The Wadi Zaghra metasediments of Sinai, Egypt: new constraints on the late Cryogenian–Ediacaran tectonic evolution of the northernmost Arabian–Nubian Shield

Arild Andresen*, Mahrous M. Abu El-Enenb, Robert J. Sternc, Simon A. Wilde and Kamal A. Ali

*Department of Geosciences, University of Oslo, Oslo, Norway; bGeology Department, Faculty of Science, Mansoura University, El-Mansoura, Egypt; cGeosciences Department, University of Texas at Dallas, Richardson, TX 75080, USA; dDepartment of Applied Geology, Curtin University, Perth, Australia; eDepartment of Mineral Resources and Rocks, Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia

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The depositional age of the Wadi Zaghra metasediments (Zaghra Formation) of the Sa’al-Zaghra metamorphic complex (Sinai) in the Arabian–Nubian Shield (ANS) has been constrained by LA-ICP-MS dating of zircons from (1) metagraywacke-argillaceous and metagraywacke-argillaceous matrix, (2) the metaconglomerate matrix, (3) biotite-schist, and (4) diorites and granites intruding the metasediments. Three detrital zircon age populations indicate deposition after 630–625 Ma. The emplacement age of the post-depositional intrusives is enigmatic due to a large population of xenocrystic zircons, but is interpreted to be as old as ca. 615 Ma. This implies deposition and deformation of the Zaghra Formation in the time interval 625–615 Ma, thus older than the inferred depositional age of the Hammamat deposits in the Eastern Desert of Egypt, which is commonly correlated. The inferred depositional age is similar to the deposits in nearby Rutig Basin, where conglomerates were deposited in two pulses; at ca. 620–610 and 600–590 Ma. The appearance of late Mesoproterozoic (ca. 1.1 to ~1.0 Ga) detrital zircons in the fine-grained laminated matrix facies of the Zaghra Formation demonstrates that ~1.0 Ga basement rocks (Sa’al terrane?) were exposed when Zaghra basin sediments were being deposited.

Keywords: Arabian–Nubian Shield; Neoproterozoic crust; U-Pb zircon age; Zaghra Formation; Egypt; Sinai

1. Introduction

The Arabian–Nubian Shield (ANS) is well exposed on the flanks of the Red Sea (Figure 1a), making it an excellent place to study Neoproterozoic processes of crustal growth and obduction–accretion tectonics (Kröner 1985; Kröner et al. 1994; Stern 1994; Johnson and Woldehaimanot 2003; Johnson et al. 2011). The ANS is dominated by large volumes of juvenile Neoproterozoic igneous rocks in addition to variably deformed and metamorphosed supracrustal rocks. The geochemistry and age of ANS igneous rocks have been thoroughly described and discussed in numerous papers, with the goal of deciphering the tectonomagmatic evolution of the northern part of the East African Orogen (e.g. Johnson et al. 2011; Fritz et al. 2013). Distinctly less is known about the supracrustal deposits and what they can tell us about the collisional process, and the subsequent late- and post-collisional evolution of the ANS (e.g. orogenic collapse basins, strike-slip basins, foreland basins, rift basins). Recent investigations indicate that supracrustal rocks within the ANS can be subdivided into (1) old arc-related assemblages and (2) younger post-amalgamation basin deposits. The former are dominated by volcano-sedimentary rocks generally older than 650 Ma (Johnson 2003; Johnson et al. 2011; Nasiri Benzenjani et al. 2014), with most of the typical island arc associations being ca. 750 Ma (Ali et al. 2009). The 30-plus post-amalgamation basins within the ANS differ from the older volcano-sedimentary arc-assemblages by having an unconformable basal contact, varying from angular unconformities to nonconformities, and commonly starting with a poorly sorted, short-transported clastic sequence (Johnson 2003). These basins are generally weakly to moderately metamorphosed and deformed. The metamorphic grade in the post-amalgamation basins seldom exceeds greenschist facies conditions, but may locally reach lower amphibolite facies conditions. Both continental and marine basins are present and the proportion of clastic versus volcanic deposits varies from one basin to another (Johnson et al. 2011).

The structural control and depositional ages of the post-amalgamation basins of the ANS are poorly constrained (e.g. Johnson et al. 2011). Sedimentary basins...
with deposits ranging in age from 660 to 600 Ma have been identified in Saudi Arabia (Johnson 2003; Johnson et al. 2011), whereas ages between 600 and 595 Ma have been reported from the Saramuj conglomerate in southwest Jordan (Jarrar et al. 1993; Yaseen et al. 2013) (Figure 1a). The depositional age of post-amalgamation basins in the Eastern Desert (ED) of Egypt (Wilde and Youssef 2002) and in Sinai (e.g. Samuel et al. 2011; Eyal et al. 2014) is in the time interval 632–590 Ma. In this paper we report new LA-ICP-MS zircon ages on zircons from igneous clasts, and detrital zircons in the matrix of metamorphosed diamictites of the Zaghra Formation within the Sa’al-Zaghra metamorphic complex in central Sinai (Figure 1b). Detrital zircons from biotite-schists considered to be part of the Zaghra Formation are also dated. The depositional age of the diamictite and related basin deposits is furthermore constrained by dating undeformed igneous rocks that intrude the Wadi Zaghra metamorphic complex (Figure 2). Whereas some authors link the term diamictite to glacially related deposits, we use it as a purely non-genetic descriptive term, meaning a poorly sorted matrix-supported conglomerate (Flint et al. 1960).

2. Geological setting

The ANS represents the northern termination of the East African Orogen, and is the result of accretion of Cryogenian island arc terranes prior to collision of East and West Gondwana in the late Cryogenian–early Ediacaran (e.g. Johnson et al. 2011; Fritz et al. 2013). The various island arc terranes constituting the ANS on the Arabian Peninsula and in eastern Egypt are separated by regionally extensive shear zones, often decorated with ophiolite fragments (e.g. Johnson et al. 2011). ANS rock assemblages on the Egyptian side of the Red Sea and in Sinai are considered by most authors to be correlative with rocks of the Midyan terrane (Figure 1) in NW Saudi Arabia (Johnson et al. 2011). Typical protolith ages for the island-arc rocks constituting the Eastern Desert and Midyan Terranes range between 810 and 710 Ma (e.g. Johnson et al. 2011). Both the individual terranes and the terrane boundaries are transected by a series of long-lived NW–SE-striking shear zones, commonly referred to as the Najd Fault System (Stern 1985). Their presence in Sinai is questionable, but El-Shafei and Kusky (2003) and Abu-Alam and Stüwe (2009) have reported structures in

Figure 1. (a) Simplified map of Arabian–Nubian Shield (ANS) showing locations of some volcano-sedimentary successions: 1, Sa’al-Zaghra (Sinai); 2, Rutig and Solaf (Sinai); 3, Kid conglomerate (Sinai); 4, Hammamat–Dokhan (NE desert); and 5, Saramuj Conglomerate (Jordan). (b) Geological sketch map of Sa’al metamorphic complex (Sinai, Egypt; modified after Shirmon et al. (1993) and Be’eri-Shlevin et al. 2012), showing location of study area (Wadi Zaghra).
the Feiran-Solaf metamorphic complex that may be linked to the Najd Fault System.

Rock assemblages within the Eastern Desert–Sinai terranes are subdivided into (1) a structurally lower unit composed of medium- to high-grade ortho and paragneisses (infrastructure or Tier 1; (2) a tectonically overlying supracrustal unit composed of greenschist-grade island-arc assemblages (suprastructure or Tier 2); and (3) plutonic rocks of differing ages that variably intrude the lower and the supracrustal units (Sturchio et al. 1983). Banded iron formations (BIFs) and diamicotics, interpreted as having a glacial origin, appear locally within the island-arc assemblages (Ali et al. 2010; Stern et al. 2011). A regionally extensive sub-horizontal shear zone separates the infrastructural and supracrustal units (Andresen et al. 2010), corresponding to Tier 1 and Tier 2, respectively, in the Eastern Desert of Egypt (Habib et al. 1985a, 1985b; El-Gaby et al. 1988; El-Gaby et al. 1990). Folding/deformation of the shear zone, either synchronously with shearing or post-dating it, exposes the infracrustal rocks in a series of gneiss domes or ‘metamorphic core complexes’. Their modes of formation have been discussed by Sturchio et al. (1983), Greiling et al. (1988), Wallbrecher et al. (1993), Fritz et al. (1996), Loizenbauer et al. (2001), Fowler and El Kalioubi (2002), and Andresen et al. (2009, 2010). Kinematic observations along the shear zone show tectonic transport of the low-grade supracrustal rocks (nappe) towards the northwest. Both units are intruded by variably deformed granitoids ranging in age from ca. 700 to 610 Ma (e.g. Lundmark et al. 2012; Abu El-Enen and Whitehouse 2013) and they are transected by NW-striking faults linked to the Najd Fault System.

Clearly younger than the island-arc assemblages are distinctly less deformed Ediacaran sedimentary and volcanic sequences, referred to as post-amalgamation deposits. These late orogenic sedimentary and volcanic rocks are commonly referred to as the Hammamat Group and Dokhan Volcanics, respectively, in the Eastern Desert (Wilde and Youssef 2000, 2002). The two lithologies appear to be interbedded in some basins (El-Gaby et al. 1990; Eliwa et al. 2010; Johnson et al. 2011). There is little agreement on the structural control and age of deposition of the various post-amalgamation deposits within the Eastern Desert terrane. Correlation between post-amalgamation basinal deposits in the Eastern Desert and those on the Arabian side of the Red Sea is even more speculative, mostly due to the lack of robust geochronological data (e.g. Nasiri Benzenjani et al. 2014). One area where the depositional age of the post-amalgamation basin deposits is fairly well constrained is the type area for the Hammamat sediments (along the asphalt road between Qena and Qesier). The undeformed Um Had granite, which intrudes the folded Hammamat sediments in this area, has a U-Pb (TIMS) zircon age of 590 ± 3.1 Ma (Andresen et al. 2009). The older age of the sediments is constrained by deformed intrusive rocks yielding a crystallization age of 606 ± 1 Ma (Andresen et al. 2009). An age of 585 ± 13 Ma for the youngest detrital zircon in the Hammamat Group at Gebel Umm Tawat, North Eastern Desert, supports this interpretation (Wilde and Youssef 2002). In this latter study, detrital zircons with ages ranging between ca. 750 and ca. 2630 Ma were also found, indicating contributions from Proterozoic and Archaean sources unknown in the North Eastern Desert.

The age and tectonic setting of the Dokhan Volcanics is also controversial (Ghobrial and Lofti 1967; Stern and Hedge 1985; Stern and Gottfried 1986; Abdel-Rahman and Doig 1987). The most recent robust U-Pb ages from the type area of Gebel Dokhan were reported by Wilde and Youssef (2002), who dated a grey andesite in the lower part of the section to 602 ± 9 Ma and pink andesite (‘imperial porphyry’) around. 400 m higher up in the sequence to 593 ± 13 Ma (SHRIMP U-Pb on zircon), corroborating contemporaneous deposition of the Hammamat sediments and the Dokhan Volcanics. Geochronological data from the Hammamat sediments and Dokhan Volcanics thus indicate a relatively short time interval for the deposition of the two units. More recently, Breitkreuz et al. (2010) reported U-Pb zircon SHRIMP ages for 10 ignimbrites and 2 subvolcanic dacitic bodies, mapped as Dokhan Volcanics, from the Ras Gharib basement segment in the North Eastern Desert of Egypt. Inferred crystallization ages from these volcanics range between 592 ± 5 and 630 ± 6 Ma (early Ediacaran). These authors argued that late consolidation of the ANS was accompanied by the evolution of isolated volcanic centres and basins developed during a 40 million year time interval, independent in time and space, and probably under changing tectonic regimes. Furthermore, they proposed that Ediacaran volcanism in the Eastern Desert occurred in two main pulses – 630–623 and 618–592 Ma. To explore the idea that post-amalgamation basinal deposits and volcanism spanned 40 million years as proposed by Breitkreuz et al. (2010), we studied metadiamicrites and the biotite-schists of the Zaghrá Formation, part of the Sa‘al-Zaghra metamorphic complex in central Sinai, a region where late Mesoproterozoic to early Neoproterozoic island-arc systems have been identified (Stern et al. 2010a; Be’eri-Shlevin et al. 2012; Eyal et al. 2014).

3. Pre-phanerozoic geology of Sinai and the study area

The Precambrian basement in southern Sinai is composed of several metamorphic complexes (Sa‘al-Zaghra, Kid, Feiran-Solaf, Tab’a/Elat) engulfed by younger, mostly non-metamorphosed intrusive rocks, and several Ediacaran volcano-metasedimentary sequences (Be’eri-Shlevin et al. 2011). The metamorphic complexes are composed of ortho- and paragneisses and schists.
metamorphosed at greenschist to amphibolite facies conditions (see review in Eyal et al. 2014). Protolith ages range from 850 to 740 Ma, although older island arc rocks, gabbroic sills, and metapsammitic gneisses (ca. 1.0–1.1 Ga) have been recently reported from the Sa’al-Zaghra and Feiran-Solaf metamorphic complexes (Be’eri-Shlevin et al. 2012; Abu El-Enen and Whitehouse 2013; Eyal et al. 2014). Orthogneisses with ages between 660 and 630 Ma are also common (Ali et al. 2009; Be’eri-Shlevin et al. 2011; Abu El-Enen and Whitehouse 2013; Eyal et al. 2014) (Figure 1). The surrounding intrusive rocks are mostly calc-alkaline plutons emplaced from 635 to 590 Ma. The terminal phase of calc-alkaline magmatism overlapped in time with alkaline magmatism. The alkaline phase lasted from ca. 608 to 580 Ma (Be’eri-Shlevin et al. 2009), this being characterized by bimodal alkaline volcanism and intrusion of epizonal A-type granites and dike swarms (Katriz et al. 2007; Samuel et al. 2007; Eyal et al. 2010).

The Ediacaran volcano-sedimentary successions of Sinai (Khashabi, Iqna-Sharà, Kid-Malhak, Ferani, Rutig, Sa’al-Zaghra) are dominated by intermediate to silicic calc-alkaline volcanic deposits, which are interbedded with minor volumes of conglomerate, diamictite, and sandstone (Moussa 2003; Azer 2007; Be’eri-Shlevin et al. 2011; Samuel et al. 2011). Recent geochronological data from the Ferani and Rutig successions indicate that basin formation took place in two phases – an older phase between 630 and 615 Ma and a younger one between 615 and 590 Ma. A period of folding and erosion separates the lower and upper Rutig successions, displayed as an angular unconformity (Be’eri-Shlevin et al. 2011).

The Wadi Kid Group is another volcano-sedimentary succession in southern Sinai that has been extensively studied (Shimron 1984; Furnes et al. 1985; Blasband et al. 1997, 2000; Abu El-Enen et al. 2003; Abu El-Enen 2008; Fowler et al. 2010a, 2010b). The most recent geochronological study (Moghazi et al. 2012) indicates that the volcano-sedimentary succession (Kid Group) was deposited in the time interval 615–605 Ma, most likely in a rift basin (Blasband et al. 1997, 2000; Brooijmans et al. 2003). The geochemistry of the volcanic rocks interbedded with the sediments shows great similarities to the temporally equivalent Dokhan Volcanics in their type area (Moghazi et al. 2012). An age of 615–605 Ma indicates furthermore that the volcanism is contemporaneous with the youngest pulse of volcanic activity in the North Eastern Desert (Breitkreuz et al. 2010).

A third volcano-sedimentary succession within the Precambrian basement of Sinai is represented by the Sa’al-Zaghra metamorphic complex (SZMC) (Figure 1b). The supracrustal rocks within SZMC, grouped together as the Sa’al Group by Shimron et al. (1993), comprise three formations – the Agramyia, the Ra’ayan, and Zaghra. This subdivision is based on differences in lithology, age, and metamorphic grade, as the contact between the three formations is tectonic or cut by younger post-depositional intrusive rocks (Eyal et al. 2014). Geochronological data on the Agramyia Formation, composed mainly of metabasic and metaandesitic flows and pyroclastics (around 1300 m) and around 1000 m of metarhyolite-ignimbrite, indicate depositional ages of ca. 1.03 and 1.02 Ga, respectively (Be’eri-Shlevin et al. 2012; Eyal et al. 2014) – clearly older than the Hammamat Group and the Dokhan Volcanics. The Ra’ayan Formation, exposed in the northwestern and central parts of the Sa’al-Zaghra metamorphic complex, is dominated by amphibolite facies schists at its base overlain by greywackes with interbedded conglomerates (Eyal et al. 2014). Detrital zircons from the Ra’ayan Formation indicate deposition after 0.95 Ga based on the age of the youngest zircon. Rb-Sr whole-rock dating of the Zaghra Formation is unclear, although some preliminary radiometric ages between 873 ± 16 Ma and 736 ± 22 Ma (Abu Anbar et al. 2009).

The Zaghra Formation crops out in two main areas in the southern part of the Sa’al-Zaghra metamorphic complex (Shimron et al. 1993; Eyal et al. 2014; Hassan et al. 2014). The northern area is dominated by volcanic deposits (tuffs and lapilli tuffs), whereas the southern outcrop area around Wadi Zaghra consists of a succession of interbedded feldspathic sandstones, conglomerate, diamictite, and schists (Hassan et al. 2014). The sediments in the southern outcrop area of the Zaghra Formation are folded and metamorphosed under greenschist facies conditions, locally transforming the pelitic units into biotite-schists (Shimron et al. 1993; Mehanna et al. 2001; Hegazi et al. 2004). The combined effect of deformation and metamorphism makes it difficult to estimate the depositional thickness and age relationship between the different lithological units within the Zaghra Formation. A distinctly higher metamorphic grade (370–420°C and around 3 kbar) is recorded in large parts of the schistose tuffs comprising the northern outcrop areas of the Zaghra Formation (Hassan et al. 2014). The depositional age of the Zaghra Formation is unclear, although some preliminary geochronological data on detrital zircons from the southernmost, isolated, outcrop area of the formation indicate deposition after 606 ± 10 Ma (Stern et al. 2010a). This interpretation is clearly in conflict with the interpretation of Hassan et al. (2014), who argue that the age of metamorphism of the Zaghra tuffs is related to a late Mesoproterozoic fragment of Rodinia.

The samples and data presented below are from the same outcrop area (Wadi Zaghra) as those studied by Stern et al. (2010a) (Figure 2). A steeply dipping, variably foliated matrix-supported metaconglomerate/diamictite appearing on both sides of Wadi Zaghra comprises most of the Zaghra Formation in this area. A thin unit of biotite-schist of unknown stratigraphic position relative to the metaconglomerates and diamictites comprises the
westernmost outcrops area. Mehanna et al. (2001) consider the biotite-schists to be younger than the metaconglomerates. The same authors considered a volcanic and volcanioclastic sequence further towards the northwest (beyond the map area in Figure 2) to represent a still younger unit within the Zaghra Formation, but convincing evidence for these age relationships was not presented. The metaconglomerates (Figure 3a) are typically poorly sorted (diamictites) and contain stretched clasts, predominantly leucogranites or pale pink granites, along with rare volcanic clasts, set in a laminated and weakly foliated sandy matrix of alternating mafic-rich and -poor bands (Figure 3b). The clasts are of different sizes, up to 50 cm long, and stretched parallel to the foliation (Figure 3b). The schist in the western outcrop area is a fine-grained grey to dark grey, weakly foliated rock composed of alternating mafic-rich and -poor layers, interpreted as representing primary bedding (Figure 3c). The foliation, defined by parallel-oriented biotite, sub-parallel to the compositional banding, is oriented WNW–ESE with a variable dip.

The metasediments of the Zaghra Formation appear to be completely engulfed in undeformed magmatic rocks, including diorite-granodiorite, monzogranite, and alkali-feldspar granite emplaced after deformation and development of the cleavage in the metaconglomerate and biotite-schist. Field observations show the diorite-granodiorite making up the western part of the mapped area to be intruded by the monzogranite and alkali-feldspar granite. The alkali-feldspar granite intrudes the monzogranite and is the youngest of the granitoids. Dikes of varying composition cut through all rock types (Figure 3a and e).

The largest of the post-tectonic plutons is the diorite-granodiorite in the western part of the traverse along Wadi Zaghra (Figure 2). It is grey, coarse-grained, and has sharp intrusive contacts against the metaconglomerate and schists and contains enclaves (Figure 3d) and roof pendants of these lithologies. Geochemical data show it to be a calc-alkaline I-type intrusive, most likely formed in an arc-setting (Mehanna et al. 2001). A pink, coarse-grained monzogranite and a buff-coloured, coarse-grained alkali-feldspar granite comprise the area east of the metaconglomerates. The alkali-feldspar granite occurs as an elongated intrusive body (Figure 3f), trending NE–SW along the boundary between the metaconglomerate and diorite-granodiorite to the west, and the monzogranite to the east (Figure 2). Bulk-rock geochemical data for the monzogranite and alkali-
feldspar granite show them to be alkaline A-type granites formed in a within-plate tectonic setting (Mehanna et al. 2001).

4. Samples

To constrain the depositional age of the Wadi Zaghra metaconglomerates, zircons from 11 samples were dated: (1) three igneous metaconglomerate clasts (Z11-11, AA08-52, and Z11-20a); (2) three metaconglomerate matrix samples (ZA-2, and Z11-14, and Z11-20b); (3) a biotite-schist sample (Z11-17); and (4) four samples of plutons post-dating deposition and deformation of the Wadi Zaghra conglomerate (Z11-7, AA08-53, Z11-2, and Z11-3). Sampling sites are shown on Figure 2.

4.1. Igneous clasts in metaconglomerate (AA08-52, Z11-20a, Z11-11)

The three metaconglomerate clasts are medium-grained and weakly foliated plutonic rocks composed of variable proportions of quartz, K-feldspar (microcline and perthite), plagioclase, biotite, muscovite, and accessory Fe-oxides and zircon. Quartz and feldspar occur as medium-grained porphyroclasts and as strained uniform, fine-grained crystals (~0.25 mm in diameter). The feldspar commonly occurs as dynamically recrystallized aggregates (Figure 4a). Medium-grained quartz forms flattened anhedral grains lying parallel to the shearing fabrics, with minor undulose extinction and widely spaced planar fluid inclusion trails. Alkali-feldspar occurs as subgrains of both anhedral microcline and lamellar lenticular perthite (Figure 4a and b). Plagioclase occurs as fine-grained...
subhedral crystals displaying both lamellar and pericline twinning, and is partly altered to sericite. The amount of biotite and white mica vary somewhat: sample AA08-52, for example, contains abundant white mica (Figure 4b). Locally, biotite flakes occur as polycrystalline aggregates, partially retrograded to chlorite. Sample Z11-20b is highly strained, with quartz, feldspars, and biotite aligned parallel to the foliation. All three clasts have undergone partial dynamic recrystallization, indicated by bimodal grain sizes and irregular and lobate grain boundaries of the individually strained quartz and feldspar grains (Passchier and Trouw 2005).

Continuation of the foliation in the clasts into the surrounding matrix without any offset indicates that the foliation in the studied clasts is linked to post-depositional deformation, unrelated to a pre-deposition tectonic event. This does not, however, exclude the possibility that clasts with a pre-depositional deformation fabric exist elsewhere within the Zaghra Formation.

4.2. Conglomerate matrix (ZA-2, Z11-14, Z1120b)
The sandstone/siltstone matrix of the metaconglomerates is highly sheared, foliated, and displays alternating mica-rich
and -poor thin bands (Figure 3b and 4c). The mica-rich bands are finely grained and composed of biotite, quartz, plagioclase, K-feldspar, and opaques (Figure 4c). Biotite, quartz, and feldspar are elongated and oriented parallel to the direction of shearing. The medium-grained, mica-poor bands have more quartz and feldspar and less biotite and opaques than the mica-rich bands. Plagioclase is occasionally altered to sericite, whereas biotite is partially retrograded to chlorite.

4.3. Biotite-schist (Z11-17)
The biotite-schist from which zircon was extracted is fine-grained, grey to dark grey in colour, and exhibits continuous schistosity sub-parallel to bedding (Figure 3c). It is composed of quartz, plagioclase, biotite with accessory magnetite, tourmaline, and zircon. The schistosity is pervasive and defined by a preferred orientation of biotite and feldspars. The mineral assemblage indicates middle to upper greenschist facies metamorphic conditions.

4.4. Post-depositional intrusive rock (Z11-7, AA08-53, Z11-2, Z11-3)
The diorite-granodiorite samples (Z11, AA08-53) are medium-grained, grey with an equigranular texture, and are without foliation. They display a hypidiomorphic-granular texture composed of zoned plagioclase, biotite, and hornblende (Figure 4e), with variable amounts of quartz. Prismatic crystals of plagioclase are commonly compositionally zoned, whereas biotite forms euhedral to rarely subhedral flakes. Accessory minerals include Fe-oxides, apatite, zircon, titanite, and allanite. Interstitial microcline and quartz are present in the granodiorites.

The monzogranite sample (Z11-2, Figure 2) is coarse-grained, pinkish to light grey, and with a granular texture. The minerals present are quartz, plagioclase, microcline, perthite, and biotite, with accessory Fe-oxide, apatite, zircon, titanite, and allanite. The monzogranite differs from the diorite-granodiorite in the lack of amphibole and a greater abundance of microcline and quartz. It exhibits a hypidiomorphic texture, with a dominance of alkali feldspar over plagioclase, and contain, 5–7 vol.% long, subhedral biotite flakes (Figure 4f). Quartz and alkali-feldspar occur as anhedral, interstitial grains with alkali feldspar exhibiting irregular vein-patch perthite texture.

The red, medium- to coarse-grained alkali-feldspar granite sample (Z11-3) exhibits a granular texture, and consists of albite, K-feldspar (microcline perthite and microcline), and quartz as the predominant minerals, with accessory muscovite, biotite, garnet, Fe-oxides (Figure 5f), and apatite. Garnet occurs as euhedral to subhedral grains (Figure 5f) and locally contains quartz inclusion trails, or forms fine-grained glomeroporphyritic

Figure 5. U-Pb concordia diagrams presenting LA-ICP-MS zircon analyses from Wadi Zaghra, Sinai, Egypt: (a) data for metaconglomerate leucogranite clast Z11-11; (b) data for metaconglomerate leucogranite clast AA08-52; and (c) data for metaconglomerate granite clast Z11-20a. Dashed ellipses indicate zircon analyses that were excluded from age calculations. Analytical data are given in Table A1 (see online supplemental material at http://dx.doi.org/10.1080/00206814.2014.907755).
aggregates. Albite occurs as long, prismatic laths, whereas microcline and perthite occur interstitially to the plagioclase. Quartz occurs in anhedral grains with embayed boundaries and locally engulfs plagioclase and K-feldspar grains. Biotite and muscovite flakes occur together as patches, commonly coexisting with garnets.

5. Analytical methods

Zircons for U-Pb geochronology were extracted from crushed and sieved material from fist-sized rock samples (~1 kg), using a Wilfli Table and heavy liquids. Magnetic separation was not used on the metasedimentary samples, only on material from the granitoid clasts and post-depositional intrusive rock. Zircons from the granitoid clasts and intrusive rocks were handpicked from the least magnetic fraction using a binocular microscope. Selection of detrital zircons from the matrix was random, to avoid any bias. The handpicked zircons were mounted in an epoxy puck and polished to reveal the grain centres. Cathodoluminescence (CL) studies to examine the growth structure of individual grains were carried out on the polished puck using a scanning electron microscope. U and Pb isotope data on zircons were obtained by laser-ablation inductively coupled plasma source mass spectrometry (LA-ICP-MS) using a Nu Plasma HR mass spectrometer and a New Wave LUV213 laser microprobe at the Department of Geosciences, University of Oslo. The analytical protocols are described in detail by Rosa et al. (2009) and Andersen et al. (2009). The 1065 ± 0.6 Ma (2σ) Geostandards zircon 91500 (Wiedenbeck et al. 1995) and 600 ± 4.5 Ma (2σ) Geostandards GJ-1 (Jackson et al. 2004) were both used for Pb/U calibration and U concentration estimates, and analysis was performed on a regular basis during the analytical sessions. A total of 423 spots on grains of unknown age were analysed. The results and analytical uncertainties were presented on a concordia diagram (Figure 6a). Four spots are discordant and two spots (2 and 20) do not cluster with the majority of the grains and yield a 206Pb/238U age of ~640 Ma but with large error, possibly due to lead loss. Spot 3 yields a discordant 206Pb/238U age of 626 ± 4 Ma, which is younger than the other analyses, whereas, spot 15b records an older 206Pb/238U age (668 ± 3 Ma) than the other analyses. The remaining 11 concordant analyses yield a 206Pb/238U weighted mean age of 651 ± 2 Ma (MSWD = 0.15). This age is interpreted to represent the crystallization age of the granitoid from which this clast was derived, and is indistinguishable from the age of sample Z11-11.

Sample Z11-20a (28°37′29.28″ N; 34°07′54.24″ E) was taken from a large clast (30 cm across) of medium-grained pink granite in a laminated matrix. One measurement was made on each of 12 zircons (Table A1, supplemental material), and these are presented on a concordia plot (Figure 5b). Three spots are discordant and are not discussed further. Spot 31 yields the oldest 206Pb/238U age (674 ± 6 Ma) and has a high U content (3076 ppm). The remaining 11 analyses yield a 206Pb/238U weighted mean age of 647 ± 3 Ma (MSWD = 1.09), interpreted to represent the crystallization age of the granitoid from which the clast was derived.

Sample AA08-52 (28°38′29.28″ N; 34°09′51.57″ E) is a medium-grained, non-foliated leucogranite clast, approximately 25 cm across, enclosed in a weakly foliated diamicite matrix. Zircons are mostly euhedral to subhedral and pale brown in colour. One measurement was made on each of 19 zircons (Table A1, supplemental material) and these are presented on a concordia plot (Figure 5b). Four spots are discordant and two spots (2 and 20) do not cluster with the majority of the grains and yield a 206Pb/238U age of ~640 Ma but with large error, possibly due to lead loss. Spot 3 yields a discordant 206Pb/238U age of 626 ± 4 Ma, which is younger than the other analyses, whereas, spot 15b records an older 206Pb/238U age (668 ± 3 Ma) than the other analyses. The remaining 11 concordant analyses yield a 206Pb/238U weighted mean age of 651 ± 2 Ma (MSWD = 0.41; Figure 5b). This age is interpreted as the crystallization age of the granitoid from which this clast was derived, and is indistinguishable from the age of sample Z11-11.

6. Results

6.1. Metaglomerate clasts

Sample Z11-11 (28°38′29.47″ N; 34°09′49.36″ E) is a fine-grained leucogranite clast (20 cm) with weak foliation, enclosed in a weakly foliated diamicite matrix. One measurement was made on each of 16 zircon grains (Table A1, supplemental material), and these are presented on a concordia diagram (Figure 5a). Four spots are discordant and are not discussed further. Spot 31 yields the oldest 206Pb/238U age (674 ± 6 Ma) and has a high U content (3076 ppm). The remaining 11 analyses yield a 206Pb/238U weighted mean age of 647 ± 3 Ma (MSWD = 1.09), interpreted to represent the crystallization age of the granitoid from which the clast was derived.

Sample ZA-2 (28°37′54.72″ N; 34°07′54.24″ E) was collected from a small metaconglomerate outcrop (Figure 2). Two samples (ZA-2 and Z11-14) were collected from the same outcrop, approximately 320 m apart, whereas the third sample (Z11-20b) was collected from a small metaconglomerate outcrop ~3.6 km to the west of the other two (Figure 2).

Sample ZA-2 (28°37′28.66″ N; 34°09′50.58″ E) is a fine-grained metasandstone representing the matrix that encloses the 20–30 cm-long granitoid clasts. Analyzed zircons are mostly euhedral to subhedral, but locally rounded and pale brown in colour, some grains showing marginal pitting. One measurement was made on each of 77 zircons (Table A1, supplemental material), and the results are presented on a concordia plot (Figure 6a).
Figure 6. U-Pb concordia diagrams presenting LA-ICP-MS zircon analyses from Wadi Zagha, Sinai, Egypt: (a) data for metapsammitic matrix of the metaconglomerate sample ZA-2; (b) probability plot of U-Pb zircon data of sample ZA-2; (c) data for laminated siltstone matrix of the metaconglomerate sample Z11-20b; (d) probability plot of U-Pb zircon data of sample Z11-20b; (e) data for metapsammitic matrix of the metaconglomerate sample Z11-14; (f) probability plot of U-Pb zircon data of sample Z11-14; (g) data for sample Z11-17 from a biotite schist in the western part of the study area; and (h) probability plot of U-Pb zircon data of sample Z11-17. Dashed ellipses indicate zircon analyses that were excluded from age calculations and probability curves for zircon data <5% discordant. Analytical data are given in Table A1 (supplemental material).
Twenty-two zircon grains are more than 5% discordant and are not discussed further. The age of 55 grains passes the concordancy test (<5% discordance) and the obtained ages range from 1001 ± 10 to 615 ± 4 Ma (Figure 6a and b). Only one concordant grain has an age younger than 620 Ma, but there are several concordant grains in the age range 630–620 Ma. Marked peaks in the relative probability plots are seen at around 0.80 Ga, 0.75 Ma, and 0.63 Ga. Analysis of one grain yields a concordant $^{207}$Pb/$^{206}$Pb age of ~1.0 Ga.

Forty-four zircon grains are discordant and are not discussed further. Ages of the remaining 61 grains that pass the concordancy test (<5% discordance) range from 1112 ± 11 to 622 ± 9 Ma (Figure 6c and d), and define three peaks in the relative probability plot at around 1.0, 0.75, and 0.65 Ga. Seven analyses yield concordant $^{207}$Pb/$^{206}$Pb ages >1.0 Ga (Table A1, supplemental material).

Sample Z11-20b (28°37′54.72″ N; 34°07′54.24″ E) is a laminated siltstone. One measurement was made on each of 105 zircons (Table A1, supplemental material), and these are presented on a concordia plot (Figure 6c). Forty-four zircon grains are discordant and are not discussed further. Ages of the remaining 61 grains that pass the concordancy test (<5% discordance) range from 1112 ± 11 Ma to 622 ± 9 Ma (Figure 6c and d), and define three peaks in the relative probability plot at around 1.0, 0.75, and 0.65 Ga. Seven analyses yield concordant $^{207}$Pb/$^{206}$Pb ages >1.0 Ga (Table A1, supplemental material).

Sample Z11-14 (28°38′35.99″ N; 34°09′52.83″ E) is also a laminated siltstone. One measurement was made on each of 45 zircons (Table A1, supplemental material), and these are presented on a concordia plot (Figure 6c). Four zircon grains are discordant and are not discussed further. The age of 39 grains passes the concordancy test (<5% discordance) and their ages range from 962 ± 11 to 628 ± 5 Ma (Figure 6c and d). Spot 11 yields a concordant $^{207}$Pb/$^{206}$Pb age of ~1.0 Ga.

Sample Z11-17 (28°38′35.82″ N; 34°08′54.83″ E) is a biotite schist that contains mostly euhedral to subhedral zircons, although some are rounded. One measurement was made on each of 33 zircons (Table A1, supplemental material), and these are presented on a concordia plot (Figure 6g). Seven zircon grains are discordant and are not discussed further. The age of the remaining 26 grains passes the concordancy test (<5% discordance) and their ages range from 1017 ± 15 to 649 ± 7 Ma. Although the limited number of analyses makes statistical analyses highly uncertain, the probability plot (Figure 6h) indicates peaks at ca. 680, 800, and possibly 745 Ma. Based on the above data, it is concluded that the pelitic protolith was deposited after ~650 Ma.

### 6.3. Post-depositional intrusive rocks

**Sample Z11-7** (28°38′28.81″ N; 34°09′58.43″ E) is a diorite that intrudes the metaglomerates. One measurement was made on each of 19 zircons (Table A1, supplemental material), and these are presented on a concordia plot (Figure 7a). Six spots are discordant and are not discussed further. Spot 23 yields a concordant $^{206}$Pb/$^{238}$U age of 630 ± 8 Ma but shows high U content (1311 ppm), whereas Spot 4 records an older concordant $^{206}$Pb/$^{238}$U age of 768 ± 8 Ma. This is older than the other analyses and is interpreted as representing a xenocryst. The remaining 11 analyses yield a $^{206}$Pb/$^{238}$U weighted mean age of 614 ± 4 Ma (MSWD = 0.25), which is taken to be the crystallization age of the diorite.

**Sample AA08-53** (28°38′23.17″ N; 34°10′16.03″ E) is a diorite sample from the same intrusive complex as sample Z11-7. Zircons are mostly euhedral to subhedral and pale brown in colour. One measurement was made on each of 12 zircons (Table A1, supplemental material), and these are presented on a concordia plot (Figure 7b). Two analyses are discordant and are not discussed further. Two spots (11 and 14) are concordant and yield $^{206}$Pb/$^{238}$U ages of 612 ± 6 and 598 ± 7 Ma, respectively, but with high common Pb (1.6 and 1.1%, respectively). One analysis (spot 4) yields a concordant $^{206}$Pb/$^{238}$U age of 621 ± 6 Ma, which is younger than the other analyses. The remaining seven analyses yield a $^{206}$Pb/$^{238}$U weighted mean age of 631 ± 4 Ma (MSWD = 0.29). This age is older than that obtained for sample Z11-7 (614 ± 4 Ma), interpreted to be from the same pluton, and also older than several detrital zircons in the conglomerate it intrudes. The age is, however, identical to the age of 632 ± 3 Ma obtained for the Sa’al granitic gneiss located around 5 km north-northeast of our sampling locality (Eyal et al. 2014). The data allow two alternative interpretations: (1) samples AA08-53 and Z11-7 are from two different plutons, or (2) the 631 Ma zircons represent xenocrysts in a 614 Ma post-tectonic intrusion. The two alternatives are discussed further below.

**Sample Z11-2** (28°38′0.01″ N; 34°10′50.53″ E) is from a coarse-grained monzogranite east of the diorite intrusion (Figure 2). One measurement was made on each of 57 zircons (Table A1, supplemental material), and these are presented on a concordia plot (Figure 7c). Most of the analyses are discordant (~56%). Two concordant spots (20 and 28) yielded younger $^{206}$Pb/$^{238}$U ages of 578 ± 7 and 592 ± 8 Ma than the remaining concordant analyses, but record high common Pb of 1.6 and 1.1%, respectively. The remaining 23 analyses are concordant and yield $^{206}$Pb/$^{238}$U ages from 605 ± 7 to 651 ± 9 Ma (Figure 7c). The age of 651 ± 9 Ma is interpreted as being inherited from older granitoids that are common in the area, whereas, the 605 ± 7 Ma age is taken to be the crystallization age of the monzogranite, which is slightly younger than the diorite ages (614 ± 4; 631 ± 4 Ma).
The zircons show significant lead loss (50% of the analyses are discordant; Figure 7d). Fourteen analyses yield $^{206}\text{Pb}/^{238}\text{U}$ ages from 622 ± 6 to 778 ± 9 Ma (Figure 7d), with a cluster of eight analyses defining an age of 744 ± 6 Ma. Two other concordant zircons define an age of 626 ± 9 Ma. The large number of discordant grains makes it difficult to obtain an absolute emplacement/crystallization age for the alkali-feldspar-granite. Field observations, including the intrusive relationship with the sediments, and lack of ductile deformation structures demonstrate that it was emplaced after deposition and deformation of the metacoglomerates. Our preliminary interpretation is that the emplacement age is 622 ± 6 Ma.

7. Discussion

7.1. Depositional age and provenance of the Zaghra Formation

The depositional age of the metasediments making up the southern outcrop area of the Zaghra Formation in southern Sinai has to be younger than the age of the youngest granitoid clasts and concordant detrital zircon in the conglomerate matrix. The youngest clast in the metacoglomerates is the pink, medium-grained granite clast dated to 640 Ma, constraining the depositional age to be younger than this age. Several detrital zircons in sample ZA-2 have concordant $^{206}\text{Pb}/^{238}\text{U}$ ages between 625 and 620 Ma, constraining the depositional age of the Zaghra Formation to be <625 Ma. Detrital zircon ages from the
biotite-schist differ slightly from the zircon age populations seen in the matrix of the conglomerate, in that all the detrital zircons are older than 650 Ma. One interpretation of this is that the protolith age of the biotite-schist is greater than the studied metaconglomerates, possibly deposited in a separate basin. An alternative and more attractive explanation for the apparent difference in zircon age population between the biotite-schist and metaconglomerates could be the difference in source areas, combined with differences in depositional environments, the schists being composed of more distal (far-travelled) detritus than the metaconglomerates. It should, however, be kept in mind that the number of zircon analyses from the biotite-schist is limited.

The Zaghra Formation in the study area must have been deposited before the granitoids that intruded it. The most reliable emplacement age on the oldest post-depositional granitoids comes from diorite-sample Z11-7, with an emplacement age of 614 ± 4 Ma. The apparent difference in age between this sample and the majority of concordant zircons ages obtained from sample AA08-53 is enigmatic, as in the field they both are interpreted to be from the same pluton. Whereas 11 concordant zircons from sample Z11-7 indicate an emplacement age of 614 ± 4 Ma, the majority (7) of concordant ages from sample AA08-53 cluster around 631 ± 4 Ma. Concordant ages of 598 ± 7 and 612 ± 6 Ma are, however, also present in this sample. Despite the cluster of concordant ages around 631 Ma, we do not interpret this as the emplacement age of the pluton for two reasons: (1) the presence of detrital zircons with ages from 630 to 620 Ma in the metaconglomerate matrix/country rock to the pluton and (2) the large number of concordant zircons with an age of 614 ± 4 Ma from the same pluton (sample Z11-7). The seven concordant zircons defining an age of 631 ± 4 Ma are therefore considered to be xenocrysts in a younger pluton. A likely source rock for these xenocrystic zircons could be the Za’al gneiss-granite, located approximately 5 km from our study area, and dated to 632 ± 3 Ma (Eyal et al. 2014). An emplacement age of 614 ± 4 Ma is thus inferred for the oldest igneous rock intruding the deformed Zaghra Formation. This magmatic age, in combination with the age of the detrital zircons in the metaconglomerates matrix, restricts deposition of the Zaghra Formation exposed along Wadi Zaghra to the time interval from 622 ± 9 to 614 ± 4 Ma. In addition to being deposited in this short time interval, the Zaghra Formation was also buried to greenschist facies conditions and folded. This is consistent with the older metamorphic event at 627 ± 7 Ma reported by Abu El-Enen and Whitehouse (2013) in the Feiran-Solaf metamorphic complex. The inferred crystallization age of 605 ± 7 Ma on the coarse-grained alkali-feldspar granite (sample Z11-3), intruding both the diorites, represented by samples Z11-7, AA08-53, and the monzogranite intrusion (Z11-2), supports the field relationships showing that this pluton is the youngest granitoid rock in the area.

It is important to note that a gneissic-granite intruding another volcano-sedimentary succession in the upper part of Wadi Moqfe, considered as part of the Zaghra Formation and located around 5 km northeast of the study area, has an emplacement age of 631 ± 4 Ma (Eyal et al. 2014). If the ages for the post-depositional intrusive rocks (632 and 614 Ma) both represent emplacement ages, it follows that the sediments exposed in Wadi Moqfe are older than those exposed in Wadi Zaghra and reported here.

A depositional age between 622 and 614 Ma, followed by deformation and greenschist facies metamorphism in the same time interval, is clearly in conflict with the idea of Hassan et al. (2014), who argue that the three formations making up the Sa’il-Zaghra complex (Ra’ayn, Agramyia, and Zagra formation) have undergone only a single metamorphic event (M1) in the time interval 1030–1017 Ma. Their argument is based on the crystallization ages of metatuffs and gabbroic sills by Be’eri-Shelvin et al. (2012). If Hassan et al. (2014) are correct in their interpretation, this implies a depositional age for the Zaghra tuffs prior to 1030 Ma, clearly older than the Zaghra sediments studied here. Keeping in mind that the metamorphic studies on the Sa’il complex by Hassan et al. (2014) are restricted to metamorphosed tuffs from the northern outcrop area of the Zaghra Formation, this may indicate that the two outcrop areas belong to two distinctly different supracrustal sequences. It should also be kept in mind that the age constraints on the metamorphism reported by Hassan et al. (2014) are based on geochronological data from the Ra’ayn and Agramyia formations, not the Zaghra Formation itself. Until geochronological data are available from the northern outcrop area of the Zaghra Formation, we prefer to interpret deformation and metamorphism of the formation to have taken place in the time interval 622–614 Ma.

The geochronological data presented above demonstrate a time gap of almost 400 million years between deposition of the Agramyia and Ra’ayan formations (Eyal et al. 2014) and the Zaghra Formation. This time gap indicates that the former two volcano-sedimentary formations belong to the island-arc stage (Eyal et al. 2014), whereas the Zaghra Formation was deposited in one of the many post-amalgamation basins present throughout the ANS (Johnson et al. 2011). One can only speculate that an extensional shear zone separates the Agramyia and Ra’ayana formations from the Zaghra Formation, and that the latter was deposited in grabens controlled by the rider faults of this inferred detachment zone, comparable to what has been proposed for the relationship between the Hammamat sediments and Meatiq gneiss dome in the Eastern Desert (Andresen et al. 2010).
The inferred depositional age of the Zaghra Formation, restricted to the time interval 622–614 Ma, is comparable to the depositional ages obtained for the lower part of the Rutig succession but clearly older than the age of the Ferani succession (Figure 2). (Samuel et al. 2011; Be’eri-Shlevin et al. 2012; Eyal et al. 2014).

7.2. Implications for ANS crustal evolution

The geochronological constraints presented here, as well as those in several other recent publications, demonstrate that the early Ediacaran was a period of considerable relief in the northern ANS, as indicated by the deposition of poorly sorted conglomerates/diamicrites associated with thick sequences of volcanic and volcanioclastic deposits. The age of the various clasts, particularly the cobble- and pebble-sized clasts, provides valuable information about the various rocks exposed in the source areas for the basinal deposits, and thus information about older episodes of volcanic and magmatic activity (Table A1, supplemental material). The igneous clasts in the Zaghra Formation indicate exposure of two magmatic rocks in the vicinity of the Zaghra basin, a ca. 650 Ma diorite and a ca. 640 Ma granite. The presence of these two suites is also seen in the detrital zircon age data from the conglomerate matrix. The matrix data indicate additional periods of magmatic/volcanic activity in Sinai at ca. 750, ca. 770, ca. 800, and ca. 1000 Ma, comparing well with recent geochronological data from the Feiran-Solaf metamorphic complex, located around 60 km east of Wadi Zaghra (Abu El-El Enen and Whitehouse 2013) and elsewhere in Sinai (Eyal et al. 2014). Zircons sourced from 670, ca. 800, and 850 Ma rocks are also present in the biotite-schist. However, the zircon age populations of the Wadi Zaghra biotite-schist differ from those of the Sa’al schist, which has no zircon younger than 930 Ma (Be’eri-Shlevin et al. 2009, 2012). The latter thus belongs to a much older island-arc sequence (Eyal et al. 2014), unrelated to the post-amalgamation basins of the ANS.

Most of the zircon age peaks recognized in the conglomerate matrix data are also present in the detrital zircon age data from the Rutig volcano-sedimentary sequences (Samuel et al. 2011), and the Um Zariq and Malhaq metasediments of the Wadi Kid area (Moghazi et al. 2012). Also, the Cambrian–Ordovician and Cretaceous sediments that unconformably overlie the ANS rocks have the same peaks as those seen in the Zaghra Formation, in addition to the 600 Ma and younger zircons (Avigad et al. 2003; Kolodner et al. 2006, 2009).

The reported zircon age peaks in the probability plots for the Zaghra Formation samples have counterparts in dated igneous and volcanic rocks found elsewhere in Sinai and the Eastern Desert of Egypt. Of particular interest is the recent documentation of metavolcanic and metagneous rocks with robust crystallization ages older than 800 Ma – rocks not known in the Eastern Desert of Egypt. The presence of late Mesoproterozoic to early Cryogenian crust is well documented from the Sa’al metamorphic complex (Figure 2) by Be’eri-Shlevin et al. (2012) and Eyal et al. (2014), and for the Feiran-Solaf metamorphic complex (Figure 2) by Abu El-Enen and Whitehouse (2013) (Figure 8). The extent of Mesoproterozoic crust in the otherwise juvenile Neoproterozoic ANS appears to be limited to northern basement exposures in Sinai. Be’eri-Shlevin et al. (2010) have shown that the Nd-Sr-Hf-O isotope signature of younger igneous rocks in the northwestern part of the ANS is different from that seen elsewhere in the ANS.

One question as yet unanswered regarding detrital zircons from the Zaghra Formation is the origin of the few grains older than 1.0 Ga seen in our analysed material. This can be explained either by inheritance from a contaminated mantle source region or the incorporation of sediment shed from surrounding Archaean and Palaeoproterozoic cratons (Ali et al. 2009; Stern et al. 2010b; Be’eri-Shlevin et al. 2012). Ali et al. (2010) reported U-Pb zircon ages from metaconglomerate clasts and matrix in the Atud diamicrite of the Central Eastern Desert of Egypt ranging from 1017 ± 20 Ma to 2943 ± 27 Ma. These metaconglomerates were deposited not long after ~750 Ma, and were interpreted as being deposited during a glacial episode (Ali et al. 2010) near a continental margin (Abu El Ela 1990; Akaad et al. 1996). The Atud metasediments are definitely older than the Zaghra Formation and other Ediacaran conglomerates (Ali et al. 2010). A pre-amalgamation island-arc setting seems likely for this sedimentary succession.

Many post-amalgamation deposits in the ANS are correlated with the Hammamat succession, with a depositional age between 606 and 590 Ma (Wilde and Youssef 2000, 2002; Andresen et al. 2009). A depositional age between ca. 622 and 614 Ma for the Zaghra Formation, as argued here, shows that the two units are not temporally equivalent. The Zaghra Formation therefore was most likely deposited in one of the many isolated post-amalgamation basins that developed in the ANS following collision between East and West Gondwana in late Cryogenian–Ediacaran time.

The metamorphic grade recognized in the Zaghra Formation appears to be higher than that recorded in the other post-amalgamation basins elsewhere within the ANS (Johnson et al. 2013). This may indicate that the primary depositional thickness of the formation was distinctly greater than that observed in other post-amalgamation basins. An alternative explanation may be that the subsequent deformation involved greater tectonic thickening and more intense Ediacaran deformation in this part of the Arabian Nubian Shield. A combination of both is also possible.
8. Conclusions

New LA-ICP-MS U-Pb ages of zircons from the Zaghra metaconglomerates and post-collision intrusive rocks from Wadi Zaghra led to the following conclusions:

(1) The Zaghra Formation consists of interbedded feldspathic sandstones, conglomerates, and pelites deposited in small basins fed by detritus shed from erosion of slightly older granitoid and volcanic rocks. These observations imply intense tectonic activity and a considerable relief at the time of deposition.

(2) The Zaghra Formation was deposited and deformed after 622 ± 6 Ma, but before 614 ± 4 Ma. This conclusion is based on the youngest concordant zircon ages in the matrix of the Zaghra metaconglomerate and the emplacement age of 614 Ma for a dioritic pluton intruding the metacoglomerate. A late Mesoproterozoic age for the deformation and metamorphism of the Zaghra Formation, as postulated by Hassan et al. (2014), is in direct conflict with our data.

(3) Detrital zircons from the Zaghra Formation have ages indicating magmatic/volcanic activity in northern Sinai at ca. 630 to 650, ca. 770, ca. 800, and ca. 1000 Ma.

(4) The metasediments of the Zaghra Formation exposed in Wadi Zaghra are younger than the other supracrustal sequences (e.g. Sa‘al schists) and island arc sequences making up the Sa‘al metamorphic complex further north.

(5) The ca. 1.0 Ga detrital zircons present in the Zaghra Formation indicate the presence of a late Mesoproterozoic source area in the northern part of ANS.

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Supplemental data

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