Sm-Nd and U-Pb isotopic constraints for crustal evolution during Late Neoproterozoic from rocks of the Schirmacher Oasis, East Antarctica: geodynamic development coeval with the East African Orogeny

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Abstract Recent post-750 Ma continental reconstructions constrain models for East African Orogeny formation and also the scattered remnants of ~640 Ma granulites, whose genesis is controversial. One such Neoproterozoic granulite belt is the Schirmacher Oasis in East Antarctica, isolated from the distinctly younger Pan-African orogen to the south in the central Droning Maud Land. To ascertain the duration of granulite-facies events in these remnants, garnet Sm-Nd and monazite and titanite U-Pb IDTIMS geochronology was carried out on a range of metamorphic rocks. Garnet formation ages from a websterite enclave and gabbro were 660±48 Ma and 587±9 Ma respectively, and those from S-type granites were 598±4 Ma and 577±4 Ma. Monazites from metapelite and metaquartzite yielded lower intercept U-Pb ages of 629±3 Ma and 639±5 Ma, respectively. U-Pb titanite age from calcsilicate gneiss was 580±5 Ma. These indicate peak metamorphism to have occurred between 640 and 630 Ma, followed by near isobaric cooling to ~580 Ma. Though an origin as an exotic terrane from the East African Orogen cannot be discounted, from the present data there is a greater likelihood that Mesoproterozoic microplate collision between Maud orogen and a northerly Lurio-Nampula block resulted in formation of these granulite belt(s).

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Introduction

The East African Orogeny (EAO) (Stern, 1994) resulted in formation of HP/HT granulites in southern Kenya, Tanzania and northern Mozambique (Meert, 2002, Sommer et al., 2003) (Fig. 1). Whereas the southern continuation of the EAO into the Dronning Maud Land, East Antarctica, was proposed by Jacobs et al., (1998, 2003), Ravikant et al., (2004) correlated granulites in the Schirmacher Oasis with those of the Lurio Belt, SE Mozambique. Recently, Collins and Pisarevsky (2005) placed the coastal East Antarctica, including central Dronning Maud Land, as a ~1.1 Ga-aged peninsula of the Kalahari craton having a distinct latitudinal separation between the Congo-Tanzania-Bangweulu (C-T-B) craton. In view of this continental separation, the Late Neoproterozoic high-grade metamorphic events in the Lurio Belt-Schirmacher Oasis and possibly the Sor-Rondane and Yamato Belgica Mountains either a) cannot be explained as a direct southern continuation of the EAO or b) these mobile belts represent southern extension of the EAO amalgamated to East Antarctica along large strike-slip faults (exotic terranes). The Schirmacher Oasis is critically positioned as Late Mesoproterozoic metamorphic rocks were reworked and reactivated during the Late Neoproterozoic orogeny (Mikhalsky et al., 2003, Ravikant et al., 2004, Ravikant, 2006).

To constrain the time of the granulite-facies metamorphic event(s) and test hypotheses on their formation, garnet Sm-Nd and monazite and titanite U-Pb IDTIMS analyses were done for a range of exposed metamorphic rocks in the Schirmacher Oasis.

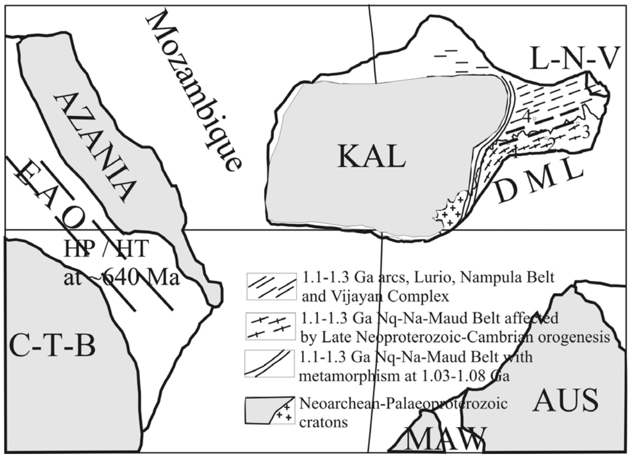

Figure 1. Paleogeographic reconstruction at 630 Ma of the Kalahari (KAL), Congo-Tanzania-Bangweulu (C-T-B), Australian (AUS) and the Mawson (MAW) cratons, after Collins and Pisarevsky (2005). L-N-V, Lurio-Nampula-Vijayan Complex, DML, Dronning Maud Land. Nq-Na-Maud- Namaqua-Natal-Maudheim Belt. Neoproterozoic remnants, 1-Schirmacher Oasis, 2-Sør Rondane Mountains, 3-Yamato-Belgica Mountains, 4-Mugeba Klippe.

Geologic setting

The Schirmacher Oasis high-grade metasedimentary rocks (Fig. 2) comprise quartz-garnet-sillimanite (± kyanite)-perthite gneiss (with accessory zircon, monazite and graphite) intercalated with m-scale layers of calcsilicate and sillimanite and kyanite ± garnet quartzite.

Garnet-bearing foliated S-type granites (sample 4/23 and shown in Fig 12 of Sengupta, 1993) occur as lenses upto a few metres thick within metapelite and truncate the S_2 foliation.

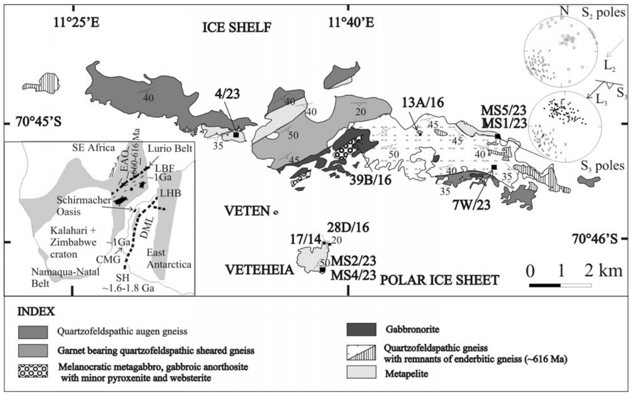

Figure 2. Geological map of the Schirmacher Oasis (after Ravikant, 2006), showing the distribution of high-grade lithounits

Enderbitic gneisses (13A/16), emplaced broadly syntectonic to the D_2 deformation, contain deformed enclaves of metagabbro. These metagabbroic enclaves contain metaultramafic pods including the sampled melanocratic gabbro (7W/23) and garnet-bearing websterite (39B/16). The dominant S_2 foliation in the enderbitic gneiss formed coeval to the transposed earlier (S_1) foliation in the metapelitic rocks (Sengupta, 1993).

Monazite grains (0.1-0.2 mm) from the metapelite (MS1/23) forms part of the quartzofeldspathic matrix whereas it occurs with kyanite and quartz in the metaquartzite (MS 2/23) and were pale green and ellipsoidal. Titanite (~1 mm) from the calcsilicate gneiss (MS5/23, plagioclase-calcite-clinopyroxene-scapolite-quartz) is reddish brown and ellipsoidal. In their BSE images both minerals show patchy domains.

The rocks were metamorphosed to 6.5-8 kbar and 750°C (Dasgupta et al., 2001, Ravikant, 2005), with relics of earlier high-temperature sapphirine-orthopyroxene-garnet bearing assemblages reported by Baba et al., (2006). Textures related to near isothermal decompression, preserved in the sample 39B/16, indicate that this stage preceeded the widespread near isobaric cooling stage in the retrograde metamorphic history (Ravikant and Kundu, 1998). From the coronal garnet-bearing enderbitic gneiss and garnet-bearing foliated granite, Rameshwar Rao et al., (1998), and Dasgupta et al., (2001) estimated lower metamorphic conditions of ~650-700 °C and ~5-6 kbar.

Methods

The separation of Sm-Nd from (aggressively leached) garnet and whole rocks was done using conventional two-stage ion exchange method as described by Gioia and Pimentel (2000); isotopic analyses and data reduction of Sm and Nd follows Laux et al., (2005). Monazite and titanite were separated using conventional heavy mineral separation methods. Single monazite crystals, spiked with a ^{205}Pb-^{235}U tracer solution, were dissolved in 7 ml Teflon Savillex vials using a solution of concentrated ultrapure H_2SO_4 (5 μL), 6M HCl (40 μL) and 7M HNO_3 (40 μL). Dissolution of monazite was achieved by placing the vials on a conventional hot plate (~125-140°C) for 24 hours. Samples were then partially dried and conditioned with 3.1 M HCl prior to microcolumn chromatography (modified after Krogh, 1973). Titanite was dissolved in HF and 7M HNO_3 and U was eluted and collected with HBr. Isotopic analyses were done on a Finnigan MAT 262 mass spectrometer, equipped with an ion counting system, at the Geochronology Laboratory, University of Brasilia. Both Pb and U isotopic compositions were analyzed on single Re filaments using silica gel and phosphoric acid and corrected for average mass discrimination of 0.12 ± 0.05% per mass unit for multi-collector analyses (based on replicate analyses of common Pb standard SRM 981). Uranium fractionation was monitored by replicate analyses of SRM U-500. Uncertainties in U/Pb ratios due to uncertainties in fractionation and mass spectrometry were around ± 0.5%, as all signals measured were relatively strong. Radiogenic Pb isotopes were calculated by correcting for modern blank Pb and for original nonradiogenic Pb corresponding to Stacey and Kramers (1975) model Pb for the approximate age of the sample. PBDAT (Ludwig, 1993) and ISOPLOT-Ex (Ludwig, 2001) were used for data reduction and age calculations, with 2σ errors. Total procedural blanks, at the time of analyses, were < 50 pg for Sm and Nd and <20 pg for Pb.

Results

The Sm-Nd and U-Pb isotopic data are given in Tables 1 and 2 and Fig. 3. Garnet from websterite yielded an imprecise date of 660±48 Ma, whereas coronal garnet from gabbro gave a date of 587±9 Ma, and from S-type granite were 598±4 Ma and 577±4 Ma. The slope of the isochrons is controlled by the highly radiogenic garnet fractions with high ^{147}Sm/^{144}Nd ratios in the garnets (1.2-2.4), except for garnet from the websterite; Nd concentrations are in the normal range in garnet (e.g. Thöni, 2003).

Though monazite from the metapelite and metaquartzite yielded a lower intercept U-Pb age of 629±3 Ma and 639±5 Ma (2σ), respectively, (Fig. 3a,b), their U-Pb ages are discordant. Similar discordance in U-Pb age is seen in calcsilicate gneiss titanite analyses, which gave a lower intercept age of 580±5 Ma (2σ) (Fig.3c). The monazite and titanite from the central Schirmacher metapelite-calcsilicate units apparently have (inherited) poorly constrained Archean upper intercept ages. Monazite from the Veteheia metaquartzite has an upper intercept Mesoproterozoic age (~1.26 Ga) and Nd-model age (1.26 Ga), which places an upper limit to the time of deposition of these (meta) sediments.

Table 1. Sm-Nd isotopic data for granulites and their separated garnet and granites of the Schirmacher Oasis

Sample	**Sm (µg/g)**	**Nd (µg/g)**	**^{147}Sm/^{144}Nd [2σ error 0.5 %]**	**^{143}Nd/^{144}Nd (± 2SE)**	**Whole rock-garnet age (Ma) [2σ errors]**	**T_{DM} (Ga) [after Goldstein et al., 1984]**
SR 39B/16	0.698	1.96	0.2157	0.512884±0.000008	-	(T_{CHUR} 1.97)
SR 39B/16 Grt	0.260	0.419	0.3745	0.513571±0.000030	660±48	-
SR 7W/23	12.3	40.2	0.1850	0.512765±0.000007	-	2.07
SR 7W/23 Grt	2.50	1.23	1.233	0.516794±0.000030	587±9	-
SR 4/23	8.93	38.2	0.1412	0.512391±0.000011	-	1.60
SR 4/23 Grt	8.22	2.04	2.440	0.521397±0.000008	577±4	-
MS 4/23	12.8	62.4	0.1239	0.512491±0.000006	-	1.13
MS 4/23 Grt	18.1	4.59	2.380	0.521015±0.000056	598±4	-
MS 2/23	5.58	27.2	0.1237	0.512202±0.000006	-	1.26
MS 5/23	15.8	105	0.0907	0.512141±0.000007	-	1.61

Table 2. U-Pb isotopic data for single monazite and titanite separated from metasedimentary granulites of the Schirmacher Oasis

Sample / fraction	**Size (mg)**	**U (ppm)**	**Pb (ppm)**	**^{206}Pb/ ^{204}Pb**	**^{207}Pb*/ ^{235}U**	**%**	**^{206}Pb*/ ^{238}U**	**%**	**Corr Coeff. (ρ)**	**^{207}Pb*/ ^{206}*Pb**	**%**	**^{206}Pb*/ ^{238}U age (Ma)**	**^{207}Pb* / ^{235}U age (Ma)**	**^{207}Pb* / ^{206}Pb* age (Ma)**	**(Ma)**
MS1 Mnz															
2	0.014	415.9	354	942.6	0.972	0.69	0.1067	0.62	0.91	0.0661	0.28	653	689	809	5.9
4	0.010	3283	1377	1738	0.874	0.42	0.1030	0.41	0.98	0.0615	0.09	632	637	656	1.9
8	0.010	3163	1636	4967	0.889	1.12	0.1039	0.95	0.87	0.0621	0.56	637	646	676	12
MS2 Mnz															
1	0.016	466.1	214	470.5	0.820	1.01	0.1002	0.97	0.97	0.0593	0.24	615	608	580	5.3
2	0.020	1909	1038	4110	0.850	0.53	0.1024	0.49	0.93	0.0602	0.19	628	625	613	4.1
4	0.010	214.2	160.5	518	1.553	1.8	0.1520	1.16	0.71	0.0741	1.26	951	951	1044	25
MS5 Ttn															
4	0.182	360.6	60.6	960	0.945	1.10	0.0984	0.98	0.97	0.0697	0.22	604	676	920	4.6
6	0.155	249.9	44.7	420	0.773	1.12	0.0940	1.01	0.91	0.0596	0.46	579	581	589	9.9
7	0.167	321.2	88.4	79.2	1.085	0.38	0.1009	0.35	0.93	0.0780	0.14	620	746	1146	2.7

Discussion

Age of the high-grade metamorphism

Monazite and titanite U-Pb ages in high-grade metamorphic rocks are usually concordant.

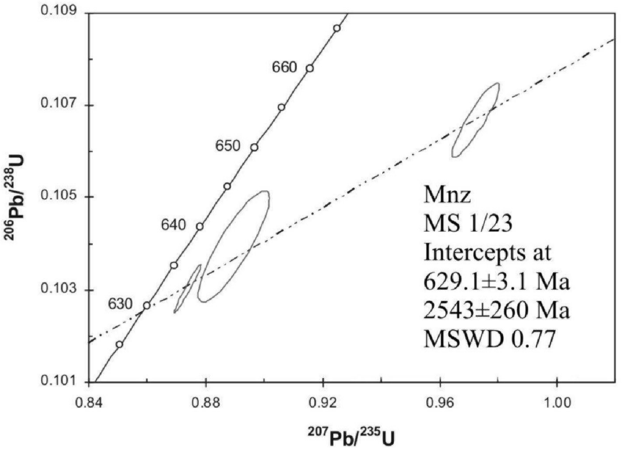

Figure 3a. U-Pb concordia plot for monazite in metapelite

That monazite (and titanite) grains in these metasedimentary rocks have had an earlier inheritance (probably detrital) is seen from their discordant U-Pb ages. Such discordant monazites have been shown to represent mixed domains, where inherited older grains have undergone regrowth and recrystallization due to dissolution and reprecipitation (Seydoux-Guillaume et al., 2002, Board et al., 2005, Timmermann et al., 2006). This process leads to the resetting of U-Pb systematics, rather than by Pb-loss due to thermally driven volume diffusion.

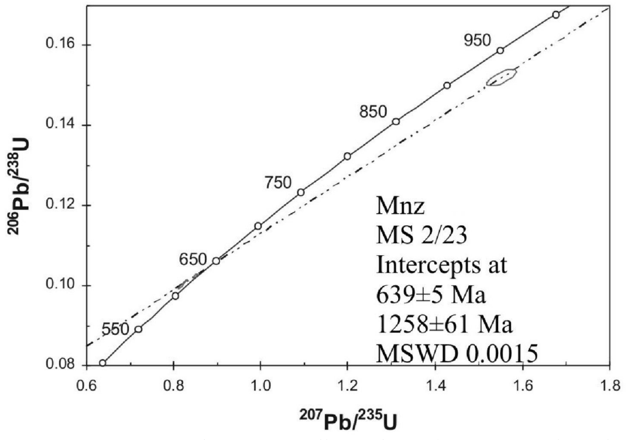

Figure 3b. U-Pb concordia plot for monazite in metaquartzite

As the closure temperature for monazite is ~800°C, it is very resistant to thermal resetting; this coupled with the ~750°C metamorphic conditions attained, suggests that monazite probably recrystallized from dissolution of older inherited grains close to its closure temperature. The discordant titanite U-Pb analyses to an upper intercept can be interpreted with the episodic Pb-loss model in rocks that have experienced brief thermal events (reviewed in Möller et al., 2000).

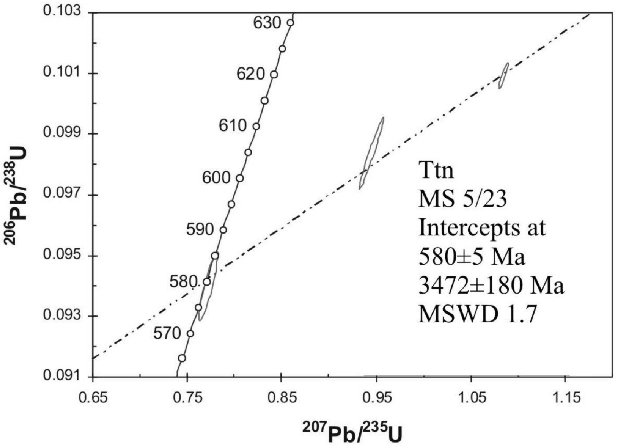

Figure 3c. U-Pb concordia plot for titanite in calcsilicate gneiss

The ~ 630-580 Ma ages from Sm-Nd garnet (with closure temperature of >650°C) and U-Pb titanite (closure temperature of ≥ 650°C) time the growth or recrystallization of these minerals during the retrograde near isobaric cooling stage. Hence considering that the monazite lower intercept ages, of 639±5 Ma and 629±3 Ma, lie between the younger garnet Sm-Nd age of 632±8 Ma (Ravikant et al., 2004) and older garnet age of 660±48 Ma, they are interpreted as metamorphic recrystallization ages. Furthermore, the Sm-Nd isochron age of 632±8 Ma on texturally late undeformed coronal garnets in the enderbitic gneiss (location 13A/16 on Fig.2) is evidence to support a single granulite-facies metamorphic event.

Geodynamic development of the Late Neoproterozic granulite belt

Collins and Pisarevsky (2005) considered the EAO to have formed by collision of older Neoarchean-Palaeoproterozoic terranes (forming a hypothetical continent, Azania) with the eastern margin of the combined Congo-Tanzania-Bangeweulu craton, resulting in the formation of the ~640 Ma high pressure and high temperature granulites in the EAO (Fig. 1). In contrast, to explain the presence of remnants of the 640±20 Ma medium pressure granulites in the Lurio-Schirmacher Oasis Belt the existence of colliding ~1.1 Ga-aged microplates was proposed (Collins and Windley 2002, Jacobs and Thomas, 2002, Ravikant et al., 2004).

The data from the present study, Ravikant et al., (2004) and Henjes-Kunst (2004), forms the most comprehensive geochronological data base for the high-grade rocks in the Schirmacher Oasis and indicates a prominent Neoproterozic orogen. A most likely interpretation for the medium-pressure granulite-facies metamorphic conditions is an increased geothermal gradient due to crustal stacking and inflation by intrusion of phases of enderbitic gneiss protoliths (statistically indistinguishable dates of 681±43 Ma and 712±20 Ma by U-Pb on zircon, Mikhalsky et al., 2003 and 616±52 Ma from a Sm-Nd whole rock isochron, Ravikant et al., 2004), at an active continental margin. Spatially combining the ages of medium pressure high-grade metamorphism, from the Schirmacher Oasis (this study), the Lurio Belt (~615 Ma U-Pb zircon age from the Mugeba klippe, Kröner et al., 1997), the Sør Mountains (~624 Ma, Sm-Nd reworking of Late Mesoproterozic gneisses, Shiraishi and Kagami, 1992), Yamato-Belgica Mountains (661±11 Ma U-Pb zircon age of high-grade metamorphism, Shiraishi et al., 1994) and the ~608-611 Ma U-Pb age of high-grade metamorphism in the Highland and Vijayan Complexes, Sri Lanka (Hölzl et al., 1994), reveals the extent of this orogen (Fig 1). This orogen would have formed by collision of the ~1.1 Ga Namaqua-Natal-Maud Belt (Jacobs et al., 1993) with the ~1.1-1.3 Lurio-Nampula block of juvenile arcs having formed adjacent to the Kalahari craton (Grantham et al., 2003, Johnson et al., 2005). The collision of only Mesoproterozoic-aged arc terranes, having developed in proximity to each other since ~1.1-1.3 Ga, appears to support a localized microplate origin for this Neoproteroozic orogen as opposed to its formation at the southern extremity of the EAO and assembled to East Antarctica by the Cambrian Period.

Summary

Formation of Neoproterozic granulites, remnants of which are exposed in coastal Antarctica and SE Africa, is controversial; dating was performed to correlate these granulite-facies remnants. The results of this Sm-Nd garnet and U-Pb monazite and titanite geochronological study from metasedimentary rocks, melanocratic gabbro and websterite, indicate peak granulite-facies metamorphism to have occurred between 640 and 630 Ma followed by cooling to ~580 Ma. The ages are older than those determined earlier on zircon at ~ 624-626 to 615 Ma. This supports a short time span for the medium-pressure granulite-facies metamorphism by increased geothermal gradient due to crustal stacking and inflation, due to intrusion of quartz-diorite and tonalite (enderbite protoliths), at an active continental margin. A collision between the ~1.1 Ga orogenic Maud Belt with a northerly Mesoproterozoic arc-defined Lurio-Nampula block was responsible for formation of this Neoproterozic orogen, as opposed to its formation at the southern extremity of the EAO.

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