Chapter 2

Geology, Tectonic Setting and Seismicity

2.1 Geological Setting

The Dead Sea Transform fault (DST) system is the major tectonic feature controlling the stratigraphic and structural evolution of the region since the Miocene. The Neoproterozoic basement is usually divided into the Aqaba and the Araba complexes separated by a regional unconformity.

The Aqaba complex consists of two units.

1) Metamorphic Rocks

The metamorphic rocks are found as blocks within the surrounding Neoproterozoic intrusive rocks. At Gharandal area, in Wadi Abu Burqa (in Jordan), they were preserved from erosion before deposition of the Cambrian rocks. Jarrar et al. (1983) interpreted the metamorphic rocks to have a maximum age of 700-800 M.Y. This age coincides with the age obtained for the metamorphic rocks of the Elat area (Kroner et al., 1990).

2) Igneous Rocks

The igneous rocks consist of highly weathered granites, granodiorites and quartz-diorite. The plutons of the Aqaba complex have an average of 630-580 M.Y. (Ibrahim and McCourt, 1995).

The Araba complex consists of three units:

1) **Sarmuj Conglomerates**

   The Sarmuj conglomerates are the base of the Araba complex. They occur in very small outcrops along the lower course of Wadi Abu Burqa, with an exposed thickness of about 40 m (Bender, 1974).The unit consists of conglomerates, with well rounded clasts of plutonic and metamorphic rocks in a partly brecciated, arkosic-sandy matrix. The base of the Sarmuj conglomerates is demarcated by the age of the unconformably underlying calc-alkaline granitoids (Jarrar, 1985). These granitoids were emplaced in the time span 625-600 M.Y.

2) **Hayyala Volcaniclastic Unit**

   Volcaniclastic sediments are exposed in the margin of Wadi Araba. It is a series of stratified, steeply east dipping, green weathering tuffs with thin horizons of volcaniclastic sandstone. It is overlain with an angular unconformity by Cambrian sedimentary rocks. Ibrahim (1993) interpreted this unit to be Late Neoproterozoic in age, between 595-550 M.Y.

3) **Rhyolite Volcanics**

   This unit has been recognized in Wadi Rum. The upper part of the rhyolite is highly weathered and cut by doleritic dykes. The ryholite have intensive joints and are unconformably overlain by Cambrian sandstones. An age of 550-542 M.Y. is suggested for this unit (McCourt and Ibrahim, 1990).

Fig. 2.1 (a and b), is a simplified geological map and a geological cross section along the NVR (see Fig. 1.1 for the location of the NVR profile), respectively. The red line is the smoothed reflection line of the NVR experiment. Six dominant faults are identified in black. The arrow indicates the Wadi Araba fault, the dominant fault of the DST.

Wadi Araba fault extends about 170 km from the Gulf of Aqaba to the southern shoreline of the Dead Sea in the north with a trend of about N15°E. The average width of the Wadi is about 15 km, but it varies between 25 km in the north and about 9 km in the south. It is the southern segment of the DST.

The floor of the Wadi Araba rises gradually to 250 m above sea level from the Gulf of Aqaba up to the central Wadi. Then the floor decreases gently northwards to the surface of the Dead Sea, at 392 m below the sea level (Bender, 1975). Unconsolidated sediments of Quaternary and older clastic sediments occupy most of the Wadi Araba floor.

The Phanerozoic along the northwestern part of the NVR profile is dominated by Cretaceous and Tertiary rocks underlain by Jurassic, Triassic and Permian sequences that thin out towards the east. East of the DST, Permian to Triassic strata are missing and Lower Cretaceous rocks unconformably overlie Ordovician and Cambrian sandstones. (DESERT Group, 2003).

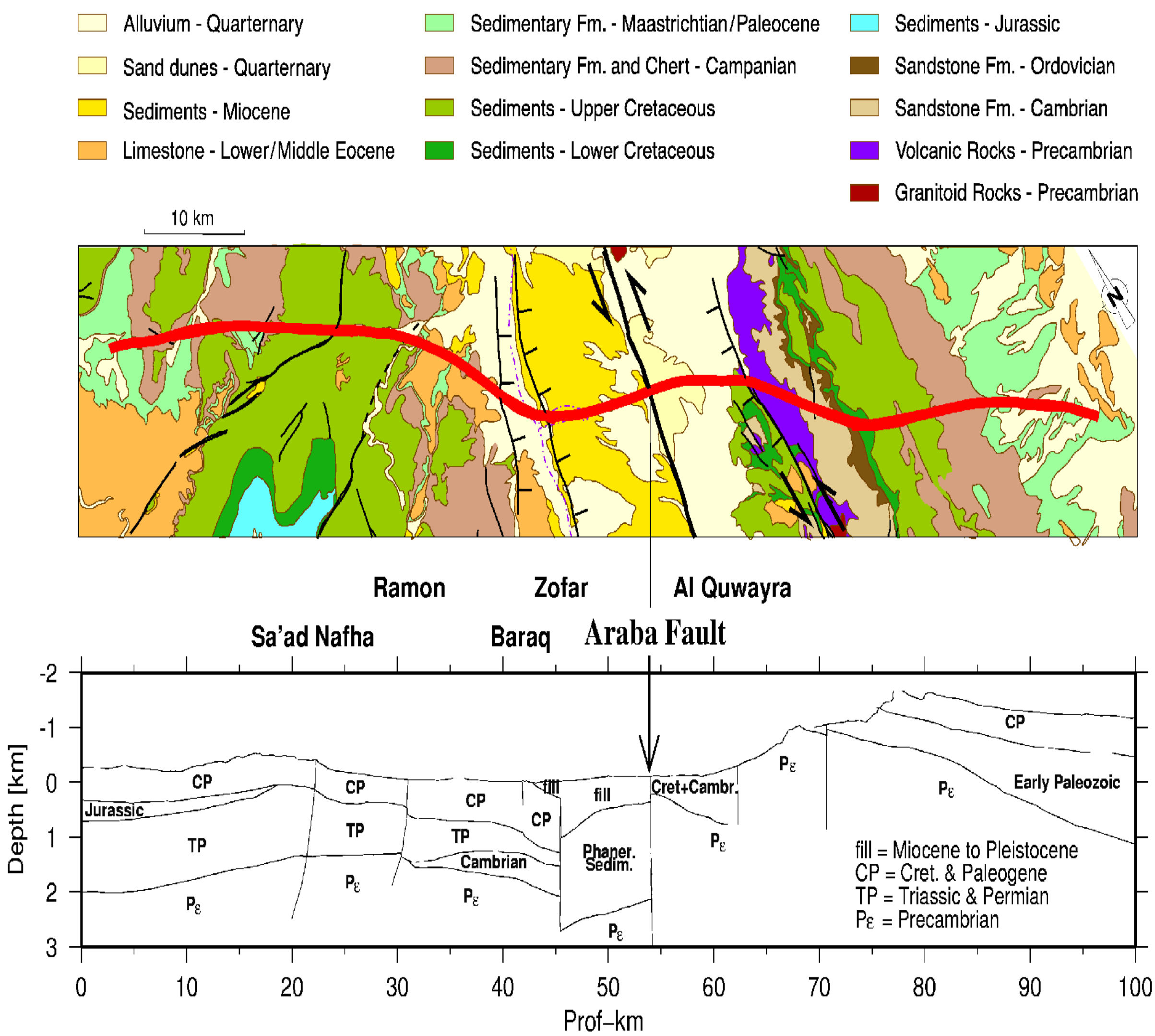

Figure (2.1). The upper panel is a simplified geological map (after Sneh et al., 1998; Bartov et al., 1998 and DESERT Group, 2003). The red line is the smoothed reflection line at the NVR experiment (see Fig. 1.1 for location). The lower panel is a geological cross section along the NVR profile. The arrow indicates the Araba fault.

2.2 Tectonic Setting

2.2.1 Introduction

The tectonics of the Middle East are controlled by the DST fault system, a major tectonic accident responsible for most recent structures of the region (Abou-Karaki, 1987; Quennell, 1958; Garfunkel et al., 1981), and it is of great interest to geologists and geophysics working in the area.

The DST forms the accurate plate boundary between the Arabian plate and the Sinai plate (Quennell, 1959; Freund et al., 1970; Garfunkel, 1981; Kashia and Crocker, 1987), so at global scale the DST is a part of the boundary between the African and Arabian plates (Fig. 2.2), that probably started forming around 20 M.Y. ago (Bartov et al., 1980).

The DST strikes from N15°E to N20°E and extends over some 1100 km from the Red Sea northwards, where crustal spreading occurs, along Wadi Araba, Dead Sea, Jordan valley, lake Tiberias and central Lebanon to the continental collision zone in the Taurus-Zagross mountain belt. Quennell (1959), first recognized the 107 km left lateral movement of the plates bordering the DST.

Regional uplift and basaltic volcanism are characteristics of the DST and the Red Sea region. More than 3 km uplift is believed to have taken place in the Red Sea since the Oligocene (Choubert, 1968; Garfunkel, 1981). In the Dead Sea region uplift is of the order of 1-2 km.

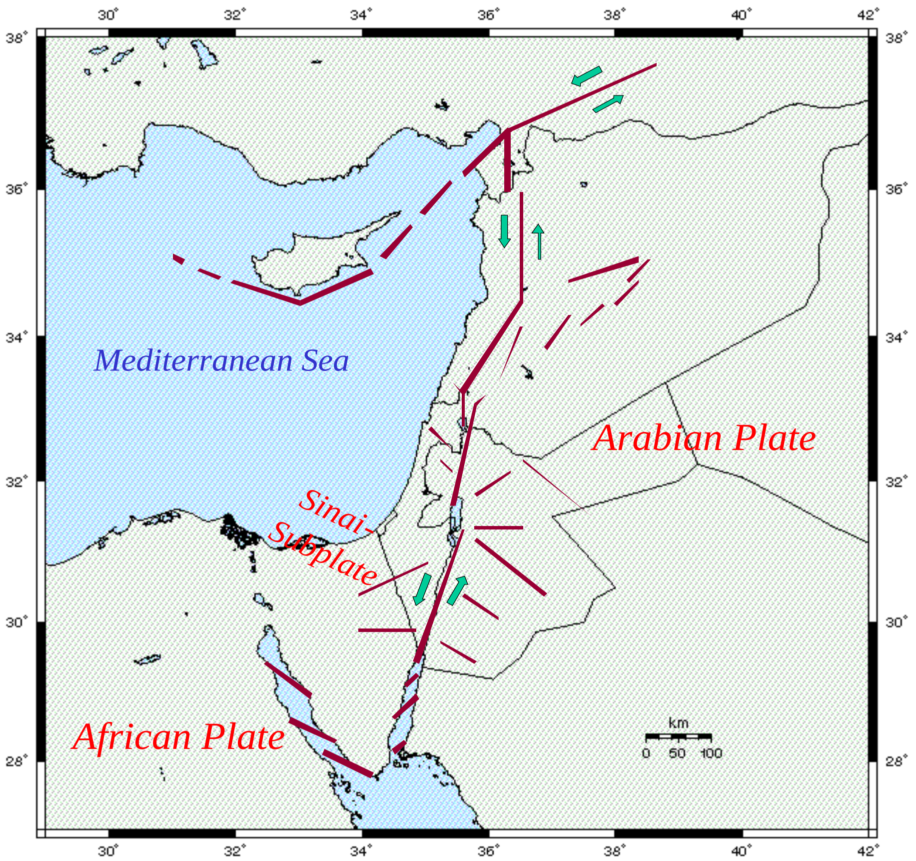

Figure 2.2: General trends of the Dead Sea Transform fault system. Modified from Quennell (1958), Barazangi (1983) and Al-Qaryouti (2002).

Abo-Karaki (1994) stated that the Arabian plate and Sinai plate are both moving northward within the more general context of the active African-Eurasian convergence, but the Arabian plate is moving faster than the Sinai plate, because Arabia is integrating a supplementary component of motion resulting from the oblique opening of the Red Sea.

Two deep seismic sounding experiments have been conducted in the DST in order to study the crustal structure of the area. The first was carried out in 1977, it was conducted in the Sinai plate (Ginzburg et al., 1979, 1981), and the second was conducted in 1984 on the eastern flank of the DST (El-Isa et al., 1987).

Beneath the western flank of the DST, the 1977 experiment of deep seismic sounding shows a crustal thickness of about 35 km in the Gulf of Aqaba area, that increases slightly northward and decreases southward to some 27 km. The experimental data also determined a maximum sedimentary layer of thickness of about 5.5 km within the transform. Further west towards the Mediterranean (Oceanic crust), the thickening of sediments were interpreted by Ginzberg et al. (1979) as a Pre-Jurassic crustal deformation.

In the eastern flank of the DST, the results of the 1984 experiment show a crustal thickness not less than 32 km in the Aqaba region, increasing to some 35 km in Amman area.

2.2.2 Deformations

Three major deformational phases characterised the region (Quennell, 1958; Garfunkel et al., 1981; Freund et al., 1970; Barazangi, 1983). These phases are as follows:

1. **The Folding Episode along the Syrian Arc**: This structure is a series of anticlines and synclines, which extends from central Syria (the Palmyra fold belt), Jordan, Palestine and Sinai (Levantini fold belt) forming an S-shaped fold belt that crosses the DST. Most of the folds are asymmetrical and locally faulted by normal and strike-slip fault types.

Three stages of folding affected the region, the first of Pre-Jurassic age, the second is of a Late Mesozoic-Early Cenozoic age, and the third is of a Late Eocene-Oligocene age.

2. **The Erythrean Fault System**: This structure consists of northwest-southeast and east-west oriented normal and strike-slip faults from the Late Miocene-Early Pliocene age. During the erythrean phases many of the faults and rifts were formed such as Wadi Sirhan graben and the Karak-Fayha fault in Jordan.

3. **The DST**: It was formed in the Cenozoic as a result of the breaking off of the Arabian plate from the African plate (Rotstein and Garfunkel, 1982). From geological field observations about 107 km of left lateral motion has taken place along the transform since Post-Cretaceous time (Quennell, 1958,1959; Freund et al., 1970; Garfunkel, 1981; Quennell, 1984; Walley, 1988; Girdler, 1990).

2.2.3 Displacement and Motion

The movement of the Arabian plate in relation to the Sinai is believed to have taken place during two stages:

1. The first involved a horizontal displacement of about 62 km which took place during the Lower Miocene (Quennell, 1958, 1959; Freund et al., 1970).

2. The second resulted in a horizontal displacement of about 45 km, during the Plio-Pleistocene (Quennell, 1983, 1985). The total amount of strike-slip displacement is about 107 km.

Girdler (1990) suggested that the 107 km horizontal displacement corresponds to 5.6° anticlockwise rotation of Arabia with respect to Sinai and stated that the average velocity of Arabia with respect to Sinai is 0.9 cm/year. While Ben-Menahem et al. (1976), suggested that the velocity to be 0.7-0.9 cm/year.

Estimates of the slip rate along the DST have been obtained either from geological analysis (Garfunkel et al., 1981; Ginal et al., 1998) or from regional kinematics (Jestin et al., 1994) and vary between 10 and 1 mm/year. An estimate of about 5mm/year was obtained from the analysis of offset geomorphic features of Late Pleistocene to Holocene age (Klinger, 1999; Klinger et al., 2000).

2.2.4 Dead Sea Deformation

The Dead Sea occupies the lowest basin on the continental part of the earth. It strikes in an almost N-S direction. The width of this basin varies in the range of 10-18 km, and its length is about 80 km, through only its northern 55 km is still covered with water in the present. Its maximum depth is about 750 m below mean sea level.

The Dead Sea is a complex structural feature bordered by two faults, the first is Wadi-Araba fault that runs from the Gulf of Aqaba to the north over some 190 km and the second is Jericho fault that seems to start some 20 km west of the northern end of Wadi Araba fault in the western part of the Dead Sea and runs in a NNE direction to the Tiberias lake over a length of about 150 km.

This led Blankenhorn (1896) to recognize it as a rift (tensional graben). From Lartet's work (1869) it would be inferred that the Dead Sea is the result of the left lateral motion between the Arabian and Sinai plates which is known as pull-apart. The pull-apart idea was clearly expressed and associated with the Dead Sea structure in the work of Quennell (1958,1983).

2.2.5 General Features of the DST: This can be summarized after Garfunkel (1981) as follows:

1. Before continental breakup the lands bordering the transform of the Middle East were parts of a craton that stabilized after the Late Precambrian Pan African orogony. A sedimentary cover accumulated during several depositional cycles from Early Cambrian to Late Eocene times. Igneous activity was sparse in this period.

2. Continental breakup began in the middle Cenozoic and was accompanied by widespread, predominantly basaltic, and volcanism. Radiometric dates from Arabia (Coleman et al., 1977; Blank, 1977), Yemen (Civetta et al., 1978), Afar (Barberi et al., 1975), Egypt (Meneisy and Kreuzer, 1974), and Sinai (Steinitz et al., 1978) indicate that the igneous activity began in the Oligocene, mainly 20-30 M.Y. ago, while major rift faulting began only after 20 M.Y. ago, in the Miocene.

3. The greater part of the DST is marked by conspicuous morphotectonic depressions, 10-20 km wide, partly filled by sediments. These are generally delimited by normal faults, but they differ from typical extensional rift valleys by their much smaller width, presence of internal structural saddles, and mainly by the presence of major strike-slip faults on their floors which are typically arranged en-echelon (Quennell, 1956; Zak and Freund; 1966; Garfunkel et al., 1981).

2.3 Seismicity

2.3.1 Instrumentally Recorded Seismicity

Instrumental monitoring of earthquakes in the Middle East region began in 1899 with the installation of the seismological station in Egypt (HLW), followed by the Ksara station in Lebanon in 1910, then the installation of a seismic station in 1935 in Istanbul (El-Isa, 1981).

The local instrument monitoring of earthquakes in the DST area began in 1954 with the installation of two seismographic stations, one was installed in Jerusalem and the other in Safad, later on in Haifa (Arieh et al., 1985).

In 1964 a Word Wide Standardized Seismograph Network (WWSSN) station was installed in Jerusalem. In Jordan, the first permanent seismic station was installed in the Jordan University area in Amman in June, 1981. It consists of a three-component shortperiod seismograph (El-Isa, 1983).

The systematic monitoring was started in 1982-1983 by the installation of the Institute for Petroleum Research and Geophysics (IPRG), based on Holon west of the DST, and the Natural Resources Authority (NRA), based in Amman east of the DST.

In the northern part of the DST, the general establishment of geology and mineralogy resources in Syria started a seismic monitoring by the end of 1994 (SNSC, 1996). The Syrian National Seismic Network (SNSN) monitoring consists of 20 shortperiod telemetry seismic stations through two sub-networks, which covered northern and southern Syria.

In Saudi Arabia, there are two independent seismic telemetry networks, the first was established in 1985 and the second began in 1993.

Most events have small magnitudes. Only two major events have been recorded along the DST over the period of instrumental recording. The first was occured in July, 11, 1927. Its magnitude was evaluated to be 6.25 and epicentered some 25 km north of the Dead Sea. Ben-Menahem et al. (1976) proposed a left lateral strike-slip mechanism for this earthquake. The total number of people killed is reportedly as high as 342 persons (Sieberg, 1932). (see Fig 1.1 for the location).

The second occured in November, 22, 1995, the largest earthquake sequence of mainshock-aftershock type began in the central part of the Gulf of Aqaba and continued until December 25, 1998. The peak events (Ml=6.2, Mw=7.2) had an origin time of 04:15 GMT, latitude of 28.76 N and longitude 34.63 E (according to the JSO determination).

This main event was followed by more than seven thousands aftershocks (Ml > 1.5) within 100 days following the main shock (Fig. 2.3). The 1995 Gulf of Aqaba earthquake was felt over a wide area, at places as far as Lebanon, Sudan, southern Syria and western Iraq. However, damage effects were felt in Aqaba area, Elat, Haql (Saudi Arabia), and Nuweiba (Egypt). At least 11 people were killed and 47 injured (Al-Tarazi, 2000).

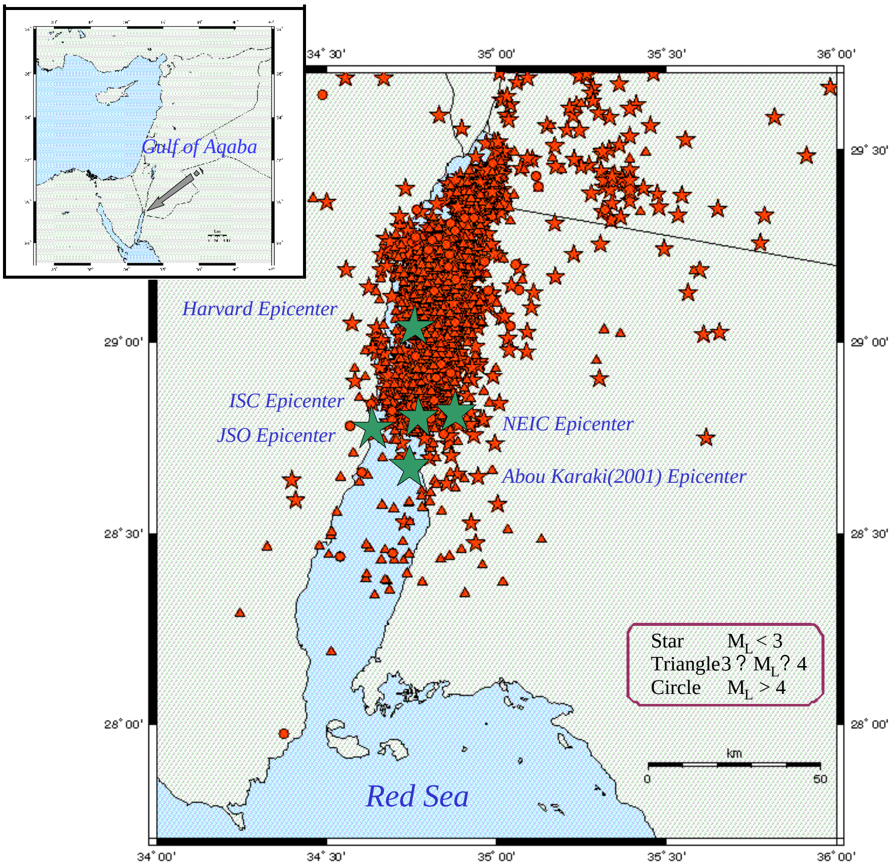

Figure 2.3: Earthquake epicenters of the 1995 Gulf of Aqaba sequence (from November 22, 1995 to December 25, 1998). Data from JSO (1995-1998). Green stars show the epicenters determinations of the main shock by different sources (after Al-Qaryouti, 2002).

Many earthquakes including the largests are epicentered along the DST (Fig. 2.4). Many of the earthquakes on either side of the transform seem to correlate with the two other tectonic elements, namely, the Syrian arc and the Erythrean systems.

In order to determine the level of activity for each tectonic element in the region, energy calculations has been made by El-Isa (1992) to all instrumental earthquakes for the period 1903-1990, utilizing the equation of Gutenberg and Richter (1956), emphasising on the 1981-1990 the most reliable data. The results of the energy calculations indicate that, about 80% of the total seismic energy has been released from within the DST. Most of the largest instrumental and historical earthquakes are epicentered along the DST and reported to be strike-slip mechanism (e.g. Ben-Menahem et al., 1976; Abou-Karaki, 1987; El-Isa and Hashweh, 1988). While the Erythrean and the Syrian arc accounts for some 17% and 3%, respectively. This means that, the DST is the major source of seismic risk in the Middle East region. The next source of seismic risk seems to be the Erythrean while the Syrian seems to be the least active element.

2.3.2 Seismicity of the Gulf of Aqaba-Wadi Araba Region

The seismicity of the region indicates that the Gulf of Aqaba has been the more active segment of the plate boundary between Arabian and Sinai plates. Since 1983, the Gulf region was affected by four major earthquakes sequences.

The first swarm was on January 21, 1983 that lasted for a few months. There were 181 earthquakes listed in the IPRG bulletin and 60 shocks from the swarm were recorded by the Jordan University Seismological station . More than 500 shocks ($Ml > 3.5$) were recorded by Saudi local mobile network of 6 stations within a period of 72 days operation. The largest shock had a magnitude of 5 and about 10 events had a magnitude greater than or equal to 4.4 (El-Isa, 1984; Al-Qaryouti, 2002).

The second swarm occured in the southern part of Aqaba on April 20-27, 1990 having a peak magnitude of $Ml=4.2$.

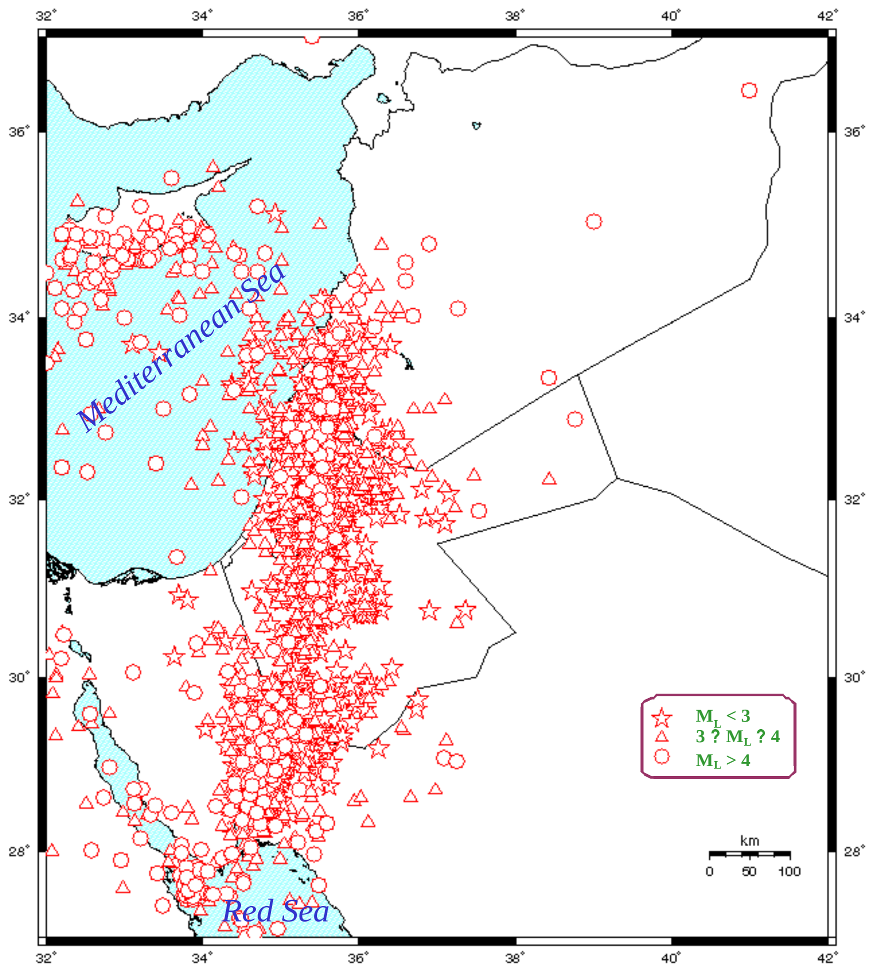

Figure 2.4: Seismicity map of the Dead Sea Transform region for the period 1900-2000. (after Al-Qaryouti, 2002).

The third swarm was on July 31, 1993, and continued until the end of August, 1993. More than 600 events with 420 of magnitude equal to or greater than 3. The peak event (Ml=5.8, Mw=6.1) occured on August 3 (see Fig. 1.1 for location) and was felt on both side of the DST (Al-Qaryouti, 2002), and the fourth swarm was on November 1995, which has been already described. On the other hand, Wadi Araba segment of the DST (Fig. 2.5) has a lower activity level during instrumental monitoring, and this might be due to lack of seismograph stations in the vicinity of the fault.

2.3.3 Historical Seismicity

The Middle East region is a unique example of an area for which information and documentation on historical earthquakes cover a time of tens of centuries.

Islamic and Arabic manuscripts and writtings containing detailed description of damage and featuring deformation due to earthquakes have been used to establish catalogues of historical seismicity. Al-Sa'adani (1971) was the first who collected the historical earthquakes of the Middle East area during the period from the seventh to the eighteenth century.

Historical seismicity has received much attention recently, many efforts have been devoted to the establishment of reliable catalogues (e.g. Abou-Karaki, 1987; Al-Tarazi, 1992; Piorrier and Taher, 1980; Ambraseys et. al., 1994; Ben-Menahem, 1991; Amerin et al., 1994).

Fig. 2.6 depicts some of the historical earthquakes occured in the DST region. In 1068 A.D., a major earthquake occured in the area and was reported to have killed 1500 to 20,000 people. The ancient city of Aila (Aqaba and Elat) was completely destroyed. The 1212 A.D. earthquake occured in south Palestine and affected Egypt and destroyed a number of houses at Al-Shaubak and Al-Karak in Jordan (Abou Karaki, 1987; Ambraseys et al., 1994). Zilberman et al. (1998) show that at least magnitude 7 was derived from damage reported of 1212 A.D. earthquake. The 1293 A.D. earthquake occured in the region of Gaza, affecting Ramallah, Lid and Al-Karak (Ambraseys, 1994). The largest reported magnitudes along the DST are of the order of 6.5-7.5.

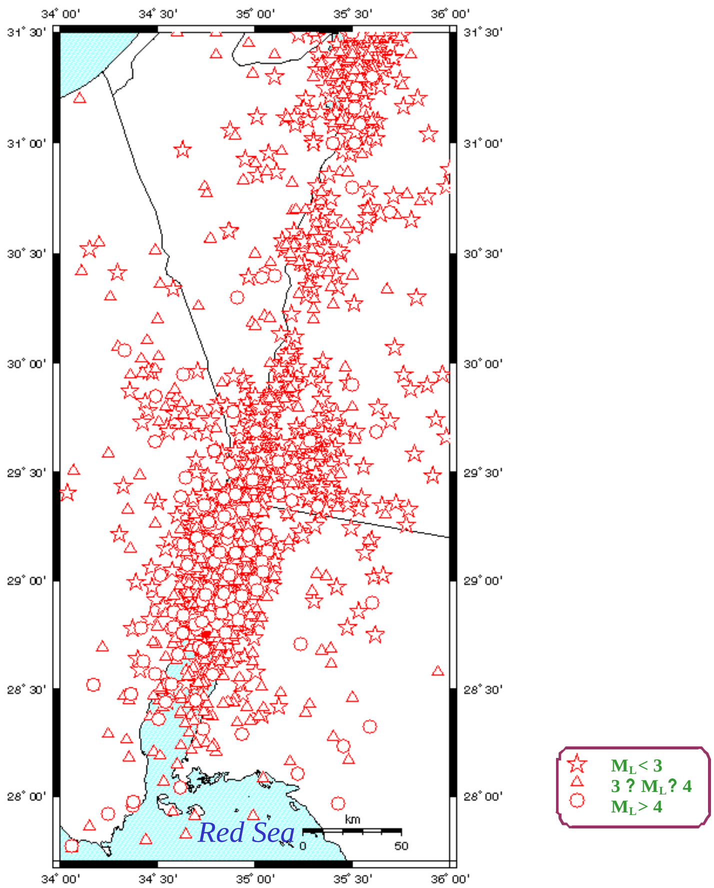

Figure 2.5: Seismicity map of the Gulf of Aqaba-Wadi Araba region for the period 1900-2000. Data from JSO (1984-2000).

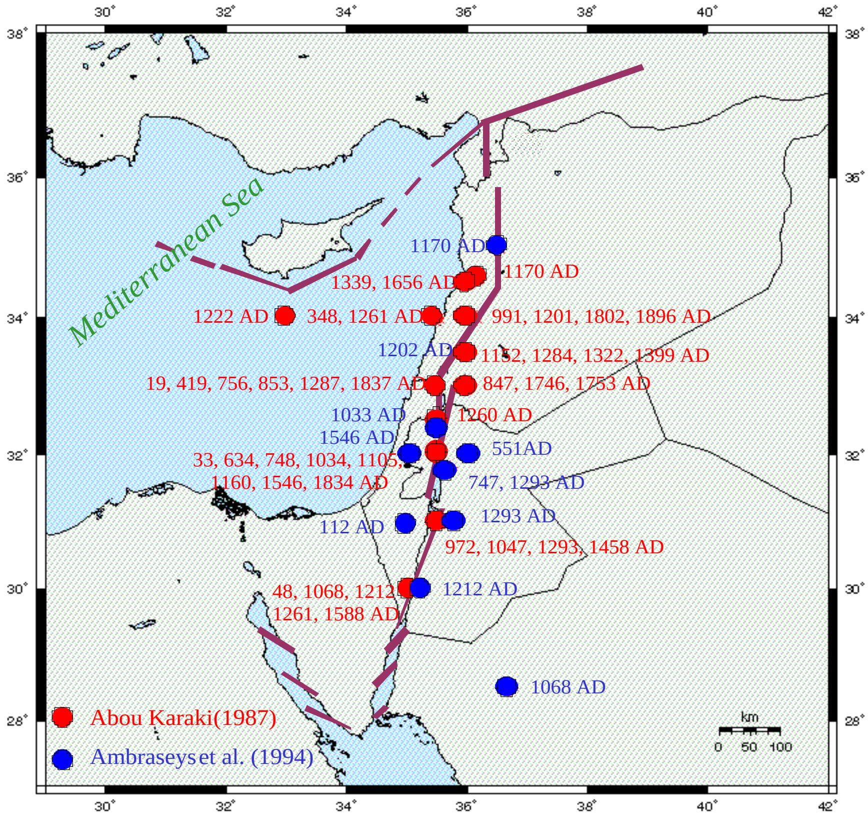

Figure 2.6: Historical seismicity map of the Dead Sea Transform region according to Abou-Karaki (1987) and Ambraseys et al. (1994).