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Reactivation of Ramadi-Musaiyib Fault-Najd Faults System, Iraq

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Abstract
Nine earthquakes inside Mesopotamia Plain from 2016 to 2018 were analyzed. Three seismic networks have been relied on to relocate these events and know their responsible fault. These networks are; Mesopotamian Seismological Center, Al-Refaei Seismic Array and Iranian Seismological Center. The results showed that the root mean square (RMS) values for all relocated events ranged between 0.002-0.997. The results of the error ellipse ranged from 0.24 - 4.17 km with longitude and 0.76 - 8.24 km with latitude. The new locations of these events are on or near the Ramadi-Musaiyib Fault. This means that the Ramadi-Musaiyib Fault, which belongs to the Najd fault system, is currently in reactivation.

Keywords: Ramadi-Musaiyib Fault; Najd faults System; Reactivation, Relocated

اعادة تنشيط فالق الرمادي مسيب – نظام فوالق نجد، العراق

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الخلاصة
تم تحليل تسع هزات ارضية حدثت داخل سهل بلاد ما بين النهرين من العام [2016 إلى 2018]. تم الاعتماد على ثلاث شبكات رصد زلزالي لغرض اعادة تحديد مواقع هذه الهزات ومعرفة الفالق المسؤول عنها، هذه الشبكات هي مركز رصد الزلازل في بلاد ما بين النهرين ، شبكة الرفاعي الزلزالية والمركز الزلزالي الايراني. أظهرت النتائج أن قيم الخطأ الـ (RMS) لجميع الهزات الارضية التي تم اعادة تحديد مواقعها تراوحت بين 0.002–0.997. وتراوحت نتائج نسبة خطأ القطع الناقص من 0.24 – 4.17 كم مع خط الطول ومن 0.76 – 8.24 كم مع دائرة العرض. المواقع الجديدة لهذه الهزات الارضية تقع على أو بالقرب من فالق الرمادي – مسيب. وهذا يعني أن فالق الرمادي – مسيب والذي ينتمي إلى نظام فوالق نجد يمر بحالة إعادة تنشيط في الوقت الحالي.

1. Introduction

The Ramadi-Musaiyib Fault is one of the major faults in Iraq. It appears as a distinct feature on gravity gradient maps in the northwest-southeast direction. It starts from Rawah and Aana, specifically where the Euphrates River changes its course from east to southeast. It continues northeastward, passing through Rawa, Haditha, Fallujah, Mahmudiya, and Al-Hay. Between Baghdad and Al-Kut, this fault clearly controls the course of the Tigris River (Figure 1). The

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buried West Baghdad Structure is situated where the Ramadi-Musaiyib Fault is present, which is associated with elongated NW-SE buried anticlines in southern Iraq. The fault plays a crucial role in determining the location of the buried structure [1] [2] [3].

This fault belongs to the Najd Fault System. The Najd Fault System is an extensive set of northwest-southeast left-lateral strike-slip faults and flexible shear zones in the Precambrian basement rocks of the Arabian and Egypt. It formed between 540 and 620 million years ago [3]. The faults system is 400 km wide and over 2000 km long, with 1100 km of faults exposed at the surface. The Najd Faults System is considered one of the most considerable and best-exposed faults set before the Mesozoic era on Earth [4].

In Iraq, the Najd Fault System is of great importance. It represents the boundary of tectonic zones and the boundaries of the Pre-Cambrian terrains. The most effective way to identify these faults system is through gravity interpretation, although they may also be evident on the surface and detectable through satellite imagery. The sinistral transpressional shear zone that emerged during the Nabitah orogenesis gave rise to this system, which is particularly well-developed in the Arabian Shield, occurring in zones roughly 50 to 100 km apart.

Getech and Jassim [1] expanded the mapping of shear zones beyond the borders of the Arabian Shield, including some in Iraq. The displacement along certain Najd shears minimizes towards the northwest, primarily due to stress partitioning along some N-S oriented Nabitah shear zones [2]. Nehlig et al. [5] studied the development of the Najd system and mentioned it as around 670 million years ago; the Najd System emerged as a system of faults as a sinistral strike-slip. Also, being linked to extensive ductile deformation that led to the formation of gneiss domes. Subsequently, it transformed into an extensional system between 640 and 530 million years ago. According to Mogren [2], the Najd shearing can be attributed to the period between 680-640 million years ago, based on the age of dyke systems that may have been linked to the faulting. The NW-SE and NE-SW oriented extensional volcano-sedimentary basins are associated with the thinning of the crustal, caused by the dismantling of the Nabitah orogen [6]. Vertical displacement along the Najd Fault System occurred between the Jurassic and Quaternary periods. The most important longitudinal fault zones of the Najd Fault System in Iraq are Tar Al Jil Fault Zone; Euphrates Boundary Fault Zone; Ramadi-Musaiyib Fault Zone; Tikrit-Amara Fault Zone; Makhul-Hemrin Fault Zone, and Kirkuk Fault Zone. According to the structural division of the Mesopotamian plain that consists of the Tigris Subzone, Euphrates Subzone, and Zubair Subzone, the Ramadi-Musaiyib Fault significantly affects the anticlines in the Tigris Subzone. These anticlines lie on this fault and take an NW-SE trending.

According to the seismic activity of the Mesopotamian plain, this fault is responsible for some recent earthquakes that occur along or near it. Therefore, this study attempts to shed light on the reactivation of this fault. Jassim and Goff [3] indicated that the Ramadi-Musaiyib Fault was "probably" active during the Mio-Pliocene time.

2. Seismotectonic of Iraq

Iraq is located near a region of high seismic activity, with a complex seismotectonic setting influenced by the interaction of several tectonic plates. It is situated on the eastern boundary of the Arabian plate and the western boundary of the Eurasian plate, with the boundary between these two plates being the Zagros fold-thrust belt that extends from southeastern Turkey to the Persian Gulf [7].

The seismotectonic setting of Iraq is further complicated by the presence of several large active faults, including the North Arabian Fault Zone, the Zagros Thrust System, and the Bitlis-Zagros suture Zone [8]. The North Arabian Fault Zone runs from the Gulf of Aqaba in the south to the East Anatolian Fault Zone in Turkey, passing through Iraq and Syria. It is a left-lateral strike-slip fault system responsible for several large regional earthquakes [7].

The Zagros Thrust System is a major tectonic feature that runs through western Iran and eastern Iraq, extending for over 1,500 km. It is responsible for forming the Zagros Mountains and has been the source of many large regional earthquakes [9].

The Bitlis-Zagros suture zone is a major tectonic boundary separating the Arabian and Eurasian plates. It runs through southeastern Turkey and northern Iraq and is marked by thrust faults and folds. The zone has been the source of several large earthquakes in the past [10]. Given the high seismic activity in Iraq, there is a need for ongoing monitoring and research to understand the seismotectonic setting of the region better and to improve earthquake hazard assessments. This includes efforts to map and characterize active faults, study earthquake recurrence patterns, and assess seismic hazards.

Tectonically, Iraq is comprised of two primary tectonic regions: the inner and outer Arabian platforms. The boundary between these regions is marked by the Anah Graben fault in the west and the Abu Jir-Euphrates active fault zone in the southwest.

The unstable outer platform includes the Zagros fold-thrust belt and the Mesopotamia foredeep. It features surface folds at the Zagros fold-thrust belt and subsurface folds at the Mesopotamia foredeep (Figure 1). In contrast, the inner platform is stable and encompasses the western desert of Iraq, which forms part of the Arabian platform and lacks anticlines [11] [12] [8].

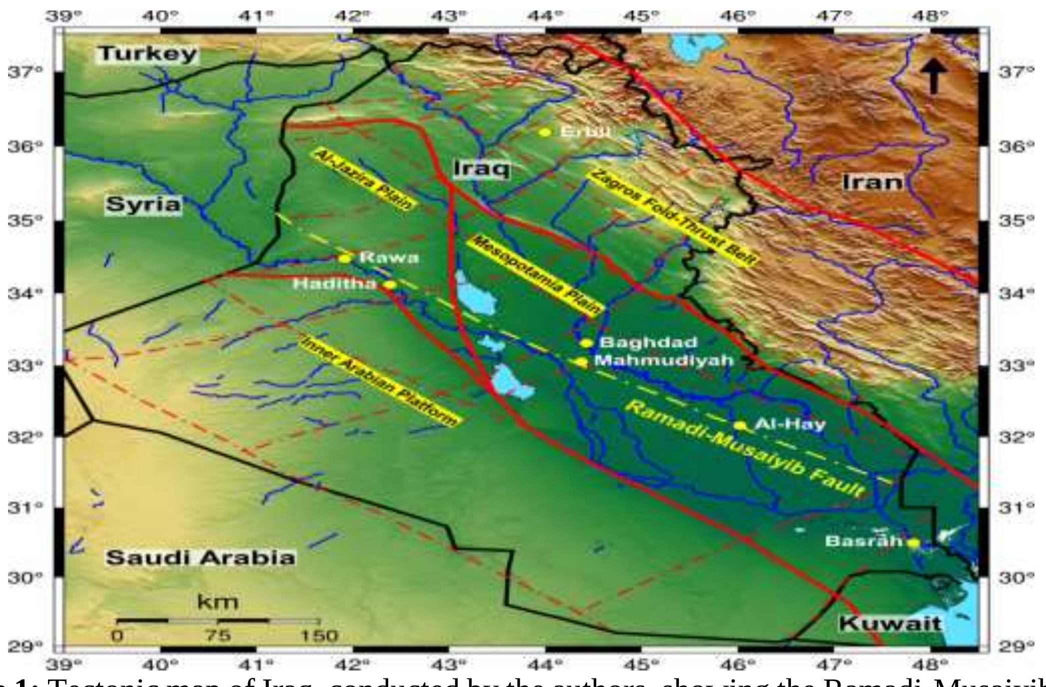

Figure 1: Tectonic map of Iraq, conducted by the authors, showing the Ramadi-Musaiyib Fault in a yellow dashed line. The thick red lines represent the tectonic division of Iraq, according to Fouad [11]. The red dashed lines represent the Najd Faults System in Iraq, according to Jassim and Goff [3]

3. Source Data and Methods

The raw data were obtained from three networks; the Mesopotamian Seismological Center in Iraq, established in 2014. It is a network of broadband seismic stations with about +10 seismic stations distributed across Iraq. The Seismological Laboratory manages these stations at the University of Basrah. The second network is the Al-Refaei Seismic Array, which is a local network consisting of seven-element high-frequency seismic stations installed from 2014 to 2018 to monitor the active faults in the Al-Refaei area - Mesopotamian plain, which the University of Sumer managed. The third network is the Iranian Seismological Center which consists of more than 30 broadband seismic stations; the University of Tehran manages this network (Fig.2). The data was in SAC format, and the relocation of the recorded events was calculated using Geiger's method within the CPS package for Herrmann and Ammon [13]. The Generic Mapping Tools (GMT) (version 6.0) packages for Wessel et al. [14] were used to draw the maps in this study.

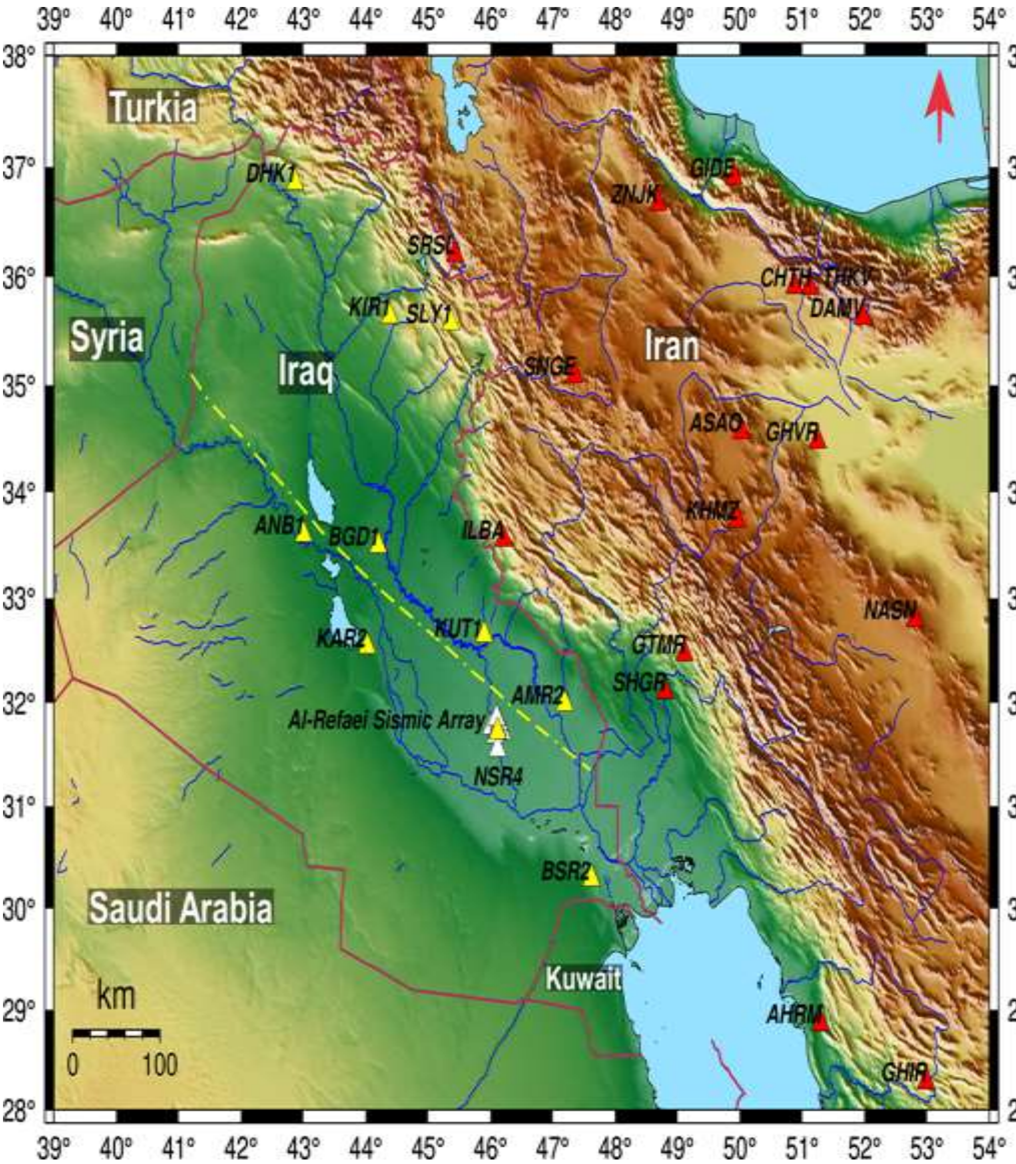

Figure 2: GMT map, conducted by the authors, shows the locations of the stations that were used in this study. The red triangles are the stations of the Iranian Seismological Center, the white triangles are the stations of the Al-Refaei Seismic Array, and the yellow triangles are the stations of the Mesopotamian Seismological Center

4. Results and Discussion

4.1 Relocation Events

Nine earthquakes recorded within the networks were examined. These events fall within the study area, with at least five records of each event, and their location has been relocated. Four of these events are not recorded in any seismic agencies; they were discovered during the analysis and recorded in the network of the Mesopotamian Seismological Center and Al-Refaei Seismic Array. The other five events were recorded and taken from the Iranian Seismological Center. The elocate program and al- Refaei velocity model (REF1) were used to determine the final locations. The process involved initial depth probabilities of 5, 10, 15, 20, and 25km to obtain the most precise origin time, depth, and coordinates of the earthquakes. In many cases, there is an inaccuracy in the estimation location of earthquakes, especially if the stations are far away, in addition to the chosen velocity model. In this study, to accurately calculate the area of earthquakes, the al-Refaei velocity model was used (Table 1). REF1 velocity model was produced by Ramthan [15]. It was derived from the receiver function and ambient seismic noise of three seismic stations: NSR1, NSR2 and NSR3. All these stations are located in the study area. This model gave us a small root-mean-square (RMS) travel time residual compared with other models such as Mesopotamia (MESO) for Mooney et al. [16] or Kuwait (KUW) for Pasyanos et al. [17] and others that are used to calculate the location of earthquakes. Choosing a velocity model expressive of the study area is considered the main step in obtaining the exact locations of earthquakes. It gives an idea of the sedimentary thicknesses and identifies the area's main discontinuities and dynamic processes.

Table 1: Al-Refaei velocity model (REF1) that was used in this study [15]

Layer	Depth (km)	P-wave velocity (km/s)	S-wave velocity (km/s)	Density (gm/cm3)
Sediment 1	0.0 – 4.0	4.38	2.44	2.38
Sediment 2	4.0 - 12	5.69	3.17	2.63
Continental crust	12 - 46	6.93	3.87	3.05
Moho discontinuity	46	8.03	4.48	3.32

The elocate program within the Computer Programs in Seismology (CPS) package for Herrmann and Ammon [13] is based on Geiger’s method. The Geiger's method is employed to identify the hypocenter of an earthquake. Estimating the distance between the seismic station and the earthquake's hypocenter depends on the difference in the arrival times of P and S waves. The method can be summarized in five steps. Firstly, record the P-wave and S-wave arrival times at least three seismic stations.

Location accuracy improves as the number of stations increases. Secondly, determine the difference in arrival times for P-waves and S-waves at every station. Utilize these differences to approximate the distance between the hypocenter and each particular station. In the third step, the distance approximations and the seismic station coordinates are used to triangulate the earthquake hypocenter's location. This process often involves "spherical triangulation," as the Earth's surface is curved. Fourthly, the initial estimate of the hypocenter might be imprecise due to several factors, including the Earth structure and fluctuating seismic wave velocities. Geiger's method used an iterative approach to refine the hypocenter estimation by reducing the difference between the observed and the predicted arrival times based on the current hypocenter estimate. This is accomplished by using an algorithm known as the least-squares method. Lastly, refine the hypocenter estimate until the difference between the observed and predicted arrival times is reduced below a pre-established threshold. The final hypocenter estimate is considered to be the best approximation of the earthquake's true origin. All these steps performed by the CPS algorithms.

The results showed that all events' root mean square (RMS) values ranged from 0.002-0.997 (Table 2). This small value is due to the majority of stations used and the chosen velocity model. Seven new locations lie directly on the Ramadi-Musaiyib Fault; two are close to it (Figure 3). All focal depths of events are within the basement rocks (more than 10 km) except two events with a depth of less than 7 km. Figure 4 depicts an example of the earthquake's seismic waveform that happened on January 15th, 2018.

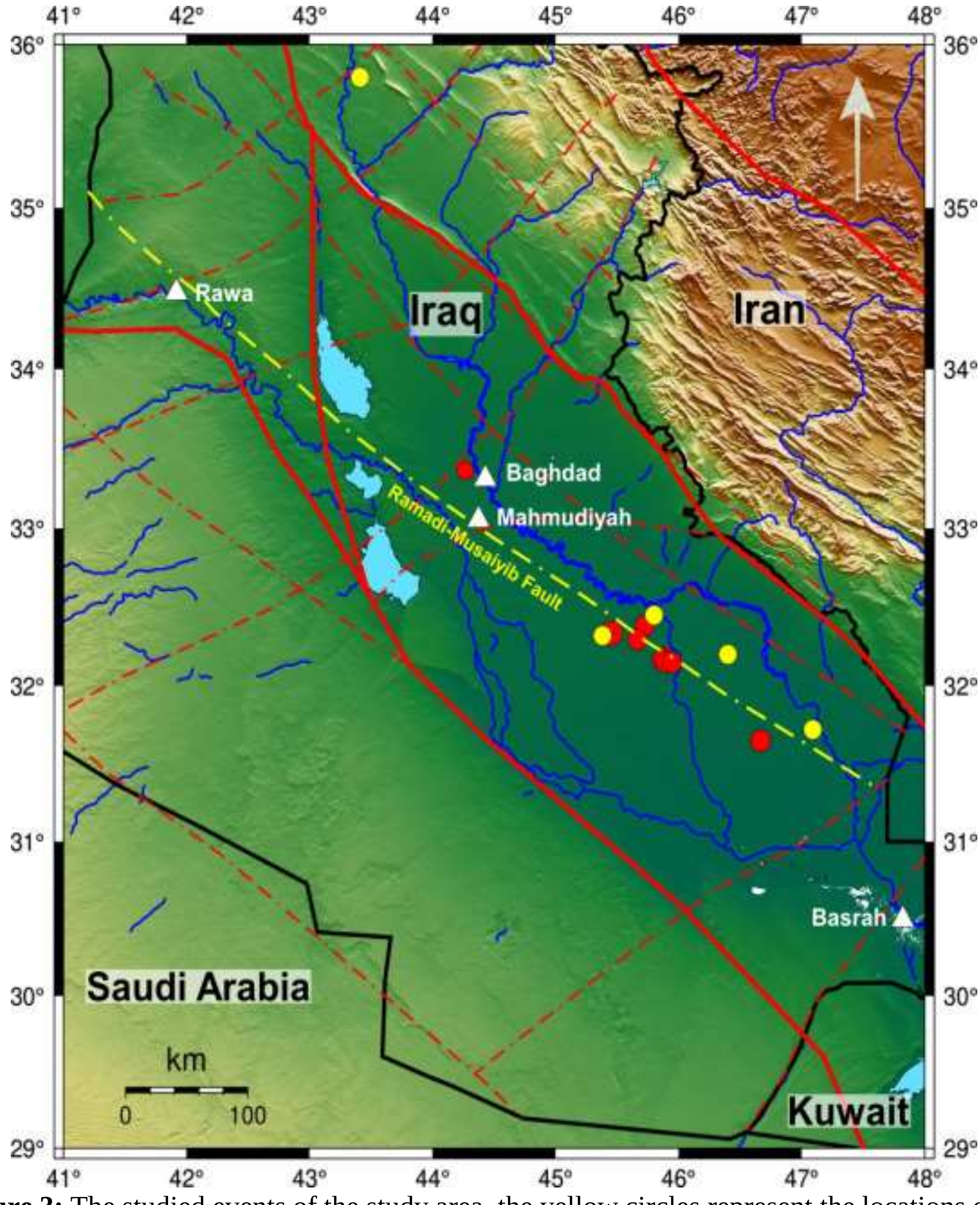

Figure 3: The studied events of the study area, the yellow circles represent the locations of the earthquakes recorded by the Iranian Seismological Center (the old locations), while the red circles represent the new location of the relocated earthquakes

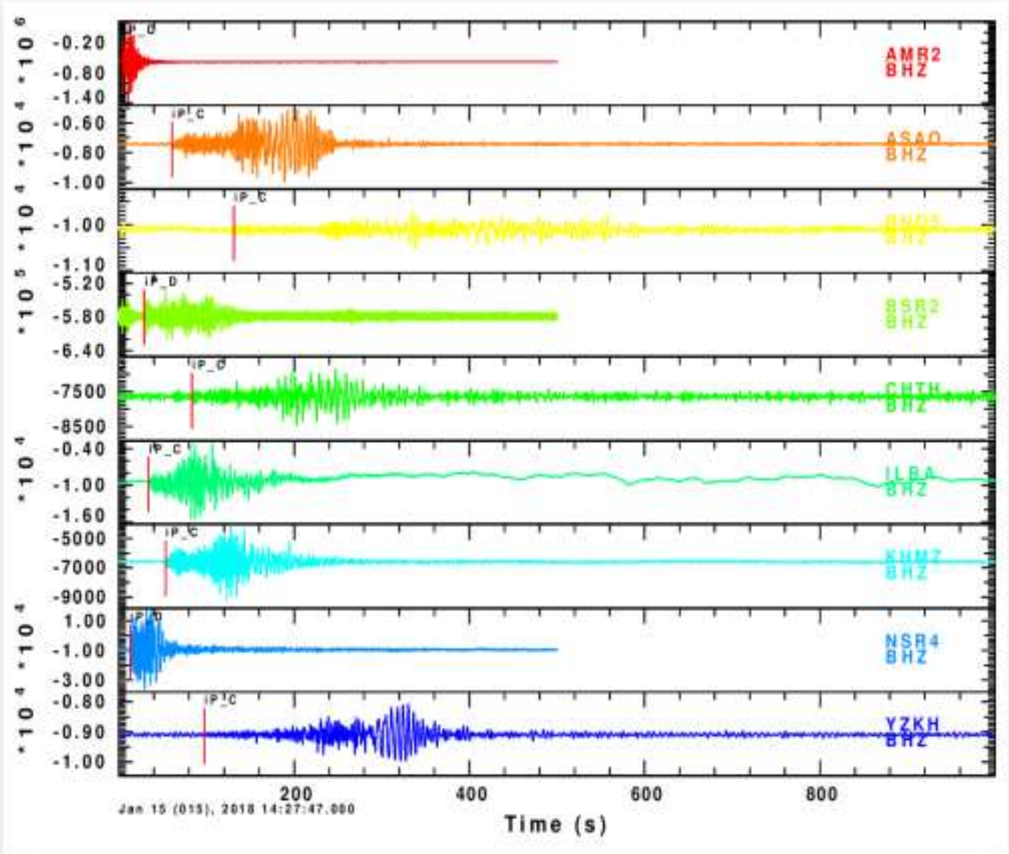

Figure 4: An example of the seismic waveform of the earthquake that happened on January 15, 2018 at 14:27:44:403 (event No.7 in Table 2)

4.2 Location Uncertainty

Table 2. Shows the results of the error ellipse of the events that were relocated in this study. Linearized location algorithms, such as HypoEllipse, Hypo71, and HypoInverse, employ diverse statistical measures and levels of confidence to calculate regions of confidence or uncertainties in location [18]. The joint hypocentral confidence region is used as a basis to determine the confidence regions for the epicenter and depth in HypoEllipse. This involves projecting the error ellipsoid for the joint hypocenter onto the corresponding regions and adjusting the major axis by scaling it with the appropriate ratios of the X2 value for varying degrees of freedom [19]. As a consequence of this method, the resulting confidence levels are greater than the 68% joint hypocentral confidence region, which Boyd and Snoke established in 1984 [20]. In Hypo71, the error in the epicenter is determined using the square root of the sum of the estimated variances for latitude and longitude [21]. Meanwhile, the horizontal and vertical errors are simplified representations of errors projected onto the corresponding axis based on the lengths and directions of the principal axes of the error ellipsoid [22]. These three algorithms also permit the adjustment of the size of the determined location uncertainties through the final data fit.

Based on this, Table 2 and Figure 3 display the error ellipse results of all relocated events. The value of the error ellipse with the X-axis (longitude) ranges from 0.24-4.17 km; along the Y-axis (latitude), it ranges from 0.76-8.24 km. This means that any area within the error ellipse is a potential location for the earthquake epicenter (Figure 4). All new locations are located exactly within the fault. Thus the results confirm that the Ramadi-Musaiyib Fault is the proposed fault for this activity.

Table 2: Source parameters of the earthquakes that were analyzed in this study

No	Date	Time	Lat.	Long.	Depth	RMS	Error Ellipse		
							X	Y	Theta
1	16/02/2016	09:16:30:257	32.1793	45.8817	24.05	0.011	0.7393	1.5921	329.4073
2	19/02/2016	17:08:52:921	32.1687	45.8630	18.72	0.033	1.2512	2.2641	325.8169
3	19/02/2016	17:11:04:589	32.1520	45.8872	25.78	0.015	0.9030	1.4769	328.9507
4	19/02/2016	21:17:57:182	32.1510	45.9442	24.60	0.082	0.8966	1.1954	354.0449
5	03/12/2016	15:57:52:395	32.3352	45.4511	18.43	0.171	4.1741	8.2482	075.5220
6	17/05/2017	03:07:45:354	32.3819	45.7251	13.91	0.002	0.3275	1.0160	324.6019
7	15/01/2018	14:27:44:403	31.6491	46.6668	07.61	0.997	3.1998	5.8021	069.9187
8	23/06/2018	00:04:54:719	32.2956	45.6641	5.40	0.017	0.2499	0.7625	297.7408
9	10/07/2019	10:56:20:126	33.3636	44.2662	13.80	0.071	0.5487	1.1072	011.1655

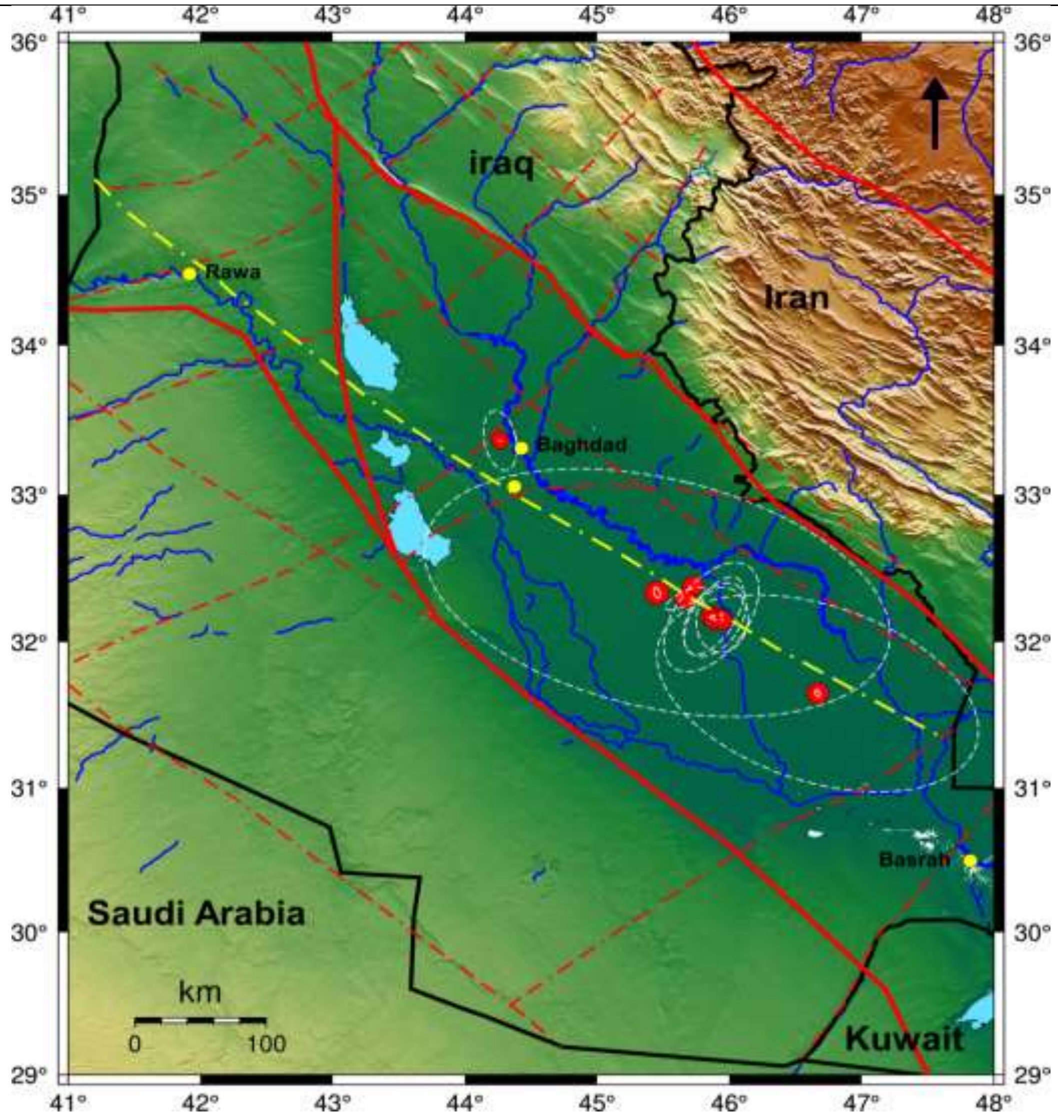

Figure 4: Location and uncertainty for the relocated events. The error ellipse in the azimuth from the x and y axis is shown in white dashed circles around each event.

5. Conclusions

The use of many seismic stations helps to improve the earthquake sites. Nine earthquakes that occurred inside Mesopotamia Plain from the years [2016 to 2018] were analyzed. Three seismic networks have been relied on to relocate these events and know the fault responsible for them. At least six stations per event were used. The new locations of these events are located on or near the Ramadi-Musaiyib Fault. This means that Ramadi-Musaiyib Fault, belonging to the Najd fault system, is currently in a state of reactivation. This system was mainly active during the Mio-Pliocene time. The results showed that all events' root mean square (RMS) values ranged from 0.002-0.997. This small value is due to most stations used and the chosen velocity model. The Al-Refaei velocity model (REF1) was used in this study to relocate the locations of earthquakes. This model is derived mainly from the seismological data of stations located inside Mesopotamia Plain, which gives reassurance to the speed of the P-S recorded seismic waves.

The error ellipses have been calculated to verify the new locations and know the possibility of error. The results of the error ellipse ranged from 0.24 - 4.17 km with longitude and from 0.76 - 8.24 km with latitude, confirming the new locations' accuracy. It can be said that the possibility of changing the location of any earthquake is not less than 8 km around it. This means that every place within the error ellipse is possible for the earthquake. All these places are located within the Ramadi-Musaiyib Fault.

6. Acknowledgements

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