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Thermochronology and geochemistry of the Pan-African basement below the Sab'atayn Basin, Yemen

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ABSTRACT

Three important lithologies occur in two drill wells from the Pan-African basement underlying the Mesozoic Sab'atayn Basin, in a previously undocumented area of the Pan-African, 83 and 90 km NE of known exposures in Yemen. Cores from well 1 include amphibolite, with basaltic to andesitic compositions, affected by crustal contamination during emplacement into a thickened crust. Deeper in the well, an unfoliated dark red monzogranite has a U–Pb zircon age of 628.8 ± 3.1 Ma and a Rb–Sr biotite cooling age of 591.6 ± 5.8 Ma (~300 °C). Regional constraints suggest emplacement in a transitional tectonic setting with compressional terrane amalgamation followed by extensional collapse. Sm–Nd isotope analysis yields a T_{DM} model age of 1.24 Ga with negative ε_{Nd} values, suggesting the monzogranite is part of the Al Bayda island arc terrane. Cores from well 2 contains a weakly deformed, massive (unbedded) medium grey meta-arkose exhibiting essentially no geochemical signature of weathering and with an almost pure dacitic composition. This rock may have been directly derived from an (extrusive) granitoid that was emplaced prior to, or during terrane amalgamation. A (U–Th–Sm)/He zircon age of 156 ± 14 Ma constrains the time of basement cooling to ~180 °C, synchronous with basin formation. These lithologies provide new insights in the development of the Pan-African basement of Yemen, extending our knowledge of the nearby surface geology to the subsurface.

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1. Introduction

The Pan-African basement in Yemen represents the south-eastern part of the Arabian–Nubian Shield (ANS), which formed between ca. 870 and 542 Ma as a result of the amalgamation of several (mostly juvenile) terranes (see Fig. 1, e.g. Johnson et al., 2011). The late stage evolution (650–542 Ma) of the ANS was characterized by orogenic collapse, with NW–SE to NNW–SSE oriented extension (Blasband et al., 2000; Johnson and Woldehaimanot, 2003; Shalaby et al., 2005; Johnson et al., 2011), associated with sinistral transpressional faulting in the NW–SE oriented Najd Fault System (615–585 Ma). Extension caused significant, mostly A-type, (anorogenic) granitoid magmatism throughout the ANS (Johnson et al., 2011; Moghazi et al., 2011). This late stage evolution is best recognized in the northern and central part of the ANS.

The ANS is well exposed both west and east of the Red Sea, with a western boundary likely along the Nile valley (Johnson et al., 2011). In contrast, its eastward extent is buried under post-Pan-African sedimentary rocks. Although indirect (e.g. geophysical) methods give evidence for the extent of the Pan-African basement further east, only drilling provides samples for determining the regional distribution and thermal history of the basement.

Here we present new geochemical and geochronological results from the Pan-African basement in two wells drilled through the Mesozoic Sab'atayn Rift Basin (or Marib(-Shabwa(h)-Hajar) Basin, Beydoun, 1997; Le Garzic et al., 2011), Shabwa province, central Yemen (Fig. 2). The wells are ~7 km apart and pass through the (syn-)rift basin sedimentary rocks into the Pan-African basement, providing new insights into the evolution of the poorly known Pan-African basement of Yemen.

2. Geological background

The break-up of Rodinia (870–670 Ma) led to the formation of the Mozambique Ocean, with subsequent collision between East and West Gondwana, forming the East African Orogen (EAO). Overall, the EAO extends from Sinai to East Africa/Mozambique, with low-metamorphic grade rocks in the north (forming the ANS), and high-grade rocks in the Mozambique Belt in the south (Whitehouse et al., 2001; Fritz et al., 2013).

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The ANS, located in NE Africa and the Arabian Peninsula, is characterized by a collage of island-arc terranes that formed in the Mozambique Ocean and subsequently collided between ca. 870 and 542 Ma (Stoeser and Camp, 1985; Genna et al., 2002; Kröner and Stern, 2004; Stern and Johnson, 2010; Johnson et al., 2011). Most terranes, including those west of the Nabitah Orogenic Belt (inset Fig. 2), comprise juvenile Neoproterozoic rocks with an oceanic-arc affinity. However, four terranes in Saudi Arabia (east of the Nabitah Mobile Belt), Yemen and Sudan contain pre-Neoproterozoic micro-continental rocks (Stoeser et al., 2001). The suture zones between the ANS terranes include fragmented ophiolite complexes (Hargrove et al., 2006). Pan-African crustal shortening was followed by late- to post-orogenic granitoid magmatism, orogenic collapse and escape tectonics (ca. 650–542 Ma; Blasband et al., 2000).

About 42% of the exposed ANS is plutonic (mostly felsic; Stoeser and Camp, 1985), with large amounts of A-type (anorogenic) granitoid bodies, mostly in the north (Blasband et al., 2000; Moghazi, 2002; El-Bialy and Hassen, 2012; Moghazi et al., 2012). However, in Yemen, late- to post-tectonic granitoids appear less common and few have been studied (Fediuk and Balogh, 2009; Johnson et al., 2011; Le Garzic et al., 2011).

The ANS basement in Yemen lies between the typical main body of the ANS and the higher metamorphic grade Mozambique Belt (Whitehouse et al., 2001; Kröner and Stern, 2004). Although several relatively small but nonetheless important terranes separated by ophiolitic suture zones have been identified in Yemen, detailed information is limited and mostly based on samples from surface exposures (Windley et al., 1996; Whitehouse et al., 1998, 2001), borehole data (restricted to oil companies) and satellite imagery (Le Garzic et al., 2011).

2.1. Accretionary terranes in Yemen

Windley et al. (1996) recognised six high-grade pre-Neoproterozoic gneissic terranes and lower-grade Neoproterozoic island-arc terranes in Yemen, all with an essentially NE–SW structural grain. From NW to SE, these are the: Asir island arc terrane, Afif continental terrane, Abas gneiss terrane, Al Bayda island arc terrane, Al-Mahfid gneiss terrane and Al-Mukalla island arc terrane (Fig. 2).

The Abas, Al Bayda and Al-Mahfid terranes form the Al-Mahfid uplift and are separated by km-scale ophiolitic suture zones. The Al Bayda island arc terrane is characterised by more juvenile (Neoproterozoic) components, similar to most ANS terranes (cf. Johnson et al., 2011) whereas both the Abas and the Al-Mahfid terranes are Paleoproterozoic gneiss terranes, having T_{DM} model ages older than that of the Al Bayda island arc terrane (Windley et al., 1996). Note that gneissic domes, which formed both in relation to the Najd Fault System and within suture zones, are structurally different from the gneiss terranes (Genna et al., 2002; Johnson et al., 2011).

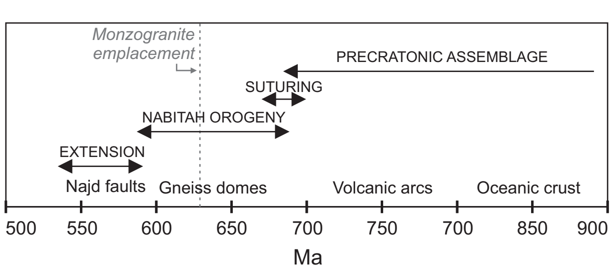

Fig. 1. Schematic chronology of tectonic events within the Arabian Shield.

The Abas, Al Bayda, Al-Mahfid and Al-Mukalla terranes are bounded to the NE by the Late Jurassic Sab'atayn Basin; the sampled drill cores penetrated the basement below this (Fig. 2).

2.1.1. Abas gneiss terrane

This continental terrane (Fig. 2) dominantly comprises relatively homogeneous Palaeoproterozoic hornblende–biotite gneiss and metamorphosed supracrustal rocks (Whitehouse et al., 2001). Felsic veins or plutons are generally absent but abundant mafic to intermediate dykes cut the gneisses. These dykes are up to 5 m thick and are related to the extensional phase of ANS formation.

The Sm–Nd depleted mantle model ages (T_{DM}) from gneiss samples lie between 1.7 and 2.3 Ga, with $\varepsilon_{Nd}(0)$ values between −18.2 and −10.6 (Windley et al., 1996). No Archean model ages have been determined, except for one 3 Ga T_{DM} point from a meta-sediment (Whitehouse et al., 2001).

2.1.2. Al Bayda island arc terrane

The suture between the Abas gneiss and Al Bayda island arc terranes is a vertical, ductile to brittle high-strain zone several km wide (Windley et al., 1996; Whitehouse et al., 2001). The Al Bayda terrane contains greenschist facies, arc-type rhyolites, andesites, basalts and tuffs. Additionally, a significant amount of ophiolitic rocks have been recognized, particularly close to the suture zones. This assemblage of ophiolitic rocks and arc-type rocks was intruded by a range of plutons and dyke swarms related to late extension during ANS formation. Despite narrowing towards the SE, Whitehouse et al. (1998) correlated the Al Bayda island arc terrane with a similar terrane in northern Somalia. How far the Al Bayda island arc terrane continues towards the NE is unknown.

Sm–Nd (T_{DM}) model ages from undeformed (late) intrusions yielded T_{DM} ages of 1.2–2.53 Ga (Windley et al., 1996), in which only one sample (a gabbro) yielded the distinctly younger T_{DM} age of 1.2 Ga. All other samples (granitoids) yielded ages between 1.99 and 2.54 Ga. $\varepsilon_{Nd}(0)$ values are −20 with one junvenile $\varepsilon_{Nd}(0.7)$ of 4.3 (Windley et al., 1996). Ba-Bttat (1991) and Whitehouse et al. (1998) determined hornblende Ar–Ar ages for felsic dykes between 715 and 615 Ma, where the youngest age is interpreted as the minimum age of terrane assembly.

2.1.3. Al-Mahfid gneiss terrane

The suture between the Al Bayda island arc and the Al-Mahfid gneiss terranes is also a steep ductile to brittle deformation zone several km wide (Whitehouse et al., 2001). The Palaeoproterozoic Al-Mahfid gneiss terrane, which is the most complex terrane discussed, is essentially composed of grey, amphibolite-facies orthogneiss that is cut by several phases of granitoid intrusions. Multiple generations of mafic dykes intrude the complex. The grey orthogneiss alternates with, and is overlain by, two supracrustal successions (amphibolite, quartzite, marble and rhyolite; Whitehouse et al., 1998, 2001) that are not intruded by dykes. The orthogneiss has (T_{DM}) model ages of 2.7–3.0 Ga within the oldest recognized gneiss, making it clearly distinct from the Abas gneiss terrane. The gneiss also yielded negative $\varepsilon_{Nd}(0)$ values ranging from ca. −39.8 to −25.6, lower than that of the Abas gneiss terrane (Windley et al., 1996; Johnson et al., 2011). Whitehouse et al. (1998) presented U–Pb zircon ages indicating a protolith age of ca. 2.55 Ga, with Pb-loss at around 760 Ma, implying that Neoarchean crust is present in Yemen. Note that the T_{DM} ages younger than 2.55 Ga, with $\varepsilon_{Nd}(0)$ values between −20 and −10, were derived from the ca. 760 Ma granitic rocks (Whitehouse et al., 1998). The 760 Ma age has also been recognised in orthogneiss from the Abas terrane (Whitehouse et al., 1998).

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