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Study of the 26 December 2011 Aswan earthquake, Aswan area, South of Egypt

Ahmed Hosny · Sherif M. Ali · Azza Abed

Abstract The source process and parameters for a moderate earthquake of magnitude Ml 4.1 that occurred on the Kalabsha fault at the Aswan area are analyzed. The derived focal mechanisms of this event and other two aftershocks using polarities of P, SV, and SH waves show strike-slip fault with minor vertical movement of normal type. The solutions give two nodal planes trending ENE–WSW and NNW–SSE in close agreement with the surface traces of the faults crossing the area. The movement is right lateral along the first plane while left lateral along the second one. The rupture process characterization of this event has been investigated by using the empirical Green's function deconvolution method. By inversion only for the P wave part of the records of these three events (main and other two aftershocks), the source time function for the master events and the azimuthally variations in the (RSTF) pulse amplitude are retrieved for estimating the rupture directivities. The estimated rupture direction is combined with the P-wave focal mechanisms for the three events to identify the fault plane solution for these earthquakes. Based on the width, amplitudes, and numbers of the isolated source time functions, a complex bi-lateral rupture of the studied earthquake is delineated. The source parameters of the master event is calculated and the derived corner frequencies f_o for P-wave spectra show a value of 6.6 Hz; the seismic moment (M_o) is 4.2×10^{22} Nm; the average displacement (U) is 0.5 m; fault radius (r) 40 m; the average value of the stress drops ($\Delta\sigma$) is 0.6 Mpa, and the moment magnitude (M_w) is 4.4.

Keywords Aswan earthquake · Rupture process · Focal mechanisms · Source parameters

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Introduction

The Aswan area is located in the south part of Egypt, called Upper Egypt, between latitudes 23.00–24.00 ° N and longitudes 32.12–33.10 ° E. Such region is characterized by its strategic importance, especially after the establishment of the High Dam in 1960. The area has been subjected to numerous geological and geophysical investigations such as the structural settings and geomorphologic conditions of the study area (e.g., El-Shazly 1977 and Issawi 1978); gravity and geodesy (Mahmoud 1994); 3D Vp, Vs, and Vp/vs tomography (Taha 1997; El-Hady et al. 2004; Khalil et al. 2004); subsurface tectonic structure and crustal deformation (Mekkawi et al. 2008), and focal mechanisms of source zones (Kebeasy et al. 1987; Kebeasy and Tealeb 1997; Hassib 1997; Tealeb 1999; Fat-Helbary and Tealeb 2000; Awad et al. 2005).

Additionally, most of the mineral resources and the high tourism activities are concentrated at that part of Egypt. Therefore, the Egyptian government recently gave a significant importance by establishing numerous national economic projects inside and around the vicinity of the Aswan area.

On 26 December 2011, a moderate earthquake of local magnitude 4.1 occurred at the west bank of Lake Nasser, Aswan area and some areas near and surrounding the epicenter is shacked such as, Aswan city and the Sahary cities, south Aswan city. Because of the geologic, geophysical, and strategic importance of this part of Egypt, the occurrence of the 14 November 1981 earthquake (Ms=5.3) and the 26 December 2011 event (Ml=4.1) in the study area has our interest in terms of seismotectonics and seismic hazard assessment.

By applying the empirical Green's function (EGF) technique, the rupture direction and source properties can be retrieved from the isolated relative source time function (RSTF). The detailed studies of a source process revealed rupture complexities and directivity, not only for large earthquakes but also for moderate and micro-earthquakes (e.g.,

Frankel et al. 1986; Li and Thurber 1988; Mori and Frankel 1990; Abdel Fatah 1999). The EGF deconvolution method is used to isolate the source effects (source time function (STF) or moment rate function) from those of the path, site, and instrument responses. The advantage of the EGF method is that detailed knowledge of the earth structure, instrument response, and attenuation effect is not required. For two earthquakes having similar hypocenters and focal mechanisms but different sizes, one can treat the waveform of the smaller event as the EGF and deconvolve it from that of the large event to obtain a relative moment rate function (RMRF) for the large earthquake. RMRFs have been used to describe the source process and to estimate the source parameters, such as time raise, seismic moment, fault radius, and stress drop (e.g., Frankel et al. 1986; Li and Thurber 1988; Mori and Frankel 1990; Xie et al. 1991).

In this study, as an important step in seismic hazard assessment, we studied and investigated the focal mechanism, the description of the source process (the dynamic rupture directions), and the source parameters of the 26 December 2011 Aswan earthquake.

Geologic and tectonic setting

The study area is composed of Precambrian granite rocks that are unconformably overlain by a series of sedimentary units of Late Cretaceous–Lower Eocene. The sedimentary cover, about 500-m thick, forms a generally flat area of low relief varying from 150 to 350 m. The Quaternary formation is represented by the calcite and Nile deposits (Issawi 1978, 1982). The major geomorphologic features of the study area from east to west are Aswan hills, the River Nile valley, Nubian plain, and Sin El-Kaddab plateau, respectively (Woodward Clyde Consultants 1985). Precambrian basement rocks are distributed in the area at small localities along the western bank of the Nile between the Kalabsha fault in the south and the city of Aswan in the north, (Issawi 1978 and Woodward Clyde Consultants 1985). This is besides the basement rocks outcropping to the east of the Lake Nasser. Figure 1 shows the general distribution of rock units and basic structural and topographic characteristics of these features.

The study area is highly affected by tectonic movements, which had a profound effect on the geomorphology of the area, leading to many uplifts, faulted blocks, and folds. Faults in the study area are subdivided into two fault systems, East–west and North–south, as shown in Figs. 1 and 2. The east–west fault system (Kalabsha, Seiyal, and Rawraw fault), which passes through the Sin El-Kaddab limestone plateau, is considered as the most active fault system in the study area. The Kalabsha fault is trending right lateral-slip fault that is considered to have been the source of the 14 November 1981 earthquake (Kebeasy et al. 1982; Simpson et al. 1990; Awad 1994). Along some parts of the Kalabsha fault, the faulting is

of reverse type (Issawi 1978). There are geomorphologic and stratigraphic evidences that the Kalabsha fault is an active fault (Awad et al. 2005).

The north–south fault systems (Kurkur, Khour El-Ramla, Gazal, and Abu-Dirwa) affect mainly the Nubian plain and are essentially of strike-slip with a normal component. These faults run parallel to each other by a 20-m throw to the west and east with recording seismic activities. Figures 1 and 2 show all faults cut the study area. The east–west and north–south fault systems affect the sandstone beds of the Nubian Plain by normal and strike-slip faults.
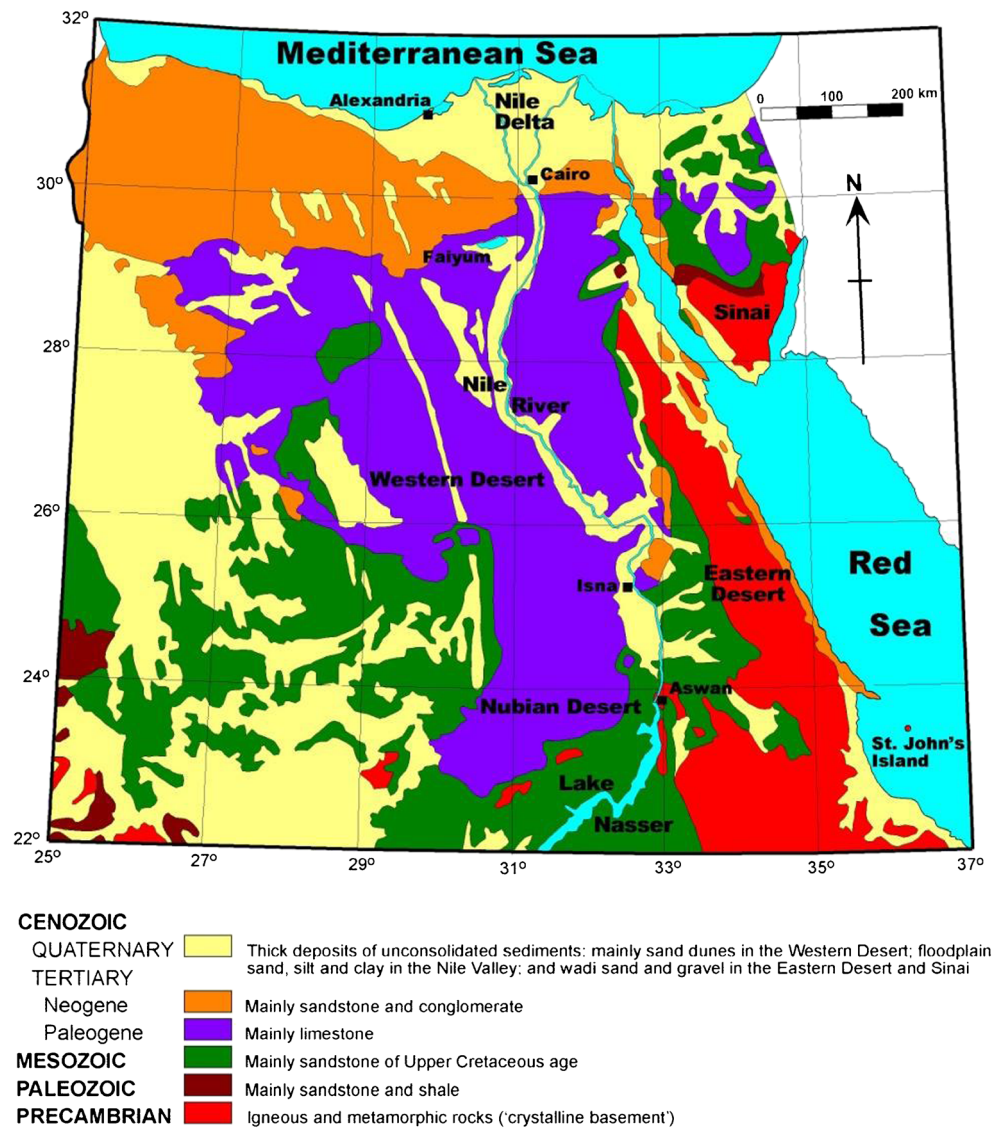
Seismic network of the Aswan area

In 1982, after the 14 November 1981 earthquake, the National Research Institute of Astronomy and Geophysics deployed about eight digital seismic telemetric stations around the northern part of Lake Naser. In 1985, the network was expanding to 13 telemetric stations, installed to continuously monitor the seismic activity around the northern part of Lake Nasser (Fig. 2). Two of these stations (GMR and GRW) were equipped with three component seismographs while the remnants are single vertical components.

Recently, with aim of expanding the frequency bands of recording, these seismic stations have modified and became broad band, and very broad band seismic stations. On the other hand, a specific strong-motion network is distributed at different levels of the High Dam in order to record any trigger due to seismic activities around the Dam, especially the large events. The collected data is analyzing by the seismologists at the Aswan seismological center.

On 14 November 1981, an earthquake of magnitude (mb= 5.5) occurred at the south of Aswan City and as a result, several studies were carried out to investigate the earthquake time and spatial distributions and to determine the active seismic patterns (e.g., Woodward Clyde Consultants 1985 (WCC); Kebeasy et al. 1982; Kebeasy and Gharib 1991; Awad and Mizoue 1995; Awad 2002; Hassib 1990; Mekkawi et al. 2004). The occurrence of this event was initially thought as possibly being triggered by the presence of the reservoir (Kebeasy et al. 1987). WCC (1985) concluded that the reservoir itself does not produce earthquakes, but it serves to trigger the release of preexisting stress stored in the earth's crust. Both water load and pore pressure effects played a big role in triggering the shallower activity (Abou Elenean 2007; WCC 1985). The focal mechanism solutions of that event indicate a dominant strike-slip movement with minor normal dip-slip component (Abou Elenean 2007). The normal dip-slip component increased considerably towards the lake due to the increment of water load effect over the lake (Abou Elenean 2007).

Woodward Clyde Consultants (1985) and Simpson et al. (1986) concluded that the active faults, which can be

Fig. 1 Geologic map of Egypt modified after WCC 1985. The geologic units are represented by *color rectangles* below the map. *Black square* is the study area

CENOZOIC
QUATERNARY ☐ Thick deposits of unconsolidated sediments: mainly sand dunes in the Western Desert; floodplain sand, silt and clay in the Nile Valley; and wadi sand and gravel in the Eastern Desert and Sinai
TERTIARY
Neogene ☐ Mainly sandstone and conglomerate
Paleogene ☐ Mainly limestone
MESOZOIC ☐ Mainly sandstone of Upper Cretaceous age
PALEOZOIC ☐ Mainly sandstone and shale
PRECAMBRIAN ☐ Igneous and metamorphic rocks ('crystalline basement')

considered as potential seismic sources, are Kalabsha, Gabel El-Barqa, Kurkur, Gazal, Abu-Dirwa, and Seiyal faults.

In 1997, as start time for installing and modifying the Egyptian national seismic network (ENSN), we started recording the seismicity around Egypt, as shown in Fig. 3, the seismicity map of a period from January 1997 to December 2011. As can be seen in this figure, most of the seismic activity is clustered in definite zones and along specific trends. It is concentrated along the Kalabsha fault and its extension towards the east and also cluster along the faults trending north–south (Khur El-Ramla and Kurkur faults). Low activity is observed in the N–S directions along Abu-Dirwa fault and at the intersection of Gebel El-Barqa and Seiyal faults. A cluster of smaller events is located in the middle part of the lake (east of GRW station) in east–west direction.

Recently, on 26 December 2011, a moderate earthquake of local magnitude ML 4.1 occurred. This event has been felt at

the surrounding areas of the focal point like Aswan city and high felt at the Sahary area located south Aswan city. No loss in life or structure damages is recorded. This earthquake occurred on the Kalabsha fault at the east part with a depth of 10 km and towards the west bank of Nasser Lake, see Table 1.

Focal mechanism

The software package for the focal mechanism solution by Suetsugu (1998) is used in order to obtain the fault plane solutions of these events by studying the data from the recording stations around the epicenter. Most of the ENSN seismic stations recorded the main shock. Since these events are located inside the Aswan seismic network, more accurate locations for these events are obtained. More than seven stations are used for locating and deriving the focal

Fig. 2 Distribution of the Aswan seismic network. *Squares* represent seismic stations annotated by their station codes. The *lines* denote surface faults crossing the area (*dotted* where concealed)
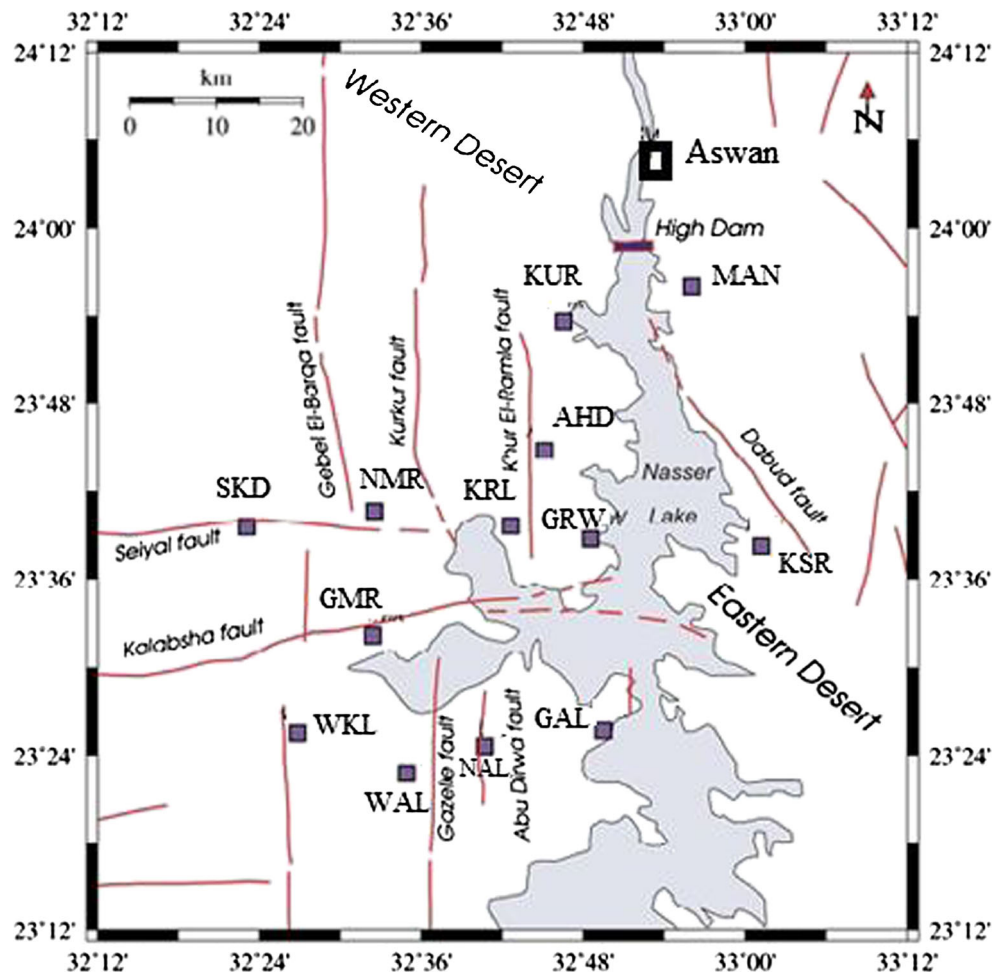
Fig. 3 Seismicity map of Aswan for a period from 1997 up to 2011 (different symbols for different magnitudes). The active faults cut the study area are represented by *solid lines*. The main earthquake occurred on 26 December 2011 delineated by the *red ring* sign. The *big diamond* is the location of the 14 November 1981 event
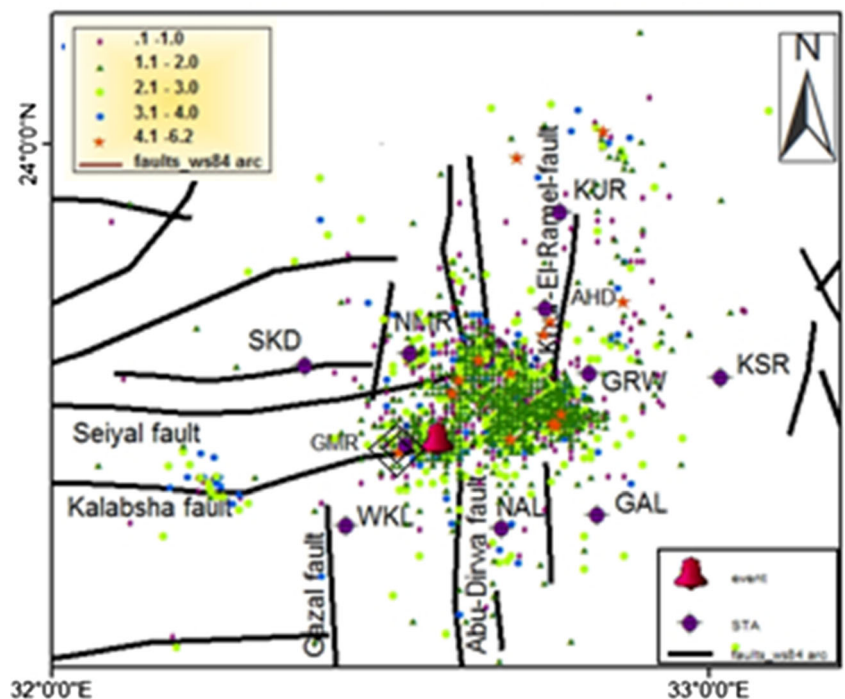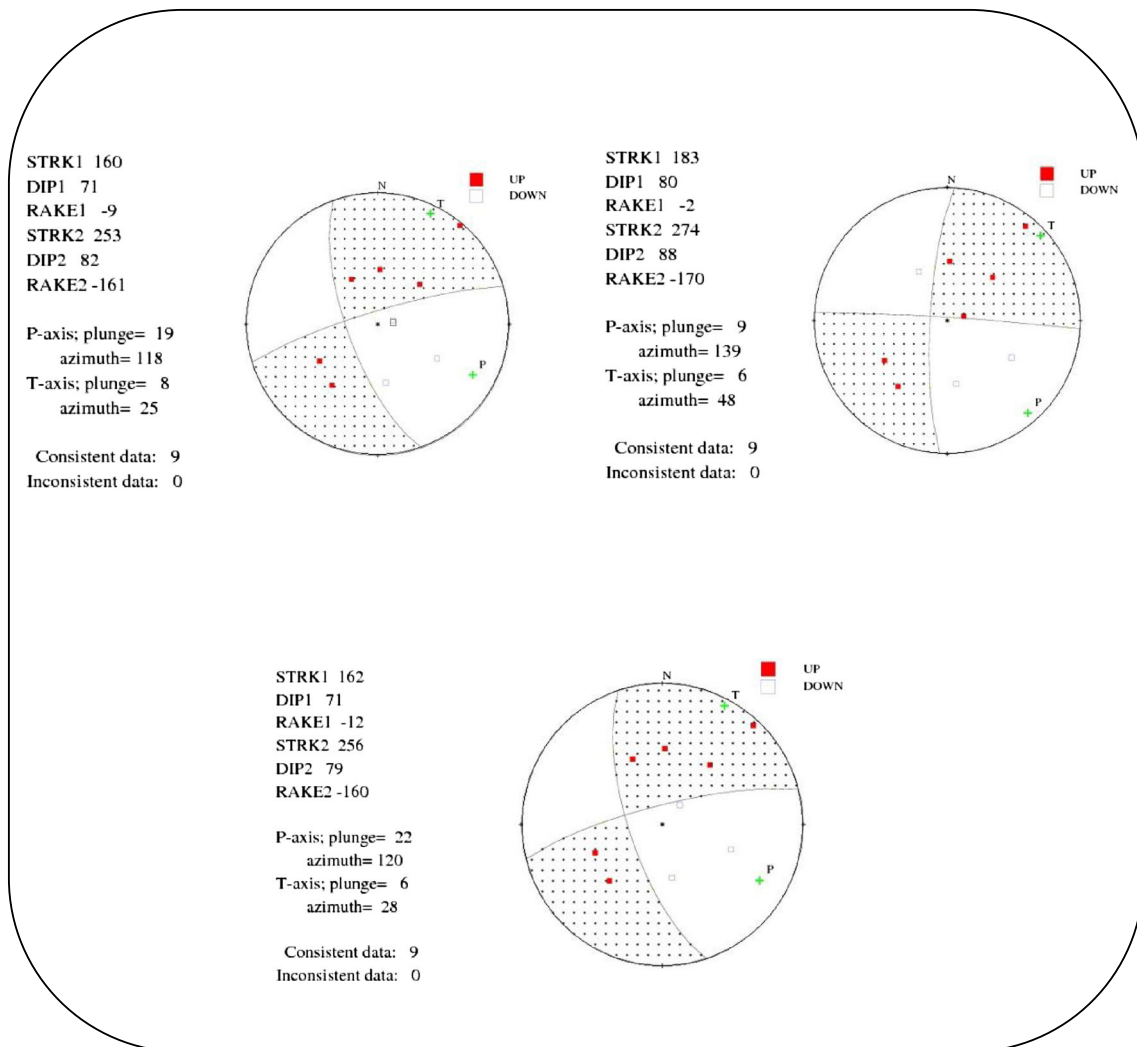
Table 1 Date and location parameters of Aswan earthquake and the other two aftershocks

Date	Origin time	Location		Depth (Km)	Ml
		Lat	Lon		
26 December 2011	17:01:00	23.54	32.85	10	4.1 (main)
26 December 2011	18:37:32	23.54	32.59	3	2.5
26 December 2011	22:17:14	23.54	32.58	3	2.76

mechanisms of these three events, (main and two aftershocks). As can be seen from the obtained fault plane solutions (Fig. 4), the three events are very similar in their derived focal mechanisms, which delineated two kinds of movement; the major one is the strike-slip movement, and the minor one is the normal dip-slip movement. Previous studies (i.e., Awad 1994; Awad and Mizoue 1995; Hassib 1990; Awad 2002) indicate that the Kalabsha and Rawraw faults are dominated by the strike-slip fault mechanism.

The solutions gave two nodal planes frequently trending ENE–WSW to E–W and NNW–SSE to N–S. The first nodal plane is consistent with the direction of Kalabsha fault and its extension towards east for the events located over it. However, the other plane is consistent with the N–S faults for the events located to the north of Kalabsha near Kurkur, Khor El-Ramla, Dabud, and Abu-Dirwa faults. The movement along the ENE–WSW plane is right lateral, while it is left lateral along the NNW–SSE plane. Abou Elenean (1997, 2007), studied the

STRK1 160
DIP1 71
RAKE1 -9
STRK2 253
DIP2 82
RAKE2 -161

P-axis; plunge= 19
    azimuth= 118
T-axis; plunge= 8
    azimuth= 25

Consistent data: 9
Inconsistent data: 0

STRK1 183
DIP1 80
RAKE1 -2
STRK2 274
DIP2 88
RAKE2 -170

P-axis; plunge= 9
    azimuth= 139
T-axis; plunge= 6
    azimuth= 48

Consistent data: 9
Inconsistent data: 0

STRK1 162
DIP1 71
RAKE1 -12
STRK2 256
DIP2 79
RAKE2 -160

P-axis; plunge= 22
    azimuth= 120
T-axis; plunge= 6
    azimuth= 28

Consistent data: 9
Inconsistent data: 0

Fig. 4 Fault plane solutions for the 26 December earthquake and other two aftershocks using P- and S-waves polarities

Table 2 Calculated earthquake source parameters of the event 26 December 2011 17:01

Station	f_o (Hz)	M_o (dyne/cm)	r_o(m)	U (m)	$\Delta\sigma$ (dyne.cm-)	M_w
WAL	5.50	1.1×10^{22}	43.50	0.9	5.88E+08	4.00
GRW	5.10	6.8×10^{22}	46.90	0.3	2.90E+08	4.50
KUR	6.70	3.8×10^{22}	36.00	0.3	3.64E+08	4.30
NAL	6.50	3.8×10^{22}	37.00	0.3	3.16E+08	4.30
AHD	5.80	4.7×10^{22}	40.90	0.3	3.02E+08	4.40
GMR	10.00	5.0×10^{22}	23.80	0.6	1.66E+09	4.40

focal mechanisms and stress tensors for some events located in the same study area. He concluded that the focal mechanisms show two kinds of movement, the major one is the strike-slip movement and the minor one is the normal dip-slip movement with two nodal planes ENE–WSW to E–W and NNW–SSE to N–S. As a comparison, our obtained results implied good agreement with those previous studies.

Source parameters and rupture directivity

To understand the generating mechanism of an earthquake sequence, it is necessary to know the source parameters of the respective events and their mutual relationships. Also, the variations between the seismic source parameters associated with specific events simply reflect the irregularities of the evolving stress field. Additionally, source parameters, particularly the stress drop are crucial in micro-zonation and the assessment of the seismic hazard (Abdel-Fatah and Badawy 2002). A fundamental measure of the earthquake size is the radiated seismic energy, scaled with parameters estimating the stress release, as the stress drop, the apparent stress, the dynamic stress drop, etc. (Choy and Boatwright 1995; Abercrombie 1995; McGarr and Fletcher 2002 and many others). The most frequently used scaling parameter is the stress drop because it can provide information about the earthquake mechanics.

In this study, we focused on source parameters determination using the P-wave spectra, which is done using the PITSA program version 3.4B (Scherbaum and Johanson 1992).

Brune's model (1970, 1971) is assumed and, in consequence, the far-field displacement spectra are sufficient to describe the far-field shear radiation, and the physical interpretation of the spectra, which is reduced to three independent parameters, is correct. The three independent spectral parameters are as follows:

(1) The long period spectral level Ω_o, which is proportional to seismic moment.
(2) The corner frequency f_c, the frequency at the intersection of the low- and high-frequency trend in the spectrum.
(3) The parameter γ controls the high-frequency decay, physically; it measures the ratio of stress drop to the

shear stress difference available to accelerate particles on the fault surface.

Uncertainties in source parameter determinations are directly related to theoretical and observational uncertainties in the specification and determination of far-field displacement spectra.

In this study, we calculated the source parameters (seismic moment, stress drop, displacement, and fault length) for the Aswan event (main event) and summarized them in Tables 2 and 3. The derived corner frequencies f_o for P-wave spectra shows an average value of 4.84 Hz, the average seismic moment (M_0) is 4.2×10^{22} Nm, the fault length (r) 40 m, while the average value of the stress drops ($\Delta\sigma$) is 0.6 Mpa. The displacement amplitude spectra for the Aswan event recorded by WAL, GRW, KUR, NAL, NHD, and GMR seismic stations have been determined as shown in Figs. 5 and 6.

Source time functions

By applying the EGF, (Hertzell 1978), the rupture direction and source properties from the isolated RSTF of the Aswan earthquake were retrieved. The detailed studies of a source process revealed rupture complexities and directivities not only for large earthquakes but also for moderate and micro-earthquakes (e.g., Frankel et al. 1986; Li and Thurber 1988; Mori and Frankel 1990; Abdel Fatah 1999). The EGF deconvolution method is used to isolate the source effects (source time function or moment rate function) from those of the path, site, and instrument responses. The advantage of the EGF method is that detailed knowledge of the earth structure, instrument response, and attenuation effect is not required. For two earthquakes having similar hypocenters and focal mechanisms but different sizes, one can treat the waveform of the smaller event as the EGF and deconvolve it from

Table 3 The average calculated values of source parameters of the Aswan event

f_o (Hz)	$U(m)$	M_o (Nm)	r_o(m)	$\Delta\sigma$ (Mpa)	M_w
6.6	0.50	4.2×10^{22}	40	0.6	4.4
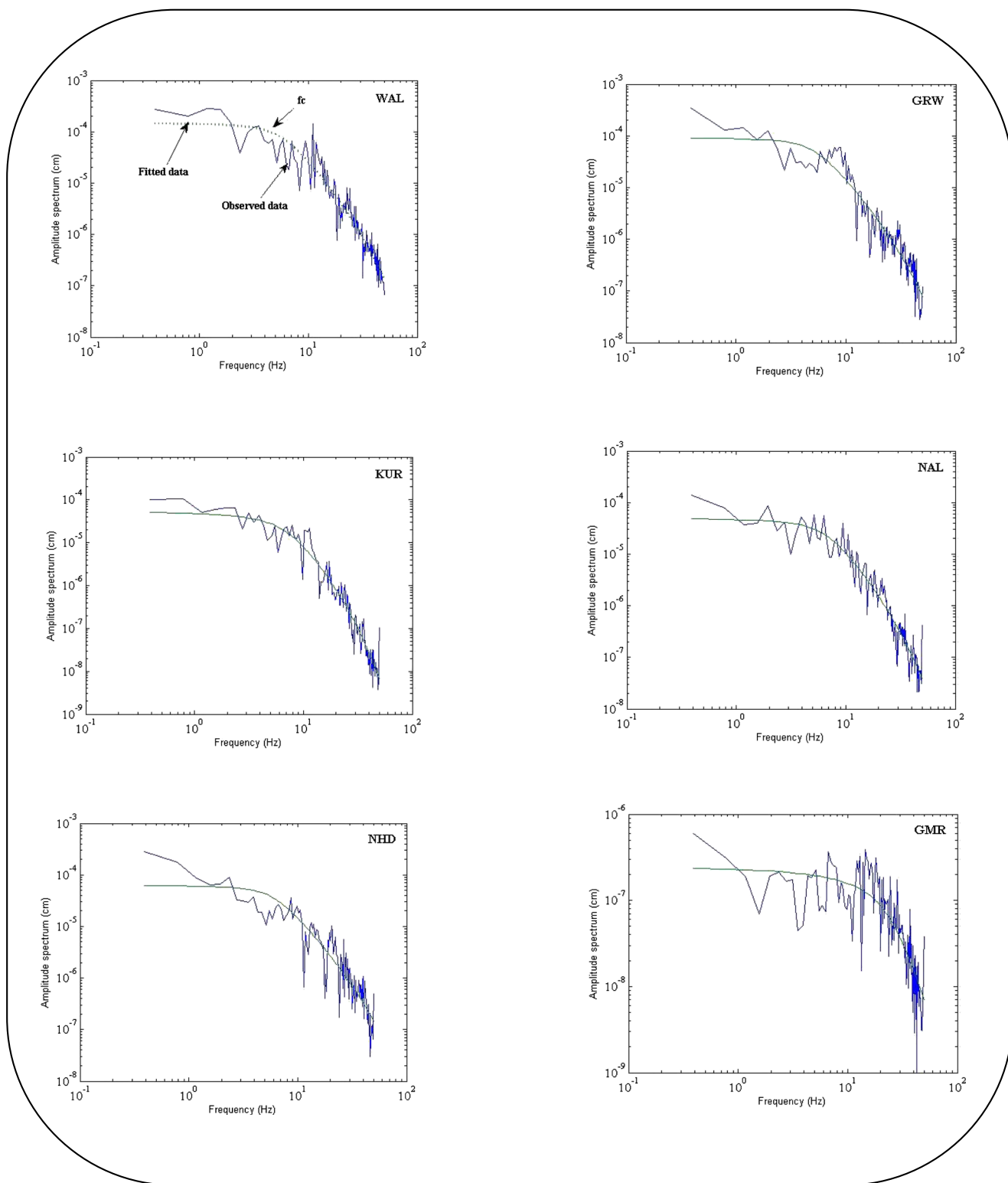
Fig. 5 Displacement amplitude spectra for Aswan event at the WAL, GRW, KUR, NAL, NHD, and GMR seismic stations

that of the large event to obtain a RMRF for the large earthquake. RMRFs have been used to describe the source process and to estimate the source parameters, such as time rise, seismic moment, fault radius, and stress drop (e.g., Frankel et al. 1986; Li and Thurber 1988; Mori and Frankel 1990; Xie et al. 1991).

Here in this study, our data (master event and two aftershocks) is sufficient and applicable to apply the EGF

method, since the three events are similar in mechanisms with different magnitudes. RMRF of the master event has been obtained by performing the deconvolution as a linear least square estimation problem in the time domain with positively constraints by using NNLS Fortran subroutine. Applicable example of this procedure can be seen in Fig. (6). Due to the fact that the EGF deconvolution is not a stable operation, it is important to reduce this instability in the higher frequency's noise. And consequently, the deconvolved pulses are low-pass casual filtered at 30 HZ high-cut frequency with a Butterworth filter. These noises, which causes this instability is due to the variation in the background noise at each seismic station and also due to the spatial separation between the master event and the EGF event in addition to the nondeltaness of the RMRF of the EGF event (Frankel et al. 1986; Li and Thurber 1988; Li et al. 1995). The pulses obtained after deconvolution conclude more information through the amplitudes and widths of these pulses, in which factors such as the radiation pattern, geometrical spreading, free surface amplification, and instrument response are removed. Therefore, the amplitudes and pulse's width of the retrieved source time function at each seismic station can be used as an indication for the directivity of the rupture direction.

Based on the retrieved source time functions, (STF), most of them consist of two or three peaks, which can be interpreted as this source is excited by multiple sources, more than one subevent. This means that the rupture of the Aswan earthquake is complex and started by small or low energy before the big dynamic rupture occurred, which describe of nucleation phase (Ellsworth and Beroza 1995). At each seismic station, the large pulse of the retrieved STF represents the large event and the others of the small subevents. The pulses arrived after the large ones at some stations (WAL) may reflect also the directivity of that earthquake.

As can be seen in Fig. 7, the normalized amplitudes of these STF for some selected seismic stations such as, WKL, WAL, SKD, and AHD, are nearly the same, although they are located in different azimuth in relating to the event location. This means that the directivity of rupture delineated to different directions, which indicates to a fault associated with bi-lateral movement. This movement could take place due to the rupture which occurred at the intersection area between the north–south and the east–west fault systems as shown in Fig. (4). The intersection areas are convenient locations for stress accumulation. Therefore, reactivation to the existing faults occurs (Sykes 1978; Talwani and Rajendran 1991). Then, the rupture may occur in different directions. This is exactly what we observed in our results, since the obtained STF for some stations located in different azimuths have high amplitudes and pulse width.

Fig. 6 Isolated source time functions at five recording stations (AHD, WAL, SKD, WKL, and GRW) of the Aswan seismic network. *Numbers* indicate the number of peaks or subevents

Discussion and conclusions

Generally, The present day tectonic deformations within Egypt are related to the regional tectonic forces of the surrounding plate boundaries including the African-Eurasian plate margin, the Red Sea plate margin, and the Levant transform fault in addition to the local tectonics of Egypt. Very important information about the tectonics of Egypt can be obtained from the spatial distribution of earthquakes and their derived mechanisms. In the southern part of Egypt, based on the background seismicity (14 November 1981 event, earthquake swarms, 2004, in addition to some moderate earthquakes), the Aswan area is considered a local active seismic area.

With the aim of hazard assessment for the Aswan area, we studied the 26 December 2011 earthquake (Mw=4.4). The focal mechanisms, source parameters, and the source time functions for that event are investigated. The derived mechanisms of the Aswan event and other two aftershocks as shown in Fig. 3 are very similar and exhibit major strike-slip component with minor-dip component faulting styles. The two nodal fault planes are trending nearly in ENE–WSW to E–W and NNW–SSE to N–S directions. The east–west trend is more consistent with the trend of the Kalabsha fault and the north–south with the north south trend faults and perpendicular to Kalabsha fault.

By determining the source time functions for some selected seismic stations at the Aswan area, we identified the rupture directivity of the Aswan event. Based on the amplitudes, pulse width, and number of peaks of the STF for specific stations around the epicenter, we suggested that a complex rupture and bi-lateral movement associated with the occurrence of this event. The bi-lateral movement is attributed to reactivation of some existing faults at the intersection area between north–south and east–west fault systems.

Furthermore, as a crucial step in seismic hazard assessment or earthquake prediction at the study area, using the P-wave spectra, the source parameters of the Aswan earthquake were calculated. Source parameters, such as seismic moment (M_o), fault radius (r_o), corner frequency (f_o), and the stress drop ($\Delta\sigma$) have been calculated for that event.

When considering the occurrence of this event and other background seismicity, we conclude that the seismic activity of the Aswan area is related to the local, regional, and global stresses. The regional stress is generated by the Red Sea rift system; the local one could be coming from the load of Lake Nasser reservoir (increasing of pore pressure, serves to trigger the released of preexisting stress stored in the earth's crust); and the global stresses due to the African-Eurasian margin plate. Then, we conclude that the Aswan area, which has been considered as an active seismic area, is still active.
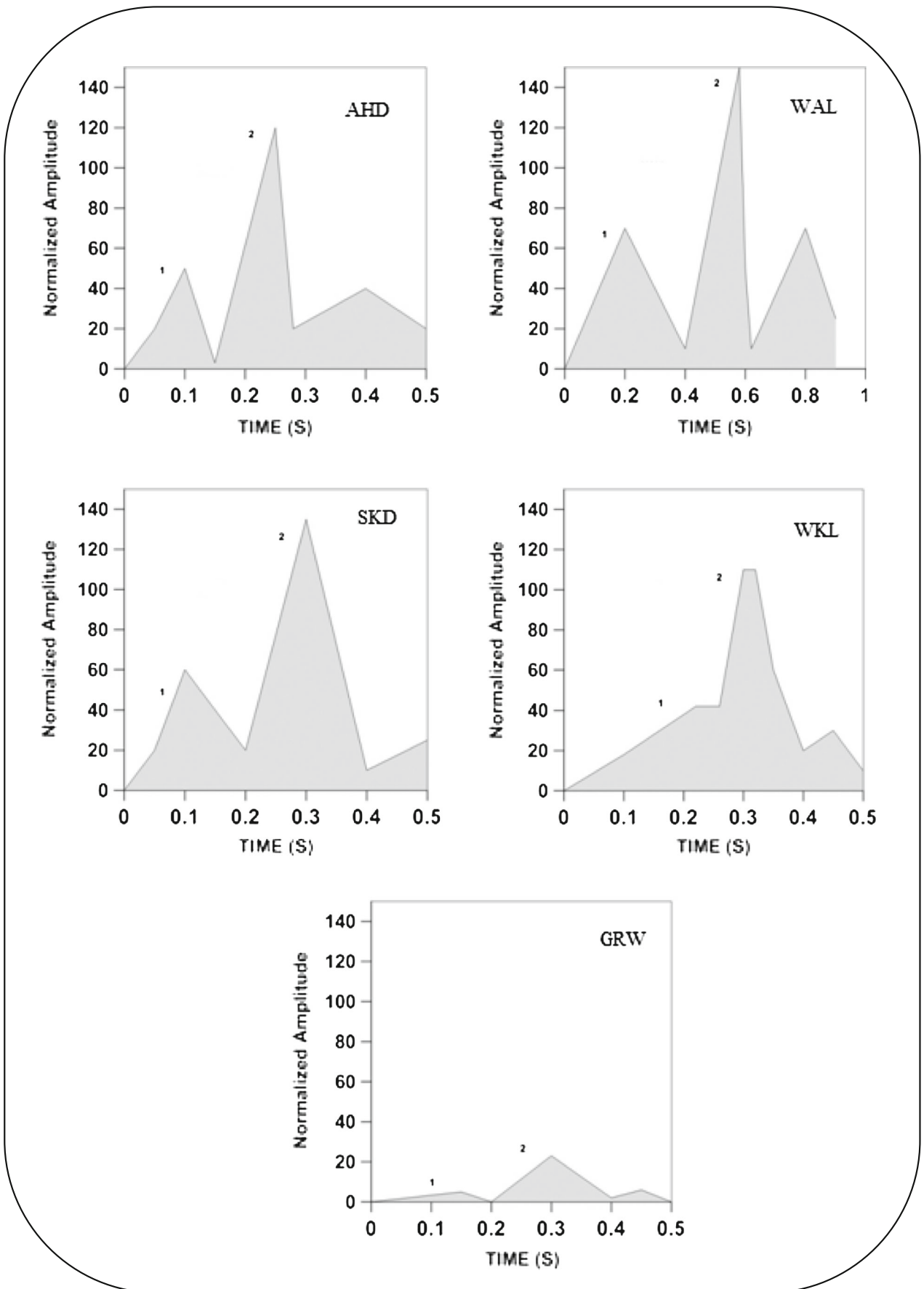
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