Sr-Nd Isotope Composition of Uraniferous Leucogranites in the Gaudeanmus area, Central Damara Belt, Namibia

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Abstract. The leucogranite-hosted uranium deposit in Namibia is a well-known intrusive uranium deposit in the world. In this paper, a systematic study of Sr-Nd isotopes has been carried out on uranium mineralized leucogranites in the Gaudeanmus area, Namibia. The results show that uranium-bearing leucogranites were formed in the post-orogenic extensional environment, the εNd(t) values of the rock are from -13.5 to -17.4, with the initial ⁸⁷Sr/⁸⁶Sr ratios of 0.73035 ~ 0.79345; and the ages of two-stage Nd model are between 2.32 ~ 2.63 Ga. The Sr-Nd isotopic geochemical results of the pre-Damara basement, Damara sequence and uraniferous leucogranites indicate that the contribution of uranium rich pre-Damara basement to the ore-forming materials is dominant during the main magmatic epoch of magmatic crystallization differentiation, while the extra uranium mineralization at the later hydrothermal stage may be from the primary uranium minerals such as uranite and coffinite.

1. Introduction
The leucogranite-hosted uranium deposit has been attached great importance from the industry due to its huge potential of mineral resources, the variety of ore components and the significance of deposit types. In addition, the genesis and ore-forming materials of the deposit are still in debate. Therefore, as an important type of intrusive uranium deposit, the leucogranite-hosted uranium deposit has become an important research objective for uranium geologists. The super-large Rössing deposit in Namibia is a typical example of the leucogranite-hosted uranium deposits. Located to the southeast of Rössing deposit, the Gaudeanmus area is another leucogranite-hosted uranium deposit. Recently, along with the study of uranium mineralogy and fluids in uraniferous leucogranite in this area [1], as well as research findings in Rössing, Rössing South, and Ida Dome deposit [2-3], it is believed that the mineralization mechanism and mineralization theory have been preliminarily understood, with the consensus that leucogranite-hosted uranium deposits were mainly formed during the process of magmatic crystallization differentiation.

However, the uranium source and genesis of the deposit are still in debate, and there are mainly four theories: Smith (1965) explained uraniferous leucogranites as forming from an anatectic origin during amphibolite-phase metamorphism from uranium-bearing protosediments, based on the composition of uraniferous leucogranites and the occurrence at the boundary between the Rössing and Khan Formations [4]; Barnes and Hambleton-Jones (1978) considered the Khan Formation as a source rock for the leucogranite-hosted uranium mineralization by interpreting the oxidation halos as cryptic enclaves of meta-sediments of the Khan Formation [5]; Brynard and Andreoli (1988) suggested that...
uranium bearing leucogranites are produced by remelting of high-heat producing red granite [6]; Nex et al. (2001) and Jacob et al. (1978) proposed that the pre-Damara basement lithologies are highly radioactive and can therefore provide a suitable uranium source [2, 7]. The paper presents a systematic research on the Sr-Nd isotopes of uranium bearing leucogranites, and discusses genesis of uranium bearing leucogranites in this area.

2. Geological settings

The Damara belt was formed by continental collision of the Kalahari and Congo Cratons during the late Precambrian to early Paleozoic (650 ~ 460 Ma) [8]. It is a part of Pan African orogenic belt and straddles the whole African continent. In Namibia, it composes of two parts, the NE-trending inland branch and the N-trending coastal branch. From south to north, the intracontinental branch can be subdivided into Southern Foreland, Southern Marginal Zone, Southern Zone, Okahandja Lineament Zone, Central Zone, Northern Zone, and Northern Platform according to the interpreted regional aeromagnetic lineaments or structures [9]. All the leucogranite related uranium mineralized points in Namibia are located in the Central Zone [10]. Tectonically the Gaudeanmus area situates in the southern Central Zone (Fig. 1), which is characterized by a metamorphism at amphibolite to granulite-facies conditions and a large number of granitic intrusions [11].

![Figure 1. Geological map of uranium deposits near Gaudeanmus area, Namibia [1]](image-url)
In the Gaudeanmus area, the pre-Damara basement gneisses (~2 Ga) are unconformably covered by Neoproterozoic Damara sequence, which includes the Swakop Group and the Nosib Group. The basal fluviatile Nosib Group commences with meta-conglomerates, quartzites, schists, and gneisses of Etusis Formation, mainly occupying domal and anticlinal cores. The age of rift related felsic volcanics near the base is 746±2 Ma [12]. The grayish-green Khan Formation is intruded by large volumes of granitic dykes and consisting of pyroxene-garnet gneisses, schists, and amphibolites. The upper Damara sediments of Swakop Group reflect deeper basin conditions. Overlying unconformably the Khan Formation, the Rössing Formation at the bottom of the Swakop Group accommodates most of uranium anomalies and comprises marbles, cordierite gneisses, and quartzites. The Chuos Formation is represented by a thickness glacial diamicite, and composed of diamicite, calcsilicates, and quartzites. These glacial deposits are associated with the Sturtian glaciation, and thereby the Chuos Formation is constrained to ca. 710 Ma [13]. Hosting several uranium deposits, the Karibib Formation is composed of thick-layered marbles with strong schistosity, schists, gneisses, and calcsilicates, and overlain by the Kuiseb Formation, which comprises pelitic schists, gneisses, migmatite, calcsilicates, and quartzites.

3. Sampling and analytical method

Samples for the study were collected from outcrops and drill cores, including banded migmatite, granitic gneiss, biotite schist and biotite gneiss in pre-Damara basement, cordierite-bearing gneiss, biotite schist, biotite gneiss and granitic gneiss in the Kuiseb Formation, and uraniferous leucogranites (D-type). Most samples were collected in the Gaudeanmus area (Fig. 1).

Sr and Nd isotopic compositions were determined at the State Key Laboratory for Mineral Deposits Research, Nanjing University. About 50 mg of powdered sample was dissolved in a mixture of HF + HNO₃. Sr and Nd were separated by cation-exchange resins, respectively. After purification, the separated Sr and Nd were dissolved individually and then loaded for analysis using a Finnigan Triton TIMS. Detailed analytical methods were described by Pu et al. (2004) [14]. ¹⁴³Nd/¹⁴⁴Nd ratios were normalized to ¹⁴⁶Nd/¹⁴⁴Nd=0.7219 and ⁸⁷Sr/⁸⁶Sr ratios to ⁸⁶Sr/⁸⁸Sr=0.1194. Total analytical blanks were (2–5) × 10⁻¹⁰ g for Rb and Sr and 5×10⁻¹¹ g for Sm and Nd. For the calculation of ⁸⁷Sr/⁸⁶Sr, εNd(t) and Nd model ages, the following parameters were used: λSm=6.54×10⁻¹² year⁻¹; λRb=1.42×10⁻¹¹ year⁻¹; (¹⁴⁷Sm/¹⁴⁴Nd)CHUR=0.1967; (¹⁴³Nd/¹⁴⁴Nd)CHUR=0.512638; (¹⁴³Nd/¹⁴⁴Nd)DM=0.513151, (¹⁴⁷Sm/¹⁴⁴Nd)DM=0.2136 [15-16]. Two-stage mode was adopted to calculate Nd mode age, and the equations [17] as follow:

εNd=((¹⁴³Nd/¹⁴⁴Nd)s/(¹⁴³Nd/¹⁴⁴Nd)CHUR-1)×10000. \hspace{1cm} (1)

fSmNd=((¹⁴⁷Sm/¹⁴⁴Nd)s/(¹⁴⁷Sm/¹⁴⁴Nd)CHUR-1). \hspace{1cm} (2)

where s stands for sample, (¹⁴⁷Sm/¹⁴⁴Nd)CHUR=0.1967 and (¹⁴³Nd/¹⁴⁴Nd)CHUR=0.512638.

Mode ages:

\[ t_{DM1}=\frac{1}{\lambda}\times\ln(1+\left(\frac{(¹⁴³Nd/¹⁴⁴Nd)}{(¹⁴³Nd/¹⁴⁴Nd)CHUR}\right)^{-1})\times10000, \] \hspace{1cm} (3)

\[ t_{DM2}=t_{DM1}-\left(t_{DM1}-0(f_{cc}-f_{ci})\right)/f_{DM}. \] \hspace{1cm} (4)

where \(f_{cc}, f_{ci}, \) and \(f_{DM}\) represent mean values in crust, samples, and depleted mantle, respectively; \(f_{DM}=0.08592, f_{cc}=-0.4, \) \(t=\)emplacement age; if \(-0.6<f_{SmNd}<-0.2,\) then \(t_{DM1}\) was adopted, whereas if \(f_{SmNd}<-0.6\) or \(>0.2,\) then \(t_{DM2}\) was adopted.

4. Results

Analytical results for Sr and Nd isotopes are given in Table 1, where isotopic ratios of Kuiseb formation and pre-Damara basement were all age corrected to 550 Ma, as this age represents the inception between the Congo and Kalahari Cratons, and it is also the time when partial melting in pre-Damara basement and Damara sequence started [18]. Isotopic ratios of uraniferous leucogranites were all age corrected to 502 Ma, which represents the diagenesis age and the mineralization age of leucogranites in the Gaudeanmus area [19]. (⁸⁷Sr/⁸⁶Sr) ratios of the pre-Damara basement are relatively higher and fluctuating between 0.73368 and 0.81824, though to be due to the heterogeneity of the basement itself. (¹⁴³Nd/¹⁴⁴Nd) ratios range from 0.510771–0.511163, averagely
0.510977 with small changes, and $\varepsilon_{Nd}(t)$ of -15 to -22.6. The Sr-Nd isotopic compositions of Kuiseb meta-sedimentary rocks also have high ($^{87}$Sr/$^{86}$Sr) ratios of 0.71421~0.73648, $\varepsilon_{Nd}(t)$ values of -3.7 to 9.5, and ($^{143}$Nd/$^{144}$Nd) ratios of 0.511441~0.511738.

Table 1 Sr-Nd isotopic compositions of the uraniferous leucogranites, Damara sequence and pre-Damara basement in Gaudeannus area, Namibia

| Sample no. | Lithology | Rb (ppm) | Sr (ppm) | Sm (ppm) | Nd (ppm) | $\varepsilon_{Nd}$ | Rb/Sr | Sr/Nd |
|------------|-----------|----------|----------|-----------|----------|-----------------|--------|-------|
| 10H-10     | Cordierite-bearing gneiss | 311 | 245 | 3.6771 | 0.749230±7 | 0.7204 | 8.04 | 41.1 |
| ZK15-2-1   | Granitic gneiss | 105 | 74.9 | 4.0731 | 0.771561±10 | 0.7396319.31 | 136 | 0.0856 |
| ZK20-1-7   | Banded migmatites | 273 | 261 | 4.2694 | 0.782141±12 | 0.7372060.97 | 4.07 | 0.1439 |
| ZK0-11-4   | Biotite schists | 280 | 145.9 | 2.1402 | 0.753265±12 | 0.736487.73 | 40.2 | 0.1162 |
| ZK10-18    | Biotite gneiss | 204 | 242.9 | 1.1096 | 0.733836±12 | 0.7164111.87 | 44.3 | 0.1506 |
| ZK12-2     | Biotite gneiss | 105 | 74.9 | 4.0731 | 0.771561±10 | 0.7396319.31 | 136 | 0.0856 |
| ZK10-19    | Biotite gneiss | 204 | 242.9 | 1.1096 | 0.733836±12 | 0.7164111.87 | 44.3 | 0.1506 |
| ZK12-2     | Biotite gneiss | 105 | 74.9 | 4.0731 | 0.771561±10 | 0.7396319.31 | 136 | 0.0856 |

For the calculation of ($^{87}$Sr/$^{86}$Sr), $\varepsilon_{Nd}(t)$ and Nd model ages, the following parameters were used: ($^{143}$Sm/$^{144}$Nd)$_{CHUR}$ = 0.1967; ($^{143}$Nd/$^{144}$Nd)$_{CHUR}$ = 0.512638; ($^{143}$Nd/$^{144}$Nd)$_{DM}$ = 0.51351; ($^{143}$Sm/$^{144}$Nd)$_{DM}$ = 0.2136 [15-16].

The initial $^{87}$Sr/$^{86}$Sr ratios of uranium bearing leucogranites are relatively higher with a wider fluctuation range of 0.73035~0.79345, all greater than 0.707, which suggests a source of crustal material. ($^{143}$Nd/$^{144}$Nd) ratios of 0.511102~0.511301 vary within a small range, and $\varepsilon_{Nd}(t)$ values lie between -13.5 and -17.4.

5. Discussion

Based on the components of uraniferous leucogranites and their spatial relationships with Rössing Formation and Khan Formation, Smith (1965) assumed that the uranium bearing leucogranites, which intruded into Khan and Rössing Formations, was metamorphosed from U-rich sedimentary rocks under the condition of amphibolite facies [4]. However, field observations don’t support this assumption. Although in some deposits, uraniferous leucogranites only intruded into Khan and Rössing Formations, such as Rössing deposit, in the Goanikontes area, it was observed that uraniferous leucogranites direct contacted with Etusis Formation and Chaos Formation [2]. In the Gaudeannus area, uraniferous leucogranites were mainly emplaced in Karibib Formation and Kuiseb Formation, with a portion in Khan Formation, Rössing Formation, and basement as well. Meanwhile, this phenomenon contradicts the viewpoint that inclusions in uraniferous leucogranites came from meta-sedimentary rocks in Khan Formation [5], so the latter can be served as the protolith of uraniferous leucogranites. Moreover, study showed that the chemical components of these inclusions are comparable to granite, not meta-sedimentary rocks [2].

It has reached an agreement that as the product of partial melting, uraniferous leucogranites were formed after D$_1$ tectonodeformation. Brynard and Andreoli (1988) pointed out that the emplacement of leucogranites occurred at the late stage of Damara Orogeny. Brynard and Andreoli (1988) also
assumed that uranium bearing leucogranites are the melting product of high-heat producing red granites [6]. Whereas Nex et al. (2001) indicated that except for uranium, this granite contained much more high-field-strength (HFS) elements than uraniferous leucogranite [2], and so it couldn't be the protolith of uraniferous leucogranite. It is suggested that uraniferous leucogranites are U-rich because the D3 structural deformation related to dome formation resulting from partial melting of a pristine section of pre-Damara basement which was not affected by earlier appreciable melt extraction [2, 18]. And that the basement lithologies show abnormal radioactivity and can therefore provide a suitable uranium source [7]. The results of Sr-Nd isotopic analysis in this paper also confirm this view.

The $\varepsilon_{\text{Nd}}(t)$ vs. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagram illustrates that uraniferous leucogranites in Gaudeanmus area have high initial Sr values and negative $\varepsilon_{\text{Nd}}(t)$ values, and plotted sample points basically stay in the area of pre-Damara basement (Fig. 2), indicating that uraniferous leucogranites may have been sourced from the partial melting of pre-Damara basement.

The $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios of uranium bearing leucogranites are high and variant. It is possible that slight disturbance in Rb-Sr isotopic system causes apparent influence on the calculation of initial values due to samples’ high Rb/Sr ratios, or the Rb/Sr system didn’t keep close well as a result of post orogenic geological events [20]. Namely that the $(^{87}\text{Sr}/^{86}\text{Sr})_i$ variation of uraniferous leucogranites could come from large heterogeneity of Sr isotopic composition in the pre-Damara basement, or the subsequent hydrothermal event possibly altered the Sr isotopic compositions of uraniferous leucogranites. The Sm-Nd isotopic system is less active, and thus the tracing effect is obviously better than the Rb-Sr system. The evolution lines for Kuiseb Formation, Khan Formation, and Etusis Formation refer to McDermott (1996) [21] in the $\varepsilon_{\text{Nd}}(t)$-$t$ diagram (Fig. 3). The evolution line for Etusis Formation is located in the pre-Damara basement, indicating an amount of basement components was mixed in the strata of Etusis Formation, or even the strata itself came from the basement. Uraniferous leucogranites are constrained in the evolution area defined by the pre-Damara basement and Etusis Formation (Fig. 3), and the Etusis Formation itself may also come from the pre-Damara basement, so it is concluded that uranium bearing leucogranites are mainly derived from the U-rich pre-Damara basement.

Figure 2. $\varepsilon_{\text{Nd}}(t)$ vs. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagram of uraniferous leucogranites in Gaudeanmus area, Namibia (modifies from De Flierdt et al., 2003 [22]). Data of pre-Damara basement are from this study and the references [23-24]; Data of uraniferous leucogranites and Kuiseb Formation are from this study (CZ-Central Zone).
Granites’ Nd model age may help to determine its sources. The two-phase Nd model ages Nd model ages for uraniferous leucogranites are between 2.32~2.63 Ga, comparing well with the two-phase Nd model age for the pre-Damara basement (2.26~3.32 Ga) [24], which mirrors that the contribution of uranium rich pre-Damara basement to the ore-forming materials is dominant during the main metallogenic epoch of magmatic crystallization differentiation.

As per uranium mineralogy, the uranium mineralization during the hydrothermal superimposition-reformation epoch may come from the self re-distribution of uranium minerals. The veinlet-shaped coffinite and pitchblende are always observed around or in fissures the euhedral uraninite, coffinite, and pyrite. It is therefore suggested that veinlet-shaped coffinite and pitchblende were formed through hydrothermal mobilization of primary uranium minerals formed during the main metallogenic stage of magmatic crystallization differentiation, followed by reducing reactions with pyrite and other sulphide minerals and precipitation nearby.

6. Conclusion
Uraniferous leucogranites have high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.73035~0.79345, low $\varepsilon_{\text{Nd}}(t)$ values of -13.5~17.4, $(^{143}\text{Nd}/^{144}\text{Nd})_i$ ratios of 0.511441~0.511738, and two-phase Nd model ages of 2.32~2.63 Ga. In both the $\varepsilon_{\text{Nd}}(t)$-$t$ diagram and the $\varepsilon_{\text{Nd}}(t)$-$^{87}\text{Sr}/^{86}\text{Sr}$ diagram, the plotted leucogranite sample points all fall within the pre-Damara evolution area, indicating that the uranium during the main metallogenic stage of magmatic crystallization differentiation in the Gaudeanmus area mainly originated from the uranium bearing pre-Damara basement. Also according to uranium mineralogy, the uranium mineralization during the hydrothermal superimposition-reformation epoch was formed as a result of self re-distribution of primary uranium minerals from the main mineralization epoch.
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