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Banded iron formations of Um Nar, Eastern Desert of Egypt: P–T–X conditions of metamorphism and tectonic implications

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ABSTRACT

Banded iron formations (BIF) in Um Nar, central eastern desert of Egypt, occur intercalated with schists of volcaniclastic and epiclastic origins within "ophiolitic–island arc rocks" of the Arabo–Nubian Shield. The BIF and its host rocks were affected by folding, thrusting, and regional metamorphism during the Pan-African Orogeny resulting in the development of north-verging overturned folds and E–W striking, S-dipping thrusts. Following the intrusion of granitoids, the entire sequence was refolded into south-plunging folds with NW–SE trending fold axes. Peak mineral assemblages of hornblende + plagioclase, and garnet + biotite + plagioclase + quartz in the host rocks, and andradite-rich garnet + epidote + hematite + magnetite + quartz in the BIF indicate metamorphism under epidote amphibolite facies conditions. Using the multiequilibrium approach of Thermocalc, and conventional thermobarometry, peak P–T conditions of metamorphism are estimated at 520 ± 30 °C, 5 ± 2 kbar. Fluids attending peak conditions in the oxide facies layers of the BIF were characterized by XCO_2 ~ 0.03 and log fO_2 ~ −40. Textural and mineral chemical criteria suggest that, following peak conditions, the rocks underwent a stage of near-isobaric cooling or cooling and compression characteristic of a counter-clockwise P–T path.

These results are consistent with a model in which the BIFs formed by hydrothermal activity from off-axis submarine vents in several pulses during a protracted event of oceanic crust generation in an inter-arc basin. Concomitant arc volcanism supplied the basin with pyroclastic material that imposed suboxic conditions on the basin leading to increased concentrations of soluble Fe^{2+}. During periods of arc quiescence, Fe^{2+} was likely oxidized, leading to deposition of several layers of BIF. During the Pan-African Orogeny, the BIFs, tuffs, oceanic crust and lithospheric mantle were deformed and metamorphosed while being emplaced onto the continental margin.

Abbreviations: All mineral abbreviations are after Whitney and Evans (2010). End-member components are in lower case; mineral abbreviations are capitalized. Other abbreviations: ANS, Arabo–Nubian shield; BIF, banded iron formation; BSEI, back scattered electron image; CED, central Eastern Desert; Lpc, lepidocrocite; Mg #, Mg/(Mg + Fe^{2+}); NED, northern Eastern Desert; PPL, plane-polarized light; ps, pistacite; RL, reflected light; SED, Southern Eastern Desert; XPL, cross-polarized light.

1. Introduction

Banded iron formations (BIFs) are low grade, high tonnage chemical deposits that consist of iron oxide-rich layers (>15% Fe, usually 25–35% Fe) alternating with chert bands (e.g. James, 1954). They are widely accepted as products of chemical precipitation of Fe^{2+} and Fe^{3+} oxides and hydroxides, Fe-rich silicates, and silica in a marine environment, followed by significant diagenetic and metamorphic modification (e.g. James, 1992; Klein and Beukes, 1993a). Most BIFs are Archean to Palaeoproterozoic in age (Abbott and Isley, 2001; Huston and Logan, 2004; Klein and Beukes, 1993a), having formed prior to the Great Oxygenation Event (GOE) at *c.* 2.4 Ga (e.g. Garrels et al., 1973; Klein, 2005; Simonson, 2003). A few smaller-sized Neoproterozoic BIFs (specifically deposited 850–700 Ma; e.g. Ilyin, 2009; Klein and Ladeira, 2004; Yeo, 1986), have led most scientists to suggest a genetic relationship to global glaciation (Snowball Earth, Hoffman et al., 1998; Kirschvink, 1992), although this is still debated. Alternatively, tectonic and/or volcanic events are preferred by some authors (e.g. Basta et al., 2011; Eyles and Januszczak, 2004; Freitas et al., 2011). As a result, BIFs have become instrumental to understanding the paleotectonic setting and paleoenvironment of an area.

Based on geological setting, Gross (1965, 1980) classified BIFs into Algoma type deposits of submarine volcano-sedimentary origin, and Superior BIF which are shallow marine. Since then, Neoproterozoic BIFs have been recognized as a third type often referred to as Urucum or Rapitan (e.g. Klein, 2005; Klein and Beukes, 1993b; Klein and Ladeira, 2004; Yeo, 1986). Mineralogical, textural, and chemical traits have also been used for classification of BIFs. For example, Beukes and Gutzmer (2008) classified iron formations into granular iron formation (GIF) and femicrite based on relative abundance of allochems, matrix, and

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microcrystalline quartz, again, each with its genetic connotations, whereas Webb et al. (2003) defined "fresh" BIFs as those predominated by magnetite, siderite and quartz, and characterized by Fe/Si *c.* 1.8, and "altered" BIFs as dominated by hematite, quartz and goethite, with Fe/Si > 2.

In Egypt, BIFs occur in 13 localities in an area of *c.* 30,000 km^2 in the Central Eastern Desert (CED, Fig. 1). These small deposits have been classified as Algoma type (e.g. Sims and James, 1984), although they occur intercalated with Neoproterozoic volcaniclastic sediments (e.g. Ali et al., 2009) of intermediate composition rather than the typical Archean/Palaeoproterozoic basic volcanic rocks associated with most Algoma type BIFs (e.g. Bekker et al., 2010; Gross, 1996; Klein, 2005). Most of these BIFs are "altered" femicrites with relatively high Fe/Si ratios (1.8–6.2; cf. Khalil and El-Shazly, 2012). All deposits and their host rocks were regionally metamorphosed under greenschist to amphibolite facies conditions, most likely during the Pan-African Orogeny (e.g. Ali et al., 2009; Loizenbauer et al., 2001). Despite numerous studies on the Egyptian BIFs (cf. Khalil and El-Shazly, 2012 for a review), their origin and evolution are still poorly understood, with models focusing on either (i) chemical precipitation on a continental shelf with the iron source being continental (e.g. El Aref et al., 1993; El Habaak and Soliman, 1999), (ii) precipitation following submarine volcanism and hydrothermal activity in an island arc setting (El Habaak, 2004; El-Gaby et al., 1988; Sims and James, 1984; Takla et al., 1999), or (iii) precipitation triggered by melting of glacial ice during interglacial periods of a Snowball Earth (Ali et al., 2010; Stern et al., 2013).

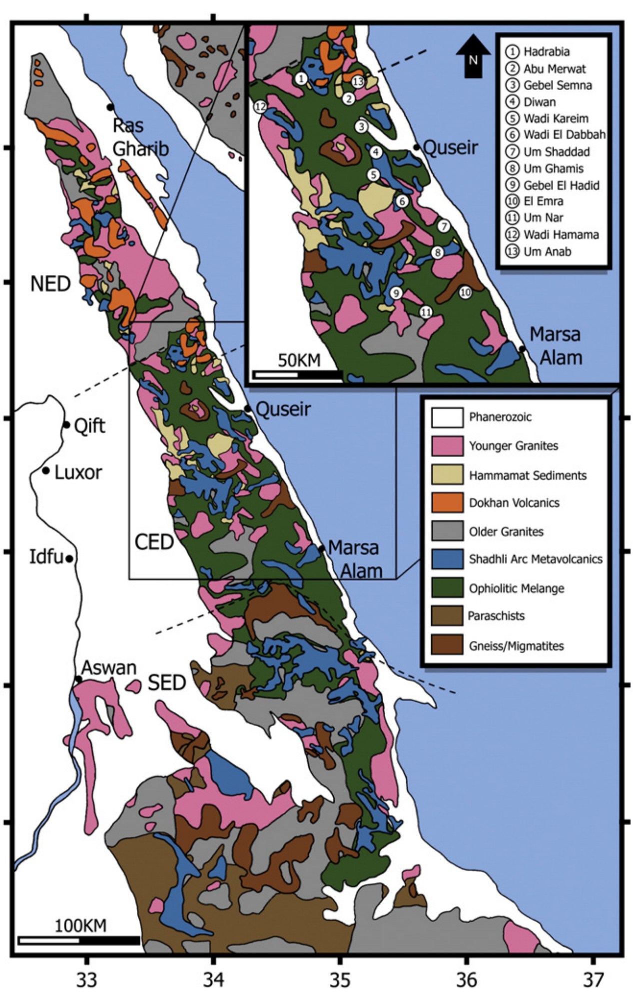

Fig. 1. Simplified lithological map of the Eastern Desert basement in Egypt (compiled from Breitkreuz et al. (2010), Egyptian Geological Survey (1981), Hassan and Hashad (1990), and Stern and Hedge (1985)). Dashed lines represent the boundaries between the northern, central and eastern deserts (cf. Stern and Hedge, 1985). Inset shows the locations of 13 banded iron-ores (open circles).

The Um Nar deposit (# 11, Fig. 1) is the southernmost and one of the largest BIFs in the Central Eastern Desert of Egypt. It is estimated to contain 13.7 million tons of ore, second only to the Wadi Kareim BIF (Dardir, 1990 in Abouzeid and Khalid, 2011). The Um Nar area is structurally complicated, showing evidence of multiple deformational events and numerous igneous intrusions closely associated in space to the iron ore (e.g. Akaad et al., 1996a; Shalaby et al., 2005). Along with the very small deposit of El-Imra (ca. 8 km to the NW, # 10, Fig. 1) the Um Nar BIF is the only deposit containing significant amounts of coarse-grained andraditic garnet and epidote (El Habaak, 2004), and is hosted by some relatively coarse-grained schists, possibly indicating a higher grade of metamorphism compared to the other BIF localities in the CED.

Although the Um Nar BIF has attracted the attention of numerous workers leading to some excellent regional studies (e.g. Akaad et al., 1996a, 1996b; El-Ramly et al., 1963; Shalaby et al., 2005), its age, origin, and conditions of metamorphism are debated. For example, following a field, petrographic and XRD study, El Aref et al. (1993) related mineral parageneses to deformational events, but did not quantify the conditions of metamorphism of Um Nar BIF and its host rocks beyond suggesting "middle greenschist facies" conditions. El Aref et al. (1993) then suggested a Superior type model of formation of this BIF during the Paleoproterozoic, but did not provide any geochronological data to support their claim. Following a study of El-Imra BIF, Salem et al. (1994) concluded that it formed by contact metasomatism. Akaad et al. (1996a, 1996b) compiled a map of the area between Wadi Mubarak and G. Hadeed (# 9, Fig. 1) at the scale of 1:100,000, accompanied by a detailed petrographic description of major lithological units, but again did not quantify the conditions of metamorphism. El Habaak (2004) presented the only mineral chemical and microthermometric study to date of Um Nar BIF, and concluded that the garnet- and/or epidote- bearing bands represent a skarn formed by mixing of hydrothermal and meteoric fluids driven by granitic intrusions. El Habaak (2004) constrained the conditions of skarn formation at $T \leq 524$ °C, low pressures, and relatively high XCO_2 and fO_2 conditions. Shalaby et al. (2005) focused on the structural evolution of the area, tying it to the tectonic framework of the CED established by Neumayr et al. (1998) and Fritz et al. (2002). Based on a stable isotopic study of carbonates from Um Nar and Um Ghamis (# 8, Fig. 1) BIFs, Salem and Hamdy (2011) concluded that the latter deposit was metamorphosed under higher temperature conditions, contrary to the generally accepted concept of Um Nar and El-Imra representing the highest grade of metamorphism among CED BIFs (e.g. El Habaak, 2004).

In this paper we present field, petrographic, and mineral chemical data on the Um Nar BIF and its host rocks. The main objectives of this study are to (i) utilize the new structural data for tectonic interpretations, (ii) constrain the peak P–T conditions of metamorphism of this area, (iii) provide a better understanding of the P–T evolution of these rocks, (iv) characterize the chemical nature (XCO_2 and fO_2) of the fluid attending metamorphism through mineral equilibrium calculations, and (v) present a working model for the formation of this BIF in the context of the tectonic framework of the CED and the Arabo–Nubian shield. To achieve these objectives, we will focus on rocks with low variance mineral assemblages and/or those with assemblages amenable to conventional thermobarometry (and geochronology). Data on whole-rock geochemistry and geochronology of these rocks, along with paleotectonic interpretations will be presented elsewhere (El-Shazly et al., in preparation).

2. Geological setting

2.1. General setting and lithotectonic units of the Eastern Desert of Egypt

The Arabo–Nubian shield consists of a series of Proterozoic units representing intra-oceanic arcs and back arc basins that were amalgamated during the Pan-African Orogeny (e.g. Avigad et al., 2007). In Egypt, the geographic distribution and absolute ages of these units led Stern