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Altered mafic lower continental crust as a source for low $\delta^{18}O$-granodiorites (Damara orogen, Namibia)?

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Summary

New oxygen isotope data for metaluminous granites from the basement-dominated part of the Damara orogen (Namibia) range from 9.1 to 11.9‰. These data, together with previously published Sr, Nd and Pb isotope data indicate that these granites and associated peraluminous granites originated from felsic meta-igneous basement sources. New and unusually low oxygen isotope data for metaluminous granodiorites extend now the range of $\delta^{18}O$ values from ca. 12 to 6‰ for this rock type. These low oxygen isotope values approach the values observed in mafic quartz diorites for which a model of derivation from depleted mafic lower crust has been established. In view of the higher Pb isotope ratios but lower oxygen isotope values of the granodiorites relative to the mafic quartz diorites, it is concluded that the granodiorites represent partial melts of an undepleted but strongly altered mafic lower crust. Most of the peraluminous and metaluminous granites and the metaluminous granodiorites have identical U–Pb monazite, allanite and zircon ages of ca. 510–500 Ma implying partial melting of distinct basement rocks of Archaean to Proterozoic age at the peak of regional high-grade metamorphism.

Introduction

Precambrian high-grade terranes were commonly affected by pervasive tectonic processes in the deep crust, and then uplifted to higher crustal levels followed by extensive erosion. Tectono-metamorphic processes at high-grade conditions, including reworking of pre-existing continental crustal material are usually accompanied and followed by syn- to post-tectonic low- and high-level intrusions. Due to these processes, intense deformation and complex structures largely obliterated earlier relationships and are a major hindrance to the understanding of the premetamorphic history of such terranes. Furthermore, Precambrian high-grade terranes may consist of new continental crust in the form of granites that are made up from reworked older continental crust introduced into the source of the newly formed crust by subduction. Alternatively, granites in Precambrian terranes may represent differentiation products of juvenile material derived from the mantle (*Nelson* and *DePaolo*, 1984; *Patchett* and *Bridgwater*, 1984; *Patchett* and *Kouvo*, 1986). Another possibility is the derivation of orogenic granitic magmas from an ancient source that contained both juvenile and older crustal components (*Moorbath* and *Taylor*, 1989; *Hill* et al., 1989). Moreover, the distribution of continental lithosphere has changed constantly through geological time, with larger continental masses periodically fragmenting into smaller crustal blocks, and later re-amalgamating in different configurations as new supercontinents (i.e., *Rogers*, 1996). The apparent random nature of this process also hinders the reconstruction of ancient crustal terranes. Because granitoids often inherit geochemical and isotopic characteristics from their crustal sources, their isotopic compositions can be used to reconstruct the geochemical composition of basement terranes and provide useful information about crustal provinces.

The high-grade, basement-dominated part of the Damara orogen in Namibia offers a good opportunity to study these complexities because it consists of reworked basement complexes and granulite-facies metasedimentary rocks whose precursor sedimentary rocks were deposited onto that basement before the Pan-African orogeny. In addition, syn- to post-orogenic granodiorites and granites (i.e. *Miller*, 1983; *Tack* and *Bowden*, 1999) that have a large range in isotopic composition (*Jung* et al., 2003) occur in this part of the orogen. On the basis of remarkable good correlation of oxygen isotope values with major element data and other isotope data, i.e. Sr and Pb isotope ratios or ε Nd values (*Haack* et al., 1982; *Jung* et al., 2002, 2003, 2004), most of the δ^{18}O values are considered to represent primary oxygen isotope compositions inherited from the sources of the granites and granodiorites. In this study, we present new and unusually low δ^{18}O values from these rock types and evaluate these data together with previously published Nd whole rock isotope data and Pb isotope data from acid-leached feldspars. It will be shown that whole rock δ^{18}O and Pb isotope compositions are well correlated and can be used to constrain the composition of the lower crust in the high-grade basement-dominated part of the Damara orogen in Namibia.

Previous studies

The Damara orogen can be subdivided into a Northern, Central and Southern Zone (see inset to Fig. 1). In the Northern Zone, greenschist facies conditions with temperatures and pressures of 430–530 °C and 2–3 kbar are recorded (*Miller*, 1983). In the Southern Zone, the metamorphic grade ranges from greenschist to amphibolite facies at temperatures and pressures from 400 to 600 °C and 6 to 8 kbar. Here, the metamorphic grade increases from south to north (*Miller,* 1983). In the Central Zone, there is an increase in metamorphic grade from east to west reaching high-grade conditions with local partial melting (Fig. 1). The metamorphic evolution

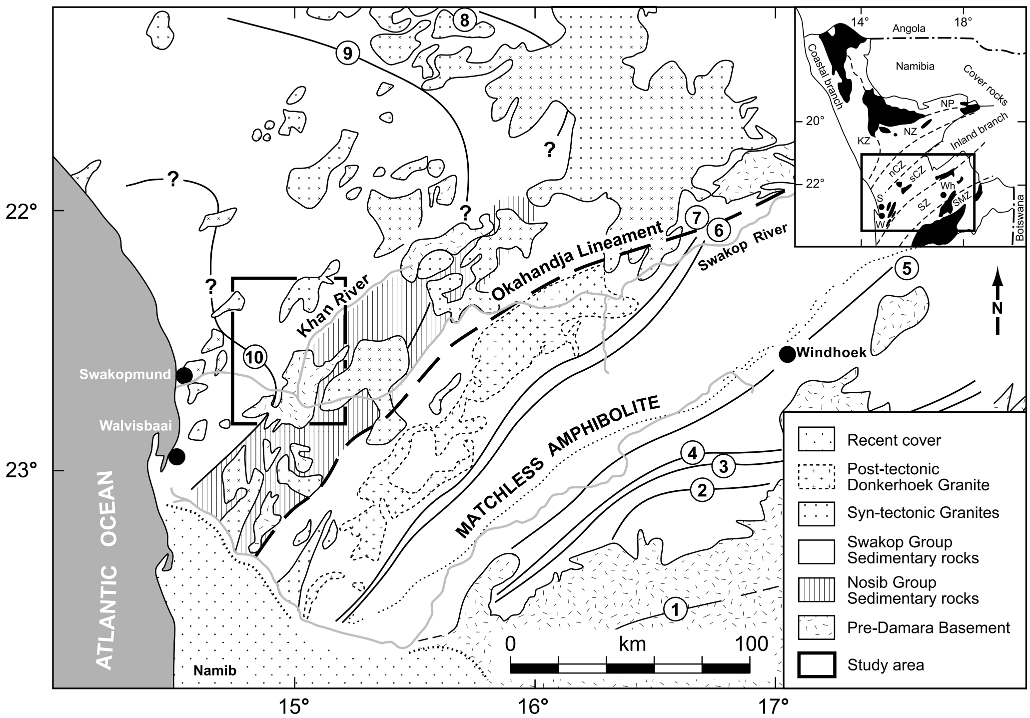


Fig. 1. Generalized geological map showing the study area within the Central Zone of the Damara orogen, Namibia. Abbreviations in inset: *KZ* Kaoko Zone, *NP* Northern Platform, *NZ* Northern Zone, *nCZ* northern central Zone, *sCZ* southern Central Zone, *SZ* Southern Zone, *SMZ* Southern Margin Zone. Isograd map (*Hartmann* et al., 1983) gives the distribution of regional metamorphic isograds within the southern and central Damara orogen. Isograds: *1* biotite-in, *2* garnet-in, *3* staurolite-in, *4* kyanite-in, *5* cordierite-in, *6* andalusite $\longleftrightarrow$ sillimanite, *7* sillimanite-in according to staurolite-breakdown, *8* partial melting due to: muscovite + plagioclase + quartz + H_2O $\longleftrightarrow$ melt + sillimanite, *9* K-feldspar + cordierite-in, *10* partial melting due to: biotite + K-feldspar + plagioclase + quartz + cordierite $\longleftrightarrow$ melt + garnet. *W* Walvisbay, *S* Swakopmund, *Wh* Windhoek

and geochronology of the basement-dominated part of the Damara orogen in Namibia was presented in detail by *Jung* and *Mezger* (2003). On the basis of thermobarometric data the peak of regional metamorphism reached ca. 700–750 °C and ca. 5 kbar. Uranium-Pb monazite and Sm–Nd garnet mineral ages obtained from unmigmatized garnet- and cordierite-bearing metapelites indicate that these peak metamorphic conditions were attained between 525 ± 2 Ma and 509 ± 3 Ma. Some migmatites with restitic melanosomes record Sm–Nd garnet ages of 518 ± 3 Ma indicating that high-grade regional metamorphism also culminated in partial melting. Syn-orogenic, crust-derived granites intruded at 515 ± 2 Ma, 512 ± 3 Ma and 509 ± 5 Ma whereas late orogenic granites were emplaced at 469 ± 3 Ma.

The geochemical and isotope evolution of the granitoids from the basement-dominated part of the Damara orogen is given in *Jung* et al. (2003). On the basis of their appearance in the field, the granitoids can be divided into red granites, white granites and grey granodiorites. Red granites and some of the white granites from the Khan area (Fig. 2) are isotopically evolved (initial ε Nd: -12.5 to -18.6) and

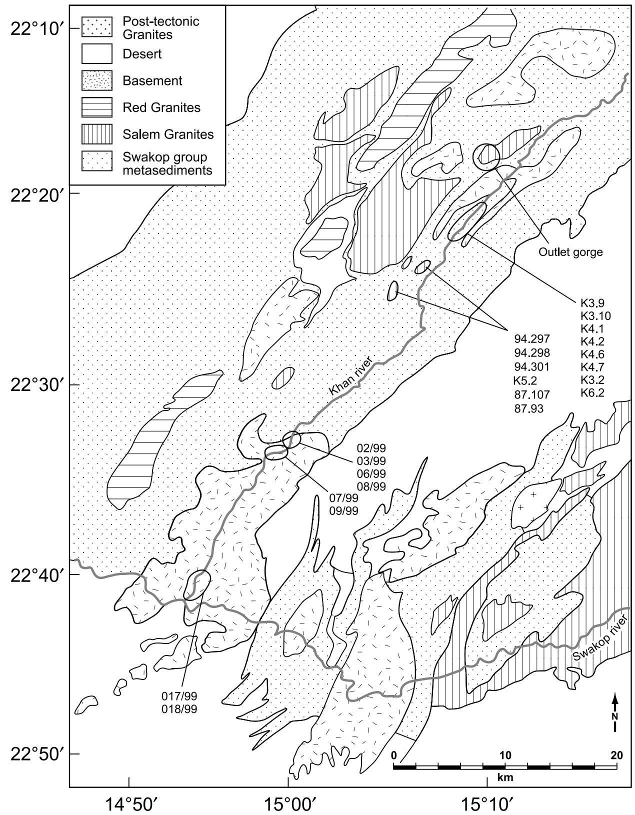


Fig. 2. Detailed geological map of the Khan and Outlet gorge areas

were likely derived from meta-igneous sources with late Archaean to early Proterozoic crustal residence ages. Other white granites are isotopically less evolved (initial ε Nd: -6.5 to -8.8) and originated by partial melting of metasedimentary sources that are similar to the country rock metapelites. Grey granodiorites from the Khan and Outlet gorge areas, emplaced into the cover sequence of the Damara orogen, are also isotopically evolved (initial ε Nd: -9.9 to -13.1) and are products of partial melting processes involving meta-igneous sources with younger, late Proterozoic crustal residence ages. Highly evolved Pb isotope compositions, strongly negative ε Nd values and radiogenic Sr isotope compositions and fairly good correlations between the isotope systems argue for a deep-crustal undepleted nature of the basement (*Jung* et al., 2003).

Results

Analytical methods are given in the appendix. New oxygen isotope data for the red granites and grey granodiorites from the Khan area are presented in Table 1. For all samples studied previously (*Jung* et al., 2003), Table 2 list Fe_2O_3 and FeO values together with the corresponding Fe^{3+}/Fe^{2+} ratios. All samples show moderately low LOI values mostly below 1.5 wt% (Jung et al., 2003) and also rather low Fe^{3+}/Fe^{2+} ratios (<1.4). Red granites have $\delta^{18}O$ whole rock values ranging from 9.1 to 11.9‰. These values overlap with those measured on Damaran upper crustal

Table 1. *New oxygen isotope data (in per mil relative to V-SMOW) for basement-derived granitoids from the central Damara orogen (Namibia)*

Sample	Rock type	$\delta^{18}O$
09/99	red granite	9.6
07/99	red granite	9.1
017/99	red granite	11.9
018/99	red granite	11.5
02/99	grey granodiorite	6.0
03/99	grey granodiorite	6.3
06/99	grey granodiorite	8.1
08/99	grey granodiorite	8.4

Table 2. *Loss-on-ignition (LOI), Fe_2O_3 and FeO values and Fe^{3+}/Fe^{2+} ratios of white granites, red granites and grey granodiorites from the Damara orogen (Namibia)*

	LOI	Fe_2O_3 (total)	FeO	Fe^{3+}/Fe^{2+}
White granites				
94.301	0.80	1.00	0.65	0.43
94.298	1.20	0.86	0.60	0.32
K6.2	0.66	1.58	0.99	0.48
K5.2	0.28	0.63	0.44	0.32
K4.6 L	1.31	1.59	1.14	0.28
87.107	0.06	0.49	0.30	0.52
K3.2	0.30	0.07	0.05	0.29
K4.2 L	0.59	2.33	1.50	0.44
K4.7 L	0.15	2.55	1.75	0.35
K4.1	0.62	2.60	2.03	0.17
94.297	1.10	1.23	1.00	0.12
K3.9	0.82	1.02	0.73	0.29
K3.10	0.54	1.80	1.24	0.34
Red granites				
09/99	0.81	2.37	0.96	1.36
07/99	0.57	1.23	0.58	1.01
017/99	0.63	2.60	1.20	1.06
018/99	0.46	2.54	1.36	0.76
Grey granodiorites				
02/99	1.48	3.61	1.64	1.09
03/99	1.87	6.77	3.15	1.04
06/99	0.91	2.49	1.17	1.02
08/99	0.58	6.10	2.91	0.99
87.93	1.12	5.40	2.54	1.01

granites which usually have high $\delta^{18}O$ whole rock values between 10 and 15‰ (*Haack* et al., 1982; *Jung* et al., 2003). The grey granodiorites have lower $\delta^{18}O$ whole rock values between 6.0 and 8.4‰ and some of these values are the lowest ever measured on Damaran granitoids. Quartz diorites derived from mafic lower crustal sources tend to have similarly low δ^{18}O values (6.8–8.1‰; *Jung* et al., 2002) although these rocks are distinctly more mafic in composition than the granodiorites investigated here. Archaean to Palaeoproterozoic basement complexes from the Kaoko Belt, situated farther north have also similar low δ^{18}O values ranging from 6.8 to 9.9‰ (*Seth* et al., 2002).

Discussion and conclusion

It has previously been established that the isotope systematics of granites and granodiorites from the basement-dominated part of the Damara orogen correlate quite well. Initial ε Nd values are negatively correlated with initial ^{87}Sr/^{86}Sr and ^{207}Pb/^{204}Pb ratios implying that the terrane consists of a stratified and undepleted basement at depth because rocks with the most negative ε Nd values have the highest ^{207}Pb/^{204}Pb values and the most radiogenic ^{87}Sr/^{86}Sr ratios. Moreover, granites and granodiorites have variable Pb isotope compositions, implying sources with distinct μ and κ values. Oxygen isotope values of the granites and some granodiorites from the Khan area range from 10 to 15‰ and are not unusual for igneous rocks from the Damara orogen (*Jung* et al., 2003 and references therein).

The low δ^{18}O values obtained on the granodiorites may represent primary values or may result from interaction of the granite magma with meteoric water, a process which is known to lower whole rock δ^{18}O values. Interaction with meteoric water may be viewed as a distinct process of hydrous alteration *sensu lato*. However, field evidence and petrographic observations indicate that hydrous alteration is very limited because the rocks have a fresh and unaltered appearance in the field and are not characterized by the appearance of chlorite and sericite that were formed at the expense of biotite and feldspar. Moreover, most whole rock loss-on-ignition (LOI) values are lower than 1.5 wt% (Fig. 3), indicating only limited amounts of volatiles in the samples. The notable exceptions are two mafic granodiorites with 1.5 and 1.9 wt% LOI, however, these samples have also fairly large amounts of biotite (up to 15 vol.%) which accounts in part for the higher loss-on-ignition values.

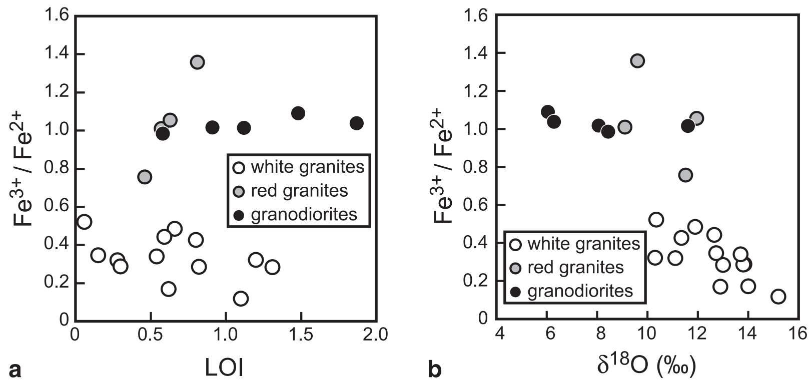


Fig. 3. (a) Fe^{3+}/Fe^{2+} vs. LOI and (b) Fe^{3+}/Fe^{2+} vs. δ^{18}O for red and white granites and grey granodiorites from the Khan area (Damara orogen, Namibia)

A reasonably good measure for alteration is the whole rock Fe^{3+}/Fe^{2+} ratio which should increase during hydrous alteration under oxidizing conditions. Moreover, the Fe^{3+}/Fe^{2+} ratios should also correlate positively with the loss-on-ignition values which usually also increase during alteration because of the breakdown of primary biotite and feldspar to chlorite and sericite. A plot of Fe^{3+}/Fe^{2+} ratio vs. LOI and vs. $\delta^{18}O$ is presented in Fig. 3a and b. The lack of a positive correlation between Fe^{3+}/Fe^{2+} and LOI for the granodiorites further suggest that these samples are not altered. The red granites show a steep positive correlation between LOI and Fe^{3+}/Fe^{2+} ratio and probably some of these granites are slightly altered. In a plot of Fe^{3+}/Fe^{2+} ratios vs. $\delta^{18}O$ values, the white and red granites show broadly negative correlations between these parameters whereas the grey granodiorites with their unusually low $\delta^{18}O$ values show no apparent correlation between Fe^{3+}/Fe^{2+} and $\delta^{18}O$. Note that for the red granites the samples with distinct $\delta^{18}O$ values come from different parts of the pluton (*Jung* et al., 2003; Fig. 2) and for those samples the shift in $\delta^{18}O$ values with increasing Fe^{3+}/Fe^{2+} is only 0.4–0.5 per mil. These features suggest that alteration was not operative to any appreciable extend and therefore, the $\delta^{18}O$ values are interpreted as near-primary features.

Previous work (*Jung* et al., 2003) revealed a positive correlation between $\delta^{18}O$ values and initial ε Nd values for the white granites. The new data for the red granites show that they plot in continuation of the white granites towards slightly lower values (Fig. 4). The apparent good correlation of $\delta^{18}O$ values with whole rock ε Nd values (which are known to be largely insensitive with respect to hydrous alteration) for red and white granites indicates that these granites are not altered (Fig. 4). The lack of correlation between $\delta^{18}O$ values and initial ε Nd values for the granodiorites suggest that these rocks originate from sources that have similar Sm–Nd isotope systematics but have undergone different degrees of alteration. Considering the data for basement rocks from the Kaoko belt (*Seth* et al., 2002) and metasedimentary rocks from the Damara belt (*Jung* et al., 2003; *Jung*, 2005), it is suggested that the majority of the samples reflect derivation from felsic meta-igneous basement. Only three samples were probably derived from upper crustal metasedimentary rocks. Some of the red granites contain dispersed fragments of strongly foliated lower crustal rocks and this may account for the lower $\delta^{18}O$ values. It is important to note that all samples of the white granites lack signs of assimilation of basement lithologies. It is, therefore, concluded that the range in

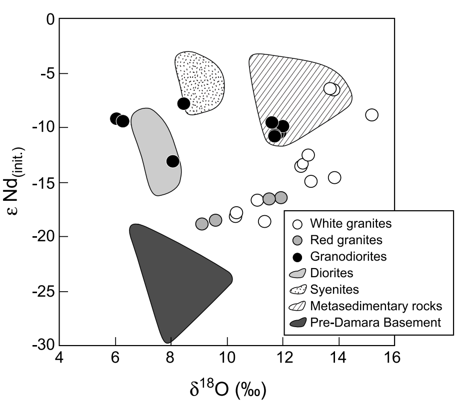
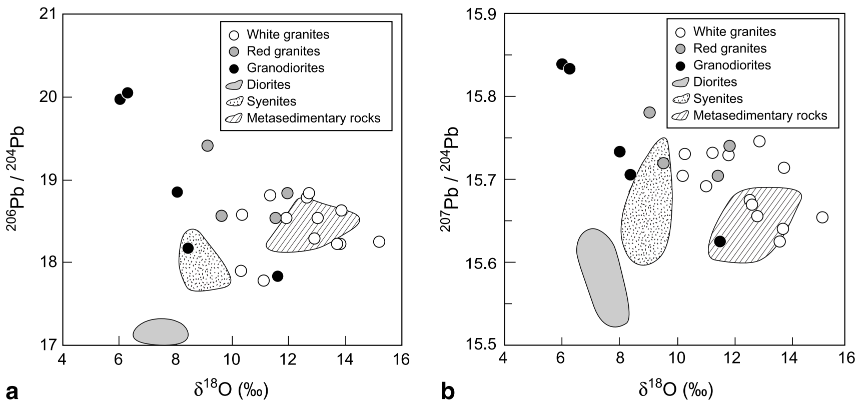


Fig. 4. Plot of $\delta^{18}O$ vs. initial εNd values for various granitoids from the basement-dominated part of the Damara orogen (Namibia). Data for diorites, syenites and metasedimentary rocks are from *Jung* et al. (2002, 2004) and *Jung* (2005). Data for basement rocks from the Kaokoveld are from *Seth* et al. (2002)



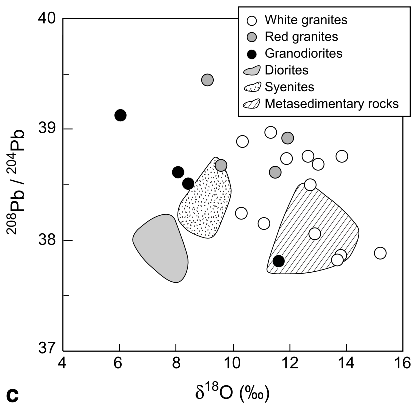


Fig. 5. Plot of δ^{18}O vs. (a) ^{206}Pb/^{204}Pb, (b) ^{207}Pb/^{204}Pb and (c) ^{208}Pb/^{204}Pb for various granitoids from the basement-dominated part of the Damara orogen (Namibia). Data for diorites, syenites and metasedimentary rocks are from *Jung* et al. (2002, 2004) and *Jung* (2005)

δ^{18}O and ε Nd values broadly represents the range of isotopic compositions of the basement. The unusually low oxygen isotope data for the grey granodiorites now extend the range of δ^{18}O values from ca. 12 to 6‰ for this rock type. The low values may indicate the influence of a mantle component in the genesis of these rocks. However, lithospheric mantle-derived nepheline-normative syenites have mostly higher δ^{18}O values (>8.4‰; *Jung* et al., 2004). On the other hand, the granodiorites approach the low values observed in lower crustal mafic quartz diorites (*Jung* et al., 2002).

Lead isotope ratios show no obvious correlation with δ^{18}O values for the white and red granites (Fig. 5). The granodiorites show a well-developed negative correlation of Pb isotope composition with δ^{18}O values with lower δ^{18}O values at a given Pb isotope composition. Mafic quartz diorites have significantly lower ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb ratios than the granodiorites and these features were interpreted to reflect an ancient, depleted mafic lower crustal source (*Jung* et al., 2002). In view of the distinctly more radiogenic Pb isotope composition of the granodiorites, it is suggested that the granodiorites represent partial melts of an undepleted part of mafic lower crust. This view is corroborated by the observation that the granodiorites have higher initial ^{87}Sr/^{86}Sr ratios (0.716–0.728; *Jung* et al., 2003) relative to the quartz diorites (0.709–0.712; *Jung* et al., 2002).

In conclusion, the new oxygen isotope data for some granodiorites and granites of the high-grade basement-dominated central part of the Damara orogen in

Namibia further constrain their dominantly deep crustal origin. Based on the good correlation of oxygen isotopes with Pb isotope ratios obtained on acid-leached feldspar for the granodiorites it is concluded that the oxygen isotope values represent near-primary values. Although low values of ca. 6‰ can be interpreted in terms of involvement of a mantle component, strongly radiogenic Pb isotope compositions and initial ε Nd values of ca. -10 indicate that these rocks represent reworked crustal material. Therefore, these low values are interpreted to reflect the isotope composition of the basement source which, in this case, is most probably the undepleted, but strongly altered mafic lower crust.

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Appendix

Analytical techniques

Fe_2O_3 was determined on fused lithium-tetraborate glass beads using standard XRF techniques. LOI (loss on ignition) was determined gravimetrically after heating the samples at 1050 °C for one hour. Results were corrected for Fe^{3+} gain during heating and oxidation (*Lechler* and *Desilets*, 1987). FeO was measured titrimetrically with standard techniques using a HF-H_2SO_4 decomposite and a 0.02 N $KMnO_4$ solution (*Pratt*, 1894). Accuracy has been controlled by repeated measurements against several international and in-house standards. Typical in-run reproducibilities are ca. 5% for LOI, 1–3% for Fe_2O_3 analyzed by XRF and 2–4% for FeO analyzed by titrimetric techniques. Oxygen isotope analyses were performed at the University of Bonn on $\sim$10 mg aliquots of powdered whole-rock samples, using purified flourine for oxygen extraction, followed by conversion to CO_2 (*Clayton* and *Mayeda*, 1963). $^{18}O/^{16}O$ measurements were made on a SIRA-9 triple-collector mass spectrometer by VG-Isogas. Analytical uncertainties are <0.2‰.

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