Structural interpretation of the Wadi Hafafit culmination: A Pan-African gneissic dome in the central Eastern Desert, Egypt

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ABSTRACT

The emplacement and exhumation of gneissic domes of continental lithospheric fragments within the Pan-African oceanic crust in the Arabian-Nubian shield have been subjects of debate in the recent literature. The Wadi Hafafit culmination is one of the largest metamorphic dome complexes, not only in the Eastern Desert, but also in the Arabian-Nubian shield. The culmination forms a northwest-trending folded belt including five individual gneissic domes that show complex interference fold patterns, bounded by northwest- to west-northwest–trending marginal shear zones (the Nugrus and Hafafit shear zones), which belong to the late Proterozoic Najd fault system in the Eastern Desert of Egypt. The Hafafit metamorphic dome forms a positive flower structure that is characterized by a vertical stretch in the central part with subvertical foliation at the individual dome peripheries, subhorizontal flattening in the roof, and near simple shear at the complex margins defined by the Nugrus and Hafafit shear zones. This study presents arguments concerning the folding pattern and exhumation of the culmination and its relation to sinistral, transpressional kinematics along the branches of the Najd fault system. The folded axial surfaces of the gneissic domes are interpreted in terms of interference of two fold generations: (1) an early fold generation that developed east-northeast–trending axial surfaces, which may have formed during late Pan-African northwestward nappe stacking, and (2) a late fold generation that developed north-south–trending fold axes that deformed the axial surfaces of the first fold generation, and probably associated with sinistral shearing on the Nugrus and Hafafit shear zones. The fold interference patterns associated with exhumation of the Hafafit gneissic domes are consistent with published geochronological data and the tectonic evolution of the Arabian-Nubian shield.

INTRODUCTION

The Neoproterozoic Arabian-Nubian shield consists of a collage of ophiolites and juvenile island arcs (Abdelsalam and Stern, 1996). This rock assembly evolved and cratonized during the Pan-African orogeny (900–550 Ma) through oblique convergence of post-Rodinia continental masses (Stern, 1994; Fritz et al., 2013). The Eastern Desert of Egypt represents the northern arc terrane of this shield (Fig. 1A). There, rocks are grouped into two major tectono-stratigraphic units, infrastructural and suprastructural units (El Gaby et al., 1990), and their tectonic relationship is the subject of this paper. The suprastructural units involve a low-grade rock assembly that is dissected into a series of stacked nappes. The infrastructural units involve gneisses that underwent amphibolite-facies metamorphic conditions (Fritz et al., 1996; Neumayr et al., 1998) and are exposed within cores of antiforms that are tectonically separated from the suprastructure units. Some 20 such metamorphic domes are known throughout the Arabian-Nubian shield across Saudi Arabia, Yemen, and the Eastern Desert of Egypt (Fig. 1A). The Wadi Hafafit culmination is the southernmost, the largest, and the most remote metamorphic dome of Egypt (Fowler and Osman, 2001). The culmination is located between latitudes 24°33′N and 24°50′N and longitudes 34°24′E and 34°48′E, southwest of Marsa Alam at the Red Sea coast in a remote part of the Eastern Desert region.

The origin and tectonic evolution of these metamorphic domes in the Arabian-Nubian shield have been debated for some time (El Gaby et al., 1984; Fritz et al., 1996; Genna et al., 2002; Johnson and Woldehaimanot, 2003) and remain a subject of interest (Meyer et al., 2014; Abu-Alam et al., 2014). Geochronological age data for the gneissic domes cluster around 750 and 600 Ma, and zircon crystals typically show no older cores (Kröner et al., 1994). Therefore, the gneissic domes appear to be juvenile continental crust formed during the Pan-African orogeny, and information about their structural relationship to the overlying suprastructure may help to clarify their original position.

Based on recent studies of the Feiran-Solaf complex in Sinai, the Baladiyah complex in Saudi Arabia, and a literature review of all gneissic domes of the shield, Abu-Alam and Stüwe (2009) and Abu-Alam et al. (2014) concluded that there is probably no unifying exhumation mechanism for the entire group of metamorphic domes in the Arabian-Nubian shield. However, there is a general consensus that most of the domes were exhumed in connection with the activity of the Najd fault system at the end of the Pan-African orogeny.

This paper presents an alternative interpretation of the Wadi Hafafit culmination in the Eastern Desert of Egypt with the aim of clarifying the role of the Najd fault system in the development of its complex fold patterns and finally gneissic dome exhumation. Earlier studies have variably...
Figure 1. (A) Location map of the Wadi Hafafit culmination within the Arabian-Nubian shield, also showing the most important shear zones and metamorphic domes (Abu-Alam and Stüwe, 2009). (B) Geological map of the Wadi Hafafit culmination, Eastern Desert, Egypt (modified after El Ramly and Greiling, 1988). The five domes are labeled A, B, C, D, and E from north to south. SZ—shear zone.
inferred that the geometry and exhumation of the Wadi Hafafit metamorphic domes formed due to fold interference (Fowler and El Kalioubi, 2002) or due to sinistral wrenching (Shalaby, 2010), but the relationship between the observed deformation phases relative to the Najd fault system has not yet been interpreted. Here, we present new structural data, mapping results, and Landsat imagery for the Hafafit region, and its relationship to the bounding shear zones is discussed. This study also presents interpretation of the Wadi Hafafit fold patterns in terms of a more simple history involving deformation of northwest-verging thrust-related fabric by transpressive left-lateral shearing of the Najd fault system in the Arabian-Nubian shield.

ARABIAN-NUBIAN SHIELD IN THE EASTERN DESERT OF EGYPT

In a brief review, the geological buildup of the Arabian-Nubian shield can be described quite simply. The metamorphic domes (referred to as the infrastructure in Egypt) occupy the lowermost structural level. This level is represented by high- to medium-grade metamorphic rocks including amphibolite, granite gneiss, and schists that were typically metamorphosed between 6 and 12 kbar and at 650 °C to 700 °C (Neumayr et al., 1998; Abd El-Naby et al., 2008; Abu-Alam and Stüwe, 2009). The most important domes of the northern part of the shield are the Meatiq, Sibai, and Hafafit domes in the Eastern Desert of Egypt, the Feiran-Solaf, Kid, and Tabia belts of Sinai, and the Qazaz, Hamadat, Baladiyah, and Wajiyah metamorphic complexes of Saudi Arabia (Fig. 1A). The suprastructure is composed of Pan-African cover nappe rocks, including dismembered ophiolites, island-arc–back-arc volcano-sedimentary associations, and tectonic mélangé (El Gaby et al., 1990). These rocks were accreted in the Neoproterozoic during the collision of East and West Gondwana, forming a series of thin-skinned nappes (e.g., Stern, 1994; Kröner et al., 1994).

In the late stages of the Pan-African orogeny, the entire sequence was dissected by the northwest-southeast–trending Najd fault system. This sinistral shear zone system strikes from Egypt across the Red Sea into Saudi Arabia and continues into Yemen and has been referred to as the largest Proterozoic shear zone on Earth (Stern, 1985). The activity of this shear zone constrained the exhumation of the Meatiq and Sebai domes in the Eastern Desert of Egypt (Fritz et al., 2002). Based on restoration of the Arabian-Nubian shield about the Red Sea coasts, Shalaby (2010) suggested that the Wadi Hafafit culmination was exhumed in a wrenching continuation of the Ajjaj shear zone. The latter is one of the largest branches of the Najd fault system in Saudi Arabia.

During the Pan-African orogeny, the Arabian-Nubian shield was intensively intruded by large volumes of pre- to syn- and post-tectonic granitoids. These granitoid intrusions often obliterate the margins of the metamorphic domes, so that shear zone boundaries are imprecisely mappable. For example, the Feiran-Solaf belt of Sinai is of particular interest, because it records the highest pressures of any of the belts, but its exhumation mechanisms can only be studied indirectly because all of its margins have been completely obliterated by late-stage granites. In contrast, the margins of the Hafafit culmination are well exposed, making it a prime target for the investigation presented here.

At the end of the Pan-African orogeny, the Arabian-Nubian shield was covered with molasse-type terrestrial sedimentary rocks. During its Phanerozoic evolution, these sedimentary rocks were largely removed by erosion, but they are preserved in small molasse basins that are often conspicuously linked to the metamorphic domes (Fritz and Messner, 1999; Abd El-Wahed, 2010). Conglomerates in these basins are occasionally highly deformed, but overall these sedimentary rocks are partially deformed and largely unmetamorphosed. In the Eastern Desert of Egypt, these basins include the Hammamat, Kareim, Iгла, and El Mayah Basins.

SOUTHERN PART OF THE CENTRAL EASTERN DESERT REGION

The geological map of the Wadi Hafafit culmination shows map-scale shear zones bounding the culmination to the northeast, southwest, and northwest along the trunk streams of Wadi Nugrus, Wadi Hafafit, and Wadi Shait, respectively (Figs. 1B and 2A). The Nugrus and Hafafit bounding shear zones merge southward at a pivot, where the culmination tapers. The Shait structural line extends roughly in an east-northeast direction further north and juxtaposes the culmination against the low-grade cover
nappe northward (Fig. 2A). The bounding shear zones separate the Wadi Hafafit culmination from three distinct structural provinces northeast, southwest, and northwest of the culmination.

To the northeast, there is the East Nugrus area, extending from the Nugrus shear zone to the Red Sea coast. It is dominated by northwest-verging thrust packages of low-grade suprastructural nappes, forming an imbricate fan structure (Makroum, 2003; Abd El-Wahed et al., 2016). The fan geometry is delimited to the north by a northeast-striking thrust-related frontal ramp and to the west by a northwest-trending sinistral-dominated transpressional lateral ramp that is oriented parallel to the Nugrus shear zone (Fig. 2B). Lenticular masses of serpentinite and talc-carbonate rock assemblage mark fronts of northwestward-verging and east-northeast–trending thrusts that are warped in a southwest direction along the Nugrus shear zone. Mica and talc schists frequently delineate thrust and shear contacts. The top-to-the-northwest tectonic transport direction is clearly indicated by drag folds of the mica schist, asymmetric pressure shadows, and S-C shear bands at talc-carbonate the overthrust (Fig. 3A). The foliation is formed by flattened rock fragments and is penetrative in distinct bands as bedding plane–parallel schistosity. The foliation strikes in a northwest direction and dips mostly shallowly to the southwest and northeast, implying macroscopic northwest-trending fold axes.

The Wadi Nugrus belt is the region between the East Nugrus area and the Wadi Hafafit culmination. It involves three main contiguous fish-shaped sigmoidal blocks of map-scale metasedimentary rock assemblages. These blocks occur between two main northwest-trending marginal shears that run through the trunks of Wadi Sikeit and Wadi Nugrus.

Figure 3. Field photos of representative rock types and structures of the Wadi Hafafit region. (A) S-C structure of the talc carbonate suprastructural rocks indicating a top-to-the-northwest tectonic transport direction. (B) Rotated rock fragment mantled by asymmetrical pressure shadows indicating sinistral shearing sense of the Nugrus shear zone. (C) Sheets of continental Dokhan volcanics unconformably overlying the infrastructural gneisses. (D) Boudinage structure of the pegmatite veins manifesting northwest crustal extension along the Shait structural line. (E) Rhythmic layering of the granite gneiss. (F) Deformed xenolithic rock fragment within the granite gneiss.
The eastern Sikeit marginal shear juxtaposes the low-grade nappe rock assemblage of the east Nugrus area against the Nugrus-Sikeit metasedimentary rocks. The Nugrus-Sikeit rock assemblage, in turn, juxtaposes the gneissic domes of the Wadi Hafafit culmination along the western Nugrus marginal shear (Figs. 1B and 2A). These two marginal shears merge to the northwest and southeast at pivots and are bridged by transpressive Riedel shear arrays along Wadi Sikeit and Wadi Abu Roushaid. The sigmoidal blocks exhibit shear-related en-echelon arrangement of north-south fold patterns, and the individual blocks are separated by transpressive Riedel shears showing strike-slip duplex geometry (Fig. 2C; Makroum, 2003). Fabric asymmetry about boudins indicates that the Nugrus and Sikeit shear zones are left-lateral–dominated transpressional shear zones (Fig. 3B). Far from these shear zones, the northwest-trending stretching lineations on southward-dipping foliations within the wrench corridor and the monoclinic asymmetry of many strain fabrics (Fowler and El Kalioubi, 2002; Makroum, 2003; Shalaby, 2010) indicate that the serpentinite-rich volcano-sedimentary associations of the cover nappe assemblage were stacked northwest onto the Nugrus-Sikeit metasedimentary rocks.

The West Hafafit area, located to the west of Wadi Hafafit, is dominated by associations of orthogneisses and paragneisses that are stacked by the Pan-African cover nappes at higher structural levels. Fabric asymmetry, including drag folds, asymmetric pressure shadows, and S-C shear band cleavages, indicates that the West Hafafit belt is sinistrally displaced against the core gneisses of the Wadi Hafafit culmination (Shalaby, 2010). The north-northwest–trending Riedel shear arrays linking the Hafafit master shear enclose trails of southward-plunging folds. The Hafafit gneisses at the extreme northwestern corner are unconformably overlain by sheets of continental Dokhan volcanics (Fig. 3C). These volcanics are mainly rhyolitic in composition, showing well-developed columnar jointing. These volcanic sheets are tilted concordantly with the regional structure of the area, implying late Pan-African northwest crustal extension.

The Wadi Shait area is the region northwest of the Wadi Shait structural line, and it represents the northern limit of the Wadi Hafafit culmination and juxtaposes the Wadi Hafafit infrastructural gneiss along a normal fault against the low-grade cover nappe units to the northwest (Fig. 1B; Fowler and Osman, 2009; Shalaby, 2010). Boudinaged pegmatite veins cutting the infrastructural gneiss at the northern culmination boundary (Fig. 3D) indicate late Pan-African ductile extension that is overprinted by the brittle normal faulting along the Wadi Shait structural line. Molasse-type sedimentary rocks are rarely recorded northwest of the Hafafit domes, while a huge exposure is represented by Wadi Iglia Basin near the Red Sea coast.

**WADI HAFAFIT CULMINATION**

The Wadi Hafafit culmination is bounded by the Nugrus, Hafafit, and Shait shear zones, which separate it from the provinces discussed in the previous section. The culmination includes five separate gneissic-cored domes that are labeled A, B, C, D, and E, from north to south (El Ramly and Greiling, 1988). The orientation of the axial trace of the gneissic domes A, D, and E shifts gradually from the north-northwest to north-northwest directions, while domes B and C display complex fold interference patterns that will be discussed separately later.

**Rock Types**

Lithologically, the Wadi Hafafit culmination represents a spectacular zonal arrangement of a series of rock units, including: (1) medium- to high-grade gneiss at the core of the domal structures; (2) amphibolite and metagabbro constituting mafic rims surrounding the core gneisses; and (3) psammitic gneisses of the Wadi Sikeit metasedimentary rock assemblage (Fig. 1B). This sequence is intruded by granite protolith (which now constitutes the granite gneiss infrastructure), and it is overthrusted by the low-metamorphic-grade cover nappe (Makroum, 2003).

The core gneisses commonly display low-lying topography against the surrounding Pan-African cover nappes, exhibiting different map-view geometries ranging from oval to crescent shapes. They are heterogeneous in composition, at the scale of few centimeters up to several meters, where the gneisses exhibit strong foliation with well-developed gneissic banding of felsic- and mafic-rich alternating bands (Fig. 3E). The core gneiss has deformed intrusive contacts with the surrounding amphibolites, while the deformed amphibolite xenoliths and enclaves supported its magmatic protolith (Fig. 3F). The gneisses are invaded by numerous pegmatitic dikes and veinlets, which in some places contain garnet (Fig. 3D).

The banded amphibolites are pervasive, with dark tones and strong foliation, and with alternating bands of metamorphic biotite- and hornblende-gneisses of amphibolitic metamorphic facies (Rashtwan, 1991; El Ramly et al., 1993; Abd El-Naby and Frisch, 2006). The amphibolites form a series of isoclinal upright folds with steeply inclined limbs occupying the structural lows between the granite gneissic domes (Fig. 4A). They are locally associated with sheared metagabbró, and both rocks probably belong to the calc-alkaline metagabbros associated with the Hafafit gneiss (El Ramly et al., 1993).

The Wadi Sikeit metasedimentary rock unit (Fig. 1) forms northwest-verging thrust sheets overprinting both the orthogneisses and amphibolites (Fig. 4B). This unit consists of an interleaved sequence of garnet-bearing metapelites and metapamousites. The psammitic gneiss is characterized by its pervasive red color and forms the highest peaks in the Wadi Hafafit culmination overlying the low-lying core gneisses. The psammitic gneiss consists essentially of bands of quartz and feldspars with minor amphiboles and biotite. Garnet crystals reach up to 1.5 cm in diameter and exhibit synkinematic growth, as indicated by spiral-shape patterns (Fig. 4C). The psammitic gneiss locally contains discrete irregular lenses of highly deformed and locally migmatized garnet-rich metasediments. The Wadi Sikeit unit itself is overthrusted by serpentinite and talc schist pertaining to the low-grade suprastructural nappes.

**Geometry of the Hafafit Gneissic Domes**

The five gneissic domes of the Wadi Hafafit culmination display different geometries due to fold superpositions (Fowler and El Kalioubi, 2002) and have a long-term exhumation history since the Pan-African nappe accretion and formation of the Najd fault system (Shalaby, 2010). Dome A has an elliptical form that is rimmed by amphibolite bands (Fig. 1B). The concentric zonation pattern of amphibolite around the dome is narrower to the east of the core gneiss than to the west, indicating asymmetric folding of dome A around NNW-SSE–trending fold axis. Domes B and C are sandwiched between domes A and D, and their cores are also occupied by granite gneisses that are surrounded by thick amphibolite and mafic bands. Both domes B and C show an unlikely folding pattern, with axial planes dipping roughly to the south-southeast, crosscutting the northwest-trending fabric of the culmination. The two domes are separated by an east-northwest–trending synform that is occupied by banded amphibolites. Dome B is folded around dome C at the extreme eastern parts, indicating that their axial surfaces may be refolded about the north-south axial trace that runs along the main stream of Wadi Abu Higleig. This north-south axial trace extends northward, affecting the amphibolite rocks occupying the structural low between domes A and B. Foliation trajectories indicate that the eastern limb of the Abu Higleig fold is constituted of a folded interlayered sequence of granite gneiss and banded amphibolite, while its fold axis plunges southwest. Dome D is the largest dome in the Wadi Hafafit culmination, and it...
exhibits a rectangular form in general; however, its northern part, toward its western side, becomes narrow and extends like an outstretched finger from a fist. The sinuous-shaped gap behind its northern extension is occupied by the western parts of domes B and C. The southernmost dome E has an oval shape bounded by the Nugrus and Hafafit shear zones.

The zonal pattern of lithological compositions is reflected clearly in the color band ratio images for the Wadi Hafafit culmination (Fig. 5). The color ratio images across the gneissic domes constituting the culmination imply that the core of dome A is comparable with that surrounding the central part of dome D, while the color ratios of the cores of domes B and C are comparable to the outer rims surrounding the cores of domes D and E. Moreover, the central part of dome E shows randomly arranged granitic fractures rimmed by concentric foliation of the granite gneiss, which may imply intrusion of less-deformed granitoids at the core of dome E (Fig. 6).

Structural Data

The geological map of Greiling and El Ramly (1990), the structural data of Fowler and El Kalioubi (2002), and the data presented here show that the foliation trajectories at the eastern and western boundaries of the culmination strike in northwest direction parallel to the bounding shear zones, while they show a concentric pattern at cores of the gneissic domes of the culmination (Fig. 7). In the central part of the domes (Fig. 4D), they are flat-lying, while they are gradually inclined more steeply at the dome margins. The amphibolite bands surrounding the core gneiss are oriented in northwest-southeast direction and dip subvertically (Fig. 4E). At the Wadi Nugrus area, the foliation (S₁) trends generally northwest and dips at various angles, either to the southwest or northeast. Poles-to-foliation planes are clustered along a northeast-trending fold girdle and reflect folding around a northwest-plunging fold axis (Fig. 7). The foliation of dome A dips moderately north-northwest and south-southeast at the northern and southern parts, respectively. It dips steeply to the northeast in the eastern part and shallowly to the southwest in the western part of the dome, as indicated by the apparent thickness variation of the surrounding amphibolite, since its outcrop pattern is thick on the western limb relative to the eastern limb. The poles-to-foliation planes at dome A accumulate along two great circles dipping south-southeast and northeast, which imply folding around two north-northwest- and southwest-plunging
fold axes, respectively. At domes B and C, the foliations dip mainly in the south-southeast and north-northwest directions, implying that the gneissic foliations of both domes B and C are folded around an east-northeast–trending axial surface. The area between the two gneiss cores represents a structural low, occupied by folded and steeply foliated amphibolite. The gneissic foliation of dome D dips shallowly to the southwest and southeast, which indicates folding in a north-south direction. The foliation pattern developed in dome E shows concentric trajectories. However, at the eastern and western margins, the foliation trends in the northwest to west-northwest directions, parallel to the orientations of the Nugrus and Hafafit shear zones, respectively.

The stretching lineations ($L_1$) at the Wadi Hafafit culmination plunge mostly to the northwest and southwest, following the main tectonic fabrics of Precambrian domal structures in the Eastern Desert (Fig. 7). In the Wadi Nugrus area, the stretching lineation plunges shallowly to the northwest. In dome A, the contour diagram reveals two trends for the stretched mineral lineation: The first plunges subhorizontally to the north-northwest, and the second plunges moderately to the southwest. This contour pattern reflects that the gneissic foliation of dome A is folded around an east-northeast axial surface. In contrast, the stretched mineral lineation at domes B, C, and D shows that they plunge, with a symmetrical distribution, to the southwest and southeast, implying folding of their gneissic foliation around a north-south–trending axial surface. At dome E, the stretched mineral lineation plunges subhorizontally toward the northwest.

Despite the two general northwest and southwest stretching lineations, there is no evidence of southwest thrusting. Many shear sense indicators, including the monoclinic asymmetry of pressure shadows coating rotated fragmental fabrics, S-C fabric, and asymmetric parasitic folds, indicate that the area of the Wadi Hafafit culmination, like many areas elsewhere in the Pan-African orogenic belt in the Eastern Desert of Egypt, has experienced top-to-the-northwest tectonic transport. The tectonic nature of certain shear planes depends on their attitude relative to the general transport direction in the Wadi Hafafit area. The steeply inclined foliation of the Nugrus and Hafafit shear zones carries a subhorizontal northwest stretching mineral lineation with sinistral shear sense indicators (Fig. 3B). However, far from the shear zones and close to the core of the gneissic domes, the foliation is flat or gently dips southeastward. It carries a north-west stretching lineation, while the shear sense indicators manifest a top-to-the-northwest tectonic transport direction. The northern boundary of the Wadi Hafafit culmination is characterized by northwest-dipping foliation, northwest-plunging mineral lineation, and a top-to-the-northwest sense of motion along a normal shear zone. This down-dip transport direction

![Figure 5. Remote-sensing image analysis in red-green-blue (RGB) of the Wadi Hafafit culmination: (A) Principal component Enhanced Thematic Mapper Plus (ETM+) images (PC3, PC2, and PC4), (B) Landsat Thematic Mapper (TM) ratio image (1/4, 1/7, and 3/5), (C) Landsat TM ratio image (1/4, 3/5, and 4/7), and (D) Landsat TM ratio image (5/7, 5/1, and 5/4*4/3) after Sultan et al. (1988).]
Different mechanisms have been proposed to explain the tectonics and exhumation history of the Wadi Hafafit culmination, including: (1) buoyancy-driven exhumation and diapirism within a scissor-like sinistral wrench system pertaining to the Najd shear zone (Shalaby, 2010), (2) antiformal stacking, where the Wadi Nugrus roof thrust juxtaposes the low-grade cover nappe against the infrastructural gneiss (Greiling et al., 1988; El Ramly et al., 1993), (3) orogen-parallel crustal extension and wrench system pertaining to the Najd shear zone (Shalaby, 2010), (2) orogen-parallel crustal extension and wrench system pertaining to the Najd shear zone (Shalaby, 2010), (3) orogen-parallel crustal extension and wrench system pertaining to the Najd shear zone (Shalaby, 2010), and (4) fold interference patterns involving multiply deformed sheath folds (Fowler and El Kalioubi, 2002). However, the role of the Najd fault system in the structural evolution of the different fold generations remains unclear.

**Interpretation of Wadi Hafafit Culmination as the Product of Fold Interference**

The Wadi Hafafit culmination displays a complex pattern of fold geometry where the fold axes trend northwest-southeast, east-west, and north-south. Moreover, mesoscopic folds exhibit complex mushroom, crescent, and dome geometries, sometimes with undulating axial surfaces, which are interpreted as type 1, 2, and 3 interference fold patterns (Fig. 8: Ramsay and Huber, 1987). These mesoscopic folds display geometrical patterns similar to that of the Wadi Hafafit domes, which may support the interpretation of the Wadi Hafafit culmination on the basis of superposition of two fold generations. Two scenarios are proposed: The first postulates superposition of early northwest-trending folds by a later north-south-trending fold generation; the second is the superposition of an early east-northeast–trending fold by a later north-south–oriented fold generation.

The first scenario might be true if the first generation of folds, formerly oriented in a northwest-southeast direction, developed in an en-echelon arrangement of a southeast-plunging fold set, namely, A, B, C, D, and E from north to south, within a north-south–oriented dextral wrench corridor (Fig. 9). Subsequent left-lateral shearing along the Nugrus and Hafafit marginal shears would have resulted in refolding of the early northwest-trending fold generations across north-south axial surfaces. The data presented here reveal the absence of any evidence that may support an early north-south dextral shearing that predated the activity of the northwest left-lateral shearing at the Wadi Hafafit culmination, and so the first scenario does not appear to be supported by the evidence.

In the second more likely scenario, dome A is interpreted as an asymmetrical doubly-plunging fold, since its fold axis plunges gently southeast at the southern part and moderately to steeply northwest at the northern part. The axial surface trends north-northwest and dips subvertically in the west-southwest direction. The northwest- and southwest-plunging stretching lineation at dome A is likely related to refolding around a gently plunging, east-northeast-trending fold axis or northeast monoclinical flexing due to northwest-southeast shortening (Shalaby, 2010; Fowler and El Kalioubi, 2002). As a consequence, the geometry of dome A can be interpreted as a type 1 interference pattern of two perpendicular fold generations with subvertical axial planes (Fig. 10A). The transport direction of the second generation runs parallel to the axial surface of the first one, while the first-generation fold axis trends perpendicular to the second-generation axial plane. Type 1 interference is represented by the dome and basin structures (Ramsay and Huber, 1987): The geometry of dome A is established by an eastern dome of cored granitic gneiss mantled by dark-green amphibolite bands and a western basin constituted of interlayered thick amphibolite and mafic bands (Fig. 10A).

Domes B and C commonly develop northeast-oriented S-shaped fold geometries, cored by granite gneiss and rimmed by amphibolite on the fold limbs (Fig. 10B). This geometry can easily be interpreted in terms of refolding of an early east-northeast–trending fold generation (F1) about two north-south–striking axial surfaces (F2). It possesses two sinuous-shaped geometrical spaces: The northward-facing sinuous space fringes the southern extreme of dome A, while the southward-facing one is occupied by the central part of dome D. The western parts of domes B and C, dominated by a folded amphibolite carapace, partially occupy the sinuous-shaped space lifted behind the northern narrow segment of dome D and form a northwest-plunging fold belt. On the other hand, the central parts of domes B and C trend east-northeast, where their cores are occupied by granite gneiss. Dome B is refolded around the eastern end of dome C, while the folded amphibolite carapace extends further south, fringing the eastern limb of dome D, where its fold axis plunges southeast. The hinge-line geometry of domes B and C matches an S-fold pattern of drag folds developed within a northwest-trending left-lateral wrench corridor.

Dome D is geometrically mapped as a northward-facing crescent shape that converges southeast and wings to the northwest. The crescent geometry of dome D is interpreted as the interference of two fold generations through superposition of the east-northeast–trending by the northward-trending axial surfaces of the early (F1) and late (F2) fold generations, respectively. The western limb of the dome D crescent geometry extends likely northward as an arm of a northwest-plunging anticline, while the eastern limb is poorly developed, possibly either due to the asymmetry.

**DISCUSSION**

[Figure 6. (A) Landsat imagery of dome E shows concentric gneissic foliation intruded by less-deformed fractured granite at the dome center. (B) Simplified geological map of dome E. (C) Geological map of dome E.]
of the second generation fold ($F_2$) about the north-south–trending axial surface or due to its subsurface protuberance underneath both domes B and C (Fig. 10C). On the other hand, the banded amphibolite, occupying the structural low between domes D and E, shows an S-shaped fold geometry. This S-shaped pattern, like the interference patterns of domes B and C, is folded around two north-south–trending axial surfaces ($F_2$), since the northwest foliation of the amphibolite to the east of dome E is folded to trend east-northeast at the structural low separating domes E and D and then is refolded again to the northwest parallel to the western limb of dome D (Fig. 6). Consequently, the southwestern corner of dome D and northeastern corner of dome E acquired their rounded outlines. The symmetrical distributions of the stretching lineation at domes B, C, and D about a north-south axial surface, and their consistent patterns with the traced foliation trajectories at the Wadi Hafafit culmination indicate a reasonable type 2 interference pattern for domes B, C, and D by early east-northeast–trending axial surfaces and lately north-south–oriented fold generations.

Consequently, the following observations suggest an interference pattern due to the superposition of the early east-northeast and late north-south fold generations:

1. There is a remarkable lithologic zonation in the Hafafit domes, varying from low-grade rocks at the rim (particularly at dome A) to banded
amphibolites and granite gneisses at the core. The entire sequence shows similar structural fabrics, indicating that these rocks were subjected to the same deformation history subsequent to the Pan-African nappe accretion. The total radial pattern of the stretched mineral lineation at the Wadi Hafafit culmination supports the up-doming of the culmination after the accretion of the Pan-African nappe assemblage.

(2) The fold geometry of domes B and C trending in the east-northeast direction, crosscutting the northwest orientation of the Wadi Hafafit culmination, reveals that both domes were possibly reoriented as drag folds due to sinistral shearing at the Nugrus and Hafafit marginal shears (Fig. 1B).

(3) The oblique convergence, in a scissor-like wrench corridor (Shalaby, 2010), during northwestward tectonic escape of the Pan-African cover nappe was responsible for the development of the northwest-verging fold system of domes A, B, C, and D. The northwest stretched mineral lineation at dome A was deformed by folding about an east-northeast axial surface; however, the symmetric distribution of the mineral lineation at domes B, C, and D (Fig. 7) suggests reorientation and folding around north-south–trending axial surfaces (F2).

This scenario is not only more likely, it is also more consistent with the interference history suggested by Fowler and El Kalioubi (2002), who suggested that the domes of the Wadi Hafafit culmination formed due to four folding events, the first three of which were largely associated with northward transport, and the last one of which was related to northeast-southwest compression. In this way, it can easily be postulated that the last folding event was related to transpressive sinistral shearing of the Najd fault system.
Three main aspects led Fowler and El Kalioubi (2002) to suggest a sheet fold interference model to interpret the tectonic setting of the Wadi Hafafit culmination. These were: (1) The radial distribution of the stretched mineral lineation was interpreted as being related to outward migration of the stretching lineation toward the hinge lines of sheet folds; (2) no basin structures are evident in the Wadi Hafafit culmination, since the domes are well developed; and (3) the domes of the Wadi Hafafit culmination are concentrated in a narrow northwest- to north-northwest–trending zone, rather than forming a uniformly distributed set of structures. The present study reveals that the radial distribution pattern of the stretching lineation can possibly be interpreted in terms of superposition of two fold generations and extrusion of the gneissic domes eventually postdating the northwestward accretion of the Pan-African cover nappes, since the fabrics of both gneissic domes and the overlying nappe carapace display uniform patterns. With respect to the second aspect, the amphibolite rocks rimming the gneissic cores form isoclinal synforms occupying the structural lows between these gneissic domes. The third aspect relates to the narrow folded belt of the Wadi Hafafit culmination, which tapers southeast, suggesting that the tectonic setting of the Wadi Hafafit culmination is related to the Nugrus and Hafafit transpressive marginal shear zones.

The Nugrus and Hafafit marginal shears bordering the Wadi Hafafit culmination trend in the northwest and west-northwest directions, respectively, and are parts of the Najd fault system in the Eastern Desert of Egypt (Fritz et al., 1996; Makroum, 2003; Shalaby, 2010). These marginal shears merge southward into one single shear zone that seemingly represents the northern continuation of the Ajaj shear zone in Saudi Arabia (Sultan et al., 1988; Hassan et al., 2016). It is suggested here that the marginal shears also merge northward into one single shear within the downthrown block northwest of the Shait normal fault (Figs. 2A and 10D). The up-doming of the Wadi Hafafit culmination and vertical extrusion of its core gneisses were accommodated by horizontal shortening partitioning left-lateral–dominated transpression at the Nugrus and Hafafit marginal shears, which might sole deeply into a single fault. As such, the geometry of the Wadi Hafafit culmination is that of a positive flower structure (Fig. 10D). The flat and steep foliation with subhorizontal mineral lineation that characterizes the central and peripheral parts of the individual gneissic domes, respectively, formed coeval with extensional fabrics parallel to the lineations. This indicates a pronounced lateral compression at the time of vertical extrusion of the granite gneiss–cored domes. This geometry led Shalaby (2010) to suggest that the culmination developed by oblique convergence in a scissor-like wrench corridor along the Najd fault system. Left-lateral shearing on the Nugrus and Hafafit shear zones has resulted in refolding of the east-northeast first fold generation (F1) about the north-south axial surfaces (F2), as well as northwest reorientation of the earlier-formed structural elements. The positive megascale flower structure extended laterally to involve the Wadi Nugrus domain eastward, and this explains the en-echelon arrangement of the sigmoidal folded horses (Fig. 2C). Further north, the geometry of the flower structure of the Wadi Hafafit culmination is abruptly terminated on the northward-dipping Shait normal fault (Fowler and Osman, 2009), which juxtaposes the gneissic domes of the culmination south of the fault with the nappe assemblage to the north. The Shait normal fault is oriented in an east-northeast direction parallel to the first fold generation and crosscuts the northward-striking axial surfaces of the second fold generation of the Wadi Hafafit culmination. This implies that activity on the normal fault occurred subsequent to up-doming of the Wadi Hafafit culmination. The extension parallel to the foliation at the northern margin of the Wadi Hafafit culmination

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**Megascale Positive Flower Structure in the Najd Fault System**

Figure 9. Sketch diagram showing how the interference patterns of the Wadi Hafafit culmination can be formed by superposition of northwest en echelon fold set by north-south fold generation (no scale). (A) Earlier-formed northwest-southeast–trending fold generation. (B) Left-lateral shearing and development of north-south–trending second fold generation. (C) Interference pattern of the two fold generations. (D) Interpretation of the Wadi Hafafit culmination as interference patterns of superposed folding.
Figure 10. Three-dimensional cartoon illustrating the geometry of the Wadi Hafafit domes as interference patterns of two superposed east-northeast– and north-south–trending fold generations: (A) dome A, (B) dome B and C, and (C) dome D. (D) Sketch diagram showing the Wadi Hafafit positive flower structure, characterized by subvertical foliation at the margins and subhorizontal foliation near the center of the individual domes. Rock symbols are as in Figure 1. SZ—shear zone.
expressed by boudinaged pegmatite veins supports a phase of ductile northwest crustal extension that predated the low-angle normal faulting along the Wadi Shait line.

**Wadi Hafafit Culmination in a Regional Context**

The Wadi Hafafit culmination represents one of the largest metamorphic domes in the Eastern Desert of Egypt. This culmination and nearly more than 20 domes in the Arabian-Nubian shield are located within the Najd fault system, where its activity triggered their emplacement and exhumation (Abu-Alam and Stüwe, 2009). Among them, the Hafafit, Shaloul, Sibai, and Meatiq gneissic dome complexes are located in the Eastern Desert; the Feiran-Solaf, Sa’al, Kid, and Tabas belts are located in the Sinai Peninsula, Egypt; and the Hamadat, Qazzaz, Baladiyah, and Wajiyah complexes are located in Saudi Arabia (Stern, 1994; Loizenbauer et al., 2001). These tectonic events are portrayed by two major Precambrian structures, the northeast arc sutures and the northwest Najd fault system, which extends across the Arabian-Nubian shield in Saudi Arabia and the Eastern Desert of Egypt and explains the superposition of both accretion and shear-related structures (Abdelsalam and Stern, 1996; Johnson and Woldehaimanot, 2003).

The Wadi Hafafit arc sutures represent the first (890–710 Ma) accretion stage (Fritz et al., 2013), comprising the Barka-Ad Damam, Nakaash-Bir Umq, and Allaq-Haiiani-Oni-Sol Hamed-Yanbu sutures from south to north (Johnson and Woldehaimanot, 2003).

The Najd fault system is a northwest-directed anastomosing network of sinistral ductile shear. It is up to 400 km wide and >1000 km long and was developed during the interval 620–540 Ma (Stern, 1985). The Najd fault system in Saudi Arabia extends northwest in the central Eastern Desert of Egypt, affecting the area between the Hamrawin (Duwi) shear zone to the north and the Kharit-Hodein shear zone to the south. Three main shear zones are correlated between Saudi Arabia and the Eastern Desert of Egypt. These are the Hamrawin (Duwi)-Dubai, Sibai-Muwaylah, and Hafafit–Al Wajh shear zones (Sultan et al., 1993). These shear zones deform and sinistrally dislocate the earlier-formed Pan-African sutures, and the imbricated fan structures may represent disconnected arc sutures (e.g., East Hafafit and Wadi Mubarak imbricite fan structures; Makroum, 2001, 2003). The emplacement and exhumation mechanisms of the core complexes during the Pan-African activity of the Najd fault system can be interpreted in terms of the orientation of the complexes relative to the trend of the bounding shear zones and the changes in the kinematics of the shear zones with time:

1. The obliquity of the core complexes relative to the trend of the bounding shear zones can be illustrated in terms of depth of emplacement within transpressive or transtensional tectonic regimes. Exhumation of the gneissic domes within a transpressive regime is favored if the dome trends are perpendicular to the maximum principal stress axis and is bounded by two transpressive marginal shear zones (e.g., Feiran-Solaf and Baladiyah core complexes; Abu Alam and Stüwe, 2009; Abu Alam et al., 2014; Hassan et al., 2016). In contrast, those exhumed within a transtensional regime are oriented orthogonally to the minimum principal stress axis, while the marginal shear zones are linked by low-angle normal faults. This setting is favored by the development of molasse sedimentary basins (e.g., Sibai core complex and Karein Basin; Fritz et al., 1996; Bregar et al., 2002). In Saudi Arabia, the Wajiyah core complex bounds the Hadyiah Basin to the north, while the Talbah Basin is located northwest of the Baladiyah complex and to the west of the Qazzaz complex (Davies 1985; Genna et al., 2002).

2. The tectonic evolution of the shear zone may involve a change in the shear kinematics from transpressive to transtensional through time. A close relationship between shear tectonics and active magmatism defines the exhumation history of the magmatic core complex in the Arabian-Nubian shield (Fritz et al., 1996). Subduction-related calc-alkaline granitoid at the Sibai core complex was emplaced at 690–670 Ma within an island-arc setting, while transtension- and transpression-related granitoids were emplaced at 655 and 645 Ma, respectively (Bregar et al., 2002). These ages coincide with those of granite gneiss protoliths at the Wadi Hafafit dome, which gave ages of 712 and 654 Ma, respectively, and were intruded at 33 km depth in the midcrust, as shown by pressure-temperature paths (Abu El-Enen et al., 2016).

From this discussion, the Wadi Hafafit dome can be interpreted in terms of two pervasive deformation phases followed by an extensional event, as required from the dome geometry of the culmination and the complicated distribution of stretching lineations. These deformation phases were: (1) an early foliation- and lineation-forming event due to northward transport that may have been related to oblique convergence and island-arc accretions; (2) a transpressive event due to sinistral shearing along the bounding shear zones, exhuming the culmination as a flower structure; and (3) an extensional event that offset the positive flower structure along the Shait normal fault. This interpretation fits well into the established geological history of the Arabian-Nubian shield.

This northward thrusting was likely related to late Pan-African oblique convergence, tectonic escape, and accretion of the Pan-African nappe onto juvenile crust northwestward, while evidence of a southwest tectonic transport direction is entirely absent. This event involved development of the east-northeast, asymmetric, northwest-verging fold system (Makroum, 2001, 2003). The first event corresponds to the first three folding phases of Fowler and El Kalioubi (2002). Khudeir et al. (2008) has argued that an older crust was involved in this early deformation.

The late Pan-African oblique convergence of post-Rodinia continental masses involved bulk east-west compression, which commonly deformed the Arabian-Nubian shield and developed left-lateral displacement on the Najd fault system (Stern, 1994). This constrained the exhumation of the gneissic domes in the Eastern Desert of Egypt (Fritz et al., 1996). The east-west shortening across the Wadi Hafafit culmination induced left-lateral displacements on the Nugrus and Hafafit marginal shears, which resulted in refolding of the early east-northeast fold generations about the north-south axial surfaces.

**CONCLUSIONS**

The Wadi Hafafit culmination represents a tectonic window dominated by infrastructural high- to medium-grade metamorphic rocks surrounded by suprastructural low-grade cover nappes. The similarity of the structural elements indicates that both the infrastructural and the suprastructural rocks were subjected to folding and up-doming postdating the accretion of the Pan-African oceanic and island-arc terranes. The culmination is bounded by the Nugrus and Hafafit marginal shears that merge southward into one single shear zone pertaining to the Najd fault system, and represents the northern continuation of the Ajaj shear zone in Saudi Arabia. The Wadi Hafafit culmination is interpreted as a megascale positive flower structure and consists of complex fold patterns of five cored gneissic domes. These fold patterns are attributed to superposition of east-north-east– and north-south–directed fold generations. The early east-northeast fold generation (F1) was tectonically related to oceanic and island-arc accretion northwestward onto Pan-African juvenile crust, while the second north-south fold generation (F2) is attributed to transpressive left-lateral shearing along the Nugrus and Hafafit marginal shear zones. Superposition
Figure 11. Pan-African structural trends of the Afro-Arabian shield, including major sutures, shears, and fault zones. Metamorphic dome complexes and ultramafic rock bodies are well shown. The map was compiled from various sources, including Sultan et al. (1993); Abdelsalam and Stern (1996); and Johnson and Woldehaimanot (2003). Sz—shear zone.
of these fold generations explains the dome and basin geometry of dome A, the S-shaped pattern of domes B and C, and the crescent-shaped pattern of dome D. Moreover, mesoscopic mushroom, dome, and crescent-shaped fold patterns are also recorded, as well as refolded axial surfaces of the earlier fold generation. This megascopic positive structure is faulted along the Shait low-angle normal fault, where the Wadi Hafafit culmination juxtaposes the low-grade cover nappe northwestward.

ACKNOWLEDGMENTS
Field work for this paper was undertaken during a number of field trips from 2005 to 2010. A. Shalaby and M. Abu El-Enen are thanked for logistic field support and critical scientific discussion. E. Hassan is thanked for his help with remote-sensing satellite image interpretation. K. Stüwe is thanked for a review of a presubmission version of this manuscript. S. El Bialy is thanked for linguistic revision of the manuscript.

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