The late Ediacaran (580–590 Ma) onset of anorogenic alkaline magmatism in the Arabian–Nubian Shield: Katherina A-type rhyolites of Gabal Ma’ain, Sinai, Egypt

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A R T I C L E   I N F O

Article history:
Received 29 September 2011
Received in revised form 25 April 2012
Accepted 3 June 2012
Available online xxx

Keywords:
A-type rhyolite
Anorogenic
Arabian–Nubian Shield
Volcanics
Geochemistry
Sinai

A B S T R A C T

The Katherina Volcanics of Gabal Ma’ain in the Sinai comprise an Ediacaran (580–590 Ma) approximately 450 m thick succession dominated by porphyritic rhyolite lava flows with subordinate related pyroclastics. These volcanics unconformably overlie the calc-alkaline Younger Granites (\(\geq 590\) Ma) and are intruded by alkaline granitoids (578 ± 8 Ma). The rhyolites have a potassic alkaline affinity and peraluminous to slightly metaluminous character. They exhibit many of the classic features of A-type magmas, including enrichment of incompatible elements, such as Zr, Nb, Y, Ga, Zn and Ce and total REE, as well as high FeO*(FeO* + MgO) and 10,000 Ga/Al\textsubscript{2}O\textsubscript{3} ratios. The A-type rhyolites have LREE-enriched patterns with pronounced negative Eu anomalies that are comparable with typical REE profiles for “hot-dry-reduced rhyolites”. Saturation thermometry has yielded zircon and apatite crystallization temperatures ranging between 913 and 923 °C and 669 and 931 °C, respectively. The investigated trace element patterns indicate that the Katherina A-type rhyolites were very likely to have evolved through simple fractional crystallization of a parental magma derived from an enriched (most probably arthenspheric) mantle source, supplemented by a crustal component inherited from post-collisional subduction events, or a ‘recycled component’ in the source. Katherina A-type rhyolites were likely erupted in a within-plate setting. The eruption of these rhyolites marks the onset of the anorogenic period during which the rigid massif (Arabian–Nubian Shield) was subjected to post-collisional tectonic stresses and intra-plate rifting.

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1. Introduction

The Arabian Nubian Shield (ANS) extends over most of NE Africa and the western part of the Arabian Peninsula, representing an area of about 3 million km\(^2\). It is considered by some to be the best-preserved and most widely exposed Neoproterozoic juvenile continental crust on Earth (Dixon and Golombek, 1988; Vervoort and Blichert-Toft, 1999; Patchett and Chase, 2002; Stern, 2002; Gradstein et al., 2004). The ANS evolved during the Neoproterozoic East African Orogeny (900–550 Ma), by accretion of juvenile volcanic arc terranes and associated ophiolite remnants plus microcontinental plates that were assembled to form eastern Gondwana (Kröner et al., 1992; Stern, 1994, 2002; Beyth et al., 1994; Stein and Goldstein, 1996; Jarrar et al., 2003; Johnson and Woldehaimanot, 2003; Meert, 2003; Hargrove et al., 2006; Stoeser and Frost, 2006; Stern et al., 2010; Farahat et al., 2011; Johnson et al., 2011). The latest tectonomagmatic stages of the Arabian–Nubian Shield (610–550 Ma) record the growth and maturation of the continental crust from orogen to craton. Throughout this phase magmatism changed from calc-alkaline to alkaline, and the tectonic regime in which these magmas were generated changed from collision to post-collision to within-plate extension, and ultimately to a stable cratonic setting (Bentor, 1985; Stern and Hedge, 1985; Beyth et al., 1994; Garfunkel, 1999; Jarrar et al., 2003; Johnson and Woldehaimanot, 2003; Moussa et al., 2008; Ali et al., 2009; Be’eri-Shlevin et al., 2009a,b, 2011; El-Bialy, 2010; Morag et al., 2011; Johnson et al., 2011). The final chapter in the Precambrian history of the ANS commenced with intense alkaline volcanism (590–550 Ma) marking the transition to intra-plate setting that was to prevail throughout the Phanerozoic. These late Precambrian alkaline volcanics are represented by minor exposures that are nevertheless widespread across the Arabian–Nubian Shield (Harris, 1982).

The Precambrian basement exposures of Sinai (Fig. 1), along with those of the Eastern Desert of Egypt, southern Israel and Jordan constitute the northern portion of the ANS and share some common features in their post-collision geological history (Stern, 1994; Garfunkel, 1999; Jarrar et al., 2003; Meert, 2003; Katzir et al., 2007; Samuel et al., 2011). In Sinai, the late Neoproterozoic alkaline volcanism was mainly represented by alkaline rhyolitic flows and pyroclastics, known as the “Katherina Volcanics” (Eyal and Hezkiyahu, 1980; Agron and Bentor, 1981).
Petrologic and geochemical characterization and mineralization of the metavolcanic rocks of the Heib Formation, Kid Metamorphic Complex, Sinai, Egypt

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Received 1 January 2011; accepted 28 March 2011
Available online 12 June 2011

Abstract Metavolcanic rocks hosting base metal sulphide mineralization, and belonging to the Kid Metamorphic Complex, are exposed in the Samra-Tarr area, Southern Sinai. The rocks consist of slightly metamorphosed varicolored porphyritic lavas of rhyolite-to-andesite composition, and their equivalent pyroclastics. Geochemically, these metavolcanics are classified as high-K calc-alkaline, metaluminous andesites, trachyandesites, dacites, and rhyolites. The geochemical characteristics of these metavolcanics strongly point to their derivation from continental crust in an active continental margin. The sulphide mineralization in these metavolcanics occurs in two major ore zones, and is represented by four distinct styles of mineralization. The mineralization occurs either as low-grade disseminations or as small massive pockets. The associated hydrothermal alterations include carbonatization, silicification, sericitization and argillic alterations. The base metal sulphide mineralization is epigenetic and was formed by hydrothermal solutions associated with subduction-related volcanic activity.

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1. Introduction

Neoproterozoic basement rocks are exposed in the Sinai Peninsula, south of latitude 29°N and constitute jointly with those in the northern Eastern Desert of Egypt, the most extreme northwestern part of the Arabian–Nubian Shield. The area investigated in this study (Samra-Tarr area; 67 km²) is located in the southeastern part of Sinai between longitudes 34°17′–34°23′E and latitudes 28°10′–28°14′N, and belongs to the Kid Metamorphic Complex (Fig. 1). The main four Neoproterozoic metamorphic complexes of Sinai, Feiran-Solaf, Taba, Sa’al-Zaghra and Kid complexes have been extensively investigated, but their geology still remains a matter of debate and controversy, most probably due to the
On the Pan-African transition of the Arabian–Nubian Shield from compression to extension: The post-collision Dokhan volcanic suite of Kid-Malhak region, Sinai, Egypt

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ARTICLE INFO

Article history:
Received 19 March 2009
Received in revised form 18 May 2009
Accepted 12 June 2009
Available online 21 June 2009

Keywords:
Pan-African
Arabian–Nubian Shield
Volcanic suite
Petrography
Geochemistry
Tectonic setting

ABSTRACT

The Pan-African Kid-Malhak Dokhan volcanic suite (609±12 Ma) is exposed in the northernmost part of the Arabian–Nubian Shield. The suite consists of non-metamorphosed varicolored alternating succession of porphyritic lava flows of commonly felsic composition (rhyolite–dacite) interlayered with compositionally equivalent pyroclastic beds (dominantly ignimbrites). These Dokhan volcanics are quite evolved (SiO₂ ≈ 65–77 wt.%), with strong high-K calc-alkaline affinity and are characterized by relative enrichment in total alkalies, Ba, Y, Zr and total REEs, depletion in Sr, and a LREE-enriched REE patterns with significant negative Eu anomalies. The Kid-Malhak Dokhan lavas display geochemical characteristics of both orogenic arc-type and anorogenic within-plate environments, suggesting eruption in a transitional "post-collisional" tectonic setting. The ages of emplacement of the Dokhan volcanics in Egypt including that of Kid-Malhak region (580–620 Ma) coincide with end of the documented collision between the juvenile Arabian–Nubian crust and Saharan Metacraton and the subsequent extensional collapse event. This post-collision transition from compression to extension is explained by the extensional collapse following continental collision, which was controlled mainly by lithospheric delamination and slab breakoff (passive rifting). Various trace element characteristics discussed herein have indicated that the studied Dokhan magma was highly likely generated from crustal sources and that assimilation–fractional crystallization (AFC) and crustal contamination have played a major role and are most probably superimposed on fractional crystallization during the magmatic evolution of Kid-Malhak Dokhan volcanic suite. The eruption of the high-K calc-alkaline post-collisional Dokhan volcanics in Egypt defines a tectono-magmatic transition between the older calc-alkaline arc-related and the subsequent alkaline magmatism in the northern part of the Arabian–Nubian Shield.

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1. Introduction

The Egyptian basement complex of the Eastern Desert and Sinai consist of Neoproterozoic juvenile crust developed in the northeastern part of the Arabian–Nubian Shield (Stern, 1994, 2002). The most prominent feature of this crust is the presence of dismembered ophiolites, metamorphosed volcano-sedimentary successions and calc-alkaline I-type intrusive complexes. Current idea on the tectonic evolution of these orogenic terrains points to an essential role of convergent processes, through the formation of intra-oceanic island arc system, subsequent ocean closure, amalgamation of the arc complexes and accretion to continental crust, followed by crustal thickening (Bentor, 1985; Abdel-Rahman and Martin, 1987; Kröner et al., 1988; Stern, 1994, 2002); These tectonic events took place during the Pan-African orogenic event between 900 and 614 Ma (Stern and Hedge, 1985; Kröner et al., 1992; Beyth et al., 1994; Stern, 1994). The final stage (between 614 and 550 Ma) in the Pan-African crustal evolution in Egypt was characterized by the eruption of K-rich volcanic rocks (Dokhan volcanics) and emplacement of shallow level felsic intrusions (Egyptian Younger Granites). The term "Dokhan volcanics" refers to varicolored thick sequence of lava flows and pyroclastics of predominantly andesitic to rhyolitic composition in association with ignimbritic rhyolites (Basta et al., 1980; Heikal et al., 1980; Stern and Gottfried, 1986). The Dokhan volcanic sequences are widely distributed and extensively studied in the Eastern Desert of Egypt, whereas they are much less known in Sinai (Fig. 1). However, some workers consider some comparable non-metamorphosed volcanic sequences in Sinai (e.g. G. Khashabi, G. Fierani, W. Kid, W. Meknas and others) as representatives and equivalent to the Dokhan volcanics of the Eastern Desert (e.g. Bentor, 1985; Hassan and Hashad, 1990; El Metwally et al., 1999; Azzaz et al., 2000; Hassan et al., 2001; El-Bialy and El Omlla, 2007). The various studies carried out on the geochemistry of the Dokhan volcanics in the Egyptian Eastern Desert revealed that they have medium- to high-K calc-alkaline affinities. There is general agreement that fractional crystallization of basaltic magma...
Late Neoproterozoic alkaline magmatism in the Arabian–Nubian Shield: the postcollisional A-type granite of Sahara–Umm Adawi pluton, Sinai, Egypt

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Abstract The Sahara–Umm Adawi pluton is a Late Neoproterozoic postcollisional A-type granitoid pluton in Sinai segment of the Arabian–Nubian Shield that was emplaced within voluminous calc-alkaline I-type granite host rocks during the waning stages of the Pan-African orogeny and termination of a tectonomagmatic compressive cycle. The western part of the pluton is downthrown by clysmic faults and buried beneath the Suez rift valley sedimentary fill, while the exposed part is dissected by later Tertiary basaltic dykes and crosscut along with its host rocks by a series of NNE-trending faults. This A-type granite pluton is made up wholly of hypersolvus alkali feldspar granite and is composed of perthite, quartz, alkali amphibole, plagioclase, Fe-rich red biotite, accessory zircon, apatite, and allanite. The pluton rocks are highly evolved ferroan, alkaline, and peralkaline to mildly peraluminous A-type granites, displaying the typical geochemical characteristics of A-type granites with high SiO₂, Na₂O + K₂O, FeO*/MgO, Ga/Al, Zr, Nb, Ga, Y, Ce, and rare earth elements (REE) and low CaO, MgO, Ba, and Sr. Their trace and REE characteristics along with the use of various discrimination schemes revealed their correspondence to magmas derived from crustal sources that has gone through a continent–continent collision (postorogenic or postcollisional), with minor contribution from mantle source similar to ocean island basalt. The assumption of crustal source derivation and postcollisional setting is substantiated by highly evolved nature of this pluton and the absence of any syenitic or more primitive coeval mafic rocks in association with it. The slight mantle signature in the source material of these A-type granites is owed to the juvenile Pan-African Arabian–Nubian Shield (ANS) crust (I-type calc-alkaline) which was acted as a source by partial melting of its rocks and which itself of presumably large mantle source. The extremely high Rb/Sr ratios combined with the obvious Sr, Ba, P, Ti, and Eu depletions clearly indicate that these A-type granites were highly evolved and require advanced fractional crystallization in upper crustal conditions. Crystallization temperature values inferred average around 929°C which is in consistency with the presumably high temperatures of A-type magmas, whereas the estimated depth of emplacement ranges between 20 and 30 km (upper-middle crustal levels within the 40 km relatively thick ANS crust). The geochronologically preceding Pan-African calc-alkaline I-type continental arc granitoids (the Egyptian old and younger granites) associated with these rocks are thought to be the crustal source of this A-type granite pluton and others in the Arabian–Nubian Shield by partial melting caused by crustal thickening due to continental collision at termination of the compressive orogeny in the Arabian–Nubian Shield.

Keywords Alkaline magmatism · A-type granite · Arabian–Nubian Shield · Sinai · Post-collisional
The Sharm El-Shiekh alkaline granite is a typical Late Pan-African A-type granitoid pluton in Sinai segment of the Arabian-Nubian Shield. Such granitoids represent in general the last major magmatic activity, and in specific the terminal granitic plutonism in Sinai massive. They are hypersolvous textured, ranging in composition from alkali feldspar perthitic granite to quartz alkali feldspar syenite.

The most striking compositional feature of the studied granites is their extreme enrichment in K2O and total alkalis that led to formation of normative acmite and sodium metasilicate, and consequently a strong alkaline and peralkaline nature. The present granitoids exhibit typical features of A-type granitoids, characterized by low CaO content (averaging 0.71wt.%), high FeO/T/MgO ratios (9.28-115.5) and NK/A ratios (1.01-1.36), with exceptionally high concentrations of the trace elements Y, Nb, Zr, Zn and Ga and low Sr and Ba contents.

The use of different petrogenetic discrimination criteria and diagrams reveal that they are anorogenic A-type granites, evolved in within-plate (rift-related) setting. However, the Yb/Nb ratio has given rise to a contrasting dual source material derivation and tectonic setting of these A-type granitoids. The studied samples are discriminated between granitoids derived from sources like those of oceanic-island basalts but emplaced in continental rifts or during intraplate magmatism (Anorogenic), and granitoids derived from continental crust or underplated crust through a cycle of continent-continent collision or island-arc magmatism (Post-orogenic).
PETROGRAPHY AND CHEMISTRY OF PYRITE FROM THE
META-ANDESITE ROCKS AT WADI SA’AL AREA, SOUTH SINAI, EGYPT

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ABSTRACT
Epigenetic disseminated sulphide mineralization occurs in the meta-andesite rocks of Wadi Sa’al area. The sulphide-bearing meta-andesite rocks have been extensively altered by subsequent postmagmatic hydrothermal-metamorphic events as designated by the alteration of hornblende, biotite and plagioclase feldspars and the presence of elongated veins filled with secondary minerals and secondary quartz.

Pyrite is seen to be present in cubic form, skeletal shape, brecciated forms and anhedral elongated thread and/or subhedral crystals filling the microfractures. However, chalcopyrite occurs usually as subhedral to anhedral disseminated grains embedded in the silicate matrix and as inclusion in pyrite. Pyrite crystals show extensive replacement of Fe$^{2+}$ by Co$^{2+}$, Zn$^{2+}$ and Ca$^{2+}$ as well as alteration of some pyrite crystals into complex Fe-Cu-silicate mineral.

Factor analysis of the variables S, Fe, Co, Cu, Al, Mg, Si, Ca and Ti in pyrites of the meta-andesite rocks reveals two factor models one related to the alteration of pyrite into copper silicate minerals and the another to the substitution of Fe$^{2+}$ by Co$^{2+}$ and Ca$^{2+}$ in the atomic structure of pyrite crystals.

I. INTRODUCTION
Sulphide mineralization is widely distributed in the volcanic and metavolcanic rocks exposed in south Sinai. Excellent example are shown by the sulphide occurrences in the Rutig Volcanics exposed in Saint Catherine area (Khalifa, 1997), Meknas Volcanics in Nweiba area (Khalifa and Ibrahim, 2000) and in the Kid Volcanics (Soliman et al, 1996, Khalifa, 1997 and Hassaan et al, 2001). Pyrite represents the major sulphide minerals in the former occurrences, followed by chalcopyrite and occasionally galena and sphalerite. Khalifa (1997) detected up to 8.31% Co, up to 0.86% Cu, up to 0.10% Zn and up to 900ppm Au in the pyrite crystals in the Rutig Volcanics exposed at El-Sheikh Awad area, southern Sinai by microprobe analyses. Sulphide mineralization is previously recorded in the in Sa’al area. Soliman (1996) recorded the presence of pyrites in the granodiorite rocks however; El-Shafey et al. (1992) mentioned the presence of pyrite aggregates in the hing zone of folds related to the second phase of deformation. Mamoun et al. (2004) reveals the presence of subsurface sulphide minerals in Sa’al area controlled by structural elements striking NE-SW developed at the second stage of deformation.

The present study aims to delineate the ore petrographic characteristics of the sulphide minerals, and the petrography of their hosting meta-andesite rocks along with their associated alteration features at Wadi Sa’al area, south Sinai. Furthermore, the geochemical behaviour and element concentration in pyrite crystals are also considered.

II. METHODS OF STUDY
The methods of study include field observations and collection of selected samples from the metavolcanic rocks which are exposed at Wadi Sa’al area, followed by preparing thin sections for microscopic studies for rock forming minerals and determination of various metasomatic mineral assemblages. On the other hand, 18 polished surfaces were prepared to study the ore mineral composition and texture. A total of 25 bedrock samples were analyzed for Cu, Pb, Zn, Cd, Ni, Co and Mn by atomic absorption spectrometry at the National Institute of Oceanography and Fisheries, Red Sea, Hurgada. According to Chester et al. (1994), the trace metals...
PETROLOGICAL AND PETROCHEMICAL CHARACTERISTICS OF SOME OLD GRANITES IN SOUTH SINAI

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ABSTRACT: The old granites in south Sinai are granodiorite, quartz diorite tonalite and quartz monzodiorite, and rarely monzogranite in compositions. They have been intruded by the younger granites and on the other hand, they commonly intrude the older metagabbro-diorite complex rocks. At Wadi Dahab area, they intrude the Fierani complex. Their contacts either with the pre-existing basement or the younger granites are often sharp non reactive contacts. They commonly have undigested blocks, rafts and small relics of older pre-existing basement mostly of the migmatites, schists, gniesses and the metagabbro-diorite complex rocks. They are characterized by the occurrence of mafic enclaves of quartz diorite composition produced by mixing between a cognate mantle-derived mafic magma and a felsic crustal magma.

The SiO₂ content in the south Sinai old granites is variable and ranges between 56.73 to 73.04% with an average of about 64.46%. They chemically belong to the calc-alkaline, metaluminous to slightly peraluminous I-type granitoids of subduction-related environments.

The old granites are distinguished as high-temperature tonalitic (Cordilleran) I-type granites that are derived by partial melting of infracrustal mafic M-type rocks of primitive island arcs. They have been underplated beneath the crust in the deep crust zone or perhaps modified mantle. These tonalitic I-type granitoids are presumably the source rocks of the afterward-evolved felsic low-temperature granodioritic I-type granites by subsequent partial melting at relatively higher levels in the lower crust.

1- INTRODUCTION

Granites and granitoid rocks constitute an important rock group that covers a vast area of the Arabian-Nubian Shield. In Egypt the Proterozoic Shield rocks crop out over an area of about 100,000 km², mainly in the Eastern Desert, southern Sinai and the southern part of the Western Desert. The granitoid rocks constitute about 40% of the basement rocks occur in these area (Hussein et al., 1982).

The old granites constitute a major unit of the Precambrian Basement Complex of Egypt including an assemblage of felsic plutonic rocks of essentially intermediate composition. They are previously referred to as ‘grey granites’ by Hume (1935), as ‘synorogenic granites’ by El Shazly (1964), as ‘older granite’ by El Ramly & Akaad (1960), as tonalite, granodiorite-adamellite complex (Sabet, 1961 & 1972) and as syntectonic to late tectonic granites (El Raml, 1972). They are well defined and studied by extensive workers in the Eastern Desert of Egypt during the last decades, while those of Sinai have received a more little investigations. In this paper, the authors aims to elaborate and investigate the Sinai old granitoids status through the following aspects: their field settings, geochronological relations, their commonly associated mafic enclaves, mineralogical and chemical composition, the different processes and conditions involved in their genesis, and their tectonic setting (s).

Five selected studied areas represent the major exposures of the Precambrian old granitoid rocks in south Sinai were selected in this study. They are roughly distributed across south Sinai; Gabal Samra and Wadi Nesryin areas in southwestern Sinai, Wadi El Akhdar-El Sheikh area in central south Sinai and Wadi Dahab and Wadi Yahmid areas in southeastern Sinai (Fig.1).

2- REGIONAL GEOLOGIC SETTING OF THE OLD GRANITES

The investigated old granites differ in their stratigraphic position from those of the Eastern Desert. Accordingly, they are intruded directly by the younger granites, in opposition with old granites of the Eastern Desert, which are separated from the younger granites by the Dokhan Volcanics and the Hamammat sediments Group. However, in both cases they intrude the older metagabbro-diorite complex rocks. An exception do occur in one of the investigated areas; W. Dahab area, where the metagabbro-diorite complex rocks are not exposed and the old granites are geochronologically preceded by the volcanic rocks of Fierani complex. A series of modified and revised geologic maps for the five investigated areas showing the old granites exposures as well as their surrounding country rocks are represented in figure (1).

The altitude of old granitoid rocks vary from highly topographic terrains with conspicuous mountain peaks to low and moderately high relief landscape. The former is characterized by various degrees of weathering effects such as spheroidal weathering, exfoliation, extensive kaolinized surfaces, cavernous structure, and quadrangle detached blocks. They usually have gentle to slightly steep mountain slopes, compared with their counterpart- younger granites which often show steep mountain faces and escarpments. These rocks occur as batholiths or scattered oval or regular plutonic bodies.

The old granites show appreciable variation in grain size, from coarse to medium-grained and in relative granularity from granular to porphyritic. The gradual change in grain size can be noticed between...