, enriched in volatile and incompatible trace elements, which carried the plume isotopic signature. These early melts may have erupted to the surface under the right tectonic conditions but they can also be expected to intrude and enrich the base of the lithosphere (le Roex and Lanyon, 1998; Class *et al.*, 1998; Maittelli *et al.*, 1999). It was suggested by Le Roex and Lanyon (1998) that remelting of such plume-enriched lithospheric mantle gave rise to the Damaraland carbonatites and lamprophyres. If the plume head was heterogeneous because of material entrained from the local mantle during ascent and/or by interaction with the lithosphere on arrival, the huge volumes of flood basalts may be expected to sample that heterogeneity and to have an isotopic composition different from either the low-degree, selective melts

formed early or those produced later from the plume tail (the Tristan hot spot today).

Felsic units and crust-mantle interaction

The three largest Damaraland complexes, Brandberg, Erongo and Paresis, are dominantly felsic in composition and therefore represent anorogenic granitic magmatism. It is instructive to plot the samples on discrimination diagrams designed to reveal tectonic setting and granite type (Fig. 4). The Rb vs. Nb+Y diagram of Pearce *et al.* (1984) would suggest that the Brandberg and Paresis granitic magmas formed in a within-plate setting (which they did) whereas the Erongo granite would classify as a synollisional granite. There is clearly no difference in the tectonic setting of these complexes which underscores the common observation (e.g., Twist and Harmer, 1987; Förster *et al.*, 1997) that tectonic discrimination of granitoids by their chemical composition is imperfect. The Nb vs. Ga/Al diagram of Whalen *et al.* (1987) would classify most samples as A-type granites, with the Paresis rhyolites being borderline between A- and I/S-types.

Given their similar setting and age, it is perhaps surprising that all three of these felsic complexes differ greatly in isotopic compositions. None of the three closely resembles the felsic volcanics (quartz latites of the Awahab Formation) which are prominent in the Etendeka CFB sequence and which Ewart *et al.* (1998b) suggest to be dominantly crustal melts (Fig. 2b,e). Thus, it appears that the origin of felsic magmas in this province was not uniform and we suggest that the isotopic compositions at each complex reflect specific combinations of crustal composition and crust/mantle

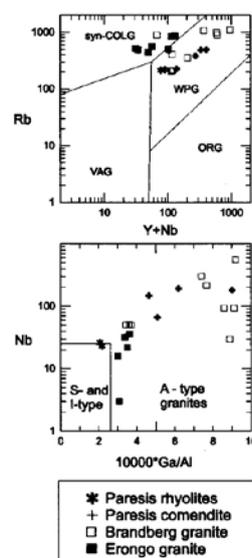


Figure 4 : Samples of the Damaraland felsic complexes with $\text{SiO}_2 > 70$ wt.% plotted in granitoid discrimination diagrams of Whalen *et al.* (1987) and Pearce *et al.* (1984). ORG = ocean-ridge granites, WPG = within-plate granites, VAG = volcanic arc granites, syn-COLG = syn-collisional granites.

proportions.

Harris (1995) attempted to estimate crust/mantle proportions in several of the Damaraland felsic complexes based on their oxygen isotope compositions. In this section we offer a further constraint on the relative contributions of crustal and mantle material in the felsic complexes based on Nd isotope data. This has the advantage that the Nd isotope compositions and Sm/Nd ratios are less dependent on lithologic makeup and metamorphic grade than many other petrogenetic indicators and much less prone to changes by alteration. From the data and arguments outlined in the previous section, we assign the mantle component an ϵNd value of 0 ± 2 . We then use published Nd isotopic data of Damara meta-sediments (McDermott and Hawkesworth, 1990), granites (McDermott *et al.*, 1996) and pre-Damara gneisses (Seth *et al.*, 1998) to derive estimates for the ϵNd value of the crustal component(s) following the methods of DePaolo *et al.* (1990) and DePaolo *et al.* (1992, eq. 3 and 4). The calculated values of $\epsilon\text{Nd}(\text{Crust})$ are -9.8 and -11.3 for Damara rocks corresponding to T_{DM} values of 1.7 Ga and 1.8 Ga, respectively (Table 2). The pre-Damara basement gneisses (Seth *et al.*, 1998) are assigned average values for $\epsilon\text{Nd}(\text{Crust})$ of -22.9 and -26.6 for Eburnian ($T_{\text{DM}}=2.5$ Ga) and Archaean gneisses ($T_{\text{DM}}=2.7$ Ga) respectively.

The mantle and crustal compositions so defined allow calculation of the Neodymium Crustal Index (NCI), introduced by De Paolo *et al.* (1992). The values of this index for the different complexes, shown in Table 2 for a range of assumed crustal and mantle components, represent the fraction of Nd in the rocks which is derived from the crust. Thus, for the Brandberg main massif (biotite-hornblende granite), the range of solutions indicates 11 to 42% crustal Nd, for the Erongo granite from 55 to 76% and for the Erongo granodiorite from 75 to 93%. The Paresis rhyolites have ϵNd values of -21 which rule out a Damara crustal source at

depth. Therefore, NCI values for the Paresis felsic units were calculated using $\epsilon\text{Nd}(\text{Crust})$ values of -23 to -27 for pre-Damara crust. The results indicate between 77 and 92% crustal Nd in the metaluminous/peraluminous rhyolites and only 34 to 52% in the peralkaline comendites. Clearly, these estimates are model-dependent and examination of Table 2 shows how sensitive the NCI values are to the composition assigned to the crustal and mantle end members. However, the agreement with crust/mantle proportions estimated by Harris (1995) from O-isotope data is quite good. Taking an average $\delta^{18}\text{O}$ value of -11.2 ‰ for Damara granites as a crustal end member and -6.5 ‰ for the mantle component, Harris (1995) suggested a crustal contribution of 38% in the main Brandberg granite and 85% in the Erongo granite. It must be emphasized that the uncertainty in both approaches is large because the Damaran crust is heterogeneous in terms of both neodymium and oxygen isotope composition.

Regional zonation of the Damaraland complexes

The distribution of Damaraland complexes covered in this study extends some 300 km across the central and northern zones of the Damara Belt, from Messum near the Atlantic coast to Paresis near the southern margin of the Congo Craton. The alkaline units from Paresis and Messum have closely similar isotopic compositions and there is no indication for a greater involvement of a sub-cratonic, enriched mantle lithosphere in complexes farther inland. Instead, the mantle component in all the complexes studied appears to be the same regardless of position in the province.

This is not the case for the felsic units. The isotopic data strongly suggest that the crustal material involved in the sources of the Erongo complex and Paresis complex is different. Erongo is located within the central zone of the Damara Belt, where the crust is dominated by thick meta-sedimentary sequences and S-type granites. The Erongo granites have isotopic compositions which overlap with those of the local basement. The Paresis complex intrudes the northern zone of the Damara Belt near tectonic inliers of the Congo Craton. The isotopic ratios of Paresis rhyolites rule out derivation from the Damara Belt lithologies, but are entirely consistent with a source in pre-Damara cratonic crust.

Conclusions

The different compositional units of the Damaraland igneous complexes show a great range in isotopic composition. The Nd isotopic data, in particular, provide important constraints on the composition and relative proportions of mantle and crustal material involved in the magma source(s).

New data presented here from quartz-undersaturated basic and alkaline rocks (lamprophyre, phonolite, alkaline basalt, nepheline syenite) and carbonatites from the

Table 2: Values of the neodymium crustal index (DePaolo, 1992) calculated for the felsic Damaraland complexes.

Complex	Unit	crustal type*	T_{DM}	$\epsilon\text{Nd}_{\text{(rock)}}$	$\epsilon\text{Nd}_{\text{(CC)}}$	NCI VALUES**		
						$\epsilon\text{Nd}_{\text{(MC)}}$	$\epsilon\text{Nd}_{\text{(MC)}}$	$\epsilon\text{Nd}_{\text{(MC)}}$
						= -2	= 0	= 2
Brandberg	main granite	Damara 1	1.7	-3	-9.8	0.13	0.31	0.42
		Damara 2	1.8	-3	-11.3	0.11	0.26	0.38
Brandberg	monzonite	Damara 1	1.7	-1	-9.8	-0.13	0.10	0.25
		Damara 2	1.8	-1	-11.3	-0.11	0.09	0.23
Erongo	granite	Damara 1	1.7	-7	-9.8	0.64	0.71	0.76
		Damara 2	1.8	-7	-11.3	0.54	0.62	0.68
Erongo	Ombu g-diorite	Damara 1	1.7	-9	-9.8	0.89	0.92	0.93
		Damara 2	1.8	-9	-11.3	0.75	0.79	0.83
Paresis	Fsp-rhyolite	Eburnian	2.5	-21	-22.9	0.91	0.92	0.92
		Archaean	2.7	-21	-28.1	0.73	0.75	0.76
Paresis	comendite	Eburnian	2.5	-11	-22.9	0.43	0.48	0.52
		Archaean	2.7	-11	-28.1	0.34	0.39	0.43
Paresis	qz-syenite	Eburnian	2.5	-9.7	-22.9	0.37	0.42	0.47
		Archaean	2.7	-9.7	-28.1	0.29	0.34	0.39

* Damara 1 - metasediments, Damara 2 - granites; data from McDermott & Hawkesworth (1990) and McDermott *et al.* (1996).

** $\text{NCI} = (\epsilon\text{Nd}_{\text{(rock)}} - \epsilon\text{Nd}_{\text{(MC)}}) / (\epsilon\text{Nd}_{\text{(CC)}} - \epsilon\text{Nd}_{\text{(MC)}})$. Values give the fraction of Nd derived from the crust, where CC = crustal component, MC = mantle component. Values for $\epsilon\text{Nd}_{\text{(CC)}}$ were derived from average T_{DM} Nd model ages listed, following DePaolo *et al.*, 1990, 1992.

complexes Messum, Paresis, Kalkfeld, Ondurakorume and Etaneno yield a very close range of values for ϵNd and Sr_i (at 132 Ma) of -2 to +2 and 0.7037 to 0.7054, respectively. When combined with published data on similar rocks from these and an additional three Damaraland complexes (Okenyenya, Osongpmbo, Okorusu; see Le Roex and Lanyon, 1998; Harris *et al.*, 1999), the isotopic evidence indicates that the dominant mantle component in the Damaraland complexes has a near bulk-earth isotopic composition consistent with an origin from the Tristan mantle plume. The plume signature is present in all of the complexes studied so far.

The felsic Damaraland complexes, by contrast, are isotopically distinct from each other. The peraluminous Erongo granites ($\epsilon\text{Nd} = -7$ to -9) overlap in isotopic composition with Damara Belt metasediments and granites and are considered to represent crustal melts of the mid to upper crust. Mantle-derived material dominates the source of metaluminous to peralkaline Brandberg granites ($\epsilon\text{Nd} = -1$ to -3). Finally, extremely low ϵNd values and moderate Sr initial ratios of rhyolites from Paresis are unique to that complex (-21 at $\text{Sr}_i = 0.71170$) and indicate an important contribution of pre-Damara basement in the source. This is probably due to the fact that Paresis is the farthest inland of all complexes containing felsic magmas and is close to pre-Damara inliers south of the craton margin.

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