Journal of African Earth Sciences 57 (2010) 227–241

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

The northern dome of Wadi Hafafit culmination, Eastern Desert, Egypt: Structural setting in tectonic framework of a scissor-like wrench corridor

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ARTICLE INFO

Article history:
Received 18 November 2008
Received in revised form 21 July 2009
Accepted 29 August 2009
Available online 6 September 2009

Keywords:
Pan-African orogeny
Eastern Desert
Gneissic domes
Orogen-parallel oblique convergence

ABSTRACT

Although the gneissic domes in Eastern Desert of Egypt have been studied recently in a considerable detail; their origin remains controversial. Basically four schools of thought exist: one argues for an origin parallel crustal extension, a second suggests emplacement within antiformal stacks, a third envisages young emplacement within a core of a sheath fold and finally some authors believe that the emplacement is due to overlap of regional folds and extension parallel to the fold axes. The Wadi Hafafit Culmination is one of these domes and occupies the southern part of the Central Eastern Desert of Egypt. The culmination is cored with five separated gneissic domes ranging in composition from orthogneiss to paragneiss. They are overthrust by a low-grade, volcano-sedimentary association constituting the Pan-African cover nappes. Detailed structural mapping of the northern dome reveals that, the gneisses are vertically emplaced through the cover rock units. This is based on field evidence which shows that the gneisses experienced vertical flattening associated with exhumation corresponding to coaxial deformation. It is suggested that the emplacement of gneissic core occurred during accretion of the Pan-African nappes. Later, strike-slip shear zones of Najd Fault System and the associated subsidiary shear arrays postdate emplacement of the dome. The gneisses contiguously underlie the Pan-African nappe assemblages through discrete low-angle left-lateral thrust-dominated shear zones from the east. Ongoing accretion of nappe assemblages on the gneisses increases the density contrast between the overlying denser nappe and the underlying lighter quartz-rich gneisses, leading to squeezing the gneissic materials in oblique convergence regime. As a consequence, the gneisses are suggested to have up-domed vertically through the nappe rock units.

1. Introduction

The central Eastern Desert of Egypt is characterized by a series of antiformal structures (Fig. 1a), which can be described as metamorphic core complexes surrounded by low-grade Pan-African volcano-sedimentary nappes of Neoproterozoic age (Sturchio et al., 1983; El Gaby et al., 1990; Wallbrecher et al., 1993; Fritz et al., 1996, 2002; Fowler and Osman, 2001; Loizenbauer et al., 2001). These antiformal domal structures include Hafafit, Sibai and Meatiq culminations (Fig. 1a), and are composed of orthogneisses, paragneisses, migmatitic gneisses, amphibolites and other medium-grade metamorphic rocks (Habib et al., 1985; Hassan and Hashad, 1990). The origin and tectonic evolution of these gneissic domes have been discussed by many authors. Based on structural arguments and the succession of magmatic events, they were interpreted as a remobilized early Proterozoic older continental crust (Sturchio et al., 1983; El Gaby et al., 1990, 1994; Hassan and Hashad, 1990). However, the available geochronological data of thermal events within these domes cluster around two peaks at 750 and 600 Ma (Stern and Hedge, 1985; Kröner et al., 1994; Loizenbauer et al., 2001); therefore, early Proterozoic affinity of these rocks is poorly constrained. Kinematically, four tectonic models were proposed to decipher their origin: (1) development of fault-bend fold “antiformal stacks” (e.g. Hafafit domal structure; Greiling et al., 1988a), (2) orogen-parallel crustal extension (e.g. Hafafit, Sibai and Meatiq domal structures; Wallbrecher et al., 1993; Fritz et al., 1996, 2002; Bregar et al., 2002; Loizenbauer et al., 2001; Abdel Wahed, 2008; Khudeir et al., 2008), (3) emplacement within regional domal structures (Ibrahim and Cosgrove, 2001) followed by extension parallel to their fold axes (e.g. Sibai dome, Fowler et al., 2007), and (4) interference patterns of sheath folds (e.g. Hafafit domal structure, Fowler and El Kalioubi, 2002).

The Hafafit domal structure (Wadi Hafafit Culmination, WHC) represents the largest antiformal structures in the Nubian Shield. It is considered as one of spectacular structures in the Eastern Desert, but its structural history has not been entirely clarified. The WHC has been subdivided into five separated gneissic domes (labeled A–E core gneisses; Fig. 1b) of various aerial extends (El Ramly and Greiling, 1988). The present contribution describes the

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doi:10.1016/j.jafrearsci.2009.08.003

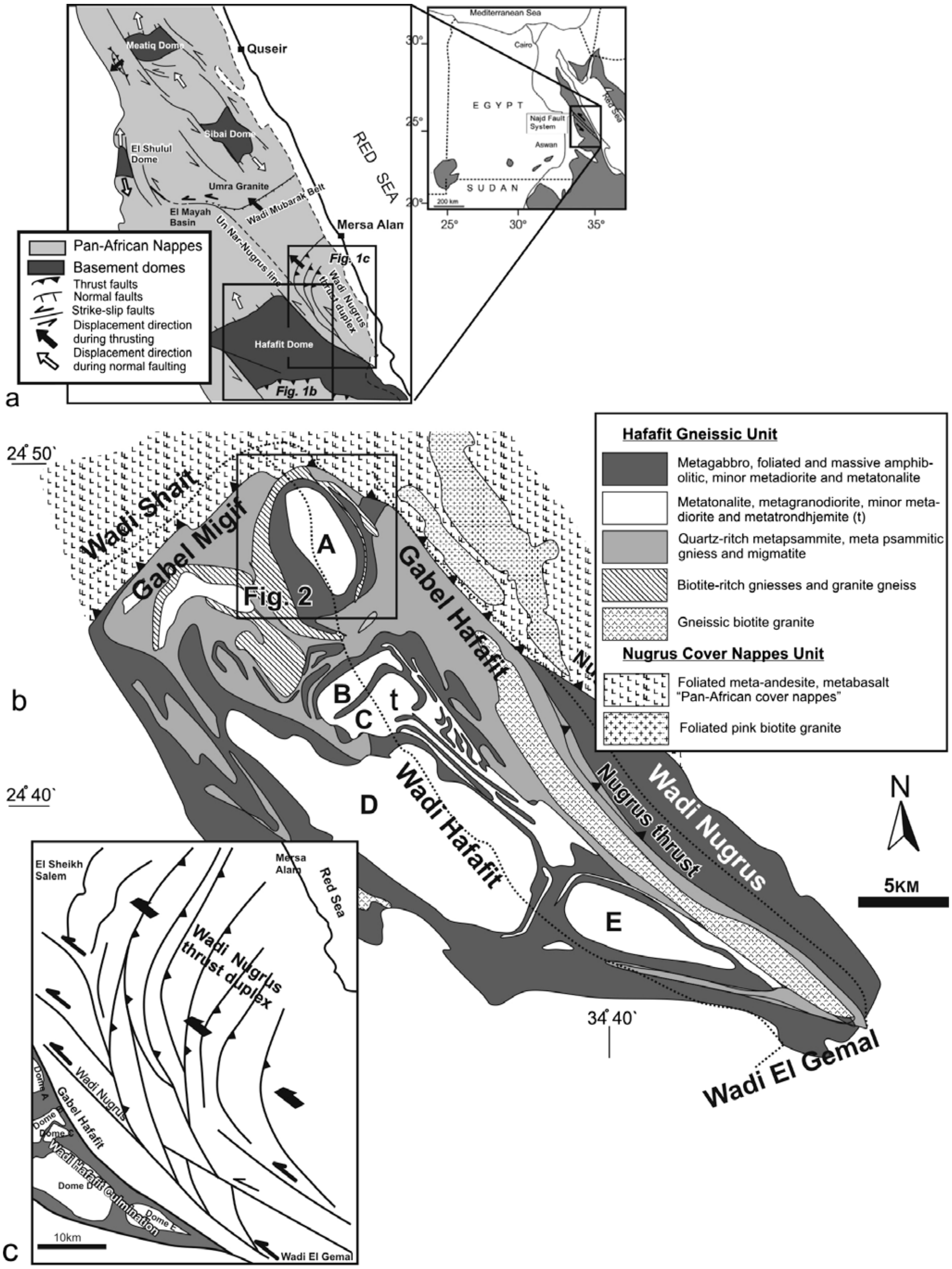

Fig. 1. (a) Tectonic map of Central Eastern Desert showing that the formation of gneissic domes in Eastern Desert is linked by development of Najd fault system from their eastern and western boundaries and normal faults in the northern and southern boundaries (Fritz et al., 1996). (b) The geologic map of WHC (modified after El Ramly and Greiling, 1988) geometrically shows a triangle shape with pivot in the south and open free-boundary to north. (c) Landsat image of the area east of WHC showing the formation of Nugrus thrust duplex that is later crossed by the Nugrus left-lateral shear zone.

structural characteristics of the northern dome (dome A) of WHC. Field descriptions of the dome and surroundings are discussed with emphases to their relations with the overlying Pan-African cover nappes and the bounding ductile shear zones. Furthermore, the structural fabrics will be analyzed to demonstrate its deformational history in order to present a tectonic model of the area.

2. Geological framework

The crystalline basement of the Eastern Desert is commonly subdivided into two major tectono-stratigraphic units (El Gaby et al., 1990) distinguished by means of their different metamorphic grades and deformational complexity. These units are expressed as: (1) a lower infrastructure unit of medium-grade gneisses occupying the cores of the domal structures (Habib et al., 1985; El Gaby et al., 1990), and (2) an upper suprastructure unit of low-grade, arc/back arc volcano-sedimentary associations with some slabs of dismembered ophiolites; commonly known as Pan-African Nappe Complex. The upper unit occupies the largest part of the Neoproterozoic rocks exposed in the Eastern Desert. The accretion of Pan-African nappes and subsequent greenshist facies metamorphism occurred in Neoproterozoic (e.g. Gass, 1982; Stern, 1994; Kröner et al., 1994 Neumayr et al., 1998). The infrastructural unit beneath the obducted cover nappe is exposed within structural domes of magmatic and metamorphic rock assemblage that are tectonically separated from the cover suprastructural unit (Sturchio et al., 1983; Fritz et al., 1996; Fowler and Osman, 2001; El Gaby et al., 1991; Blasband et al., 2000). The medium-grade gneissic domes of the infrastructural unit (Fig. 1a) are exposed in tectonic windows extending NW–SE in the Central Eastern Desert (Fritz et al., 1996), and parallel to the trend of the left-lateral shear zones of Najd Fault System (Stern, 1985). The gneissic domes comprise orthogneisses, psammitic schists and rare amphibolites that suffered amphibolite metamorphic conditions (Neumayr et al., 1996, 1998). These domes are described as core complexes (Wallbrecher et al., 1993; Fritz et al., 1996, 2002; Loizenbauer et al., 2001; Bregar et al., 2002; Abdel Wahed, 2008; Khudeir et al., 2008). Other authors (e.g. Fowler and Osman, 2001; Fowler and El Kalioubi, 2002; Fowler et al., 2007) refused this suggestion and explained their exhumation to be related to generation of sheath folds (e.g. Hafafit domes) and/or regional scale of antiformal domal structures (e.g., Sibai dome).

The gneissic domes constituting the WHC are largely cored by granitioid gneisses (Fig. 1b). The domes are composed of medium-grade gneisses and migmatites, outlined by gneissic metagabbro. The psammitic gneisses occur at the rims of the domal structure with a left-lateral thrust-dominated strike-slip shear contact against the underlying gneisses. The culmination forms a macroscopic fold interference pattern (Fowler and El Kalioubi, 2002) that is separated from the overlying low-grade metamorphic rocks by low-angle thrusts. To the east, WHC is bound by a major

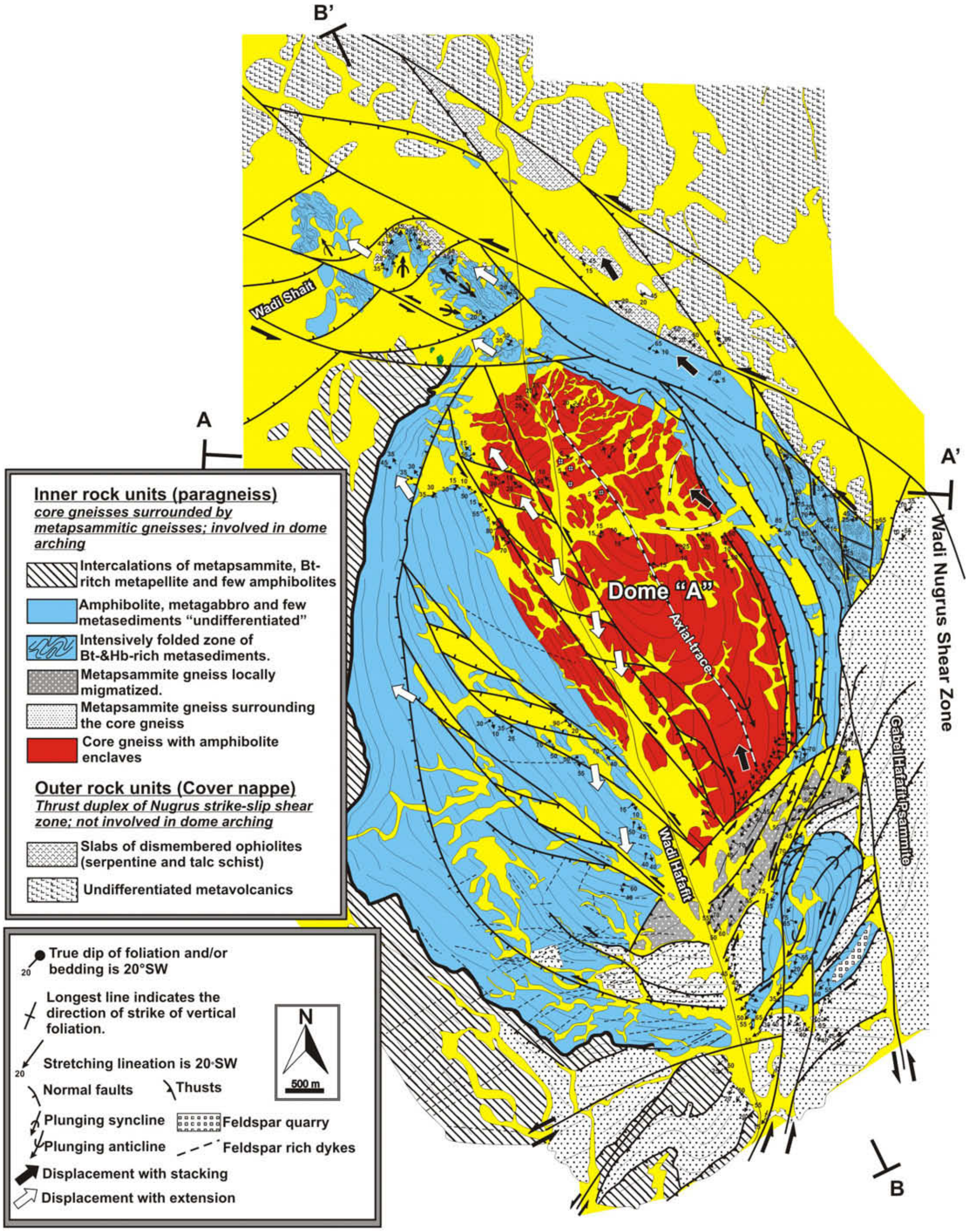

Fig. 2. The geologic map of the northern dome "Dome A" of WHC showing that the eastern and southern areas are thrust dominated while the western and northern areas are exclusively characterized by low-angle ductile normal faults. Note that thrusts are later crossed by left-lateral shear zones.

low-angle thrust (the Nugrus thrust), indicated by a thick mylonite shear zone (Greiling et al., 1988a; El Ramly et al., 1993). This thrust separates the medium-grade metamorphic rocks from the overlying low-grade metamorphic ophiolitic and arc volcanic assemblages (El Ramly et al., 1984). The later assemblages consist mainly of low-grade meta-andesite, meta-basalt, slightly foliated metagabbro and metasediments with intervening remnants of ophiolites (El Bayoumi and Greiling, 1984). The ophiolitic and arc volcanic assemblages represent a thick sequence of northwestward-stacking thrust duplexes of Pan-African cover nappes that are later crossed by NW–SE trending left lateral strike-slip wrench corridor of Wadi Nugrus (Makroum, 2003, Fig. 1c). To the south and southwest, the culmination is bound by Wadi El-Gemal low-angle thrust which separates the culmination from the overlying low-grade metamorphic and weakly deformed volcanogenic sediments (Greiling, 1997).

The investigated northern dome (dome A of WHC) consists of two major rock units. The *inner unit* comprises, from the core to rims: (1) a package of highly deformed ortho- and para-gneisses with intercalated bands of amphibolites; collectively known as core gneisses, and (2) a thick sequence of well-banded amphibolite and metasediment surrounding the core gneisses (Abd El-Naby and Frisch, 2006; Figs. 2 and 3). The whole inner unit is structurally conformable forming an oval-shaped antiform that is elongated in the NW–SE direction (Fowler and El Kalioubi, 2002), and displays low-lying topography against the surroundings. Field observation indicates that the core gneisses 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. The gneisses are invaded by numerous pegmatitic dykes and veinlets, which in some places contain garnets. The amphibolite bands surrounding the core gneisses are also strongly foliated and display alternating bands of metamorphic biotite- and hornblende-gneisses of amphibolitie facies (Rashwan, 1991; El Ramly et al., 1993; Abd El-Naby and Frisch, 2006). The banded amphibolites are overlain, to the east, by a package of a triangular zone of intensively folded biotite- and hornblend-rich metasediments, and by Hafafit psammitic gneisses to the south (Figs. 2 and 3a). The Hafafit metapsammite is characterized by its pervasive red colour and forms the highest elevated peaks in the WHC in contrast to the low-lying core gneisses. The psammitic gneisses consist essentially of quartz and feldspars with minor amphiboles and biotite. Immediately south of the core gneisses, the psammitic gneisses form a zone of NE–SW trending inter-stacked irregular lenses of highly deformed and locally migmatized garnet rich metasediments (Figs. 2 and 3b).

The *outer unit*, located to the north and northeast of the inner unit; is characterized by north- and northwest-ward imbrications of the Pan-African nappes which cover most of Eastern Desert territory (Figs. 1 and 2). In the Hafafit area, the nappe assemblage consists of low-grade volcano-sedimentary association with deformed lenses and boudinaged serpentinites and talc schist derivates

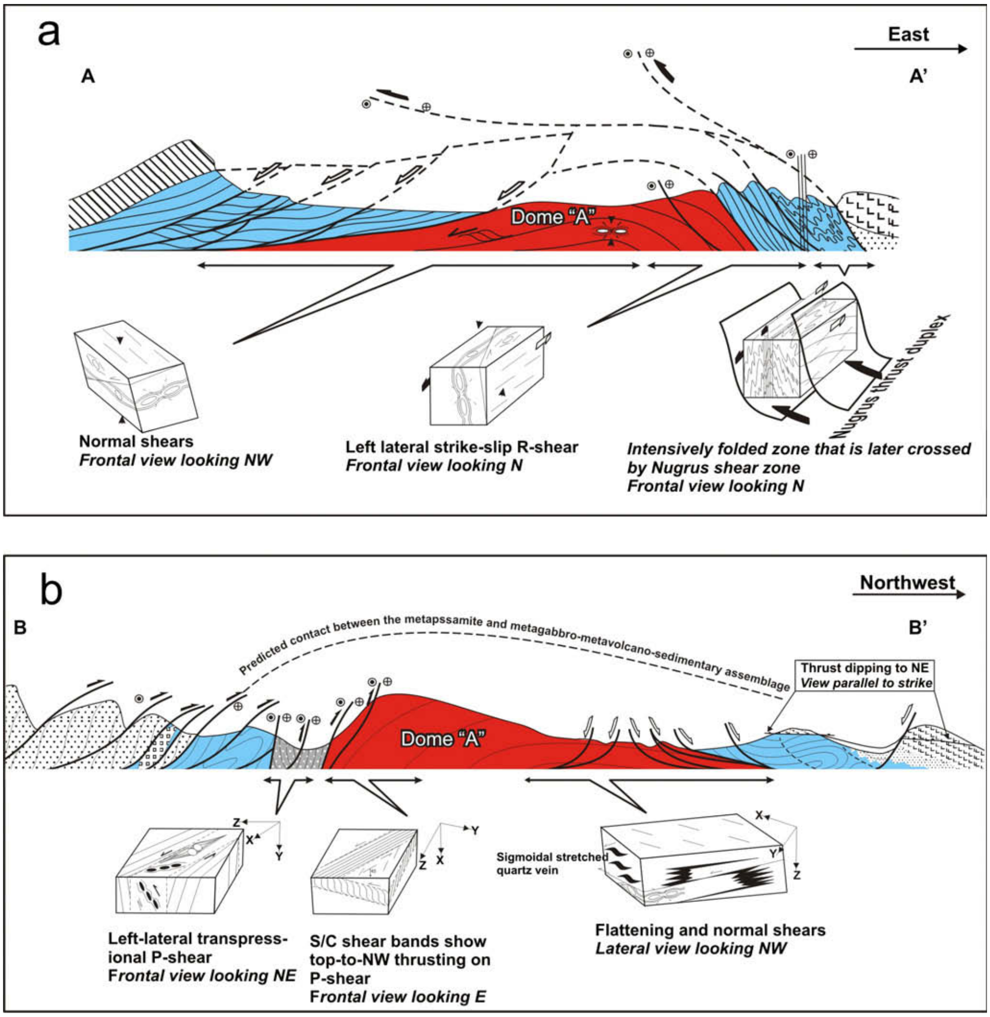

Fig. 3. Schematic cross-sections to illustrate the structural setting in two profiles crossing the geological map in Fig. 2. Block diagrams associated with each section show the fabric characteristics along the given profiles.

(Fig. 2). This unit represents the western limit of the westward imbricate thrust packages of the Pan-African Nappe assemblages constituting the Nugrus thrust duplex (Figs. 1b and c; Makroum, 2003). These thrust packages form sigmoidal horses within low-angle, left lateral strike-slip shear zones of Nugrus wrench corridor (Makroum, 2003). El Gaby et al. (1994) mapped the rock units in the area of Nugrus shear zone as NE–SW trending doubly plunging anticlines bounded by NW–SE trending thrusts. Fowler and Osman (2009) observed that the folds in the nappe assemblages are later subjected to NW-crustal extension with development of NE–SW trending, and NW-dipping low-angle normal fault along Wadi Sha'it (Fig. 2).

3. Structural setting

3.1. Planar, linear and shear sense data

The WHC is exposed within NW–SE elongated tectonic window; bordered to the east and west by two NW–SE trending left-lateral strike-slip shear zones (Fritz et al., 1996, Fig. 1). These shear zones are known as Najd Fault System (Stern, 1985) in the Arabian–Nubian Shield. The shear zones juxtapose the core gneisses of WHC against the Pan-African cover nappes. The culmination tapers to the south and opened to the northwest (Fig. 1b). Within the culmination, the structural setting of the five separated core gneisses have been interpreted as macroscopic non-cylindrical curved hinge antiforms or sheath folds (Fowler and El Kalioubi, 2002). However, details of the structural setting of the investigated dome (Dome A) have not been clearly determined by Fowler and El Kalioubi (2002) where its emplacement mechanism is still unclear. The investigated dome occupies the northern part of the culmination that is structurally dominated by development of northward dipping low-angle normal faults (Fowler and Osman, 2009). In this study, it will be shown that the extensional fabrics throughout the northern and western boundaries of the dome ''A'' overprint the earlier structures. The structural setting of the northern dome displays different orientations of planar and linear fabrics across the dome from the north to south and east to west (Fig. 4). From the spatial

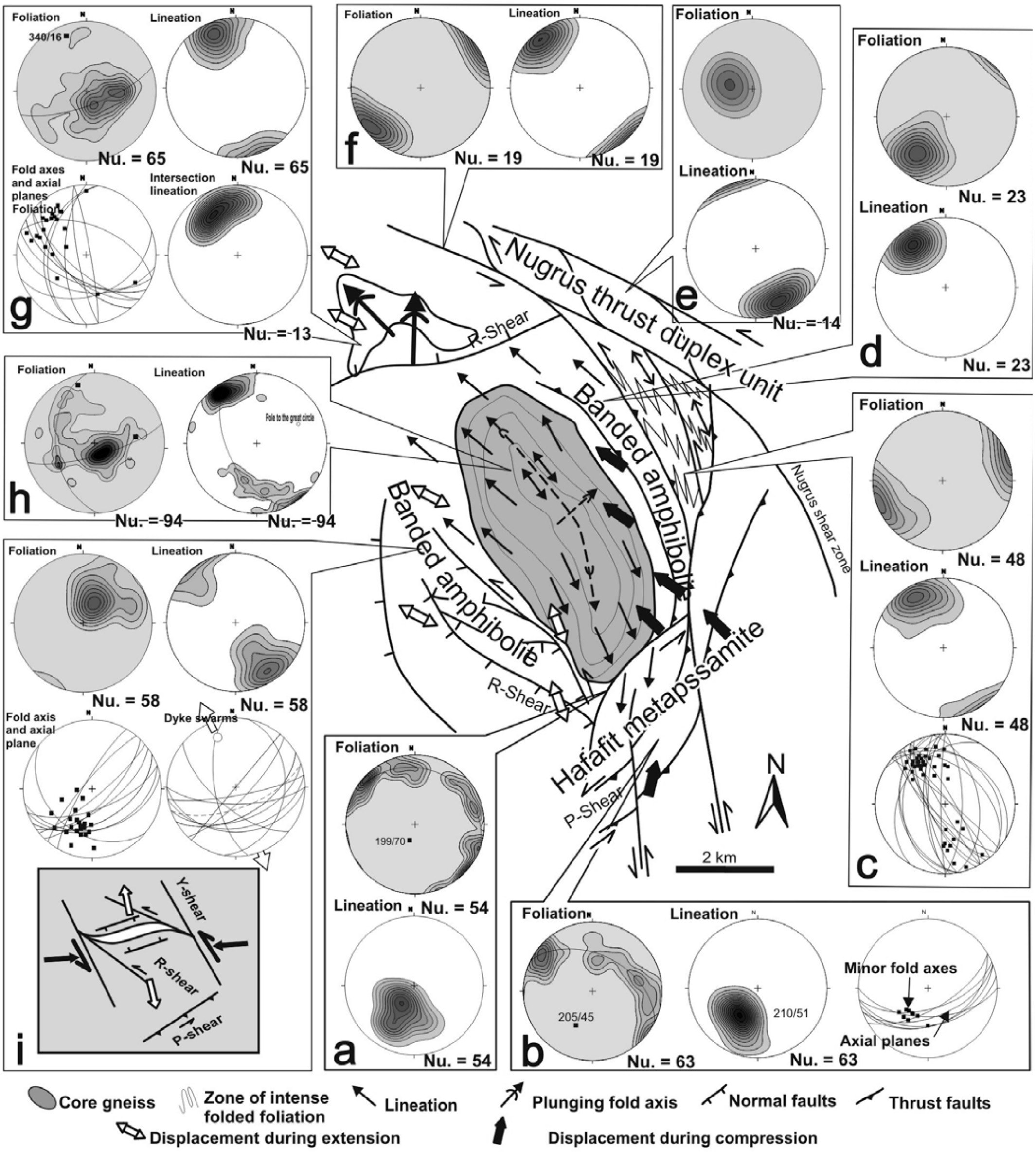

Fig. 4. Simplified structural map of the dome ''A'' with the location of linear and planar structural field data. Inset shows that the western domain is characterized by development of regional extensional gashes between well-developed R-shear arrays formed due to left-lateral displacement on NW–SE trending master shear arrays (Y-Shear).

distribution of the planar and linear data (Fig. 4), the investigated dome can be subdivided into five distinct structural domains; diagrams (a and b), (c–f), (g), (h) and (i) for southern, eastern, northern, core gneisses and western domains, respectively.

The southern structural domain (Fig. 4a and b) is located north of dome "B" (Fig. 1b) and immediately south of the core gneisse of the investigated dome (Dome "A"; Fig. 4). It extends NE–SW for about 5 km long and 3.5 km width. This domain is characterized by interstacking slices of Hafafit psammites and some minor amphibolites. The metasediments are strongly deformed along discrete shear zones with development of ultramylonites (Figs. 5a and b). Degree of deformation is progressively decreased away from these discrete shear zones. Generally, the metasediments are highly deformed and locally migmatized particularly close to the gneissic dome "A". The foliation is penetrative and commonly well defined by aligned hornblende, mica and chlorite as well as by the grain-shape fabric of dynamically recrystallised quartz and feldspars. The poles to foliations define gently dipping girdle with gently SSW plunging girdle axis that is parallel to the plunging axes of the associated mesoscopic and macroscopic folds (Figs. 4a and b). In addition, poles to foliation on the thrusts and strike-slip shear zones show vertical foliation trending mostly NE–SW. The stretching lineation plunges gently and homogenously to SW in all parts of this domain (Fig. 4). Rootless tight-folds of deformed amphibolite enclaves and

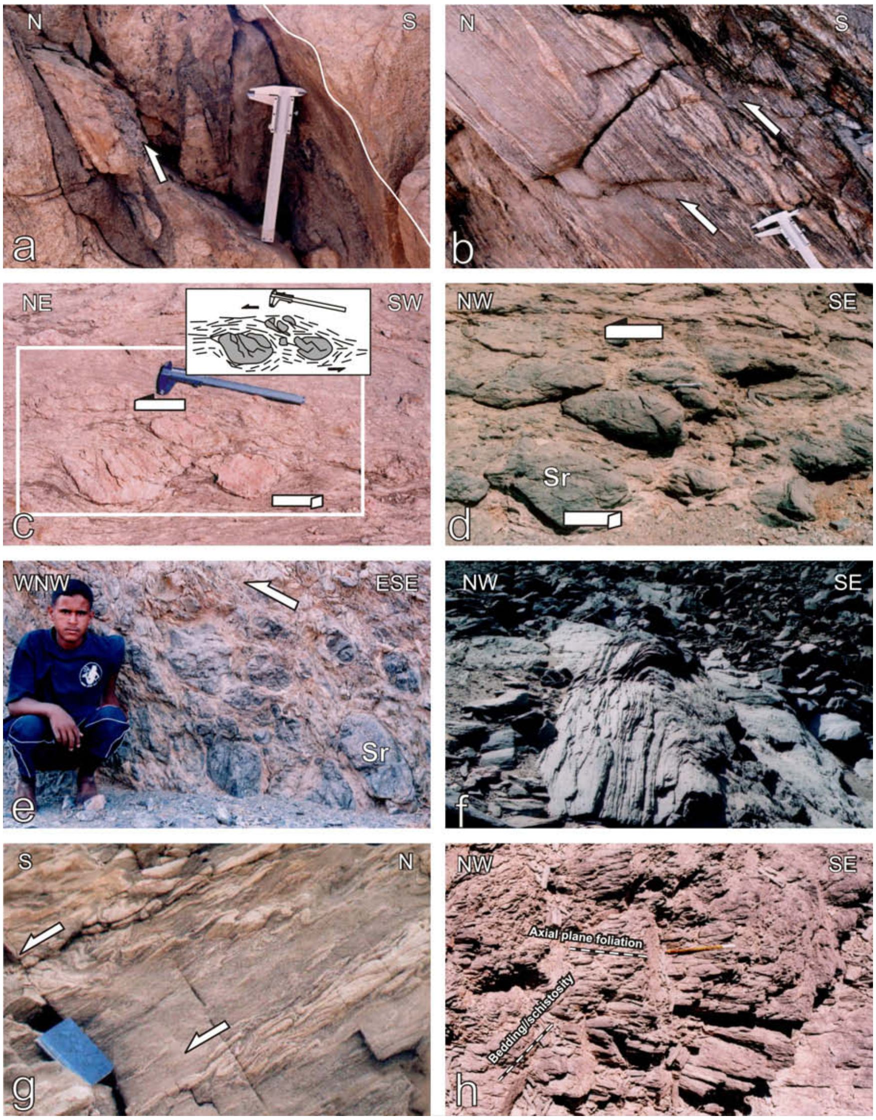

Fig. 5. Field photos in the area of dome "A". (a) Rootless isoclinal amphibolite folds along the thrusts in the southern boundary of the investigated dome showing transportation to N. (b) Ultramylonites in the metapssamite at the southern boundary of the dome with deformed quartz aggregates showing top-to-N tectonic transportation. (c) Map view on a NE–SW trending shear zone crossing the southern thrusts showing left-lateral shear sense by development of σ-porphyroclasts of potash feldspars in a matrix of quartz-rich metasediments. (d) Map view of deformed serpentine fragments (Sr) in a matrix of pulverized talc schist derivatives showing monoclinic symmetry with left-lateral shear sense in the eastern domain of the dome "A". (e) Cross-sectional view of the serpentine fragments (Sr) given in photo (d) showing top-to WNW tectonic transportation. (f) NW–SE trending isoclinal doubly plunging fold in the zone of intense folding between the core gneisses and the nappe units in the eastern domain. (g) Rootless drag folds and S–C′ fabrics indicate low-angle normal faults in the eastern domain of the investigated dome. (h) Intersection lineation resulted from intersection of bedding plane parallel schistosity and axial plane foliation in the northern domain of the investigated dome. (i) S–C′ shear bands showing low-angle normal faults at the northern boundary of the dome. (j) Formation of drag folds on the normal faults located north of the dome "A". (k) S–C fabrics showing thrusting to N in the southern and eastern parts of the core gneisses of dome "A". (l) In most central part of the core gneisses, the foliation is horizontal developing orthorhombic deformed feldspar grains indicating vertical flattening. (m) Three dimensional diagram formed by two field photo mosaics indicating formation of isoclinal recumbent folds due to vertical flattening coeval with extension in *X*–*Z* and *Y*–*Z* planes, respectively, in the western part of the core gneisses of dome "A". (n) S–C′ shear fabrics showing extension to south in the western part of the core gneisses.

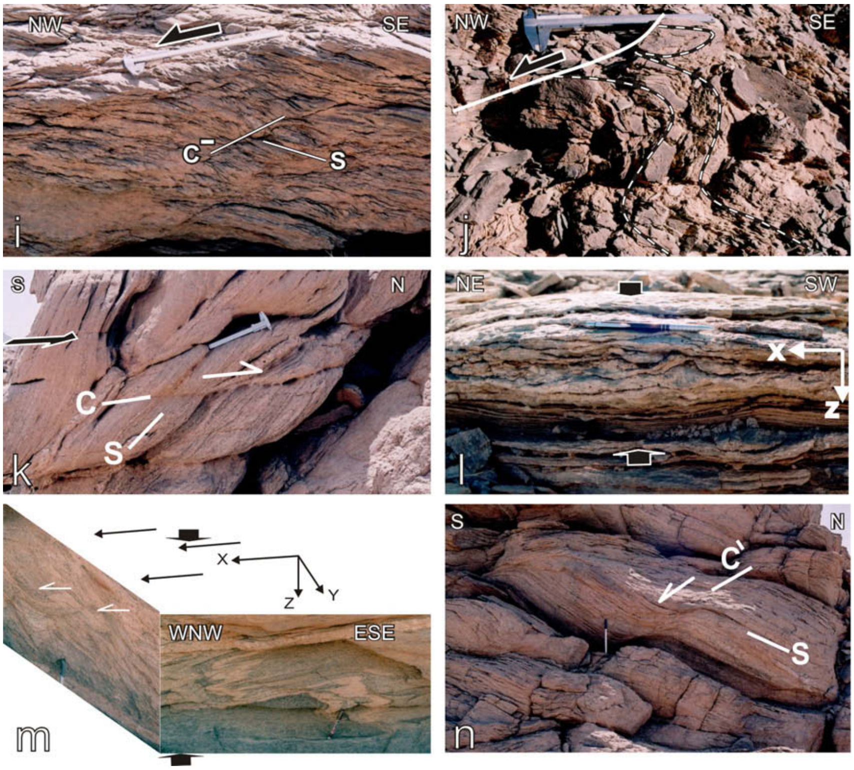

Fig. 5 (*continued*)

deformed quartz aggregates on a cross-section view suggest stacking from south to north (Figs. 5a and b). The monoclinic symmetry of core-mantle fabrics and the S/C shear bands on the steeply dipping NE-SW trending strike-slip shear zones and thrust planes argue for left-lateral shear sense on a map view (Fig. 5c). Field relationships and geological mapping for the southern domain (Fig. 2) indicate that the northeast-southwest trending thrusts and folds are crossed by the left-lateral strike-slip shear zones.

The eastern domain (Figs. 4c–f) contains the two main lithological units described before as inner and outer units (Fig. 2). The banded amphibolite of the inner unit overlies directly the gneissic dome and display homogenous structural fabrics with the underlying core gneisses. The foliation is defined by deformed mica and amphiboles with stretched quartz veins. Stretched grains of amphiboles and micas and rod-like aggregates of quartz grains constitute the stretching lineations. Some aggregates of needle-like chlorites covers, in most cases; the stretching lineations. The foliation extends NW–SE and dips gently to NE while lineation plunges moderately to NW (Fig. 4d). The outer unit is structurally composed of northwestward-stacking thrust duplexes of Wadi Nugrus area (Fig. 2), which represents the rock assemblages of Pan-African cover nappes (Makroum, 2003; Fowler and Osman, 2009). The foliation and lineation are defined by well deformed volcanogenic clasts and serpentine fragments (Figs. 5d and e), which are locally coated by fibers of chlorites and serpentinites. The foliations at boundaries of such duplex are vertical and trend NW–SE, whereas the stretching lineation plunges sub-horizontally to NW (Fig. 4f). S/C shear bands and stair-stepping around highly strained clasts indicate left-lateral sense of shearing (Fig. 5d). The vertical foliation and sub-horizontal lineation at duplexes boundaries are interpreted as the thrust duplexes are crossed by the NW–SE trending Nugrus shear zone (Fig. 2). In contrast, the foliations within horses, developed in such duplex, dip moderately to E, while the stretching lineations plunge sub-horizontally to SSE (Fig. 4e). Monoclinic symmetry of deformed serpentine clasts in highly sheared and pulverized matrix of different rock grains indicates top-to-NW (Fig. 5e). The foliation in the triangular area between the inner and outer units is penetrative; defined by well aligned micas and amphiboles. The foliation is vertical and oriented NNW–SSE, whereas the stretching lineation plunges relatively shallowly to NNW. The mesoscopic folds developed in this area are tight, isoclinal and doubly plunging folds (Fig. 5f). The fold axes plunge moderately NNW and SSE, parallel to the stretching lineations, with axial planes trending NW–SE (Fig. 4c). High-angle, left-lateral NNW–SSE trending strike slip shear zones are developed between these folded foliations (Fig. 2).

The western domain (Fig. 4i) is located west of the investigated dome extending generally north–south but it swings westward as a curve-linear outcrop pattern around the western boundary of the core gneisses (Fig. 2). This domain is represented by banded amphibolites of the inner rock unit which conformably overlies the core gneisses. The foliation dips moderately to SW while stretching lineation plunges shallowly to SE and NW (Fig. 4i). The fold axes of rootless shear-related drag folds (Fig. 5g) plunge moderately to SSW, and their axial planes dip mostly to SE (Fig. 4i). The S/C shear bands, asymmetry of rootless drag folds and rotated fabrics in the amphibolite sequence indicate NW–SE extension on low-angle ductile normal faults (Fig. 5g). The NW–SE extension is followed by emplacement of ENE–WSW trending aplite veins (Fig. 4i). Asymmetrical sigmoidal shears oriented NW–SE around two unnamed valleys are bridged by WNW–ESE trending horsts and grabens formed on normal faults (Fig. 2). These sigmoid structures are developed as mega-scale extensional gashes developed in Riedel shear array (sketch in Fig. 4i).

The northern domain (Fig. 4g) occupies the area joining the thrust duplex of Wadi Nugrus (eastern sector) with the northwest dipping low-angle normal faults, north of WHC, (Fowler and Osman, 2009) that are considered as the northern extension of the western domain (Figs. 2 and 4g). The foliation across the rock sequence from the east to west indicates two main shallow dipping maxima which from one girdle with a pole plunging sub-horizontally to NNW. The stretching lineations plunge sub-horizontally to NNW; relatively parallel to the plunge of associated mesoscopic folds axes whose axial planes dip mostly to SW (Fig. 4g). The intersection lineations, which are developed by intersection of axial plane foliation with bedding plane parallel schistosity (Fig. 5h), also plunge moderately to NNW (Fig. 4g). The S/C′ extensional shear band cleavages and associated drag folds indicate NW–SE extension (Figs. 5i and j), which associated with formation of outcrop-scale drag folds (Fig. 5j). The drag folds in this zone are overturned plunging shallowly to NW and SE. These folds are developed between NW–SE trending left-lateral strike-slip shear zones and NE–SW striking normal faults (Fig. 2).

The core gneisses structural domain (Fig. 4h) is exposed in the lower structural unit that is comparable to other basement domes within the Eastern Desert. The core gneiss of the investigated dome has an elliptical shape extending NNW–SSE. The gneissic bands vary in thickness from few centimeters to about 20 cm. The gneissic foliation is penetrative and consists of deformed quartz ribbons, intervening bands of feldspars, micas and amphiboles. Stretching lineation is defined by rod-like stretched mineral grains constituting the foliation surfaces. The steronet-plots for the poles to foliations exhibit two great girdles in which their poles plunge sub-horizontally to NNW and moderately to ENE (Fig. 4h). The stretching lineation plunges moderately to NW and to SE in the northern and southern part of the dome, respectively, forming one girdle with a pole plunging moderately to ENE (Fig. 4h). The S/C fabrics are the most common kinematic indicators at the extreme southern and eastern parts of the dome "A" reflecting top-to-N tectonic transportation (Fig. 5k). In the central part of the core gneisses, the horizontal and sub-horizontal foliation and the development of orthorhombic symmetry of strain shadows in core-mantle fabrics with formation of tight isoclinal recumbent folds indicate high component of vertical flattening (Fig. 5l and m). In the western part of the dome, the S/C′ fabrics and extensional crenulation cleavages, asymmetric boudins and rootless folds indicate southward and northward extensions on ductile low-angle normal faults (Fig. 5n). The geologic map (Fig. 2) shows that the fault patterns in the western part of the core gneisses form extensional duplexes bordered by two NW–SE trending low-angle left lateral strike-slip ductile faults.

3.2. Interpretation of structural data

Two major structural units can be distinguished from description of structural data: (1) the antiformal dome, and (2) the thrust duplex of Wadi Nugrus with the development of Nugrus master and subsidiary shear zones.

The antiformal dome involves the core gneisses and the overlying amphibolite bands which totally constitute the inner rock unit. The foliation and stretching lineation in the inner rock unit are conformable, insomuch the foliation trajectories in both rock types suggest one major structural unit. The structural data of this major unit indicate that: (1) the foliation trajectories (Fig. 2) converge to the NNW and SSE in the northern and southern parts of the dome, respectively. (2) The pole to girdle passing through the two clusters of poles to gneissic foliations plunges shallowly to NNW (Fig. 4h). (3) The foliation dips moderately to east and shallowly to west in the eastern and western boundaries of the core gneisses, respectively (Fig. 3a). Consequently, the dome is explained geometrically as doubly plunging asymmetrical antiform that is folded shallowly about NNW–SSE trending axis (Fig. 6a). This axial trend is oriented parallel to the axis of elongation of the investigated dome suggesting that the NNW–SSE trending axis represent the early phase of folding, associated with initial up-doming of the inner rock unit (Fig. 6). The NW and SE plunging stretching lineation are oriented oblique to the early phase of folding axis (Fig. 6a), and because the NW–SE trending lineation is generally related to accretion of the Pan-African cover Nappes in Nugrus area (Fritz et al., 1996; Makroum, 2003), it is accepted that the up-doming and resulted antiform are formed with ongoing westward stacking of the Wadi Nugrus rock units. The NW and SE plunging stretching lineation in the northern and southern half of the dome, respectively (*the simplified map in* Fig. 4), and the eastward plunging pole to girdle of a second group of foliation poles (Fig. 4h) indicate that the earlier lineation was refolded around gently ENE-plunging macroscopic fold axis, superimposing the NNW–SSE trending earlier regional antiform (Figs. 6b and c).

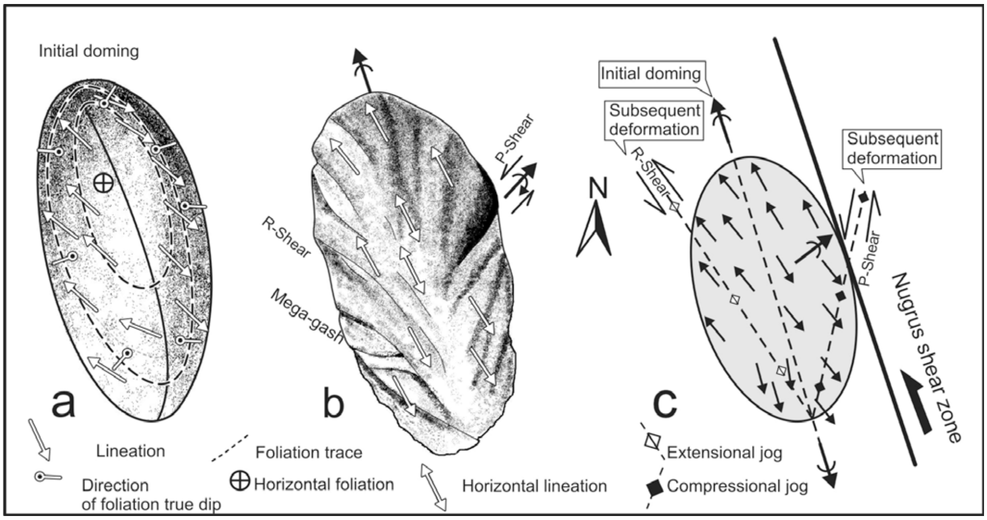

Fig. 6. Sketches showing structural geometry of dome "A" based on integration of previously described structural data. (a) Three dimensional cartoon for the early formed domal structure of core gneisses. Note that stretching lineation is oriented oblique to fold hinge. (b) Subsequent deformation to (a) resulted in development of NE-plunging fold and extensional mega-gashes in the eastern and western half of the domal structure, formed within P- and R-shear arrays, respectively. (c) A diagram showing that the NE- and NW-trending Riedel shear arrays are synthetic to Nugrus master shear zone. Northeast plunging superimposed fold and thrusting to NW (Figs. 5k) suggest development of compressional jogs on NE-trending P-shear array in the eastern half of the dome "A" while formation of extensional gashes and fabrics (Fig. 5m and n) in its western half indicate development of extensional jogs on NW-trending R-shear array. Note that stretching lineation is refolded around NE-plunging fold.

The thrust duplex of Wadi Nugrus is located east of the investigated dome dislocating the thrust packages of volcano-sedimentary association against the antiformal dome with shear sense criteria showing top-to-NW tectonic transportation. The packages are subsequently deformed into sigmoidal horses by Wadi Nugrus left-lateral strike-slip shear zone (*simplified map of* Fig. 4). The Nugrus shear zone is considered as one of master shear zones of Najd Fault System of Stern (1985) in the Eastern Desert of Egypt (Makroum, 2003; Shalaby et al., 2005, 2006). It has been shown that the Nugrus master shear zone is linked with subsidiary "Riedel" shear arrays that are oriented NE and NW oblique to its main trend (Fig. 6c). These shear arrays cross-cut both antiformal domal structure and the Nugrus thrust packages (Fig. 2). The NE- and NW-trending arrays are left-lateral shear zones, synthetic to the Nugrus master shear (Fig. 6c). In contrast, the NE-trending shear array is linked with development of (1) ENE plunging open fold associated with top-to-NW tectonic transportation in the eastern part of the gneissic dome (Fig. 6b), (2) high-angle NE–SW trending left-lateral thrust-dominated strike-slip shear zone on the southern contact of the core gneisses with Hafafit metapssamite (*simplified map of* Fig. 4). Along this contact, the metapssamites are directly thrust over the core gneisses where amphibolite bands surrounding the core gneiss are abruptly removed (Fig. 2). These structural observations on the NE-trending shear array and its synthetic shear sense to Nugrus master shear explain shortening strain across its trend. Therefore this trend is depicted, with development of compressional jogs, as P-shear array to the Nugrus master shear zone (Fig. 6c). In the same manner, the NW-trending shear array is characterized by dilatational jogs since this trend is constrained by extensional fabrics, such as normal faults and mega-gashes that are widely common in the western half of the core gneisses (Figs. 2 and 6b). In addition to its synthetic shear sense to Nugrus master shear, it is considered as R-shear array (Fig. 6c). These Riedel shears affect the earlier fabrics in the antiformal dome and the Nugrus thrust duplex structural units suggesting their subsequent deformation to up-doming of the core gneisses (Fig. 6c).

4. Integrated structural evolution

The structural evolution of dome "A" of WHC can be interpreted in terms of a sequence of deformation events (Fig. 7). The sketch in Fig. 7 is drawn W–E, comparable to the profile in Fig. 3a. Four Neoproterozoic deformational events are suggested in contribution of final geometry of the investigated dome.

From overall geometry and succession of events, the earlier deformation is concerned with formation of the core gneisses of dome "A" and the surrounding amphibolite bands (Fig. 7a). The genesis of core gneisses is a point of great controversy, some authors attributed the core gneisses of dome "A" to sedimentary origin (e.g. Abu El Enen and Massonne, 2008), others related the gneisses to I-type, subduction related calc-alkaline protoliths (Abd El-Naby and Frisch, 2006; Abd EL-Naby et al., 2008). Khudeir et al. (2008) attributed similar core gneisses in the Eastern Desert to pre-Neoproterozoic continental crust. Geochemistry and isotope analyses are not the target of this study to decipher the genesis of core gneisses of dome "A". However, field observations indicate that the gneisses are heterogeneous in composition showing intercalations of discrete bands of quartz-plagioclase and hornblende-biotite rich gneisses. This heterogeneity suggests sedimentary origin of these core gneisses; also supported by geochemistry of gneisses occupy the northern half of WHC (Abu El Enen and Massonne, 2008). The protolith age of these gneisses may be similar to other core gneisses in the Eastern Desert that were formed around 780 Ma (e.g. Loizenbauer et al., 2001). The amphibolite bands overlying the core gneiss are formed in back-arc setting (Abd El-Naby and Frisch, 2006), and their contribution to the sequence is ambiguous because of their structural homogeneity with the underlying core gneisses. Consequently, they are considered as part of Hafafit core gneisses (Fig. 7a). The gneissic bands and the associated isoclinal folds are considered by Greiling et al. (1984, 1996) and El Ramly et al. (1993) as structural fabrics related to early deformation episodes, which precede accretion of the Pan-African cover napps in Eastern Desert (Fritz et al., 1996).

The next two events are interpreted to represent one continuous deformation event that is associated with accretion of the Pan-African nappe sequences onto the remobilized, polymetamorphosed and polydeformed granite gneisses (Fritz et al., 1996; Loizenbauer et al., 2001). The cover nappes are best developed in the area east of WHC forming imbricate packages of Nugrus area (Makroum, 2003). In this deformation event, the Hafafit metapsammite is thrust over the gneissic core package, and shallowly folded around NNW–SSE trending fold axis (Fig. 7b). Shear sense indicators imply that the transportation was from SE to NW on southeastward dipping faults (Fig. 3). The planar and linear fabrics constituting the Hafafit metapsammite and the underlying core gneisses are unlike, while their fabrics are well matched with the rock package of the overlying Nugrus thrust duplex. Therefore, the tectonic position of Hafafit metapsammite is suggested to straddle the inner rock units "granite gneisses and amphibolites" to the overlying Nugrus cover nappes. It is likely that this deformation represents the onset of Pan-African nappe accretion that is correlated with the structural evolution within metapelites elsewhere in the Eastern Desert that is bracketed around 660 Ma (Loizenbauer et al., 2001; Fritz et al., 2002).

Continued E–W bulk shortening resulted in accretion of low grade arc/back arc volcano-sedimentary association of Pan-African nappe assemblage from the SE to NW around 620 Ma (Loizenbauer et al., 2001). This deformation resulted in emplacement of Nugrus thrust nappes onto the remobilized gneisses of WHC through N- to NW-verging thrusts (Fig. 7c). Vergence is oriented oblique to the WHC on southeasterly dipping thrust faults cross-cutting the early thrust-related Pan-African Hafafit metapssamite (Fig. 3b). During this deformation event: (1) parts of amphibolites overlying the core gneisses in the eastern boundary of the dome are intensively folded (Figs. 4a "*the simplified map*" and 7c), in which the fold asymmetry indicates transportation was from SE to NW, and (2) the metapsammites and the overlying cover nappes are stacked over the gneisses of dome "A". Stacking suggests horizontal and vertical attitudes of ($\sigma1$) and ($\sigma3$), respectively, at the eastern contact of the investigated dome (Fig. 7c). Nappe accretion and consequently progressive crustal thickening caused enhancement of gravitational forces within the future dome and finally a shift of ($\sigma1$) to a vertical orientation. This is triggered with vertical flattening in the central part of the dome, coeval with formation of some synthetic ductile normal faults to the western half of the dome area. These faults are precursors of Riedel shears that are reactivated and developed in later deformation event. These conditions favored the core gneisses to onward up-doming vertically through overlying rock assemblages.

The late stage of Pan-African orogeny in Eastern Desert is characterized by formation of NW–SE trending, left-lateral strike-slip dominated transpressional shear zones (Fritz et al., 1996); known in the Arabian Nubian Shield as Najd Fault System (Stern, 1985). This event is associated with emplacement of gneissic domes around 580 Ma (Fritz et al., 1996; Loizenbauer et al., 2001; Bregar et al., 2002). In the investigated dome, the formation of Nugrus shear zone and the subsidiary synthetic shear arrays are correlated with this deformation event in Eastern Desert because: (1) The Nugrus shear zone strikes parallel to the trend of the Najd Fault System and is also characterized by sinistral displacement. (2) The Nugrus shear zone and subsidiary shear arrays cross-cut the

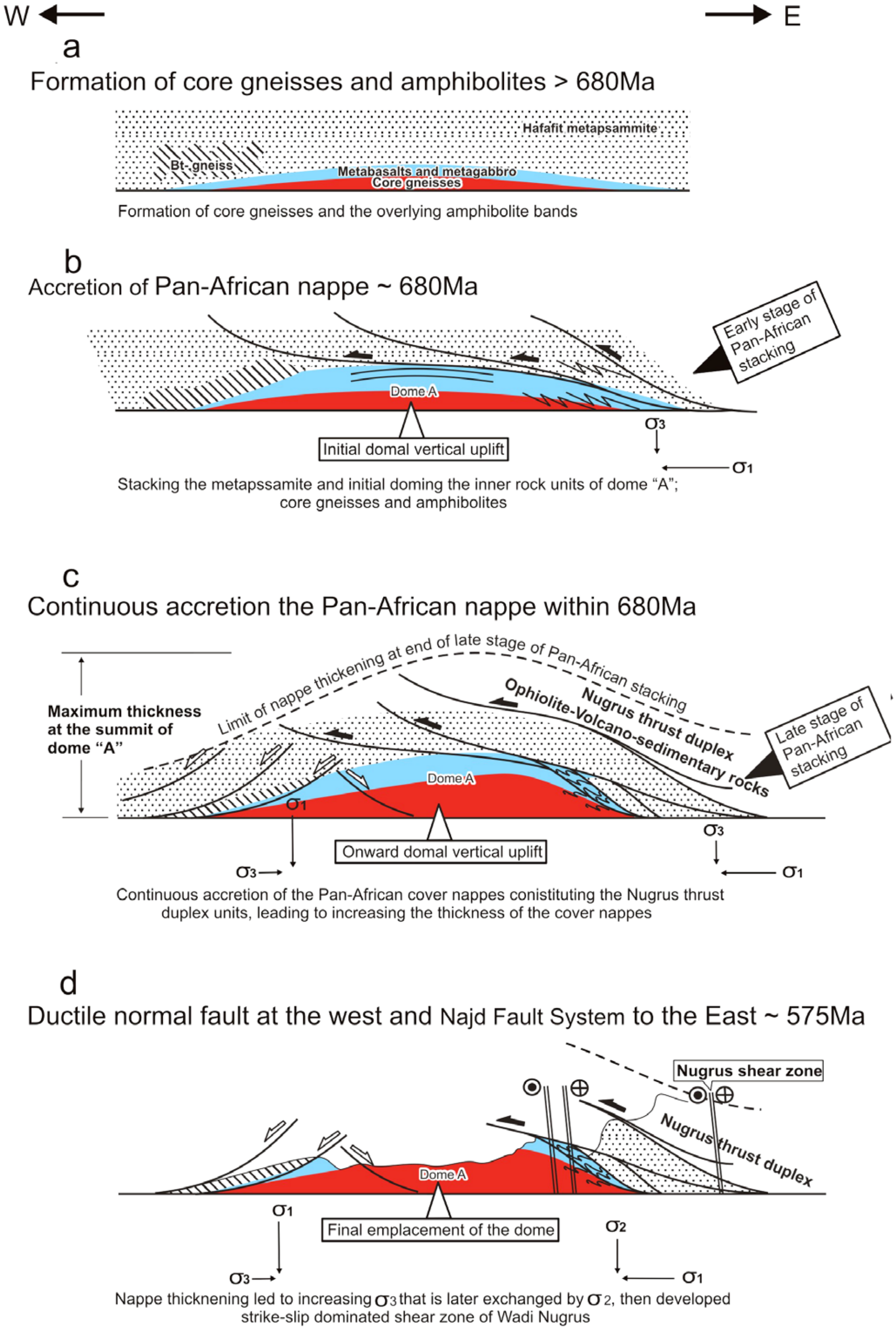

Fig. 7. Interpretative cartoons showing the emplacement history of the dome "A". For succession of events age data by (Fritz et al., 1996, 2002; Loizenbauer et al., 2001; Bregar et al., 2002; Moghazi et al., 2004) were used.

earlier Pan-African thrust nappes, the Hafafit metapsammite south of the core gneiss of dome "A" and the zone of intense folding east of the investigate dome (Figs. 2 and 4). (3) Emplacement of leucogranites in the area east of WHC suggests that the Nugrus shear zone was formed around 594 (Moghazi et al., 2004), and Ar/Ar cooling ages from Hafafit have approximately the same age (Fritz et al., 2002). In this deformation event, the NW–SE trending strike-slip shear zones are developed in the eastern part of dome "A" with E–W bulk compression associated with horizontal attitudes of (σ1) and (σ3).

5. Discussion

5.1. Kinematics during formation of dome "A"

The main aspect of this paper is to contribute the origin of gneissic dome "A" that crops out in the northern area of WHC. This study has shown that the northern and western half of dome "A" are characterized by extensional collapses to NW affecting both the core gneisses and surrounding rock units whereas its eastern and southern extremities show only stacking to NW (Fig. 3). There-

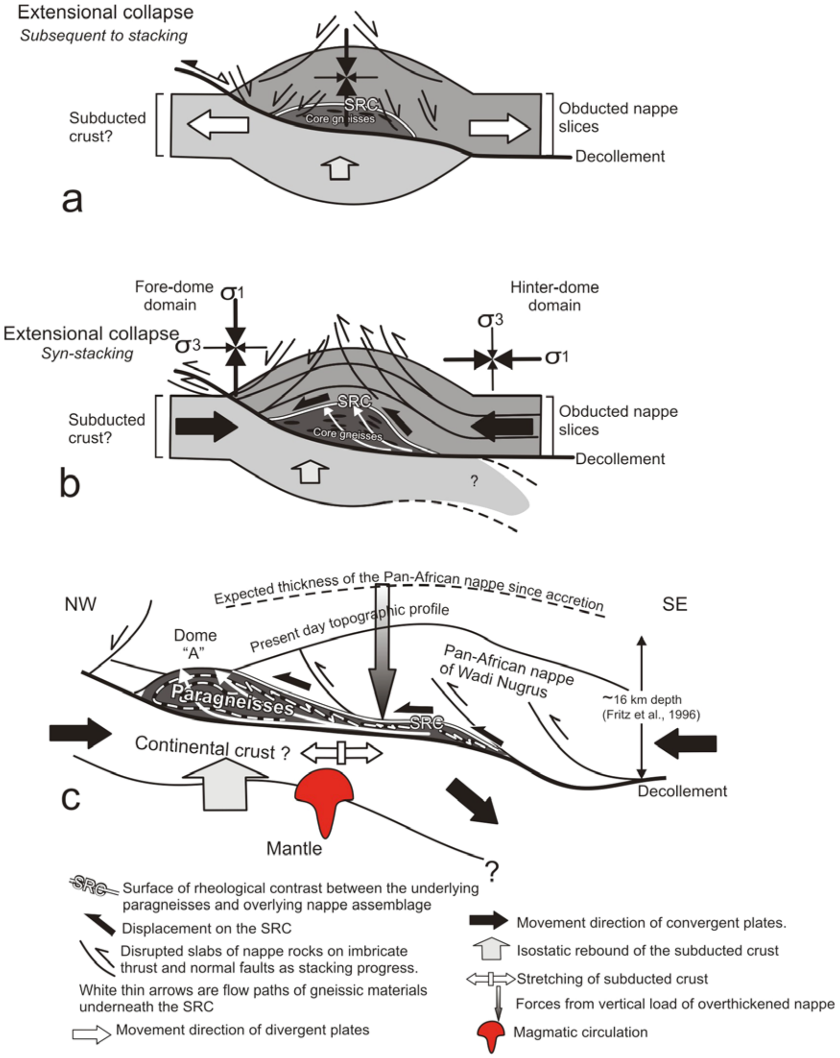

Fig. 8. Interpretative cross-sections showing the possible scenarios of extensional collapses (e.g., Ratschbacher et al., 1989; Kilias et al., 1994; Muñoz et al., 1994 *and from own drawings*) that might have operated in the study area. (a) A classical extensional tectonic model consequence of terminal continental collision with gravitational adjustment of an unstable overthickened crust. Normal faults spread laterally away from the exhumed core gneisses overprinting fabrics of earlier stacking. The SRC appears symmetrical and shallow dipping on both sides of the domal structure. (b) Crustal stacking and extension are synchronous in regions of frontal ramps. The obducted plate undergoes extension in fore-dome domains, contemporaneous to nappe stacking hinter-dome domains. The SRC is formed of ramp and flat segments and displacement on it causes gneissic materials to migrate obliquely away from the ramp and accumulate under the flat segment. The overall geometry of the domal structure is an asymmetrical antiform. (c) The cross-section across dome "A" shows that diagram (b) is relevant for its formation. The overthickened and denser Nugrus thrust nappes induces vertical load on SRC and decollément; the upper and lower confining boundaries of core gneisses, that squeezed the gneissic materials to flow laterally underneath the accreted nappe. Northwestward displacement on the SRC, the fore-dome extensional collapse in upper crustal levels and isostatic rebound on subducted crust accommodate final ascent of gneissic materials to northwest.

fore it is envisaged that the crustal stacking and extensional collapses have occurred simultaneously during accretion of the Nugrus cover nappe (Fig. 7c). Consequently the interpretation of such extensional collapse as subsequent to contractional separate deformation events seems unlikely. Although previous geological investigations carried out on the whole culmination and Nugrus shear zone (Greiling et al., 1988b; Rice et al., 1992; Makroum, 2003; Fowler and Osman, 2009) show discrete extensional lineaments and regional scale normal faults, field observations in this study attribute these mapped extensional lineaments to reactivation of early ductile extensional fabrics during terminal emergence of the whole culmination at upper crustal levels. Evidences illustrate these observations will be discussed later in some detail. In order to understand the kinematics of simultaneous crustal stacking and extensional collapse in the investigated dome, this study presents two possible diagrammatic models of orogenic collapses based on author field observations and some of published works (Figs. 8a and b).

There are two possible scenarios of extensional collapses (e.g., Ratschbacher et al., 1989) that might have operated in the study area. The first one is a classical extensional tectonic that occurs as a consequence of terminal continental collision and represents gravitational adjustment of an unstable thickened orogenic wedge. Fig. 8a shows that the overthickened crust is proposed to have spread laterally away from the exhumed core gneisses, and the decollément is bowed as gravitational collapse progressed (e.g. Kilias et al., 1994). In this scenario, normal faults are a common feature on both sides of the exhumed gneisses overprinting fabrics of earlier stacking. The surface of rheological contrast (SRC), separating the ductile core gneisses from the stacked semi-ductile to brittle cover nappes, appears symmetrical and shallow dipping on both sides of the domal structure. Crustal extension in the next scenario is usually accompanied by crustal stacking and is common in regions of frontal ramps (e.g. Muñoz et al., 1994). In convergence tectonics (Fig. 8b), the obducted plate undergoes extension in fore-dome domains, concomitant to crustal or nappe stacking hinter-dome domains. In this scenario one side of the dome is dominated by extensional fabrics while the opposite side is a thrust dominated. Ongoing convergence resulted in frontal imbrication, nappe slices are disrupted on imbricate thrust faults hinter-dome and the upper plate undergoes extensional collapse in fore-dome areas. The SRC is formed of ramp and flat segments in hinter- and fore-dome domains with developing contractional and extensional fabrics, respectively (Fig. 8b). The gneissic materials migrate obliquely away from the ramp and accumulate under the flat segment. The overall geometry of the domal structure is an asymmetrical antiform. This later extensional model interprets the structural inversions across dome "A". Normal faulting, uplifting and erosion are the results of isostatic rebound of the decollément as extensional collapse proceeds.

In application to the dome "A", the WHC is tectonically underlain by northwestward verging Nugrus thrust nappes extending for about 30 km between Meras Alam to the culmination. Greiling et al., 1984 and Kröner et al., 1987 envisaged that the Hafafit gneissic domes are the boundary of frontal ramp of the imbricate thrust packages of Wadi Nugrus, giving rise to nappe thickening on the hanging wall east of WHC (Fig. 8c). The excess area balancing method using the surface geology of WHC estimated about 16 km depth to the decollément (Fritz et al., 1996) which represents a minimum depth for core material below the domes in late Neoproterozoic, and however, it does not give too much about the entire crustal thickness during the collision process that might be much higher (Fig. 8c). The Nugrus cover nappes, which are composed of arc/back arc volcano-sedimentary associations with stacking slabs of dismembered ophiolite, are denser than the underlying silica-rich Hafafit core gneisses. This overthickened denser nappe induces vertical load on both the SRC and the decollément that represent the upper and lower confining boundaries of core gneisses, respectively (Fig. 8c). Cover nappe overthickening and thermal weakening of the lower crust, resulted from voluminous magmatic circulation from the area east of WHC (Ghazala, 2001), led to stimulating crustal stretching for the lower crust and consequently enhance the buoyancy forces that favors emplacement of gneissic materials (Fig. 8c). The downward and upward directed forces from vertical load on the SRC and from the buoyancy forces on the decollément, respectively, squeezed the gneissic materials to flow laterally underneath the accreted nappe. Meanwhile, the northwestward displacement on the SRC and the fore-dome extensional collapse in upper crustal levels accommodate final ascent of gneissic materials to northwest (Fig. 8c).

5.2. Debates on Wadi Hafafit culmination

Exhumation of gneissic domes in WHC had been a substantially debated topic within scientific community in recent years. The fault-bend fold model is the first model suggested to interpret the tectonic setting of the WHC (Greiling et al., 1988b, 1996; Greiling, 1997). In this model the WHC fold pattern has been interpreted to be partly composed of large-scale fault-bend folds, including monoclines, antiforms cored with domal structures and synforms occurred between such domes, associated with ramps and major thrusts bounding the culmination from the east and west. Fowler and El Kalioubi (2002) refuted the model of fault-bend fold by considering that the entire concept of ramps in the hypothetical Hafafit thrust model is not supported by their field evidences concluding that the dome "D", which represents the largest dome in the culmination, does not contain the discrete antiform suggested by Greiling (1997). Furthermore, the fault-bend folds are typical for low-grade rocks and confined to upper crustal levels but they unlikely occur at high-grade metamorphic conditions with spectacular evidences of ductile flow (e.g. Kisters et al., 2004). Accordingly, and because the core gneisses of WHC are composed of domes of variable sizes that are located one over another in a typical ductile flow regime (Fowler and El Kalioubi, 2002); perhaps on thrust zones located between such domes, the fault-bed fold model should be reviewed with detail mapping of the whole culmination and its surroundings. However, it is not possible to neglect the foreland thrust imbrications of the cover nappes (Makroum, 2003) in developing ramps and antiformal geometries of shallower rock units at Hafafit area.

The model of orogen-parallel crustal extension has been previously proposed for interpretation of the exhumation of core complexes in Eastern Desert (Fig. 1a; Wallbrecher et al., 1993; Fritz et al., 1996, 2002; Loizenbauer et al., 2001; Bregar et al., 2002; Abdel Wahed, 2008). In this model, core gneisses, in which Hafafit dome is one of these, are exhumed within a left-lateral dominated transpressional wrench corridor of Najd Fault System coeval with development of NW- and SE-dipping low-angle normal faults at their northern and southern boundaries, respectively. These structural fabrics were evaluated by Fowler and Osman (2001) for the Um Had dome, located about 40 km west of Meatiq core complex, and re-consistently reviewed by Fowler et al. (2007), for Sibai core complex, as to formation of NW–SE trending doubly plunging folds that are paramount regional structure of the whole Central Eastern Desert (Abdeen and Greiling, 2005), coeval with extension parallel to fold hinge and orthogonal to E–W bulk compression. Description of Hafafit dome in a context of core complex models in Eastern Desert is not discussed properly in detail so far.

Recently, the WHC has been explained by Fowler and El Kalioubi (2002) as a peculiar model of interference large-scale sheath fold. In this model, they attributed the formation of dome "A" to a refolded monoclinally buckled upper limb of a sheath fold. Despite their well documented field evidences of interpretation of sheath fold geometry for domes "B"–"E", their interpretation for formation of dome "A" as a sheath fold needs some convincing arguments. Although they documented that sheaths of typical elliptical outcrops show radial distribution of stretching lineation, migrating towards the sheath fold hinge and acquire curvature near the tip of the fold, the field data presented in this study for dome "A" does not adopt sheathing because:

(1) The stretching lineations show two great clusters trending sub-horizontally to NW and SE (Fig. 4h), with insignificant curvature patterns on map view (*simplified map,* Fig. 4).

(2) Poles to foliations show two girdle patterns demonstrating two superimposed cylindrical fold geometries with gently early NNW- and later NE-plunging fold axes. Its elliptical shape is therefore, simply described as NNW–SSE trending doubly plunging antiform (Fig. 4h).

(3) The steepness of gneissic foliation of core gneisses at the southern boundary of dome "A" is attributed by Fowler and El Kalioubi (2002) to a southward verging monoclinal flexure superimposing the early developed sheath fold as a result of NW–SE shortening. The southward verging monoclinal flexure, if it occurs, *should be* kinematically resulted in overprinting the southern boundary of the proposed sheath fold (i.e. the steepest limb of the monocline) with shear sense fabrics showing southward verging normal faults. Evidences of normal shear senses are not documented southward, but it has been shown that this boundary is a left-lateral dominated transpressional shear zone dislocating and overthrusting the Hafafit metapssamite on the core gneisses (Figs. 5b and c).

(4) The vertical flattening documented in the core gneisses of dome "A" indicates that the dome has suffered coaxial deformation coeval exhumation, while sheath folds of regional-scale are favorable in regions suffered non-coaxial progressive

simple shear deformation regime (e.g. Lacassin and Mattauer, 1985; Vassallo and Wilson, 2002). Although sheaths may be developed in conditions of general shear deformation (e.g. Alsop and Holdsworth, 2006), the transportation induce sheathing, as may be anticipated, would be oriented in direction orthogonal to flattening (i.e. parallel to axis of elongation of elliptical sheath) and consequently possesses components of simple shear deformation in direction of material flow that is parallel to extension lineation, and this is not also considered in dome ‘‘A’’ (Figs. 5i and m).

5.3. So, what model could be suitable for interpretation of Hafafit Culmination?

Structural observations in WHC show that the culmination is bounded from east and west by two non-parallel left-lateral strike-slip shear zones; namely, Nugrus and El Gemal shear zones, where they intersect south of dome ‘‘E’’ by a pivot and spread away northward, giving rise to the V-geometry for the whole culmination (Fig. 9). Published structural data in WHC (e.g. Greiling et al., 1988b; Rice et al., 1992; Fritz et al., 1996; Unzog and Kurz, 2000; Fowler and El Kalioubi, 2002; Makroum, 2003; Fowler and Osman, 2009) elucidate:

(1) Northwestward tectonic transportation on thrust zones with gradual decrease of shortening across the culmination from south to north, which is indicated by stronger buckling in dome ‘‘E’’ at the pivot and weak buckling in dome ‘‘A’’ northward.
(2) Fabrics in cross-sections parallel to stretching lineation show evidences of northwestward ductile stretching involved within gneissic bands especially in domes located further north.
(3) Opposite to pivot and especially north of zone between domes ‘‘A’’ and ‘‘B’’, ductile normal shears are frequent, dipping mostly shallowly to NW. These extensional fabrics are reactivated into brittle normal faults of regional extend. (e.g. Sha’it normal fault)
(4) The northern area is intensively crossed by roughly E–W trending dykes that rather disappear southward.
(5) The dome ‘‘B’’ and ‘‘C’’ is crossed by N–S trending left-lateral strike-slip fault. Displacement on this fault is fading towards zero at dome ‘‘D’’.

These structural observations to the culmination satisfy the synthetic components of the scissor-like deformation model described by Fowler and Osman (2001); and this study prefers this interpretation. In this model, vertical extrusion of high-grade gneisses is accomplished by orogen-parallel oblique convergence and coeval uplift (Genna et al., 2002; Wang et al., 2005). Simple shear deformation on edges of the model at higher structural levels resulted in horizontal extension in a direction opposite to the pivot (Fowler and Osman, 2001) and accommodates ductile flow of gneissic materials away from the pivot (Fig. 9). Within this wrench system, overall convergence was accompanied by extrusion of the Hafafit gneiss complex to the surface.

5.4. Significance of extensional ductile–brittle fabrics in northern part of WHC, is it a core complex?

Two major extensional deformational regimes are recognized in WHC; the ductile and brittle normal shears. Both regimes are widely common in the area north of the zone between domes ‘‘A’’ and ‘‘B’’ while they rather disappear within the culmination southward where core gneisses display evidences of top-to-NW stacking. It has been shown that, these ductile extensional shears are concomitant to extrusion of gneissic materials of WHC at

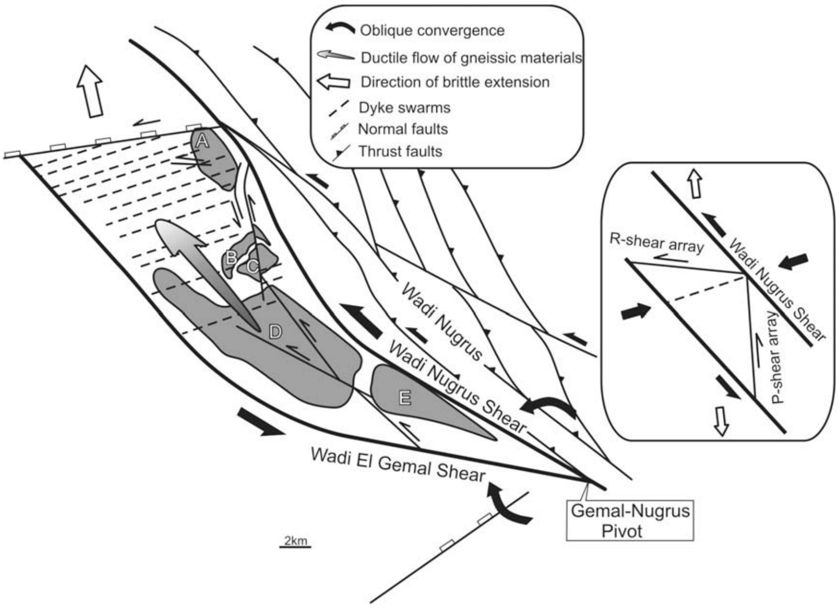

Fig. 9. Simplified structural map for the WHC, collected from landsat images and different literatures (e.g. Greiling et al., 1988b; Rice et al., 1992; Fritz et al., 1996; Unzug and Kurz, 2000; Fowler and El Kalioubi, 2002; Makroum, 2003; Fowler and Osman, 2009). The V-geometry for the whole culmination is formed with intersection of two non-parallel left-lateral strike-slip shear zones (Nugrus and El Gemal shear zones) at a pivot, located south of dome ‘‘E’’, while they spread away northward. Stronger domal buckling close to the pivot and weak buckling further north, northwestward ductile stretching in gneissic domes located further north with development of early ductile, later brittle, Sha’it normal faults, the frequent distribution of E–W trending dykes to north and their rather disappear southward, are structural elements that satisfy the synthetic component of the scissor-like deformation model described by Fowler and Osman (2001). In this model, exhumation of Hafafit gneisses is expected to be accomplished by orogen-parallel oblique convergence and coeval uplift. Inset is a diagram shows the trends of Riedel shears to the Nugrus shear zones.

deeper crustal levels accompanying the oblique convergence across the culmination, scissor-like, wrench corridor. The ductile normal shears are overprinted by E–W trending dyke swarms that are intensively frequent also north of the culmination (Fig. 9; Greiling et al., 1988b). The E–W trend of these dykes is consistent with trends of ductile normal shears recorded in dome "A" and its surrounding (Fig. 9), suggesting that the northern area of the culmination underwent solid-state deformation at upper crustal levels reactivating the early formed ductile extensional shears. Therefore it can be concluded that the culmination is passively tilted/rotated southward probably on northward dipping brittle normal faults bounding the culmination from the north and south (Fig. 9), to commence a later phase of vertical exhumation of the culmination at upper crustal levels.

With some details, the culmination is bound immediately to north by northwestward dipping and NE–SW striking Sha'it normal fault (Fig. 9, Fowler and Osman, 2009). The Sha'it normal fault ends eastward on the Nugrus left-lateral strike-slip shear zone. Two possible interpretations can explicate this; the Sha'it fault is (1) older than Nugrus shear zone or (2) synchronous to Nugrus shear zone as being "Riedel shear". It has been also considered that the domes "B" and "C" are crossed by N–S trending left-lateral strike-slip fault dislocating both domes along their axial plane in a brittle condition and ends also on the Nugrus shear zone (Greiling et al., 1988b). This study thinks also that these brittle faults are due to upper crustal reactivation of early ductile extensional fabrics, resulted from oblique convergence across WHC. Their senses of shearing as well as their orientation indicate that they represent subsidiary R- and P-shears to the Nugrus master shear zone (Fig. 9, *see inset*). Moreover, two regional scale normal faults occurred south, *not within*, of the culmination trending roughly E–W. The southward throwing Durunkat normal fault (Rice et al., 1992) is located at about 50 km south apart from the culmination, and the next throwing north and located closed to the pivot of the culmination from the west. These faults are brittle and cross-cut the nappe assemblage, thereby postdating exhumation of the culmination, i.e. not accompanying the early oblique convergences in wrench corridor of WHC.

Do these normal faults, early ductile and later brittle, north of WHC satisfy a core complex model for the culmination? It is known that metamorphic core complexes form as a result of major continental extension, for example, either via gravitational collapse (Fig. 8a; e.g. Rey et al., 2001) or via deeply penetrated detachment passing though the lithosphere or may terminates within the lithosphere into a shallow ductile shear zone (Lister and Davis, 1989; Wernick, 1992). All of these methods involve wide rifts at upper crustal levels and considerable stretching for the lower crust that is dragged to the surface by buoyancy forces. It has been shown that crustal extension is essentially limited to the northern area of WHC and they seemingly formed during oblique convergence in a scissor-like wrench corridor model not to regional scale lithospheric extension associated with formation of core complexes. Although this study thought stretching for the lower crust by (1) pulling it deeper underneath the overriding nappes (Fig. 8c), due to effect of crustal load induced by the overthickned cover nappes and/or (2) by thermal effect of syn-tectonic magmatic intrusions, buoyancy forces perhaps not enough to play a considerable role of exhumation of the gneissic domes but they may have some contribution to final exhumation of the culmination. Thus the WHC can not be fully interpreted as a classical core complex, but interestingly considered as due to exhumation within oblique convergence regime rather than due to regional scale lithospheric extension. However, this is primarily interpretation that still needs further argumentations.

Generally, this paper is essentially concerned with detail geological mapping of the dome "A" to suggest an alternative possible model that may interpret the formation of WHC. Thus it is recommended that each of the gneissic domes constituting WHC deserve further detailed field mapping to decipher their emplacement mechanism and their regional implications with the surrounding structural backgrounds. This is attributed to the fact that the gneissic domes constituting WHC display some of specific structural features where: (1) vertical flattening in dome "A" is attributed to vertical up-doming, (2) dome "B" and "C" shows more complex patterns of superimposed interference folds (Fowler and El Kalioubi, 2002), (3) preliminary field observations to dome "D" indicate stacking to NW, and (4) dome "E" geometrically reflects tectonic escapement to NW due to oblique convergence at a pivot located further southern tip of WHC. Therefore, it can be concluded that, the gneissic domes constituting the WHC are not as simple as to be explained in one of the models described previously.

Acknowledgments

The author is grateful to K. Stüwe and H. Fritz, Graz University, Austria for their critical reading of the manuscript and fruitful continuous discussions. Special thanks to H. Massonne, Universität Stuttgart, Germany, M. Abu El-Enen and F. Makroum, Mansoura University, Egypt for their field work assistance and fruitful discussions. Thanks are extent to A. El Shahat, Mansoura University for his final linguistic revision of the manuscript. The manuscript was substantially improved by the helpful comments of two anonymous referees.

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