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Source composition, fractional crystallization and magma mixing processes in the 3.48–3.43 Ga Tsawela tonalite suite (Ancient Gneiss Complex, Swaziland) – Implications for Palaeoarchaean geodynamics

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ABSTRACT

The ca. 3480–3430 Ma Tsawela Gneiss (TG) is a well-preserved coarse-grained diorite to tonalite suite within the Ancient Gneiss Complex of Swaziland, eastern Kaapvaal craton. These gneisses are texturally and compositionally distinct from the hosting oldest components of the ca. 3200–3660 Ma TTG-type Ngwane Gneisses (NG). Major and trace elements, in combination with whole-rock hafnium-neodymium isotopic data, were analyzed in the TG and in three samples of ca. 3450 Ma grey NG to constrain sources and magmatic processes. High-field-strength element data (HFSE) were combined with U-Pb SHRIMP II ages and Hf-in-zircon data for key samples to constrain their ages and petrogenesis.

In contrast to the widespread view that Archaean crust is mainly composed of TTG igneous suites that formed from juvenile sources, the geochemical and isotopic compositions of the TG indicate that these rocks represent a calc-alkaline plutonic suite which possibly formed by magma mixing processes involving juvenile, mantle-derived tholeiitic melts as well as partial melts of the older Ngwane gneiss. Alternatively, the TG may represent a magmatic suite that formed by fractional crystallization of a hydrous intermediate magma. These results contrast with field evidence of a relatively uniform and homogeneous composition. Our geochronological and isotopic data show that the TG intruded the NG during a time span of at least 50 Ma without any significant compositional change of the source. The predominant influence of fractional crystallization of a tholeiitic mafic magma, as well as assimilation-fractional-crystallization processes (AFC) can be excluded for the TG from major and trace element modelling. The magma processes proposed here suggest efficient mixing of approximately equal amounts of TG magmas with those derived from the NG basement and is supported by the largely homogeneous Hf-Nd isotopic compositions of the whole-rock samples.

We propose that melting and mixing occurred in the lower crust that mainly consisted of >3.50 Ga NG and was possibly triggered by plume-related underplated and intraplated tholeiitic magmas in sills and/or laccoliths. This model is supported by geochemical evidence for a mafic end member lacking a negative Nb anomaly and implying that subduction processes were not involved in the formation of the TG.

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1. Introduction

The nucleii of all cratons consist of Archaean (2.5–4.0 Ga) continental crust, predominantly exposed as medium- to high-grade gneiss terranes. The granitoid composition in these terranes is different from modern granitoids and is dominated by grey gneisses with predominantly tonalite-trondhjemite-granodiorite (TTG) compositions (e.g., Barker and Arth, 1976; Jahn et al., 1981; Kröner, 1985; Martin, 1987; Condie, 1994; Foley et al., 2002; Bédard, 2006; Kröner et al., 2014). Minor components are mafic-ultramafic-felsic greenstone sequences, locally associated with chemo-clastic metasedimentary units and post-tectonic granites (e.g., Nutman et al., 1996).

Detailed regional geochemical, geochronological and petrological studies (Luais and Hawkesworth, 1994; Champion and Sheraton, 1995; Whalen et al., 2002; Clemens et al., 2006; Halla et al., 2009) combined with data compilations, including those of several cratons, have shown that Archaean granitoids do not only consist of TTGs but also contain more diverse compositions (Bickle et al., 1983; Moyen et al., 2007; Laurent et al., 2014b).

Data compiled by Moyen (2011) document that only 70–75% of the Archaean granitoids have a sodic TTG composition, whereas 10–15% have potassic compositions (e.g., sanukitoids), and 15% have variable compositions that do not fit into common classification schemes. Therefore, Moyen (2011) suggested to collectively name all Archaean deformed granitoids as 'grey gneisses', and he proposed a sub-classification based on several characteristics such as mineralogy as well as major and trace element compositions (Moyen and Martin, 2012).

Several scenarios for juvenile, sodic TTG formation have been proposed in the literature, and various geodynamic settings were suggested for their formation (e.g., Martin et al., 2005; Moyen and Stevens, 2006; Hoffmann et al., 2011a,b, 2014; Willbold et al., 2009; Nair and Chacko, 2010; Nagel et al., 2012; Zhang et al., 2013a; Kröner et al., 2014; Martin et al., 2014). In contrast, the genesis of other granitoid types found in Archaean cratons was not studied in detail so far. As summarized by Heilimo et al. (2011) and Laurent et al. (2014b), the major magmatic pulses of most Archaean granitoid domains can be separated into two phases: (1) terranes dominated by protracted TTG plutonism, followed by (2) a phase with diverse types of intermediate to felsic granitoid emplacement. The latter phase was reached in most cratons towards the end of the Mesoarchaean, at about 3.0 Ga, and has been interpreted globally, to reflect the onset of modern-style plate tectonic processes (e.g., Dhuime et al., 2012, 2015; Næraa et al., 2012; Laurent et al., 2014b). Typical of the second phase granitoids is the appearance of sanukitoids (e.g., Shirey and Hanson, 1984; Halla et al., 2009), hybrid granitoids, as well as biotite- and two-mica granites (e.g., Laurent et al., 2014a,b). These suggest a change in the style and composition of Archaean granitoids towards the Mesoarchaean and involve interaction of mantle-derived melts or juvenile TTGs with older TTG crust (e.g., Friend et al., 2009; Næraa et al., 2012) and possibly an enrichment of mantle sources by crustal recycling processes (e.g., Dhuime et al., 2015).

Recent studies by Schoene et al. (2009), Zeh et al. (2011), and Kröner et al. (2014), based on Hf and Nd isotope compositions, have shown, however, that the oldest gneisses of the eastern Kaapvaal craton, in the Ancient Gneiss Complex (AGC) of Swaziland, already incorporated older crustal components, which is not in agreement with traditional models of juvenile TTG formation. The major and trace element compositions of some of the oldest AGC grey gneisses are granitic (Kröner et al., 2014).

The Ancient Gneiss Complex of Swaziland is predominantly made up of granitoid gneisses that range in age from 3.66 to about 3.2 Ga (Kröner, 2007). The oldest gneiss generation (named Ngwane Gneiss) is characteristically compositionally layered and yielded ages between 3.66 and 3.45 Ga; together with interlayered amphibolite layers it was previously known as Bimodial Suite (Hunter et al., 1978). Several younger generations of plutonic rocks intruded the >3.45 Ga components between ca. 3.45 and 3.20 Ga, contributing to crustal growth and stabilization of the continental crust in the eastern Kaapvaal craton. One of these younger ca. 3450 Ma plutonic suites is exposed in west-central Swaziland (Hunter et al., 1984; Jackson, 1984; Kröner, 2007; Zeh et al., 2011) and is named Tsawela Gneiss (TG). It is relatively homogeneous, mostly coarse-grained and not compositionally layered, and occurs as intrusions into older phases of the Ngwane Gneiss and some greenstone remnants (Jackson, 1984).

We studied samples of the TG suite and several samples of the ca. 3450 Ma grey Ngwane gneiss generation to constrain magmatic processes that contributed to the formation of early Archaean continental crust in this region. Source compositions of both suites are evaluated in order to reconstruct possible geodynamic settings. We report major and trace element data (including high-precision analyses for the high-field-strength elements) as well as whole-rock ^{176}Lu-^{176}Hf and ^{147}Sm-^{143}Nd isotopic systematics in combination with SHRIMP II zircon ages and Hf-in-zircon isotopes for selected samples of the TG and associated rocks.

2. Geological overview

Rocks of the Ancient Gneiss Complex (AGC) are widespread in Swaziland and comprise some of Africa's oldest fragments of continental crust (Compston and Kröner, 1988; Schoene et al., 2008; Kröner et al., 2014). The evolution of the AGC covers almost the entire Palaeoarchaean, with the oldest gneisses yielding protolith ages of up to 3666 Ma (Compston and Kröner, 1988; Schoene et al., 2008; Zeh et al., 2011; Kröner et al., 2014), and the youngest components having ages of ca. 3.2 Ga (Kröner, 2007 and references therein). The AGC rocks are intruded by the ca. 3.1 Ga Piggs Peak batholith and several smaller granite plutons at ca. 2.7 Ga (Fig. 1; e.g., Wilson, 1982; Kröner, 2007; Zeh et al., 2011; Mukasa et al., 2013).

The AGC, as defined by Hunter (1970), comprises lithologically and geochemically distinct units of grey gneiss with predominantly TTG compositions. Some of these gneisses have highly siliceous compositions (SiO_2 >74 wt.%; Hunter et al., 1978, 1984; Kröner et al., 2014) and are true granites. These gneisses are tectonically interlayered with amphibolite bands and rare metasedimentary sequences, ranging in scale from cm to km (Hunter et al., 1978; Kröner, 2007). Locally, remnants of the amphibolites represent mafic dykes (Hunter et al., 1984; Jackson, 1984), whereas in some cases they may represent infolded greenstone remnants. The oldest part of the AGC is exposed in the small Phophonyane gneiss inlier of Ngwane Gneiss, several kilometres north of Piggs Peak town in northwestern Swaziland and in faulted contact with mafic-ultramafic rocks of the Barberton Greenstone Belt. These predominantly migmatitic gneisses yielded ages up to 3666 Ma as summarized above. The oldest component of the AGC in the Mankanyane area of west-central Swaziland is also the Ngwane Gneiss (Wilson, 1982) or Bimodal Suite (Hunter, 1970), consisting of grey gneisses interlayered with amphibolites (e.g., Hunter, 1970, 1978; Jackson, 1984; Fig. 1). The metamorphic grade of the AGC gneisses is dominantly amphibolite-facies, however, small areas preserve granulite-facies assemblages (Hunter, 1970; Kröner et al., 1993; Condie et al., 1996; Suhr et al., 2015). The >3420 Ma Dwalile greenstone remnant is exposed southwest of Mankanyane along the border with South Africa. It contains mafic-ultramafic metavolcanic rocks as well as banded iron formations (BIF), metagreywacke and metachert with detrital zircon ages of ca. 3420 Ma to 3563 Ma that provide a maximum age for greenstone formation and constrain the age for the source area (Kröner and Tegtmeyer, 1994).