U–Pb ID-TIMS dating of igneous and metagneous rocks from the El-Sibai area: time constraints on the tectonic evolution of the Central Eastern Desert, Egypt

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Abstract This paper presents new ID-TIMS U–Pb zircon and titanite ages from the El-Sibai gneiss complex in the Eastern Desert of Egypt. The zircon data support previous studies, indicating that the protoliths of the gneissic (oldest) units in the area were emplaced during the East African orogeny, and do not represent an older pre-Neoproterozoic, reworked cratonic basement. The crystallization ages of three compositionally distinct orthogneiss protoliths are c. 685, 682 and 679 Ma, respectively. A U–Pb titanite age from one orthogneiss overlaps with the protolith age, indicating that the gneisses did not undergo post-magmatic high-temperature metamorphism. The gneissic textures of the rocks are therefore interpreted to reflect syn-emplacment deformation. This, and evidence for static amphibolite facies metamorphism in country-rock metavolcanics, lead us to conclude that the gneisses of El-Sibai do not represent an exhumed middle crustal gneiss dome, but are part of the island arc affined allochthon into which they were emplaced synchronously with NW-ward nappe translation. We also report ages from rocks cross-cutting the gneisses and the surrounding island arc affined assemblages that yield the hitherto youngest robust pre-Cretaceous intrusive ages in the Eastern Desert. The dated rocks are an orthosite and a cross-cutting syenogranite giving ages of c. 541 and 540 Ma, respectively. We consider this late magmatic pulse to be anorogenic, most likely reflecting a separate extensional event involving

asthenospheric upwelling and decompression melting of the mantle.

Keywords East African orogeny · Neoproterozoic · U–Pb Geochronology · Egypt · Eastern Desert · El-Sibai gneisses · Cambrian magmatism

Introduction

The Neoproterozoic East African orogeny was a major crust-forming event in large parts of E and NE Africa, terminating with the collision of East and West Gondwana (Stern 1994). The southern part of the East African Orogen (Mozambique Belt) is dominated by intensely deformed and reworked older crustal rocks (e.g. Meert 2003; Muhongo et al. 2001; Stern 1994). The northern part of the Orogen (NE Africa and western Arabia) is dominated by juvenile Neoproterozoic rocks of the Arabian–Nubian Shield (ANS). The juvenile rocks (e.g. island arcs and volcanoclastic sequences, back arc and fore arc spreading ridges and calc-alkaline intrusives) of the ANS are interpreted by most authors to have formed by processes in and along the margins of the Mozambique Ocean, which separated East and West Gondwana during the Neoproterozoic (Farahat 2010; Gass 1981; Kröner et al. 1994; Stern 1994; Stern et al. 2004). The presence and origin of gneiss complexes (e.g. Megif-Hafafit, Meatiq and El-Sibai) at low or apparently low structural levels in the Eastern Desert of Egypt are however controversial. Some researchers have argued that the gneisses represent tectonic windows into the easterly extension of the Sahara Metacraton, remobilized during the Neoproterozoic East African orogeny (El-Gaby et al. 1990; El-Gaby 1994; Habib et al. 1985; Hassan and Hashad 1990; Khudeir et al. 1995, 2008;

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Sturchio et al. 1983), whereas others have argued that these rocks represent the deeper, higher-grade crustal section of juvenile Neoproterozoic intra-oceanic island arc(s) or continental magmatic arc(s) developed along the eastern margin of the Sahara metacraton (Andresen et al. 2009; Bregar et al. 2002; Kröner et al. 1994; Stern and Hedge 1985; Stern 1994). The most recent geochemical and isotopic data from the Central Eastern Desert (CED) support a juvenile Neoproterozoic origin and age for most even not all plutons and orthogneisses in the gneiss domes in this area (e.g. Andresen et al. 2009; Liégeois and Stern 2010).

The structural evolution of the gneiss complexes in the Eastern Desert is also highly controversial. Greiling et al. (1988) related formation of the Megif-Hafafit domal structure (Fig. 1) to fault-bend folding, whereas Fowler and El Kalioubi (2002) favoured a model involving refolding of sheath folds to explain the appearance of 5 or 6 subdomes in the area. Diapiric rise of late orogenic magmas is a third model which has been proposed to explain the Meatiq and El-Sibai gneissic complexes (Fritz and Messner 1999; Loizenbauer et al. 2001; Neumayr et al. 1998). Another group of authors explain the gneiss complexes as a result of orogen-parallel extension caused by oblique collision (Abd Ell Wahed 2008; Bregar et al. 2002; Fritz et al. 1996, 2002; Walbrecher et al. 1993).

The Meatiq and Megif-Hafafit orthogneiss-dominated complexes, also referred to as the infrastructure, are domal structures with a tectonic boundary separating medium- to high-grade gneisses in the footwall from low-grade metasediments and metavolcanics of island arc and oceanic affinity in the overlying allochthon or superstructure (e.g. Andresen et al. 2009; Fowler and Osman 2008). The El-Sibai gneiss complex has traditionally also been regarded as a gneiss dome (Abd Ell Wahed 2008; Bregar et al. 2002; El-Gaby et al. 1984). Fowler et al. (2007), however, have recently challenged this view and argued that the infrastructural gneisses in the El-Sibai complex represent granitoids intruding the island arc affiliated allochthon synchronously with top-to-the-NW thrusting during nappe assembly. In this contribution we present new U–Pb ID-TIMS data from the El-Sibai complex, further adding to the growing amount of evidence showing that the Arabian–Nubian Shield in the Eastern Desert of Egypt is mainly juvenile, with no exposures of rocks formed prior to the Neoproterozoic East African orogeny. Our data support the interpretation by Fowler et al. (2007) that the El-Sibai gneiss complex is not an infrastructural orthogneiss-dominated dome separated from the island arc affiliated allochthon by a tectonic boundary (like the Meatiq and Megif-Hafafit gneiss domes). We also show that the El-Sibai area was magmatically active until the earliest Cambrian, manifested by the Um Gheigh anorthosite and the Um Gheigh syenogranite which intrude various

Fig. 1 a Simplified geological map of the Arabian–Nubian Shield and the Sahara Metacraton. b Geologic map of the Eastern Desert Egypt. After Liégeois and Stern 2010

gneisses and plutons in the area. The new data thus document magmatic activity in the Eastern Desert almost 50 m.y. later than previously reported and show that juvenile material was added to the crust in the Eastern Desert during a time interval spanning more than 150 m.y.

Geological setting

The Eastern Desert of Egypt (Fig. 1) is to the east dominated by a Neoproterozoic basement and supracrustal complex that westward is unconformably overlain by Cretaceous and younger cover rocks. This basement complex and similar rocks along the Red Sea coast in Saudi Arabia make up the Arabian–Nubian Shield (ANS), representing the northern segment of the Neoproterozoic East African Orogen (Fig. 1). Most ANS rocks in the Eastern Desert are today considered to represent juvenile Neoproterozoic rocks generated in one or more island arcs within the Mozambique Ocean prior to accretion onto the Sahara

metacraton (e.g. Gass 1981; Kröner et al. 1994; Stern 1994). Several gneiss complexes occur throughout the Eastern Desert, exemplified by the high- to medium-grade gneiss domes appearing in the Meatiq and Hafafit areas (Fig. 1). These domes are today accepted by most researchers to represent the exhumed magmatic part of (an) early Neoproterozoic island or continental arc(s). Appearance of a regionally extensive shear zone separating the low-grade island arc volcanics and volcanoclastic sediments from the underlying gneisses in the Central Eastern Desert indicates that this shear zone must either be (1) a crustal scale extensional shear zone or (2) represent a highly disturbed Neoproterozoic basement-cover contact. Both these alternatives can explain the dramatic change in metamorphic grade (e.g. Neumayr et al. 1996) between the gneisses and the island arc affined allochthon (Andresen et al. 2009). Andresen et al. (2010) named the shear zone the Eastern Desert Shear Zone (EDSZ). Other gneiss complexes, e.g. the El-Sibai gneiss complex (Fig. 2), do not show this obvious infrastructure-allochthon tectonostratigraphy, and their structural setting has been the subject of a recent debate (e.g. Bregar et al. 2002; Fowler et al. 2007).

Geology of the El-Sibai area

The first contributions discussing the El-Sibai granitoid gneisses are by Hume (1934), Schumann (1966) and Sabet

(1961). The two first authors speculated that the granitoid gneisses were younger than the low- and medium-grade supracrustals surrounding the gneisses, whereas Sabet (1961) consider all the mafic rocks (both volcanics, metasediments and amphibolites) to be part of one supracrustal sequence. El-Gaby (1994) and El-Gaby et al. (1984) advocated the idea that the gneisses in the Meatiq, Hafafit and El-Sibai domes were all pre-Neoproterozoic infrastructural rocks exposed in the hinge zone/core of one or more NW-trending antiform(s). The structural model proposed by El-Gaby et al. (1984) may be correct, but the protolith age proposed for the gneisses finds little support in the emerging body of new isotope and geochronological data from CED (e.g. Andresen et al. 2009; Liégeois and Stern 2010).

Geological and structural investigations in the El-Sibai area (Fig. 2) have documented an association of (1) arc metavolcanics, metasediments, tectonic melanges, ophiolite fragments and minor intrusions subjected to greenschist-grade metamorphism, and (2) a gneissic association of amphibolite, gneissic diorite, tonalite and granite (Akaad and Abu El Ela 2002; Bregar et al. 2002; Fowler et al. 2007). Both “units” are intruded by variably, but weakly deformed plutons (Akaad and Abu El Ela 2002; Bregar et al. 2002; Fowler et al. 2007).

The El-Sibai area differs from the Hafafit and Meatiq gneiss domes in that a domal or anticlinal structure with

Fig. 2 Simplified geological map of the El-Sibai area. After Fowler et al. (2007). Sample locations are indicated by black circles. WES Wadi El Shush, WUG Wadi Um Gheigh, WAM Wadi Abu Markhat

high-grade gneisses in the core is not present in the El-Sibai area. Such a structure may have been present prior to emplacement of large volumes of younger intrusives and the development of numerous cross-cutting steep shear zones and late brittle faults, but is not easily recognized today. Fowler et al. (2007) interpreted the gneissic association of diorite–tonalite–granite on both sides of Wadi El-Shush (Fig. 2) to represent a synmagmatically deformed tabular intrusion into the island arc affinity units. The same authors considered the syn-kinematic El-Shush tonalite, the Abu Markhat granodiorite, and possibly the Delihimmi granodiorite (Fig. 2) to have been emplaced during this event, dated to around 700–660 Ma based on Pb/Pb ages published by Bregar et al. (2002). The highest metamorphic grade, with migmatization of metasediments and hornblende growth in metavolcanic rocks, is recorded in the island arc affinity rocks associated with foliated metabasite and granitoid intrusions (Fowler et al. 2007). Fowler et al. (2007) related the static amphibolite facies metamorphism to magma emplacement into shear zones developed during NW-ward nappe stacking of island arc assemblages. They furthermore argued that there was no structural break between the granitoid gneisses and adjacent amphibolite facies supracrustal rocks grading into low-grade metasediments away from the orthogneisses. This interpretation is in conflict with the interpretations of most other workers, e.g. Abd Ell Wahed (2008), Kamal El Din (1993), El-Gaby et al. (1984), Bregar et al. (2002), Fritz et al. (2002), all of whom argued for a tectonic break between the orthogneisses and the island arc affinity metasediments.

Two models have been proposed to explain the tectonic evolution of the Sibai area in time and space based on $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological data from Bregar et al. (2002) and Fritz et al. (2002), respectively. Bregar et al. (2002) and Fritz et al. (2002) postulated the presence of two parallel sinistral strike-slip shear zones north-east and south-west of the El-Sibai gneiss complex, linked by a top-to-the-NW extensional shear zones in the north-west and a top-to-the-SE shear zone in the south-east. These shear zones define together the boundaries of the gneiss complex. Based on these postulated shear zones, they explained the gneiss complex as an exhumed gneiss dome resulting from orogen-parallel (NW–SE) extension caused by oblique collision, similar to the model proposed for the Meatiq gneiss dome (Abd Ell Wahed 2008; Fritz et al. 1996, 2002; Walbrecher et al. 1993). Fowler et al. (2007) rejected the existence of the so-called external strike-slip shear zones crucial to the exhumation model by Bregar et al. (2002) and Fritz et al. (2002) and explained the appearance of the El-Sibai gneisses as the result of synmagmatic deformation of tabular granitoid bodies contemporaneous with NW thrusting and nappe stacking.

Fowler et al. (2007) also reported NW–SE-trending open folds and subsequent NW–SE-directed extensional structures post-dating the NW thrusting, but emphasized that these structures pre-date development of semi-brittle to brittle strike-slip shear zones present in Wadi El-Shush (Fig. 2). There are, in addition to the gneisses, several undeformed plutons intruding both the gneissic rocks and the surrounding metasediments in the area (Abdel-Rahman and El-Kibbi 2001; Akaad and Abu El Ela 2002; Bregar et al. 2002; El-Sayed et al. 2002; Fowler et al. 2007). Bregar et al. (2002) grouped these intrusives into (1) exhumation-related granites and (2) “late tectonic” granitoids based on a combination of field relations and geochemical characteristics. Clearly post-dating the “late tectonic” granitoids are some gabbroic complexes, composed of leucogabbros, anorthosites and diorites, and alkaline granitoids (Akaad and Abu El Ela 2002).

Previous geochronological data in the El-Sibai area comprise $^{207}\text{Pb}/^{206}\text{Pb}$ single zircon evaporation ages (Kober method) on three orthogneisses (Bregar et al. 2002), yielding 680 ± 10 Ma for the oldest and 650 ± 10 Ma for the two youngest, and $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende ages c. 623 and 606 Ma, respectively, from the Abu Markhat gneiss and amphibolites close to the El-Shush gneisses (Fritz et al. 2002).

Sample descriptions

El-Shush granodioritic gneiss (AA07–16)

The analyzed sample is a foliated biotite–muscovite granodiorite from the inner part of Wadi El-Shush (Fig. 2; Table 1), where it is intercalated with the El-Shush granitic gneiss. Many of the plagioclase crystals preserve a magmatic zonation. Accessory zircon and titanite are present.

El-Shush granitic gneiss (AA07–17)

The granitic orthogneiss studied here was collected next to the granodioritic gneiss (AA07–16; Fig. 2, Table 1). Due to syn- or post-emplacement deformation, we were not able to determine the relative age relationship between the two units in the field. The granitic orthogneiss has a more porphyroclastic texture than the granodiorite, with both quartz and feldspar appearing as porphyroclasts. Muscovite appears as “mica fish” elongated parallel with the gneiss foliation. Accessory zircon and titanite are present.

El-Shush coarse granitic gneiss (AA07–18)

This sample was collected in the eastern part of Wadi El-Shush (Fig. 2, Table 1) from coarse-grained foliated

Table 1 U–Pb analytical data

An no	Properties	Weight (ug)	U (ppm)	Th/U	Pbcom (pg)	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	2 sigma (abs)	$^{206}\text{Pb}/^{238}\text{U}$	2 sigma (abs)	rho	$^{207}\text{Pb}/^{206}\text{Pb}$	2 sigma (abs)	$^{206}\text{Pb}/^{238}\text{U}$	2 sigma (abs)	$^{207}\text{Pb}/^{235}\text{U}$	2 sigma (abs)	$^{207}\text{Pb}/^{206}\text{Pb}$	2 sigma (abs)	Disc. (%)
El-Shush granodioritic gneiss, AA 07–16 (25°37.697'N, 34°13.197'E)																				
1	3 clear, colourless, euh. zr, w/few incl. A.r. 1:3–4	1	1,241	0.30	1.5	5,348	0.88240	0.00916	0.10328	0.00106	0.99	0.06197	0.00011	633.6	6.2	642.3	4.9	673.0	3.7	6.1
2	5 clear, colourless, euh. zr, w/few incl. A.r. 1:3–4	3	225	0.39	0.7	7,038	0.94720	0.07059	0.11016	0.00821	1.00	0.06236	0.00015	673.7	47.5	676.6	36.2	686.5	5.0	2.0
3	6 clear, colourless, euh. zr, w/few incl. A.r. 1:3–4	1	202	0.41	0.4	3,123	0.93181	0.03238	0.10834	0.00394	0.93	0.06238	0.00081	663.1	22.9	668.6	16.9	687.1	27.5	3.7
4	5 clear, colourless, euh. zr, w/few incl. A.r. 1:3–4	6	98	0.35	3.4	1,237	0.96803	0.01315	0.11284	0.00130	0.84	0.06222	0.00045	689.2	7.5	687.4	6.8	681.6	15.4	–1.2
5	1 large, red, euh. zr, w/incl. A.r. 1:4	3	225	0.29	4.3	1,147	0.97859	0.02892	0.11483	0.00327	0.94	0.06181	0.00062	700.8	18.9	692.9	14.8	667.4	21.4	–5.3
6	1 clear, colourless, euh. zr, w/few incl. A.r. 1:4	1	795	0.32	3.9	936	0.60433	0.00386	0.07210	0.00032	0.70	0.06079	0.00028	448.8	2.0	480.0	2.5	631.8	9.8	30.0
El-Shush granitic gneiss, AA07–17 (25°37.697'N, 34°13.197'E)																				
1	1 large, red, subheadr., red, metamict zr. A.r. 1:4	6	1174	0.25	157.1	241	0.68059	0.00838	0.07961	0.00035	0.26	0.06200	0.00074	493.8	2.5	527.1	5.5	674.2	25.3	27.8
2	2 clear, colourless, euh zr prisms	2	402	NM	14.8	239	0.54753	0.00699	0.06547	0.00028	0.26	0.06066	0.00075	408.8	2.0	443.4	4.9	627.0	26.4	35.9
3	1 small, clear, colourless, euh zr prisms	1	31	0.30	0.9	252	0.94854	0.02372	0.11106	0.00040	0.53	0.06195	0.00144	678.9	2.3	677.3	12.3	672.2	49.0	–1.0
4	1 red, metamict, euh. zr prism	1	592	0.14	3.9	1,027	0.89237	0.00487	0.10535	0.00034	0.68	0.06143	0.00025	645.7	2.0	647.6	2.6	654.4	8.6	1.4
5	1 red, metamict, euh. zr prism	1	809	0.10	15.7	306	0.76203	0.00711	0.08932	0.00024	0.31	0.06188	0.00055	551.5	1.4	575.2	4.1	669.8	18.9	18.4
6	1 clear, colourless, euh zr prisms	1	105	0.24	1.5	504	0.92972	0.01244	0.11080	0.00038	0.48	0.06086	0.00074	677.4	2.2	667.5	6.5	634.3	25.9	–7.2
7	1 clear, colourless, euh zr prisms	1	439	NM	8.1	364	0.88278	0.01020	0.10275	0.00049	0.44	0.06231	0.00065	630.5	3.0	642.5	5.6	684.8	22.0	8.3
El-Shush coarse granitic gneiss, AA 07–18 (25°37.661'N, 34°13.012'E)																				
1	8 clear, colourless, euh. zr, pyr., few incl., A.r. 1:3–4	4	292	0.26	8.0	999	0.91553	0.01172	0.10775	0.00165	0.70	0.06162	0.00069	659.7	9.6	660.0	6.2	661.0	23.7	0.2
2	4 yellow titanite fragments	1	673	0.32	9.2	527	0.96475	0.00826	0.11161	0.00053	0.53	0.06269	0.00045	682.1	3.2	685.8	4.4	697.7	15.4	2.4
3	4 clear, colourless, euh. zr, pyr., few incl., A.r. 1:3–4	1	549	0.28	5.8	670	0.94763	0.00859	0.11003	0.00081	0.80	0.06246	0.00034	672.9	4.8	676.9	4.5	690.0	11.6	2.6
4	7 clear, colourless, euh. zr., few incl., A.r. 1:3–5	1	1,484	NM	2.0	5,331	0.96961	0.00460	0.11307	0.00048	0.92	0.06220	0.00012	690.5	2.8	688.3	2.4	680.9	4.1	–1.5
5	10 fragments of brown titanite	18	169	0.30	50.9	430	0.94938	0.00607	0.11026	0.00025	0.31	0.06245	0.00038	674.3	1.6	677.8	3.3	689.5	12.9	2.3
6	10 fragments of clear yellow titanite	10	107	0.38	10.2	752	0.95890	0.00454	0.11200	0.00033	0.61	0.06210	0.00023	684.3	2.0	682.7	2.4	677.4	8.0	–1.1

Table 1 continued

An no	Properties	Weight (ug)	U (ppm)	Th/U	Pbcom (pg)	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	2 sigma (abs)	$^{206}\text{Pb}/^{238}\text{U}$	2 sigma (abs)	rho	$^{207}\text{Pb}/^{206}\text{Pb}$	2 sigma (abs)	$^{206}\text{Pb}/^{238}\text{U}$	2 sigma (abs)	$^{207}\text{Pb}/^{235}\text{U}$	2 sigma (abs)	$^{207}\text{Pb}/^{206}\text{Pb}$	2 sigma (abs)	Disc. (%)
7	8 fragments of clear yellow titanite	12	119	0.33	19.3	534	0.95621	0.00579	0.11130	0.00028	0.42	0.06231	0.00034	680.3	1.6	681.3	3.0	684.7	11.7	0.7
8	4 greyish, slightly metamict euh. zr, w/incl., a.r. 1:4	1	613	0.23	2.5	1,755	0.97316	0.00503	0.11335	0.00049	0.73	0.06227	0.00022	692.2	2.8	690.1	2.6	683.3	7.6	-1.4
9	3 clear, colourless, euh. zr, few incl., a.r. 1:3–4	1	129	0.42	0.7	1,308	0.96186	0.00768	0.11180	0.00058	0.64	0.06240	0.00038	683.2	3.4	684.3	4.0	687.8	13.0	0.7
10	4 clear, colourless, euh. zr, pyr., few incl., a.r. 1:3–4	1	1,260	0.20	14.3	558	0.83927	0.01195	0.09769	0.00128	0.93	0.06231	0.00034	600.9	7.6	618.7	6.7	684.7	11.4	12.8
11	2 clear, colourless, euh. zr, pyr., few incl., a.r. 1:2–4	3	212	0.25	2.5	1,786	0.96913	0.01014	0.11269	0.00113	0.96	0.06237	0.00018	688.4	6.6	688.0	5.2	686.9	6.1	-0.2
Umm Gheigh anorthosite, AA 07–25 (25°37'203" N, 34°25'931"E)																				
1	1 clear, colourless, euh. zr, w/few incl.	1	895	0.98	1.0	4,840	0.67719	0.01710	0.08510	0.00210	0.95	0.05772	0.00047	526.5	12.5	525.1	10.3	519.0	17.6	-1.5
2	2 clear, colourless euh. zr, w/incl. A.r. 1:2	1	2,452	1.08	1.5	8,378	0.67244	0.00340	0.08322	0.00039	0.94	0.05860	0.00010	515.3	2.3	522.2	2.1	552.4	3.7	7.0
3	1 greyish, euh. zr, w/incl. A.r. 1:3	1	229	NM	1.0	1,161	0.62879	0.00406	0.07679	0.00021	0.55	0.05939	0.00032	476.9	1.3	495.3	2.5	581.3	11.8	18.6
4	2 colourless, euh. zr, w/incl., a.r. 1:3	1	1,358	0.93	1.0	7,086	0.68703	0.00224	0.08548	0.00026	0.89	0.05829	0.00009	528.7	1.5	531.0	1.3	540.8	3.2	2.3
5	2 lrg. colourless euh. zr, w/incl., a.r. 1:1	7	1,790	0.96	4.6	15,003	0.70723	0.00218	0.08767	0.00025	0.97	0.05851	0.00004	541.7	1.5	543.1	1.3	548.9	1.6	1.4
6	3 clear, colourless, euh. zr, w/few incl. A.r. 1:2	1	637	0.96	0.8	4,559	0.70579	0.00246	0.08744	0.00023	0.82	0.05854	0.00012	540.4	1.4	542.2	1.5	550.1	4.3	1.9
7	6 greyish, euh. zr, w/incl. A.r. 1:1	1	341	0.90	0.6	2,944	0.70222	0.00353	0.08734	0.00040	0.77	0.05831	0.00019	539.8	2.4	540.1	2.1	541.6	7.2	0.3
8	3 greyish, euh. zr, w/incl. A.r. 1:1–2	3	321	0.94	1.4	3,822	0.70580	0.00376	0.08782	0.00041	0.87	0.05829	0.00015	542.6	2.4	542.2	2.2	540.6	5.7	-0.4
Umm Gheigh syenogranite dike, AA 07–26 (25°36'893" N, 34°26'209"E)																				
1	5 clear, pinkish, euh. zr, w/few incl. A.r. 1:4	3	340	0.44	1.2	4,918	0.73491	0.00312	0.09039	0.00037	0.79	0.05897	0.00016	557.9	2.2	559.4	1.8	565.8	5.8	1.5
2	4 pinkish euh. zr, incl. rich. A.r. >1:5	7	160	0.58	2.7	2,251	0.69972	0.00288	0.08680	0.00023	0.76	0.05847	0.00016	536.6	1.4	538.6	1.7	547.4	5.9	2.1
3	6 pinkish euh. zr, incl. Rich. A.r. >1:5	5	182	0.58	2.1	2,478	0.71100	0.00281	0.08831	0.00026	0.73	0.05839	0.00016	545.5	1.5	545.3	1.7	544.5	5.9	-0.2
4	4 pinkish euh. zr, incl. Rich. A.r. >1:5	1	191	NM	0.9	1,161	0.65409	0.00545	0.08222	0.00038	0.56	0.05770	0.00040	509.4	2.3	511.0	3.3	518.3	15.0	1.8
5	2 clear, colourless euh. zr, w/few incl. A.r. 1:3	1	204	NM	1.4	817	0.69903	0.00677	0.08742	0.00041	0.52	0.05799	0.00048	540.3	2.4	538.2	4.0	529.6	18.1	-2.1
6	8 yellowish, euh. zr., few incl. A.r. 1:1–2	4	203	0.49	0.8	5,735	0.74242	0.00309	0.09118	0.00033	0.89	0.05905	0.00011	562.5	2.0	563.8	1.8	569.1	4.1	1.2
7	1 flat clear, pinkish euh. zr, incl. Rich. A.r. 1:3	1	229	0.87	0.5	2,643	0.70614	0.00452	0.08802	0.00051	0.91	0.05818	0.00016	543.8	3.0	542.4	2.7	536.6	5.9	-1.4
8	4 clear, pinkish, euh. zr, incl. Rich. A.r. 1:4	8	222	0.46	2.6	3,722	0.71269	0.00208	0.08816	0.00020	0.81	0.05863	0.00010	544.7	1.2	546.3	1.2	553.4	3.7	1.6

Table 1 continued

An no	Properties	Weight (ug)	U (ppm)	Th/U	Pbcom (pg)	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	2 sigma (abs)	$^{206}\text{Pb}/^{238}\text{U}$	2 sigma (abs)	rho	$^{207}\text{Pb}/^{206}\text{Pb}$	2 sigma (abs)	$^{206}\text{Pb}/^{238}\text{U}$	2 sigma (abs)	$^{207}\text{Pb}/^{235}\text{U}$	2 sigma (abs)	$^{207}\text{Pb}/^{206}\text{Pb}$	2 sigma (abs)	Disc. (%)
9	2 clear, pinkish, euh zr, incl. Rich. A.r. 1:4	8	95	0.35	1.3	3,526	0.81352	0.00293	0.09768	0.00034	0.69	0.06041	0.00017	600.8	2.0	604.4	1.6	618.1	6.0	2.9
10	3 pinkish euh zr, incl. rich. A.r. >1:5	1	507	0.56	4.5	627	0.67965	0.03512	0.08554	0.00434	0.98	0.05762	0.00057	529.1	25.7	526.6	21.0	515.5	21.4	-2.8
11	4 pinkish euh zr, incl. rich. A.r. >1:5	2	561	0.95	1.6	1,384	0.21927	0.00224	0.03044	0.00026	0.60	0.05225	0.00045	193.3	1.6	201.3	1.9	296.3	19.3	35.3

GPS positions of the different samples are given in parentheses. Analytical and calculated errors are reported at a 2σ level. All 2σ errors are absolute

Th/U: modelled from 6/8-ratio + age. Pbcom: initial common Pb + blank. 6/4: corrected for spike and fractionation. All ratios: corrected for spike, fractionation, blank, initial common Pb

Ar analysis, No number, NM not measured, Zirc. Zircon, euh. euhedral, pyr. pyramidal shape, fragm fragment, incl inclusions, a.r. aspect ratio

granite with variably deformed large K-feldspar porphyroclasts. Although most of the feldspars are altered, relict magmatic growth zonation is observed in many of the plagioclase and K-feldspar grains. Chlorite is common, most likely replacing primary magmatic biotite. Titanite and zircon are present as accessory minerals.

Umm Gheigh anorthosite (AA07–25)

The sampled rock was collected in western Wadi Um Gheigh (Fig. 2, Table 1) and is a dark porphyritic rock with large plagioclase phenocrysts in a finer-grained matrix, and with less than 10% mafic phases. Accessory rutile and some zircons are present. The rock also occurs as a coarse-grained equigranular variety. The anorthosite intrudes the island arc affinity rocks (Fig. 2) and is part of a gabbroic complex, and probably represents a cumulate sequence (Akaad and Abu El-Ela 2002).

Umm Gheigh syenogranite dyke (AA07–26)

A c. 1-m-wide syenogranite dyke (AA07–26) intrudes the anorthosite (AA07–25) in the western part of Wadi Um Gheigh (Fig. 2, Table 1). The rock is fine-grained with amphibole (c. 10%) and biotite (c. 5%) as mafic phases. Opaques and zircon occur in accessory amounts.

Geochronology

Zircon and titanite crystals extracted from the three different gneissic units within the El-Shush gneiss complex, and from the two undeformed intrusives, anorthosite and syenogranite from the Wadi Um Geigh area, have been analyzed to constrain the chronology of events in the area. The sample locations are given in Fig. 2, and the exact GPS positions are given in Table 1. All U–Pb analyses in this study were conducted by isotope dilution thermal ionization mass spectrometry (ID-TIMS) at the Department of Geosciences, University of Oslo. Zircon and titanite descriptions, analytical procedures and results are presented below.

Analytical procedure

The samples were crushed, and the different minerals were separated by magnetic and heavy liquid separation methods. Zircon and titanite were then handpicked and grouped on the basis of morphology, transparency, colour and internal textures. Air-abrasion (Krogh 1982) was conducted on selected grains. These grains were subsequently washed in dilute HNO_3 , ionized water and acetone using an ultrasonic bath, before weighing and spiking

(^{202}Pb – ^{205}Pb – ^{235}U tracer). The zircons and titanites were dissolved in HF and a drop of HNO_3 in Teflon bombs at c. 190°C for 5 days. Dissolved samples weighing more than 0.004 mg and all titanites were chemically separated using micro-columns and anion-exchange resin in order to remove cations that may inhibit ionization (Krogh 1973). U/Pb solutions were dried down and loaded on degassed single Re filaments with silica gel and measured on a Finnigan MAT 262 mass spectrometer, using either Faraday cups in static mode or, for low-intensity samples, a Secondary Electron Multiplier (SEM) in peak jumping mode. $^{207}\text{Pb}/^{204}\text{Pb}$ ratios were measured on SEM for all samples. SEM data were corrected for non-linearity based on measurements of the standard NBS 982-Pb + U500 (Corfu 2004). Measurements were corrected for a 0.1 pg U and 2 pg Pb blank, with Pb blank compositions: $^{206}\text{Pb}/^{204}\text{Pb} = 18.3$, $^{207}\text{Pb}/^{206}\text{Pb} = 0.85$ and $^{207}\text{Pb}/^{204}\text{Pb} = 15.555$ (Corfu 2004). Common Pb corrections were made using the depleted mantle Pb-evolution by Neymark (1990) at the age in question. Uranium source fractionation was estimated to be 0.12‰/a.m.u. Lead source fractionation was corrected by using the measured $^{205}\text{Pb}/^{202}\text{Pb}$ tracer ratio, normalized to the certified value of 0.44050. A standard fractionation error of 0.06‰/a.m.u. was incorporated in the calculations if the $^{205}\text{Pb}/^{202}\text{Pb}$ ratio was determined very precisely and the fractionation corrections became unrealistically precise. If $^{205}\text{Pb}/^{202}\text{Pb}$ ratio was not determined, or the measured $^{205}\text{Pb}/^{202}\text{Pb}$ ratio deviated considerably from 0.44050, Pb fractionation was set at 0.1‰/a.m.u. Lead fractionation values between 0.06 and 0.1‰/a.m.u. were generated by this procedure. The analytical errors and corrections were then incorporated and propagated using the ROMAGE 6.3 program, originally developed by T. E. Krogh. Graphic presentations and age calculations were performed using the ISOPLOT program of Ludwig (2003). All errors are reported at the 2-sigma confidence interval.

Results

El-Shush granodioritic gneiss (AA07–16)

This sample has abundant zircon, and most grains are colourless, clear, euhedral prisms, dominated by (100) crystal faces. These zircons have few inclusions and aspect ratios between 1:3 and 1:4, and five fractions of 1–6 grains of this type were analyzed. CL-imaged zircons of this type show regular magmatic zircons (Fig. 3f). In addition, one large, partly metamict, reddish, euhedral zircon with numerous inclusions was analyzed. Uranium content of the zircon fractions varies from c. 100 to 1,200 ppm, but most have U concentrations of c. 200 ppm. The Th/U ratios are

in the range 0.29–0.41. All the analyses are discordant, but five of the analyses are less than 6.1% discordant (Table 1; Fig. 3a). The sixth (No. 6) analysis is 30% discordant (Table 1; Fig. 3a). A five-point discordia line through all analyses except the reversely discordant analysis, No. 5 (Fig. 3a, grey error ellipse; Table 1) gives an upper intercept age of $682 \pm 4\text{ Ma}$ (2σ , MSWD = 0.97), which is considered the crystallization age of the igneous protolith of the El-Shush granodioritic gneiss. The reason for the discordance is attributed to later Pb-loss (Fig. 3; Table 1). The reverse discordance of analysis No. 5 may reflect some unknown analytical error.

El-Shush granitic gneiss (AA07–17)

This sample has few zircons, and the extracted zircon population can be divided into two main groups; (1) large, red, metamict euhedral zircon prisms with inclusions, and (2) small, colourless, clear, euhedral zircons with fewer inclusions. Both groups have aspect ratios between 1:3 and 1:5 and are dominated by (100) crystal faces. Three single zircons of the large metamict group (No. 1, 4 and 5) and three single zircon and one fraction with two zircons of the small clear ones (No. 2, 3, 6 and 7) were analyzed. Uranium concentrations in the zircon fractions range from 31 to 1,174 ppm, where the metamict zircons have the highest concentrations. The Th/U ratios range between 0.10 and 0.25. All analyses are discordant, but analysis No. 3 is only –1% discordant and No. 4 is only 1.4% discordant (Fig. 3b). The best estimate for the crystallization age of the granite protolith is considered to be the calculated Concordia age for analysis No. 3 (mainly controlled by $^{238}\text{U}/^{206}\text{Pb}$ -age), which is $679 \pm 2\text{ Ma}$ (2σ , MSWD = 0.074; Fig. 3b; Table 1). This age is also identical, within error, to the $^{238}\text{U}/^{206}\text{Pb}$ -age of analysis No. 6. The fact that analysis No. 4 is only slightly discordant and has a $^{207}\text{Pb}/^{206}\text{Pb}$ -age of c. 654 Ma (Fig. 3b, dashed grey error ellipse), younger than both the least discordant point and the upper intercept age of the rest of the analyses, indicate that this zircon preserves an overprint of about this age. A similar age of one of the zircon fractions from sample AA07–18 with a well-constrained older crystallization age indicates that the disturbance of the isotope systems at c. 650–660 Ma may be a common feature in the El-Shush gneisses (see “Discussion” in the next paragraph).

El-Shush coarse granitic gneiss (AA07–18)

This rock has abundant zircon, most of which are dominated by small colourless, clear, euhedral prisms. Crystal faces are dominated by (100) and (211) or (101), and aspect ratios of most grains are between 1:3 and 1:5. Some metamict, reddish crystals are also present. The rock is rich

Fig. 3 Concordia diagrams from the analyzed rocks from the El-Sibai area. **a** Sample AA 07-16; **b** Sample AA 07-17, **c** Sample AA 07-18, **d** Sample AA 07-25; **e** Sample AA 07-26. All errors are 2σ absolute errors. Decay constant errors are not included in the calculations. Arrows of discordia lines point toward lower intercept ages. **f** CL image of a representative zircon of the dated fractions of sample AA07-16 showing magmatic zonation. **g–i** CL images of zircons from sample AA 07-18. **g** shows a magmatically zoned zircon representative of the main population of sample AA 07-18. **h, i** shows magmatically zoned zircons with the zonation cut by zones of recrystallized low U-zircon. *Conc* Concordia, *int* intercept, *Const* constant, *Errs* errors, *ex* except, *zr* zircon

in titanite, which occur in a brown, cloudy and a yellow, clear variety. Eight multigrain zircon fractions were analyzed. Also, two fractions of clear yellow titanites and one fraction of brown, cloudy titanites were analyzed. Uranium concentrations in the zircon fractions range from c. 70 to c. 1,200 ppm, and in the titanite fractions from c. 119 to 169 ppm (Table 1). The Th/U ratios in the zircon fractions range between 0.20 and 0.42 (Table 1). All analyses except No. 10 are less than 2.6% discordant, and four of the analyses are concordant (Fig. 3c, Table 1). A two-point Concordia age of zircon analyses No. 9 and 11 of 685 ± 3 Ma (2σ , MSWD = 0.46), overlapping with a six-point zircon upper intercept age of 684 ± 3 Ma (2σ , MSWD = 0.93; anchored at 0 Ma), is considered the best estimate for the crystallization of the granite protolith (Fig. 3c, grey error ellipses). A three-point titanite

Concordia age of 682 ± 3 Ma (2σ , MSWD = 0.83; Fig. 3c black error ellipses) is considered to date cooling of the original pluton through $660\text{--}700^\circ\text{C}$ (Scott and St-Onge 1995). The discordant fractions have probably undergone recent Pb-loss, as the lower intercepts in all calculations are close to 0 Ma. The younger concordant analysis (Fig. 3c, grey, dashed error ellipse; No. 1; $^{207}\text{Pb}/^{206}\text{Pb}$ -age c. 661 Ma) is interpreted to represent fluid-induced recrystallized zircon based on textures observed in some of the CL-imaged zircons. In Fig. 3, h and i recrystallized low U zones cross-cut the magmatic zoning in zircons, indicating that recrystallization occurred locally in some of the zircons. This interpretation is corroborated by the titanite data that bear no indications of a metamorphic overprint younger than c. 682 Ma and the absence of zones of regular metamorphic overgrowth in the CL-imaged zircons. We

suggest that the same explanation is valid for the younger age of analysis No. 4 in sample AA 07–17. Such fluids could be associated with granitoid plutons intruding at c. 650 Ma as indicated in the data by Bregar et al. (2002).

Umm Gheigh anorthosite (AA07–25)

Zircons in this sample are few and constitute a heterogeneous population. The grains that are not fragmented occur either as (1) small, clear, colourless, euhedral, almost inclusion-free zircons with aspect ratios between 1:1 and 1:4, (2) as subhedral/subrounded short, colourless, clear zircons with few inclusions, or (3) as reddish to yellowish, inclusion-rich, stubby, euhedral to subhedral, metamict zircon. Euhedral zircons, from the three populations, were analyzed. Selection and discrimination within these groups were done mainly on the basis of aspect ratios. Two single zircons and six fractions of 2–6 zircons were analyzed. Uranium concentrations varies between 230 and 2,450 ppm (Table 1). The Th/U ratios are in the range 0.90–1.08. Two of the analyses are concordant, while the rest are up to 18% discordant (Table 1; Fig. 3d). A Concordia age of two zircon analyses (No. 7 and 8) of 541 ± 2 Ma (2σ , MSWD = 0.043), identical to a three-point upper intercept age of 541 ± 2 Ma (2σ , MSWD = 0.045; Fig. 3d, black error ellipses), is considered to be the crystallization age of the anorthosite and the associated gabbroic complex. The reversely discordant analysis (No. 1) appears younger than the other analysis, but this is probably due to the poor precision and large analytical uncertainty (Fig. 3d, largest grey error ellipse). The discordant points, except analysis No. 4, seem to have traces of inheritance, which together with recent Pb-loss could give the observed discordance (Fig. 3d, grey error ellipses). Another, less likely, possibility is that the analyses with an older $^{207}\text{Pb}/^{206}\text{Pb}$ -age represent the true age and that an upper intercept age (anchored at 0 Ma) of 550 Ma is the true age of the anorthosite. This interpretation would, however, make it difficult to explain the concordant younger data. We therefore prefer the first interpretation.

Umm Gheigh syenogranite dyke (AA 07–26)

The zircons from this sample can be grouped in three main categories, (1) weakly pink, long, thin, euhedral, inclusion-rich prisms, dominated by (110) crystal faces, with aspect ratios $>1:5$, (2) clear, colourless to light pink, inclusion-poor euhedral prisms dominated by (100) crystal faces, with aspect ratios between 1:3 and 1:4, and (3) euhedral, stubby, weakly pink to yellow, clear grains dominated by (101) crystal faces, with aspect ratios of 1:1 to 1:2. Cores were present in some zircons of the latter group. Five

multigrain fractions of group (1), three multigrain fractions of group (2), and one single and two multigrain fractions of group (3) were analyzed (Table 1; Fig. 3e). Uranium concentrations in the different fractions vary from c. 100 ppm to c. 500 ppm. The Th/U ratios range from 0.35 to 0.87. Four analyses have an obvious component of inheritance (No. 1, 6 and 9), together these analyses give upper and lower intercepts of 544 ± 14 and 750 ± 82 (2σ , MSWD = 0.52), respectively. One analysis (No. 3) of a fraction of six zircons of group (1) is concordant (Fig. 3e, grey error ellipse in the inset), and the Concordia age of this analysis is 546 ± 2 (2σ , MSWD = 0.112). However, these ages are slightly older than the age of the anorthosite (AA 07–27) in which the syenogranite intrudes. A Concordia age of a slightly reversely discordant analysis (No. 7) of 540 ± 2 Ma (2σ , MSWD = 1.4), is thus, based on the field relations, a maximum age of the dyke and the probable crystallization age (Fig. 3e, bold black error ellipse in the inset). The older zircon fractions are hence interpreted as significantly older, but still Neoproterozoic (max. 750 Ma based on the upper intercept of analyses No. 1, 6 and 9) xenocrystic material (Fig. 3e). A younger age limit of the dyke is provided by an upper intercept age of the slightly discordant youngest analysis (No. 5) of 518 Ma (Fig. 3e, grey, dashed error ellipse). However, we prefer a similar explanation of the younger age as for sample AA 07–17 and AA07–18, i. e. fluid-induced recrystallization effective only locally in the rock. This event may be linked to the strike-slip shear zones cutting through the El-Sibai area.

Discussion

Evidence for juvenile Neoproterozoic magmatism

The new data presented here add to the growing body of evidence that no “pre-Pan African” crust is present in the Eastern Desert of Egypt (Andresen et al. 2009; Bregar et al. 2002; Kröner et al. 1994; Liégeois and Stern 2010). Our data match previous zircon evaporation $^{207}\text{Pb}/^{206}\text{Pb}$ -ages reported by Bregar et al. (2002). However, the new data provide robust evidence for c. 685–679 Ma crystallization of the three gneisses dated in this study and eliminate the uncertainty inherent in the interpretation of $^{207}\text{Pb}/^{206}\text{Pb}$ minimum ages as crystallization ages. The oldest c. 685 Ma gneiss in this study has an age comparable to undeformed granitoids in the island arc affined allochthon north of the Megif-Hafafit dome (Pease et al. 2010; Lundmark et al. 2009). Ages of two other orthogneisses in the El-Sibai complex are in the same age range (682 Ma and 679 Ma), and together with the c. 689 Ma El Sukkari granite (Lundmark et al. 2009) and the c. 680 Ma Dabur intrusive

complex (Pease et al. 2010), probably form part of an extensive pulse of calc-alkaline magmatism between c. 700 and 680 Ma. Available geochemical and isotope data from the rocks in this age range from the El-Sibai gneiss complex and elsewhere in the Eastern Desert show that they are calc-alkaline and juvenile (Bregar et al. 2002; Liégeois and Stern 2010; Lundmark et al. 2009). They are interpreted as plutonic rocks formed above a subduction zone in an island arc setting as there is little or no trace of old crustal influence in the isotope systematics (Bregar et al. 2002; Liégeois and Stern 2010; Lundmark et al. 2009).

Structural setting of the El-Sibai gneisses

The titanite data from the El-Shush coarse granitic gneiss yield roughly the same age as the zircons and thus appear to record magmatic cooling. Within c. 3 m.y. after the c. 685 Ma emplacement of the protolith, the rock therefore must have remained at temperatures below the Pb retention temperature of titanite (c. 660–700° C; Scott and St-Onge 1995). Thus, the development of the gneissic fabric (and associated metamorphism) occurred either at temperatures well below this, or was synmagmatic. Although no reliable titanite data from the other two gneiss units exist, it is reasonable to assume that they have undergone the same post-magmatic history as the El-Shush coarse granite gneiss, as the three different gneisses were all sampled within a small area of Wadi El-Shush, have the same textures and almost identical ages. It is also worth noting that both the El-Shush granodioritic gneiss and the El-Shush coarse granitic gneiss have feldspars with preserved magmatic zonation. This indicates that the rocks were not subjected to medium–high-grade metamorphism/anatexis and associated recrystallization after intrusion.

Our titanite data thus support the tectonostratigraphic division of Fowler et al. (2007); the El-Sibai gneiss complex is not a true “infracrustal” gneiss dome tectonically separated from the overlying allochthon. Fowler et al. (2007) showed that amphibolite facies rocks to the north of the gneisses were statically metamorphosed, which they attributed to contact metamorphism associated with intrusion of the El-Shush granitoids. They did not recognize a tectonic contact separating the amphibolite facies rocks from the low-grade metasupracrustals. This implies that El-Shush gneisses were emplaced into the allochthon and are not separated from the lower-grade island arc affiliated rocks by a shear zone. If this interpretation is correct, the El-Shush gneisses belong to the island arc affiliated allochthon (Fowler et al. 2007), and they are not part of a structurally lower gneiss dome tectonically separated from the allochthon. This means that the El-Shush gneisses themselves were not metamorphosed at amphibolite facies conditions after intrusion, but that their gneissic texture rather was

the result of synmagmatic/syn-emplacement deformation. Fowler et al. (2007) also showed that the space between fractured feldspars in the El-Shush tonalite gneiss was filled by magmatically textured quartz, plagioclase, K-feldspar and biotite, interpreted to indicate syn-magmatic deformation. Based on our titanite data and the presence of preserved magmatically zoned feldspars, we concur with the interpretation by Fowler et al. (2007) that the deformation of the El-Shush gneisses was synmagmatic and synchronous with the deformation and folding of the island arc affiliated rocks, probably related to NW-ward thrusting of these allochthonous rocks during nappe assembly at c. 685–680 Ma.

The apparently old $^{40}\text{Ar}/^{39}\text{Ar}$ -hornblende ages of 623 Ma and 606 Ma from the Abu Markhat gneiss and amphibolites north of the El-Shush gneisses, respectively, were by Fritz et al. 2002 interpreted to date either (1) early exhumation of the El-Sibai gneisses compared to the Meatiq and Megif-Hafafit gneiss domes ($^{40}\text{Ar}/^{39}\text{Ar}$ -hornblende ages of c. 585 Ma); or (2) exhumation of the El-Sibai gneisses from a shallower crustal level than the Meatiq and Megif-Hafafit gneiss domes. The latter explanation is consistent with the interpretation by Fowler et al. (2007) and supports the interpretation that the El-Sibai gneiss complex is not a gneiss dome comparable to the Meatiq and Megif-Hafafit domes, but rather is part of the oceanic affiliated allochthon belonging to a higher structural level than the other, younger gneiss domes.

Early Cambrian juvenile magmatism

The Um Gheigh anorthosite, part of a gabbroic complex, and the cross-cutting Um Gheigh syenogranite dyke dated here, are the youngest pre-Cretaceous rocks dated by robust methods in the Eastern Desert so far. They give ages of 541 ± 2 and 540 ± 2 Ma, respectively. The ages of these two rocks are indistinguishable, and the syenogranite is probably cogenetic with the anorthosite/gabbro complex. An alkali granite and two felsic dykes from the North Eastern Desert yielded Rb/Sr whole rock model ages of ca 550–540 Ma (Stern and Hedge 1985). NE-ESE-striking bimodal dykes with ages in the same range have also been reported from Jordan (K–Ar-ages of 545 ± 13 and 544 ± 11 Ma; Jarrar et al. 1992). These dykes are interpreted to represent magmas generated in the subcontinental mantle lithosphere during an initial stage of NW–SE continental rifting (Jarrar 2001; Stern and Hedge 1985). The tectonic environment linked to the formation of the Um Gheigh anorthosite and syenogranite is uncertain, but the contemporaneous (and possibly cogenetic) nature of the gabbroic complex and the highly alkaline syenogranite leads us to speculate that these late magmas were generated in a similar tectonic setting as that proposed for dykes of

similar age occurring in Jordan (and probably in the North Eastern Desert). We thus propose that asthenospheric upwelling and decompressional sublithospheric mantle melting at an early stage of rifting produced the apparent bimodal, juvenile high-alkaline magmas seen in the El-Sibai area. This tectonomagmatic event is inferred to post-date the East African orogeny. Further geochemical and isotopic studies are required to determine the actual setting of these late juvenile rocks.

Conclusions

New U–Pb ID-TIMS zircon and titanite data from the El-Sibai area in the Eastern Desert of Egypt corroborate earlier studies that find no evidence of pre-Neoproterozoic crust in gneiss complexes in the Eastern Desert (e.g. Andresen et al. 2009; Bregar et al. 2002; Kröner et al. 1994; Liégeois and Stern 2010; Lundmark et al. 2009; Stern 1994). The data further support the tectonostratigraphic interpretation by Fowler et al. (2007) that the gneisses of the El-Sibai area are not part of a gneiss dome separated from an overlying low-grade sequence by a shear zone, but rather represent syn-kinematic granitoids intruded during a stage of assembly of the island arc affiliated allochthon (Andresen et al. 2010) in the Eastern Desert. Finally, we document the presence of Early Cambrian juvenile intrusives and suggest that these represent an anorogenic magmatic phase post-dating and unrelated to the East African orogeny.

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