Arab J Geosci (2017) 10: 11
DOI 10.1007/s12517-016-2786-y

ARABGU2016

A new tectonic model for Abu-Dabbab seismogenic zone (Eastern Desert, Egypt): evidence from field-structural, EMR and seismic data

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Received: 31 August 2016 / Accepted: 5 December 2016 / Published online: 29 December 2016

Abstract Abu-Dabbab area is the most active seismic zone in the central Eastern Desert of Egypt, where seismic activities are daily recorded. The reported earthquakes are microearthquakes of local magnitudes (ML < 2.0). A spatial distribution of these microearthquakes shows that the earthquakes of the area follow an ENE–WSW trending pattern, which is nearly perpendicular to the Red Sea Rift. Focal mechanisms of different fault styles were recognized with dominant normal faulting (with a strike-slip component) events characterized by focal depths greater than 7 km and reverse ones of shallower focal depths. Several lines of evidence indicating that the brittle-ductile transition zone underlies the Abu-Dabbab area occurs at a relatively shallow depth (10–12 km) and it is acting as a low-angle normal shear zone (LANF). Field-structural, EMR and seismic data (this study) reveal that the maximum compressive stress (σ1) in the area is perturbed from the regional NW–SE direction to ENE–WSW orientation. This stress rotation is evidently akin to the reactivation of the crustal scale Najd Fault System (NFS), where such reactivation is attributed to the ongoing activity/opening of the Red Sea. Our tectonic model proposes that the continuous activity on the brittle-ductile transition zone including the LANF led to stress localization, which triggering a brittle deformation in the upper crustal-levels and associated shallow dipping thrusts. Such bimodal tectonic model suggests that the deep earthquakes are owing to the tectonic movement on the LANF (transtension), whereas the shallow earthquakes are related to a brittle deformation inside the fault blocks of the upper crust (transpression). Deformation creep along this zone didn't permit continuous accumulation of strain and hence reduce the possible occurrence of large earthquakes.

Keywords Abu-Dabbab area · Seismotectonics · EMR-data · Tectonic model

Introduction

Abu-Dabbab area is located in the central Eastern Desert of Egypt, some 30 km north of Marsa Alam city on the Red Sea coast (Fig. 1). Three main wadis (valleys) are draining Abu-Dabbab area; Wadi Mubarak, Wadi Abu-Dabbab, and Wadi Dabr. The Abu-Dabbab area is one of the seismic source zones in Egypt, characterized by cannon earthquakes, long seismic activity, and earthquake swarms. The seismicity and unique geologic setting of the area have attracted the attention of many workers (e.g. Fairhead and Girdler 1970; Daggett et al. 1980 and 1986; Hassoup 1987; Kebeasy 1990; El-Hady 1993; Ibrahim and Yokoyama 1998; Badawy et al. 2008; Hosny et al. 2009 and 2012; Azza et al. 2012; Mohamed et al. 2013; Basheer et al. 2015; El Khrepy et al. 2015). The area has been subjected to two significant earthquakes on 12 November 1955 and 2 July 1984 with magnitudes 5.6 and 5.2, respectively (Fairhead and Girdler 1970; Badawy et al. 2008). The recorded seismic activity from Abu-Dabbab region by the Egyptian National Seismic Network (ENSN) ranges from 10 to 15 events/day to greater than 60 events/day during swarms (Badawy et al. 2008; Mohamed et al. 2013). Many earthquake swarms (1976, 1984, and 1993) were instrumentally recorded and discussed by several authors (e.g. Hamada 1968; Fairhead and Girdler 1970; Dagget

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This article is part of the Topical Collection on *Current Advances in Geology of North Africa*

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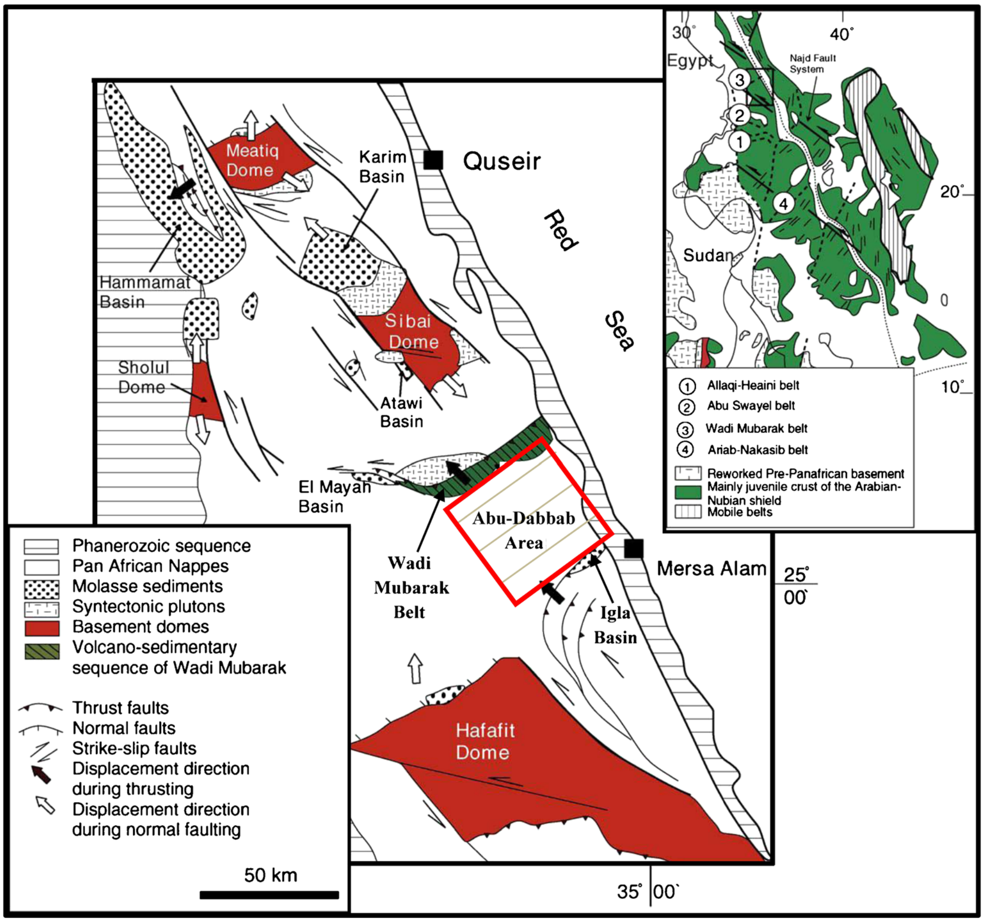


Fig. 1 Tectonic map of the central Eastern Desert showing the core complexes, the northwest–southeast striking Najd fault system and the location of Abu-Dabbab area (after Fritz et al., 1996; Shalaby et al., 2005). The inset map shows the Najd fault system and other deformation belts along the Arabian-Nubian shield

and Morgan 1977; Daggett et al. 1986; Hassoup 1987; Kebeasy 1990; El-Hady 1993; Ibrahim and Yokoyama 1998; Badawy et al. 2008). In addition, four micro-earthquake swarms (January 2003, April 2003, October 2003, and August 2004) were also recognized (Badawy 2005). The magmatic origin of the seismicity and associated shallow and deep earthquakes is promoting most of the publications dealt with the tectonic setting and seismic activity of Abu Dabbab area. Sabet et al. (1976) suggested that the tectonic evolution of the area was associated with volcanic activity, whereas Daggett et al. (1980) attributed Abu Dabbab seismicity to the subsurface volcanic environment of a cooling pluton. Meanwhile, Hassoup (1987) interpreted this seismicity in the light of the subsurface structural heterogeneity. Hosny et al. (2009) proposed a structural model for the area based on seismic velocity tomography, and related the P and S-wave velocity anomaly to magmatic intrusion. Recently, El Khrepy et al. (2015) reveal strong arguments for the tectonic origin of the seismicity of Abu Dabbab area in despite of the prevalent magmatic origin.

The present study is an attempt to set up a model for Abu-Dabbab seismogenic zone based on results obtained from field-structural study and electromagnetic (EMR) measurements, in addition to the available seismic data analysis.

Geological setting

The crystalline basement lithologies outcropping in the Eastern Desert and southern Sinai Peninsula occupy the northwestern segment of the Arabian-Nubian Shield (ANS), which is itself represents the northern continuation of the East-African Orogen (EAO), one of the largest tract of juvenile continental crust on the Earth (Stern 1994). The EAO is made up of a collage of juvenile intra-oceanic volcanic arc terrains and associated ophiolite remnants that are evolved during the Neoproterozoic East African Orogeny at 900–550 Ma (Stern 1994), concurrent with the oblique convergence between East and West Gondwanalands (Johnson et al. 2011).

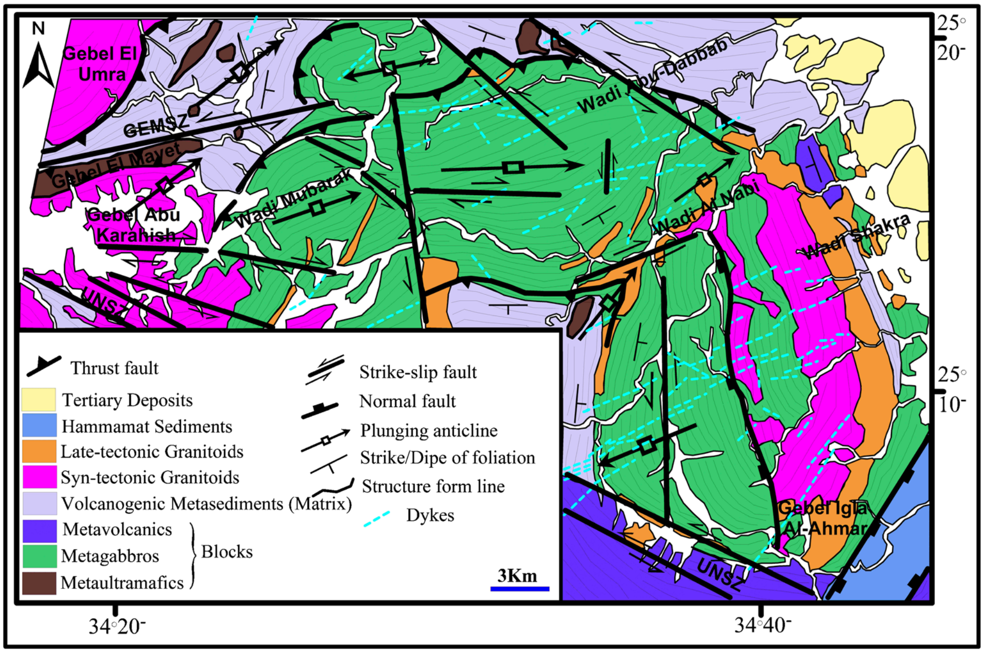
Several attempts have been made to classify the basement of the Eastern Desert. The most plausible, and at the same time the much debatable, one is given by El-Gaby et al. (1990) who suggested two major tectono-stratigraphic units; lower infrastructure and upper suprastructure. These two units are equivalent to tier-1 and tier-2, respectively, of Bennet and Mosely (1987), and juxtapose along major Pan-African thrusting indicated in many places by narrow zones of mylonites and intensive degree of shearing. They are overlain by molasse-type Hammamat sediments and Dokhan Volcanics which are dominated in the northern Eastern Desert, and the whole package is intruded by voluminous post-tectonic granitoids and gabbros. The infrastructure comprises medium- to high-grade gneisses, migmatites and amphibolites, together with remobilized equivalents. The suprastructure forms imbricated thrust stacks and nappes of ophiolitic mélange (comprising variably-sized blocks of metaultramafics, metagabbros and pillow basalts embedded in a matrix of volcano-sedimentary sequence and highly sheared serpentinites), with subordinate island arc metavolcanics and volcaniclastics.

On both sides of the Red Sea, the major tectonic trend strikes NW-SE and is attributed to a crustal-scale left-lateral shear zone called the NFS, which extends about 1000 km crossing the Red Sea into the Nubian Shield (Stern 1985). However, some belts have a principal structural fabric strikes E-W to ENE-WSW, transversally dissecting the NFS. The Abu-Dabbab area is related to these belts and its structural and tectonic setting in the framework of the central Eastern Desert remains debatable. Nevertheless, as a part of the central Eastern Desert, the Abu-Dabbab area consists of a thick succession of low-grade volcano-sedimentary rocks of arc to back-arc affinity (Akaad et al. 1995), with large gabbroic and granitic intrusions (Fig. 2). This belt is dominated with northwestward propagating thrusts that have been originated from possible subduction and collision phases dated back to the suturing events of the Neoproterozoic Pan-African Orogeny (Abdelsalam and Stern 1993; Stoeser and Camp 1985; Blasband et al. 2000). The concerned area is bounded from the north by the Wadi Mubarak fold and thrust belt, while to the south and west the belt is terminated against the Um Nar Shear Zone; UNSZ (Fig. 2). However, the general characteristics of the basement succession of the Abu-Dabbab area are given in the following paragraphs.

Volcano-sedimentary sequence

The volcano-sedimentary succession of the Abu-Dabbab belt can be subdivided into two major parts. The western part comprises fine-grained metavolcanic and metasedimentary schists that are intercalated with banded iron formation (BIF). It extends to Gabal El-Hadid, the northwestern continuation of Um Lassaf-Um Nar belt to the west of Gabel El Mayet, Shalaby et al. (2005). Meanwhile, the eastern part is characterized by the absence of the BIF and dominantly consists of low-grade volcano-sedimentary rocks including slates, schists and fine-grained tuffs. However, in the eastern part, metaultramafic (mainly serpentinites) and metagabboric blocks and fragments, as well as metavolcanics (Fig. 3), are incorporated within a matrix of volcano-sedimentary sequence (Abu El Ela 1985; El Bayoumi and Hassanein 1987; Akaad et al. 1995 and 1996). The belt as a whole is deformed by folded and imbricate thrusts forming a typical tectonic mélange (Fig. 4). Thrust-bound ophiolitic slabs almost large and have several kilometers in length (see Fig. 2). One of these slabs is the massive serpentinites that form the main body of Gabel El Mayet. Several large slabs of ophiolitic metgabbros are apparently exposed at the central and southeastern parts of the belt. The belt is also intruded by younger granitoids and pegmatite veins, which are apparently affected by deformation (Figs. 5, 6). The older granitoids correlate with the 'calc-alkaline older granitoids' known in many areas in the Eastern Desert (Akaad et al. 1996). In the study area, these older granitoids are represented by the Gabel El Umra granitid in the northwest and the Gabel Abu Karahish granitoid to the southwest (see Fig. 2). The 'older granites' are yellow to white, coarse grained, exfoliated and occasionally enclose amphibolite zenoliths and bands and

Fig. 2 Geological map of Abu-Dabbab area (present study)



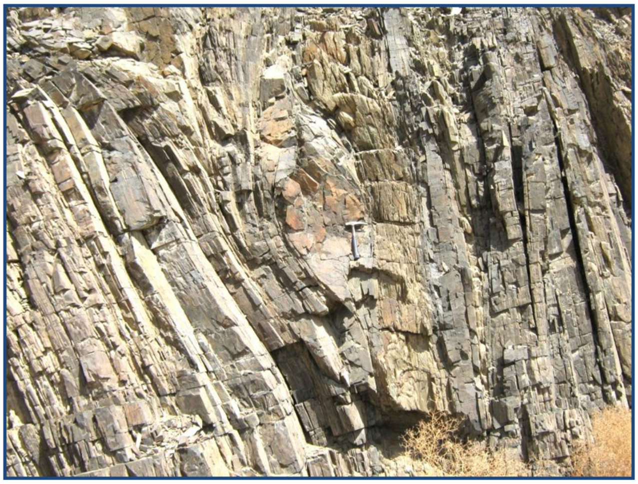


Fig. 3 Metavolcanic fragment embedded within the volcano-sedimentary sequence of Abu-Dabbab belt

Fig. 5 Remarakable folding in pegmatite vein invaded with volcano-sedimentary sequence

affected by deformation (Figs. 7, 8). The younger granitoids are scattered throughout the belt, and follow dilatational fractures forming cross-cutting dykes or small lensoidal-shape bodies. They are comparable well with the 'younger granitoids' of alkaline nature, which are well known in the Eastern Desert (Akaad et al. 1996) and are easily discriminated by lack of deformation and their pink color.

The Gabal el Umra granitoid

Gabal El Umra granitoid is extending about 20 km in east–west direction (Akaad et al. 1996). It has an oval shape and variable composition ranging from granodiorite to tonalite, including some enclaves of amphibolites and metavolcanics. At the contact between the older granite and the mélange and within the older granite itself, intrusions of younger granite are found. This granitoid complex was dated using U/Pb dating and gave ages of 690 ± 90 Ma and 654 ± 5 Ma (Shalaby et al. 2005).

The Gabal Abu Karahish granitioid

Gabal Abu Karahish granitoid is relatively smaller than Gabal El Umra granitoid. It exposes at the southwestern corner of Abu-Dabbab area. It varies in composition with several intrusions depicting its evolution. The contact of this granitoid with the volcano-sedimentary rocks to the east and the south is a sharp intrusive contact. However, its northern boundary is defined by the Gabal El Mayet Shear Zone (GEMSZ), which was originated as a dextral strike-slip shear zone and superposed later by a left-lateral sense of shear (Shalaby et al. 2005). To the west, this granitoid is bounded by the UNSZ, which is highly deformed. The foliated planes within the granitoid body are oriented east-west in relation to the northern limb of the macroscopic fold developed in the vicinity of the GEMSZ (see Fig. 2). The granitoid occupies the central part of the fold along a secondary shear zone parallel to its axial plane. Such field relation may indicate that folding and shearing are kinematically-related. Enclaves of highly deformed pelitic-metasediments are encountered in the northern part of the deformed granitoid.

Structural deformations and tectonic phases

Field and overprinting relations indicate that Abu-Dabbab area has a prolonged polydeformed structural history involving at least four deformations.

Fig. 4 Imbricated thrust stacks and thrust-related folding in the tectonic mélange of Abu-Dabbab area

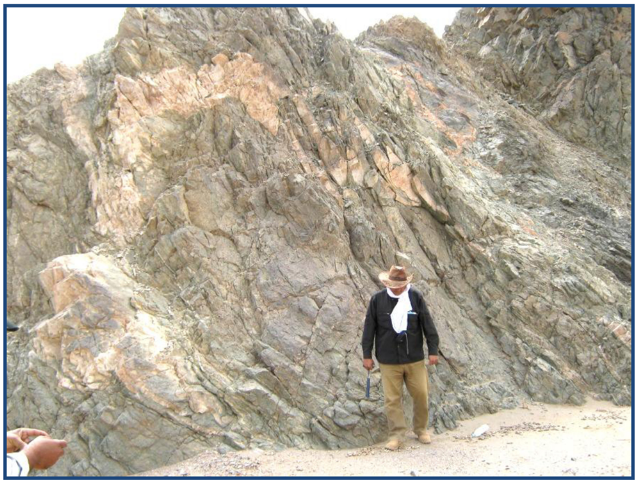


Fig. 6 Passive folding in pegmatites indicated by slip planes parallel to the axial plane

Fig. 8 Obvious folding in amphibolite bands and xenoliths inside the older granitoids

D_1 and D_2 deformations

$D_1$is the oldest recorded deformation phase all over the central Eastern Desert of Egypt and is related to a pre-Pan-African deformation (Loizenbauer et al. 2001). Of great importance is that garnet-bearing metapelites are recorded in Wadi Mubarak (to the north of the study area) within the deformed granitic-rocks of the Gabal Abu Karahish. Shalaby et al. (2005) interpreted them as remnants of a metasedimentary thrust sheet within a nappe structure deformed during the Neoproterozoic Pan-African accretion. Medium to high grade minerals like garnet have produced from metamorphism that has been reported from metamorphic core complexes (Neumayr et al. 1998). Accordingly, these enclaves demonstrate D_1 in Wadi Mubarak and Abu-Dabbab belts.

The formation of the major thrusting and associated thrust-related folding (Figs. 9, 10) is the main deformation event recognized in the Abu-Dabbab area. As in the most of the central Eastern Desert (e.g. Morgan 1990; Stern 1994) thrusting in the study area has the same direction of tectonic transport, top to NW (see Fig. 4). On a regional scale, D_2 deformation is resulted from the oblique convergence between the arc and back-arc assemblage and the Nile Craton at about 620–640 Ma (Fritz et al. 1996). D_2 deformation here was originated through a greenschist facies conditions (Neumayr et al. 1996). This is already reflected on the minerals forming foliations and lineations in the study area. During D_2, the volcano-sedimentary succession was northwesterly obducted over the El Umra granitoid. The age dating of the El Umra granitoid (690–654 Ma) suggests intrusion preceding D_2 thrusting (Shalaby et al. 2005), whereas thrusting that has been formed at the top of Gabal El Mayet was occurred through D_2 thrusting phase. The mylonitized granite of the Gabal El Umra, which is characterized by shallow foliation (Fig. 11) and gneissified and folded granites (see Fig. 8), is highly comparable with the mylonitized granite at the center of the Meatiq dome that was deformed during the D_2 Pan-African accretion phase.

Fig. 7 Amphibolite bands within the older granitoids

Fig. 9 D1 thrusting in the volcanogenic-metasediments of Abu-Dabbab belt

Fig. 10 F1 thrust-related folding with long upper limbs and inclined/overturned short limbs

D_3 deformation

NW-trending left-lateral transpressional regime is very characteristic for the D_3 deformation within the central Eastern Desert of Egypt (Loizenbauer et al. 2001). The NFS and the gneissic core complexes has been originated and exhumed during this event (Fritz et al. 1996). In the Abu-Dabbab and Wadi Mubarak areas, the formation of two major shear zones (UNSZ and GEMSZ) seems to also be concomitant with this event. The UNSZ oriented NW-SE parallel to the NFS and is also has a left-lateral sense of displacement. This shear zone is suggested to be deep-seated as estimated from the magnetic and radiometric data in Ghazala (2001). The Gabal El Mayet shear zone has the E-W orientation and a dextral sense of shear that make it a conjugated set to the Um Nar shear zone. This deformation style is characteristic for most of the shear zones developed during D3 in the central Eastern Desert. Of great importance is that the sense of displacement on the Gabal El Mayet shear zone was changed from right-lateral sense in the early stages of D3 (Shalaby et al. 2005) to a current left-lateral sense in the later stages. The other minor shear zones and the strike-slip faults mapped in the study area are interpreted here to be a conjugated set of shear fractures related to the NFS. Major folding (see Fig. 2) of the volcanogenic-metasediments (the matrix) and the associated metagabbros and metaultramafites (the blocks) is most probably affiliated to this transpressive event.

Fig. 11 Shallow foliation in Gabal El Umra granitoids

D_4 deformation

The deformation history of the D_3 is most probably terminated before the intrusion of the younger gabbros and younger granites. The younger gabbros intruded the UNSZ without evidence on a synmagmatic deformation (Shalaby et al. 2005). The same case is recorded for the younger granitoids intruded the Neoproterozoic basement succession in the Abu-Dabbab area. This indicates a passive intrusion into small pull-apart structures originated during later reactivation of the preexisting shear system. Formation of E-W oriented granitic to granodioritic dykes (see Fig. 2) is an evidence for solid-state deformation and shows a phase of N-S extension (Shalaby 2003). The forgoing field relations and observations point out that the younger gabbros and younger granitoids were intruded during a transtensive regime.

Electromagnetic data (EMR-technique)

The electromagnetic radiation (EMR) is a suitable technique that accurately facilitates investigation of geological structures and associated stress field. It is essentially based on the electromagnetic energy emitted from the brittle materials while exposed to a mechanical stress. The characteristic behavior and foundations of EMR and its application in structural geology and neotectonics were extensively discussed in some works such as Bahat et al. (2005), Lichtenberger (2006a) and Greiling and Obermeyer (2010). The EMR-Technique and Cerescope were the focus of many publications as Reuther et al. (2002), Lichtenberger (2005, 2006a, b), Mallik et al. (2008), Reuther and Moser (2009) and Hagag and Obermeyer (2016a, b).

The current work aims at using the EMR-method and a Cerescope for surface detection and investigation of an active fault system and its related horizontal stress field (σH) at Abu-Dabbab area in the central Eastern Desert. Six linear EMR-profiles were measured using Cerescope to define the location and geometrical style of the active faults, which deform the uppermost Neoproterozoic basement succession of the Abu-Dabbab fold/thrust belt. Horizontal measurements were also recorded to estimate the direction of maximum horizontal stress axis (σ1) which is directly related to the direction with highest EMR-intensity. The results of the EMR-measurements and the seismic data will be integrated and discussed in the light of the strong seismotectonic activity of Abu-Dabbab area.

Methodology

EMR-measurements are taken with the Cerescope (Fig.12). The composition of the Cerescope device and the most important adjustment steps were involved in the Cerescope manual guide in Obermeyer (2001). The calculated values are recorded by the Cerescope as Parameters from A to E (Table 1). Both parameters A and D are the most benefit for meaningful interpretation. For complete measurement procedures, linear and horizontal measurements and their significance, refer to Hagag and Obermeyer (2016a, b).

EMR measurements at Abu-Dabbab area

Linear measurements

EMR-measurements were surveyed by the Cerescope along six linear profiles (Fig. 13), which are generally oriented N to NW. The main target was to transect the Wadi Abu-Dabbab that running E-W along a major shear fracture evidenced from the clustering of the most of earthquakes of Abu-Dabbab area along its path and also in its vicinity (Fig. 14, Mohamed et al. 2013). Abu-Dabbab area is characterized by rugged topography and high mountainous peaks. As a consequence, the EMR- measurements were taken with a car of regular speed. The Cerescope device was adjusted where the Cerescope antenna oriented vertically to the ground surface. The measurements have been taken during April 2015, with optimum conditions suitable for EMR-measurements to avoid the artificial signals from very low frequency transmitters (VLF), the daily fluctuation and irradiation from the sun (Lichtenberger 2005).

Fig. 12 General view showing the Cerescope device used in the present study

Most of the recorded EMR signals are clear with minor disturbance and hence very low noisy level. The signals recorded from artificial sources are easily interpreted as the EMR intensity dramatically increase or decrease towards these sources.

The measured linear EMR-profiles in Abu-Dabbab area are interpreted within the light of the data available from the previous literature. On EMR-curves, the high intensities are marked as peaks (Fig. 15). Each peak can be dealt with as a fault/fracture emitting EMR-signals. Figure 15 is a possible interpretation for the EMR-peaks recorded during the measured N to NW- oriented EMR linear profiles in Abu-Dabbab area. The inclined gray lines demonstrate shallow or gently-dipping faults according to the amount of inclination of each line. Based on the geology and mapped faults of Abu-Dabbab area (see Fig. 2), an active shear system of shallow dipping fractures oriented ENE-WSW and NNW-SSE are postulated. This fracture system suggested here to affect the upper crustal levels and indicates ongoing brittle deformation in that part from the central Eastern Desert of Egypt.

Horizontal measurements

Twelve horizontal measurements were recorded in Abu-Dabbab area at the start and the end points of each linear EMR-profile. Performing such horizontal measurements is useful for identification of a direction of the maximum horizontal stress (σH). On the location map (Fig. 13), these horizontal measurements were represented on polar diagrams. Geometrical analysis of the EMR horizontal data from the Abu-Dabbab area including related polar diagrams indicates that the maximum horizontal stress direction is dominantly oriented E to NE (058°-110°). A secondary direction of a horizontal stress, oriented NW to NNW (130°-170°) is also indicated. These results point to the effect of the ongoing rifting of the Red Sea, where the maximum extension along its axis deforms its shoulder areas with W to SW directed compressional stresses. However, the secondary stress direction estimated from the horizontal EMR-measurements could be interpreted as continuing activity on the NW-SE oriented NFS, which is a penetrative feature well known elsewhere in the Eastern Desert of Egypt. The faulting activity along such shear system is easily explained in the light of the tectonics of the Red Sea.

Table 1 The typical data recorded by the Cerescope device

Object-Abu-Dabbab___, Profile – 5_____, 26.04.2015 12:14:45

Picket	Parameter A	Parameter B	Parameter C	Parameter D	Parameter E	Azimuth	Time
1	**4**	**0**	**0**	**0**	**0**	**0**	**4/26/2015 12:14**
2	**15**	**1**	**77**	**0**	**13**	**0**	**4/26/2015 12:14**
3	**11**	**1**	**69**	**134**	**27**	**0**	**4/26/2015 12:14**
4	**12**	**0**	**0**	**0**	**0**	**0**	**4/26/2015 12:14**

Seismogenic activity of Abu-Dabbab area

Abu-Dabbab area is characterized by tight clustering of the earthquake hypocentres and high level seismicity for long periods. The heat flow was measured at 92 mW/m2 and considered among the highest values in the Eastern Desert of Egypt (Morgan et al. 1985; Boulos 1990). The spatial distribution of micro-earthquakes aligns ENE–WSW depicting a zone of activity transverse to the Red Sea (Fig. 14). In addition, a high level seismic activity without a main shock with high magnitude is observed in Abu-Dabbab area. The area had been hit by two recent events (12 November 1955 and 2 July 1984) with magnitudes 5.5 and 5.1, respectively. It is clear that the majority of the earthquakes that occurred in the study area are micro-earthquakes; greater than 75% of the events not exceed 2.0 ML. The seismicity at Abu-Dabbab is concentrated at focal depth from 2 to 16 km. Fewer number of these events is recorded at depths 17 km and no events of deeper depths are recorded, which means that ductile rocks beneath this depth could be found (Mohamed et al. 2013). The focal mechanisms obtained from the area indicate different faulting styles with mechanisms range from normal, reverse to strike-slip (Hosny et al. 2012). Normal faulting with a subordinate strike-slip component is dominant. The normal faulting events are occurred at focal depths greater than 7 km, whereas the events with reverse faulting occurred at shallower focal depths of about 6 km (Hosny et al. 2012). From the seismic tomography and the 3D Vp and Vp/Vs crustal models, Hosny et al. (2009) indicate that high Vp/Vs values reflect an central elongated anomaly extends at a depth range of 12 km to about 1–2 km, and that shallow seismic events are characterized by a high CLVD ratio. A high CLVD ratio is a tectonic indicator on tensile earthquakes being related to the shear rupturing during opening of the fault (Vavrycuk 2011; Hosny et al. 2012), while the areas of high Vp/Vs ratio are crustal rocks with a soft ductile behavior (Seiduzova et al. 1985).

The distribution of Vp and Vp/Vs shows marked lateral and vertical (depth) variations, suggesting significant structural heterogeneities, where these velocity contrasts expressing the crustal discontinuities (Mohamed et al. 2013; Hosny et al. 2009). This phenomenon can be confirmed by the slowness vectors determined in the study of Sami et al. (2014). The heterogeneity within the upper crustal levels within the Abu-Dabbab area led Hassoup (1987) to describe the seismicity of the region in light of the subsurface structure heterogeneity. This structure heterogeneity can be attributed to the difference in rock composition and its conductivities, where the places of high resistivity values clearly show sites of faults (Basheer et al. 2015). In the same context, the fault trends both parallel and transverse the Red Sea direction may be the cause of the microearthquake seismicity in Abu-Dabbab area (Badawy

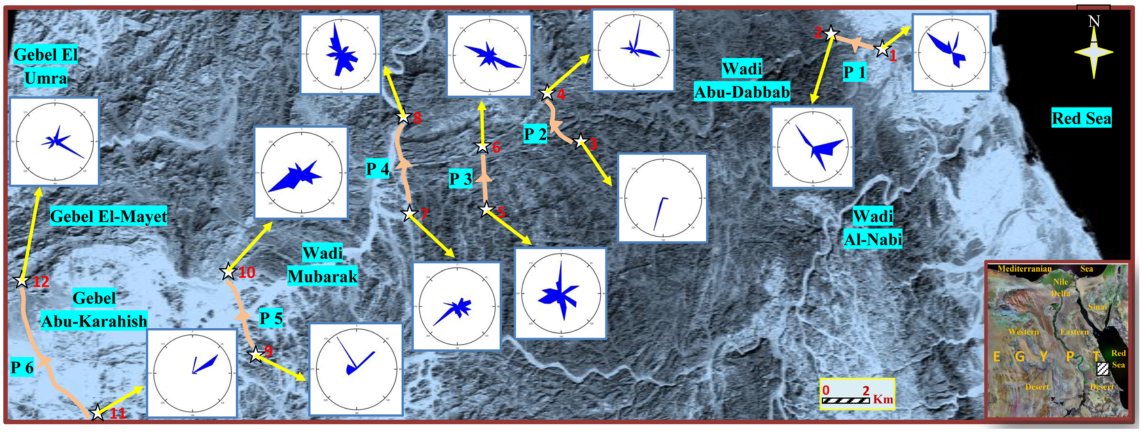
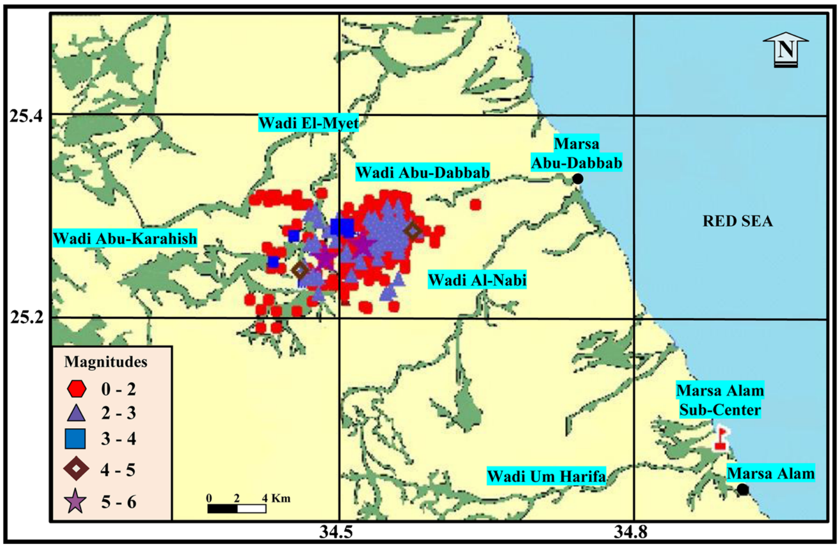


Fig. 13 Location of the EMR-profiles and horizontal measurememts in the study area

Fig. 14 Simplified map showing the spatial distribution of the seismicity in Abu-Dabbab area in the period of 1900–2012 (after Mohamed et al. 2013)



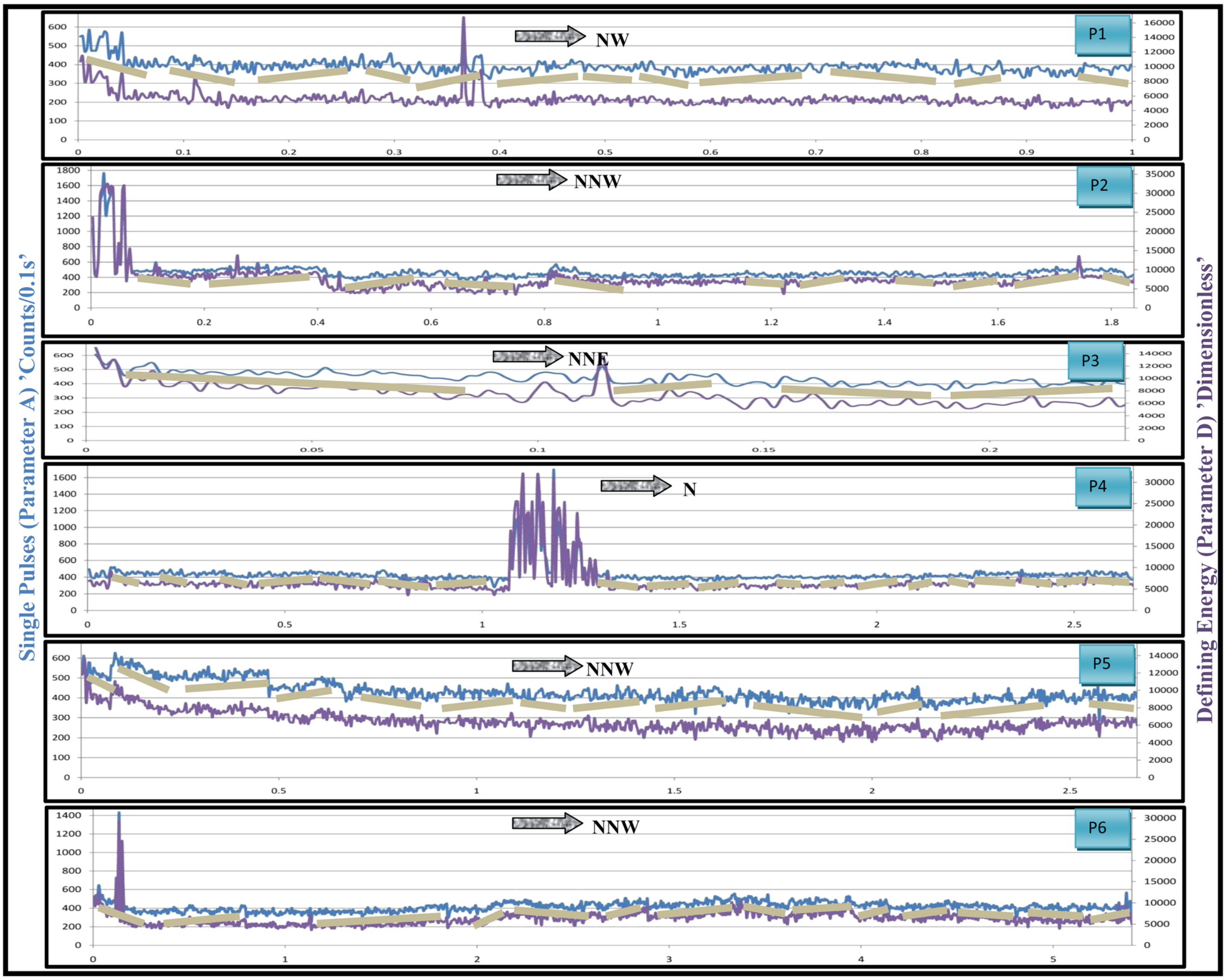


Fig. 15 EMR-profiles of Abu-Dabbab area

et al. 2008). From the measured velocity values (Mohamed et al. 2013), the movement direction is generally to the northeast with inhomogeneous magnitudes ranging from 1 to 3 mm/yr. This direction is typically the direction of the African plate motion. This important tectonic feature is fairly supported by the regional stress field around Abu-Dabbab area, which is characterized by maximum compressive stress ($\sigma 1$) perturbed from the regional NW–SE direction to E–W and ENE–WSW orientation (Badawy et al. 2008).

The abovementioned discussion demonstrates that Abu-Dabbab area is an earthquake prone area with high micro-seismicity and structure heterogeneity in its upper crustal levels. It is clear also that most seismic and other geophysical studies (e.g. Hosni et al. 2009; Pasheer et al. 2015) indicate that such structural heterogeneity is owing to the fault system affecting that area as a part of the central Eastern Desert of Egypt. According to the tectonic scheme of the Eastern Desert of Egypt, this fault system is mostly related to the NFS, which oriented mainly NW-SE. Based on the EMR data recorded in the study area, such fault-system shows ongoing activity that is most probably responsible for the micro-seismicity in the Abu-Dabbab area. Thus, the upper crustal levels of the study area currently undergo some sort of brittle deformation converted into ductile deformation along the shallow brittle-ductile transition zone underlies the Abu-Dabbab area. The horizontal EMR-measurements refer also to the same conclusion, where the major direction of main horizontal stress is oriented ENE that point to the compressive stresses induced from the opening along the NW-SE oriented axis of the Red Sea (Mohamed et al. 2013).

A proposed tectonic model for Abu-Dabbab area

The need to a tectonic model for the Abu-Dabbab area is attributed to the importance of this area that comes from its high seismicity level and high heat flow. The more realistic tectonic model will be of great value as it can be used as a reference, where the seismicity and seismological parameters of the area could be analyzed and interpreted. In the present study, our tectonic model will be discussed in three interrelated directions; magmatic versus tectonic origin of micro-seismicity in the area, brittle-ductile transition underneath the area and the Low Angle Normal Fault (LANF) or low angle extensional shear zone.

Magmatic versus tectonic origin of Abu-Dabbab seismicity

The clustering of the Abu-Dabbab hypocentres and the relatively high seismicity level for long periods led many seismologists to rule out the influence of regional tectonics, and to link up the seismicity with igneous activity or an intrusive body underneath the Precambrian crust (e.g. Ibrahim and Yokoyama 1998; Morgan et al. 1985; Hassoup 1987; Boulos 1990; Daggett et al. 1986). From seismic tomography inversions in 2D and 3D, Hosny et al. (2009) realized from the tomographic images of Abu Dabbab area a shallow magma chamber with low-velocity bounded by high-velocity magmatic bodies. The absence of main shock with high magnitude, the periodical swarms with hypocenters located at focal depths not exceed 16 km, the high Vp/Vs ratio and the frequent tensile earthquakes with high CLVD ratios led Hosny et al. (2012) to consider this seismic swarm as a temporary igneous activity increasing the fluid and gases pressure in the lowermost crust of the study area. In the same context, and based also on the results of seismic tomography, source mechanisms and crustal deformation, Mohamed et al. (2013) concluded that the seismic activity in Abu-Dabbab area is associated with crustal deformation owing to some magma activity beneath the crust. However, the heterogeneity in the crustal structure of Abu-Dabbab area was interpreted by Sami et al. (2014) as magmatic activity beneath the crust or due to fluids in the upper crust. On contrary, some authors (e.g. Badawy et al. 2008) advocated that the stress field in Abu-Dabbab area is originated by local tectonic features and the micro-events and earthquake-swarms are related to local tectonic sources. Basheer et al. (2015) applied the Helicopter Electromagnetic (HEM) technique to the Abu-Dabbab area and came to the same conclusion that the detected structures (the N- and NE- oriented faults) are responsible for the local stresses which increase the seismic activities in the area. According to the stress and strain field estimations from GPS study of Mohamed et al. (2013), the maximum compressive stress is changing from the regional NW–SE direction to E–W and ENE–WSW orientation. Hosny et al. (2012) realized that most of the recorded micro-events are located close to major fault intersections, faults both parallel and perpendicular to the Red Sea margin. A schematic geodynamic model of El Khrepy et al. (2015) proposed that the linear seismic zone in Abu-Dabbab area is owing to an active fault at a depth of about 10 km, below a large block of Precambrian igneous rock. The surface of this fault is lubricated by fluids penetrating the crust from the Red Sea as a result of combined strike-slip and thrust movements along the fault. The role of the regional compressive stresses resulted from the Red Sea rift in Abu-Dabbab area is not ignored by other investigators, such as Mohamed et al. (2013) and Sami et al. (2014).

In the present study, we strongly support the tectonic origin of the seismicity in Abu-Dabbab area. Field-structural investigation, EMR-surveying and interpretation of the available seismic data during the present study suggest a current phase of reactivation on the fracture system follow the same trends of the NFS. The major thrust faults that bound the large Precambrian fault-blocks reactivated with reverse sense of displacement in the upper crustal levels of the study area. This conclusion is supported by the seismic data (focal mechanisms) which recorded normal faulting events at focal depths greater than 7 km and the reverse ones at shallower focal depths, less than 6 km. Also, the high Vp/Vs ratio until 12 km depth and the occurring of more deeper tensile earthquakes of high CLVD ratios, which reflect the tensional characters of the deep crust of Abu-Dabbab area and the role of the low angle extensional shear zone (brittle-ductile transition). The role of the brittle-ductile transition in Abu-Dabbab area will be discussed below.

Brittle-ductile transition beneath Abu Dabbab area

El-Hady (1993) discussed in general the earthquake activity in the Red Sea margin and suggested the presence of the brittle-ductile transition at the Abu Dabbab region at depth between 9 and 10 km, which is consistent with the measured high heat flow values of the Abu-Dabbab area (Morgan et al. 1985; Boulos 1990). The earthquakes seem to occur in the area at lower crustal depths not exceed 15 km at the boundary between the brittle and ductile rocks, at the brittle-ductile transition (Mohamed et al. 2013). An interesting observation is that given by Mohamed et al. (2013), where they realized the maximum values of compressional strain increase close to the Red Sea coast and decrease farther from the shore that indicates a direct relation between the Red Sea tectonics and the seismogenic activities of Abu-Dabbab area. This can be easily explained within the framework of the tectonic setting of both the central Eastern Desert, including the study area, and the Red Sea rift. The present study results based on EMR and seismic data suppose that the present day deformational strain in the study area and probably elsewhere in the central Eastern Desert is attributed to ongoing activity on the inherited fracture system (most probably NFS), owing to the current Red Sea active tectonics and anticlockwise rotation of African-Arabian and Eurasian plates. Furthermore, the rate of the accumulated strains in Abu-Dabbab area is small and lies in the lowest class (Mohamed et al. 2013), which make the possibility of induced larger earthquakes is low. This may be described as a sort of seismic creep underwent inside a shear or deformation zone, which postulated in the present study to be a low angle extensional shear zone or LANF underlying Abu-Dabbab area at the shallow brittle-ductile transition.

Low angle extensional shear zone (LANF)

Gently dipping normal faults (00°–30°), low angle normal faults (LANF) or low angle extensional shear zones have been widely mapped in areas of continental extension. These structures have been recognized in the Basin and Range region in the United States (Longwell 1945; Anderson 1971; Wernicke 1981) and then recorded in most of the tectonic settings subjected to crustal extension. Several lines of evidence suggest that these structures accommodated a subordinate amount of crustal extension at depth where a regional stress field characterized by vertical σ1 (e.g., Lister and Davis 1989; John and Foster 1993; Hayman et al. 2003; Collettini and Holdsworth 2004; Jolivet et al. 2010). The seismically active brittle faults in upper crustal levels cut down across a thermally activated transition at about 10–15 km depth, into ductile shear zones where deformation occurs by a seismic creep (Sibson 1977; Schmidt and Handy 1991; Imber et al. 2001; Scholz 2002). Brittle faults are mainly affected by discontinuous and localized deformation within rocks undergoing elastic-frictional behavior (e.g. Sibson 1977), whereas ductile shear zones are mainly characterized by processes of viscous creep (Schmidt and Handy 1991) like crystal-plastic deformation (Drury and Urai 1990; Hirth and Tullis 1992) and diffusion creep (Rutter 1983; Schmidt and Handy 1991). The Brittle–ductile or frictional–viscous transition is the zone where the elastic-frictional behavior converted into viscous creep.

Low angle extensional shear zones are zones that ultimately lead to the formation of detachment planes at mid-crustal depths during post-orogenic extension as a result of strain localization (Gueydan et al. 2004). These extensional shear zones act as leakers for fluid flow and hence they may promote fluid overpressure. The interaction between Fluids and rock along some detachments resulted in the development of phyllosilicates that are characterized by lower frictional strength. This behavior of phyllosilicates can explain movements on LANF and the velocity-strengthening behavior of the phyllosilicates favor fault creep and explain the scarcity of moderate to large earthquakes on LANF in seismological records (Collettini 2011).

Concerning the Eastern Desert and the study area, the most widely known Late Cryogenian-Ediacaran low-angle normal faults or detachments reported from the Arabian Nubian Shield (Johnson et al. 2011) are in the north and central Eastern Desert and Sinai in Egypt, described from gneissic domes and structural highs. The Meatiq and Hafafit domes are flanked on the north and south by NNW- and SSE-dipping normal faults (Fig. 1), comprising post-accretion low-angle ductile shear zones with top to NNW or top to SSE senses of slip (Fritz et al. 1996, 2002; Fowler and Osman 2009; Rice et al. 1992). The exhumation of the core-complex gneisses in the Eastern Desert was postulated (e.g., Fritz et al. 1996) to be achieved as the result of enhanced heat flow along the fault systems (Najd Fault System) during oblique NW–SE transpression, where the extension on normal faults or along the extensional shear zones was a predominating mechanism. These observations indicate a mutual link between the Najd Fault System and the produced low-angle extensional shear zones or detachments. It worth mentioning here that the UNSZ that is dissecting the study area to the southwest and considered as Najd-related left-lateral NW-SE oriented shear zone, is advocated to be deep-seated as estimated from the magnetic and radiometric data in Ghazala (2001). Overall, the previous crustal scale structures and their interplay indicate the importance of the crustal scale Najd Shear Faults and associated low-angle shear zones or detachments in modeling the seismicity of the Abu-Dabbab area.

The tectonic model for Abu-Dabbab area

From the present study results and previous observations and discussions, the following main points are of great importance to build up a new tectonic model for the study area.

- The seismicity in Abu-Dabbab area is mainly of tectonic origin.
- The area is characterized by high heat flow but not magmatic activity.
- The normal faulting events are characterized by focal depths greater than 7 km and associated with sub-vertical maximum principal stress axis (σ1), whereas the reverse ones are shallower with focal depths less than 6 km. This observation refers to a mechanical decoupling between the upper and lower levels of the Neoproterozoic crust in the area.
- The direction of maximum horizontal stress (σ1) in the area ranges from the NW–SE direction to ENE–WSW orientation. This stress rotation is evidently attributed to the reactivation of the crustal scale NFS, where such reactivation points to the ongoing activity/rifting of the Red Sea.
- The brittle-ductile transition is shallow and at depth of less than15km.
- The brittle-ductile transition in Abu-Dabbab area represents a detachment plane, a low-angle extensional shear zone or LANF that promoting fluid overpressure and evidenced by: (i) the absence of a large seismic main shock, (ii) the periodically recorded swarm's hypocenters of focal depths not deeper than 15 km, (iii) the high Vp/Vs ratio (from seismic tomography) until 12 km depth, (iv) the occurrence of tensile earthquakes of high compensated linear-vector dipole (CLVD) ratios, and (v) the high heat flow rates (about 92 mW/m2 ± 10, which is more than twice the average value of Egyptian Eastern Desert, 47 mW/m2).
- The presence of such low-angle extensional shear zone or LANF could explain the scarce of moderate to large earthquakes in seismological records of Abu-Dabba area.

Our tectonic model (Fig. 16) advocates that the tectonic activity on the brittle-ductile transition underneath Abu-Dabbab area including the LANF led to the localization of stresses and triggering of a brittle deformation in the upper crustal-levels and associated shallow dipping thrusts (i.e. the brittle-ductile transition (BDT) controls the seismic cycle, Doglioni et al. 2015). This tectonic model attributes the deep earthquakes in the concerned area to the transtensional movements occurring on the LANF, whereas the shallow earthquakes to a brittle deformation (transpression) localized inside a thick crust of fold and thrust stacks in the upper crustal levels. Deformation creep along the LANF does not permit continuous accumulation of strain and hence reduce the possibility of large seismic shocks; e.g. 12 November 1955 and 2 July 1984 with magnitudes 5.6 and 5.2, respectively (Fairhead and Girdler 1970; Badawy et al. 2008). Interestingly, the focal mechanism solution of the second event (Badawy et al. 2008) showing a normal faulting mechanism with a strike-slip component and two fault planes oriented NW-SE and ENE-WSW, which support the claims of the present model. The ongoing activity on such low angle extensional shear zone is akin (according to this model) to the reactivation of the crustal scale NFS, which reflects the long-term activity along the central Eastern Desert of Egypt, originating from the continuous spreading/rifting on the Red Sea axis. The rotation of principal stresses from the upper to lower crustal-levels in the study area as evidenced from the location of normal and thrust events, where the later formed at greater depths with (σ1) being vertical and the former occurred at shallow levels with sub-horizontal (σ1), indicate some sort of mechanical decoupling between the shallow and deeper crustal-levels in Abu-Dabbab Neoproterozoic crust.

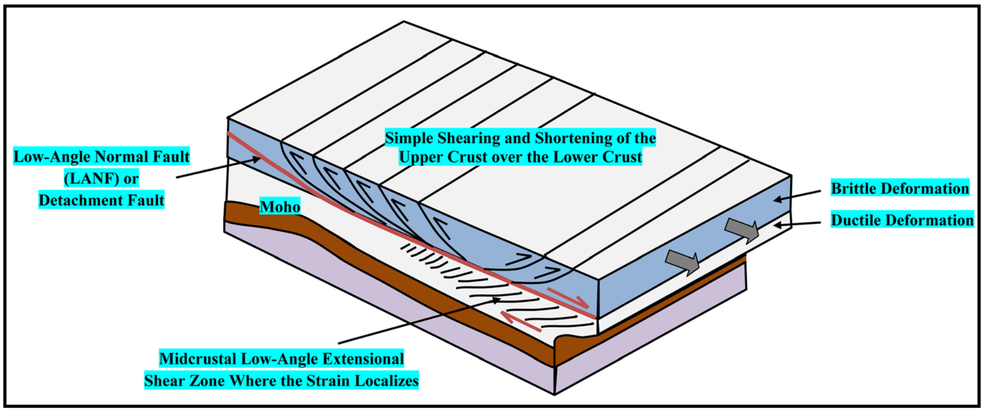


Fig. 16 3-D cartoon illustrating the proposed tectonic model for Abu-Dabbab seismogenic zone (modified after Lister and Davis, 1989; Gueydan et al., 2004)

Conclusions

Abu-Dabbab area is regarded as the most active seismic source zone in the central Eastern Desert of Egypt. Results obtained from this study demonstrate a present-day activity on the crustal scale NFS deforming the Precambrian succession in the central Eastern Desert and Abu-Dabbab area, and relate such activity to the ongoing Red Sea rift-neotectonics. Such deformation reactivates the brittle-ductile transition underneath the Abu-Dabbab Precambrian crust with a LANF. The tectonic movements on such LANF localize a brittle deformation within the uppermost crustal-levels in the area and trigger shallow earthquakes with low local magnitudes, whereas tectonic activity at the brittle-ductile transition (seismic creep) reduces the possibility of occurrence of deep earthquakes with high local magnitudes. Our proposed tectonic model suggests that there is a mechanical decoupling between the shallow and deep crustal-levels of Abu-Dabbab Neoproterozoic basement succession, where the maximum principal stress axis (σ1) rotates from a sub-horizontal position at the uppermost crustal-levels practicing transpressional deformation to a near vertical attitude in the deeper levels, where the transtensional deformation is predominating.

Acknowledgements The authors are grateful to the GE&O Karlsruhe (Company of exploration and radiolocation, Karlsruhe, Germany) and Dr. Hennes Obermeyer for providing a Cerescope device to conduct the section of EMR-Technique. The authors also thank the editors and the anonymous reviewers for their comments which helped improve the manuscript.

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