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Source Mechanisms of Recent Earthquakes in Southern Saudi Arabia: Detecting of New Seismic Sources

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Abstract

Recently in 2020, in southern Saudi Arabia three felt earthquakes occurred in Asir region, in the Khamis Mushait, Ahad Rafidah, and AL-Shuqiq area, of magnitude 3.45, 3.1, and 3.5, respectively. The most interesting event was the earthquake that occurred in Khamis Mushait area, along a lake formed behind the Tadhah Dam (~7 km), fearing any damage to the dam's body and the consequent destruction. Moment tensors for each event were computed for determining fault plane solutions, seismic moment, moment magnitude (Mw) and the CLVD ratio. In addition, the frequency contents in the waveforms of each event were identified. The obtained focal mechanisms represent different styles of faulting, normal movement with strike slip and strike slip with reverse. These tectonic movements on faults parallel to the Red Sea refer to the tensional forces due to the Red Sea rift system. These events occurred due to a natural tectonic movement, with considering the Khamis Mushait event as an induced event because of the lake behind the Dam. Many previous seismic hazard assessment studies have been conducted in southern Saudi Arabia without considering these recent seismic sources. Thus, our study provides new information related to detecting of new active seismic sources, which contributes to updating studies of seismic risk assessment in this region. In addition, our study pushes us to establish other additional seismic stations around these new seismic sources. This in turn will play a pivotal role in controlling seismic sources and then reassessing the seismic hazard in southern Saudi Arabia.

Keywords

New Seismic Sources, Local and Regional Stresses, Updating Seismic Hazard

1. Introduction

The Arabian Plate was part of the African Plate during most of the Phanerozoic Eon (Paleozoic-Cenozoic), until the Oligocene Epoch of the Cenozoic Era. The separation of Africa and Arabia occurred approximately 25 million years ago in the Oligocene, and since then the Arabian Plate has been slowly moving toward the Eurasian Plate. Thus, this separation resulted in the closure of the subducting Tethys sea in the northeast [1]. The rifting of Africa and Arabia opened the Red Sea as well as the Gulf of Aden, bordering the plate on the southwest and southern sides respectively (see **Figure 1**). The Red Sea has a spreading half rate of roughly 10 mm/yr and the Gulf of Aden is believed to be a propagating rift opening westward at a rate of approximately 3 mm/yr [2]. As the Red Sea continued to open, the Arabian plate eventually collided with Eurasia which was delineated by the Zagros Mountains. This mountain chain has a shortening rate of 9 ± 3 mm/yr in the SE and 5 ± 3 mm/yr in the NW [3].

Additionally, since the Pliocene the Arabian plate has been subjected to great lateral tectonic movements that moved the continental blocs to the north (40 km) and formed the Bab al-Mandab Strait, [4]. These movements continued to the north-eastern direction along the Gulf of Aqaba (150 km), [5] with Left-Lateral movement (40 - 45 km) for the Miocene rocks and led to the formation of the axial trough of the Red Sea. It was also noted through the change in

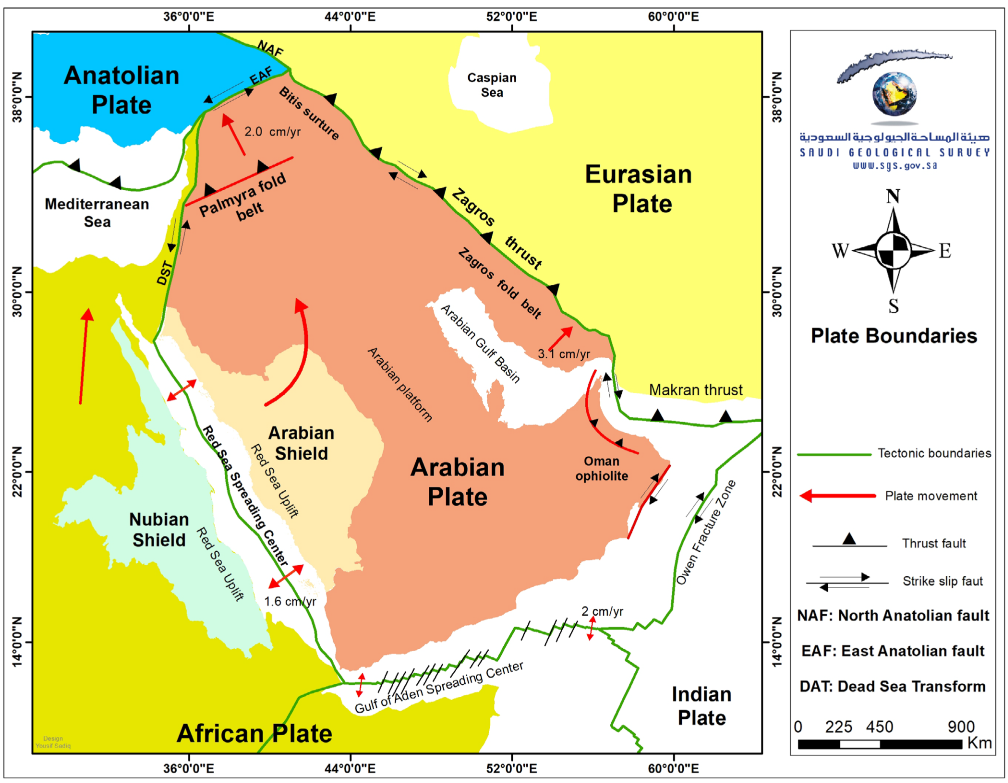

Figure 1. Tectonic map of the Arabian plate, with tectonic boundaries and principle geologic features. Arrows represents movement of the Arabian plate and solid triangles show subduction areas, (modified after Stern and Johnson, 2010).

the width of the axial trough that the rate of spread along the Red Sea during these movements was not symmetrical. Thus, more complex structures, including major faults, parallel or perpendicular on the Red Sea axis have been formed in southern Saudi Arabia, and causing many moderate to large earthquakes.

Seismic activity occurs in the Arabian Peninsula, particularly in Saudi Arabia due to the continuous stresses on the earth's crust because of surrounding regional tectonic. Represented by extensional forces due to rifting of the Red Sea and Gulf of Aden from the west and the south side; collision zone with the Eurasian plate at the Zagros and Makran mountains in southern Iran and the Taurus Mountains in southern Turkey from eastern and northern side; and the effect of the transform tectonic movement in northwest of the Arabian plate due to the horizontal movement of Gulf of Aqaba, [6]-[11]. These regional stresses move to the inner part of the plate and collect until they reach a limit that exceeds the bearing of the rocks, which leads to the reactivation of the existing faults in the crust, causing seismic activity.

The monitoring of seismic activity in Saudi Arabia began since the eighties (1984 AD) coinciding with the necessity of urban expansion and the establishment of major strategic projects in all provinces of the Kingdom. And was required attention to knowing the extent of the sustainability of these projects and facilities with their resistance to seismic risks. This monitoring system in general required the establishment of many of seismic stations, with well distributed to cover all parts of the Kingdom, which was achieved when Cabinet Resolution was issued in 2004 to start establishing the Saudi National Seismic Network (SNSN). Thus, the SNSN became consists of about ~250 seismic stations for monitoring the seismic activity occurs inside and around the Kingdom. The seismic stations are equipped with Broadband seismometers, Trillium 40, and 120 sec and seismic data are sending via satellite from their locations to the main center at Saudi Geological Survey (SGS), to analyse and locate the seismic activity with determining the source parameters.

Recently in 2020, in southern Saudi Arabia three felt earthquakes occurred in Asir region, located in the Khamis Mushait, AL-Shuqiq, and Ahad Rafidah area, of magnitude 3.45, 3.1, and 3.5, respectively, with no recording of large damages. The most interested event for people there was the earthquake that occurred in Khamis Mushait area near the Tandaha Dam (~7 km), fearing any damage to the dam's body and the consequent destruction. This earthquake occurred along a lake formed behind the Tadhah Dam at the intersection area of valleys crossing the area, some of which are parallel to the Red Sea and others are perpendicular. Moment tensors for each event were computed for determining fault plane solutions, seismic moment, moment magnitude (Mw) and the CLVD ratio, in addition to determining the frequency contents in the waveforms of each event. The obtained focal mechanisms represent different styles of faulting, normal movement with strike slip and strike slip with reverse. These tectonic movements on faults parallel to the Red Sea refer to the tensional forces due to the Red Sea rift system. This study will lead us to consider the redistribution of some seismic stations of the ENSN and establishing other additional stations, especially around new seismic sources.

To identify the real reasons behind the occurrence of these events, whether they occurred due to a natural tectonic movement or due to volcanic activity, more than one factor was taken into consideration, which indicated that it was due to a natural tectonic movement, with considering that the Khamis Mushait event may occurred due to the loading of the lake formed behind the Tandaha Dam.

By considering these new seismic sources detected in southern Saudi Arabia, we may update seismic hazard assessment studies for this region, as a direct contribution to updating the Saudi building code.

2. Seismic Activities in Arabian Plate

2.1. Historical Seismicity

Based on previously published research, [12] [13] [14] [15] [16] the historical earthquakes that occurred in the Middle East were in the form of seismic swarm, some of which are related to volcanic eruptions in the region, [6]. In southern Arabian plate, in the period from 200 to 1900 there are about 78 earthquakes have occurred and most of these events are concentrated around Sana'a-Aden along the Red Sea. In addition, some of these historical earthquakes occurred on offshore and were felt on the land. In the period from 1900 till 1964, about 22 earthquakes occurred with magnitude ranges from 4 and 6.3 and seem to correlate with the general tectonics of the region [6]. The epicenters of these events were trending in northeast, in parallel to the main axis of the Red Sea where some instrumental seismicity occurs as well, and in a perpendicular alignment.

2.2. Recent Seismic Activities

According to the records of the Saudi National Seismic Network (SNSN), the regions of Asir and Jizan, in the south of the Saudi Arabia are areas of small to moderate seismic activity. The SNSN monitored seismic activity in these areas for a period from 2009 to 2020, with local magnitudes ML ranged from 1.0 - 3.5, as shown in **Figure 2**. The occurrence of this seismic activity may be attributed to the extensional forces resulting from the rifting process of the Red Sea from the west, in addition to the effect of tectonic movements of the triple junction of Gulf of Aden, Afar Depression, and the opening of the Red Sea from south. These tectonics stresses cause reactivation of pre-existed faults in this area, whether the faults parallel to the Red Sea or perpendicular to it.

Recently, three small earthquakes occurred in Asir area, southern of Saudi Arabia in the Khamis Mushait, AL-Shuqiq, and Ahad Rafidah area, **Figure 3** and **Table 1**. These events were felt by people especially people who lives near to the epicenter areas of these earthquakes, like slight shaking with no recording of large damages. The most interested event for people was the earthquakes that occurred in Khamis Mushait area on 9 May 2020 near the Tandaha Dam (~7 km to the east) with magnitude ML = ~3.5, **Figure 3**. People in this area became anxious, fearing any damage to the dam's body and the consequent destruction. The event occurred after other two small events with magnitudes 2.5 and 2.3, respectively.

Six months later, in the same study area during October and November 2020 two other small earthquakes with local magnitudes 3.1 and 3.5 occurred in Ahad Rafida and Al-Shuqiq area, within a distance about 30 - 40 km southwest of the Khamis Mushait earthquakes. These events were felt by the people of the vicinity villages with no recorded significant damage or losses.

Table 1. Location parameters of the three events.

Event area	Date	Time	Latitude	Longitude	Depth (km)	Magnitude
Khamis Mushait	2020-05-09	12:06:03	18.3268	42.948	8.00	3.45
Ahad Rafida	2020-10-28	11:56:07	18.1337	42.777	14.02	3.09
Al-Shuqiq	2020-11-22	20:53:27	17.6865	42.114	14.09	3.51

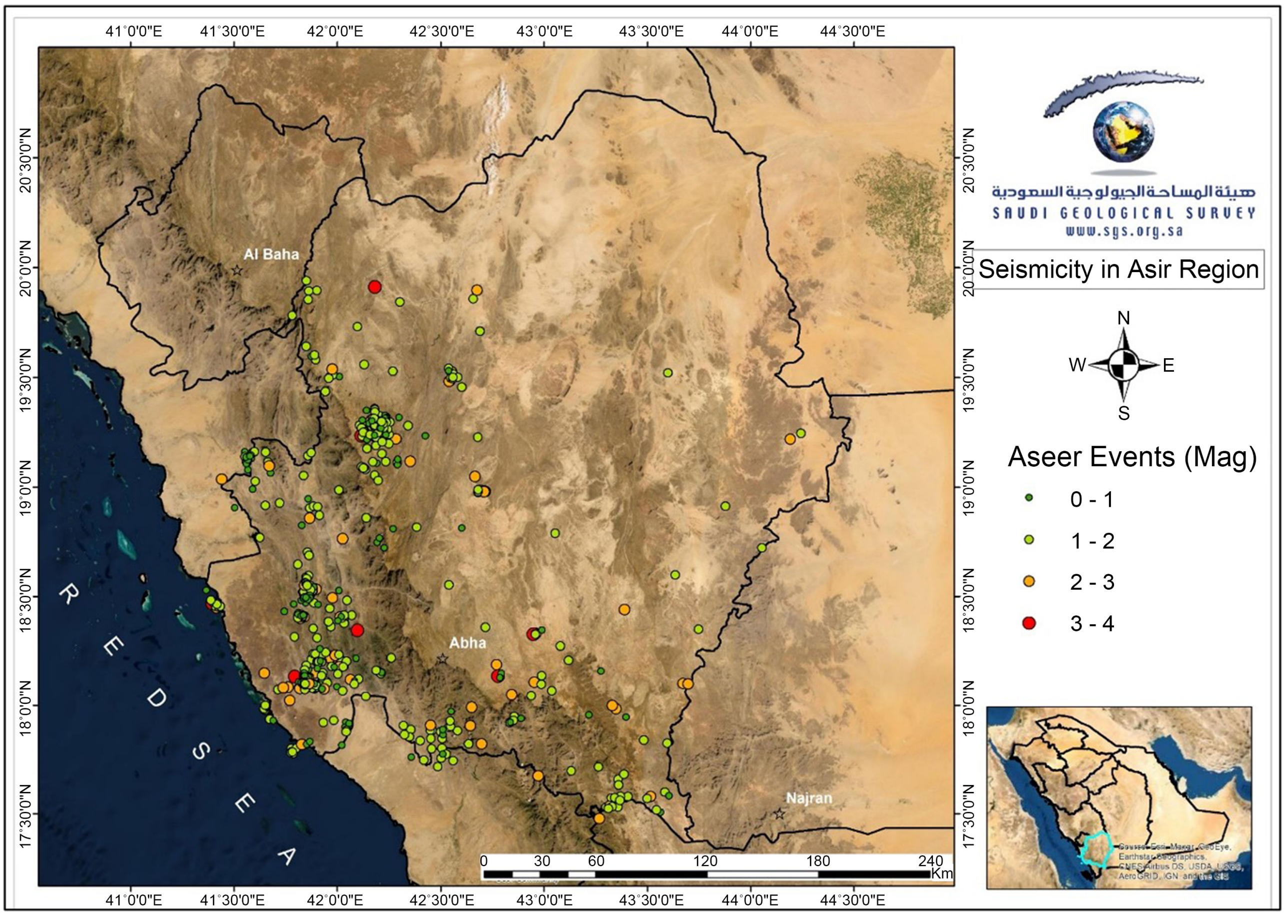

Figure 2. Seismicity map of Asir region, southern Saudi Arabia. Circles of different size represent seismic activity according to different seismic magnitudes.

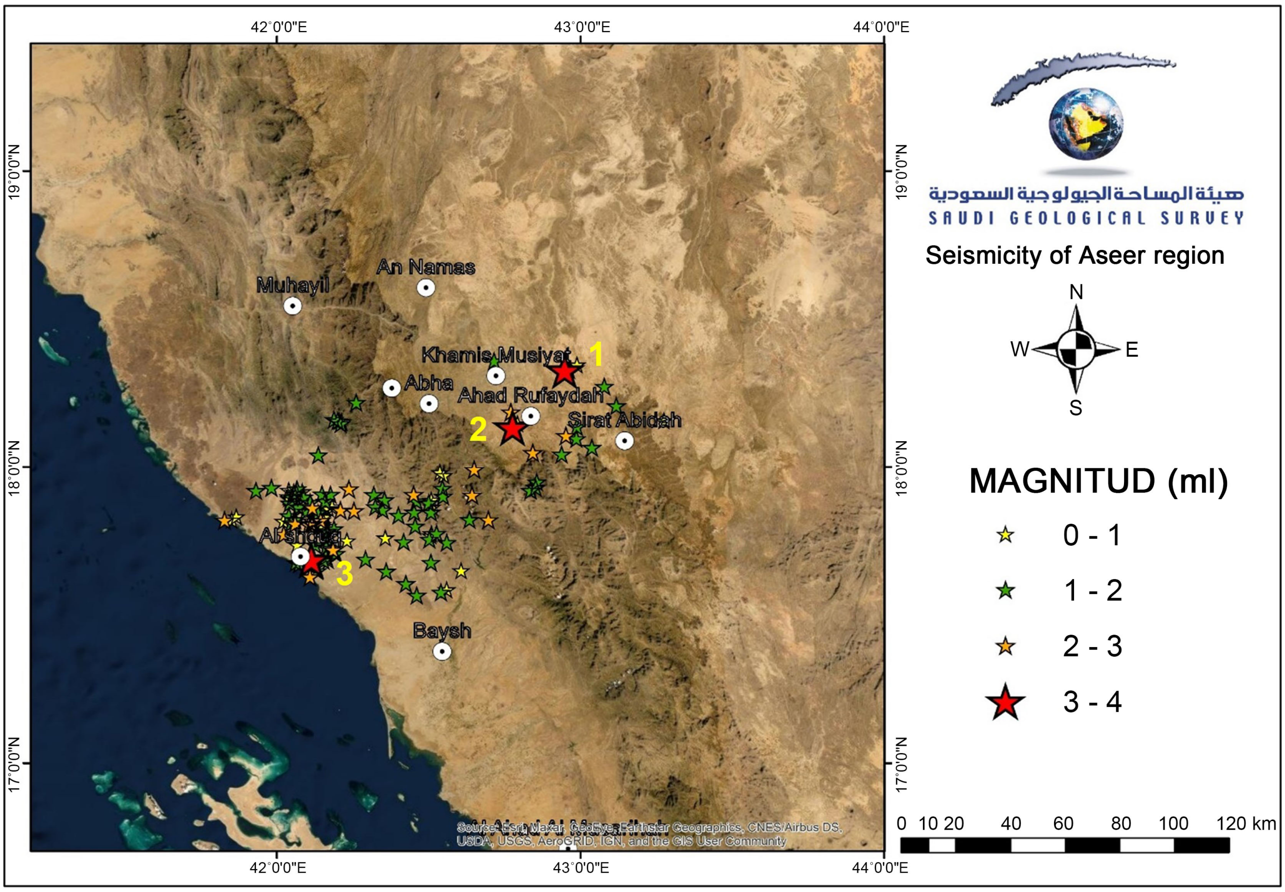

Figure 3. The locations of the three earthquakes used in the study, the numbering represents the events in order, no. 1 represents Khamis Mushait event, no. 2 represents Ahad Rafidah event, and the number 3 represents the Al-Shaqiqa earthquake. The white circles represent the locations of the seismic stations used to analyze and locate the events.

3. Field Visit

Immediately, after occurrence of these events a technical team from the National program for Earthquakes and Volcanoes, Saudi geological Survey visited these areas, around the epicenters of these earthquakes to find out their impact in the region. For the Khamis Mushait area, because the event occurred very near to the Tandaha Dam, (~7 km) the team gave a priority to visit the Dam to inspect if there was any impact on the Dam's body because of this event. Although the event was very near to the Dam, no damages were observed on the Dam, may be due to the small magnitude of the event. The visiting team also noted that the epicenter area is located along the small lake formed behind the Tandaha Dam, at the intersection area of several intersecting valleys in the area, some parallel to the Red Sea and others perpendicular. Figure 4 shows location of the Tandaha Dam with the forming of the Lake in behind.

For monitoring seismic activity continuously, especially around the Tandaha Dam area the visiting team added a broadband seismic station in the epicentre area, Figure 5. [17] stated that monitoring the seismic activity around dams and its results has become important in earthquake engineering and has a significant contribution to reducing seismic risks on dams. The aim of this monitoring is to facilitate response studies to understand the dynamic behaviour and the potential for damage to dam's structures under seismic loading. Therefore, for measuring the ground acceleration, the visiting team established a strong motion station on the body of the Tandaha Dam, as shown in **Figure 6**.

Figure 4. A photo of the Tandaha dam with the lake formed in behind.

Figure 5. A photo of a complete seismic monitoring station (weak motion station) that was established in the epicenter area of the Khamis Mushait earthquake, on the edge of the lake and ~7 km to the east of the Tandaha dam.

Figure 6. A photo of a complete seismic monitoring station (strong motion station) that was established on the body of the Tandaha dam.

4. Moment Tensors Inversion

The seismic moment tensor is one of the most important techniques that accurately describe the type of seismic sources using waveform data, rather than P-wave first polarities, [18] [19]. In general, there are three methods that are used in moment tensor research, the first is based on the amplitude ratio, (e.g., [20] [21]). The second is based on the amplitude only, (e.g., [22] [23]), while the third one is the full waveform-based technique (e.g., [24] [25] [26]).

In this study, the aim was to compute the moment tensor solutions for the three events, (**Table 1**), using complete waveforms and applying the algorithm in computer programs in seismology package, [27]. There were important steps that have been performed to compute the moment tensors for the selected three events:

4.1. Green's Functions Computation

The Green's function represents the impulse response of the medium from the source to the receiver, which depends on the velocity model and coordinates of both the source and the receiver, [28]. For computing the Green's functions for each source depth and epicentral distance, the wavenumber integration approach with a convenient 1-D structure model can be used, [29]. In this study, the convenient velocity model that gave the best fit between the synthetic and the observed seismic data is used for calculating the Green's functions and proceeding analysis. Thus, for the three mentioned events we used a local 1-D velocity model that using in the SNSN for locating seismic activities in the Asir and Gazan regions, southern of Saudi.

4.2. Data Processing

The waveforms of each event was available as SEED format, which have been converted to SAC format using RDSEED commands (http://www.iris.edu), The instrument response is removed by deconvolving the response for each sensor, and then the two horizontal components (E-W and N-S) are rotated to traverse and radial, respectively for the selected three events. A linear trend and mean are removed, and the data were tapered with a window of 0.1 and a low pass filter is applied to remove the high frequency noise. The observed and the computed Green's function are filtered within the same frequency band by using a 4-pole causal bandpass Butterworth filter.

5. Results and Discussions

In this study, seismic sources of the three events mentioned above have been studied for obtaining fault plane solutions and seismic moment (moment magnitude). The best fittings result among the observed and synthetic waveforms for the three events were obtained. In addition, the inversion results including moment tensor components, decompositions (double couple and the compensated vector dipole CLVD ratio), the moment magnitudes (Mw), and shift in origin time (velocity reduction) were also determined. The obtained focal mechanisms results revealed different styles of faulting. For Khamis Mushait event, (**Figure 7**, **Figure 8**) normal movement with strike slip component is obtained, **Figure 8** represented by double couple (DC) ratio (46% and 54% CLVD ratio). The source mechanism showed that there are two fault planes, one trending in an east west (perpendicular to Red Sea main rift axis), and the other almost perpendicular to it. The moment magnitude (Mw) was computed at 3.5 and depth at 16.0 km, **Figure 8**. The main event and the two before it occurred in an area of intersection valleys along the lake of the Tandah Dam, which may have occurred because of the effect of lake formed behind the Dam, (changing of pure pressure beneath the lake). [30] [31], in some seismically active areas in the world studied the nature and reasons of occurrence the intraplate and near plate boundary earthquakes and stated that earthquakes tend to nucleate near the fault intersections at the pre-existing weakness zones. Therefore, we may attribute the occurrence of the events of Khamis Mushait to the presence of the area of weakness behind the lake of the Tandah Dam.

For the second event occurred in Ahad Rafidah area, Figure 9, Figure 10 the obtained focal mechanism delineated normal movement with small strike slip component, Figure 10 and represented by 58% DC and 42% CLVD ratio. The source mechanism showed that there are two fault planes, all almost trending in northwest-southeast, nearly perpendicular to Red Sea main rift axis. The moment magnitude was computed at 3.7 and depth of 14 km, Figure 10. Based on what the visiting team reported, it was no valleys intersection at the site of the event, meaning that no intersection appears on the surface of any faults cut the area. Therefore, this event may have occurred because of the tension forces affecting the Red Sea, which caused the reactivation of one of the pre-existed faults in that area, parallel or perpendicular on the Red Sea main rift axis. Indeed, based on the catalog of the SNSN no seismic activity has ever been detected on this site, as well as the site of the Khamis Mushait earthquake. Thus, locations of these events are considered as new seismic sources that will contribute to updating seismic hazard studies in the south of Saudi Arabia region.

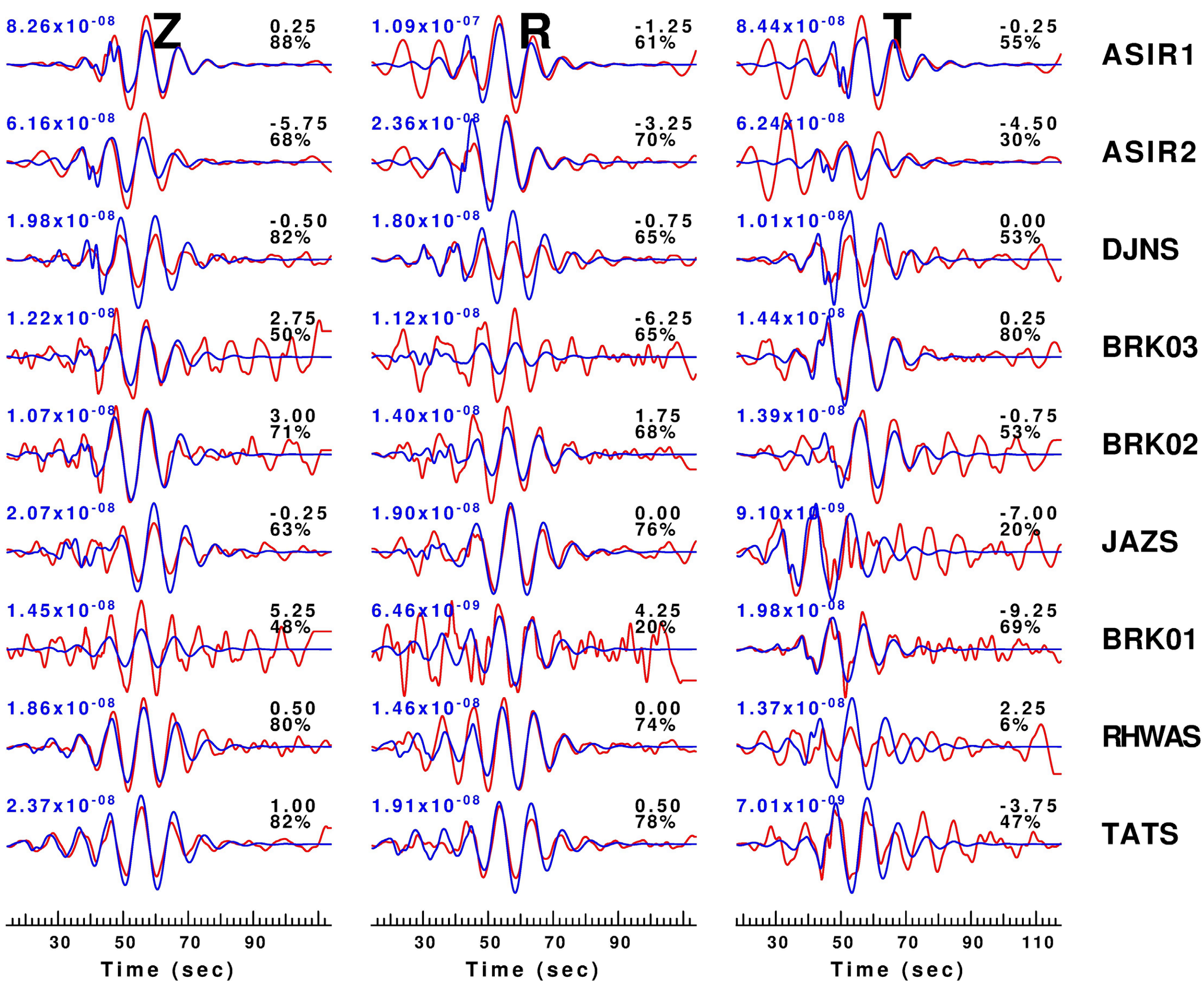

Figure 7. Inversion results for Khamis Mushait event, a waveform fit, correlation between the observed and the synthetic seismograms.

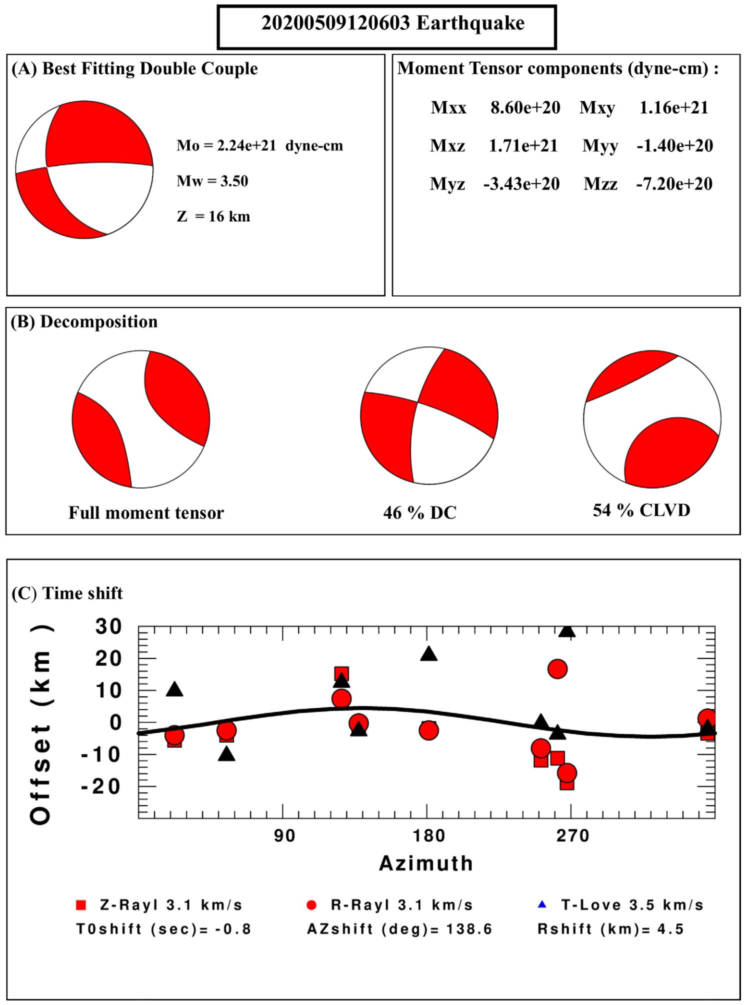

Figure 8. Result of Moment tensor inversion of Khamis Mushait event, including moment tensor component, magnitude (Mw), source mechanisms, and CLVD ratio, in addition to origin time shift.

As for the third event, Alshoqiq event, Figure 11, Figure 12 the source mechanism revealed strike slip movement with reverse component, Figure 12, the DC ratio was 70% and 30% CLVD ratio. The source mechanism showed that there are two fault planes, one trending in northwest (nearly perpendicular to Red Sea main rift axis), and the other almost parallel to Red Sea main rift axis. The computed moment magnitude was 3.78 and the depth was computed at 20 km, respectively, Figure 12. This event is located near the Red Sea coast and according to the SNSN, it occurred in an area characterized by occasional seismic activity, in opposite side of a seismically active area inside the Red Sea. Thus, we may attribute the occurrence of this event to the reactivation of one of the faults located on the Red Sea coast, parallel to the main rift axis. Here, we can ask a question: is it possible for a small earthquake to occur with a reverse movement in areas very close to the original extension zone (Red Sea)? The answer is yes, this can happen, as this reverse movement represents a reactivation of some of the normal faults that already exist in the basement of the study area. [32] studied similar cases in different regions of the world and proved that this reverse movement was originally formed by extension movement and may represent a reactivation of pre-existing normal faults.

The obtained CLVD ratio for the three events is ranging from 30% up to 54% for Khamis Mushait and Ahad Rafidah event, respectively, while reached 70% for Al-Shoqiq event. This high ratio could be artefacts due to inadequate crustal model, but it can rather be a phenomenon of tensile earthquakes being created by combining shear and tensile motions on a fault during the rupture process, [33] [34] [35]. When considering the noticed higher CLVD ratio in general for all events and especially for Al-Shaqiq event (70%), where this event is located near the coast of the Red Sea, we kept in mind the possibility of volcanic activity under this area that may have caused this event. This led us to test the frequency spectrum of some waveforms for selected stations to see whether the occurrence of these event is related to any volcanic activity or due to the natural tectonic tension forces in the Red Sea.

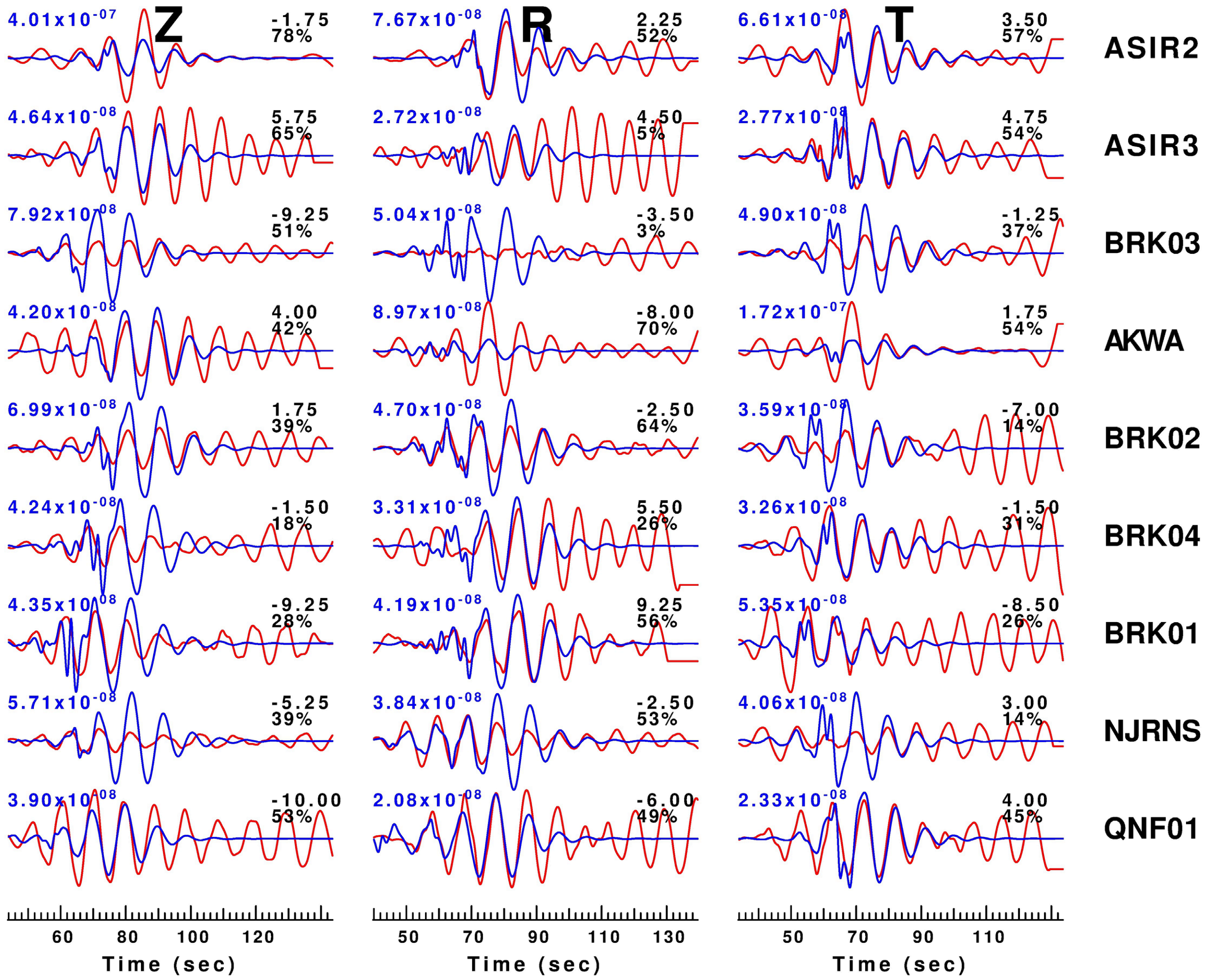

Figure 9. Inversion results for Ahad Rafidah event, a waveform fit, correlation between the observed and the synthetic seismograms.

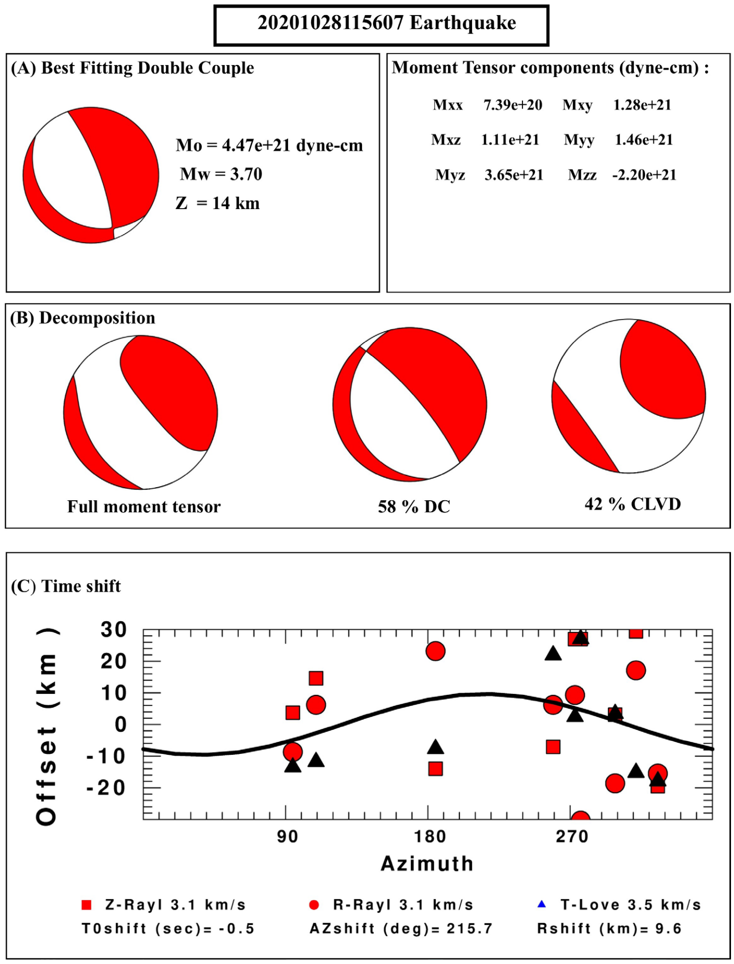

Figure 10. Result of Moment tensor inversion of Ahad Rafidah event, including moment tensor component, magnitude (Mw), source mechanisms, and CLVD ratio, in addition to origin time shift.

The determined frequency contents showed that these events occurred within frequencies greater than 10 Hz in the waveforms of stations that used in locating and in inversion for computing the moment tensors of these events, Figures 10-12. The nature of earthquakes is often classified according to the content of frequencies in the seismic waves caused by the occurrence of these earthquakes [20] [36], which most of them are divided into two groups according to the amount of signal power around the frequency 5 Hz. Thus, waveforms of high frequency content are interpreted as the result of a brittle fracture, while those with low frequencies between 0.2 to 5 Hz are due to a movement associated with a crack or a crack or a conduit section [37] [38]. In our case, when considering; 1) the frequency contents of the three earthquakes, higher than 10 Hz (Figures 13-18); 2) non-occurrence of previous earthquake swarms in these areas, even during the occurrence of these recent events; 3) no migration of seismicity has been detected (seismic activities with varying depths); and 4) no previous volcanic record, even historically, this led us to suggest that these events occurred due to natural tectonic movements on pre-existed faults due to regional stresses affect the area, (Re Sea and triple junction of Red Sea, Gulf of Aden, and Afar area).

When considering the importance of this study, it is represented in; 1) providing additional new information related to detecting of new seismic sources in the south of the Kingdom, which contributes to updating studies of seismic risk assessment in this region; 2) there are many previous seismic hazard assessment studies, [39] [40] [41] [42] [43] conducted in the southern part of the Kingdom, but the locations of these recent seismic sources have not been taken in account in their calculations; 3) the area is in the process of constructing several dams to store water for agricultural purposes and human use; and the region was exposed to more than one earthquake, whether historical or recent, that caused seismic effects in the region; and 4) according to the vision of 2030 in the Kingdom of Saudi Arabia and the beginning of development in the southern region, the region has become promising for the establishment of vital and strategic projects with establishment of new populated residential communities.

All the above-mentioned points indicate the importance of this study in terms of providing new and useful information needed for updating seismic risk assessment studies in the southern region of Saudi Arabia. In addition, this study drew our attention to increase the seismic monitoring stations around the sites of new seismic sources in the Kingdom, and to redistribute of seismic stations in some regions of the Kingdom.

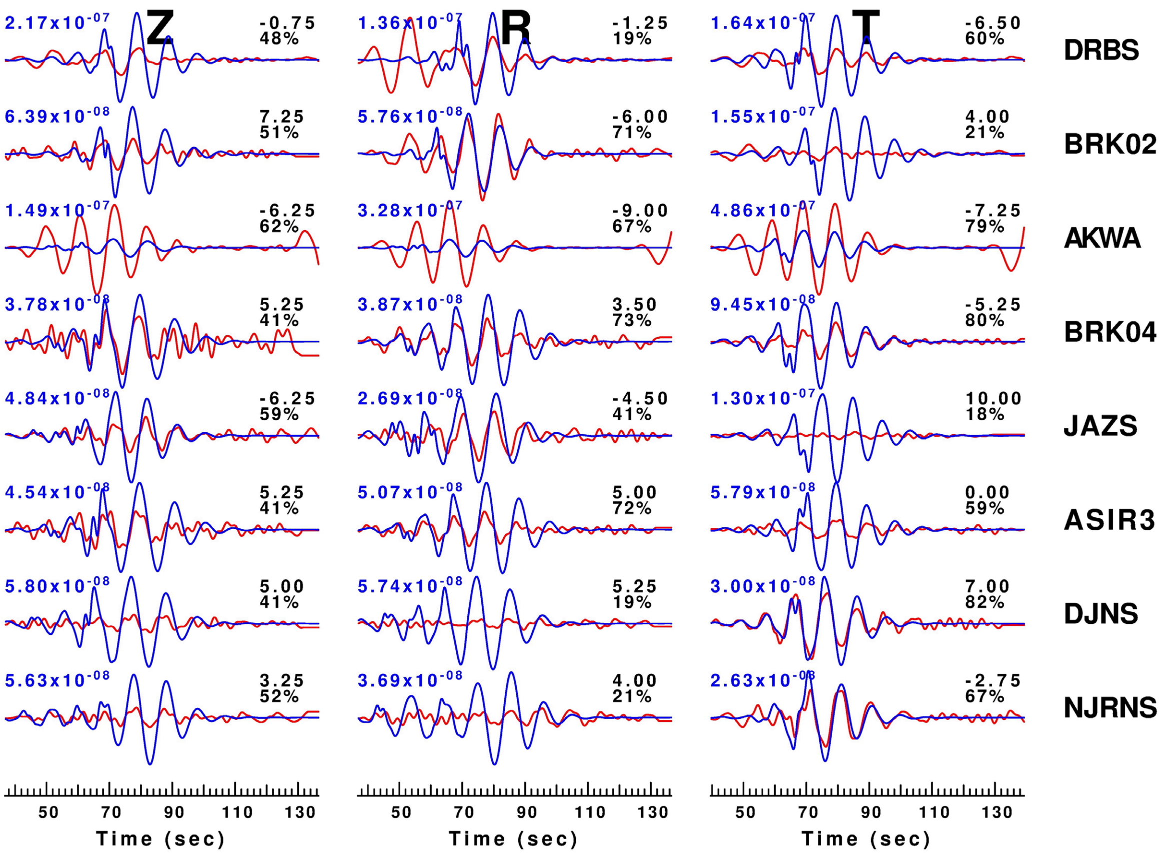

Figure 11. Inversion results for Al-Shuqiq event, a waveform fit, correlation between the observed and the synthetic seismograms.

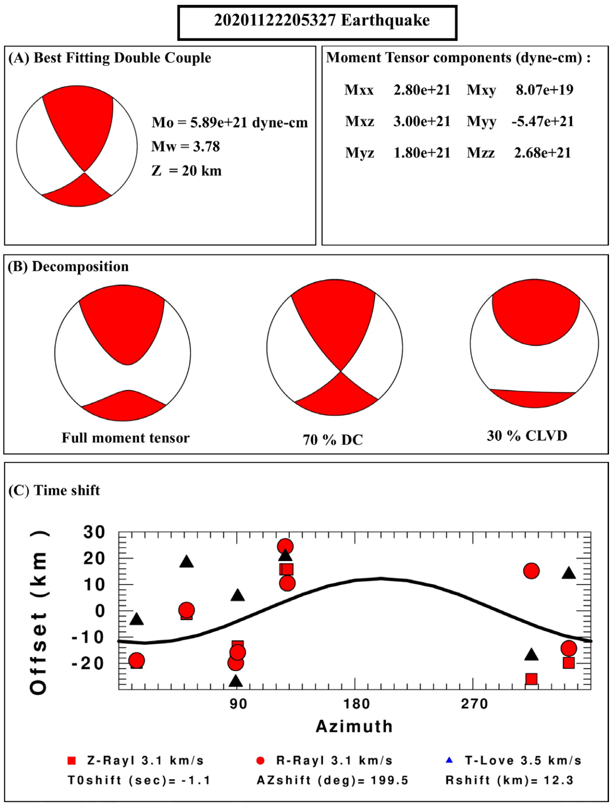

Figure 12. Result of Moment tensor inversion of Al-Shuqiq event, including moment tensor component, magnitude (Mw), source mechanisms, and CLVD ratio, in addition to origin time shift.

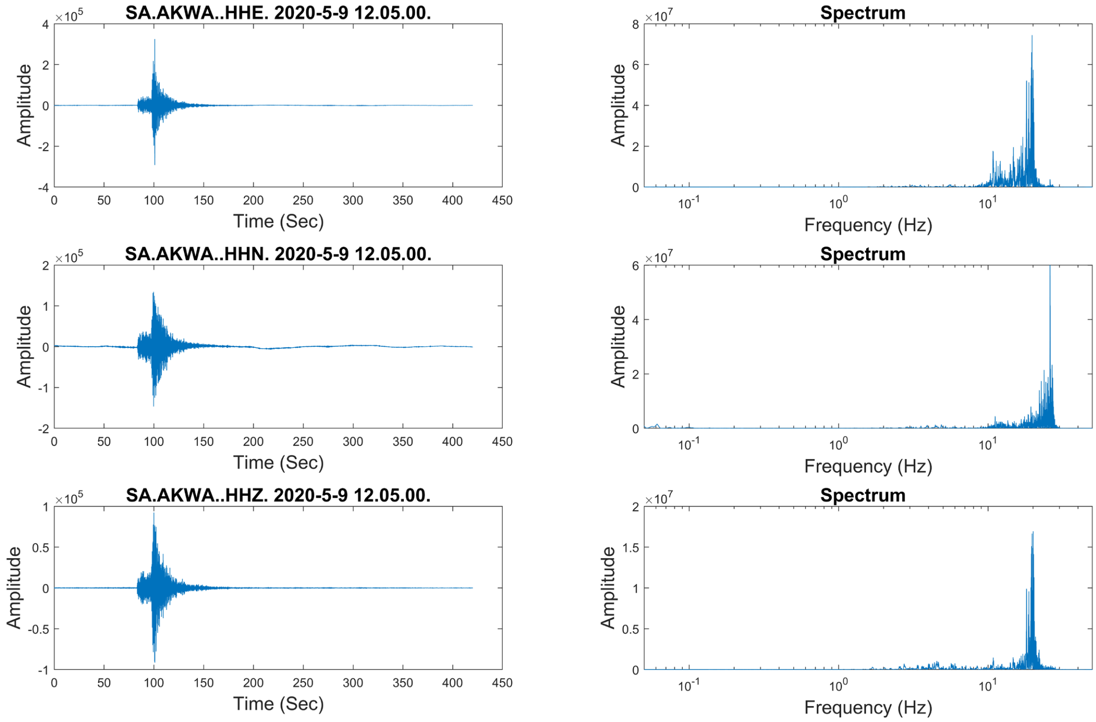

Figure 13. The frequency contents of one of the seismic monitoring stations, (AKWA station), as an example of stations recorded Khamis Mushait event, the frequency contents being higher than 10 Hz.

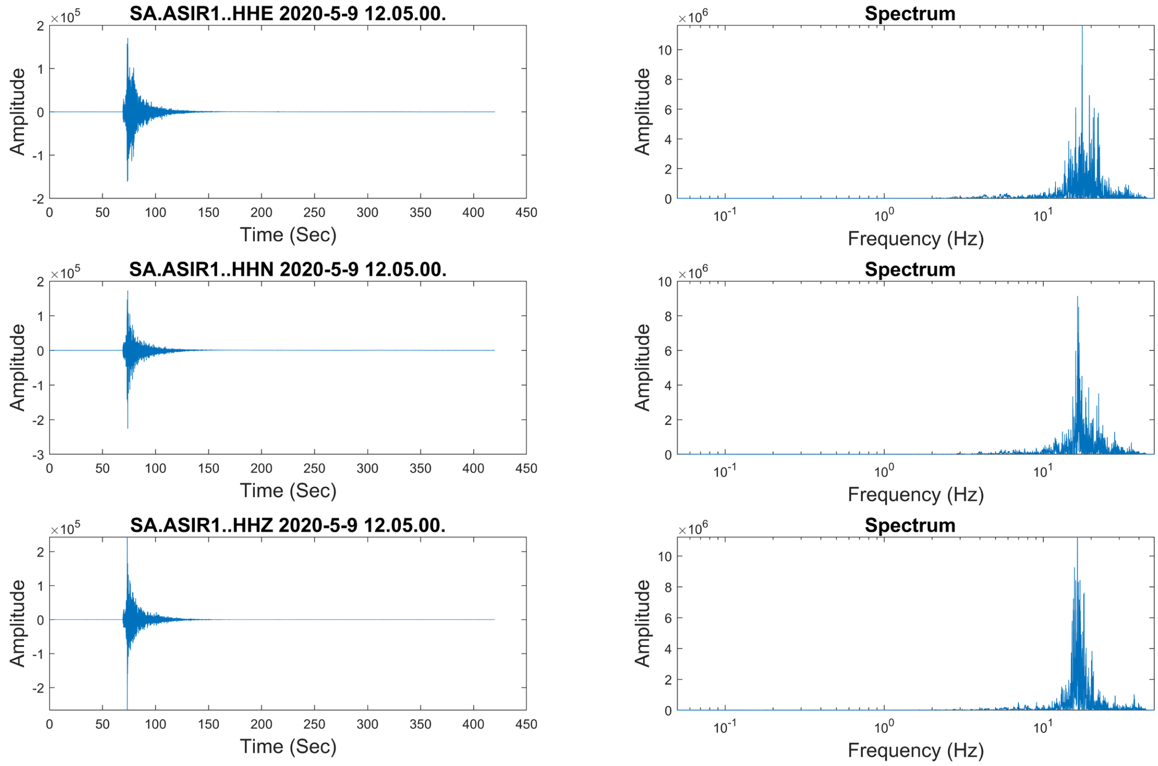

Figure 14. The frequency contents of another seismic station, (ASIR1 station), as an example of stations recorded Khamis Mushait event, the frequency contents being higher than 10 Hz.

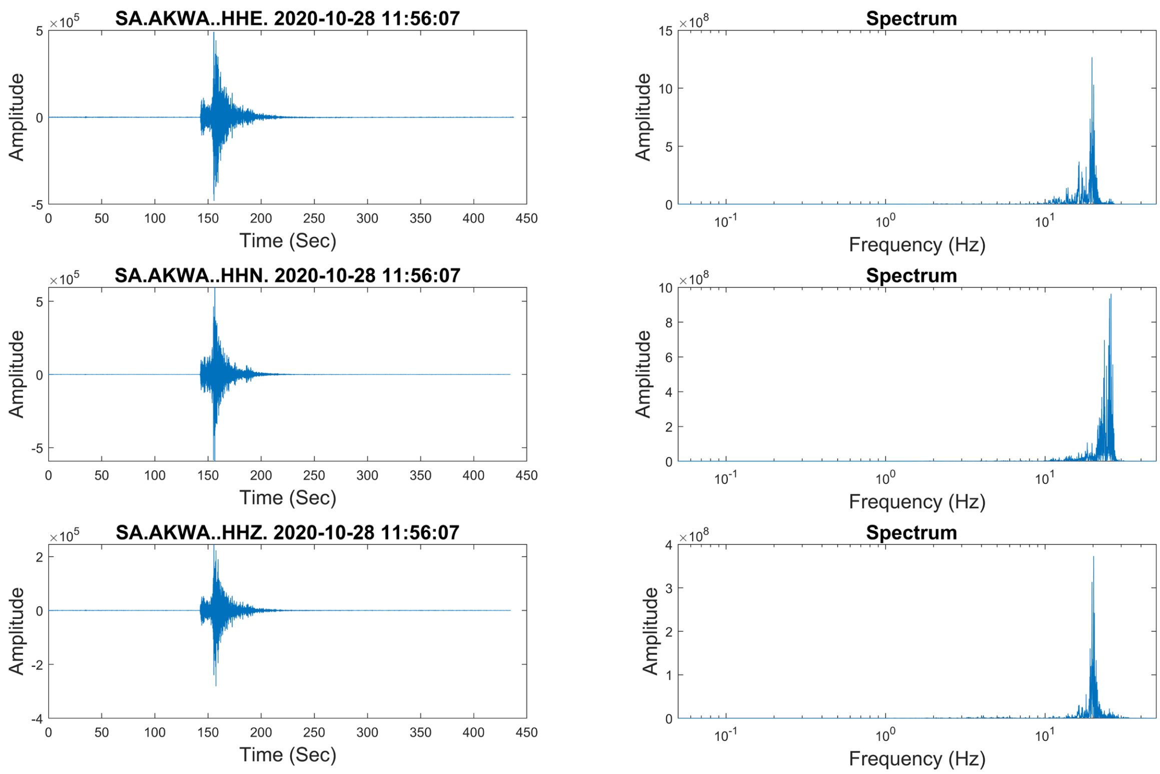

Figure 15. The frequency contents of one of the seismic monitoring stations, (AKWA station), as an example of stations recorded Ahad Rafidah event, the frequency contents being higher than 10 Hz.

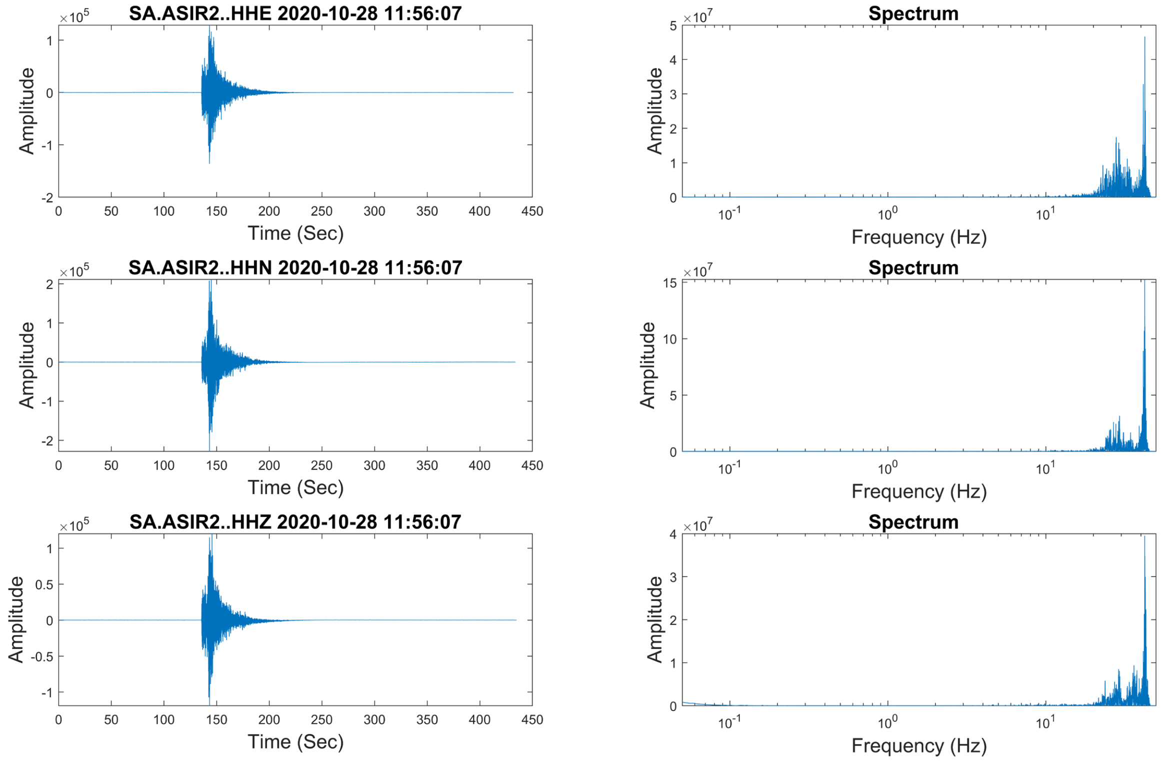

Figure 16. The frequency contents of another seismic station, (ASIR2 station), as an example of stations recorded Ahad Rafidah event, the frequency contents being higher than 10 Hz.

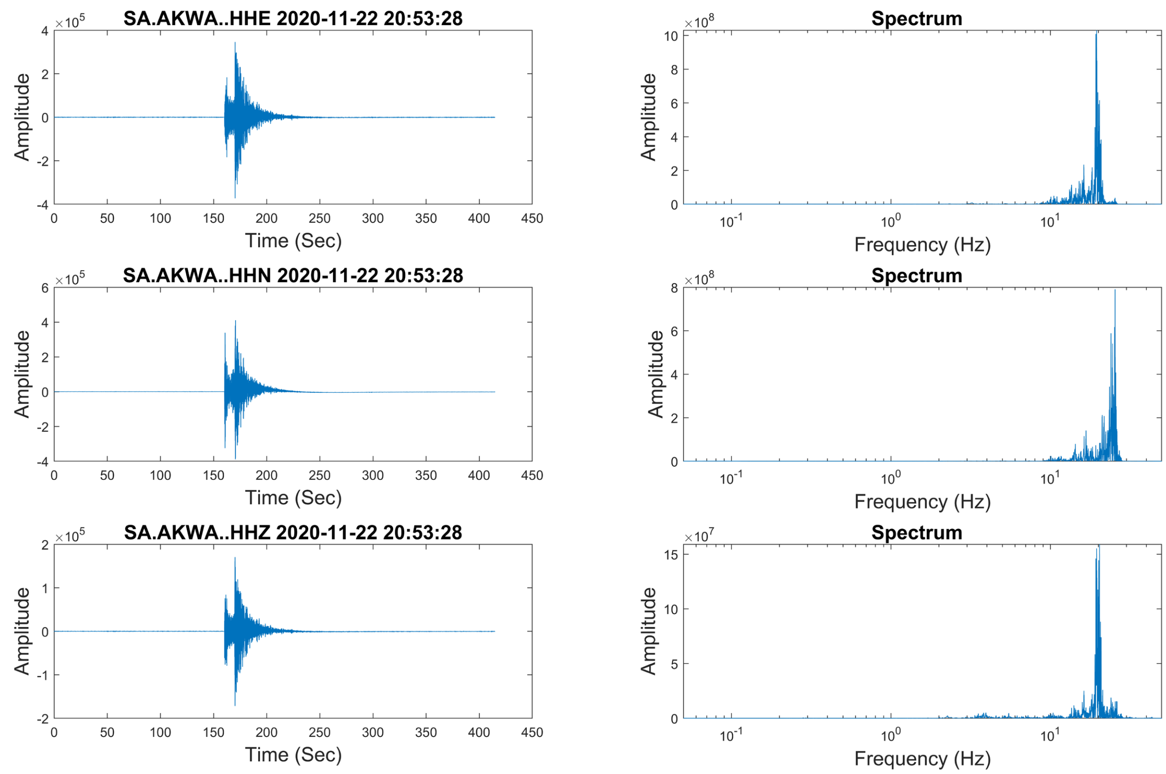

Figure 17. The frequency contents of one of the seismic monitoring stations, (AKWA station), as an example of stations recorded Al-Shuqiq event, the frequency contents being higher than 10 Hz.

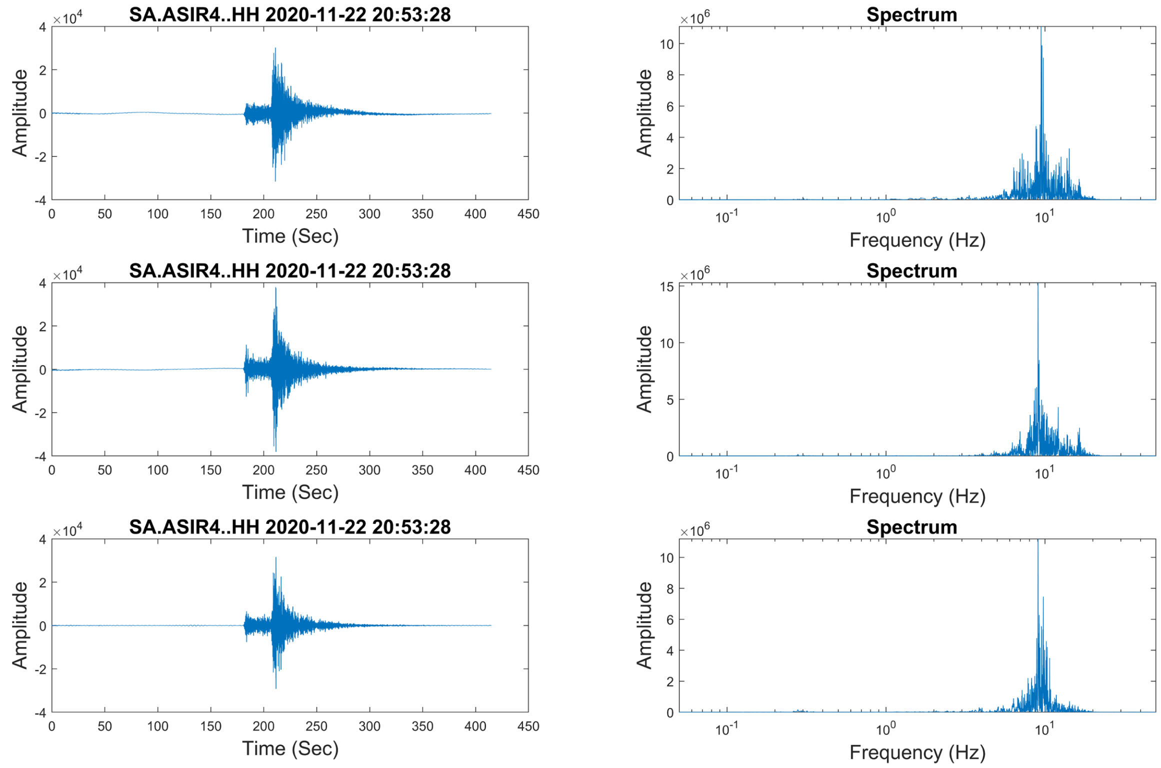

Figure 18. The frequency contents of another seismic station, (ASIR4 station), as an example of stations recorded Al-Shuqiq event, the frequency contents being higher than 10 Hz.

6. Conclusions

This study included the study of three earthquakes in the Asir region, south of Saudi Arabia, by determining the source mechanisms, seismic moment (moment magnitude), and CLVD ratio for each event. The aim was to identify to some extent the reasons of occurrence of these events. The obtained focal mechanisms represent different styles of faulting, normal movement with strike slip and strike slip with reverse. The results also concluded that there is a high percentage of CLVD ratio for the three events, which may be due to the noise in the data or non proper velocity model, or it may be the result of a tectonic phenomenon, a tensile movement affecting the region.

To identify the reasons behind the occurrence of these events in those areas, it was necessary to test the contents of the frequencies in the recordings of the stations monitoring these earthquakes, which indicated to higher frequency contents (more than 10 Hz). In addition, no occurrence of seismic activity in the form of seismic swarms, and no historical recording of volcanic activity in these areas of these events. Thus, we may conclude that these events occurred because of natural tectonic movement and not due to other reasons related to volcanic activity.

Many previous seismic hazard assessment studies have been conducted in the southern part of the Kingdom, but the locations of these recent seismic sources have not been taken in account in their calculations. Thus, our study provides additional new information related to detecting of new seismic sources in the south of the Kingdom, which contributes to updating studies of seismic risk assessment in this region.

When reconsidering the occurrence of these earthquakes in areas with no previous seismic activity, our attention may be directed to; 1) establishing of new seismic stations in those areas as a continuous monitoring; and 2) redistribution of some monitoring seismic stations in the Kingdom to cover areas with new seismic activity. Of course, all of this will contribute to reassessing the seismic risk in the Kingdom and then updating the Saudi Building Code to mitigate seismic risks.

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Article Highlights

New active seismic sources in southern Saudi Arabia.
Different Source mechanisms of recent earthquakes.
Updating the seismic hazard assessment in southern Saudi Arabia.
Contribution in updating the Saudi Building Code.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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