Seismicity, arrival time delays of the seismic phases and slowness characteristics study in Abu Dabbab area, Egypt

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Abstract

The temporal variations of seismicity from the Abu Dabbab area, 25 km west of the Red Sea coast, are collected from the Egyptian national seismic network (ENSN), which has magnified the detection capability in that area to ML < 1 earthquakes. These data show a sequence of the micro earthquake swarm during 2003–2011. This area has experienced larger shocks up to $M = 6$ during the 20th century and its seismicity is concentrated in a narrow spatial volume.

We analyze the digital waveform data of about 1000 seismograms, recorded by portable network of 10 vertical component seismographs that are employed in a temporary survey experiment in the Abu Dabbab area in 2004, and the results indicate: firstly, there are similar waveform seismograms, which are classified into three groups. In each group a master event is identified. Then, the arrival time delays of the $P$ and $S$ phases ($\Delta t_P$ and $\Delta t_S$, respectively) are measured between the master event and its slave events. $\Delta t_P$ and $\Delta t_S$ range between $0.01$ and $0.02$ s, respectively. These values are used to relocate the studied events. Secondly, the slowness vector ($\mathbf{D s}$) in 3-dimensional pattern, which is estimated using the genetic algorithms, is found $D_{sx} = 0.0153$, $D_{sy} = 0.00093$ and $D_{sz} = 0.2086$ s/km in the three spatial coordinates ($X$, $Y$ and $Z$), respectively. These analyses demonstrate the inhomogeneities within the upper crust of the study area. Also, $D_s$ shows little dependence of lateral distances and reasonably high slowness along the depth extent, which is consistent with the seismic velocity structure variations.

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1. Introduction

The seismically active zone in the Abu Dabbab area is concentrated in a narrow spatial volume between latitudes 25.15° and 25.35° N and longitudes 34.35° and 34.65° E, approximately 25 km west of the Red Sea coast in Egypt (Fig. 1). This area is located at the central part of the Eastern Desert north of Marsa-Alam tourist town. Its tectonic setting was associated with volcanic activity (Sabet et al., 1976). Daggett et al.
(1980) related the Abu Dabbab seismicity to the presence of subsurface volcanic environment or style cooling of pluton. Hassoup (1985) described this seismicity in light of the subsurface structure heterogeneity of the area. Hassoup et al. (2003) reported criteria about the co-seismic deformation in the vicinity of its earthquake source volume. On the basis of seismic velocity tomography, Hosny et al. (2009) correlated the $P$ and $S$-wave velocity anomaly to the presence of magma intrusion. These studies present highly heterogeneous medium in the earthquake zone of Abu Dabbab, that it is often characterized by materials with a variety of seismic wave velocities. The seismic wave propagation in a medium of heterogeneity materials suffer from intense attenuation and scattering processes. These distortions can be detected using different seismological techniques. For example, the network of few seismic stations is used to measure the delays in the arrival times of P and S waves that are related to the heterogeneity of the velocity structure. Also, the seismic array of dense deployments in seismic stations that provide a fine, local spatiotemporal sampling of the seismic wave fields is another technique. In both cases, the apparent slowness vectors of the wave fronts propagating can be estimated. La Rocca et al. (2001) investigated the seismogram waveforms recorded by a seismic array at the Vesuvius volcano, Italy, and found evidences of waves scattered at the main topographical discontinuities. Similarly, based on the seismic array data, Almendros et al. (2002a,b) found different wave components related to source processes, surface waves and scattering at the main discontinuities of the medium at the Kiluea volcano, Hawaii.

In this study, we used the data recorded by an array deployment during a reconnaissance earthquake monitoring experiment carried out in 2004 at Abu Dabbab region in Egypt. Since epicenters of events in this region were accurately located in narrow zone cluster beneath the seismic network stations, the analysis of the observed seismogram waveform data allows us to investigate the effect of the heterogeneous medium in the propagation of the seismic waves.

2. Geological setting

Abu Dabbab area is situated in the Eastern Desert of Egypt, which is occupied by crystalline basement of the Arabian–Nubian shield of late proterozoic orogeny, metamorphic volcano-sedimentary series of middle to late proterozoic and basic and ultrabasic plutonic rocks (Greiling et al., 1988). The area is characterized by a rugged topography and its sediments have been highly deformed and metamorphosed. The geologic map of the area was re-developed based on the geologic map of scale 1:1001000 of the Egyptian Geologic Survey and Mining Authority (EGSMA, 1991) (Fig. 2). According to EGSMA (1992), the geology of this area includes three principal lithological complexes: the basic/ultrabasic complex, the volcano-sedimentary sequence, and the intrusive complex. The intrusive complex outcrops in the southern part of the area, constituting a nearly continuous unit with approximately east–west (E–W) and WNW-ESE limits with the volcano-sedimentary sequence. Intrusion breccia in the southern contact of Abu Dabbab granite is marked. Sabet et al., 1976 reported that the tectonic activity was associated with volcanic activity, where the rocks are cut through by intrusions and stock like bodies of tale-carbonate serpentines and gabbro.

3. Seismicity

In Egypt, the first seismograph was established in Helwan town, south Cairo in 1898. This site has been equipped by a...
world-wide standard seismograph station (WWSSN) in 1963. Then, the instrumental earthquake catalogue goes back to 1989. On the basis of WWSSN data, Fairhead and Girdler (1970) located two seismic events in the northern Red Sea region nearly at latitude of 25° N. One of them occurred on 12 November 1955 with body wave magnitude (mb) = 6 and its epicenter was located at the Abu Dabbab hills (34.6° E, 25.3° N). The second was located close to the eastern margin of the Red Sea nearby Saudi Arabia. The earthquake monitoring has been improved by establishment a local seismograph network in Aswan, at an average distance of some 250 km from the Abu Dabbab region. This network is capable to record seismic events of magnitude greater than two from that area and is continuously well operated since 1982. Its seismograph data include many events from Abu Dabbab region.

The National Research Institute of Astronomy and Geophysics (NRIAG) runs a program for the establishment of national seismic network in Egypt (ENSN) since 1997. The deployed field stations send directly their seismic signals by either the radio-link or satellite transamination systems to the main recording center located at Helwan city in Cairo in Egypt. There are also other five recording units located at the sub centers, which contracted at Aswan, Marsa Alam, Burj Al-Arab and Hurghada cities and El-Kharga oasis. For research purposes, the ENSN sensors are equipped with different seismometers and consist of 11 very broad bands, 9 BB, 10 three components short period, 47 single component short period (Fig. 3). Those installed along the western coast of the Red Sea have, particularly, improved the detection capability from Abu Dabbab seismicity. Nearer field stations to that area were installed in 2003. The ENSN data provides valuable information on the temporal variation of the seismicity at Abu Dabbab region, Fig. 4. It demonstrates a sequence of the micro-earthquake activity $M < 3$.

4. Data and instruments

In Abu Dabbab region, the reconnaissance Seismicity survey carried out using different array configurations from the portable seismograph stations in 1976; 1993 and 2004 was reported by several authors (Dagget and Morgan, 1977; Daggett et al., 1986; Hassoup, 1985; Kebeasy, 1990; El-Hady, 1993; Ibrahim and Yokoyama, 1998; Badawy et al., 2008; Hosny et al., 2009). The epicentral locations reported in these surveys, ENSN data and the instrumental earthquake
catalogue of Egypt are used to develop the epicentral map of Abu Dabbab region (Fig. 5). One of the important temporary surveys in that area is the 1984 experiment, which had observed sequences of the earthquake swarms associating the July 2, 1984 earthquake of $M = 5.1$ and normal fault mechanism in 1984 (Fig. 5).

The instruments and data we analyze are part of the reconnaissance survey experiment, carried out at Abu Dabbab area in 2004 as an effort by the National Research Institute of Astronomy and Geophysics (Hosny et al., 2009). This experiment was designed to obtain a high-resolution, 3-dimensional seismic wave velocity model of the area (Hosny et al., 2009). The site investigation processes were carried out to select locations of the low ground-noise and high quality line of sight for transmission before establishment of station’s configuration, which combined a high density seismometers of the L4C type (short period only) with RD3 digitizer in telemetric mobile network. By using the radio-link of the telemetric systems, the seismic signals were sent to a recording data Center situated at Marsa-Alam city, south of the Abu Dabbab area, 35 km southeast from the network. The seismic signals move from the antenna and receiver sub-system to the data performing and acquisition computer sub-system in the recording center. Data processing and on-line analysis are automatically run for the preliminary reports. In addition, portable three component seismometers of SS-Iranger type connected with an Orion recording unit was also used in the survey. Its digital seismic data were retrieved and controlled using IBM PC compatible computer.

We selected about 100 events from the 2004 microearthquake survey for the present analysis. Their waveform recording was under homogenous time control and by using the same seismographs characteristics (vertical and short-period single-component type). The seismic signal data were subjected to data processing configuration, Fig. 6.

5. Time delay between phases

The similarity in waveform records of the Abu Dabbab earthquakes is well observed in the seismograms of a local telemetry seismic network (Fig. 7). All records were subject to precise
picking to the P-wave and S-wave arrivals and S–P time estimation. The clustering method that had been used is the K-mean clustering. K-means (MacQueen, 1967) is one of the simplest unsupervised learning algorithms that solve the well-known clustering problem. The procedure follows a simple and easy way to classify a given data set through a certain number of clusters (assume k clusters) fixed as a priori. The main idea is to define k centroids, one for each cluster. These centroids should be placed as much as possible far away from each other. The next step is to take each point belonging to a given data set and associate it to the nearest centroid. When no point is pending, the first step is completed and an early group age is done. At this point we need to re-calculate k new centroids as barycenters of the clusters resulting from the previous step. After we have these k new centroids, a new binding has to be done between the same data set points and the nearest new centroid. A loop has been generated. As a result of this loop we may notice that the k centroids change their location step by step until no more changes are done. In other words centroids do not move any more. Finally, this algorithm aims at minimizing an objective function, in this case a squared error function. The objective function

\[ J = \sum_{j=1}^{k} \sum_{i=1}^{n} \left\| x_{ij}^0 - c_j \right\|^2, \]

(1)

where \( \left\| x_{ij}^0 - c_j \right\|^2 \) is a chosen distance measure between a data point \( x_{ij}^0 \) and the cluster center \( c_j \), is an indicator of the distance of the \( n \) data points from their respective cluster centers. In our case, each node is an event and its coordinates represent the s–p for each station recovered from this event. Using the K-mean the event had been clustered into three different groups. Each group of events represents a different seismic source based on the differences in the travel times for P-wave and S-wave.

The cross-correlation function \( r_{xy}(\tau) \) is defined as a function of the delay time \( \Delta t \) of the P-and S-phases between the master and its slave events.

\[ r_{xy}(\tau) = \int_{-\infty}^{\infty} f_1(t) f_2(t + \tau) \, dt, \]

(2)

where \( f_1(t) \) is the master event, and \( f_2(t) \) is the slave event.

The time shift between the master and its slave events is taken as the value of the delay time \( \Delta t \) for which this cross-correlation function is at a maximum. To identify the master event from an event sequence for the cross correlation application we chose the first event that has been recorded in all stations to be able to be used in the cross-correlation evaluation. For example, the master and its slave are the events (S01 07:54 and S01 08:41), respectively are apparently characterized by similar waveform traces on their seismograms (Fig. 7). Then,

**Fig. 5** Seismicity map of the study area during 1900–2011. Lines are major faults and Focal mechanism solution is normal fault for the July 2, 1984 earthquake \((M = 5.1)\), after.

**Fig. 6** The seismograph network and 3-dimensional distribution of the studied events.
the correlation output is shown in Fig. 7. The offset time of the peak of the cross correlation is recorded for each one-second slice. The delay for each phase in the master and slave events is taken as the value of the delay time \( D_t \) of P and S for which this cross-correlation function is at a maximum. Initially the two traces are aligned according to the manual P-wave pick. Consequently, the time-delay \( D_t \) measured for the P phase in the slave event corresponds to an error in this original manual pick time. There is generally a moderate change in the delay time for the S wave. The time delays \( D_t \) between the master and subsequent events and the cross-correlation values are listed in Table 1.

The earthquakes we here analyzed are of magnitude <2. The seismograms of this set are characterized by an impulsive P-wave onset. Few records are interfered with artificial noise of unknown source. Due to this fact, their seismograms were excluded in the present analysis. The available hypocentral location program in ENSN database was used to obtain both the initial and relocation hypocentral parameters of the studied events (Fig. 8). The calculation is carried out assuming a half-space sequence of 4 horizontal constant-velocity layers of the model for Abu Dabbab region. The initial locations are obtained using arrival times derived from manual picking on digital seismograms retrieved using a matlab software developed by the first author for the present study. See Table 2.

### Table 1

| Event                  | P phase delay | S phase delay | Cross correlations |
|------------------------|---------------|---------------|-------------------|
| S01 (07:54) and S01 (08:41) | 0.01          | 0.02          | 85% and 89%       |

### Table 2

|            | Mean       | Variance   |
|------------|------------|------------|
| Slowness (Sx) s/km | 0.0153    | 0.0424     |
| Slowness (Sy) s/km | 0.00093   | 0.0350     |
| Slowness (Sz) s/km | 0.2086    | 0.1091     |

6. Three-dimensional slowness estimation using genetic algorithm

Let us suppose a seismic array composed of N stations at positions \( \mathbf{r}_i \), where \( i = 1 \ldots N \). In the three dimensional wave front approximations, the arrival times of a signal propagating across the array are given by:

\[
t_m^i = t_m^0 + \mathbf{r}_i \cdot \mathbf{s}_m
\]

where \( t_m^i \) is the arrival time of the wave front \( m \) to the origin of coordinates, \( \mathbf{r}_i \) is the position of the station \( i \), and \( \mathbf{s}_m \) is the apparent slowness vector that characterizes the propagation of the wave fronts.

The modulus, S, and direction clockwise from north, A, of the apparent slowness vector correspond to the inverse of the apparent velocity and propagation azimuth of the waves, respectively. The delays among arrivals of a signal characterized by three dimensional slowness vector \( \mathbf{s}_m \) to different stations of the seismic array are given by

\[
\Delta t_{ij}^m = \Delta t_{ij} - \Delta t_i
\]

where \( \Delta t_{ij}^m = t_{ij}^m - t_i^m \) is the difference of arrival times of signal \( m \) to stations \( i \) and \( j \) and \( \Delta t_{ij} = \mathbf{r}_j - \mathbf{r}_i \) represents the three
dimensional relative positions of stations \( i \) and \( j \) referenced to the signal source.

The comparison of these delays with the delays obtained from the seismic data allows us to estimate the apparent slowness vectors of the recorded signals. This estimation can be done in several ways that leads to a variety of array methods in the time and frequency domains. An intuitive example of a magnitude that is able to evaluate the similarity between the actual wave delays and the delays produced by the arrival of a wave front is the inverse of the residual of the least squares fit

\[
F_{LS}(\vec{S}) = \left( \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (\Delta t_{ij}^{measured} - \Delta t_{ij}^{predicted})^2 \right)^{1/2}
\]

A genetic algorithm (GA) is used in order to minimize the \( F_{LS}(\vec{S}) \) to get the \( \vec{S} \) value. The normal genetic algorithm is based on simulation of genetic mechanism and theory of biological evolution. GA brings theory of biological evolution into the optimization of parameters through the crossover and mutation operations. It selects the best value of the fitness function and reserves it. Then it makes up the new cluster. The genetic evolution will not stop until it satisfies the constrain condition.

6.1. Genetic algorithm process

Step1: Initialize the parameter with a population of random solutions for \( \vec{S} \), such as crossover rate, mutant rate, number of clusters and number of generations. Determine the coding mode.

Step2: Compute and evaluate the value of the fitness function \( F_{LS}(\vec{S}) \).

Step3: Go to crossover and mutation operation and make up the new solutions.

Step4: Go to step2 until the best value was obtained.

The mentioned above dataset of earthquake which records from the 2004 sequence of the Abu Dabbab seismicity is also used for measuring the slowness vectors (\( \Delta s \)) along the three spatial coordinates (\( X \), \( Y \) and \( Z \)), which trend in the east–west, north–south and down vertically directions, respectively. The slowness vectors show different magnitude patterns. Notice; the length of arrows is scaled in Fig. 9. It illustrates large slowness values along the depth planes, while it is relatively very small along the horizontal plane (Fig. 9). This is reasonably because the array seismographs are directly distributed over the hypocenters. In other words, the hypocentral distance is relatively bigger than the epicentral distance to each event.

The slowness data are also demonstrated in histograms of the number of events (count) against classes of the slowness vector (\( \Delta s \)) s/km (Fig. 10). The mean value of \( \Delta s \) along the vertical Z axis is high (approximately = 0.2 s/km). In contrast, it is negligible along the north–south direction (\( \Delta s_{NS} \)) and its pattern represents two peaks along the east–west trend, one appears at 0.05 s/km and the second goes to negative values (Fig. 10). The normal distribution pattern is evident in these three histograms, but its variance values of the analyzed data-set are quite good demonstrating reasonably applied statistical method in the present analysis.

7. Discussion

The 2004 temporal micro-earthquake survey in Abu Dabbab area has delineated records of similar waveform seismograms along its entire length of the P and S waves and coda wave train (Fig. 6). The application of the cross correlation technique in the waveform analysis of the seismograms of each single station
individually has demonstrated systematic time delay ($\Delta t$) between the seismic phases (P and S arrival times) (Fig. 7). The time delays, which are measured between each master record and its slaves, could be caused due to an error in the initial hypocentral location of the events due to the manual picking. This interpretation suggests carrying out the relocation of events after applying the time corrections based on the $\Delta t$ data (Fig. 8). The second possible cause to observe the time delay is the presence of geothermal field at the seismically focal region. El-Hady (1993) discussed the earthquake activity in the Red Sea margin in general and suggested presence of the brittle-ductile transition depth at the Abu Dabbab region between 9 and 10 km, which relates the Abu Dabbab seismicity to geothermal activity. Morgan et al. (1985) and Boulos (1990) studied the geothermal field in Egypt and observed relatively high heat flow of about 92 mW/m$^2 \pm 10$ at Abu Dabbab region and normal heat flow of about 47 mW/m$^2$ in its surrounding areas (e.g., the Eastern desert of Egypt). The third possible cause for observing the time delay ($\Delta t$) between seismic phases is a change in the P- and S-waves velocity structure during the 2004 earthquake sequence. Hosny et al. (2009) observed remarkable variation in the Vp and Vp/Vs distribution pattern with change in the lateral and depth coordinates. This conclusion is very interesting to interpret the slowness vectors determined in the present study.

The apparent slowness vectors of the first arrivals generated by Abu Dabbab earthquakes are measured using a seismic network of 10 stations. The station's configuration affects the resolving capabilities and the quality of the apparent slowness vector estimates. We use small area configuration of about $22 \times 22$ km$^2$ and the sensors were situated on sites of similar rock type (e.g., homogenous site foundation) (Fig. 6). The assumption of a common rock formation under the different stations ensures that the wave fronts propagating across the array stations can be influenced by an apparent slowness vector. Moreover, investigation of the seismograms illustrates high quality records without influence of secondary peaks due to spatial aliasing. On the other hand, application of the genetic algorithm produces very good estimation to the apparent slowness vectors with minimum uncertainties (Fig. 9). The small value of the apparent slowness vectors ensures that we are choosing the right solutions. The slowness is quite related to inhomogeneous of the structure under the network receivers. The area is occupied by high complexity of the shallow structure (Hosny et al., 2009). Several studies suggest the existence of a strong velocity change with depth in contrast to its variation along the lateral extent.

The second waveform analysis, which is carried out on the studied records of Abu Dabbab seismicity, encourages us for retrieving the slowness distribution of a medium from the first arrival travel times. It describes slowness vectors (e.g., $\Delta Sx$, $\Delta Sy$, $\Delta Sz$ and $\Delta S$ corresponding to their values in the horizontal and vertical components, as well as their sum for every individual event, respectively). Seismic ray anomalies can be attributed to irregularities beneath the array and structure near the deepest point of the ray path. Also, they provide important information regarding the lateral inhomogeneities present in the earth. The most sensitive portion of the ray path to the lateral variations in the structures occurs in the region where the rays bottom and in the region directly beneath the recording stations. To look for the evidence for anomalies in ray direction produced by structure at the region, on the basis of tomographic study (Hosny et al., 2009, 2012) noted that the distributions of Vp and Vp/Vs are characterized by marked lateral and depth variations, suggesting the presence of significant structural heterogeneities. The P-wave velocity anomalies may be seen through different depths and they could be related to the intersection anomalies along the faults cutting the area. Sometimes the high P-wave velocity anomalies (brittle rocks) are bounded by low velocity anomalies corresponding to more ductile rocks and vice versa. For example the low Vp and high Vp/Vs anomalies are interpreted by the presence of magmatic activity within normal crust.

Abu Dabbab seismicity includes volcano-tectonic earthquakes related to the activation of these sets of faults, as well as long-period seismicity mostly related to the interactions between shallow aquifers and hot materials (Daggett et al., 1986; Morgan et al., 1985; Hassoup, 1987; Boulos, 1990). Many seismic studies have demonstrated the complexity of the structure of Abu Dabbab region. For example, Hosny et al. (2009) observed low velocities of the seismic waves. They related these delays to the presence of a low velocity body. El-Hady (1993) estimated the geothermal field structure at this site, obtaining high geothermal field results. This heterogeneous medium is responsible of the ray path's bending from local earthquakes. Hosny et al. (2009) have performed active source seismic tomography inversions in 2-D and 3-D. The main feature of the tomographic images of Abu Dabbab region is the presence of a low-velocity, shallow magma chamber under that region, surrounded by high-velocity chilled magmatic bodies.

8. Conclusion

In this study, the seismic activities of the Abu Dabbab area have been investigated by applying different seismic analyses, temporal variations of seismicity occurrence; the arrival time delays ($\Delta t$) between seismic phases (change in the P and S-waves), and retrieving the slowness distribution of a medium from the first arrival times. Furthermore, based on the discussed and obtained results, from the slowness distribution, the time delay between phases, the previous studies of the seismic tomography and the source mechanisms inversion (Hosny et al., 2012), we can conclude that the crustal structure of the study area is more heterogeneous with lateral and vertical structure variations. These heterogeneities could be due to the magmatic activity beneath the crust or due to fluids in the upper crust. Many previous studies proved that the earthquake swarms from time to time occurred at the study area are
due to magmatic intrusion, Hosny et al., 2009, 2012. The magmatic activity beneath the lower crust makes pushing and pressure on the lower crust and consequently, reactivation to all existing faults at the upper crust can occur. Therefore, seismicity occurs within two clusters at the upper and lower crust especially at the intersections among the existing faults which cut the serpentines rocks. We attribute the occurrence of this seismicity to different stresses affecting the study area, local stresses due to the magmatic activity beneath the crust of the Abu Dabbab area or regional stresses due to the Red Sea rift system.

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