Transpressive Structures in the Ghadir Shear Belt, Eastern Desert, Egypt: Evidence for Partitioning of Oblique Convergence in the Arabian-Nubian Shield during Gondwana Agglutination

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Abstract: Transpressional deformation has played an important role in the late Neoproterozoic evolution of the Arabian-Nubian Shield including the Central Eastern Desert of Egypt. The Ghadir Shear Belt is a 35 km-long, NW-oriented brittle-ductile shear zone that underwent overall sinistral transpression during the Late Neoproterozoic. Within this shear belt, strain is highly partitioned into shortening, oblique, extensional and strike-slip structures at multiple scales. Moreover, strain partitioning is heterogeneous along-strike giving rise to three distinct structural domains. In the East Ghadir and Ambaut shear belts, the strain is pure-shear dominated whereas the narrow sectors parallel to the shear walls in the West Ghadir Shear Zone are simple-shear dominated. These domains are comparable to splay-dominated and thrust-dominated strike-slip shear zones. The kinematic transition along the Ghadir shear belt is consistent with separate strike-slip and thrust-sense shear zones. The earlier fabric (S1), is locally recognized in low strain areas and SW-ward thrusts. S2 is associated with a shallowly plunging stretching lineation (L2), and defines ~NW-SE major upright macroscopic folds in the East Ghadir shear belt. F2 folds are superimposed by ~NNW–SSE tight-minor and major F1 folds that are kinematically compatible with sinistral transpressional deformation along the West Ghadir Shear Zone and may represent strain partitioning during deformation. F2 and F3 folds are superimposed by ENE–WSW gentle F4 folds in the Ambaut shear belt. The sub-parallelism of F1 and F3 fold axes with the shear zones may have resulted from strain partitioning associated with simple shear deformation along narrow mylonite zones and pure-shear-dominant deformation in fold zones. Dextral ENE-striking shear zones were subsequently active at ca. 595 Ma, coeval with sinistral shearing along NW- to NNW-striking shear zones. The occurrence of upright folds and folds with vertical axes suggests that transpression plays a significant role in the tectonic evolution of the Ghadir shear belt. Oblique convergence may have been provoked by the buckling of the Hafafit gneiss-cored domes and relative rotations between its segments. Upright folds, fold with vertical axes and sinistral strike-slip shear zones developed in response to strain partitioning. The West Ghadir Shear Zone contains thrusts and strike-slip shear zones that resulted from lateral escape tectonics associated with lateral imbrication and transpression in response to oblique squeezing of the Arabian-Nubian Shield during agglutination of East and West Gondwana.

Key words: Arabian-Nubian Shield, Ghadir shear belt, transpression, splay-dominated and thrust-dominated strike-slip shear zones, Egypt

1 Introduction

Transpression is a combination of a strike-slip component and a shortening component orthogonal to the deformation zone (Harland, 1971) and includes a deformation developed between two undeformed blocks resulting from both simple and pure shear (Sanderson and Marchini, 1984; Fossen et al., 1994; Fossen and Tikoff, 1998; Jones et al., 2004). Transpression occurs in a wide variety of tectonic settings and scales during deformation of the Earth’s lithosphere such as the Archean North Caribou greenstone belt (Gagnon et al., 2016), the Pan-African Kaoko belt in Namibia (Goscombe et al., 2016, Knopásek et al., 2005), the Southern Uplands of SE Scotland (Tavarnelli et al., 2004), the Kushtagi schist belt, India (Matin, 2006), the salient-recess transition at the northern Gibraltar Arc (Barcos et al., 2015), the Sanandaj–Sirjan metamorphic belt, the Zagros mountains, Iran (Sarkarinejad et al., 2008; Shafiei Bafti and Mohajjel, 2015), Al Jubal Al Akhdar, Libya (Abd El-Wahed and Kamh, 2013), Central Asian Orogenic Belt (Li et al., 2016), the Cauvery shear zone, southern Granulite Terrain, India (Chetty and Bhaskar Rao, 2006), the Dom Feliciano Belt, Uruguay (Oriolo et al., 2016), the Salem–Attur shear zone, southern India (Kumar and Prasannakumar, 2009), the Rengali Province, eastern India (Ghosh et al., 2016),

The East African Orogen (EAO) is an accretionary orogen that extends from Arabia to East Africa and into Antarctica. It was formed by the closure of the Mozambique Ocean. Rodinia was broken up and disintegrated between 900 and 800 Ma ago resulting in the Mozambique Ocean opening (Stern, 1994, 2018). The Arabian-Nubian Shield (ANS) was deformed and squeezed during the orogenic collision between East and West Gondwana (Fig. 1a) after the closure of the Mozambique Ocean during the Neoproterozoic (800–600 Ma). The ANS (Fig. 1b) constitutes the northern extension of the EAO and was exposed because of the uplift prior to the opening of the Red Sea (Stern, 1994, 2018). It is exposed in the Egyptian Eastern Desert (ED), Sudan, western Saudi Arabia, Jordan, Yemen, Ethiopia, Eritrea, Kenya and Uganda.

In the Egyptian ED, the Nubian Shield covers a significant area and appears as a belt parallel to the Red Sea coast for about 800 km between latitudes 22°00′ and 28°40′ N (Fig. 1). These rocks are unconformably overlain on their western and eastern margins by the Nubia Sandstones and younger sediments.

Several models have been proposed to discuss the tectonic evolution of the ANS: (i) Infracrustal orogenic, whereby ophiolites and island-arc volcanics and volcanioclastics were thrust over an old craton consisting of high-grade gneisses, migmatites and remobilized equivalents during the Neoproterozoic (e.g. Akaad and Noweir, 1980; El Gaby et al, 1988; Abdel Khalek et al., 1992); (ii) Turkey-type orogenic, whereby much of the ANS was formed in broad fore-arc complexes (Sengör and Natal’in, 1996); (iii) Hot-spot, whereby much of the ANS, due to accretion of oceanic plateau was formed by upwelling mantle plumes (Stein and Goldstein, 1996); (iv) Arc assembly (arc accretion), whereby the EAO juvenile crust was generated around and within a Pacific-sized ocean (Mozambique Ocean). This last model was proposed first by Vail (1985) and Stoeser and Camp (1985), and modified by Stern (1994).

The complicated structural pattern of the ED Neoproterozoic rocks reflects a polyphase deformational event referred to a complex tectonic history. The ED is dissected by a multidirectional fault pattern, among which are NW-, N–S- and NE- trending faults. The interaction between these major fault systems resulted in a complex structural pattern.

Two distinctive tectonostratigraphic units characterize the Central Eastern Desert (CED) (Fig. 2). The first is the lower unit comprising high-grade metamorphic gneisses, migmatites, schists and amphibolites and is commonly referred to as the structural basement (El-Gaby et al., 1990; Loizenbauer et al., 2001; Abdeen, 2003) or as “lower tier” (e.g. Bennett and Mosley, 1987). The second, commonly referred to as structural cover or the Pan-African nappes, is described as the upper unit including low-grade metamorphosed ophiolite slices (serpentinites, pillow lavas, metagabbros), arc metavolcanics and arc metasediments (e.g. El-Gaby et al., 1990; El Bahariya, 2012, 2018). Collectively, both were intruded by syn-tectonic calc-alkaline granites and a metagabbros-diorite complex. The later stages of the crustal evolution of the CED is characterized by the eruption of the Dokhan Volcanic suite, which is associated with the formation of molasse-type Hammamat sedimentary rocks that were deposited in non-marine, alluvial fan/river environments (Grothaus et al., 1979; Abd El-Wahed, 2010; Bezenjania et al., 2014). The crustal rocks, in turn, were intruded by a series of late to post-tectonic granites.

The Ghadir shear belt (GSB) is in the extreme southern part of the CED. It lies approximately 30 km southwest of Marsa Alam city and extends between latitudes 24° 37” to 24° 57” N and longitudes 34°39” to 35°05” E (according to WGS84 Datum and UTM zone 36N projection) on the Red Sea coast (Fig. 2). It is limited from the East by the Red Sea and from the West by the NW-trending prominent Red Sea hills delineating the western limit of the drainage basins of the study area. To the north of the study area, the Sukari gold mine area is located (Helmy et al. 2004).

This study deals with the structural pattern of the Neoproterozoic GSB, in order to investigate transpressional structures in Ghadir ophiolite. Generally, in the areas to be discussed, two main deformation types have been recognized: shortening perpendicular to the shear zones and lateral movements (sinistral and dextral strike-slip shear zones). Based on new integrated field and remote sensing techniques, we present the first detailed structural analysis in the GSB. We discuss the relationship between the transpressional imbricate thrust system and the Najd Fault System in the Nubian Shield.

2 Regional Tectonic History of the Eastern Desert of Egypt

The ED is characterized mainly by the prevalence of a NW-trending tectonic fabric marking the NW–SE sinistral shear zone of the Najd Fault System (NFS) (Abd El-Wahed and Kamh, 2010; Abd El-Wahed, 2014; Abdeen et al., 2014; Abd El-Wahed et al., 2016). Nappe transport directions reported from the ED show variation from top to the NE (e.g. El-Bayoumi and Greiling, 1984), top to the NW (e.g. Ries et al., 1983; Greiling, 1987), top to the SE (e.g. Kamal El Din et al., 1992), and top to the SW (e.g. Abdeen et al., 2002; Abdelsalam et al., 2003). Oblique convergence transpression, whether dextral or sinistral, is a current mechanism adopted by many authors (Fritz et al., 1996, 2002, 2013; Loizenbauer et al., 2001; Makroun, 2001; Bregar et al., 2002; Helmy et al., 2004; Shalaby et al., 2005; Abd El-Wahed, 2008, 2010, 2014; Shalaby, 2010; Abd El-Wahed and Kamh, 2010; Zoheir and Lehmann, 2011; Zoheir and Wei hed, 2014; Abd El-Wahed et al., 2016; Abd El-Wahed and Thabet, 2017; Makroun, 2017; Hamdy et al., 2017; Stern, 2018; Hagaga et al.,
Fig. 1. (a) The East African–Antarctic orogen (EAAO) interpreted as the main collisional orogen along which parts of proto–East and West Gondwana collided to form Gondwana (after Stern, 1994; Jacobs and Thomas, 2002; Avigad et al., 2003, and references therein). Abbreviations: ANS—Arabian-Nubian shield; Da—Damara belt; EF—European fragments; LH—Lutzow-Holm Bay; M—Madagascar; Z—Zambezi belt. (b) Relationship between the Arabian–Nubian Shield (ANS) to the adjacent older continental crust. The border with the Saharan Metacraton, on the west, is the effective contact between ANS and West Gondwana: a border, on the east, with putative East Gondwanan crust, is not certain. NED = North Eastern Desert; CED = Central Eastern Desert; SED = South Eastern Desert; QSZ = Queih shear zone; MG = Meatiq gneisses; SG = Sibai gneisses; MG= Hafafit gneisses; SHG = Shalal gneisses; KHSZ = Kashir-Houdien Shear Zone; SHS = Sol Hamed Suture; AHS = Allaqi-Heiani Suture; GGN = Gabal Gerf Nappe; NKS = Nakasib Suture; KS = Keraf Suture; BS = Baraka Suture; AIS = Al Amar Suture; ADS = Ad Damn Suture; BUS = Bir Umq Suture; YS = Yanbu Suture; HADRS = Halayif-Ad Dafinah-Ruwah; NBS = Nabatih Suture; HZFZ = Halaban-Zarghat fault zone; ARFZ = Al Rika fault zone (compiled from Johnson et al., 2011; Abdeen and Abdelghaffar, 2011; Fritz et al., 2013; Abd El-Wahed et al., 2016).

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2018; Hamimi et al., 2019) to explain and imply the deformation styles in the CED.

Simply and collectively, Abd El-Wahed and Kamh (2010) arranged the deformation events in the CED as follows: (1) D1 linked to NNW-directed thrusts; (2) D2 related to NE- and SW-directed thrusts; (3) D3 attributed to sinistral shearing along the NFS, which bounds them from the SW and NE (Fritz et al., 1996). Not only core complexes of the CED but also the Hammamat molasse sediments are tectonically affected by the NFS (Abd El-Wahed, 2010).

Fig. 2. Geological map of the southern part of the Central Eastern Desert of Egypt (modified after Klitzsch et al., 1987).

1; core complexes 2; serpentinites, 3; ophiolitic metagabbros, 4; metavolcanics and metasediments, 5; syn-tectonic intrusive metagabbros, 6; syn-tectonic granite, 7; Dokhan volcanics, 8; molasse sediments, 9; felsites, 10; gabbros, 11; post to late tectonic granites; 12; ring complex, 13; Natashi volcanics and 14; trachyte plugs. GAK; Gebel Abu Khruq, HCC; Hafaif core complex, GOM; Wadi Ghadir ophiolitic melange, HM; Hamash gold mine, NSZ; Wadi Nugrus shear zone, GS; Gebal Sikait, WDSZ, Wadi Abu Dabbab shear zone, WUSZ, Wadi El Umea shear zone, GS; Gebel Sukkari and Sukkari gold mine, GUK; Gebel Um Khariga, IG; Igl molasse basin, DMD; Dubr metagabbro-diorite complex, GIA; Gebel IgI Al- Ahmar, HW, Gebel Homrat Waggad, GY, Gebel El-Yatima, GUS; Gebel Umm Salim, US, Gebel Umm Saltit, GK; Gebel Abu Karanish, GM, Gebel Al Miyyai, USZ; Um Nar shear zone, GUM; Gebel El-Umra, GK; Gebel Kadabora, GA; GH; Gebel El-Hidilawi, GU; Gebel Umm Atawi, GSH; Gebel El Shalul, GR; Gebel El Rukham; SCC; Sibai core complex, GS; Gebel Sibai, WZ; Wadi Zeidon, WSSZ; Wadi Sitra shear zone, WKSZ; Wadi Kab Ahmed shear zone, K; Kareim molasse basin. Major structures after Akaad et al. (1993), Fritz et al. (1996), Helmy et al. (2004), Shalaby et al. (2005), Abd El-Wahed (2008) and Abd El-Wahed and Kamh (2010).

2018; Hamimi et al., 2019) to explain and imply the deformation styles in the CED.

In the CED, exhumation of the core complexes (e.g. Meatiq, Sibai, El- Shalul and Hafafit) is related to the sinistral shearing along the NFS, which bounds them from SW and NE (Fritz et al., 1996). Not only core complexes of the CED but also the Hammamat molasse sediments are tectonically affected by the NFS (Abd El-Wahed, 2010).
Originally, the NFS and other NW-trending strike-slip faults in the ANS were considered post-accretionary structures (Abdeen et al., 1992) and interpreted to be the result of the squeezing of the ANS between East and West Gondwana (Berhe, 1990; Stern, 1994; Abdel Salam and Stern, 1996; Abdel Salam et al., 2003; Abdeen and Greiling, 2005). The NFS consists of brittle-ductile shears in a zone as much as 300 km wide and more than 1100 km long, extending across the northern part of the Arabian Shield and extending to the ED. The structures in the NFS zone were developed in response to a sinistral transpressive tectonic regime, with the axis of maximum compressional stress oriented at oblique angles to the NW-trending orogenic front (Abd El-Wahed, 2014).

Different models have been suggested to interpret one of the major landmarks of the CED, a series of gneiss domes or core complexes (e.g. Meatiq, Sibai, El-Shalul and Hafafit). Gneiss domes have either been interpreted as: (1) antiformal stacks formed during thrusting (e.g., Greiling et al., 1994), (2) core complexes during orogen-parallel crustal extension (e.g., Fritz et al., 1996; Bregar et al., 2002; Abd El-Wahed, 2008; Makroum, 2017; Hamdy et al., 2017), or (3) interference patterns of sheath folds (Fowler and El Kalioubi, 2002). Recently, there are two main tectonic models to explain the formation and exhumation of these core complexes in the CED:

(1) the orogen-parallel extension model of Fritz et al. (1996), who assigned the evolution of the core complexes to sinistral shearing along the NW-trending shear zones of the NFS; and

(2) a second model attributed the formation of gneiss-cored domes to extensional tectonics by an overlap between NW–SE complex folding and NW–SE extension (e.g., Fowler et al., 2007; Andresen et al., 2010).

The Nugrus Shear Zone (NSZ) (Fig. 2) is one of the major NW-trending shear zones forming the boundary separating the CED from the Southern Egyptian Desert (SED) and constitutes the boundary between the Wadi Ghadir area (East) and the Hafafit core complex (West). The Hafafit–Ghadir domain is interpreted as a back-arc accretion system that evolved above a NW-dipping subduction zone (Abd El-Naby and Frisch, 2006). The NSZ starts with a 750-m width near the meeting point of Wadi Nugrus and Wadi Sha’it (Fowler and Osman, 2009), preserving its width at least as far as Gabal Sikait where it decreases by 50 m (Harraz and El-Sharkawy, 2001), which decreases by 50 m (Harraz and El-Sharkawy, 2001).

Lundmark et al. (2012) assigned an age of ≤595 Ma for left-lateral shearing of the NSZ.

The NSZ has been interpreted as a thrust accommodating westward or SW-ward ophiolitic material transport over the continental margin (El-Gaby et al., 1988; El-Bayoumi and Greiling, 1984; El-Ramly et al., 1984) or as a roof thrust linked up with NW-dipping thrust imbricates of gneissic rocks and allowing NW-ward displacement of low-grade CED metavolcanics over the gneisses (Greiling et al. 1994; Greiling, 1997). Many workers considered the NSZ as a Najd-related ductile strike-slip shear (e.g. Fritz et al., 1996; Hassan, 1998a, b; Unzog and Kurz, 2000; Shalaby et al., 2005; Abd El-Wahed et al., 2016; Makroum, 2017; Hagaga et al., 2018; Hamimi et al., 2019). Fowler and Osman (2009) have argued for the NSZ being a strike-slip shear zone because the NW-trending, along strike, schistose shear foliations cease at the intersection of Wadi Nugrus with Wadi Sha’it, which is supported by the absence of field evidence about extending the NSZ structure northwestwards as a strike-slip fault into the CED. Fowler and Osman (2009) also described the NSZ as an example of a low-angle normal ductile shear (LANF) due to approximate E–W strike, low-angle N-dip and a normal shear sense.

The NW-trending sinistral shear zone related transpression is conjugated and overprinted by dominant dextral transpression along NE–SW trending shear zones (Shalaby et al., 2005; Abd El-Wahed and Kamh, 2010). Abd El-Wahed (2014) documented a huge NE-trending shear belt (up to 110 km in length) occupying the area between Wadi Barramiya and Wadi Sha’it (Fig. 2) to the west (up to 60 km in width) and extending through the whole width of the CED to include the area between Wadi Mubarak and Wadi Ghadir on the Red Sea coast (up to 120 km in width) (Fig. 2). The 40–60 km wide, EN–WNW-trending Mubarak–Barramiya shear belt (MBSZ), deforms supra-crustal successions and structures associated with the NW-trending shear fabric (Fig. 2). The MBSZ is interpreted as a dextral transpressive shear zone that caused the cessation of the extension of the NSZ and is modeled in terms of a regional ‘flower structure’ (Abd El-Wahed and Kamh, 2010).

3 Mapping the Ghadir Shear Belt by Remote Sensing

Geological information acquired from remote sensing satellite platforms provides important perspective in understanding surface lithological and structural processes. However, this information captured by satellite is all-inclusive, and for the usually complex outcropped lithological and structural units it is difficult to map them accurately and precisely with detailed field work. The integration of the processing of Landsat 8 image and field investigation is used to give insight to the deformation history of the GSB. A subset of the Landsat 8 OLI scene (Path 173/Row 43, acquired on July 18, 2018) has been analyzed, and processed using ENVI 5.3 software to enhance the geological contacts and structural elements. Some pre-processing techniques were applied to the remotely sensed data used such as atmospheric correction and re-scaling the raw radiance data from imaging spectrometer to reflectance data. After that, several techniques of satellite data processing have been applied to Landsat 8 OLI data for detailed mapping of the lithological units and structural elements exposed, including false color composite, band rationing, Principal Component Analysis (PCA) and image classification.

The ophiolite of Wadi Ghadir constitutes a wide range of lithologies. Metamorphism, alteration and weathering also play a role in mixing and muting spectral signals of different lithologies. Hence, no single ‘perfect’ technique is used to map a whole area body. Therefore, integration between various remote sensing enhancement techniques and GIS data is needed for successful lithologic mapping of the area. Thus, the Remote Sensing (RS) products for the current area geological mapping include True Color
Composites (TCC), False Color Composite (FCC) and Principal Components Analysis (PCA) using Landsat 7ETM+ Satellite images (obtained from NASA with acquisition date of October 2000 (05-10-2000) consisted of nine bands and have Path 173/Row 043 with spatial resolution 30 m).

Practically, the TC image (3, 2 and 1 in RGB) was produced for the study area (Fig. 3a) giving a reasonable lithologic discrimination. Landsat ETM+ true color image, as the name suggests, is an image like that seen or perceived by the human eye.

Several FCCs were tested and chosen to better highlight and discriminate between different types of rocks in the area. Excellent results were given through bands of 7, 5 and 4 in RGB (Fig. 3b). In the latter FCC, the Zaba granitic gneiss is eminently identified by a light orange to yellow contrasting with the dark color of mélange and serpentinites. Serpentinite rocks have a dark magenta to black color and form the most spectrally prominent rock unit for most combinations. The best ETM+ band ratios to discriminate serpentinites from other surrounding rocks are 5/1, 3/2 and 7/2 in R, G and B, respectively. The distinctive mineral assemblages of serpentinites impact their spectral characteristics and enhance their discrimination using the Landsat band ratio images (Sultan et al., 1986; Kusky and Ramadan, 2002; Frei and Jutz, 1989). This was confirmed by the case study of mapping Oman ophiolites (Abrams et al., 1988). Gad and Kusky (2006) during their work in the Barramiya area, referred the distinctive spectral reflectance of serpentinites to the abundance of antigorite, lizardite, clinoxyroxenite and magnetite in the mineral composition. The metavolcanic rocks are represented by a light greenish yellow, while gabbroic rocks are displayed as a brown color varying from pale brown for metagabbro and reddish bright brown for gabbroic rocks.

A light yellow to pale pinkish brown color represents the granitic rocks exposed at the eastern part of the study area due to prevailing of quartz and feldspar (75%) of the total rock composition. This light appearance is referred to the quartz and feldspar high reflectance in the selected bands in RGB. The two types of syn- and late-tectonic granites are also distinguishable where syn-tectonic granitic rocks are marked by pale pinkish brown contrasting the light-yellow appearance for the late tectonic granitic rocks. The color degree gradual difference is easily explained by gradual variance in the quartz percentage of the syn- to late-tectonic granites.

Principal Components Analysis (PCA) is a linear transformation technique related to Factor Analysis. Given a set of image bands, PCA produces a new set of images, known as components, which are uncorrelated with one another and are ordered in terms of the amount of variance they explain from the original band set. PCA has traditionally been used in remote sensing as a means of data compaction in various applications, including geologic mapping. These analyses were used to reduce redundancy in multispectral data. Practically, the PCA transformation was computed for the ETM+ data to produce the best PCA for the discrimination between rock units in the study area. PCA analysis results show that the first three PCs (PC1, PC2 and PC3) explain almost all the variance contained in the multi-spectral data. Respectively in RGB, (PC1, PC2 and PC3) and (PC2, PC1 and PC3) proved their useful role for the PCA in the study area lithologic discrimination and distinctiveness.

The above PCA colored composite (PC1, PC2 and PC3, in RGB) was applied for the whole study area (Fig. 4a) allowing us to conclude extremely advantageous discrepancies among the study area different rock units, where the granite rocks are displayed by a very distinctive blue in the eastern area while serpentinite rocks and mélange are indicated by a yellowish cyan. The granitic gneiss rocks are represented by a golden yellow (which better highlights topographic effects and provides an easier visual interpretation due to incorporating PC1 in the RGB color composites), while gabbroic rocks display as yellow (pale for metagabbro and bright for fresh gabbro). Besides the latter PC composite, (PC2, PC1 and PC3, in RGB) also proved its useful role for lithologic distinction (Fig. 4b), assisting in more identification, discrimination, interpretation and mapping of rocks exposed within the GSB.

4 The Geological Setting

The Wadi Ghadir area is covered mainly by the most common ophiolite in Egypt that is called the Ghadir Ophiolite (Fig. 5). This ophiolite is one of the best-preserved sections through late Proterozoic upper oceanic crust anywhere in the world (Kröner et al., 1992). Egyptian ophiolites are mainly dismembered (Basta, 1983; Ries et al., 1983; Zimmer et al., 1995; Farahat et al., 2004) and restricted to the CED and SED. These ophiolites are interpreted as formed in back-arc (e.g. Basta, 1983; Berhe, 1990; El-Sayed et al., 1999; Takla et al., 2002; Abd El-Rahman et al., 2009a), or fore-arc settings (Azer and Stern, 2007).

Wadi Ghadir contains the first recognized ophiolitic melange in the Nubian shield, which is composed of fragments derived mainly from ophiolitic sheets, greywacke, siltstone and mudstone units and granitic rocks (El-Bayoumi, 1980). The area represents a widely distributed stretch of Neoproterozoic ophiolitic mélangé constituted mainly of allochthonous ophiolitic fragments mixed firmly and incorporated in a sheared matrix as well as other different mappable units. The most extensive and widely disseminated unit of the area is the mélange assemblages (Fig. 5). The mélangé is commonly interpreted to be allochthonous with respect to underlying paragneisses and/or orthogneisses and to have been generated by gravity sliding and/or thrusting and emplaced by SE–NW-directed thrusting (Shackleton et al., 1980). The mélangé would have been transported over distances of 300–500 kilometers (Ries et al., 1983).

El-Sharkawy and El-Bayoumi (1979) and El-Bayoumi (1980) were the pioneers in recognizing the Neoproterozoic oceanic crust in Wadi Ghadir. They reported the occurrence and the description, for the first time, of a complete and genuine ophiolite sequence in the area. This section is well exposed and easily recognized to the northwest of Gabal Dob Nia (Fig. 5). In this section,
Fig. 3. Band combinations applied to the Landsat 7 ETM+ Satellite image of the Ghadir shear belt in, a) 3, 2, 1 true color composite, and b) 7, 5, 4 false color composites in RGB sequence.
Fig. 4. Principal Components for the Ghadir shear belt in RGB, a) PC1, PC 2 and PC 3, and b) PC 2, PC1 and PC3.
all the ophiolite units occur from the layered gabbro at the base to pillow basalts associated with deep-sea sediments at the top.

The other mappable units in the area include rhyolitic, andesitic, dioritic and granitic rocks. Dioritic rocks are foliated and depict as a large fold structure having a NW-trending axis in the southwestern part of the area (El-Sharkawy and El-Bayoumi, 1979). Granitic rocks that
occupy the eastern part of the area exhibit an intrusive contact with other units. They hold a plentiful number of xenoliths of older rocks in various stages of interaction. Numerous later dykes of all directions and exhibiting different compositions cut and transect all the other rocks.

4.1 Granite gneisses

Zabara granite gneisses (633±5 Ma, Lundmark et al., 2012) occupy the southwestern part of the Ghadir area. They comprise granite gneiss intercalated with bands or lenses of hornblende gneiss and minor migmatites, together with cataclased granite, mylonites and schists (Kamel et al., 2016) that are metamorphosed at pressures of 6.8–7.7 kbars (Surour, 1995). Mineralization of emerald, rare element mineralization (Ta, Nb, Be, Zr, U, Th, Sn), cassiterite and fluorite in the Zabara area are emerald, rare element mineralization (Ta, Nb, Be, Zr, U, Th, Sn), cassiterite and fluorite in the Zabara area are mainly found in schist and thought to be related to hydrothermal fluids evolved from some of the leucogranites intruded into the Nugrus shear zone (NSZ) (Harraz et al., 2005). Microscopically, granite gneiss consists of alternated felsic (quartz and plagioclase feldspars) and mafic (biotite) bands.

4.2 Serpentinized peridotites

Serpentinized peridotites constitute the lowermost unit of the ophiolite sequence of Wadi Ghadir. The ultramafics prevail among the ophiolitic rocks and exhibit variable sizes from microscopic dimensions up to mountain size (Gabal Ghadir). They are mostly sheared and exhibit mesh structure. In most cases, they are generally serpentinized, with minor amounts of fresh relics of dunite, and pyroxenite, and in many places altered and transformed into talc-carbonate rocks of cream colors consisting principally of talc and magnesite with minor amounts of dolomite.

The metamorphic peridotites occur either as large mountain-size Klippers thrust onto the mélange or as small blocks (from few meters to centimeters in diameter) frequently incorporated in the mélange. The mountainous masses of serpentinitized peridotites are rootless and seem to be dismembered parts representing the debris that was broken off from the ophiolite plate and incorporated within the mélange (El-Bayoumi, 1980). The mountainous masses of peridotites can be discriminated distinctly into two types:

(i) massive peridotites: with black-colored variety and partially altered. The masses of Gabal Lawi and Gabal Lewiwi (Fig. 5) are of this type. The largest peridotite mass at Gabal Lewiwi is elongated in shape with NE–SW trend and composed of harzburgite, wehrlite and lherzolite. The mass is altered to talc-carbonate rock at the base and becomes fresh upwards;

(ii) foliated peridotites: they are extensively sheared and altered to foliated talc-carbonate rocks, but still have relics of fresh peridotites. The best examples of this type are the peridotite masses that are located at the junction between Wadi Ghadir and Wadi Lawi (Fig. 5). These masses form a domal core structure, where the foliation in the surrounding mélange dips away from it in all directions. They are composed of fresh peridotites (harzburgite, wehrlite and dunite) surrounded by a vast talc-carbonate carapace.

Petrographically, the ultramafic masses contain partly metamorphosed dunites and peridotites, massive and schistose serpentinites, talc-carbonates and chromitites. Antigorite has several forms especially as fine-scale or lamellar aggregates, which exhibit plumeose structure and mesh texture. Lizardite is the main constituent of the massive serpentinites. Besides the serpentine minerals, chromite, magnetite, talc, carbonates, chlorite, actinolite–tremolite and olivine are also present.

4.3 Ophiolitic metagabbro

The gabbroic rocks constitute the upper part of the cumulative sequence, below the sheeted dyke complex. Gabbros are not common as the ultramafics within the ophiolitic rocks, occurring as blocks that are heterogeneous in grain size and color.

Abd El-Rahman et al. (2009b) classified the plutonic rocks of the Wadi Ghadir Ophiolite into layered, coarse-grained massive and hypabyssal gabbros. Although they are structurally imbricated units, dipping moderately to the southwest, the layered gabbro is regarded as the basal unit, transitional upward into massive coarse-grained gabbro with hypabyssal gabbro at the top. This is best seen in the well exposed section along Wadi Miyah Saudi and Wadi Miyah al-Bayda junction (Fig. 5). The main mass of this complex occurs close to Gabal Dob Nia (Fig. 5) and stretches NW where the gabbro is clearly and obviously layered at the bottom and passes gradually upwards into coarse-grained rosette gabbro, which in turn conduces upwards into microgabbro. Other mappable gabbro masses occur in Wadi Ghadir, Wadi Lawi and Wadi Lawiwi, as well as a few other places.

The basal unit of the gabbroic rocks is characterized by rhythmic layering with plagioclase-rich leuco-layers alternating with dark layers rich in altered pyroxene. The thickness of an individual layer reaches up to 50 cm. Layering is often disrupted by deformation so that single layers cannot be traced laterally for more than 20 meters.

Several other masses of massive and rosette gabbro were found in the area. They appear to be allochthonous blocks in the mélange. Commonly, the rosette gabbro grades downwards into layered gabbro and upwards into hypabyssal gabbro. This zonation can only be perceived on a large scale, but minutely, no regular contacts could be detected between the three types of gabbro.

The gabbroic complex is intruded by numerous diabasic dykes and sills with variable attitudes ranging from sub-horizontal at the base, parallel to the layered gabbro to subvertical near the top. As best seen in the gabbros of Wadi Miyah al-Bayda, subhorizontal dykes occur near the base of the section, with a gradual increase in the amount of dip towards the southwest along Wadi Miyah al-Bayda until they attain a subvertical attitude near the sheeted dyke complex.

Gabbros of the Ghadir ophiolite are tholeiitic. They have Mg-numbers between 43 and 71, and their SiO₂ content ranges from 46 to 51 wt%. They have the lowest incompatible trace element (REE, Zr, Nb) whereas values of the transition metals, Sc and Cr are close to MORB values (Abd El-Rahman et al., 2009b).
4.4 Sheeted metadiabase dykes

Sheeted dykes are recognized and best seen in the Wadi Ghadir area where they configure the intact proper unit of the ophiolite section between the underlying cumulate sequence and the overlying pillow basalts. In other places, sheeted dykes constitute dismembered blocks that were incorporated into the mélange, e.g. along Wadi al-Lawi where a huge block occurs with a clearly recognizable chilled margin. The dykes vary in thickness from about 50 cm to about 2 m (Fig. 6a and b).

There is a transitional zone between the sheeted dykes and the pillow basalts in which the contacts of the dykes become sapped and they fade away and then the rock exhibits incipient formation of pillows. Microscopically, metadiabase is composed of euhedral lath-shaped plagioclase crystals set in a finer matrix of hornblende, exhibiting blasto-diabasic texture.

4.5. Pillowed metabasalts

Two outcrops of well-exposed pillow lava occur along Wadi Miyah al-Bayda and Wadi Miyah Saudi. Morphologically, most pillows are well preserved, some are sheared and deformed. The pillows are aphanitic and grayish-green. They are rich in vesicles in their border zones. These vesicles are occasionally arranged in a zonal fashion parallel to periphery, and decrease from the border to the core. Most of the vesicles are now filled with chlorite and quartz. The pillows may be spherical, oval or elongated.

In Wadi Miyah al-Bayda (Fig. 5), the most extensive...
and well-displayed outcrop of the pillows overlying the sheeted dykes is present. Individual pillows are circular or oval (Fig. 6c and d) with massive core and a zone of vesicles near the periphery. A variolitic or schistose sheath encloses each pillow.

In a second spot on the southern side of Wadi Saudi (Fig. 5), the pillowed mass is more altered with a highly schistose sheath. Some of these pillows exhibit porphyritic texture, others show vesicles. Fragments of pillow basalt were also encountered broadly in the mélange, where the pillows are usually sheared and intensely deformed.

Abd El-Rahman et al. (2009a) mentioned that the (amygdaloidal) pillow lavas of Wadi Miyah al-Bayda plot in the tholeiitic field, whereas those of Wadi Saudi (porphyritic pillows) plot in the calc-alkaline field. The latter are more enriched in Zr and other incompatible elements relative to the former. Both have similar chondrite-normalized REE patterns and have very low Mg -numbers (Abd El-Rahman et al., 2009a).

In the Wadi Ghadir area, sediments of deep-water origin interlayer or rest on top of the pillow basalts, denoting that sedimentation occurred deep on the sea floor before the emplacement of the ophiolite sequence.

Petrographically, the metabasalt is characterized by plagioclase phenocrysts disposed in a fine-grained volcanic glassy groundmass forming blasto-interstitial and porphyritic textures. Phenocrysts are usually plagioclase or hornblende amalgamated in a fine groundmass consisting of plagioclase, hornblende, augite relics and iron oxides, with a wide range of accessory minerals forming porphyritic texture.

### 4.6 Ophiolitic mélangé

Pebbley mudstones are the dominant facies in the sedimentary matrix of the ophiolitic mélangé units. They contain a large spectrum of blocks and clasts. The ophiolitic mélangé in the study area is characterized petrographically by polymict assemblages of clasts and blocks: diachronous ophiolitic blocks, as well as a large variety of sedimentary, metamorphic, volcanic and plutonic clasts. All of them are set in a pervasively deformed, fine-grained matrix. Small blocks of plagio-granites (trondhjemite) are rarely observed in the Ghadir ophiolitic mélangé.

El Sharkawy and El-Bayoumi (1979) divided the mélangé of the study area into two facies: proximal and distal, in relation to the source of its ophiolitic components. The proximal facies is found mainly to the south of Wadi Ghadir and to the east of Wadi Lawi, whereas the distal facies occurs in the NW part of the area.

The proximal facies is composed of rolled and fragmented rock debris of highly variable sizes in a matrix of scaly and schistose mudstone. The most abundant components in it are serpentinitized peridotite blocks. Second in abundance are disrupted, fragmented parts of variably sized dykes that are mixed and squeezed with talc carbonate rock. Other rock types recognized among the debris of the mélangé are various types of volcanic rocks, greywackes, quartzites, chert, marble, shale, granite and other plutonic rocks, amphibolites and schistose rocks. Commonly, the pebbles and cobbles are stretched due to deformation.

The distal facies is composed of low-grade schists, mostly of pelitic composition. It also contains pebbles of other rock types like those in the proximal facies, but of much less abundance and smaller sizes. Metamorphism and deformation of the distal facies might have been caused by the over-riding by slices of proximal facies in the form of nappes, remnants of which are common in various parts of the area. All the contacts between the ophiolitic rocks and the sedimentary matrix are structural ones.

### 4.7 Metavolcanics

Metavolcanic rocks were found in the study area either as large outcrops or as xenoliths. The former are considered as separated blocks and best seen near the middle part of Wadi Ghadir and at the northwestern part of the study area. Petrographically, felsic, intermediate and mafic metavolcanics are represented in the study area. The felsic to intermediate metavolcanics occupy a dispersed and limited areas, whereas mafic metavolcanic rocks are represented only in the western part of Gabal Ghadir. Metavolcanic rocks are widely affected by jointing in different parts of the study area.

### 4.8 Metagabbro-diorite

Diorite occurs as a foliated mass in the southern part of the area forming an antclinal fold core (Fig. 5). The rock is highly altered and intensely foliated. It commonly incorporates patches of igneous breccia in which angular boulders of basic dykes are set and embedded in a matrix of white igneous material (Fig. 6e). Patches of this mass are gneissose due to the development of alternating quartz and mica-rich bands. Lithologically, the pluton ranges from metagabbro, diorite to quartz diorite in composition. These rocks consist essentially of plagioclase, hornblende, quartz, ilmenite, apatite and zircon. Tremolite, chlorite and muscovite are secondary minerals. Geochemically, the diorites are calc-alkaline, enriched in alkalis, Rb, Sr, Ba and particularly Zr, and depleted in FeO, MgO, Cr, Ni and Nb, which suggests their continental origin (Basta, 1983).

### 4.9 Granitic rocks

Ibrahim and Ali (2003) differentiated two types of magmatic granites in the Ghadir area: (i) quartz diorite and gneissose granodiorite, which have a metaluminous character and were emplaced during pre-plate collision, and (ii) perthitic-leucogranite and muscovite-biotite granite that contain a large quantity of gabbroic and metavolcanic xenoliths in all stages of interaction and digestion by the granitic material. Also, dykes of various composition and orientation are cross-cutting and dissecting the granitic rocks (Fig. 6f).

### 4.10 Lewiwi young gabbros

The Lewiwi young gabbros crop out along the foothills of Gabal Lewiwi as medium- to coarse-grained numerous isolated small masses (Bakhit et al., 2007). These masses were mapped as ophiolitic gabbro and serpentinites by El Bayoumi (1980). These masses are elliptical to rounded, intruded by post-tectonic granite. The gabbros intrude the
Fig. 7. Structural elements in the Ghadir shear belt on (a) Landsat 7 ETM+ false color composite image (bands 7, 4, 2 in R, G, B); (b) shade relief map of the study area derived from SRTM DEM with an azimuth and altitude of the sun, 135° and 45°.
adjacent serpentinites with sharp contacts and sometimes exhibit chilled margins.

5 Structural and Kinematic Analysis

We applied information about the structural elements extracted from the satellite images in order to better understand and assist in solving the complicated structural pattern of the GSB (Fig. 7a). To enhance the interpretability of the raster elevation, a shaded relief or hillshade is often generated. A shaded relief is a visually pleasing representation of the terrain (Marston and Jenny, 2015) and is defined as the pattern of light and dark that a surface would show when illuminated from particular angles (ESRI, 2004). It evaluates the relationship between the position of the light source and the direction and steepness of the terrain. The shaded relief map of the study area (Fig. 7b) was generated as grid cells in shades of gray with values ranging from 0° to 254° increasing from black to white. The azimuth and altitude of the illumination source (sun) are 135° and 45°, respectively. The structural pattern of the GSB is more complex because of the NE–SW-trending tectonic structures in the northeast overprinting the NW–SE structural fabrics in the west of the study area.

Based mainly on the structural deformation features, the structural belt of the area is divided into three main shear belts named, East Ghadir Shear Belt (EGSB) from the eastern border of the study area to Wadi Zabara, West Ghadir Shear Zone (WGSZ), where the high strain area is between Wadi Zabara and the western border, and finally, the Ambaut Shear Belt (ASB) to the northeastern part of the study area (Fig. 7a and b).

5.1 The East Ghadir Shear Belt (EGSB): imbricated thrust system

The EGSB contains syn-tectonic granites, syn-tectonic metagabbros, volcaniclastic metasediments, intermediate metavolcanics and late to post-tectonic granites (Fig. 5). The EGSB is characterized by a series of thrust faults that developed under greenschist facies conditions and imprinted a southward vergence. The EGSB is characterized by zones up to several meters wide composed of steep shear zone foliation planes (S1). S1 foliations and their associated thrusts are deformed, folded and transposed into the foliation within the high strain zone of these shear zones. In some areas of the EGSB, pre-existing S1 foliations are cut by a steep shear zone foliation that dips steeply away from the center of the shear zone (S2). Between the high strain zones the fabric is dominated by more gently dipping pre-existing S1 foliation planes. This pattern of deformation allowed us to determine the orientation of the boundaries of the high strain zones. The S1 foliation is the dominant fabric in the study area (Fig. 5). It is normally moderately dipping to the SW and NE (Fig. 8a) and parallel to the axial plane of F1 upright folds. Outcrop-scale F1 folds are common and affect earlier planar features. S2 mylonitic foliation is folded and crenulated around small-scale folds. Poles to the S2 foliation show moderately developed clusters of foliations, striking N30°–55° W and dipping 65°–75° toward NE and SW (Fig. 8b).

The area to the east of Gabal Ghadir and that between Wadi Lawi and Wadi Zabara (Fig. 2) is defined by a series of map-scale, relatively open, high-amplitude, NNW-trending upright anticlines and synclines. The major folds are spaced at approximately 10-km intervals and have wavelengths of up to 5 km. The axis of this fold curves from N to NW and plunges 30°/N10–30°W (Fig. 8c). The axial planes of these folds mostly have moderate to steep dips to the NE. Minor folds are abundant in schists (Fig. 9a–c) and less common in metavolcanics and absent in metagabbros. Tight folds occur in schists and volcaniclastic metasediments whereas low amplitude folds with parallel geometry occur in sheared metavolcanics. The fold axes appear to swing from N- to NNW-trending and change from inclined plunging folds to recumbent folds with reclinined geometry where overprinting produces complex refolding.

Diorites to the south of the EGSB occur as a foliated mass forming an antclinal pericline fold (Figs. 8e and 10). This structure takes a domal shape trending NW–SE and exhibits outward dipping directions. It occupies a considerable area of about 31.4 km² and has a well-defined boundary with a 21.5-km perimeter, which can be easily discriminated by the tonal contrast between diorites and other rock units in the processed images. A close relationship exists between the thrust faults in the volcaniclastic metasediments and metavolcanics and the folded diorite rocks (Fig. 5). Movement occurred along the large and gently dipping thrust faults. The thrusts propagated through the rock from E to W, with rocks at shallow depths sometimes becoming folded ahead of the advancing thrust fault. In this way, the characteristically narrow elongate folds of the diorite rocks are thought to have formed. The folds have steeply dipping beds on their western side and more gently dipping beds on their eastern flank.

Strong brittle-ductile strike-slip shear zones (Fig. 9d) occur along Wadi Ghadir forming mainly fine-grained highly sheared metavolcanics, gabbroic rocks and mylonite schists. They show steeply dipping to subvertical foliation (Fig. 9e) and shallowly south-easterly plunging lineation. Sub-horizontal slickensides overprinted by steeply dipping striae are common (Fig. 9f).

Several sinistral strike-slip shear zones were observed in the EGSB (Fig. 9c), the main shear zone of which exists between Gabal Ghadir and Gabal Dob Nia (Fig. 5). It is about 250 m wide, striking N50°W and characterized by steeply-dipping foliation, subhorizontal slickenlines and formation of mylonite and cataclasites within the volcaniclastic metasediments and the gabbroic rocks. The core of the shear zone is a sheared gabbroic rock with a well-developed L-tectonite exhibited by segregation of recrystallized quartz and feldspar-rich domains. The steeply dipping mylonitic foliation has a sigmoidal trend within the strike-slip shear zones. The foliation deflects into the shear zones, indicating a sinistral sense of shear. Foliation in the shear zones strikes NW and dips 45°–85° NE, and lineation plunges 15°–30° toward the NW (Fig. 9e). Although the shear zones are meter wide, mylonite zones are less than 20 cm in width (Fig. 9d). Foliation
outside the shear zones dips gently to steeply northeastward, and lineations are shallowly plunging northward, although they are significantly variable (Fig. 9f).

Furthermore, away from the high strain zone, there are imbricate thrusts dipping mainly to NE. The shear zone expresses as a steeply dipping foliation, with moderately to steeply plunging mineral lineation (Fig. 8d), surrounded by an imbricate thrust structure (Fig. 9g). Several indicators of oblique thrusting suggest that the shear zone is transpressional with both thrusting and strike-slip movements. In addition, some ductile shear zones have been brittlely reactivated and display fault breccia with fragments of mylonitic material at their core.

The thrusts in the EGSB show a typical sequence of propagation where volcanioclastic metasediments, metavolcanics rocks and schists form a piggy-back thrust system. This led to the development of pop-up (Fig. 9h) and flower-like structures where a block of rocks or a tectonic wedge moved upward antithetically between fore (main) thrust and back thrust. The uplifted hanging wall block between a pair of oppositely moving conjugate thrusts is the pop-up (Fig. 9g). Such structures are usually associated with flower-like cleavage and tile-like piling of subsidiary thrust sheets forming an imbricate structure.

Two systems of high-angle NW–SE and NE–SW of coeval hectometric to kilometric brittle normal fault zones, as well as hectometric joints are widely distributed within the granites and metagabbro-diorite (Fig. 9i and j). The NE–SW faults dominate and dip 50–75° with variable dip sense and slickenlines showing a main dip-slip displacement with variable throw. They represent the
latest brittle deformation event in the Wadi Ghadir area. The different structures that developed in the syn-tectonic granites include extensional faults, oblique reverse and strike-slip faults that markedly displace dykes in the granitic rocks.

5.2 The West Ghadir Shear Zone (WGSZ): transpressional structures

The WGSZ consists of an NNW–SSE striking zone of deformation that connects the EGSB to the NNW-striking structures in the Hafafit core complex (HCC). The WGSZ is highly strained and comprises an association of highly tectonized mafic metavolcanics, serpentinites, talc-carbonate and metagabbros-diorites embedded in a matrix of volcaniclastic metasediments and schists. The high-strain zone of the WGSZ represents a shear zone of ca. 5–10 km in width, composed mainly of mylonites, protomylonites and phyllonites, with predominant sinistral movement and brittle–ductile reactivations.

Foliations in the WGSZ range from sub-vertical ($S_2$, Fig. 11a–b) to steeply dipping toward the NE and ENE ($S_1$, Figs. 11c and 12a), with an average orientation being N17°W. Foliation is generally parallel to the main trend of the shear zone that varies in intensity, spacing and homogeneity (Fig. 11a–c). The $S_2$ foliation (Fig. 12a) is mainly defined by segregation of quartz/feldspar-rich microlithons from phyllosilicate-rich foliation planes in volcaniclastic metasediments, and by the alignment of actinolite in metavolcanic rocks. Prevalence of rock structure increases toward the narrow shear zones and in

Fig. 9. (a) NW-plunging open folds in volcaniclastic metasediments, (b) and (c) overturned folds in volcaniclastic metasediments, (d) strike-slip shear zone in metavolcanics, (e) subvertical foliation in ductile strike-slip shear zone, (f) subhorizontal and moderately plunging lineations, (g) thrust sheets forming an imbricate structure, (h) pop-up structure between a pair of oppositely moving conjugate thrusts, (i) and (j) NE-striking normal faults in syn-tectonic metagabbros and granites.
some cases their cores display highly recrystallized and lineated units defined by ‘rods’ of recrystallized quartz and feldspars (e.g. mylonite and L-tectonite in granitic gneiss) that moderately plunge toward the SE (L₁). In gneisses, quartz typically consists of polycrystalline aggregates of homogeneous fine-grained elongated...
crystals. These aggregates locally develop an oblique foliation. Feldspar porphyroclasts present microfracturing and cataclasis as well as recrystallization only localized in tails. Within the high-strain zones, the strike of subvertical mylonitic foliation (S₂; Fig. 11a–b) and the trend of the subhorizontal elongation lineation (L₂; Figs. 11e–f and 12d) are parallel to the trace of the shear zone. Foliation planes show slight variations in dip direction (to the north and to the south) and in inclination values. The plunge of lineations also varies, and may be gently to the south, horizontal, or gently dipping to the north.

The prominent mineral lineation on foliation planes is defined by elongated quartz and actinolite crystals and shows a girdle distribution with mean orientation plunging...
SE at moderate to steep angles in oblique shear zones and thrusts (L₁) and plunging SSE at a low angle to subhorizontal (L₂) in the high-strain zone (Figs. 11e–f, 12c and d). Asymmetric minor folds, boudins and porphyroclasts, shear band and S/C fabrics are well-developed on the horizontal planes (orthogonal to foliation and parallel to lineation) and consistently indicate sinistral kinematics.

Thrust faults are the most common structures in the WGSZ. The talc-carbonate and steeply dipping lenses and sheets of serpentinites are emplaced along thrust planes and elongated in a NNW–SSE direction parallel to the penetrative foliation of the volcaniclastic metasediments matrix. The thrust contacts between granite gneisses, tectonized serpentinites and other mélange components (Fig. 11g) is always decorated and marked by mylonite schists. The thrusts in the WGSZ show a typical sequence of propagation where each successive thrust develops in the footwall of the previous thrust in a piggy-back thrust manner (Fig. 11h). This led to the growth of flower-like and pop-up structures (Fig. 11j).

Map-scale (up to 10-km long) reclined folds (Fig. 13a–c) occur close to the eastern boundary of WGSZ. The folds have fold axes plunging down the dip of the axial surface. The axial plane dips between 55° and 65° and the pitch of the hinge line on the axial plane is more than 80°. The core of the folds contains serpentinites whereas their limbs consist of metavolcanics rocks and volcaniclastic metasediments (Fig. 13b). The foliation in the overturned folds dip in the same direction on both sides of the axial plane because one of those limbs is rotated. The forelimb of the synform was overturned with development of reverse shears sub-parallel to the back limbs (Fig. 13b). A map scale upright fold exists in the southern bank of Wadi

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Fig. 12. Structural data from the WGSZ: (a) Equal area lower hemisphere for poles to $S₁$ foliation showing moderately developed clusters with non-uniform distribution, (b) equal area lower hemisphere for poles to $S₂$ foliation, (c) mineral lineation (L₁) along the planes of thrusts, (d) mineral lineation (L₂) along strike slip shear zones, and (e) poles to fold axes (F₂).
Lawi (Fig. 5) with an axis trending NE–SW perpendicular to the axes of the major recumbent and minor folds in the EGSB and WGSZ. Also, minor folds with vertical axes occur within the high-strain zones of the WGSZ.

Asymmetric, westerly verging folds and asymmetric boudins on the sub-vertical planes (orthogonal to both foliation and sub-horizontal lineation) indicate reverse slip kinematics (with top-to-SW movement sense) where down-dipping lineation on the thrust planes becomes important. However, the thrust-related structures far outweigh in intensity than the sinistral strike-slip features suggesting an overall dominance of thrusting over strike-slip shearing in the WGSZ.

Minor F₂ folds (Fig. 14a) are abundant in the WGSZ, with fold axes plunging at low to steep angles to the SSW (Fig. 14b) and the prevailing sub-vertical foliation being axial planar to the fold structures. Quartz veins have been folded and strongly stretched parallel to the main shear plane resulting in development of boudins, en-echelon structures (Fig. 14c), asymmetric recrystallized tails and meso-scale fish structures, all indicating sinistral slip. Meso-scale overturned folds developed within the closure of the major overturned synform (Fig. 14d).

L–S tectonic fabrics are pervasively developed along the WGSZ, where both subvertical foliation and sub-horizontal stretching lineation are well developed. The foliation, formed by the preferred orientation of biotite, quartz, and feldspar ribbons, is nearly parallel to the regional fabric. There is stretching lineation, formed by elongation of quartz, feldspar, and biotite, with long tails of porphyroclasts. The L–S tectonite fabric in the granitic gneisses changes to mylonite fabric in the high-strain zones where S/C structures, asymmetric recrystallized tails on porphyroclasts and asymmetric northerly verging folds dominate in the subvertical planes (orthogonal to foliation and sub-parallel to lineation) indicating a strong component of thrust sense top-to-SW shear. The effects of this shearing are strongest to the south of Gabal Lawi and along Wadi Um Abid where there are southwest verging major thrusts in the WGSZ. These thrusts (Fig. 16a)
placed low-grade rocks (metavolcanics rocks, volcaniclastic metasediments and serpentinites) over amphibolite-grade basement gneisses (granitic gneisses and hornblende gneisses of HCC).

Within the high-strain zone of the WGSZ, tectonite fabrics, rods, mullions, boudin pods, elongate enclaves, and persistent linear features all plunge gently to the SSE. Mesoscopic folds on the sub-vertical planes (orthogonal to foliation and parallel to stretching lineation) typically show asymmetric northwesterly verging geometry with axial planes inclined southwest. Minor fold axes plunge gently to moderately due NNW or SSE. The strong, steeply dipping planar fabric is defined by elongated amphibole crystals separated by recrystallized quartz (and plagioclase) ribbons; quartz exhibits strong undulose extinction and subgrain development. The sigmoidal-shaped augens are composed of highly strained quartz (±plagioclase) that indicate sinistral displacement and represent strain focusing during deformation.

The metamorphic grade contrast along the NSZ and WGSZ constitutes the main estimated displacement along it. The footwall of the WGSZ is the Migif-Hafafit gneisses deemed to be of high temperature–low pressure amphibolite facies (El-Ramly et al., 1984, 1993). Numerically, the metamorphic conditions were estimated by Asran and Kabesh (2003) as 720–740°C for the Migif-Hafafit amphibolites and 800–820°C for associated migmatites, both under pressures of 6–7 kbars. The pressure conditions were confirmed as 6–8 kbars by Abd El-Naby and Frisch (2006). On the other hand, numerical estimations of the greenschist facies in the CED show about 450°C at 4 kbars (Fritz et al., 2002). This gives a 3±1 kbar pressure difference across the NSZ corresponding to a loss of section measuring 10±3.5 km.

5.3 The Ambaut Shear Belt (ASB): an imbricate thrust belt

The metavolcanics, volcaniclastic metasediments and ophiolitic metagabbros wedge out to the northeast where sinistral shearing along the WGSZ is partitioned into a few splays forming an imbricate thrust fan and thrust duplex characterizing the frontal ramp of the WGSZ. The ASB is elongated in a NE direction and bounded by the EGSB and WGSZ and occupied mainly by volcaniclastic metasediments, highly tectonized serpentinites, intermediate metavolcanics, metagabbro–diorites and intruded by syn-tectonic granites. The dominant foliations (S2) strike NNE–SSW close to the WGSZ but curve into a NE–SW direction around Wadi Umm Tundubah and Wadi Ambaut (Fig. 5). Chlorite and actinolite schists are strongly foliated, with the foliation defined by the alignment of chlorite, sericite, quartz and talc in schist and aligned actinolite and chlorite in metavolcanic rocks. Intensity of cleavages varies throughout the ASB from volcaniclastic metasediments to metavolcanic rocks. Poles to NW-striking S2 foliation show moderately developed

Fig. 14. (a) and (b) Asymmetric minor folds and folded quartz veins in volcaniclastic metasediments, (c) folded and strongly stretched quartz veins with development of boudins and meso-scale fish structures, (d) SSE-plunging meso-scale overturned fold developed within the closure of the major overturned syncline.
clusters (Fig. 15a). Also, poles to $S_3$ foliation show moderately developed clusters and tend to strike N20°–65° E with dips of 52°–65° toward the NW and SE (Fig. 15b). Steep crenulation cleavages (65°–85°) with an approximate NE–SW strike are developed parallel to the axial planes of NE-plunging major folds in intensely foliated schists. In narrower and discrete high-strain zones, steeply dipping mylonitic foliation ($S_3$) (Fig. 16a) has a sigmoidal trend within the strike-slip shear zones and folded into small-scale folds. Moderately to steeply plunging down-dip mineral lineation (Figs. 15c and 16b–c) along planes of intense mylonitic foliation in mylonitic schists is defined by quartz ribbons and feldspar porphyroclasts and amphibole needles. Shallowly southwesterly plunging mineral lineation is confined to steeply dipping strike-slip shear zones (Fig. 15d).

The ASB is marked by a series of map-scale, relatively open, NE-trending anticlines and synclines spaced at approximately 2–4 km intervals and with wavelengths of up to 3 km. Axes of these folds are plunging moderately to the NE and less commonly to SW whereas axial planes are moderately to steeply dipping to the NW. Minor folds with low amplitudes are common in schist, volcaniclastic metasediments and sheared metavolcanic rocks.

The ASB is marked by a series of oppositely southwestward (Fig. 16d) and northwestward dipping imbricate thrusts marked by SE- and NW-side-up thrust movements and form pop-up or flower like structures. These thrusts mark the sheared contacts between metavolcanics and metagabbro–diorite and the overlying schists and volcaniclastic metasediments.

6 Shear Kinematics

The GSB consists of three structural units: East Ghadir shear belt (EGSB), West Ghadir shear zone (WGSZ) and Ambaut shear belt (ASB). There is a clear transition along the GSB from a low-strain zone in the east to a high-strain zone represented by the WGSZ. The EGSB expresses as an imbricate structure, consisting of several parallel thrusts, rather than a near-vertical strike-slip shear zone. It is a simple piggyback imbricate thrust system with a unidirectional sense of thrust propagation to the southwest (Fig. 11b). The imbricate thrust slices in the EGSB are overprinted by a NNW-trending sinistral strike-slip shear zone of the WGSZ that changed to an imbricate thrust fan and flower-like structures to the north and the northeast occupying the ASB. Also, there is a marked change along the ASB from sinistral strike-slip shearing along the WGSZ to dextral shearing along the main stream of Wadi
Umm Taundubah to thrusting in the northern bank of Wadi Ambaut. The kinematic transition along the GSB is consistent with separate strike-slip and thrust-sense shear zones. Abundant shear criteria give a top-to-southwest sense of thrusting in the EGSB (Fig. 17a–d). The intensity of the deformation dipping angle of thrusts and plunging of mineral lineation in the EGSB increase toward and close to the WGSZ.

The WGSZ is the northern part of the major Nugrus sinistral strike-slip shear zone separating the GSB to the northeast from the HCC in the southwest. Several kinematic indicators of reverse sinistral (i.e., oblique) slip suggest that the WGSZ is a transpressional imbricate zone with both thrusting and strike-slip movements. The high-
strain zone within the WGSZ is a vertical ductile deformation zone of about 10-km width and having a strike direction of N17–20°W. The main shear sense indicators include deflected foliation (Fig. 17e), asymmetric porphyroclasts (σ type; Hanmer and Passchier, 1991) (Figs. 17f–g and 18a–f), asymmetric pressure shadows, asymmetric boudins (Goscombe and Passchier, 2003), S/C textures (Fig. 17g) and sigmoids. The porphyroclasts have a mantle of finer materials and extend out into two winged structures that orient parallel to a mylonite foliation, the wings often showing a characteristic curvature (Figs. 18a–f). The sigmoids are lozenge-shaped lenses that differ in composition from the host rock and, lack the central rigid grain of mantled porphyroclasts (Passchier and Coelho, 2006). The porphyroclasts in the granite gneisses indicate top-up-to-NW characterizing a sinistral compressional transport. Also, asymmetric folds, with fold axes at a high angle to foliation, may indicate the sense of shear (Carreras et al., 2005). The observed macro- and microstructures within

Fig. 17. (a–d) Shear criteria showing a top-to-southwest sense of thrusting in the East Ghadir shear belt, (a), (b) and (c) asymmetric s-type ultramafic and serpentine porphyroclasts, (d) folded and faulted quartz vein, (e) deflection of foliation in metasediments indicating sinistral sense of shearing, West Ghadir shear zone, (f and g) asymmetric serpentine porphyroclasts in mylonite schists indicating sinistral sense of shearing, West Ghadir shear zone, (h and i) asymmetric serpentine porphyroclasts in metasediments indicating dextral sense of shearing.
the high-strain zone are all indicative of sinistral movement through the WGSZ. Also, the observed kinematic indicators involve oblique slip vector on the shear zones parallel to strongly plunging down-dip slip.
lineations, indicating top-to-SW reverse movements. We propose a distinct explanation: a previous west-to-southwestward thrusting followed by transpressional sinistral shearing that formed a NW-shallowly plunging stretching lineation.

A fan-like structure exists at the northern termination of the WGSZ and consists of oppositely dipping foliations to the SE in its southeastern limb, and to the NW and ESE in the northwestern splay. The transpressive character of deformation in the WGSZ is shown by the coexistence of strike-slip and compressive structures.

The ASB is characterized by a bidirectional thrust system consisting of both thrusts and back thrusts, pop-up structures and flower-like structures. Two sets of striations are developed with southwestward plunge angles of 7° and 60°, respectively, implying that the ASB underwent at least two stages of oblique movements. Both reverse and strike-slip components occurred in the ASB. Steeplty NW- and NE-dipping foliation and pop-up structures indicate SE- and NW-side-up reverse movements along fore- and back-thrusts respectively. Small-scale high-strain zones are marked by S/C fabrics, asymmetric deflections of foliation planes, asymmetric tails on the porphyroclasts (Figs. 17h–I and 18g–h), boudinaged and folded quartz veins indicating sinistral sense of movement overprinted by dextral shear sense.

7 Discussion

7.1 Tectonic model for deformation

The oldest phase (D1) in the CED is an early shortening phase associated with arc collisions (740–660 Ma) and characterized by NW-directed imbrication of Pan-African nappes (Fig. 19a) with the development of SSE-plunging stretching lineations (Greiling et al., 1994). D2 is SW- and NE-directed thrusting associated with terrane assembly where regional nappe transport toward the SW is common in the Egyptian Eastern Desert, especially around core complexes and major shear zones (Greiling, 1997; Fritz et al., 1996; Shalaby et al., 2005; Abdeen and Abdelghaffar, 2011; Abd El-Wahed, 2008, 2014). D2 is a sinistral transpression associated with continued oblique convergence (Fritz et al., 1996; Makroum, 2001, 2017; Abd El-Wahed, 2008, 2014; Abd El-Wahed and Kamh, 2010; Abdeen et al., 2014; Abd El-Wahed et al., 2016; Makroum, 2017). D2 is dextral transpression in a conjugate with D3 (Shalaby et al., 2005; Abd El-Wahed and Kamh, 2010; Abdeen et al., 2014; Abd El-Wahed et al., 2016; Makroum, 2017). D2 is a sinistral transpression associated with continued oblique convergence (Fritz et al., 1996; Makroum, 2001, 2017; Abd El-Wahed, 2008, 2014; Abd El-Wahed and Kamh, 2010; Abdeen et al., 2014; Abd El-Wahed et al., 2016; Makroum, 2017). D2 is a sinistral transpression associated with continued oblique convergence (Fritz et al., 1996; Makroum, 2001, 2017; Abd El-Wahed, 2008, 2014; Abd El-Wahed and Kamh, 2010; Abdeen et al., 2014; Abd El-Wahed et al., 2016; Makroum, 2017). D3 is dextral transpression in a conjugate with D3 (Shalaby et al., 2005; Abd El-Wahed and Kamh, 2010; Abdeen et al., 2014). D3 includes later events.

Structures within the GSB can be described in terms of three main ductile to semi-ductile deformational episodes (D1−D3) associated with the collision between East and West Gondwana. D1 structures (Fig. 19a) include SW-propagated imbricate thrusts and produced NW-trending major F1 folds in volcanioclastic metasediments and metavolcanic rocks. S1 foliation is associated with movement along the southwestward imbricate thrust system and accompanied by moderately SE-plunging mineral lineation. In the EGSB, D1 deformation occurred at ~640–560 Ma ago and is manifested by the development of the steeply dipping, NW-striking shear zones, NW-trending major F2 with NW-plunging axes, F2 minor asymmetric folds of different scales, F2 upright fold trending NE-SW, S2 axial planar cleavage, and L2 subhorizontal to moderately plunging mineral stretching lineation.

D2 formed an arcuate-shaped structure constituting the WGSZ (~595 Ma) and ASB imbricate thrust. D2 structures (Fig. 19b) formed during the NNW-trending sinistral shearing along the WGSZ and its arcuate thrust fan in the ASB. The high-strain zone within the WGSZ is expressed as steeply dipping strike-slip shear zones with dominantly sub-vertical foliations and sub-horizontal lineations. In the moderately deformed zones in the WGSZ, folds have moderately plunging axes and a pervasive NNW–SSE striking axial planar slaty cleavage (S3), defined by an alignment of white mica, chlorite and elongate quartz; S2 dips 60–80° to either the SW or NE. In the GSB, two generations of fabric (S4 and S2) can be recognized around the major plunging folds. S4 is locally recognized in low-strain areas, but is commonly transposed and overprinted by S2 in high-strain zones, which is the dominant fabric throughout the WGSZ (Fig. 19b). S2 pervasive NNW-SSE striking axial planar slaty cleavage (S3), defined by an alignment of white mica, chlorite and elongate quartz; S2 dips 60–80° to either the SW or NE, and is associated with a subhorizontal to moderately stretching lineation (L2).

The NNW–SSE striking S2 fabric in the WGSZ has been progressively rotated into a NE–SW orientation (arcuate zone) in the ASB. The S2 strikes NE–SE and dipping moderately to steeply to SE and NW. Thrust faults are commonly associated with several large-scale asymmetrical ENE-plunging F3 folds (Fig. 19c). Northwestward imbricate thrusting in the northwestern part of the ASB and southeastern imbricate thrusting in the southeastern part form positive flower-like pattern. These thrusts, considered coeval with a consistent down-dip mineral elongation lineation (L3), indicate a general top-to-NW and -SE sense of reverse shear.

D2 structures formed during the NW-trending sinistral shearing along the EGSB and WGSZ and the imbricate thrust in the ASB thrust fan are strongly overprinted and dislocated by another imbricate fan (Abd El-Wahed et al., 2016) that formed during oblique NE-trending dextral shearing (D1) along the Sukari shear zone to the north of the study area (Fig. 19c). Abd El-Wahed et al. (2016) stated that the tightness and steepness of major folds and the curvature of the thrust fan in the ASB increases with increasing D3 strain. In narrower and discrete high-strain zones, steeply dipping mylonitic foliation (S1, 65°–85°) developed parallel to the axial planes of NE-plunging major folds (F1) in intensely foliated schists. The geometrical relationship between D2 major folds in the EGSB and WGSZ and the D1 NNE-dextral shearing along the ASB indicates that the two events represent stages within a progressive deformation episode, as indicated by the cessation of the D1 NNE-trending ASB along the inflection planes of D2 NNW-trending WGSZ (Fig. 15c). Sinistral transgression along the NW-trending shear zone in the CED (660–645 Ma) was accompanied and followed by NE-trending dextral transpression (645–540 Ma).

The latest structures in the GSB are normal, strike-slip
faults and major fractures in syn- to post-tectonic granites, which were probably associated with the intrusion of the post-tectonic granites.

7.2 New structural evidence for transpression
The data presented here display strong evidence for compressive and transpressive deformation affecting the GSB. Mega-scale structures are clearly visible on the satellite scene (available at http://maps.google.com).

Lineament analysis reveals linear structures within the GSB such as kilometer-scale undulations and tens of kilometers wide S-shaped features. Field investigations confirm our interpretation of the mega-scale structures presented in Figs. 5 and 7.

The EGSB is characterized by an asymmetric semi flower-like shape caused by southwestward thrusting instead of the typical features of a pop-up structure. The EGSB is almost a deformation zone with kinematics

Fig. 19. Block diagrams showing structural evolution of the Ghadir shear belt (explanations in text).
combining both southwest-directed thrusting and sinistral strike-slip shear zones with the development of a series of NNW-trending folds with southwestward vergence. Furthermore, in this belt many low-angle thrusts are developed in the volcaniclastic metasediments. Since there are more, several thrusts and folds are much tighter in the western part of the EGSB as compared to those in the eastern part; the former region is considered to have experienced much stronger deformation. These thrusts and the asymmetric folds in the western part of the EGSB jointly show the southwestward thrusting and display a semi-flower-like structure.

The most prominent outcrop-scale deformation features in the GSB, including folds, metamorphic fabric, and associated lineations, are the result of regional, NW-directed, sinistral transpression assigned to $D_2$. On outcrops along Wadi Lawi, Zabara and Fegass, the core of the WGSZ expresses as a near-vertical ductile deformation zone rather than an imbricate structure as in the east. Several kinematic indicators of oblique thrusting suggest that the WGSZ is a transpressional zone with both thrusting and strike-slip movements. The highly deformed zone is a vertical ductile deformation zone of about 10-km width and a strike direction of N17°W. Kinematic indicators, such as a sinistral porphyroclast system, reeled and vertical folds with hinges plunging to NNW at an angle of 65° in the volcaniclastic metasediments also indicate the strike-slip movement of the WGSZ. However, a series of asymmetric folds parallel to the strike of the deformation zone resulted from compression perpendicular to the deformation zone, indicating a thrust movement within the shear zone. We thus infer that the WGSZ was formed in a transpressive stress field rather than a compressive one. The transpressive stress field is expressed most clearly along Wadi Um Abid. Here, the shear zone is steep plane with a dip of 85° to N20°W. Two sets of striations are developed with northwestern pitch angles of 15° and 42°, respectively, implying that the WGSZ underwent at least two stages of sinistral strike-slip oblique thrusting. Top-up-to-NNW and less common -SSE sense-of-shear indicators are consistent with interpretations of the WGSZ as a ductile sinistral strike-slip shear zone with scarce dextral sense of shear.

Controlled by the thrust and back-thrust on the southeastern and northwestern boundaries, the ASB forms pop-up structure constituting the northeastern bidirectional thrust system and positive flower-like structure in the Ghasdir area. The ASB is characterized by two opposite thrusting directions, in the northwestern part, for example, their dip directions are to the southeast, indicating a northwestward thrusting, whereas in the southeastern part they inclined to the northwest, suggesting a southeastward thrusting (Fig. 19c), and finally, in the middle part, they are nearly upright. These structural characteristics in this section form the positive flowerlike pattern. The southeastward-thrust portion takes two-thirds of the belt, whereas the northwestward-thrust part accounts for the remaining one third. The deformational structures in the southeastern part are dominated by linear asymmetric folds with NE–SW-trending axial planes and there are more thrusts in the southeastern part than the northwestern part. From the structural style, the tightness of the folds in the southeastern part indicate that the deformational intensity of the southeastern part is inferred to be a little stronger than that of the northwestern part.

The main structural feature in the GSB is the change from thrusting in the EGSB to strike-slip shearing within the WGSZ, i.e. towards the major sinistral shear zone separating the GSB from the HCC. Although the effects of strike-slip shearing, in the form of sub-horizontal mineral lineation, shear bands, boudinage, and other shear criteria are most clear within the WGSZ, we consider that the whole shear belt was subject to prolonged transpression, with increasing shear components towards the west.

Our field observations and structural study in the WGSZ show a strong shallowly plunging stretching lineation on almost all subvertical foliation planes associated with a shearing component, consistent with major strike-slip deformation. This in agreement with the currently proposed models for the NSZ as a major sinistral strike-slip shear zone in the CED. Structures indicating subvertical movement such as steeply plunging stretching lineations have been recorded in shear zones at sheared contacts between metavolcanic and metagabbroic rocks. Furthermore, pervasive fabrics displaying strike-slip movements that show dominant sinistral and subordinate dextral kinematics seem to correlate more with a complex transpression zone with a dominant horizontal shearing component, like that suggested for the NFS.

This study favors a transpressional model with subhorizontal general shear flow instead of a simple shear model for the following reasons: (i) Simple shear flow requires a shear zone of constant thickness and has a straight parallel boundaries and the WGSZ has no parallel boundaries and shows variable thickness; (ii) the existence of shear zones with dominant sinistral and subordinate dextral components is typical for a shear belt that deforms in a bulk non-coaxial system (e.g., Gagnon et al., 2016); (iii) the WGSZ shows a relationship to shear zones in which the length of the shear zone boundaries increases and the thickness of the shear zone decreases with ongoing shear deformation (e.g. Ramsay and Graham, 1970); and (iv) the deformation intensity in the WGSZ is highly irregular and varies from weak to very strong. This variable distribution of deformation is typical for shear belt with strain partitioning between low-strain and shear zones, where the low-strain shear belt reveals the non-coaxial component of the deformation (Pennacchionia and Mancktelow, 2007).

Structural analysis in the GSB revealed a series of ~NW–SE kilometer-scale open reeled folds, which are bounded by ~NW–SE sinistral mylonite zones with steeply dipping foliation and shallowly SE- to SSE-plunging stretching lineations. The combined sinistral strike-slip shear zones, reverse shearing and folding structures have been interpreted to result from a phase of transpressional deformation in response to oblique squeezing of the Arabian-Nubian Shield between East and West Gondwana. The parallelism between the striking direction of the mylonitic foliation and the axial plane of the major folds indicates that transpressional deformation has been partitioned into a simple shear component in the
mylonite zones and a pure shear component in the fold zones (e.g. Schulmann et al., 2003).

8 Conclusions

(1) The Wadi Ghadir area represents a widely distributed stretch of Neoproterozoic ophiolitic mélangé constituted mainly of allochthonous ophiolitic fragments mixed well and incorporated in a sheared matrix, as well as other different mappable units. The most extensive and widely disseminated unit of the area is the mélangé assemblages.

(2) The structural belt of the area is divided into three main shear belts: East Ghadir Shear Belt (EGSB), West Ghadir Shear Zone (WGSZ), and Ambaut Shear Belt (ASB). The main structural feature in the GSB is the change from thrusting in the EGSB to strike-slip shearing within the WGSZ. In the EGSB, foliations associated with thrusts are deflected, folded and transposed into the foliation within the high-strain zone of the NW-striking shear zones. Foliation is steeply SE- to E-dipping parallel to the axial plane of NNW- and NE-trending folds. The thrusts in the EGSB show a typical sequence of propagation forming a piggy-back thrust system. Pop-up structures formed where the block of deformed rocks moved upward antithetically between a pair of oppositely moving conjugate thrusts.

(3) The WGSZ comprises an association of metavolcanics, serpentinites, talc-carbonate and metagabbros-diorites embedded in a matrix of volcanoclastic metasediments and schists. The WGSZ is the frontal part of the Nugu shear zone separating the Hafafit core complex in the southwest from the Ghadir ophiolitic mélangé to the northeast. The WGSZ is a NNW-trending transpressional shear zone where reverse oblique slip branching arrays propagate from the WGSZ forming the NE-trending imbricate ASB thrust fan. The thrusts in the WGSZ show a typical sequence of propagation leading to the growth of flower-like and pop-up structures. Map-scale (up to 10-km long) inclined folds mark the boundary between the EGSB and WGSZ. Thrusting dominates over strike-slip shearing in the WGSZ, where both steeply dipping and sub-horizontal stretching lineation are well developed. The main ductile deformation in the WGSZ was partitioned into a sub-horizontal sinistral strike-slip and a top-up-to-NNW and less common SSE sense of shear. Strongly plunging down-dip slip lineations along thrust planes indicate to-NW reverse movements.

(4) The ASB is elongated parallel to the axial planes of NE-plunging major folds. Shallowly south-westerly plunging mineral lineation is confined to steeply dipping strike-slip shear zones. The ASB is characterized by a bidirectional thrust system forming pop-up structures that are marked by SE- and NW-side-up reverse movements along fore- and back-thrusts, respectively.

(5) The D2–D3 deformational phases, of a ductile nature, are associated with an average E–W shortening and sinistral movements, which caused a main sinistral strike-slip displacement with a strongest thrust component toward the SW in the WGSZ and a dextral strike-slip displacement in the ASB. This deformational phase associated with sinistral movement in the WGSZ is represented by a N20°-trending shear zone, with intermediate to strong dips to the SW and two sets of stretching lineations; the first one plunging to E to SE thus giving a thrust component toward the SW; the second plunging moderately to SSE is compatible with a sinistral movements of the shear zones.

(6) The combined sinistral strike-slip shear zones, reverse shearing and folding structures are interpreted to result from a phase of transpression where East and West Gondwana collided and the Arabian-Nubian Shield was obliquely squeezed.

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