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# The 11th February, 2004 Earthquake of The Dead Sea, Jordan

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**Abstract:** The Dead Sea fault system and its branching faults represent one of the most tectonically active regions in the Middle East. The present investigation emphasis on the recent earthquake swarm, which occurred at the end of 2003 and extended to the middle of July 2004 with critical examination on the strongest event of 11th Feb. 2004. The present study examines the location of the strongest events (Dec. 31st, 2003; February 11th, 2004 and March, 15th, 2004) and correlates them with the various tectonic elements in the Dead Sea basin. The source mechanism of the three events is also examined. The focal mechanism and the depth of the events were obtained from the motion of the P waves. The fault plan solution of the main event (11th Feb.), indicates that the rupture propagated down dip, where the motion was initiated mainly as a normal component with slight strike-slip movement. At the same time, the analyses of the aftershocks during the subsequent two weeks show that the source mechanism is the same as that of the main event. The source mechanism of the event, which occurred at Dec. 31st and March, 15th indicates that the movements were initiated as left-lateral strike-slip motion with a slight normality. The seismic energy appears to have migrated from the south to the north during the period of Dec., 31 up to March, 12, where the seismic energy has a migration character to the southern block of the eastern side of the Dead Sea after March, 12, which lead the seismic event to occur in March, 15. Therefore, another relatively major event occurred in July, 8, 2005 as predicted.

**Key words:** Middle east, Dead Sea rift, earthquake swarm, focal mechanism**, s**trike slip, P-waves

## INTRODUCTION

The Dead Sea earthquake occurred on February, 11th, 2004 at 0815 UTC at 31.694° N, 35.581° E, at a depth of about 21 km, as declared by the Jordan Seismological Observatory (JSO) at the Natural Resources Authority, Jordan. Based on coda duration the calculated magnitude was Mc= 4.9. It was the largest earthquake to occur in the Dead Sea basin in the last two decades. It was felt in Jordan (strongly felt in Amman), Israel, Palestine Authority, Lebanon, southern part of Syria, Egypt and northern part of Saudi Arabia. The main shock was followed by aftershock sequence swarm. The main shock caused minor damage to the surrounding areas, where rocks slipped from the surrounding mountains on the eastern side of the Dead Sea.

This earthquake remind people with Jericho earthquake, the strongest one occurred in the last century (Ml = 6.25). Therefore, the February earthquake demonstrates the potential of the Dead Sea Rift for large destructive events.

The Dead Sea rift is a sinistral transform plate boundary separating the Sinai sub-plate in the west (part of African plate) and the Arabian plate in the East (Fig. 1A). The rift is a unique morphotectonic feature, which extends from the northern end of the spreading Red Sea to the Taurus zone of convergence in Turkey (Fig. 1A). The motion along the Dead Sea transform fault probably initiated in the Middle Miocene (15.5-11.5 million years ago). The initial movements along the Dead Sea transform were nearly pure strike-slip, but in post-Miocene time (about 5 million years ago) they may have changed to strike-slip with small component of oblique extension resulting in the opening of basins along the transform valley and the Gulf of Aqaba[1]. Since the time of its formation, 105 km of left lateral horizontal movement has occurred along the Dead Sea transform fault[1-4]. Out of the 105 km of the total left lateral offset along the transform, only 30 km occurred in the last 5 million years, implying a slow relative plate average velocity (6 mm/year) between African (Sinai sub-plate) and Arabian plates[5]. On the other hand, the global plate model indicates a faster differential motion (10-15 mm/year) between African and Arabian plates. The difference in the velocity of the plate motion along the plate boundary could be related to the fault segmentation. One of the latest study "Anatomy of the Dead Sea transform: Does it reflect continuous changes in plate motion?" carried out by

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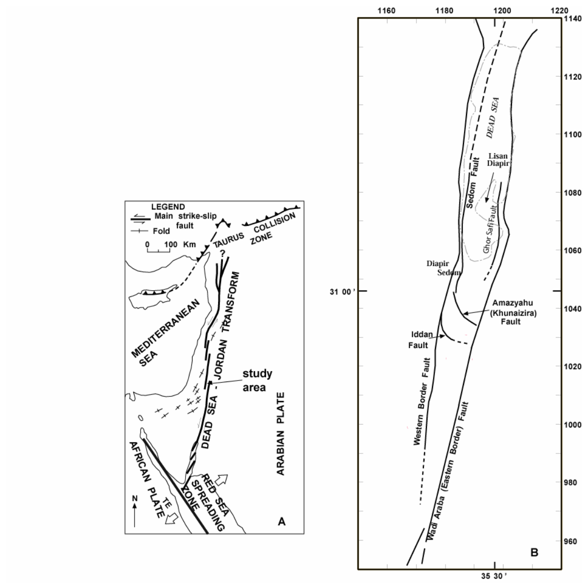


Fig. 1: A. Out line of the Dead Sea transform and main strike slip faults (modified from Gardosh *et al*., 1997). B The Dead Sea basin. The main tectonic elements shown. Coordinates in Cassini Palestine grid

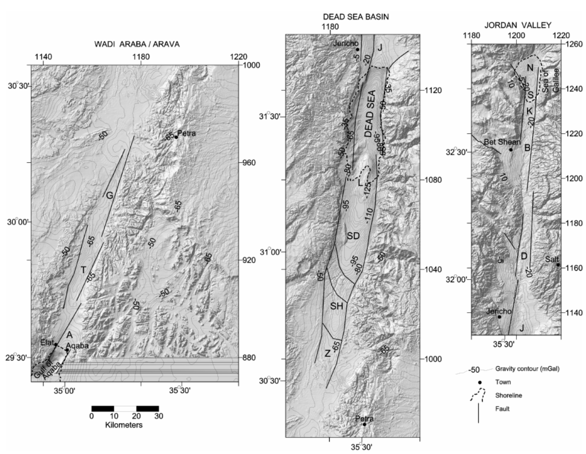


Fig. 2: Bouguer gravity anomaly map of the central and northern part of the Dead Sea transform, Jordan and Israel, corrected with density of 2670 kg/m$^3$. Contour interval is 3 m Gal. Background: shaded relief topography from digital terrain model (Hall, 1993). Abbreviated basin names: B, Bet Sheen; D, Dam; J, Jericho; K, Kinarot (Bakura). Dead Sea basin is further divided into following sub-basins (ten-Brink and Ben-Avraham, 1989; Bartov *et al*., 1998): Z- Zofar; SH, Shezaf; SD, Sedom; L, Lisan, Dead Sea, G, Gharandel, T, Timna- Qa-Taba and A, Aqaba-Elat basins

ten-Brink *et al.*[6] shows that the Dead Sea fault system which extends from north of the Gulf of Aqaba to Hulla basin (along 500 km long plate boundary) comprises at least 15 fault segments with 25-55 km lengths range

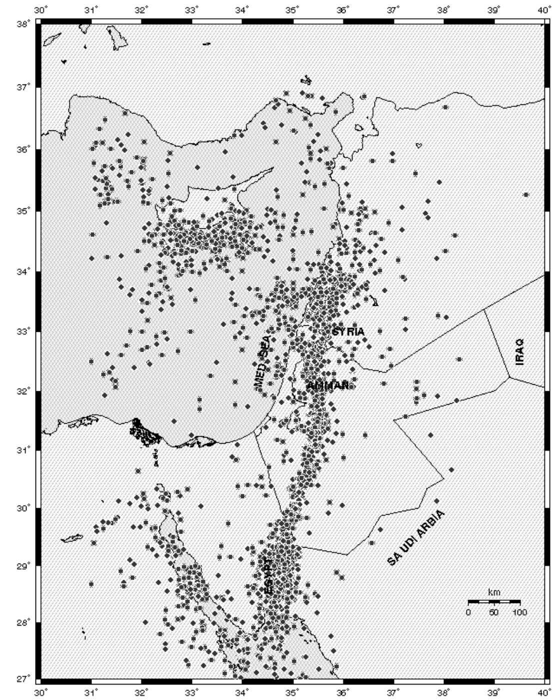


Fig. 3: The Seismicity of the Dead Sea transform (events location 1900-2003, Jordan Seismological Center)

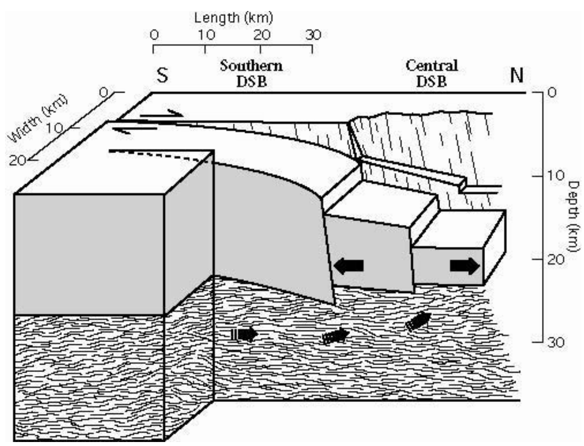


Fig. 4: Conceptual model for the development of the Dead Sea basin (Al-Zoubi & ten-Brink, 2002

(Fig. 2)[6]. Some of the fault segments are buried and do not offset or perturb the upper sedimentary section[7,8]. Several tectonic structures have formed along the fault segments. These are the Gulf of Aqaba, Wadi Araba (including Aqaba, Qa-Taba and Gharandel basins), Dead Sea, Jordan Valley (including Jericho, Damia, Bet-Shean and Bakura (Kinarot)), Sea of Galilee and Hulla basins (Fig. 2).

The Dead Sea fault system and its branching faults are associated with the highest concentration of the earthquakes in the Middle East region (Fig. 3). Numerous destructive earthquakes occurred during historical times (48, 1068, 1261 and 1588 AD[9,10].

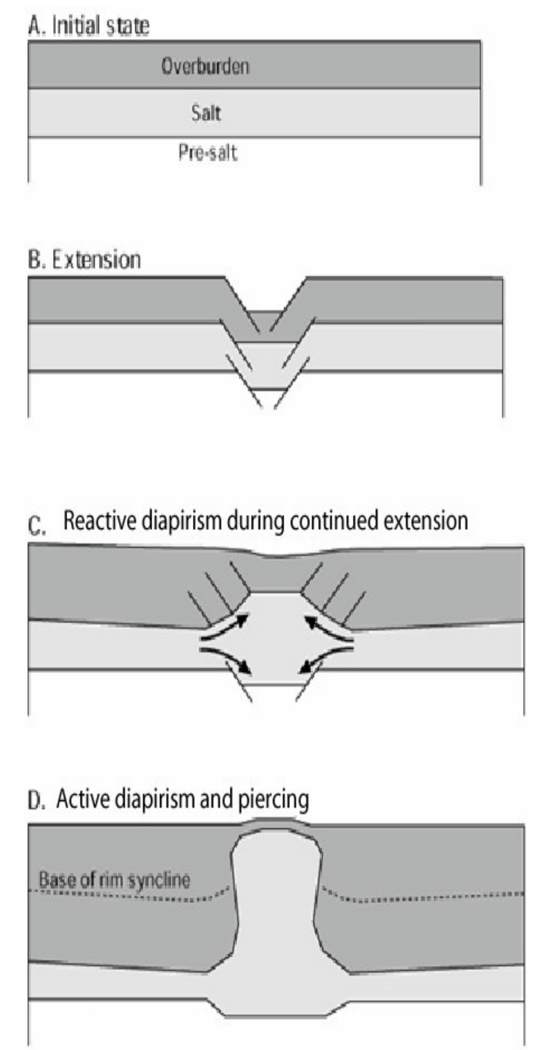


Fig. 5: A conceptual model of the Lisan Diapir during the Pleistocene. Stage A: initial stage, B and C were separated for the sake of illustrating. This model not include possible recent periods of lateral compression and renewed diapiric rise (Al-Zoubi & ten-Brink, 2001)

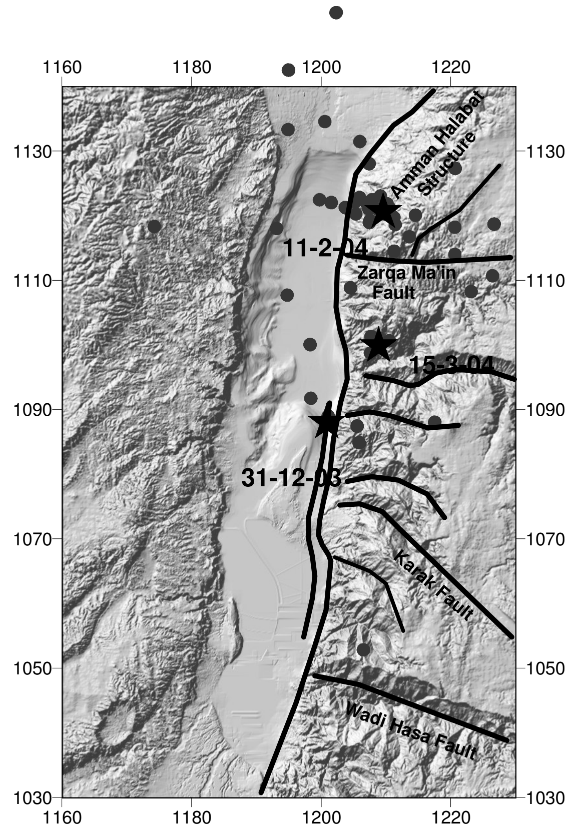


Fig. 6: The Main tectonic elements of the eastern side of the Dead Sea and the epicenter of the earthquake swarm and the major events, 2004, superimposed on shaded relief image of the Dead Sea basin (Hall, 1993)

The most recent destructive earthquakes that have ruptured the plate boundary are the 1927 Jericho earthquakes and 1995 the Gulf of Aqaba earthquake, where the Jericho earthquake occurred in the northern end of the Dead Sea basin. Therefore, the present study tries to correlate the location of the strong events with the tectonic elements of the surrounding areas and to examine the source mechanism of the main shock and the strongest events.

**Geological and structural setting of the Dead Sea basin:** The Dead Sea basin is the most prominent morphotectonic pull-apart basin along the Dead Sea rift. The basin is about 135 km long, 10-20 km wide and is, at least 8.5 km deep[11]. The basin formed between sinistral, left- stepping en-echelon strike-slip faults (Fig. 1B). The steps may have migrated northward with time[12], because of the depocenter shift towards north[6,13]. The center of the Dead Sea basin has a full pull apart geometry[14], indicating that the eastern and western bounding faults run parallel to the shore of the Dead Sea as a single major basin boundary fault. The latest studies show that the Dead Sea basin comprising of three blocks, i.e., sunken, intermediate and rim blocks. The intermediate block (median block), which is observed along the eastern and western boundaries of the basin caused by the gravitational movement (sliding). It is separated from the deeper part of the basin by the Ghor Safi fault in the eastern side (Fig. 1B)[11,15].

Katzman *et al*.[16] suggested that the Dead Sea basin is sagging towards the center. Recently, Al-Zoubi and ten-Brink[15] found that the Dead Sea basin is sagging from the south to the north (towards the center) without major offsets in the basin fill. Based on Bouguer gravity map, it is worth mentioning that the basin is not bounded by the faults at the northern and southern ends. The sagging process in the Dead Sea indicates that the upper crust has lost its foundation over a wider area than just the deepest part of the basin,

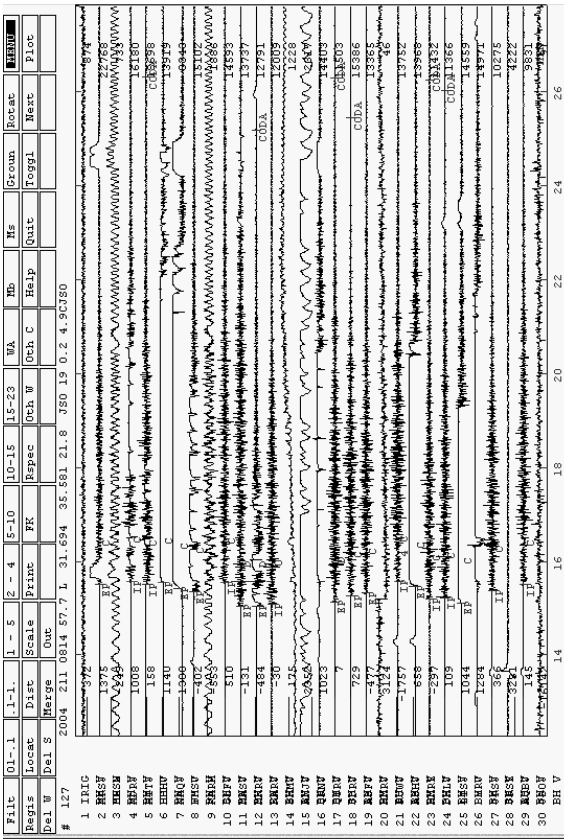

Fig. 7: The Seismogram of the main event of Feb. 11th, 2004, recorded by JSC

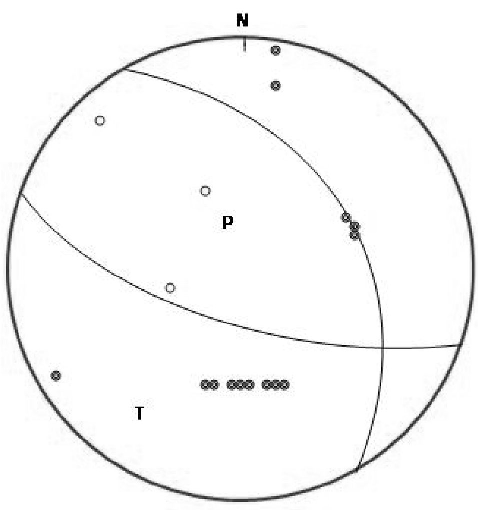


Fig. 8: Fault solution (focal mechanism) of the earthquake of Feb. 11th, 2004

which could happen if the deepest part of the basin has a finite rigidity and the ductile lower crust is also stretched and necked. Al-Zoubi and ten-Brink[15] built a conceptual model for the development of the Dead Sea basin (Fig. 4), where they show the upper crust attenuation due to lower crust flow. The subsidence process is still active due to the extensional process in the upper crust of the Dead Sea basin.

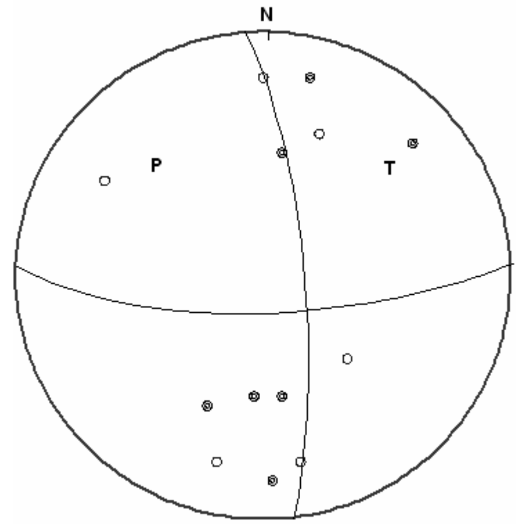


Fig. 9: Fault solution (focal mechanism) of the seismic events of Dec. 31st, 2003

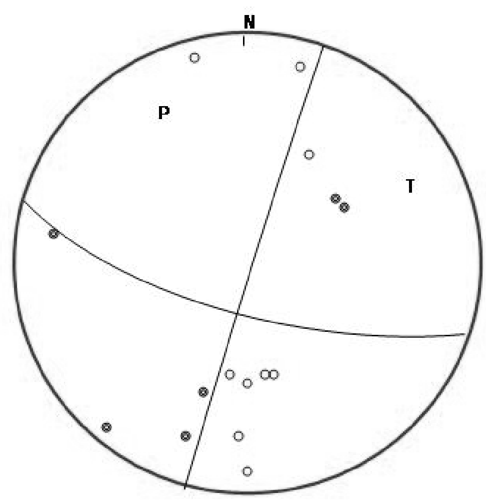


Fig. 10: Fault solution (focal mechanism) of the seismic event of March, 15th, 2004

The Dead Sea basin is divided into two parts, the northern part, which is 50 km long (Dead Sea itself), a hypersaline lake with a minimum bottom elevation of 720 m below sea level, whereas the southern part is a sub area with a minimum elevation of 410 m below sea level. In the southern part of the basin, two salt diapirs have formed: (1) the Sedom diapir in the southwestern side of the basin, along the Sedom fault and (2) the large Lisan diapirs in the central part of the basin (Lisan Peninsula). The Lisan salt diapir extends up to 65 km to the south, where its maximum salt thickness reached about 7200 m in the Lisan Peninsula. The salt roof in the Lisan Peninsula is located at a depth of 125 m below the surface. Studying the salt tectonic in the Dead Sea, Al-Zoubi and ten-Brink[11], found that Lisan diapir formed in a sunken block of the Dead Sea basin. The development of the salt diapire and the diapiric formation during the extension process in the Dead Sea could be explained by the model illustrated in Fig. 5,[11]. According to this model, a diapir developed where the overburden was thinned relative to the surrounding area, provided that the overburden is not too rigid and the viscosity of the salt is not too large to resist the rise. These conditions are met in the Dead Sea, where localized extension of the overburden is observed. The salt diapirs are still rising with a rate of about 6-7 mm/year[17], but the area is subject to a subsidence with an estimated rate of 2-3 mm/year[18].

The relationship between the major Dead Sea fault and the side faults (Fig. 6) which crosses Jordan in different directions is very complicated and yet not clarified, due to the different ages of the faults system and changing deformation pattern and their reactivation[19].

The east-west faults (such as Zarqa Ma'in, Swaqa and Hasa) show the maximum displacement near the major rift faults. This situation became very complicated around the Dead Sea basin due to the large depth of the basin (8.5 km), salt tectonic, horizontal movement and basin subsidence.

The Dead Sea basin is one of the most active seismic basins along the Dead Sea rift (Fig. 3). Several studies on the seismicity of the Dead Sea basin have been published[20-22] show that several earthquakes with magnitudes of more than 5 occurred in the Dead Sea basin.

The seismic activity (earthquakes epicenter) map (Fig. 3) shows that, not only the Dead Sea fault is active and causes earthquakes, but also the side faults, such as Zarqa Ma'in and Wadi Mujeb (on the Jordan side) are active. To the north of the Dead Sea basin the seismicity migrated towards the west to Wadi Faria fault and up to the northwest.

**Data acquisition and data analyses:** During the period of December, 31st, 2003 to April, 15th, 2004, the Jordan Seismological Observatory (JSO), which consist of 26 vertical component seismic stations, where 5 of them are three component, digitally recorded well over 70 events in the Dead Sea basin (Fig. 6). The range of the calculated magnitudes are 2 - 4.9, on the local magnitude (Mc). The data analyses show that, the location of the swarm event appears to be located to the northeast of the Dead Sea itself.

In this study we analyzed the signal we got from relatively strong events such as Dec. 31st, 2003, February, 11th, 2004 and March 15th, 2004 with a magnitude of 3.7, 4.9 and 4 respectively. The signal were recorded from these event had a clear phases of P waves (for example Fig. 7, shows the P waves recorded from the main shock: Mc = 4.9). This record was used to calculate the depth to the focal point of the earthquakes. The result shows that all of the events located at a depth of about 21 km.

The focal mechanism of the strongest three events, (Fig. 8-10) were obtained from the motion of the P waves (for example Fig. 7 shows the seismogram of the main shock). The fault plane solution program SEISAN (FOCMEC) was used to determine double couple earthquake focal mechanism, which used the polarities and /or amplitude ratios.

The result of the fault plane solution shows that, the focal mechanism of the three events is different. The main shock (Mc=4.9) was caused by normal component with slight strike-slip motion (Fig. 9), where the two others shock were caused by strike-slip motion with slight normal motion (Fig. 8 and 10).

## DISCUSSION

The Dead Sea fault system and its branching faults are associated with the highest concentration of earthquakes in the region. The Dead Sea basin is the largest basin was formed along the Dead Sea transform fault and it is one of the most actively seismic area within the rift. The seismic activity along the Dead Sea rift during the last two decades was characterized by earthquake swarms. The most significant swarms recorded in the Gulf of Aqaba, 1983, 1990, 1993 and 1995[10,23] (annual bulletins). Earthquakes with swarms character recently took place in the Dead Sea basin. In this work we studied 70 events occurred during the first quarter of the year 2004 (Fig. 6). The tectonic model of the Dead Sea shows a complex activity in the Dead Sea basin: dominant a left lateral strike-slip motion, lower crustal flow and thinning of the upper crustal, subsidence of the Dead Sea, salt tectonic and normal slip along the sides faults. These observations are in agreement with the geological and geophysical evidences[4,7,12,14,15,24,25] and the source mechanism of the strongest events recorded during the present earthquake swarm. The fault plan solution of the main event Mc=4.9, indicated that the rupture propagated down dip, where the motion was initiated mainly as a normal component with slight strike-slip movement (Fig. 8). At the same time, the analysis of the aftershocks during the subsequent two weeks showed that the source mechanism is the same as that of the main event. The source mechanism of the event, which occurred at Dec. 31st, 2003 and March, 15th (March, 16th, local time, Jordan) indicated that the movements were initiated as left-lateral strike-slip motion with slightly normal motion (Fig. 9 and 10).

The seismic activity has been examined out side of the Dead Sea basin for about 200 km to the north and south of the basin and we found that the seismic activity concentrates within the Dead Sea basin. The migration character of the seismic energy in the Jordan Valley and Wadi Araba not observed. It leads to the conclusion that the Dead Sea fault segment is broken into Jordan Valley, Dead Sea and Wadi Araba Faults segments. This conclusion is in agreement with the result obtained by ten Brink *et al*[6], where they mentioned that the Dead Sea fault broken into 15 segments along 400 km (from Gulf of Aqaba to the Hula basin, Fig. 2). At the same time[6] suggested that the plate motion changed there character to the north of the Dead Sea basin.

Therefore, to understand the seismic activity of the Dead Sea basin, we supposed to answer several questions, such as the fault geometry, the mechanism of uplifting around the basin and how the upper crust is thinning due to the lower crust flow without participation from the upper mantle.

## CONCLUSION

The tectonics of the Dead Sea basin and the tectono-structural map show that the eastern side of the Dead Sea could be divided into four blocks (Fig. 6). The first block is located to the north of Zarka Ma'in fault (block one), the second block is located between Swaqa fault at the south and Zarqa Main fault in the north. The third and the fourth blocks are located in the south of Swaqa fault. In the second block the motion is a strike-slip motion as a result of strain accumulation due to the movement along the Dead Sea transform fault. The first block located to the north of the second one as a part of Amman-Halabat structure. In this block the stress was most probably caused by the motion, which occurred in the second block. The seismic energy appears to have migrated from the south to the north during the period of Dec. 31st to March 12th, where then, after March the 12th, the seismic energy had a migration character to the southern block, which resulted in the seismic event of March, 15th. Therefore, if this interpretation is true, another event in the second block can be expected in the near future.

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