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BASEMENT FAULT REACTIVATION IN THE ZAKHO– SILOPI REGION, IRAQI KURDISTAN – TURKEY BORDER

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ABSTRACT

The nature and orientation of underlying Late Precambrian basement structures, and their relationships to the seismic distribution and surface linear structures has provided a basis for studying the basement fault reactivation in the Zakho – Silopi region. This border region between Iraqi Kurdistan and Turkey is located in the north-eastern boundary of the Arabian plate and covers some parts of the Zagros fold-thrust belt as well as the high folded and foothill zones of Iraq. The Zakho – Silopi region is characterized by moderate-sized earthquakes of shallow-focus that caused mostly by the neotectonic reactivation of Late Precambrian thrust and strike-slip basement faults due to the on-going active continental collision between Arabia and Eurasia. Four potential NE- and NW-trending seismic lineaments were identified, based on the epicentral alignments of major earthquake and the orientation of nodal fault planes, to be the most seismically active basement faults in the Zakho - Silopi region. Any potential for the future damaging earthquakes throughout this region will be more likely associated with the reactivation of the basement faults along these active seismic lineaments. Therefore, a detailed seismic hazard assessment is recommended for the major cities and urban localities. The present-day stress-field orientation inferred from the inversion of fault plane solutions and lineament analysis indicates that the Zakho – Silopi region is undergoing a continuous state of nearly N-S (N05°E) compression. The trend analysis of lineament patterns and seismic lineaments reveals three dominant basement fault trends in the Zakho - Silopi region; roughly N-S, NE-SW, and NW-SE. These basement faults were probably initiated in Late Precambrian as normal faults, and subsequently inverted into thrust faults with a significant strike-slip component, and reactivated continuously from Late Cretaceous to present-day.

KEYWORDS: *Iraqi Kurdistan, Zagros fold-thrust belt, Reactivation, Seismic lineaments, Basement faults*

INTRODUCTION

At least eleven major earthquakes, with magnitudes 4 to 5.5, occurred in the Zakho – Silopi region from November 25, 1950 to July 13, 2013. The seismicity and basement fault reactivation of this border region between Iraqi Kurdistan and Turkey so far have not received the extensive attention. The Zakho – Silopi region is located in the north-eastern boundary of the Arabian plate, between latitudes 36° 57` N - 37° 16` N and longitudes 42° 20` E - 42° 46` E, and covers some parts of the Zagros fold-thrust belt as well as the high folded and foothill zones of Iraq (Fig. 1). The Dohuk region is characterized generally by WNW-trending detachment folds that involve about 8 - 9 km of Phanerozoic sedimentary section above the Late Precambrian basement (Doski and McClay, 2011). The exposed stratigraphic section of the Zakho – Silopi region consists of the Pila Spi, Lower Fars, Upper Fars and Lower Bakhtiari formations with Quaternary sediments (Fig. 2). The topography of this region is characterized by anticlinal ridges and synclinal valleys with an elevation ranges from 400 m to over 1100 m above sea level (Fig. 3). The objective of this study is to investigate the nature and orientation of underlying Late Precambrian basement structures and their relationships to the seismicity alignments and surface linear structures in order to evaluate the basement fault reactivation in the Zakho – Silopi region.

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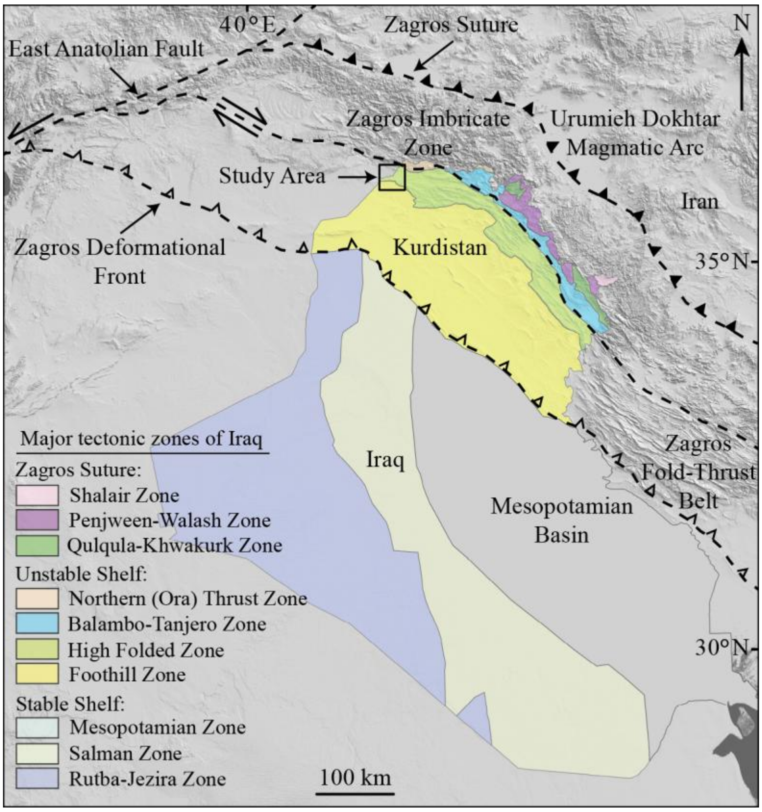

Fig.(1): Tectonic map showing the location of the Zakho - Silopi region (tectonic divisions from Alavi, 2004; Jassim and Goff, 2006).

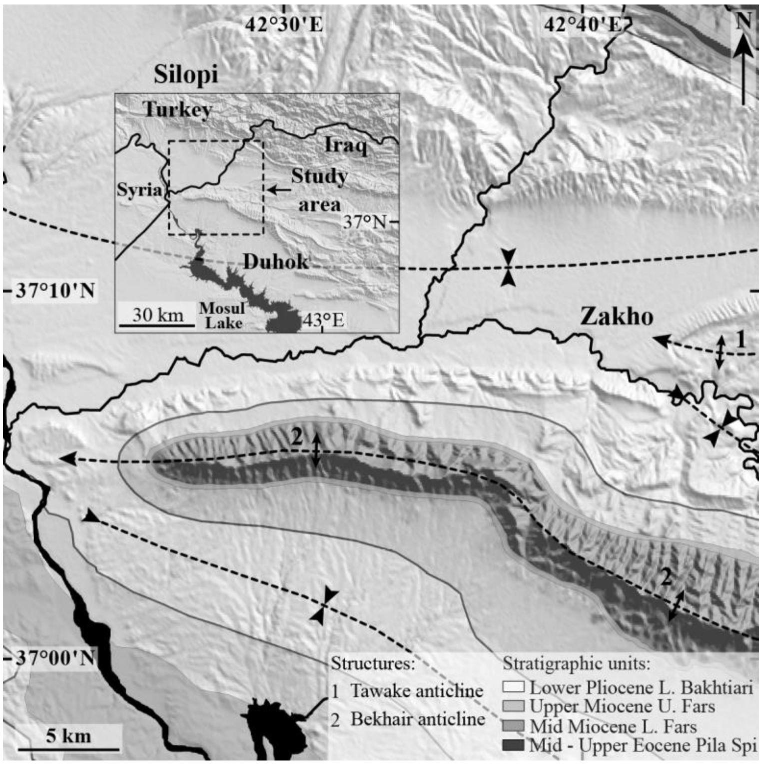

Fig. (2): Geological map of the Zakho – Silopi region (modified from Doski and McClay, 2011).

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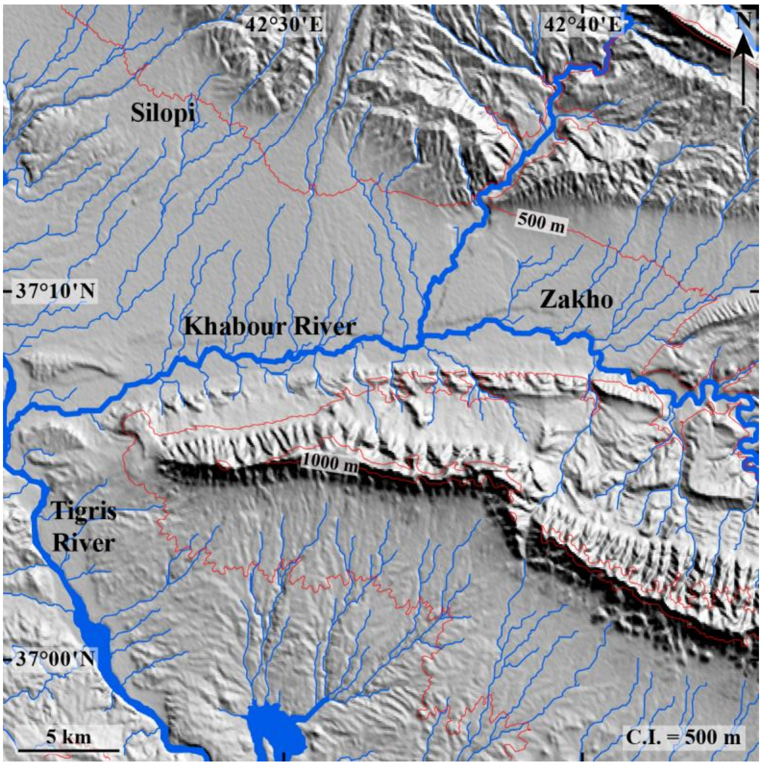

Fig. (3): Drainage network map of the Zakho – Silopi region (derived from ASTER 30 m GDEM).

There have been no specific studies done on the neotectonics of this border region. Four lineament sets, trending NW-SE, NE-SW, N-S and E-W were visually interpreted from the Landsat MSS images by Numan and Bakose (1997) in the western and southern deserts of Iraq, and the orientations of these lineaments were controlled by the basement structures. Al-Daghastani and Daood (2005) studied the relationship between seismic activities and tectonic structures in the Nineveh governorate (northern Iraq) using seismic data integrated with the analysis of geological and geomorphological features from Landsat TM images, and concluded that most of the major lineaments are related to the subsurface basement faults. Alridha et al. (2012) studied the seismicity and seismotectonics of the Altunkopri dam (northern Iraq), and the results show a good match between earthquake epicentres and the three predominant sets of lineaments (NE-SW, NW-SE and E-W), as well as concluded that surface lineaments are directly related to the subsurface basement faults that re-activated due to the continued northerly and north-easterly movements of the Arabian plate.

Four major lineament sets, trending N-S, NE-SW, NW-SE and E-W, were automatically extracted from Landsat-7 images by Thannoun (2013) in north-west of Mosul (northern Iraq), and interpreted that these four linear sets represent subsurface fracture zones that reactivated under the N-S compression, as well as field data indicates that the orientations of NE- and NW-trending sets coincide with shear fracture trends, whereas the N- and E-trending sets represent extension fractures in this region. Abdulnaby et al. (2014a and 2014b) studied the seismotectonic activity in northern Iraq and surrounding regions, and calculated the present-day stress patterns using formal inversion of fault plane solutions. The results show that the area is characterized by the dominance of strike-slip and thrust faulting regimes, with fault planes mostly trending in the N-S, NE-SW and E-W directions. Finally, active W-striking thrust and NW-trending strike-slip faults were documented in the Shaikhan area (Kurdistan) by Doski and Mohammad (2016).

Tectonic setting and seismicity

The Zagros orogen is one of the biggest regions of convergent deformation on Earth (Allen et al., 2004). It is a doubly-vergent asymmetric

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orogenic belt that resulted from the closure of the Neo-Tethys oceanic realm (Alavi, 1994). It was subdivided into three major tectonic units (Fig. 1): the Uremiah-Dokhtar magmatic assemblage, the Zagros imbricate zone and the Zagros fold-thrust belt (Alavi, 2004). The Zagros fold-thrust belt is characterized mainly by asymmetrical, overturned, doubly plunging, NW–trending anticlines, with largely NE-dipping, SW-verging thrusts (Alavi, 2007). The structure of Kurdistan is developed during the formation of the Zagros belt by the continental collision of Arabia with Eurasia followed the final Eocene closure of the Neo-Tethys Ocean (Numan, 1997; Sharland et al. 2001; Doski and McClay, 2011).

The Zagros belt in Iraq was divided into 3 main tectonic zones (Fig. 2): stable shelf, unstable shelf and suture zone (Jassim and Goff 2006). The unstable shelf of Iraq is characterized mainly by E-W “Taurus” and NW-SE “Zagros” trending fold structures, with an increase in folding intensity toward the north or northeast. The high folded zone has an elevated basement topography (~ 8 km), and characterised by harmonic fold structures with Mesozoic sequences in their cores, and Cenozoic formations on their flanks (Jassim and Buday, 2006b). The foothill zone has the deepest Late Precambrian basement in Iraq (~ 13 km) with very thick Neogene - Quaternary sediments (~ 3 km thick), and characterised by anticlines with cores of Palaeogene or Cretaceous sequences and synclines filled with Neogene - Quaternary sediments (Jassim and Buday, 2006b).

The Arabian basement was formed by terrane accretion along the continental margins in Late Precambrian (Sharland et al., 2001; Jassim, 2006). The basement depth ranges from zero on the Arabian shield to nearly 15 km in the Mesopotamian basin (Seber et al., 2000). The Triassic-Jurassic rifting and extensional tectonic regime was started at the opening of the Neo-Tethys Ocean and with the separation of the Iranian and Turkish plates from the Arabian plate, followed by the Cretaceous compressive tectonic regime due to the north and north-eastward subduction of the Neo-Tethyan oceanic crust beneath the Turkish and Iranian plates, leading to the reactivation of both strike-slip (wrench tectonic regimes) and dip-slip reverse (inversion) movements along the pre-existing listric normal faults in the basement, and continued until the final closure of the Neo-Tethys Ocean and the continental collision of the Arabian passive margin with the active margins of the Turkish and Iranian plates from the Late Eocene onwards (Numan, 1997, 2000 and 2001). The strongest orogenic movements and the most effective folding and thrusting in the border folds of Turkey occurred during the Late Miocene time (Ketin, 1966), and still active throughout the eastern Turkey (Okay, 2008).

The Zagros is a seismically active orogen (Jackson et al., 1981; Hessami, 2002). The majority of earthquake events found near the detachment surface between the Late Precambrian basement and Phanerozoic sedimentary rocks, at a depth range (5 - 15 km), with thrust and strike-slip faulting focal mechanisms (Mostafazadeh et al., 2000). Most of the earthquakes in the Zagros belt are caused by the reactivation of basement faults (Jackson et al. 1981). Iraq is characterized by moderate- to strong-magnitude earthquakes with relatively shallow focal depths, and most of the fault plane solutions show thrust and strike-slip faulting regimes (Alsinawi and Issa, 1986; Fahmi et al., 1986; Jasim, 2013). However, the seismicity and tectonic setting of the Kurdistan region reflects the present-day reactivation of steeply dipping basement faults (Alsinawi and Issa, 1986; Alsinawi, 2002; Doski and Mohammad, 2016).

MATERIALS AND METHODS

Datasets

There are some random and systematic uncertainties associated with determining the exact epicentre location, depth and magnitude of earthquakes, such as the arrival time picks (Bondár et al., 2004; Dawson and Tregoning, 2007; Husen and Hardebeck, 2010; Bernardi et al., 2014; Gomez-Capera et al., 2015). Therefore; it’s really important to use the best earthquake catalogues based on the tectonic setting of the research area. The earthquake data used for this study were obtained from the Turkish AFAD-DDA catalogue, the Turkish BOUN KOERI Regional Earthquake (BKRE) - Tsunami Monitoring Center (TMC), the European - Mediterranean Seismological Centre (EMSC), and the Iranian International Institute of Earthquake Engineering and Seismology (IIEES) as listed in Table 1.

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Table (1): List of earthquakes with magnitudes greater than 3.0 in the Zakho – Silopi region.

Date	Time (UTC)	Latitude	Longitude	Depth (Km)	Magnitude	Magnitude type	Date source
1950.11.25	17:18:55	37.07	42.48	33	4.9	Mw	BKRE-TMC
1982.01.01	19:30:24	37.24	42.61	10	4.8	Mb	BKRE-TMC
1991.01.30	19:42:54	37.11	42.65	28	4.7	Mb	BKRE-TMC
1991.02.02	6:54:43	37.2	42.56	26	4.7	Mb	BKRE-TMC
1991.02.02	9:09:01	37.17	42.59	21	4.9	Mb	BKRE-TMC
1997.04.20	21:17:31	37.011	42.646	33	4.3	Md	IIEES
2000.10.24	10:52:52	37.11	42.43	10	3.9	Md	BKRE-TMC
2004.02.01	22:11:54	37.017	42.406	10	3.7	Md	IIEES
2004.05.10	20:51:46	37.11	42.56	15	3.3	Md	BKRE-TMC
2006.02.02	5:12:33	37.0117	42.5045	32.3	3.8	Md	BKRE-TMC
2006.03.31	6:55:54	37.2663	42.671	8.3	3.4	Md	BKRE-TMC
2007.01.16	0:59:35	37.22	42.39	5	3.3	Md	EMSC
2007.05.08	18:40:17	37.2665	42.3928	5	3.5	Md	BKRE-TMC
2007.07.26	12:11:00	37.2365	42.7577	7.16	3.4	Md	AFAD-DDA
2007.09.22	8:12:34	37.15	42.61	14	3.9	Ml	IIEES
2008.01.19	4:46:42	37.2	42.75	7	3.4	Ml	EMSC
2010.01.04	7:22:35	37.2655	42.7342	5.8	3.3	Md	BKRE-TMC
2010.05.06	1:18:00	37.188	42.7183	13.64	3.1	Md	AFAD-DDA
2011.05.29	2:02:29	37.2168	42.5602	11.25	4.6	Ml	AFAD-DDA
2011.06.27	17:28:56	37.1393	42.4888	4.9	3.5	Md	BKRE-TMC
2011.07.01	0:47:00	37.1898	42.4522	7.02	3.2	Md	AFAD-DDA
2011.11.08	21:46:09	37.2803	42.4262	7.9	3.1	Md	BKRE-TMC
2011.12.04	21:56:33	37.1355	42.3622	7.2	3.2	Md	BKRE-TMC
2012.05.13	15:34:00	37.257	42.7402	7	3.2	Ml	AFAD-DDA
2012.06.09	15:16:00	37.2613	42.6638	5.28	3.2	Ml	AFAD-DDA
2012.06.14	6:25:00	37.2422	42.5342	10.52	3.7	Ml	AFAD-DDA
2012.06.14	6:38:50	37.2795	42.4408	6.2	3.1	Ml	BKRE-TMC
2012.06.14	8:50:01	37.2242	42.4355	11.06	4	Ml	AFAD-DDA
2012.06.14	8:52:51	37.1572	42.4437	11.68	5.5	Ml	AFAD-DDA
2012.06.14	11:36:33	37.2703	42.3865	5	3.2	Ml	BKRE-TMC
2012.06.14	17:17:00	37.2733	42.5633	13.2	3.4	Ml	AFAD-DDA
2012.06.14	22:37:22	37.2797	42.401	5	3.5	Ml	BKRE-TMC
2012.06.15	0:20:00	37.231	42.5283	16.94	3.3	Ml	AFAD-DDA
2012.06.16	2:10:07	37.25	42.417	5	3.9	Ml	BKRE-TMC
2012.06.16	2:44:00	37.2473	42.452	7.03	3.3	Ml	AFAD-DDA
2012.06.16	2:48:14	37.2097	42.4585	8.69	4.2	Ml	AFAD-DDA
2012.06.16	3:12:00	37.2475	42.4725	8.8	3.7	Ml	AFAD-DDA
2012.06.16	3:22:00	37.238	42.46	5.06	3.8	Ml	AFAD-DDA
2012.06.16	3:50:00	37.1648	42.4675	6.55	3.2	Ml	AFAD-DDA
2012.06.19	16:13:00	37.2583	42.5268	13.48	3.2	Ml	AFAD-DDA
2012.06.21	22:09:30	37.2852	42.363	5	3.2	Ml	BKRE-TMC
2012.06.22	23:43:00	37.2487	42.5838	6.49	3.5	Ml	AFAD-DDA
2012.07.08	7:18:22	37.2375	42.4412	8.5	3.1	Ml	BKRE-TMC
2012.07.26	19:27:00	37.2522	42.5145	5.21	3.2	Ml	AFAD-DDA
2012.11.20	7:19:23	37.2863	42.61	10.3	3.6	Ml	BKRE-TMC
2013.06.04	23:43:00	37.2028	42.4867	6.81	3.2	Ml	AFAD-DDA
2013.07.08	22:55:04	37.0835	42.4707	16.5	3.3	Ml	BKRE-TMC
2013.07.10	9:44:00	37.1438	42.4322	7.07	3.4	Ml	AFAD-DDA
2013.07.10	12:25:34	37.1055	42.4203	5	3.4	Ml	BKRE-TMC
2013.07.13	17:31:48	37.0747	42.415	8.8	4.4	Mw	BKRE-TMC
2013.07.13	18:02:35	37.2063	42.4617	7.8	3.7	Ml	BKRE-TMC
2013.07.13	18:39:00	37.1287	42.4308	9.89	3.3	Ml	AFAD-DDA
2013.07.13	19:19:00	37.155	42.4293	12.73	3.2	Ml	AFAD-DDA
2013.09.25	11:49:00	37.2555	42.5268	6.89	3.2	Ml	AFAD-DDA
2014.07.18	16:24:00	37.1033	42.4346	6.68	3.2	Ml	AFAD-DDA
2015.01.11	1:11:35	37.2372	42.4783	5.3	3.8	Ml	BKRE-TMC

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In the last 65 years, nearly 11 earthquakes of M4.0 to 5.5, and about 68 earthquakes of M3.0 to 4.0 have struck the Zakho – Silopi region (Table 1). In general, all earthquakes are shallow (depth ≤ 33 km) and of moderate magnitude (magnitude ≤ 5.5) (Fig. 4 and Table 1). Historically, there have been no earthquakes in this region (Ambraseys et al. 1994). The AFAD-DDA catalogue provides fault plane solutions for the 4 biggest events in the Zakho – Silopi region, with magnitudes of 4.0 – 5.5, and focal depths at 8.69 – 11.68 km (Fig. 5). These focal mechanisms were created by the FOCMEC program using the P-wave first motion data (Snoke et al., 1984). The FOCMEC program provides more realistic solutions even if there is a poor data or limited number of stations (Sasaki and Kaieda, 2002; Snoke 2003; Oros, 2013). The QuickBird images with 0.6 m resolution, dated 22 June 2005, were used for mapping of lineament patterns in the Zakho – Silopi region using the ArcGIS software. This data were provided by the Kurdistan Region Statistics Office (KRSO).

Stress tensor inversion analysis

Focal mechanisms are the best kinematic indicators for the active subsurface faults (Zoback, 2007; Yang et al., 2012). The moment tensor inversion was applied to estimate the directions of recent principal stresses from focal mechanisms of major earthquakes in the Zakho – Silopi region using the rotational optimization method of Delvaux and Sperner (2003) (Win-Tensor program, version 5.8.4). The state of stress is defined by the directions of the main stresses (σ1, σ2, and σ3), the horizontal stresses and the stress ratio ($R = (\sigma2 - \sigma3)/(\sigma1 - \sigma3)$).

Lineament analysis

The analysis of lineament patterns has important implications for seismological and neotectonic studies (Stefouli et al., 1996; La Pointe et al., 1999). Lineaments can be defined as natural linear to curvilinear features that extend for 1 mile or more (Lattman, 1958). Lineaments on satellite images may reflect a number of 2-dimensional features, such as fault traces, fracture zones, foliations, lithological boundaries and drainage systems, with little or no information on feature types, their dips or depths (Sander, 2007; Holland, 2012). Lineaments probably represent the surface expression of subsurface structures (Singha and Gupta 2010). The methodology of interpretation involves the identification and mapping of lineaments, based on the field experiences, from QuickBird images using the ArcMap.

RESULTS

Stress inversion

The identification of fault and auxiliary planes in the 4 earthquake focal mechanism solutions is mainly dependent on the tectonic setting of the Zakho – Silopi region (Fig. 5). Figure 6 and Table 2 show the directions of the principal stresses, the horizontal stresses and the stress ratio were inverted from the fault plane solutions of largest earthquakes using the rotational optimization method. The moment tensor solutions (no. 2 and 3) show thrust faults with two nodal planes, dipping towards north-east and south-west (Fig. 5). In this case, earthquakes can be confidently related to the NE-dipping planes, as this is consistent with under-thrusting of Arabia beneath the Eurasian plate (Allen et al. 2013). The focal mechanisms (no. 1 and 4) correspond to strike - slip faults, with orthogonal nodal planes that oriented NE-SW and NW-SE (Fig. 5). The steeply dipping planes with NW-SE strikes are considered as the probable dextral strike-slip fault planes. These NW-striking dextral strike-slip fault planes are parallel to the Main Recent Fault that trending NW-SE and forming the NE border of the Arabian plate, as well as it accommodates the right-lateral strike-slip motion of the N-S Arabia-Eurasia convergence (Talebian and Jackson, 2002; Authemayou et al. 2009).

The present-day orientation of stress calculated from the inversion of fault plane solutions (no. 1 and 4) show dextral strike-slip faulting regime, with σ1 plunging (06° towards 012°) and (16° towards 341°) respectively, whereas the σ3 trending 03°/282° and 07°/073° respectively (Fig. 6 and Table 2). The value of the stress ratio (R = 0.75) suggests that the magnitude of the intermediate principle stress (σ2) is close to the minimum stress (σ3) (Presti et al., 2013). On the other hand, the state of stress orientation derived from the mechanism solutions (no. 2 and 3) show compressional deformation (thrust faulting regime), with σ1 trending 11°/217° and 00°/232° respectively, while the σ3 plunging (79° towards 040°) and (89° towards 332°) respectively (Fig. 6 and Table 2). The stress ratio (R = 0.5) indicates unequal magnitudes of the main stresses (Witthuhn-Rolf, 1997).

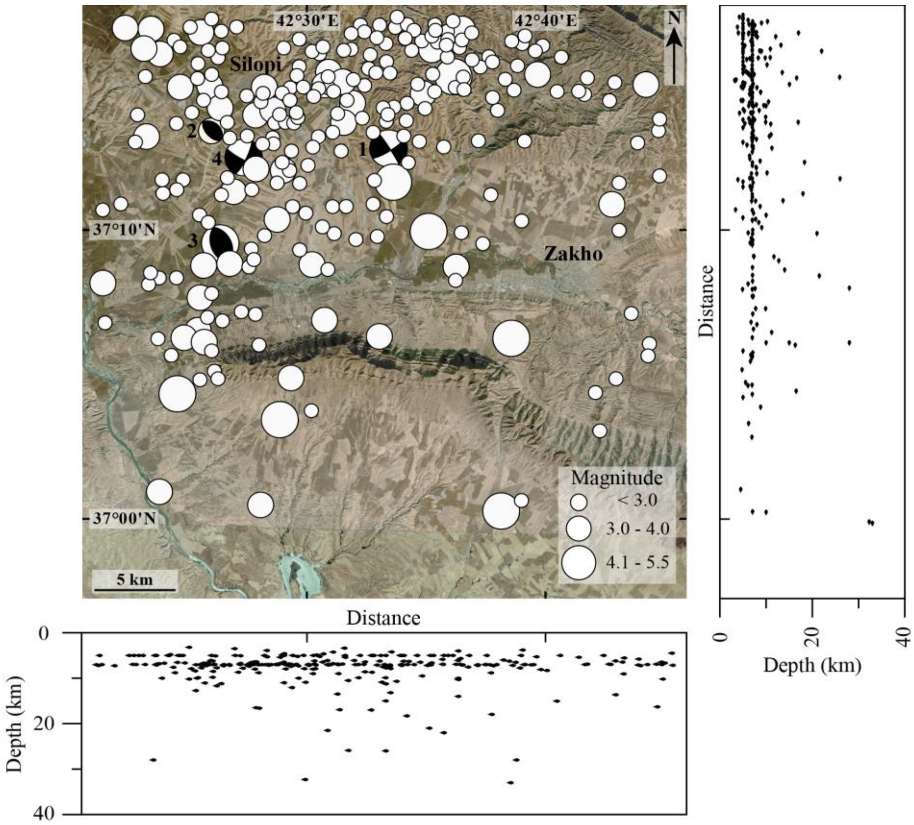

Fig.(4): Seismicity map of the Zakho – Silopi region showing the epicenter locations, magnitudes, focal depths, and focal mechanisms of largest earthquakes (see Table 1 for data sources).

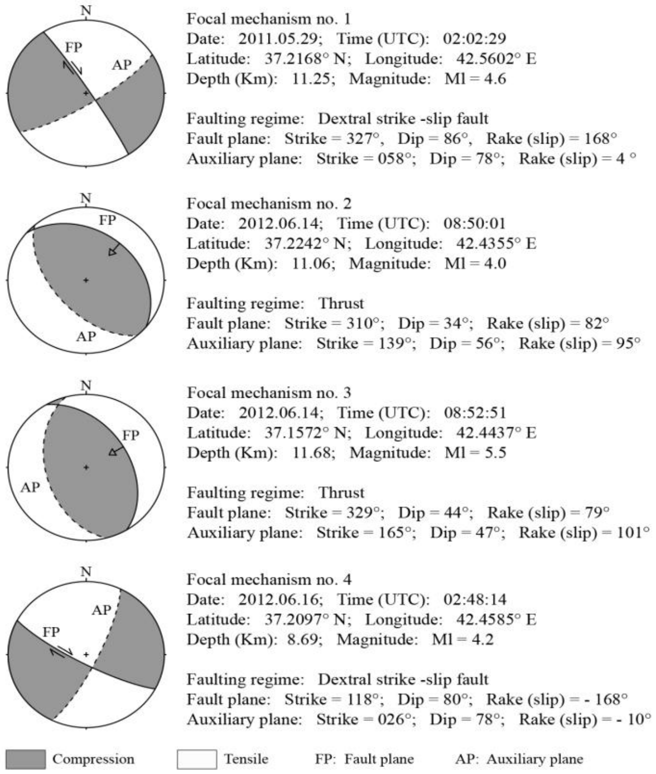

Fig.(5): Focal mechanisms of largest earthquakes in the Zakho – Silopi region (from the Turkish AFAD-DDA catalogue).

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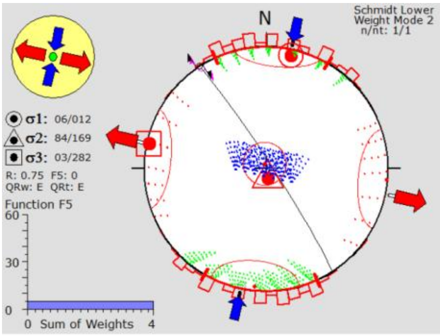
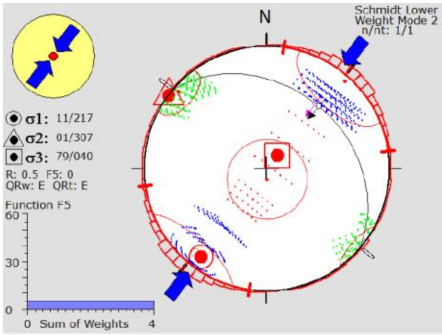
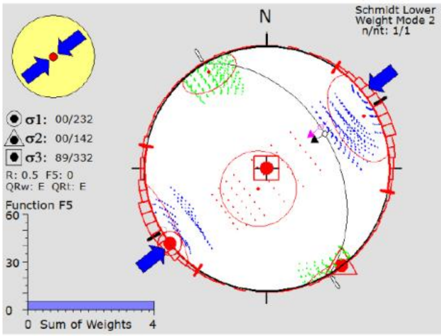


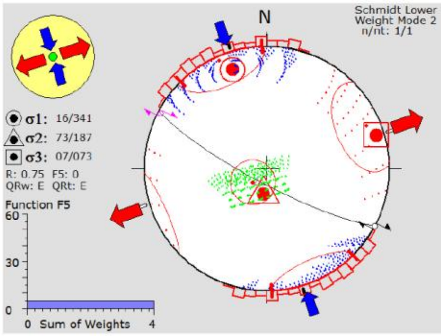
a) Focal mechanism no. 1



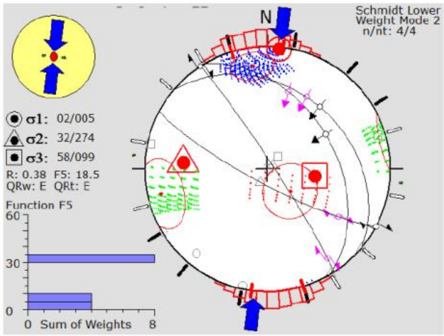
b) Focal mechanism no. 2



c) Focal mechanism no. 3



d) Focal mechanism no. 4



e) Average orientation

Fig.(6): Formal stress inversion of strongest earthquakes in the Zakho – Silopi region by the rotational optimization method (Win-Tensor program).

Table (2): Stress tensor inversion results of the rotational optimization method for the earthquake focal mechanisms in the Zakho – Silopi region.

Focal mechanism number	Moment stress axes			Map parameters			
	σ1	σ2	σ3	Maximum horizontal stress axis (SH)	Minimum horizontal stress axis (Sh)	Stress ratio (R)	Stress regime
1	06° / 012°	84° / 169°	03° / 282°	012°	102°	0.75	Dextral strike-slip
2	11° / 217°	01° / 307°	79° / 040°	040°	130°	0.50	Thrust
3	00° / 232°	00° / 142°	89° / 332°	059°	149°	0.50	Thrust
4	16° / 341°	73° / 187°	07° / 073°	163°	073°	0.75	Dextral strike-slip
Average orientation	02° / 005°	32° / 274°	58° / 099°	-	-	0.38	-

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The average stress orientations obtained from the fault plane solutions of the 4 major earthquakes show that the present-day direction of (σ1) in the Zakho – Silopi region is a nearly N-S trend (N05°E) with slightly horizontal (plunge = 2°), while the minimum compressive stress (σ3) is a nearly E-W orientation (S81°E) and plunges at (58°) (Fig. 6 and Table 2). These results are consistent with the tectonic setting of this region. However, the accuracy of the calculated stress orientations at any region is strongly depends on the appropriate choice of the available focal mechanisms (Medina and El Alami, 2006).

Lineament patterns

The visual interpreted map of lineaments from 0.6 m resolution QuickBird images of the Zakho – Silopi region was presented in Figure 7. Altogether 465 lineaments were mapped and characterized on QuickBird images based on the linear morphotectonic features, such as fracture zone traces, fault escarpments, linear ridges and valleys, linear cliff faces, linear rivers and drainage networks, as well as linear traces of vegetative covers. Lineaments range in length from 1.8 km to 17.2 km. The lineament density map shows that the distribution of lineaments is not homogeneous within the study area because the majority of lineaments occur within the competent beds of the Eocene, Miocene and Pliocene sequences (Figs. 2, 7 and 8).

The analysis of lineament orientations in the Zakho – Silopi region reveals three distinct sets; N05°E, NE-SW, and NW-SE (Fig. 9). These three dominant sets are consistent with previous lineament studies, such as Numan and Bakose (1997), Alridha et al. (2012), Thannoun (2013). Fractures are the most common result of brittle deformation of rocks that formed by the tectonic stresses (Hancock, 1985; Pollard and Aydin, 1988; Mandl, 2005). The stress fields and fracture types at the time of fracturing can be determined from the geometry of fracture surfaces and bedding planes (Stearns, 1968; Hancock, 1985 and 1991; Dunne and Hancock, 1994) (Fig. 10). Following the neotectonic stress analysis of brittle tectonic structures presented by Hancock (1985 and 1991), the orientation of the three dominant lineament sets suggests that the present-day direction of (σ1) in the Zakho - Silopi region is N05°E (Fig. 9). The same stress direction was also inverted from the earthquake focal mechanism solutions (Fig. 6 and Table 2).

DISCUSSION

The seismicity of the Zagros belt is resulted from the compressional reactivation of pre-existing basement faults due to the active continental collision between Arabia and Eurasia (Berberian, 1981). The present-day rate of N-S continental convergence between Arabia and Eurasia is calculated from the GPS measurements to be at 18 ± 2 mm/year (McClusky et al. 2000). The relative motion obtained from the GPS Euler vectors along the North Anatolian fault and the Zagros belt to the northeast are (24 ± 1 mm/year) and (19 – 23 ± 1 mm/year), respectively; whereas in the Gulf of Aqaba and on the Dead Sea fault, the relative motion increasing from 5.6 to 7.5 mm/year (± 1 mm/year) from south to north (McClusky et al. 2003). Several areas of the Kurdistan region are seismically active as evidenced by historical and recent earthquakes, as well as most of the major earthquakes were sourced by the reactivation of thrust and strike-slip basement faults (Alsinawi and Issa, 1986; Fahmi et al., 1986; Ambraseys et al. 1994; Mohammad 1998; Alridha et al., 2012; Doski and Mohammad, 2016).

The location and trend of the subsurface basement faults may be detected by a linear distribution of earthquake epicentres; these patterns are called seismic lineaments (Nowroozi, 1995). The alignment of earthquake epicentres clearly indicates that there is a subsurface seismically active basement fault and could be the source of strong earthquakes in the future (Jacobi, 2002; Almeida-Filho et al., 2009; Talukdar and Barman, 2012; Saravanavel and Ramasamy, 2014; Phelps et al., 2015). Some of the seismic lineaments were interpreted along the south-eastern region of the United States based on epicentral alignments of earthquakes (Nowroozi, 1995). The locations of these lineaments were interpreted as the intersection of pre-existing, weak planar zones with the earth's surface. Vlastos et al. (2002) identified active seismic lineaments in the Aegean area based on the linear clusters of strong earthquakes, and concluded that there is a good agreement between the seismically active linear structures and the seismotectonic setting of the Aegean area.

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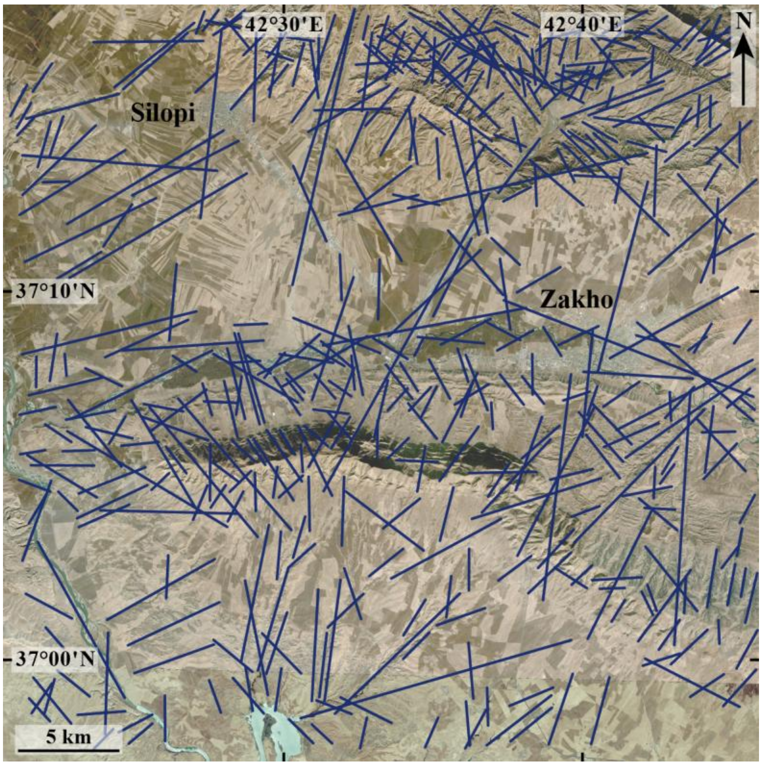

Fig.(7): Map showing the probable locations of lineaments that delineated by visual interpretation from 0.6 m resolution QuickBird images of the Zakho – Silopi region.

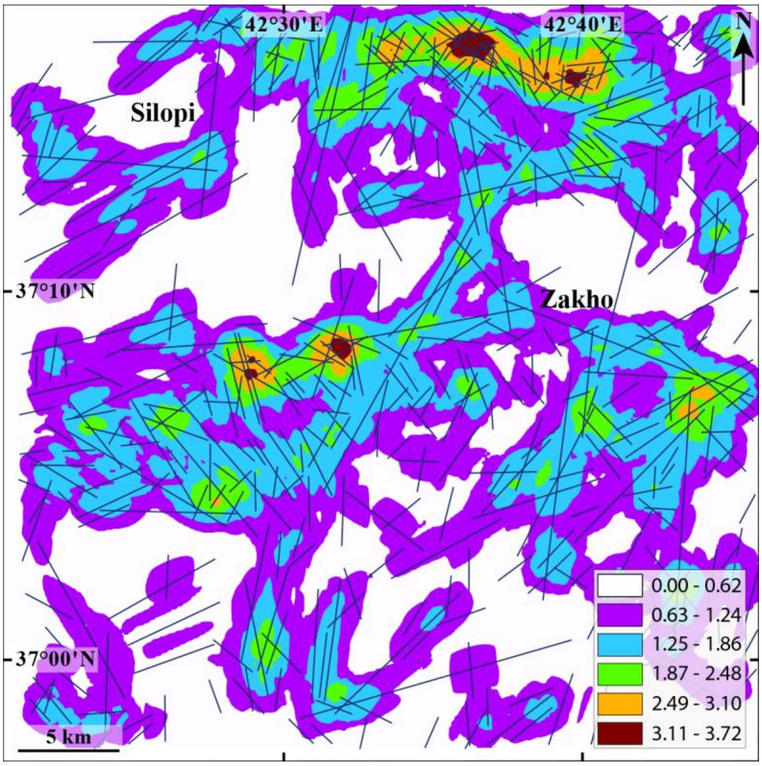

Fig.(8): Density map created from the total number of lineaments per square km area in the Zakho – Silopi region.

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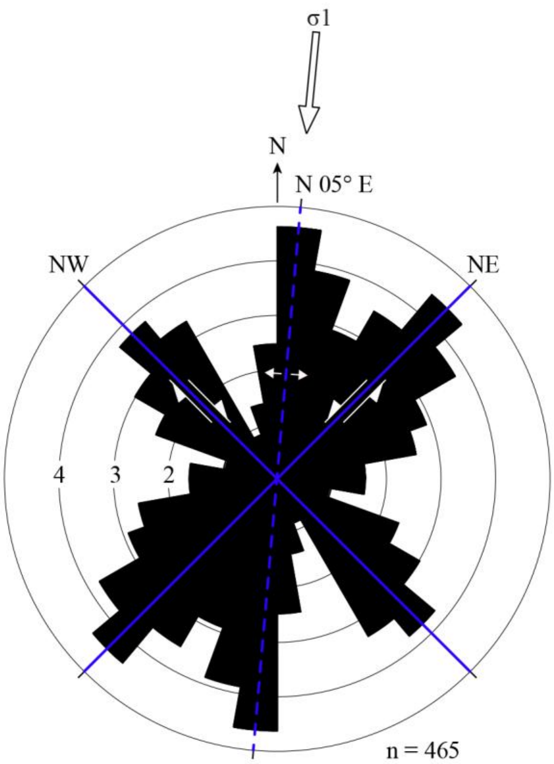

Fig. (9): Frequency rose diagrams showing the main orientation classes of lineaments within the Zakho – Silopi region.

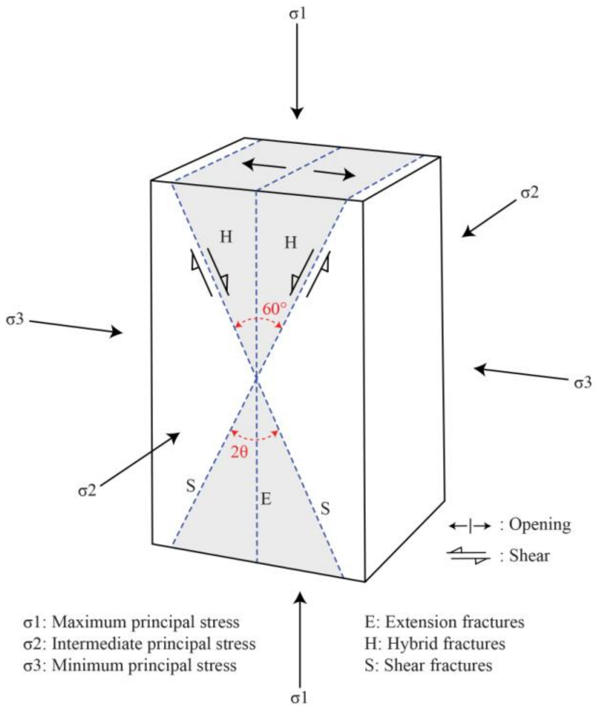

Fig. (10): Relationships between fracture types and principal stress axes during the compressive failure of brittle materials (from Hancock, 1985 and 1991).

Journal of University of Duhok., Vol. 20, No.1 (Agri. and Vet. Sciences), Pp 13-30, 2017
DOI: https://doi.org/10.26682/avuod.2017.20.1.3

Four potentially active NE- and NW-trending seismic lineaments were inferred in the Zakho - Silopi region based on the linear distribution of earthquake epicentres with magnitudes greater than (3.0) (Fig. 11). These linear structures extend from 22 km to 42 km. There is a good agreement between the orientation of nodal fault planes and the trend of seismic lineaments, except in the case of focal mechanism (no. 3) and seismic lineament (no. B) (Figs. 5 and 11). This suggests a fifth seismic lineament with NW-trending, passes through the epicentral location of earthquake focal mechanism (no. 3) and intersects with the seismic lineament (no. B). The fifth seismic lineament is considered as "uncertain" due to a few number of its earthquake epicentres. The seismic lineaments in the Zakho – Silopi region may represent reactivated basement faults that cause major earthquakes over this region (Fig. 11). Therefore, the area along or around these active seismic lineaments has the potential to produce major earthquakes in the future.

It is inferred from the trend analysis of lineament patterns and seismic lineaments that the basement faults in the Zakho - Silopi region are characterized by three linear tectonic trends: roughly N-S, NE-SW and NW-SE (Figs. 9 and 11). Many of the basement faults were exposed at the surface as lineaments or faults (Plafker, 1964; Henden, 1981; Numan and Al-Azzawi, 1993; Singh and Singh, 2005; Wilson et al., 2010; Saravanavel and Ramasamy, 2014; Sissakian et al., 2014; Abdunaser, 2015). The Zagros basement in Iran consists of seismically "active" and "inactive" faults with dominant N-S, NE-SW and NW-SE trends (Bahroudi, 2003). The same basement fault trends were also recognized by Burberry (2015) within the Kirkuk Embayment (Kurdistan) using the gravity data, fault maps of Jassim and Buday (2006a) and lineament analyses: the NW-SE 'Najd system' trend, N-S 'Nabitah system' trend, and the NE-SW 'Transverse system' trend. Kent (2010) identified three tectonic inversion trends in northern Iraq and Syria: the NW Erythrean 'Zagros' trend, the E-W Tethyan 'Taurus' trend, and the NE Aualitic 'Palmyra' trend, as well as concluded that these regional trends are related to the basement fault systems that probably originated in Paleozoic as normal faults, and inverted into thrust faults.

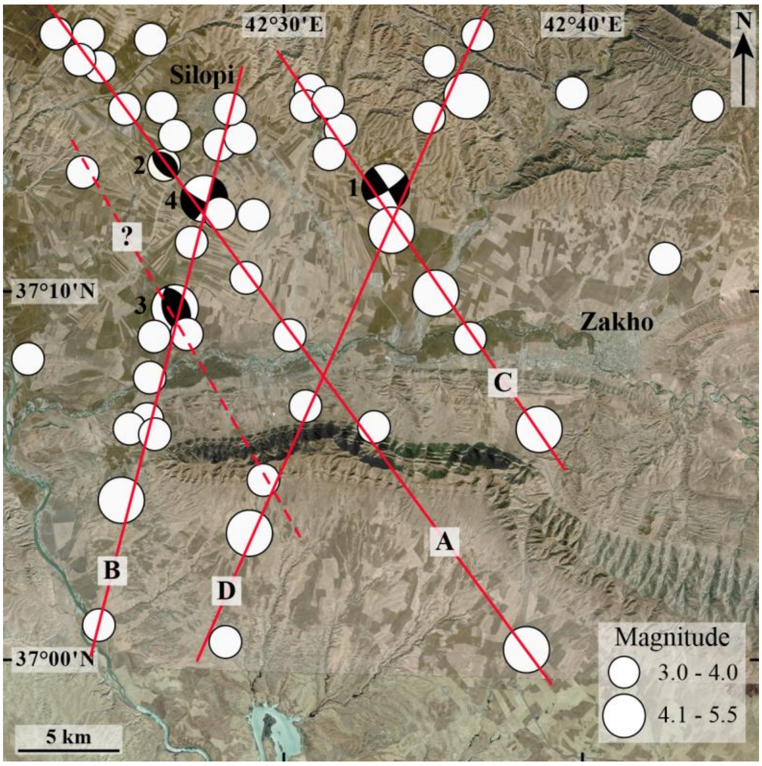

Fig. (11): Potential seismic lineaments within the Zakho – Silopi region.

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Ali et al. (2013) studied the basement structure in the United Arab Emirates using the gravity anomaly data, and concluded that the basement of the Arabian plate is characterized by N-, NE- and NW-trending lineaments. Four major fault trends were also recognized in the Arabian basement: N-S "Arabian trend", NE-SW "Aualitic trend", NW-SE "Erythraean trend" and E-W "Tethyan trend" (von Wissmann et al., 1943; Henson, 1951; Edgell, 1992). The N-S "Arabian trend" lineaments associated with the extensional basement structures (horsts and grabens) that were periodically reactivated throughout the time, whereas the NE- and NW-trending lineaments are represented by the left-lateral and right-lateral strike-slip basement faults, respectively (Henson, 1951; Edgell, 1992).

The basement faults in the Zakho - Silopi region were probably formed in Late Precambrian as normal faults, and subsequently inverted into thrust faults as well as reactivated continuously from the Late Cretaceous to the continental collision between Arabia and Eurasia from the Late Eocene onwards (Numan, 1997; Jassim and Goff 2006; Kent, 2010).

CONCLUSION

1- The present-day direction of (σ1) in the Zakho – Silopi region as inferred from the inversion of fault plane solutions and lineament analysis is N05°E. This direction is entirely consistent with the active N-S shortening across the Kurdistan region due to the Mid-Miocene collision of Arabia with the Turkish and Iranian plates.

2- The seismic activity in the Zakho – Silopi region is mainly related to the neotectonic reactivation of pre-existing thrust and strike-slip basement faults by a nearly N-S compression that resulted from the on-going convergence of Arabia and Eurasia./////**3-** Four active seismic lineaments were detected in the Zakho - Silopi region by the linear distribution of earthquake epicentres. These reactivated basement faults have the potential to produce large earthquakes in the future. Therefore, a more detailed earthquake risk assessment is necessary.

4- Three distinct basement fault trends were identified from the orientation analysis of lineament patterns and seismic lineaments in the Zakho - Silopi region; nearly N-S, NE-SW and NW-SE. These basement faults were periodically reactivated from Late Cretaceous onwards.

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دوبارە ئەکتیف کرنا پێک هاتێن شەنگەستەیی ل دەڤەرا زاخو – سلوبی یا سنوری
دناڤبەرا کوردستانا عیراقێ و تورکیا

پوختە

جور و ئاراستێ پێک هاتێن شەنگەستەیی یێن چەرخێ بەری کامبری و پەیوەندیا وان ب بیڤەلەرزا و ئاراستێن شوینا پێک هاتێن شکەستنێ بویە بناغەک ژبو شیکرنا دوبارە ئەکتیف کرنا فولتێن پێک هاتێن شەنگەستەیی ل دەڤەرا زاخو – سلوبی. ئەڤ دەڤەرا سنوری دناڤبەرا کوردستانا عیراقێ و تورکیا دکەڤیتە سەر سنورێ باکورێ روژهەلاتا پلێتا عەرەبی و پشکێن زاگروسێ ئوروجینی بخوڤە دگریت دکەل جیاێن بلند ل عیراقێ. بیڤەلەرزێن دەڤەرا زاخو – سلوبی ژ قەبارێ بچویک و توندن کو گەلەک ژ وان بوینە ئەگەرێ دوبارە ئەکتیف کرنا تەکتونی یا فولتێن پێک هاتێن شەنگەستەیی و خشیانا سترایکی ژ ئەگەرێ لێکدانا بەردەوام یا کیشوەری دناڤبەرا پلێتێن عەرەبی و اوراسی دا. چوار پێکهاتیێن هێلێن بیڤەلەرزی هاتینە دەست نیشانکرن (باکورێ روژهەلات و باکورێ روژ ئاڤا) لسەر بنەمایێ هێلێن بیڤەلەرزێن سەرەکی و ئاراستێن فولتێن بیڤەلەرزا داکو ببیتە فولتێن پێک هاتێن شەنگەستەیی یێن پتر چالاک ژ بارێ بیڤەلەرزا ڤە ل دەڤەرا زاخو - سلوبی. دەلیڤا رویدانا بیڤەلەرزا د پاشەروژێ دا ل دەڤەرێ دێ ڤەگەرێن بو دوبارە ئەکتیف کرنا پێک هاتێن شەنگەستەیی لسەر درێژاهیا هێلێن بیڤەلەرزا ژبەر وێ چەندێ یا باشە هەلسەنگاندنەکا تەمام بهێتە ئەنجامدان لسەر مەترسیێن بیڤەلەرزا لسەر باژێرێن سەرەکی . ئاراستێ ئیجهادا نوکە کو ژ ئەنجامێ ئاراستێ فولتێن بیڤەلەرزا و شروڤەکرنا ئاراستێ پێک هاتێن شەنگەستەیی ل دەڤەرا زاخو – سلوبی هاتیە دیتن کو دەڤەر د ئیجهادە کا بەردەوام دا یە ل درێژاهیا ئاراستێ باکور– باشور. شروڤەکرنا ئاراستێ پێک هاتێن شەنگەستەیی و هێلێن بیڤەلەرزا نیشان دەت کو سێ ئاراستێن پێک هاتێن شەنگەستەیی ل دەڤەرا زاخو – سلوبی هەنە و ئەوژی ب نزیکی ڤە دکەڤیتە ئاراستێ باکور – باشور، باکورێ روژ هەلات – باشورێ روژئاڤا، باکورێ روژئاڤا – باشورێ روژهەلات. فولتێن پێک هاتێن شەنگەستەیی درست بوینە د چەرخێ بەری کامبری دا ب شیوێ فولتێن نورمال باشان هاتیە گوهارتن بو فولتێن ریفیس دگەل هندەک خشیانا سترایکی و دوبارە ئەکتیف کرنا پێک هاتێن شەنگەستەیی ب شێوەیەکێ بەردەوام هەر ژ دوماهیکا جەرخێ کریتاسی تاکو نوکە.

اعادة التنشيط للفوالق القاعدية في منطقة زاخو – سلوبي الحدودية بين كردستان العراق و تركيا

الخلاصة

أن طبيعة وأتجاه التراكيب القاعدية لعصر ما قبل الكامبري المتأخر وعلاقتها بالتوزيع الزلزالي والتراكيب الخطية السطحية وفرت أساسا لدراسة أعادة تنشيط الفوالق القاعدية في منطقة زاخو- سلوبي. ان هذه المنطقة الحدودية بين كردستان العراق وتركيا تقع على الحدود الشمالية الشرقية من الصفيحة العربية وتغطي بعض الأجزاء من حزام طيات زاكروس فضلا عن نطاق الطيات العالية واقدام التلال في العراق. تتصف منطقة زاخو- سلوبي بالزلازل متوسطة الحجم والضحلة والتي نجمت في معظمها عن أعادة النشاط التكتوني الحديث للفوالق القاعدية المعكوسة والأزاحة المضربية بسبب التصادم القاري النشط والمستمر بين الصفيحة العربية والأوراسية. تم تحديد أربعة تراكيب خطية زلزالية (شمالية شرقية وشمالية غربية) على أساس التجمع الخطي للزلازل الرئيسية وأتجاه مستويات الفوالق الزلزالية لتمثل الفوالق القاعدية الأكثر نشاطا من الناحية الزلزالية في منطقة زاخو- سلوبي. ان احتمالية حدوث الزلازل المدمرة في المستقبل في هذه المنطقة ستكون على الأرجح مرتبطة باعادة النشاط للفوالق القاعدية على طول التراكيب الخطية الزلزالية النشطة لذلك يوصى باجراء تقييم مفصل للمخاطر الزلزالية على المدن الرئيسية والتجمعات الحضرية. ان اتجاه الاجهاد الحالي الناتج من انعكاس اتجاهات الفوالق الزلزالية و تحليل التراكيب الخطية في منطقة زاخو – سلوبي يشير الى ان المنطقة تعاني من اجهاد الضغط المستمر على طول اتجاه شمال - جنوب **(N05°E)**. أن أنماط تحليل أتجاه التراكيب الخطية والخطوط الزلزالية تدل على وجود ثلاثة أتجاهات خطية للفوالق القاعدية في منطقة زاخو – سلوبي وهي تقريبا باتجاهات شمال- جنوب، شمال شرق- جنوب غرب، شمال غرب- جنوب شرق. تكوين هذه الفوالق القاعدية ربما بدأت في عصر ما قبل الكامبري المتأخر على شكل فوالق أعتيادية ثم تحولت الى فوالق معكوسة مع حدوث أزاحات مضربية وأعادة التنشيط بشكل مستمر من اواخر العصر الكريتاسي الى الوقت الحاضر.