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The Cause of the Earthquake (4.7 mb) and Recent Stress Regime Occurring in Al-Refaei Area, Mesopotamian plain, August 18th, 2017

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Abstract

Al-Refaei area is considered one of the highest seismically activity in the Mesopotamian Plain according to its seismic history. Depending on the International seismological Center, four seismic swarms were diagnosed in this area; these are: August 2004, January 2013, May-Jun 2017, and August 2017. Based on three focal mechanism solutions of magnitude greater than 4 mb, the stresses in the area were analysed. The results of focal mechanisms suggest that the faults movements in the study area show reverse movements, which is generated by compression force. To determine the directions of principal stress axes that affecting the faults in the area, the Rotational Optimization method were used. The directions of the three stress axes are: 02°/32°, 10°/302°, and 80°/136° for σ1, σ2, and σ3, respectively. The collision between the Arabian and Iranian plates is the main cause of seismic activity in Al-Refaei area. Therefore, Al-Refaei active fault is responsible for most the earthquakes in the area, and responsible for the earthquake that occurred in August 18th, 2017.

Keywords: Al-Refaei active fault; Stress analysis; Seismicity of Al-Refari area; Al-Nasiriya; Iraq

1. Introduction

Al-Refaei area, located in southern Iraq, about 300 km south of the capital, Baghdad, has experienced seismic earthquakes in the past. The most significant earthquake to date occurred on August 18th, 2017, with a magnitude of 4.7 mb (body wave magnitude), resulting in damage to structures that were not sufficiently sturdy. This could be the largest earthquake that has been documented in this area so far. Al-Refaei area is situated within the unstable outer platform of the Arabian plate as shown in Fig. 1, which is positioned between latitudes 31° 30' N - 32° 06' N and longitudes 45° 30' E - 46° 30' E.

In general, the Arabian plate includes two parts, the outer and inner platform. According to Fouad (2010) and Abdulnaby (2019), the outer platform in Iraq divides tectonically into Mesopotamia foredeep and Zagros fold-thrust belt. The Mesopotamia foredeep is subdivided to Al-Jazira plain and Mesopotamian Plain. All parts of the outer platform are unstable. The Mesopotamian Plain, which include the study area, was formed in the Mid-Late Triassic period and is considered a highly restricted rift. This plain is bounded by faults systems on all sides. The Abu Jir-Euphrates Active Fault Zone is bounded on the west and north approx (Deikran and Sissakian, 2009). The east side is bounded by the Zagros Foredeep Fault (ZFF). As for the south boundary of the Mesopotamian Plain, according to Aqrawi et al. (2010) is ending either at the transversal fault or at the Al Batin fault in Kuwait. Sissakian et al. (2017) broadened the boundary of the Mesopotamian Plain to the Arabian Gulf up to the Qatar country.

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The plain is flat and slope slightly towards the Arabian Gulf in the south. It contains faults, folds, and salt structures buried under the surface by the Quaternary sediments. Most of the folds are oil reservoirs concentrated in the south, southeast and scattered areas in the center and north (Karim, 1993; Aqrawi et al., 2010). In the central and eastern parts of the Mesopotamian Plain, these folds take a northwestward trend, aligning with the orientation of the Zagros fold-thrust belt (Abdulnaby, 2019).

The Mesopotamia plain contains faults systems in all its parts and in different directions. The most directions are NE-SW follows the directions of the Najd Faults Systems, and NW-SE, aligning with the Zagros trend (Abdulnaby, 2019). The Plain currently in an uplifting and compression phase. This results from the Arabian Plate moving and collision with the Iranian micro-plate (Buday and Jassim, 1987). The Mesopotamian Plain has neotectonic movements represented by the change of rivers course, active and inactive alluvial fans, deserted river channels and others (Fouad and Sisakian, 2011). The aim of this study is to highlight the seismic history of Al-Refaei area located in the center of Mesopotamia plain, by using seismological catalog. Additionally, deriving the stress regime of principal stress axes from the focal mechanism solutions for most important events in the area.

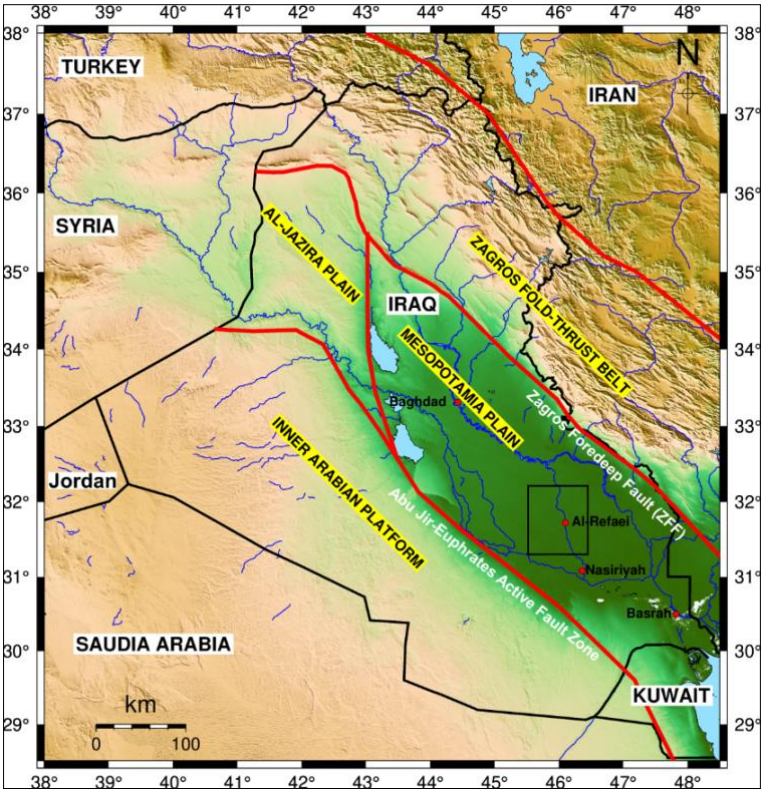


Fig. 1. Tectonic map of Iraq displaying the location of study area in black rectangle. The boundary of tectonic divisions show in thick red line according to Fouad (2010).

2. Data and Methods

Earthquake parameters and focal mechanisms solutions were collected from the international seismological center (ISC). A catalog of the study area has been prepared, and the recorded events are examined and analysis to identify seismic swarms.

The Win-Tensor software were used to analyze the stresses in the region. Win-Tensor software takes input data in the form of focal mechanisms or moment tensors, which are derived from seismic waveforms recorded during earthquakes. These data are used to represent the nature of faulting that occurred during the event, such as strike, dip, and rake of the fault plane (Delvaux and Sperner, 2003). The program employs inversion techniques to calculate the regional stress tensor, which provides

information about the orientations of the main stress axes (σ1, σ2, and σ3) as well as the corresponding stress magnitudes. This information is crucial for understanding the stress state in a specific region and assessing the potential for future seismic activity. Faults were collected from previous studies and mapped with the locations of the events to know the seismic zones. The maps were generated using GMT software, version 6, as detailed by Wessel et al. (2019).

3.Results and Discussion

3.1. Seismic History

Al-Refaei area, located in the Mesopotamian Plain, has experienced a considerable of seismic activity in recent decades. A comprehensive catalog of International Seismological Center (ISC) offers crucial insights of seismic history about this area. The seismic history of the area latitude from 31^0 to 32^0N and longitude from 45˚ to 47˚ E, spanning three decades from 1995 to 2022, documents 177 earthquakes in Al-Refaei and its surrounding areas (Fig. 2). The range of magnitudes is 1.5 ML to 4.7 mb, and the focal depths are shallow as ≤ 30 km. The most significant earthquake documented in the catalog of ISC occurred in August 18th, 2017, registering a magnitude of 4.7 mb. Although it was not considered a devastating earthquake, but this event was surprising to people. This seismic activity may be attributed to localize stress accumulation or the presence of active faults in the region. Alsinawi (in Jassim and Goff, 2006) indicated that the seismic history of the Mesopotamian Plain demonstrates consistent dynamic movements, characterized by low to moderate earthquakes occurring annually. Al-Sakini (1995) identifies a combination of factors responsible for these movements within the plain. These contributing factors include deep faults, continuous alpine tectonic processes, and the presence of thick salt beds, such as the Hormuz salt basin (Abdulnaby, 2019).

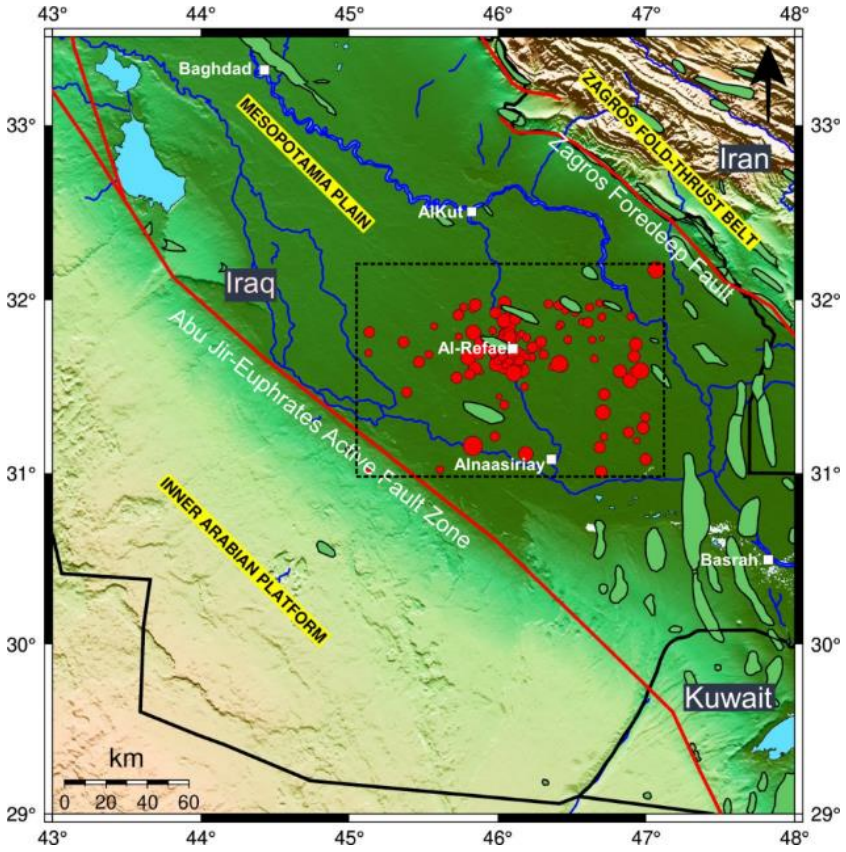
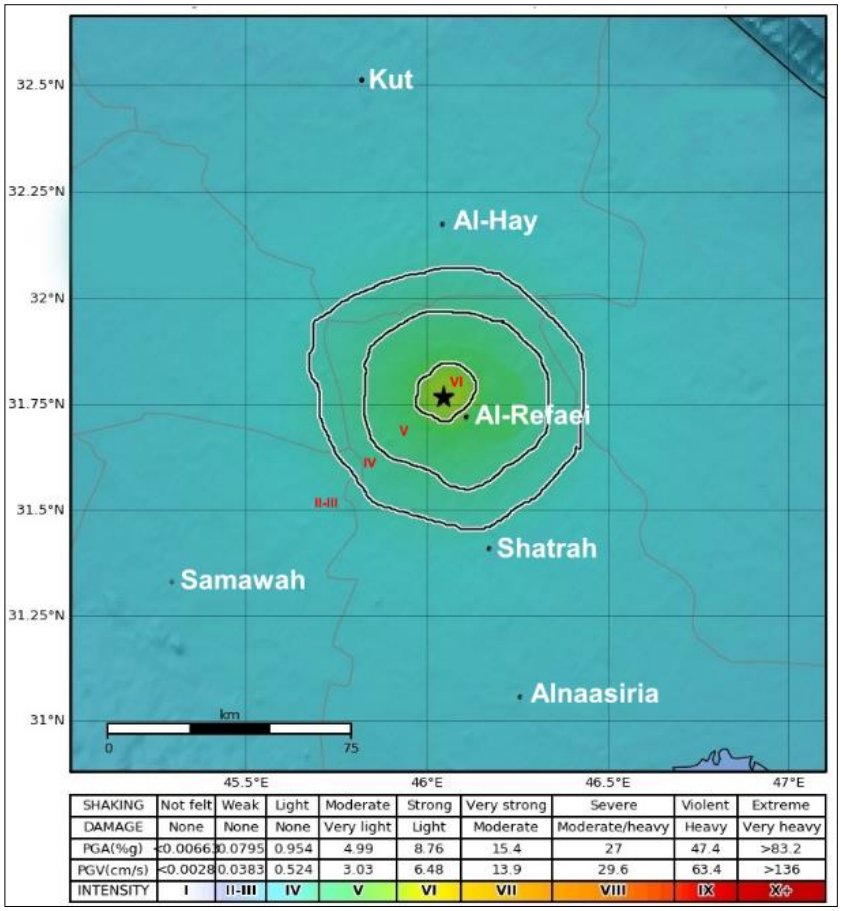


Fig. 2. Seismicity of Al-Refaei and adjacent area based on the International Seismological Center (IRC), catalog from 1995 - 2022 years. The red circles represent the locations of the earthquakes.

On August 18, 2017, at 10:18:43 UTC, Al-Refaei area, north of the Nasiriyah City, was hit by one of the largest earthquakes in its history. The earthquakes lasted about 5 seconds were recorded by all international agencies. The United States Geological Survey (USGS) shake map shows that the Al-Refaei earthquake caused a strong shaking of the earth. The intensity ranging from I and VI according to the scale Mercalli (Fig. 3). The Euro-Mediterranean Seismological Centre (EMSC), United States Geological Survey (USGS), and Iranian Seismological Center (IRSC) recorded the magnitude of the earthquake 4.7, at a depth of 10 km. The epicenter of the earthquake is located in the Al-Gharraf oil field, northeast of the Al-Refaei city. The damage caused by the earthquake was moderate to some weak buildings.



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0066	0.0795	0.954	4.99	8.76	15.4	27	47.4	>83.2
PGV(cm/s)	<0.0028	0.0383	0.524	3.03	6.48	13.9	29.6	63.4	>136
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 3. Shake map of 18th August 2017 earthquake of Al-Refaei area generated by United States Geological Survey (USGS).

To properly examine the seismic history of the study area, it is crucial to identify instances of earthquake swarms. A swarm is characterized as a sequence of seismic events that are interconnected in terms of time and location, occurring within a defined geographic region over a specific time period. Such a sequence generally includes a primary event known as the main shock, which is preceded by smaller events called foreshocks, and followed by a series of subsequent events referred to as aftershocks. Swarms can continue for varying durations, ranging from days to months or even years (Mogi, 1963; Michael and Toksoz, 1982; Jakoubková, 2018).

After carefully examining the seismic history of Al-Refaei, it can be able to identify four swarms. Although there are a large number of events in the record, it is difficult to classify them as a swarm due to the long time periods and the inability to relocate them. The four swarms belong to the period from 2004 to 2017 and are shown in Tables 1, 2 and Fig. 4. The first swarm lasts for only six days, from 05-08 to 30-08-2004, with the mainshock occurring on the third day and having a magnitude of 4.5 mb.

Table 1. The results of the statistical descriptions of the swarms of Al-Refeai area from 2004-2017

Swarm		No. of foreshocks	No. of aftershocks	No. of days
August	2004	2	5	6
January	2013	3	3	4
May-June	2017	12	8	8
August	2017	6	17	6

Table 2. Mainshocks of four swarms at Al-Refeai area during years 2004-2017 which have taken from International Seismological center

Date	Origin Time (UTC)	Lat.	Long.	Depth (km)	Magnitude
05/08/2004	20:41:48	31.6216	46.0461	42.4	4.5 mb
20/01/2013	17:12:32	31.6477	46.0466	10	4.0 mb
02/06/2017	16:09:53	31.5783	46.1086	0.7	4.4 mb
18/08/2017	10:18:43	31.6820	46.1253	12.6	4.7 mb

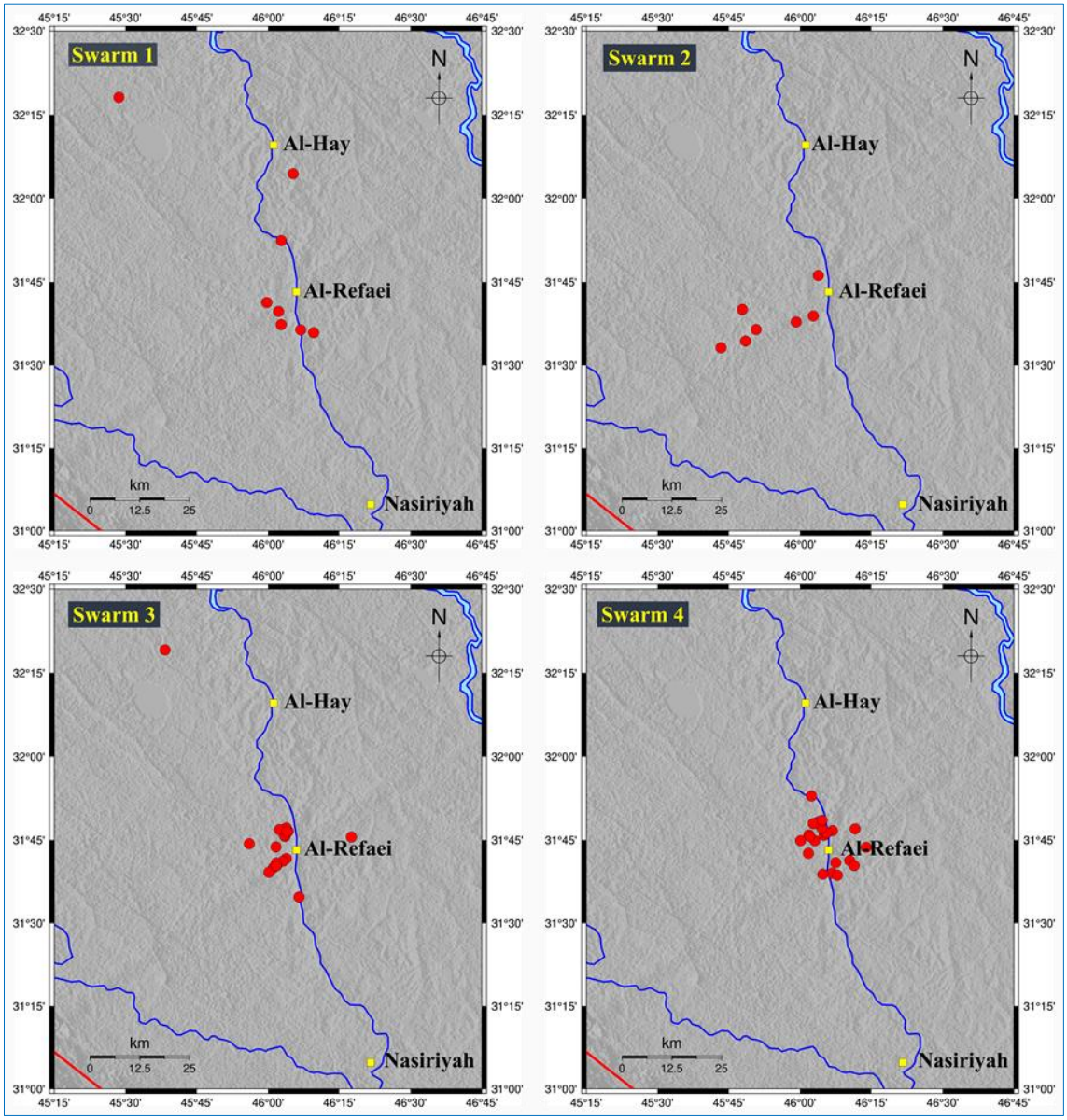


Fig. 4. Swarms of Al-Refaei area that belong to the period from 2004 to 2017

The second swarm lasted four days, started 19-01 to 24-01-2013, with the mainshock happening on the fourth day and registering a magnitude of 4.0 mb. The third swarm comprises eight days, from 17-05 to 09-06-2017, and the mainshock takes place on the fifth day with a magnitude of 4.4 mb. The fourth swarm continues for six days, from 10-08-2017 to 18-08-2017, with its mainshock measuring a magnitude of 4.6 mb.

3.2. Faults

To create a map of the existing faults, all geophysical studies related to the study area and its surroundings were collected. Fig. 5 illustrates the faults in the study area, which features numerous faults of varying lengths and trends. The main faults in Iraq represent by the dashed red lines according to Jassim and Göff (2006). The Najd fault system appears as a northwest-southeast trend, forming longitudinally, while the transverse fault system appears as a northeast-southwest trend, forming transversely. These two systems are appear as main fault systems originating from the late Precambrian (Nabitah orogeny) and were reactivated them through the Phanerozoic era. These faults are deep and reach the basement rocks, they have depths ranging from 10-15 km throughout the Iraq. These faults are important because they divide the Iraq into longitudinally and transversely blocks.

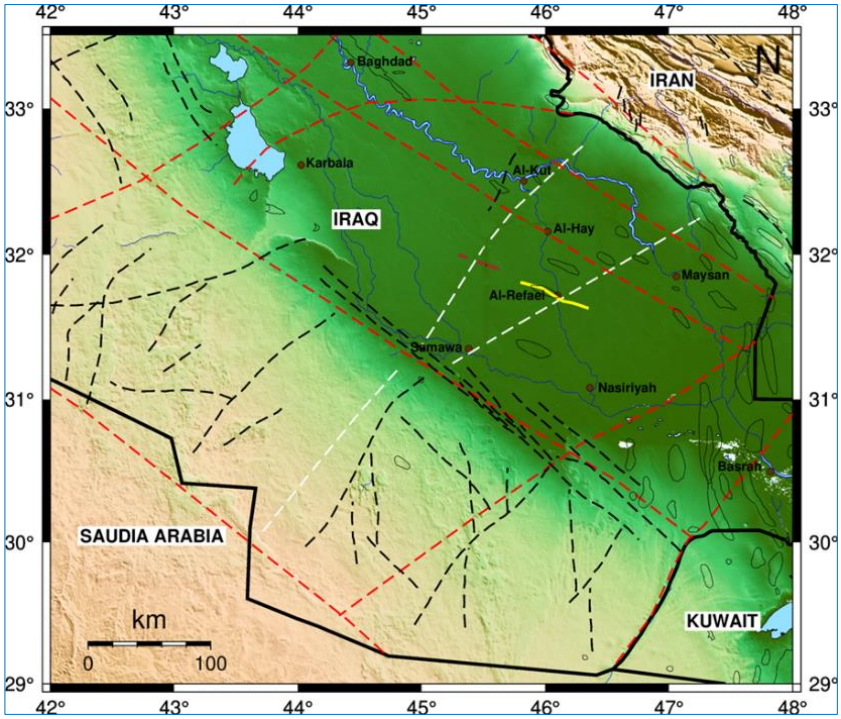


Fig. 5. Faults of the study area. Red lines represent main faults in Iraq according to Jassim and Göff (2006), white dashed lines represent faults derived from the seismotectonic map by Buday (1973) and cited in Al-Heety (2010), the dashed black lines represent the faults identified by Seber et al. (1997), the solid yellow line represents the Al-Refaei fault, as identified by Ramthan (2021a).

White dashed lines on the map represent faults derived from the seismotectonic map of Iraq, which was created using a combination of seismic, tectonic, and geological data. As noted by Buday (1973) and cited in Al-Heety (2010), these faults have been responsible for past earthquake occurrences. The dashed black lines on the map represent the faults identified by Seber et al. (1997), which used satellite images to identify these faults.

The solid yellow line represents Al-Refaei fault, as identified by Ramthan (2021a) using seismological and geophysical information. This fault is seismically active, as it has experienced swarms

of earthquakes in recent years. In northwest of the study area, there is a segment of the fault (colored brown) indicated by Al-Zubaidi (2017), we believe this segment is part of the active Al-Refaei fault.

3.3. Seismic Zones

One fundamental concept in seismology is the classification of regions based on their seismic activity, known as seismic zones (Stein and Wysession, 2009). These zones are delineated areas that exhibit varying levels of earthquake hazards, helping scientists and engineers to understand the potential risks and develop appropriate mitigation strategies. Seismic zones are typically defined by assessing earthquake occurrence rates, fault locations and characteristics, the historical and instrumental records of seismic activity within a region. Depending on the classification system used, seismic zones can be categorized into different levels of seismicity, ranging from low to high levels (Petersen et al., 2008).

In some cases, additional factors such as local geological and geophysical conditions, as well as ground motions caused by seismic events, are considered to refine these classifications further (Bommer and Scherbaum, 2005).

The Al-Refaei area is considered as a seismic zone based on structural setting of the area and available seismicity and according to the USGS definition it exhibits clear and concentrated seismic activity. This zone is situated approximately 150 km west of the Zagros fold-thrust belt (Talebian and Jackson, 2004). Based on the faults map of the study area, the Al-Refaei fault is the only active fault in the area, which has led to it classified as an independent zone with seismic activity. According to earthquakes locations of ISC and relocation of events to Ramthan et al. (2021b) that relcocated 56 events in area, Al-Refaei fault is active. This fault is visible in the 3D seismic survey, 40 km in length, and passes through the center of Al-Refaei City, the Al-Gharraf oilfield, and ends south of Al-Fajr Town. The earthquakes in this zone appear to take a linear feature with the extension of the fault.

According to the mentioned above, this area can be considered as a seismic hazard zone, as in which according to the magnitude and recurrence of earthquakes were constantly increasing, especially in recent years. The closest seismic zone to the area is the Mandali-Badra-Amarah fault which is considered as a seismic active fault (Abdulnaby, 2019).

3.4. Focal Mechanism Solutions

Focal mechanisms of earthquakes, also known as fault plane solutions or first-motion studies, are graphical representations that provide information about the geometry and kinematics of faulting during an earthquake (Stein and Wysession, 2009). These solutions describe the direction of slip along the fault, and the orientation of the fault plane, as well as the sense of motion (e.g., normal, reverse, or strike-slip) based on the observed seismic waveforms. Focal mechanisms help seismologists and geologists to understand the stress regime and deformation processes in the crust of the earth, which in turn, contribute to the assessment of seismic hazard and risk (Dziewonski et al., 1981; Ekstro¨m et al., 2012). Focal mechanisms are commonly represented by beachball-like diagrams called "focal mechanism solutions" or "moment tensor solutions" that portray compressional (P-wave) and dilatational (S-wave) first motions during the earthquake. These diagrams are derived from the analysis of seismic waveforms recorded at multiple stations and provide insights into the faulting style and stress regime in the source region (Shearer, 2009) (Fig. 6).

Table 3 shows the solutions of three focal mechanism that have been adopted in this study. Two of them taken from ISC, these are 5/8/2004 event which have 5 MW (Moment magnitude) and 25/8/2001 event which have 4.5 (MW). The third done by Ramthan (2021a), which is a composite first motion, derived from 15 earthquakes in the Al-Refaei area for swarm 2017. The results show that the movement of the faults is a clearly reverse mechanism, resulting from the compressional forces in the area (Fig. 7).

3.5. Recent Stress Analysis

The most reliable data source for determining the subsurface geological structures and the regional stress field are focal mechanisms solution (Doski, 2019). Rotational Optimization method were employed from a set of three focal mechanism solutions. This method utilized within the Win Tensor software package, developed by Vavryčuk (2001). The Rotational Optimization method implemented works by reducing the unfit between the synthetic and observed waveforms. The Win Tensor software uses the inversion of moment tensor to calculate the focal mechanisms.

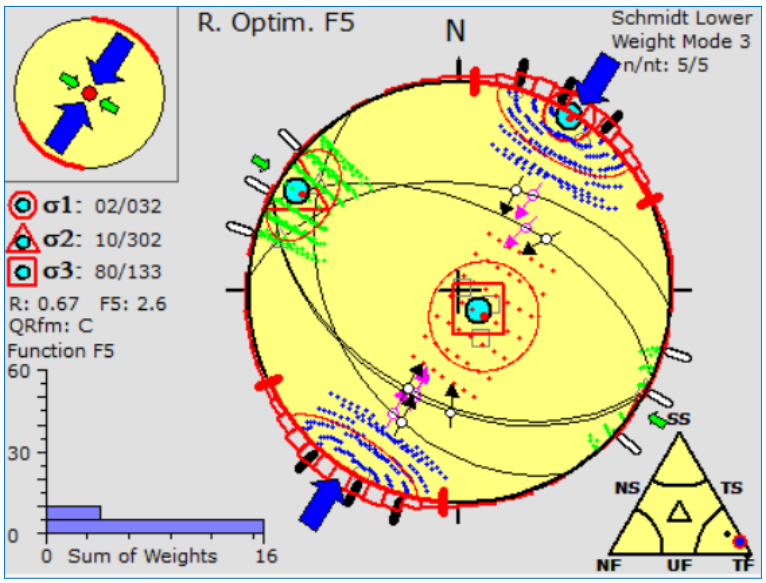


Fig. 6. displays the result of the qual-area stereographic projections using Rotational Optimization. The respective horizontal stress axes for SH and Sh are denoted by a large blue arrow and a red arrow outside the stereogram. The fault type is indicated by the triangle in the lower right corner.

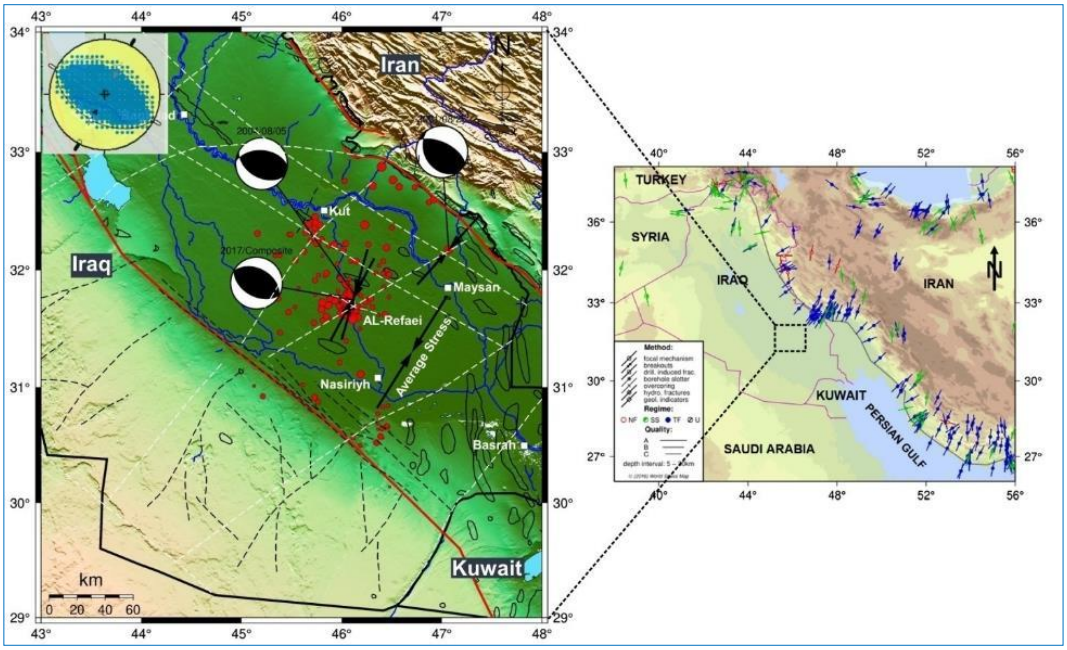


Fig.7. (Left) Focal mechanism solutions of three earthquakes in the Al-Refaei area, and the maximum horizontal stress axes (black arrows) based on Table 3. The panel in the top left of the map represents the final solution of the focal mechanism solutions in the study area. (Right) Stress map of the Zagros Foredeep Fault and the surrounding areas according to Al-Kaabi and Abdulnaby (2022).

The Rotational Optimization method, in this context, involves iteratively rotating the synthetic waveforms to find the optimal orientation that minimizes the misfit with the observed waveforms. This is done for a range of possible moment tensor solutions, and the solution with the smallest misfit is selected as the best-fitting focal mechanism (Vavryčuk, 2014). To obtain the principal and horizontal stress axes, the Win-Tensor version 5.9.2 software were utilized. These axes will give the main stress directions that affecting on faults in Al-Refaei area. σ1 is maximum stress axis, σ2 is intermediate stress axis and the σ3 is the minimum stress axis. These axes are typically transformed into the vertical stress axis (SV), maximum horizontal stress axis (SH) and the minimum horizontal stress axis (Sh), which are perpendicular to each other. This transforme is necessary for plotting stress directions on a map. Mapping the tectonic stress by the azimuth of horizontal stress is deemed highly effective, as it is the dominant stress caused by the mechanism of horizontal plate motion (Delvaux and Sperner, 2003).
Fig. 6 shows the inversion of focal mechanisms for three earthquakes that occurred in the Al-Refaei area. The inversion results are presented using equal-area stereographic projections in the lower hemisphere.

Table 3. The parameters of focal mechanism solutions for 3 seismic events from the moment tensor inversion and composite first motion. The symbols are as follows: Original time is (O.Time in UTC); the reported depth is (RD); the calculated depth is (CD); body wave magnitude is (mb); moment magnitude is (MW), seismic moment is (Mo); strike is (S); dip is (D); rake is (R); compressional forces is (P); normal forces is (N); tensional forces is (T); plunge angle is (PL) and azimuth is (AZ).

Date	O. Time	Lat. N	Log. E	RD	CD	mb	MW	Modyne-cm	Plane 1			Plane 2			Moment Stress Axes						Source
									S	D	R	S	D	R	P PA		N A		T A		
2004-08-	20:41:47	31.793	46.129	16	15	-	5	3.39	119	45	108	274	47	73	1	17	13	286	77	112	ISC
2001-08-	9:45:37	32.173	47.067	15	12	-	4.5	6.84	147	34	116	296	60	74	13	38	14	305	71	170	ISC
2017	10:18:44	31.768	46.045	-	10	4.7	-	-	298	43	90	117	37	90	2	208	0	118	88	28	Ramthan

This figure indicates that the faults in the study area are reverse faults. The orientations of the principal stress axes are: σ1 (maximum stress): Plunge angle = 02°, Plunge direction = 32°, σ2 (intermediate stress): Plunge angle = 10°, Plunge direction = 302°, σ3 (minimum stress): Plunge angle = 80°, Plunge direction = 136°. By conducting stress inversion on the earthquake focal mechanism, it has been revealed that there has been movement in the reverse fault. This suggests that the current stress state in the area is compressional, with the maximum horizontal compressive stress (SH) oriented in the northeast-southwest direction. This direction is alignment with the trend of the collision zone between the Arabian and Eurasian plates that have northwest-southeast trend. Furthermore, it is match to the converging movement between the Arabian and Iranian plates.

These stress orientations suggest that reverse faulting dominates the area. The reverse faulting is caused by the compressional stress regime resulting from the collision between the Arabian and Eurasian continental plates. Hence, the orientation of the Al-Refaei fault is nearly parallel to the convergent boundary between the Arabian and Eurasian plates, which trends NW-SE. The alignment of the Al-Refaei fault matches well with the orientations of other major faults in the area. The recent stress results in this study were compared with the world stress map (WSM) project. Espatially, study Al-Kaabi and Abdulnaby (2022) which dealt with Zagros Foredeep Fault, closest seismic zone to this study. The results is compatible with the stress regime, direction and type of faults, as shown in Fig. 7.

4. Conclusions

Al-Refaei area is considered one of the highest seismic activity in Mesopotamian Plain. Four seismic swarms were distinct in the area based on the International seismological Center (ISC); these are: August 2004, January 2013, May-Jun 2017, and August 2017. Based on three focal mechanism solutions of magnitude greater than 4, the stresses in the area were analyzed.

The results suggest that the movement on fault lines within the study area is characterized by a reverse movement, created by compressional forces. To deduce the orientations of the three principal stress axes impacting the faults in the Al-Refaei area, the Rotational Optimization method were used. The orientations of the main stress axes are the maximum principal stress axis (σ1) plunges 02° with an azimuth of 32°, The intermediate principal stress axis (σ2) plunges 10° with an azimuth of 302° and the minimum principal stress axis (σ3) plunges 80° with an azimuth of 136°. The seismic activity that occur in the Al-Refaei area are caused by the impact between the Arabian tectonic plate and the Iranian tectonic plate. As these two plates collide and grind against each other, it generates earthquakes and other seismic activity in that area. Al-Refaei active fault is responsible for most the earthquakes in the area and responsible for the 2017 earthquake. This fault is visible in the 3D seismic survey, 40 km in length, and passes through the center of Al-Refaei Town, the Al-Gharraf oil field, and ends to the south of Al-Fajr Town. Conducting more geophysical and structural studies about this fault are recommended.

Acknowledgements

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