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Metamorphic evolution of the Sa'al–Zaghra Complex in Sinai: Evidence for Mesoproterozoic Rodinia break-up?

M. Hassan[a,e,f,*], T.S. Abu-Alam[a,b,e], K. Stüwe[a], A. Fowler[c], I. Hassen[d]

[a] Institut für Erdwissenschaften, Universität Graz, Universitätsplatz 2, A-8010 Graz, Austria
[b] Geology Department, Faculty of Science, Tanta University, Tanta, Egypt
[c] Geology Department, Faculty of Science, United Arab Emirates University, United Arab Emirates
[d] Sciences Department, College of Basic Education, PAAET, Kuwait
[e] Egyptian Institute of Geodynamic, Cairo, Egypt
[f] Geology Department, Faculty of Science, Suez Canal University, Ismailia, Egypt

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ABSTRACT

Recently published age data indicate that the Sa'al–Zaghra metamorphic complex in Sinai, Egypt contains the oldest rocks found in the northernmost Arabian-Nubian Shield, preserving evidence for a 1110–1030 Ma rift-related volcanic system formed during Rodinia break-up (Be'eri-Shlevin et al., 2012). As such, its metamorphic evolution provides evidence for an important part of the geological history of the shield. Here we use petrographic, mineral chemistry and thermodynamic modeling, in combination with structural data from the field, to derive a *P–T–D–t* path for the complex. It is shown that the metamorphic rock of the complex equilibrated during an early deformation event that involves a flat lying fabric and is interpreted as an extensional event. *P–T* conditions attained during this event are between 370–420 °C and around 3 kbar. These conditions correspond to a geothermal gradient of 38–41 °C/km which is much higher than that documented elsewhere in the metamorphic complexes of Sinai (i.e. 25–27 °C/km). We suggest that this is because metamorphism in the Sa'al–Zaghra complex records an earlier stage of metamorphism and deformation during breakup of Rodinia, whereas the lower gradients documented elsewhere is related to the Gondwana collision. During the subsequent East-West-Gondwana collision, the Sa'al–Zaghra complex remained at shallow crustal levels (<9 km), and therefore it escaped the deep crustal metamorphism of the Pan-African event.

1. Introduction

The Arabian-Nubian Shield is considered to be one of the largest exposures of Neoproterozoic juvenile continental crust on Earth (Patchett and Chase, 2002; Stern et al., 2004). The shield was cratonized during the collision between East- and West-Gondwana following the closure of the Mozambique Ocean around 750–630 Ma (Stern, 1994; Cox et al., 2011; Abu-Alam et al., 2013). However, there have been reports of older (Pre-Pan-African) crustal material that exists as reworked fragments of an earlier continent, namely Rodinia (Johnson and Woldehaimanot, 2003; Hargrove et al., 2006). Today, the shield includes vast sequences of oceanic rocks and is pervasively intruded by late stage granites, but metamorphic rocks of apparently continental origin do occur. Typically, these metamorphic rocks are high-grade gneiss complexes that are exhumed from underneath the oceanic rocks along crustal scale shear zones (Abu-Alam et al., 2013), but some metamorphic complexes differ in that they are much lower grade and potentially much older. The Sa'al–Zaghra complex in central Sinai peninsula, Egypt is one of these.

This study investigates the metamorphic evolution of the Sa'al–Zaghra complex of Sinai to constrain its metamorphic evolution. The complex is one of four metamorphic complexes exposed in the Sinai Peninsula (Fig. 1). Be'eri-Shlevin et al. (2012) provided U–Th–Pb data of 1.02–1.03 Ga for the metavolcanics and mafic intrusions from the Sa'al–Zaghra complex. These data suggest that the geology of the complex may bear information on the connection between the latest Mesoproterozoic fragmentation of Rodinia and the later buildup of Gondwana. As such, the Sa'al–Zaghra complex may hold a key position for the early stages of the tectonic evolution of the Arabian-Nubian shield.

This study investigates the metamorphic evolution of the Sa'al–Zaghra complex in order to constrain the metamorphic conditions associated with what may prove to be the first deformation event in the history of the Arabian-Nubian Shield. A mineral equilibria approach is used with petrogenetic pseudosections. Our derived metamorphic conditions are then correlated with independent field evidence and existing geochronological ages from the

* Corresponding author. Tel.: +43 3163805680.
E-mail address: mahmoud.ali-hassan@uni-graz.at (M. Hassan).

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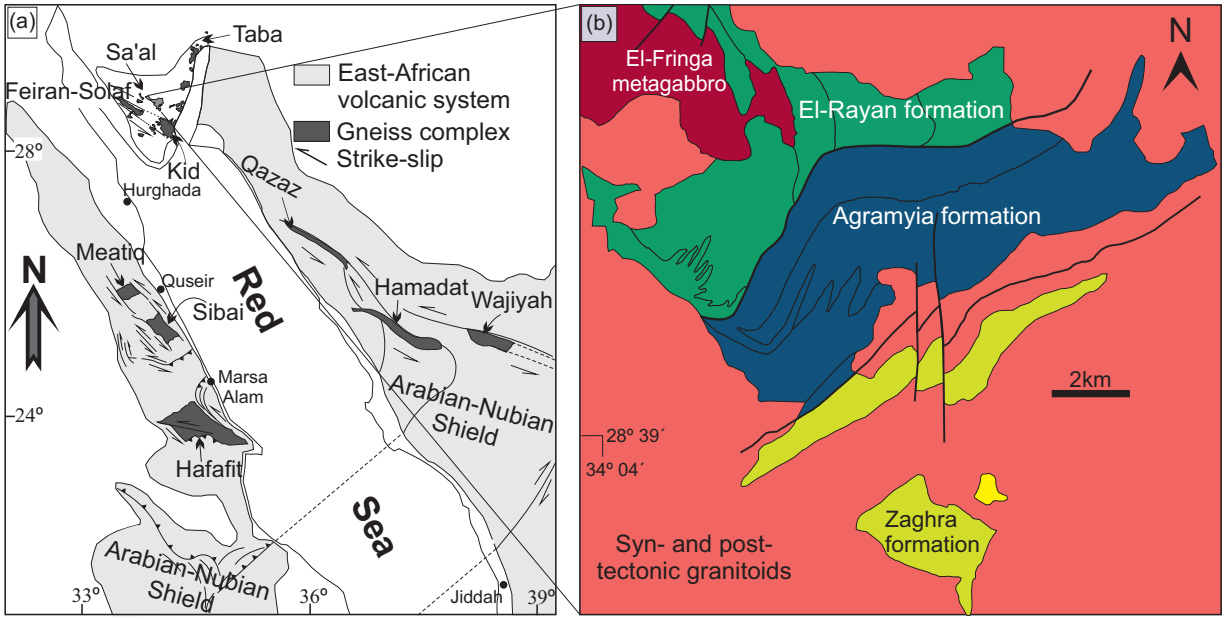

Fig. 1. (a) Geometry of the Arabian-Nubian Shield showing the volcanic-arc system, the amphibolite facies gneiss complexes, Najd Fault system and sutures of the shield (modified after Abu-Alam and Stüwe, 2009). Sinai is shown in white indicating it may not have been exclusively part of the Arabian-Nubian Shield during the formation. (b) Simplified geological map of the Sa'al–Zaghra complex (modified after Shimron et al., 1993; Fowler, unpublished data).

Sa'al–Zaghra complex and other complexes elsewhere in the shield. The results are discussed in the context of the tectonic evolution of the Arabian-Nubian Shield.

2. Geological setting and lithologies

The Arabian-Nubian Shield is mostly composed of low-grade volcano-sedimentary associations referred to as arc-assemblage that contain some metamorphic complexes in between this arc-assemblage (e.g. Meatiq and Migif-Hafafit; Fritz et al., 1996, 2000, 2002) (Fig. 1). In Sinai four such complexes are known: Kid, Taba, Feiran–Solaf and Sa'al–Zaghra with the former three being of amphibolite and granulite facies metamorphic grade and the Sa'al–Zaghra being much lower grade. The arc-assemblage is characterized by brittle-ductile deformation (Noweir et al., 2006; Abd El-Wahed and Kamh, 2010; Johnson et al., 2011) that metamorphosed at lower greenschist facies metamorphic conditions (Noweir et al., 2006; Abu-Alam et al., unpublished data).

The evolution of the Arabian-Nubian Shield probably involved at least four main deformation events (Sultan, 2003; Hegazi et al., 2004; Fowler and Hassen, 2008; Fowler et al., 2010a,b; Moghazi et al., 2012). D_1 deformation phase is synchronous with the prograde metamorphism in both Kid and Taba metamorphic complexes and D_2 occurs during peak metamorphism in both Taba and Kid complexes (Abu El-Enen et al., 2003a,b; Abu El-Enen et al., 2004; Eliwa et al., 2004; Abu El-Enen, 2008). For the Feiran–Solaf metamorphic complex, the deformation events (D_2–D_4) have been correlated with other parts of the shield (Abu-Alam and Stüwe, 2009; Abu-Alam et al., 2010), but the first deformation event D_1 and its relevance for the shield are not well understood.

The Sa'al–Zaghra complex of southern Sinai (Fig. 1) includes mainly low-grade metamorphosed volcano-sedimentary associations referred to as the "Sa'al Group" that are surrounded by large volumes of syn- and post-tectonic granites. The Sa'al Group is divided into three formations (Shimron et al., 1993) (Fig. 2). (a) *El-Rayan Formation* occupies a rugged terrain extending ENE-WSW in the northern part of the complex. The El-Rayan Formation in the west consists of a thickly layered sequence of basaltic andesite and andesite at its base, followed by layered felsic tuffs, rhyolite lava flows, rhyolite crystal tuffs and ash tuffs. In the eastern part of Wadi Sa'al, it is represented by layered felsic tuffs. In the central upper part of the complex, around the junction of Wadi Sa'al and Wadi El-Rayan, there were wide exposure of phyllite extending northward (Fig. 3a).

(b) *Agramyia Formation* occupies the central part of the belt and is dominated by volcano-sedimentary rocks (Fig. 2). It is composed of a ~2300 m thick interbedded sequence of tuffs and lapili tuffs (Fig. 3b) succeeded by rhyolitic ignimbrite (Fig. 3c) intercalated with fine tuffs, other pyroclastics and sedimentary beds of siltstone, sandstone, and conglomerates with some sheets and layers of andesitic lava (Shimron et al., 1993). (c) Finally, *Zaghra Formation* in the south of the belt is composed of conglomerates (Fig. 3d), sandstones, slates with minor calc-silicates bands, metamorphosed volcanogenic litharenite and arkoses. There is a localized zone of concordant, foliated red granite sheets intruded along the sandstone and slate bands of Zaghra Formation (Fig. 3e). These three formations are separated by two steep ENE-WSW trending thrusts.

The Sa'al–Zaghra area has been intruded by intrusive rocks ranging in the composition from gabbro, diorites, granodiorite to alkali-granites that cross-cut the foliation. A NW–SE striking gabbro-diorite complex "El-Fringa metagabbro" intruded the phyllite and metavolcanics of El-Rayan Formation in the NW part of the mapped area (Fig. 2). Minor gabbroic intrusions are also found elsewhere in the complex. Quartz-diorites crop out at the eastern side of the study area have crystallization age of 819 ± 4 Ma (Be'eri-Shlevin et al., 2012). These rocks are rich in amphiboles, coarse-grained, dark gray in color and enclose xenoliths (metasediments, metavolcanics and metagabbro) up to 1 m long. Granodiorite which crops out in the central and southwestern sectors of the area is light gray, coarse-grained and has plagioclase with amphiboles and quartz and encloses abundant ovoid enclaves and elongated xenoliths of older rock types (Fig. 3f). Similar granodiorite to the east of Feiran–Solaf complex gives a U–Pb zircon age of 782 ± 7 Ma (Stern and Manton, 1987). Alkali-granite is exposed in the central and the western part of the map area and has a Pan-African age (635–580 Ma; Eyal et al., 2010). Biotite granite intrudes and shares sharp contacts with the quartz-diorite and the granodiorites. Weak deformation can be