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The Mechanism of Induced Seismicity at Mosul Lake

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Abstract

Induced seismic activity has been studied at Mosul lake for the period March 1986 to December 1987. More than 250 micro-earthquakes of magnitude up to 3.2 ML were observed, of which 180 were located. Nearly all earthquake epicenters were located within a radius of less than 25km from the dam site. Cluster of epicentres was observed in the eastern embankment of the lake. Most of the hypocenters were located between the ground-surface and 2km of depth. It has been found that lithology and the presence of faults were the major effecting factors on the spatial distribution of seismic events. A composite fault plane solution indicates that the mechanisms of seismicity were right-lateral strike-slip faulting along N44ºE nodal plane in conformity with the local tectonics.

Keywords: Induced seismicity, Earthquake

Introduction

In many places, seismic activity has been related to the filling of large reservoirs (Simpson, 1976; Gupta and Rastogi, 1976). Simpson (1976) suggested that the filling of a large reservoir creates stresses which are superimposed on a pre-existing tectonic stress. The reservoir affects the stress regime in two ways:

1. Increases the vertical stress due to the weight of water mass (the load effect).
2. Decreases the effective stress due to increasing pore pressure (the pore pressure effect).

Whether or not seismicity is generated depends on the way in which these stresses interact within the tectonic, geological and hydrological environments. In all cases stress concentrations due to the presence of faults or to inhomogenities in the material properties play an important role in localizing induced seismicity (Kisslinger, 1976).

Mosul reservoir is located in the northern part of Iraq which is characterized by moderate to high seismic activity and which had experienced strong earthquake in the past (Ayar, 1986). The dam height is 100m while the maximum capacity of the reservoir is $11x10^9$ cubic meter.

Seismic activity has been noticed in the reservoir after starting filling of the lake in June 1985.

In this study the earthquakes recorded during the monitoring period March 1986 to December 1988 were located using the HYPO71 program written by Lee and Lahr (1972), and using a crustal velocity model for the area suggested by Al-Saigh and Toffeq (1993).

Geological and tectonic setting of the area

The main exposure rocks in the study area are the Fat`ha Formation (M. Miocene), while the Injana (U. Miocene), Miqdadia (Pliocene) and Pila-Spi (M. U. Eocene) Formations cover rest of the area (Fig.1).

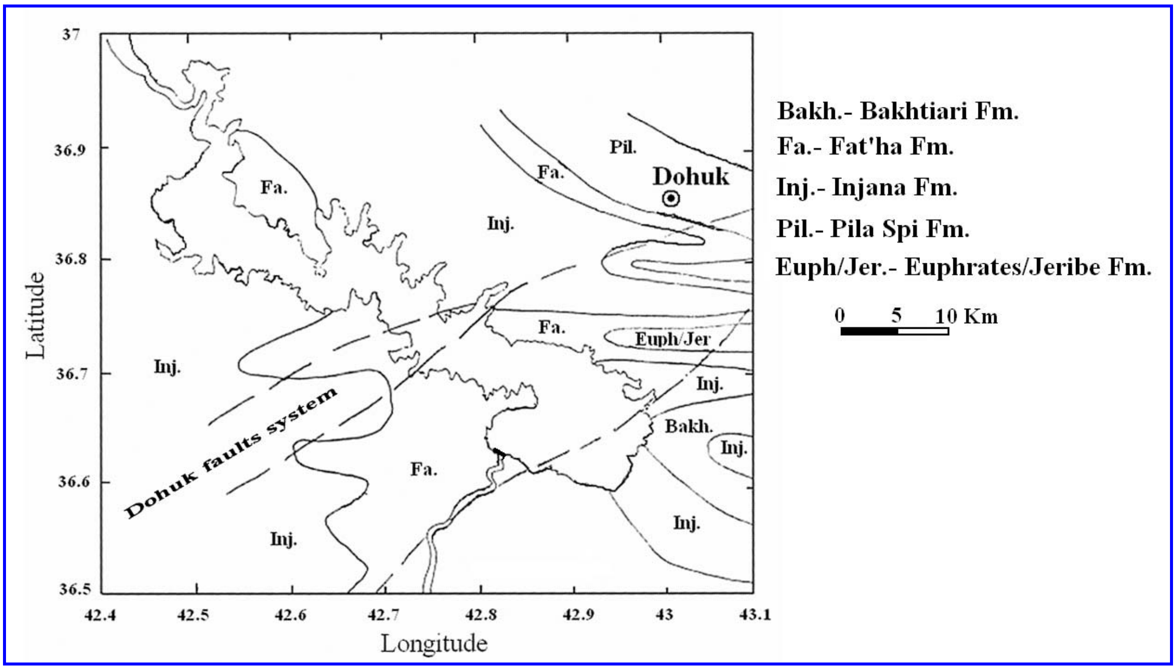


Figure 1 Geological map of Mosul’s dam lake.

The dam site is bounded by two anticlines trending E-W; namely Tayarh and Butmah East anticlines. Tayarh anticline is located on the eastern side of the river Tigris. It is a small anticline of about 4km. long and 0.5km wide, while Butmah East anticline is located on the western side of the river. It is about 12km long and 3.5km wide (Tawfiq and Domas, 1977).

Tectonically, the whole reservoir lies within the Sinjar block. The block lies only partly in Iraq, continuing westwards into Syria and Turky (Kassab and Abbas, 1987). Its superficial and subsurface structures are mostly E-W oriented and relatively long. The south-south eastern boundary of the block is expressed on the surface by a complex fault zone which is called the Sinjar-Dohouk-Kuchuk Faults System. This fault is bounded the southern border of Mosul reservoir.

A gravity survey carried out by Al-Ansari, et al. (1984) suggested the presence of three faults in the area; one cutting the northern limb of Tayarah anticline with an E-W trend, which is most probably, represents a part of Dohuk fault system. The second fault cuts the northeastern corner of the eastern plunge of Butmah East anticline, and extending in an E-W direction towards the dam. The third fault is trending NNE-SSW along the western bank of the river.

The structure and stratigraphy of the southern part of Mosul reservoir have been deduced from seismic reflection profiles and deep boreholes information (Al-Saigh and Toffeq, 1993). Nine good reflectors, lying at depths range between 700m and 7150m below the surface level, have been identified. The lithology is dominated by carbonate sediments and the dominant fault trends in the area are NE-SW.

The seismic sections show the presence of a fault zone having a width of about 8km. The faults are mostly of a reverse type with maximum displacement of about 150m. This zone of faults most probably represent the faults zone that is marked on the tectonic map of Iraq and running SW-NE to the south of Dohuk city as shown in figure (1). In the text, however, this fault system was referred to as Dohuk faults system. No longitudinal extending faults have been identified.

Spatial distribution of seismic events

More than 250 induce earthquakes were identified, of which 181 were located. Only events recorded on three or more stations were considered. Most of the events, however, were recorded on three stations. This is due to very bad recording. During the first monitoring period the recording speed was 10mm/min and since March 1987 the speed increases to 60mm/min. The relatively high noise level at three of the stations (BOT, REG, and AMR) made the determination of earthquake parameters very difficult. Moreover, most frequently, at least one of the five stations was out of operation during the monitoring period.

Fig.2 is a plan view showing the spatial distribution of earthquake epicenters in the area. Nearly all the epicenters were located within a radius of less than 25km from the dam site. The majority of the epicenters were located in the lake region, in the area between the Dohuk faults system. The width of this zone is about 17km. However, the largest concentrations of epicenters were located con the eastern embankment of the lake between the two seismographic stations AMR and KHN. This part represents the deepest part of the reservoir. No seismicity was observed along the three faults (F1-F3) that had been identified by the gravity survey (Al-Ansari, et al. 1984).

Fig.3 is a vertical section showing the distribution of earthquake hypocenters with depth. Most of the hypocenters were located between the surface and 2km deep. Very few were located between 2km and 4.5km deep.

Reservoir level and earthquake frequency

Because of instrumentation problems not all earthquakes could be located, hence the earthquake catalog shows fewer events and is not representative during the time period.

Filling of the reservoir started in June 1985. Figure 4 shows the monthly relationship between the reservoir water level and the number of induced earthquakes. There are obvious increases in seismicity following each of the yearly maxima in water level. The first highest level was reached during the period of mid May to end of July 1986 which corresponds with maximum seismic activity. The activity continued to the end of October long after the fall off the lake level which occurred from August through December. The second highest level was reached during May and June 1987. The maximum seismicity, however, was during the period September to December with a time lag of about two months. There was to months delay between the peak reservoir level and the peak seismic activity.

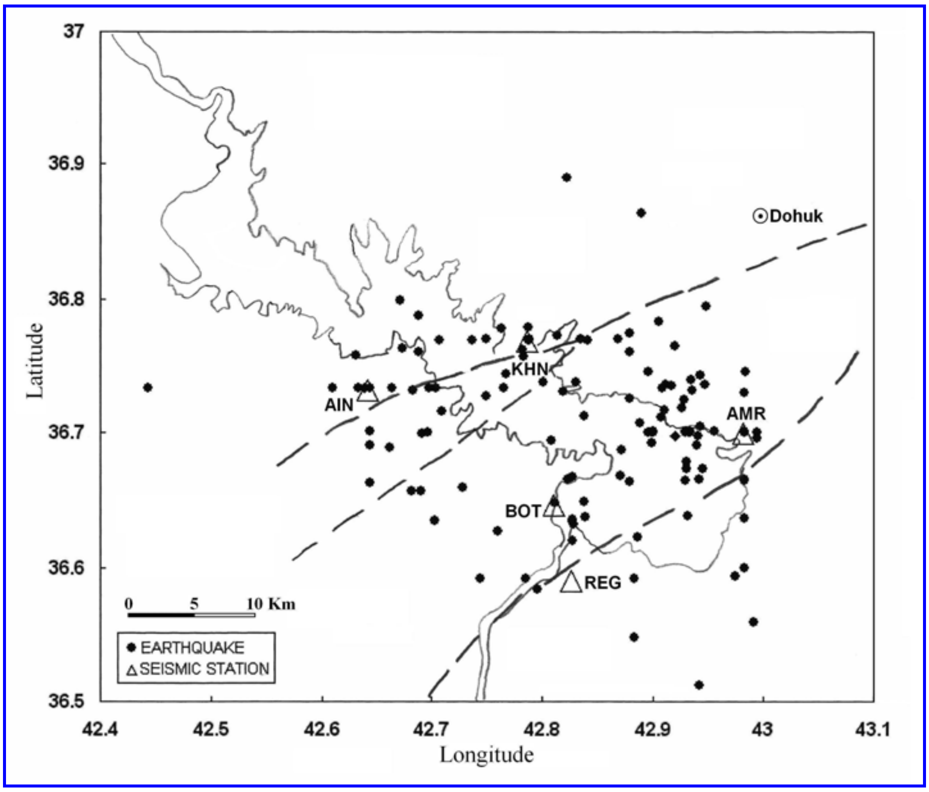
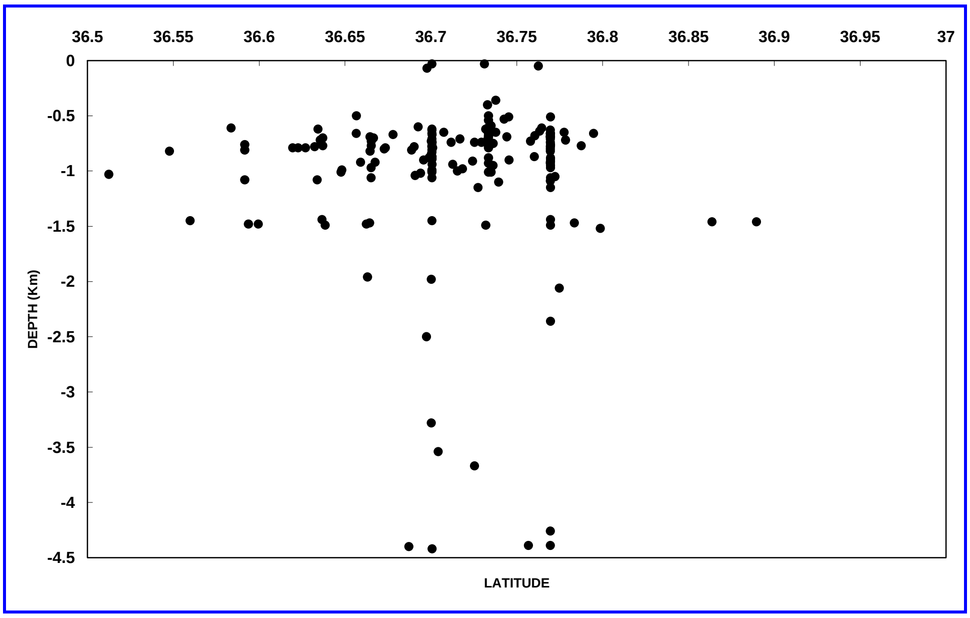


Figure 2 Seismicity map of Mosul’s reservoir for the period March 1986 to December 1987.



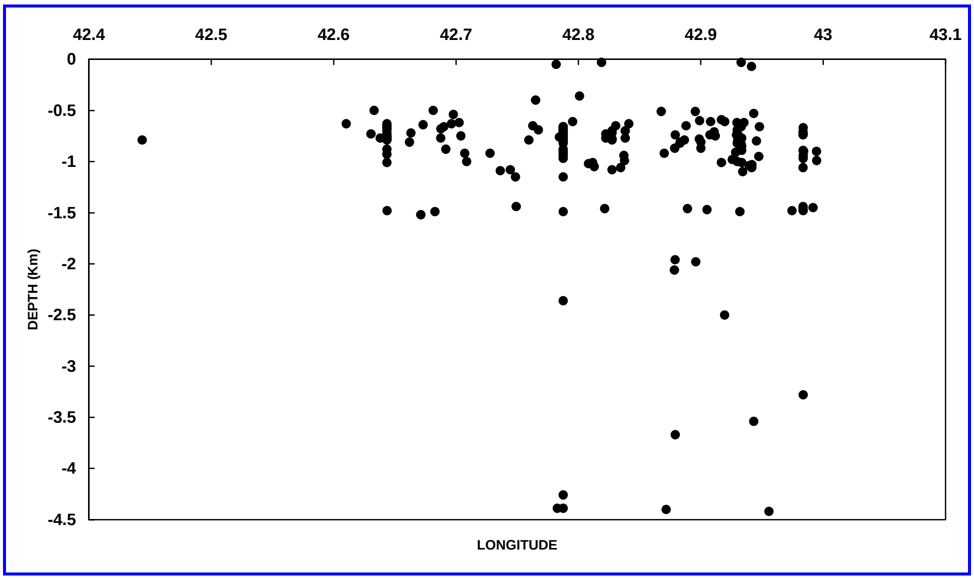


Figure 3 Vertical distributions of earthquakes' hypocenters.

A noticeable reduction of water level occurred during the period November 1986 and March 1987. Unfortunately the network was out of operation during this period to show the behavior of seismic activity during this period of reduction of water level.

Figure 5 shows the cumulative number of observed and located earthquakes during the monitoring period. Linear regression fitting indicated that the average seismicity level was 0.6 and 0.4 events per day for the observed and located events respectively, during 1986, while it was 0.5 and 0.3 events per day during 1987.

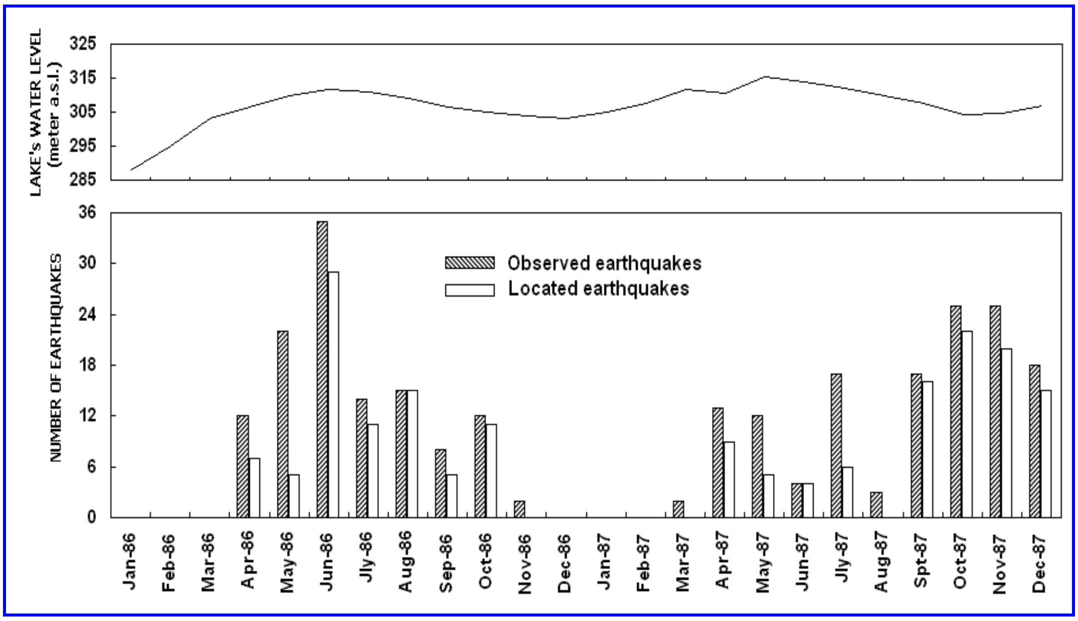


Figure 4 Relationship between water level in the lake and the number of the observed and located earthquakes, during the monitoring period.

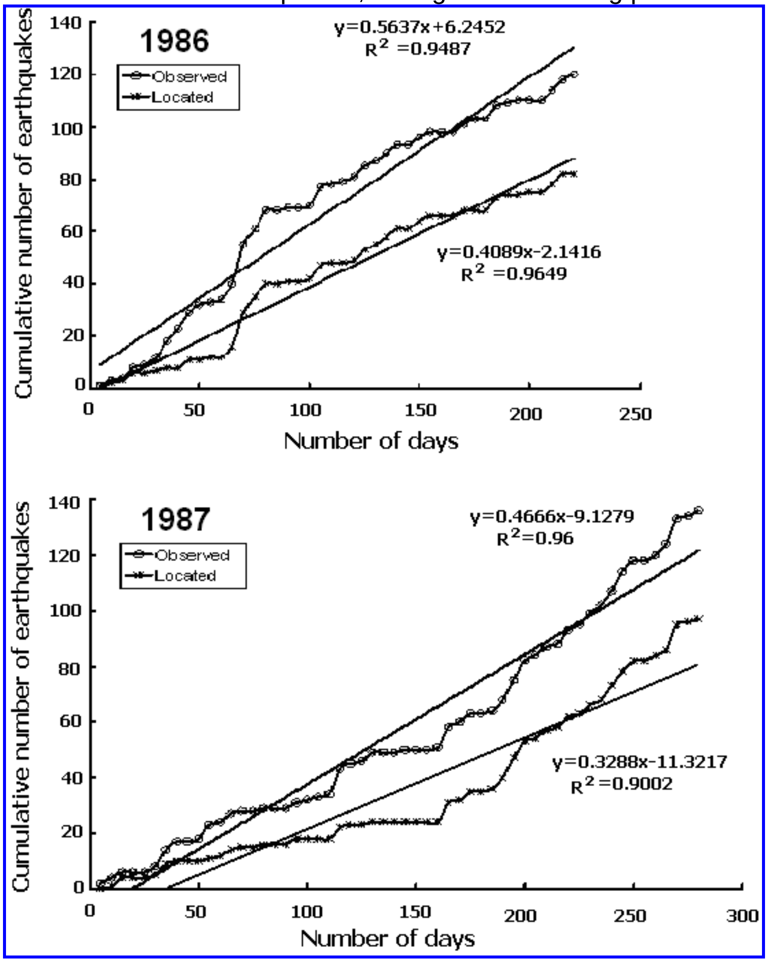


Figure 5 Cumulative numbers of earthquakes against days of the year.

Magnitude determination

Earthquake sizes were determined as ranging between –o.2 and 3.1 Ml using the magnitude-duration relationship:

$$MD=2.0 \log D- 0.87$$

where MD = duration magnitude
D = signal duration from p-wave onset to the end of discernable signal.

This relationship was determined for California (Lee et. al. 1972). While the magnitudes determined using this formula may be slightly biased in terms of any absolute comparison with magnitude scales used elsewhere, it provides an acceptable measure of the relative sizes of the earthquakes at Mosul reservoir.

The b-value in the frequency magnitude relation

The frequency-magnitude distribution of seismic events in the reservoir follows the formula:

$$\log N=3.4-0.75\, Ml$$

The constants were obtained graphically from the frequency-magnitude plots (Fig.6). There is relationship between the magnitude and the frequency in the magnitude ranges between 2 and 3 Ml. The fall-off of the number of seismic events with low magnitude values is due to a detection threshold and partly due to instrumentation problems. The value of b (0.75) in Mosul reservoir however, is lower than the values obtained in many other reservoir-associated earthquakes, the b-values are mostly higher than 1 (Gupta and Rastogi, 1976). However, since the b-value is a measure of magnitude distribution and hence depends directly on the scale used to determine magnitude, the absolute value of b determined will depend on the coefficients used in the magnitude equation.

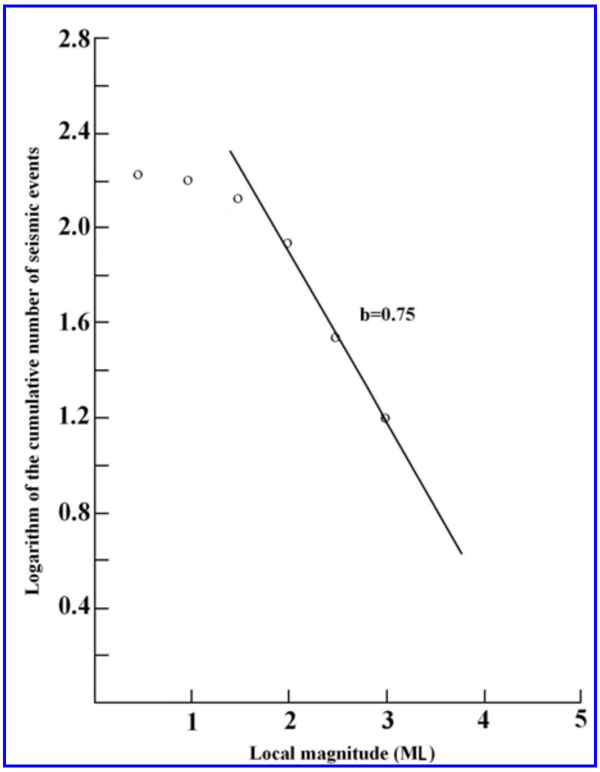


Fig.6 The frequency-magnitude relationship of the seismic events

Composite fault plane solution

A composite fault plane solution was made for events that occurred during the monitoring period. However, only 56 p-wave first motion directions read for 29 located events could be used (Fig.7). The direction (azimuth and angle with respect to vertical) of the seismic ray from the focus to each seismometer were taken from the HYPO71 computer outputs. The direction parameters were plotted on the lower hemisphere of an equal area projection, each carrying the sign of the p-wave first arrival, assuming the centre of the net to be the focus of the event. The composite focal mechanism is well determined. The solution indicates strike-slip faulting. The consistency of the first motions on the focal plot suggests that all micro-earthquakes share a similar mechanism. If the nodal plane striking N44^{o}E with a dip of 60^{o} NW is considered to be the fault plane, it will indicate right-lateral movements. This plane agrees well with the N25^{o}-45^{o}E strike of the Sinjar-Dohuk-Kuchuk faults system, i.e., it is consistent with the regional tectonics.

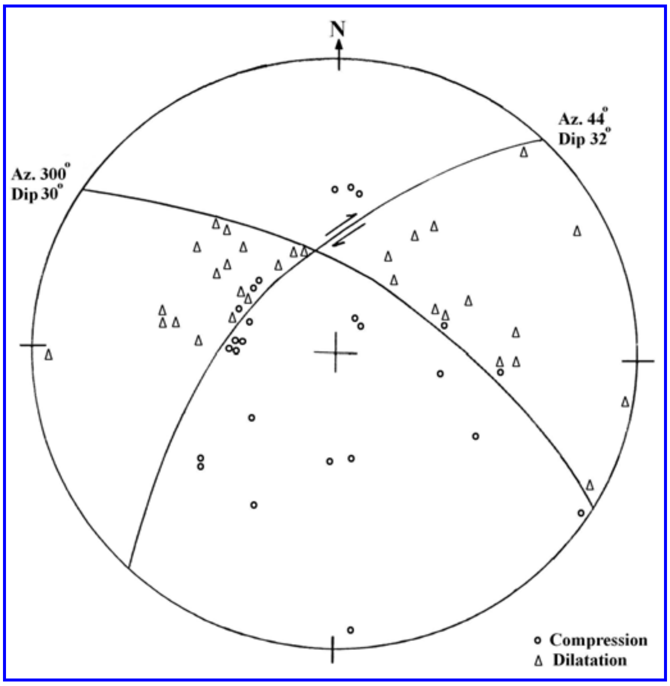


Fig.7 A composite fault-plane solution for some of the recorded events

Discussion and Conclusions

Initiation of seismicity, correlation of seismicity with water levels, confinement of epicenters in the vicinity of the lake and shallow depths of hypocenters indicated that the seismicity is reservoir induced.

Boreholes information and seismic reflection sections show that most of the sedimentary succession are consisting of limestone rocks (competent strata) which have high strength and capable to sustain high stresses (Al-Saigh and Toffeq, 1993). Therefore it has been expected that the induced earthquakes be located within these limestone beds. Shiranish Formation however is expected to make a buffer zone that does not allow pore pressure to penetrate into deeper formations. The formation composed mainly of marls (incompetent strata) which have relatively low permeability and lie at depth ranges between 1600m and 2000m. It persists throughout the area with a thickness of more than 80m. Besides its low permeability the formation show little resistance to any applied load which would deform gradually to accommodate it. The presence of Gotnia Anhydrite Formation, at depth ranges between 2150m and 2700m, beneath Shiranish Formation will enhance the effective of this zone. Therefore the effect of the reservoir pore pressure is restricted within the first 2km of depth. Consequently it is expected that most of the induced earthquake's foci be located within the first 2km of depth.

The concentration of induced earthquakes on the eastern embankment of the lake, especially along the faults system is due to the effect of pore pressure along these faults. It has been found that the most important effect of the pore pressure upon the mechanical properties of the rocks is the reducing of the frictional resistance of the sliding blocks (Hubbert and Rubey, 1959). The reduction of friction is achieved by reducing the normal component of effective stress which correspondingly reduces the critical value of shear stress required to produce faulting.

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