SEISMOTECTONICS OF BADRA-AMARAH FAULT, IRAN-IRAQ BORDER

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ABSTRACT

The Badra-Amarah fault is located in the northeastern side of the Mesopotamian Zone at the Iraq-Iran border. This fault is the most seismically active fault in Iraq and it is located within the zone of the major damage. The goal of this study is to study the seismic history, focal mechanism solutions, and the recent stress analysis of the Badra-Amarah fault. The seismic history has been studied by using the source parameters of earthquakes from different catalogs, mainly from the IRSC catalog. The focal mechanism solutions were calculated from the CMT catalog, which were analyzed in this study to derive the principal stress directions and their regimes. According the seismic history of the study area, four seismic swarms occurred at the fault in August, 2008, June, 2009, August, 2009, and April, 2012 with magnitude of main shocks ranges from 4.4 to 5.7. The focal mechanism solutions show that the Badra-Amarah fault has a reverse movement with little strike-slip displacement. The dip of the fault is 60° with dip direction equals 226°. From the stress inversion of moment tensors, the principal stress axes are: $\sigma1$ is 14°/217°, $\sigma2$ is 10°/309°, and $\sigma3$ is 72°/074°. The length of fault is about 200 km and its depth may reach the basement rocks which are about 10 km.

INTRODUCTION

Iraq represents part of the convergent plat boundary between the Arabian and Eurasian plats. The collision between these plates began after the closure of the Neo-Tethys Ocean in the Miocene and it continues to the present day (e.g. Dewey *et al*. 1973; Numan 1997). Iraq has two systems of faulting; these are the transversal faults and longitudinal faults (Najd system faults). One of the longitudinal faults is the Makhul-Hemrin fault. It trends from centerof Iraq and passing through the Makhul and Hemrin folds until Badra and Amarah cities at the Iraq-Iran border (Jassim and Goff, 2006). In this study, the Makhul-Hemrin fault is suggested to be divided into two faults based on the seismicity and structural geology of the study area. These two faults are: the Makhul-Hemrin listric fault and the Badra-Amarah fault. The listric fault is parallel to the Himrine and Makhaul fold axes and seems non-active fault. It forms the boundary between the Folded and Unfolded Zones. The Badra-Amarah fault extends from Badra to Amarah cities and it is seismically active. The seismic activity is extended only along the longitudinal area between the Badra and Amarah cities. The Makhul-Hemrin listric fault has different direction than the direction of the Badra-Amarah fault (Fig. 1).

The goal of this study is to study the seismic history, focal mechanism solutions, and recent stress analysis of the Badra-Amarah fault. This goal can be achieved by using the source parameters and moment tensor solutions of earthquakes from different catalogs, such as the Iranian Seismological Center (IRSC), the European-Mediterranean Seismological Centre (EMSC), Incorporated Research Institutions for Seismology (IRIS), and the Global Centroid-Moment-Tensor (CMT) Project.

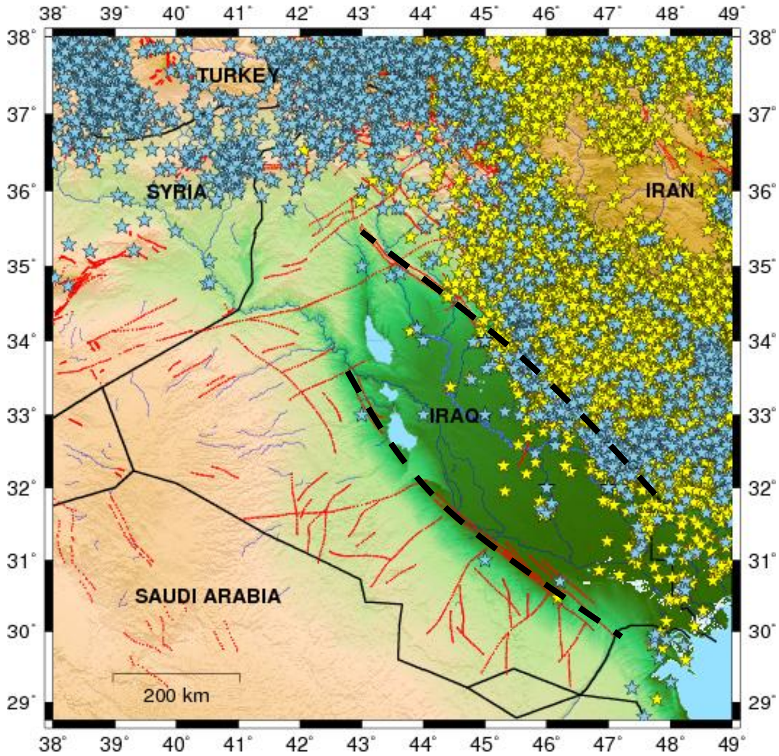

Figure 1. Seismicity of Iraq and adjacent areas taken from the IRSC (from 1/1/2006 to 1/10/2014) and the EMSC catalogs (from 1/10/ 2004 to 1/10/2014). Broken black lines represent the Makhul-Hemrin fault in the northeast and the Euphreates fault in the southwest.

SEISMOTECTONIC SETTING

The Mesopotamian Zone is bounded by the Euphreates fault in the southwest and the Makhul-Hemrin fault in the northeast. These two faults have surface expression represented by linear features and alluvial fans which border the Mesopotamian Zone on both sides. The Euphreates fault was formed by the Najd Orogeny (Pre-Cambrian). It runs from the Rutba area in western Iraq and continues towards Basra in the south. It forms the boundary between the Quaternary Mesopotamian Plain and the rocky desert of southwest Iraq. The fault was reactivated during Late Jurassic and Cretaceous time (Jassim and Goff, 2006). The Makhul-Hemrin fault extends along the Iraq-Iran border in the southeast Iraq. It forms the boundary between the unfolded zone (the Mesopotamia) and the folded zone. This fault was reactivated during the Pliocene and it is still active at the present day (Jassim and Goff, 2006). The northern boundary of the Mesopotamian Zone is represented by one of the Makhul-Hemrin anticlinal chain. The Mesopotamian Zone extends to the Gulf in the southeast of the Arabian plate.

According to Numan (1997), the Mesopotamian Zone is a sagged basin and it represents a huge half grabin that formed as a result of subsidence of the block located between the Euphreates and Makhul-Hemrin faults (Fig. 1). Alluvial fans on the eastern side of the Mesopotamia developed along the Badra-Amarah fault, which is the southern part of the Makhul-Hemrin fault as we mentioned earler, from Badra in the northwest to Amara in the southeast. Alluvial fans on the western side of the Mesopotamia are located along the Euphrates fault. The Badra-Amarah fault is the structural boundary between the Mesopotamian Zone in Iraq and the Dezful Embayment in Iran.

Studying the seismicity of the Badra-Amarah fault is important because it represents the northeastern boundary of the Mesopotamian Zone, and this zone forms about 25% of the area of Iraq and sustains 60% of its population (Jassim and Goff, 2006). According to the isointensity map, the Mesopotamian Zone is located within the zone of minor damage that follows intensities range from IV to V (MM magnitudes). Badra-Amarah fault is part of the zone of the major damage with intensity of VIII (MM magnitudes). Earthquakes in the Mesopotamian Zone cause damage due to liquefaction of the Quaternary sediments (Jassim and Goff, 2006).

Figure 1 represents the seismic activities of Iraq and adjacent areas according to the Iranian Seismological Center (IRSC) and (EMSC) catalogs. The IRSC catalog ends at longitude 42°E. This figure indicates that the seismic activity of Iraq is moderate to high at northern and northeastern boundaries, and decrease in the south and southeastern direction.

SEISMIC HISTORY OF BADRA-AMARAH FAULT

According to the Iranian Seismologic Center (IRSC) catalog, about 3074 earthquakes were recorded in the study area (latitude 31°N to 34°N and longitude 45°E to 48°E) for the period time from January 1st, 2006 to October 1st, 2014 (Fig. 2, left panel). For this period of time, four seismic swarms occurred at the Badra-Amarah fault. Swarms one and four occurred near the Amara city, while swarms two and three occurred near the Badra city (Fig. 2, right panel). Table 1 shows the basic seismic parameters of the main shocks of these four swarms taken from different catalogs.

The first swarm extends for 16 days from 27-08 to 9-9-2008. The main shock happened after three days of the foreshocks with magnitude 5.7, while the rest of days represent the aftershock. The fourth day of the swarm had 31 events which represents the largest number of earthquakes in the swarm. The second swarm lasted 10 days from 20-06 to 30-06-2009. The main shock happened at the five day of the swarm with magnitude 4.5 and this day had the largest number of earthquakes. The third swarm represents the shorter swarm. It lasted 8 days from 27-08 to 04-09-2009. The main shock occurred at the third day. The fourth swarm consists of 13 days started from 18-04 to 30-04-2012. The main shock happened after three days and represents the most frequent with rate 54 events (Fig. 3).

FOCAL MECHANISM SOLUTIONS

One of the global institutions that make an effort to determine focal mechanism solutions for the medium to large magnitude earthquakes ($mb \geq 4.0$) is the Harvard University (USA) group that estimates the Centroid Moment Tensor (CMT) solutions (Dziewonski *et al*. 1981 and Ekström *et al*. 2012).Table 2 shows 18 focal mechanism solutions in the study area that were calculated by the Harvard CMT for the time period from 1980 to 2014. These solutions were plotted on a map as shown in Figure 4. The solutions indicate that the movements on the Badara-Amarah fault is a reverse mechanisms formed by compressional forces. Only one solution out of 18 gives a strike-slip fault mechanism which may be related with other fault with direction northeast-southwest.

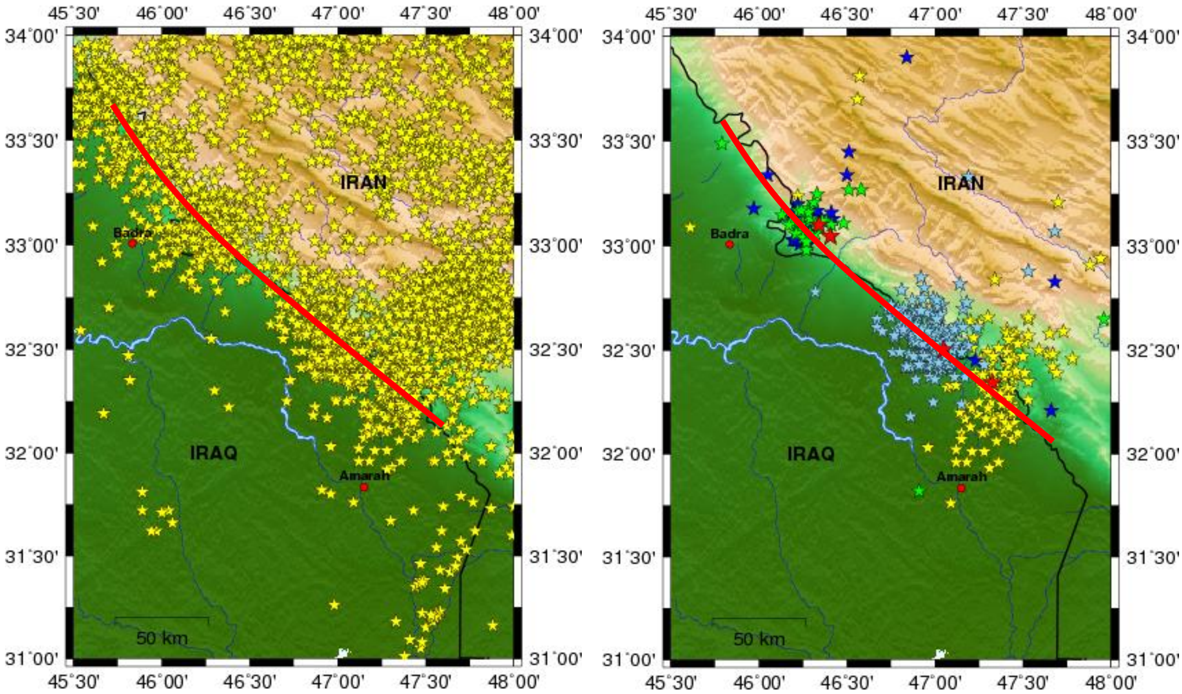

Figure 2. Seismicity of the Badra-Amara fault according to the Iranian Seismologic Center (IRSC) catalog (yellow stars in the left panel) and the Badra-Amarah fault (red line). The right panel represents the fourth swarms. Yellow, green, blue, and sky blue stars are swarms 1, 2, 3, and 4 respectively. Red stars represent the main shocks.

Table 1. The main shocks of the four swarms at the Badra-Amarah fault taken from different sources.

Swarm	Date	Time (UTC)	Lat.	Lon.	Depth km	Mag.	Mag. Type	Source
August, 2008	2008/08/27	21:52:38.8	32.450	47.350	10.0	5.7	Mw	EMSC
	2008/08/27	21:52:40.7	32.344	47.325	20.5	5.7	Mn	IRSC
June, 2009	2009/06/25	15:04:53.0	33.130	46.400	18.0	4.5	mb	IRIS
	2009/06/25	15:04:51.0	33.010	46.340	10.0	4.4	mb	EMSC
	2009/06/25	15:04:53.0	33.102	46.341	8.0	4.4	mb	IRSC
August, 2009	2009/08/30	14:04:38.0	33.190	46.370	30.9	4.8	mb	IRIS
	2009/08/30	14:04:37.0	33.160	46.470	15.0	4.7	mb	EMSC
	2009/08/30	14:04:34.0	33.047	46.405	10.0	4.6	Mn	IRSC
April, 2012	2012/04/20	01:21:07.0	32.510	47.020	10.0	5.1	mb	IRIS
	2012/04/20	01:21:10.0	32.530	47.070	30.0	5.0	mb	EMSC
	2012/04/20	01:21:07.3	32.503	47.049	20.0	5.1	Mn	IRSC

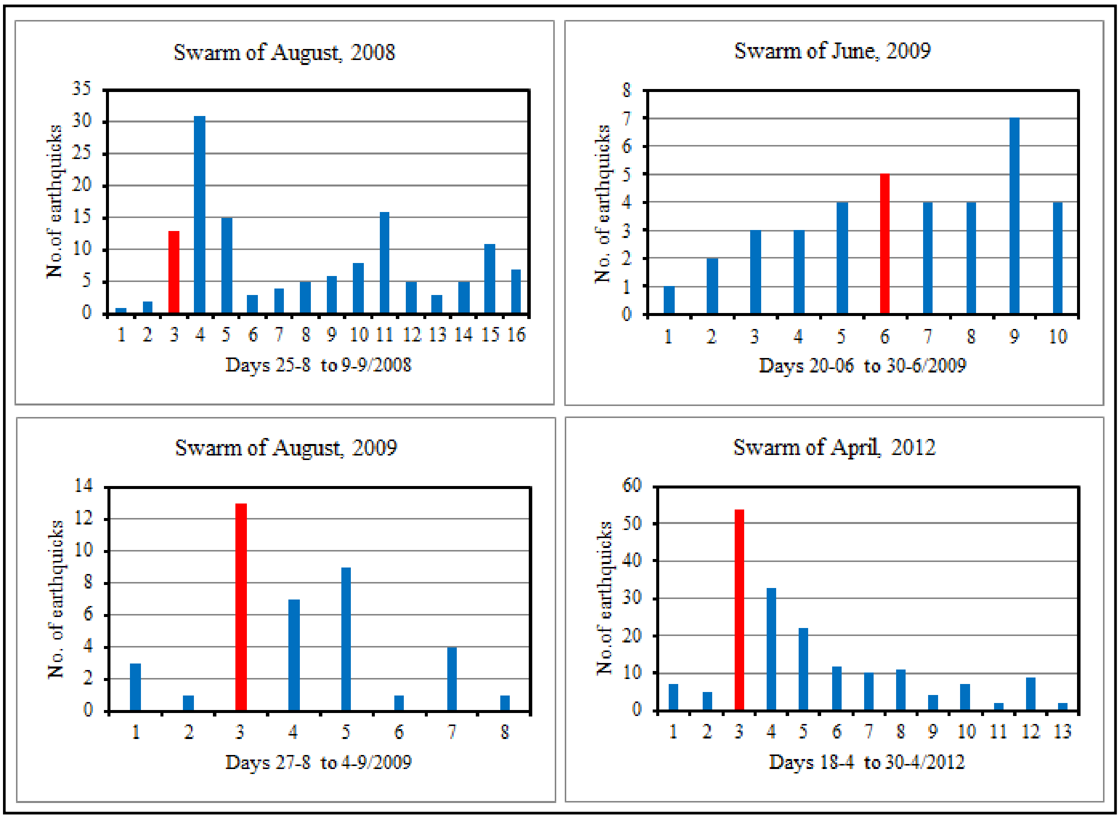

Figure 3. Statistical descriptions of swarms of the Badra-Amarah fault. Red column depicts the day of mainshock.

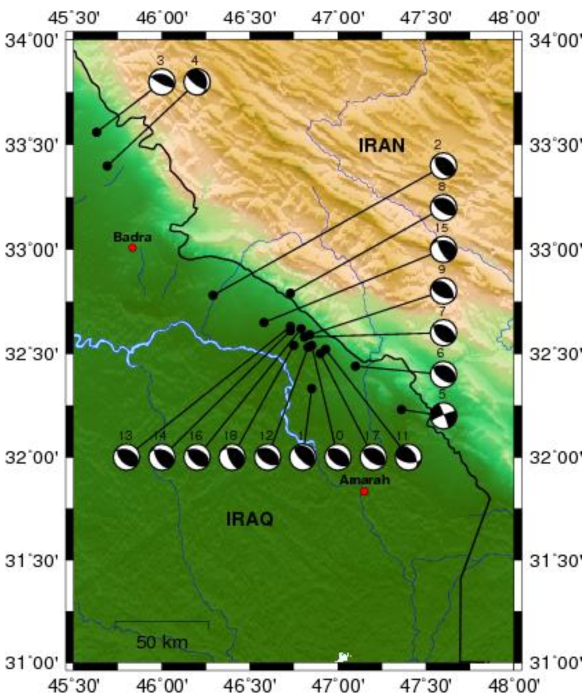

Figure 4. Focal mechanism solutions of 18 earthquakes in the Babra-Amarah fault from the Harvard CMT Catalog based on table 2.

Table 2. Source parameters and focal mechanism solutions of 18 earthquakes from the moment tensor inversion based on the Harvard CMT Catalog.

No.	Date	O. Time UTC	Lat.	Lon.	D km	Mag	Mag Type	Scalar Moment dyne-cm	Plane 1			Plane 2			Moment Stress Axes					
									S	D	R	S	D	R	P		N		T	
															PL	AZ	PL	AZ	PL	AZ
1	1988/01/26	09:34:51.1	32.33	46.85	19.9	5.5	Mw	2.62e+24	306	20	079	137	70	094	25	224	04	316	65	053
2	2001/03/23	05:24:15.2	32.78	46.29	15.0	5.4	Mw	1.45e+24	301	42	074	142	50	104	04	222	11	313	79	111
3	2004/10/16	10:04:37.6	33.56	45.63	14.2	4.8	Mw	2.18e+23	282	42	19	177	77	130	21	238	39	346	43	126
4	2005/01/25	11:39:20.9	33.40	45.69	12.0	4.9	Mw	2.97e+23	350	27	129	127	70	72	23	231	17	133	61	010
5	2008/08/27	21:52:43.4	32.23	47.36	12.5	5.8	Mw	5.81e+24	247	84	-5	338	85	-174	01	112	82	017	08	203
6	2008/09/03	22:43:16.8	32.44	47.10	12.0	5.1	Mw	5.7e+23	294	34	78	128	57	98	12	212	07	304	77	063
7	2012/02/28	23:18:53.5	32.58	46.81	12.0	5.0	Mw	3.59e+23	298	45	78	134	46	101	01	216	08	306	82	123
8	2012/03/08	18:21:38.6	32.79	46.73	15.6	5.0	Mw	4.28e+23	294	30	81	125	61	95	16	211	05	302	74	049
9	2012/03/24	05:25:37.2	32.59	46.84	12.0	4.9	Mw	2.64e+23	317	41	109	113	52	74	06	214	12	123	77	328
10	2012/04/18	18:43:00.1	32.54	46.85	12.0	5.0	Mw	4.05e+23	301	43	84	129	47	95	02	215	04	305	86	098
11	2012/04/18	20:04:07.9	32.52	46.93	12.0	4.9	Mw	2.75e+23	328	47	129	98	55	56	04	211	27	119	62	310
12	2012/04/20	01:21:08.9	32.53	46.83	12.0	5.2	Mw	8.13e+23	298	37	85	124	53	93	08	211	03	302	81	051
13	2012/04/20	03:05:45.3	32.63	46.73	12.0	5.2	Mw	8.73e+23	292	42	73	135	50	105	04	214	12	305	78	105
14	2012/04/20	03:52:37.3	32.61	46.73	12.5	4.8	Mw	2.19e+23	285	43	54	150	56	118	12	221	26	317	61	109
15	2012/04/20	03:56:27.9	32.65	46.58	12.3	4.9	Mw	2.68e+23	277	31	39	152	71	115	22	223	24	323	57	095
16	2012/04/20	15:37:06.2	32.62	46.79	17.9	4.8	Mw	1.80e+23	294	43	73	136	50	105	04	216	11	306	78	108
17	2012/04/20	16:17:52.2	32.50	46.90	12.0	5.0	Mw	4.36e+23	292	34	78	127	57	98	12	211	07	302	76	063
18	2012/04/21	05:25:11.8	32.45	46.75	18.9	5.2	Mw	7.53e+23	285	31	43	156	69	114	21	228	22	327	59	099

O. Time (UTC) original time in UTC, Lat latitude in degree, Log longitude in degree, D calculated depth, Mag reported magnitude, S strike, D dip, R rake angle, P, N, and T compressional, normal, and tensional moment stress axes respectively, PL plunge angle, AZ azimuth.

RECENT STRESS ANALYSIS

In this study, two methods of stress inversion are presented; these are the Improved Right Dihedron and the Rotational Optimization methods. These methods give four parameters; these are the three principal stress axes (the maximum stress axis σ1, the intermediate stress axis σ2, and the minimum stress axis σ3) and the stress ratio R = (σ2-σ3)/(σ1-σ3).

The Windows version of the TENSOR program (Win-Tensor version 4.0.4) was used to invert the moment stress axes to the principal stress axes and stress ratio. This program is free source program developed originally in DOS by Delvaux (1993) and then modified for Windows by Devaux and Sperner (2003). The graphical output of the stress inversion by the TENSOR program depicts the projection of the principal stress axes in a lower hemisphere equal-area projection and allows evaluating the overall quality of the result (Delvaux and Barth, 2010).

Figure 5 represents the lower-hemisphere equal-area stereographic projections of the formal stress inversion of 15 focal mechanism solutions of earthquakes occurred on the Badra-Amarah fault. The left panel is the result of applying the Rotational Optimization method, while the right panel is the final focal mechanism of the fault. The small circle on the upper left corner of the left panel shows the direction and type of the horizontal stress axes. The histograms to the lower left corner of the stereograms depict the distribution of the misfit angle F5 in the TENSOR program weighted arithmetically according to the magnitude for each case. The stress inversions 15 focal mechanism solutions of the study area were determined to be of A quality (QRfm in the left panel of Figure 5). The right panel of Figure 5 shows the two solutions of the Badra-Amarah fault which is reverse fault with little dextral strike slip movement. The fault plane solution is 60°/226° (dip angle and dip direction), while the axillary plane solution is 32°/023°. The attitudes of the principal stress axes are: σ1=14°/217°, σ2=10°/309° and σ3=72°/074°.

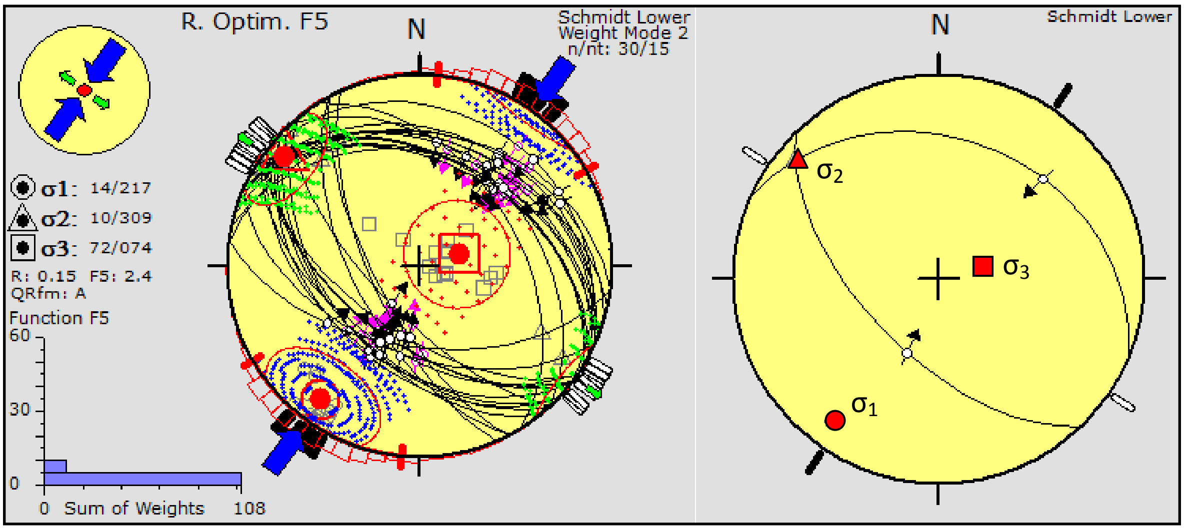

Figure 5. The results of formal stress inversion of 15 focal mechanism solutions by the Rotational Optimization method (left panel) and the final solution of the Badra-Amarah fault (right panel). For more detail see the text.

RESULTS AND CONCLUSIONS

Badra-Amarah fault represents the northeastern structural boundary of the Mesopotamian sagged basin. The length of fault is about 200 km and it may be extending more than that. The fault is remarked by alluvial fans on the eastern side of the Mesopotamia. The fault is active seismically and its seismic

history during the last ten years has four big swarms according to the IRSC. The main shocks of these swarms have magnitudes range from 4.4 to 5.7. All these four main shocks were happened after several foreshocks which can be used as a prediction sign. The focal mechanism solutions of the fault, which were collected from the CMT catalog, show that Badra-Amarah fault has reverse movement with little dextral strike-slip displacement due to the compressional tectonic forces of the collision zone between the Arabian and Eurasian plates. However, that does not mean that the fault is a reverse fault because it is a normal fault formed during the tectonic history of the region as a result of divergent tectonic movement. The dip of Badra-Amarah fault is 60° with dip direction 226° (46° SW). The attitudes of the principal stress axes that are responsible on the reverse movement on the fault surface are: $\sigma1$=14°/217°, $\sigma2$=10°/309° and $\sigma3$=72°/074°. More seismological and structural studies are needed due to the high seismic activity of the fault.

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