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Full Length Research Paper

Changes in local *B*-value prior to moderate local earthquakes: Gulf of Aqabah, northern red sea

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During the last fifteen years, the Gulf of Aqabah has been considered as one of the most seismically active zones in the Middle East region. A catalogue of 1415 events were compiled using the available data from the Seismic Studies Center Network, King Saud University and the adjacent neighboring networks. The data cover the time span that started from 1985 to 1995 and an area located between latitudes 28 to 30° N, and longitudes 34 to 36° E. The duration magnitudes for these earthquakes are equal to or greater than 2.8. The value of *b* in the Gutenberg-Richter relation for a local earthquakes catalogue was investigated. The maximum likelihood method was used in this study. The *b*-value has apparently increased sharply (1.46 ± 0.21) before the mainshock-aftershock sequence type that is accompanied by a period of quiescence. Also, the *b*-value was moderate and steadily increased (0.98 ± 0.14) before the foreshock-mainshock-aftershock sequence type. Monitoring results suggest that *b*-value temporal variation may be an effective method for predicting earthquakes in the area of interest.

Key words: Gulf of Aqabah, *b*-value, magnitude frequency relation, seismicity, statistical calculation.

INTRODUCTION

The Gulf of Aqabah area is part of the northern red sea. The study area is located between latitudes 28 to 30° N and longitudes 34 to 36° E. One large earthquake (M_D = 6.2) occurred in the Gulf of Aqabah in November 22, 1995. This earthquake was followed by an extensive and complex aftershock sequence totaling more than 11,000 aftershocks ($0.5 \leq M_D \leq 6.2$) in the following 100 days (Al-Shaabi, 1998). Similarly, Al-Arifi (1996) indicated that in August 1993, an earthquake swarm began in the Gulf of Aqabah with foreshock sequences followed by the mainshock of ML = 6.0 in August 03 of the same year. It was followed by almost 15000 events in that year. El-Isa et al. (1984), Smith and Bokhari (1984) and Bazzari et al. (1990) studied the 1983 swarm in the Gulf of Aqabah. According to El-Isa et al. (1984), the swarm started on 21st September, 1983 up to 18th October, 1984 and some 244 earthquakes ($2 < ML < 4.9$) were recorded. The seismic activities along the Gulf of Aqabah seem to be characterized by swarms and mainshock-aftershock types. Al-Amri (1990) investigated the tectonics of the Midyan-Aqabah area using local seismicity and aeromagnetic data. The result of the investigation was a detailed map of onshore basement geology and a confirmation of previous estimates of offsets across the zone of transform faulting in the Gulf of Aqabah. Al-Arifi (1996) investigated the relationship between recent micro-seismicity and lineaments of the eastern side of the Gulf of Aqabah. The result was in a form of detailed map showing a very close relationship between the seismicity and lineaments. Pinar and Turkelli (1997) studied the teleseismic body wave of the 1993 and 1995 earthquakes of the Gulf of Aqabah, and reached the following conclusions: (1) the change in mechanisms between the 1993 and 1995 events suggests segmentation of the Dead Sea Fault System beneath the Gulf of Aqabah, (2) the spatial distribution of the seismic sources of the 1993 and 1995 events and their aftershock distribution suggest a northward rupture propagation. Taking into account the long seismic quiescence on the Dead Sea Fault System, the north-

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ward migration of sources makes the area to the north of the rupture zone of 1995 event prone to a large earthquake. The aim of this study is to investigate the temporal variation of the *b*-value prior to moderate earthquakes in Gulf of Aqabah using the maximum likelihood methods.

MAGNITUDE FREQUENCY

Magnitude is the most common practice in earthquake size measurement as determined from a variety of scales. Practically, the statistical distribution of magnitudes for a group of events can be quite complicated. For purposes of comparison, the so-called Gutenberg-Richter (1954) model has provided a quite successful starting model. For most magnitude scales of narrow range of earthquake magnitudes, the distribution often appears to satisfy the following relationship:

$$\log_{10} N = a - b\,M \qquad (1)$$

where N is the number of events in the group having magnitudes larger than M, and *a* and *b* are constants. Obviously, the *b*-value is a statistic measure of the proportions of large and small events in the group. If the *b*-value is large, small events are relatively common, while when *b*-value is small, small events are relatively rare (Frochlich and Davis, 1993). In the 1960's and 1970's, *b*-values were investigated by several seismologists. The *b*-value has been widely used in studies of seismicity, tectonics, seismic risk estimation and earthquakes predication. Mogi (1962) suggested that differences in *b*-value could be observed between foreshock-aftershock sequences and at sequences between various depth. He also stated that the *b*-value increases with the degree of non-uniformity of medium. Scholz (1968) found that *b*-value depends on the percentage of the existing stress within the rock sample to final breaking stress. Others, such as Bak and Tang (1989) and Carlson (1991) believe that this value is constant, equal to about 1.0 and that the differences obtained by investigators are due to variations in data and computation methods. Most seismologists believe that the *b*-value varies from region to region and with focal depth. Its value depends on the stress conditions and on the heterogeneity of the rock volume generating the earthquakes. Frohlich and Davis (1993) suggested that while observed *b*-values equal 1.0 in the sense that *b*-value is never or almost never less than 0.5 and never or almost never greater than 2.0, its precise value is uncertain or indeterminate. Except in this above limited sense, it is simply not true that *b*-value is 1.0 (Frohlich and Davis, 1993). Gutenberg and Richter (1954), Miyamura (1962), Karnik (1969), Evernden (1970), Wang (1994) and others have shown regional variations in *b*-values with increase in size of their possible tectonic significance. Isacks and Oliver (1964) reported that *b*-values vary from 0.5 to 1.5 and mainly concentrated between 0.7 to 1.0. On the other hand, Mogi (1967) indicated that the *b*-value might not be very sensitive to the structure of the earth's crust since it falls in a narrow range of 0.6 to 1.0 for most of the regions. The mechanical structure of the earth may vary significantly from one region to another, except in some volcanic or highly fractured regions. Later, Wang (1988) reported that large *b*-values appeared in the area that includes the volcano groups in Northern Taiwan. Frohlich and Davis (1993) investigated the *b*-value for four teleseismic earthquake catalogues. They found that the *b*-value differs by 30% or more when determined in different magnitude ranges, for different catalogues or using different methods. From Equation 1, temporal variations in *b*-value may, thus, be useful in monitoring the earthquake preparatory process. Indeed, many precursory decreases in *b*-value have been reported (Wyss and Lee, 1973; Yamashita and Knopoff, 1987; Ma et al., 1990). Wyss and Lee (1973) considered a sample of many more earthquakes of much smaller magnitudes in California. They calculated *b*-value using the maximum likelihood method and a 50 event window and they claimed that it decreased both before and after the mainshock. The occurrence of a period of high *b*-values before a large earthquake has been observed in New Zealand, California and Venezuela by Smith (1981). He found that only in one case the *b*-value has been associated with a previous event, the high *b*-values followed the 1968 Inangahua earthquake in New Zealand. Imoto (1987, 1991) developed a procedure for estimating variation of the multinomial response with two parameters. This procedure can be applied to study the space-time variation of the *b*-value. In 1991, he studied the space-time variations of *b*-values in the Kanto, Tokai and Tottori areas by applying this procedure and classified the temporal variations of *b*-value into three groups: increase, decrease and no change.

Analysis of a high quality seismic catalog reveals that the average of seismic b-values in the crust, beneath most part of Northeastern Japan island arc decreased from 0.86 between 1984 and 1990, to 0.73 between 1991 and 1995. The two areas with the largest decrease are found to be in the same areas where the coupling between the North American and the Pacific plates is the highest, as suggested by a recent geodetic study (Cao and Gao, 2002). To explain the seismic activity of the Denizli region (Southwest of Turkey), the relationship between magnitude and frequency was explained by using earthquake distribution in time. Magnitude-frequency relationship of the Denizli region was calculated by means of the "Log N = 5.91 - 0.97 M" equation (Cobanoglu and Alkaya, 2011). Frequency-magnitude distribution was spatially mapped beneath Makushin Volcano, Unalaska Island, Alaska using an earthquake catalog of 491 events that occurred between

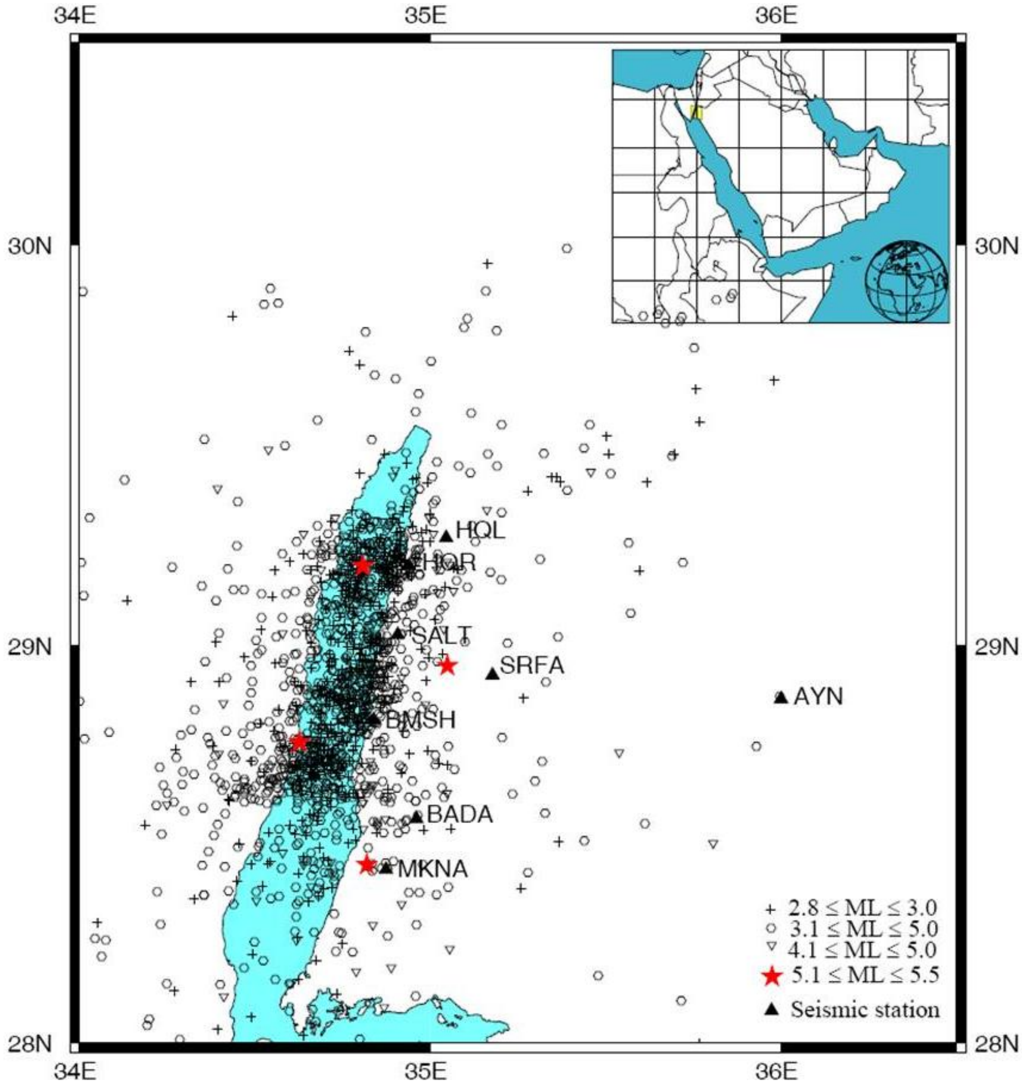

Figure 1. Epicentral distribution of the 1983, 1993 and 1995 sequences in the study area.

July 2001 and April 2005. An area of high seismic *b*-values (~2.0) is found ~4 km East of Makushin's main vent at a depth between 4 and 7 km (Bridges and Gao, 2006).

METHODOLOGY

The data were collected from a network consisting of eight seismic stations which were located on the Gulf of Aqabah (Figure 1). The earthquake data files (Al-Arifi, 1996; Al-Shaabi, 1998) for the Gulf of Aqabah was compiled using the available data at local seismic network and the adjacent neighboring networks. The data were homogenized in terms of magnitude and all were converted to duration magnitude. The parameters necessary for this study are origin time, earthquake location and magnitude for the area defined by latitudes 28 to 30° N and longitudes 34 to 36° E. The minimum magnitude of the data set completeness is determined by plotting cumulative number of events as a function of magnitude. 2.8 is the minimum magnitude of completeness as shown in Figure 2.

The *b* parameter in the frequency magnitude relation may be estimated by the least squares method or by the maximum likelihood method. According to Page (1968), the least squares method is inadequate for this type of study, because the underlying assumptions, namely, that there is no uncertainty in magnitude and that log N is normally distributed with uniform variance for all magnitude intervals, which cannot be justified. So, too much weight is given to the relatively few large events and too little to the many small events.

In this study, the *b*-value was obtained from the likelihood method. This method was suggested by Aki (1965). Statistical calculations of the constants of the frequency magnitude relation of earthquakes have been also specified by Utsu (1965). According to him, *b*-value could be obtained empirically using the following relation:

$$b = \frac{0.4343m}{\sum_{i=1}^{m} Mi - mM_{min}} \qquad (2)$$

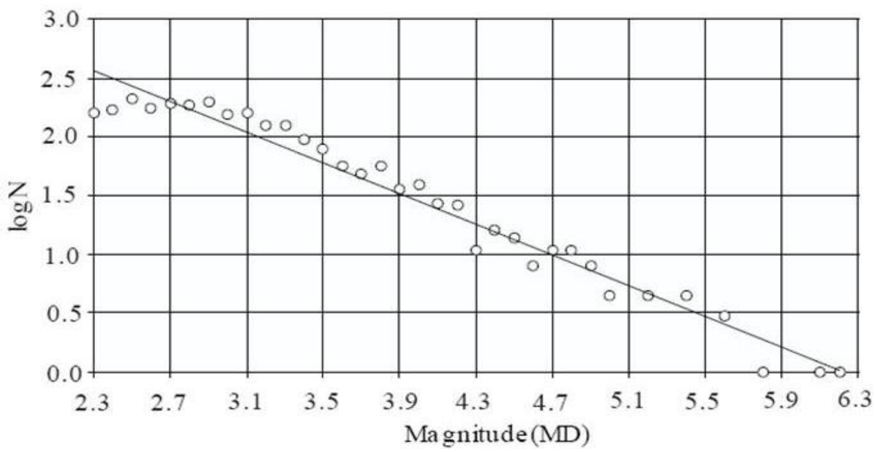

Figure 2. Log of number of earthquakes (log N) and duration magnitude (M_D) to show completeness of data used in this study. The data set is apparently complete for $M_D \geq$ 2.8.

where m is the total number of earthquake and M_{min} is the lowest magnitude considered. The standard error (δb) of the *b*-value thus estimated is $\pm b/\sqrt{n}$, where n is the number of earthquakes in the sample.

Page (1968) gives the maximum likelihood estimate of the *b*-value as:

$$b = \log_{10} e \left(m_{average} - \frac{m_{\min} - m_{\max} e^{-b'(m_{\max} - m_{\min})}}{1 - e^{-b'(m_{\max} - m_{\min})}} \right)^{-1} \qquad (3)$$

where $m_{average}$ is the average magnitude of the sample, $m_{\max}$ and $m_{\min}$ are the maximum and minimum observed magnitude and $b' = b/\log_{10} e$.

In calculating spatial and temporal variations of *b*-value in the Gulf of Aqaba, a statistical analysis based on the relation (Equation 2) was used. To eliminate the effect of having each *b*-value calculated from different events, a moving window method (30 and 50-event window sliding by 5 and 10 event, respectively) was used. The threshold magnitude was taken as M_D = 2.8 (Figure 2) for the period from 1985 to 1995.

RESULTS AND DISCUSSION

Our record of seismicity for the Gulf of Aqabah can be divided into three periods: historical (up to 1964); instrumental (1965 to 1984) and recent (1985 to 1995). The historical seismicity shows that the region suffered at least 18 moderate to large earthquakes. The instrumental seismicity includes 284 events, 244 of which were the 1983 sequence centered on Northern Gulf (Figure 1).

Recent seismicity shows that the Gulf of Aqabah seismicity (Figure 1) has been episodic. In July 1993, an earthquake sequence began with foreshocks, followed by the mainshock (M_D = 6.0) on August 3, 1993, and by 403 aftershocks ($M_D \geq$ 2.8) during four months. This sequence was concentrated in the Dakar and Tiran deeps (Figure 1). The main shock was followed by more than 100 events with M_D > 4.0 during four months. Previously, two earthquake swarms in April 1990 and in May 1991 took place with maximum magnitudes of 4.1. On November 22nd 1995, the area experienced a widely-felt earthquake located at 28.81° N, 34.75° E with a focal depth of 12 km. The mainshock (M_D = 6.2) was followed by 733 aftershocks ($M_D \geq$ 2.8) in 40 days. This sequence distributed in two clusters; the northern of which was concentrated in the Eilat deep, whereas the southern cluster was in the Aragonese and Arnona deeps (Figure 1).

b-Value prior to the 1993 earthquake

The *b*-value for all earthquakes that were recorded in the study area between 1985 and 1995 ($M_D \geq$ 2.8) is 0.88 ± 0.02. The *b*-value were calculated based on Equation 2, using a 50 event window and a magnitude threshold of M_D 2.8. Figure 3 shows the variation of *b*-value for the Gulf where the *b*-value was 0.70 ± 0.1, when the observation started in 1985. This value gradually rises till it reached 0.98 before the 1993 earthquake. After the 1993 earthquake, the value dropped dramatically to a value of 0.51 ± 0.07, which is regarded as the smallest value in the Gulf. The *b*-value rose sharply again before the 1995 earthquake as will be explain later.

When a magnitude threshold of 3 was used, the previous results did not change significantly (Figure 4). Figure 4 shows that before the1993 earthquake, there is a remarkable fall in the curve. This fall is attributed to the reduction in the number of earthquakes using 50 event window and a magnitude 3 threshold. The last point at which the 50 events were taken, the *b*-value was higher

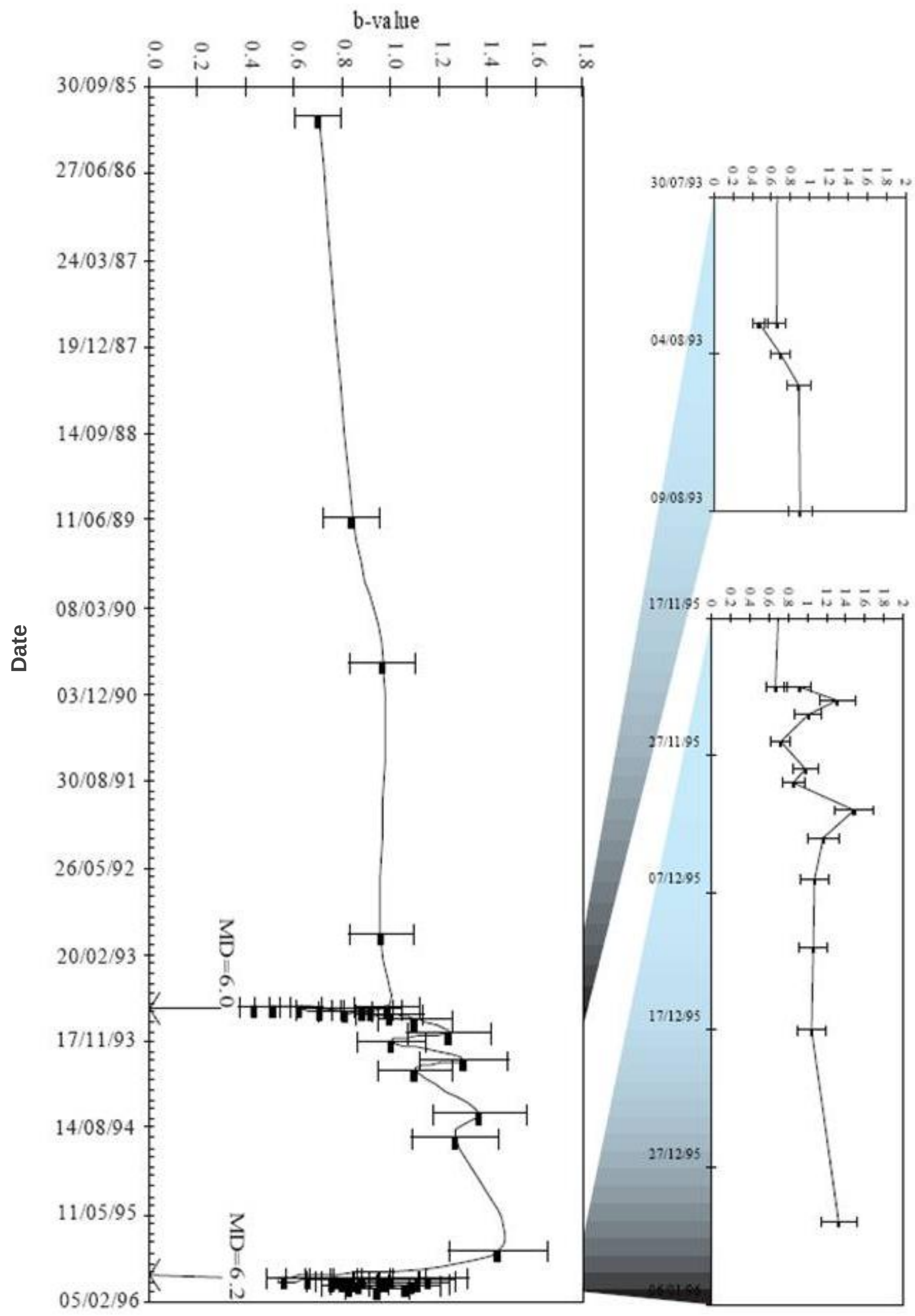

Figure 3. Variation of *b*-value for the Gulf of Aqaba. Magnitude threshold M_D 2.8, the *b*-value estimated using a window length '50 events' which slides by 10 events, and Equation 2 is employed to obtain *b*-value. The standard error in *b*-value is indicated by vertical bar. Arrows indicate the time of occurrence of earthquakes > 5.9 M_D.

than in the previous point. This becomes clear when 30 events of 3 magnitude threshold were used (Figure 5).

When a 30 event window was used (Figure 6) with the threshold of 2.8, the results did not change. The *b*-value was 0.82 ± 0.15 at the beginning of the observation period. This value increased gradually until it reached a value of 1.07 ± 0.20 in July 1993 before the 1993 earthquake. The rise in *b*-value which appears in Figure 5 during April 1990 is only a reflection of the 1990 earthquake swarm which had a maximum magnitude of 4.2.

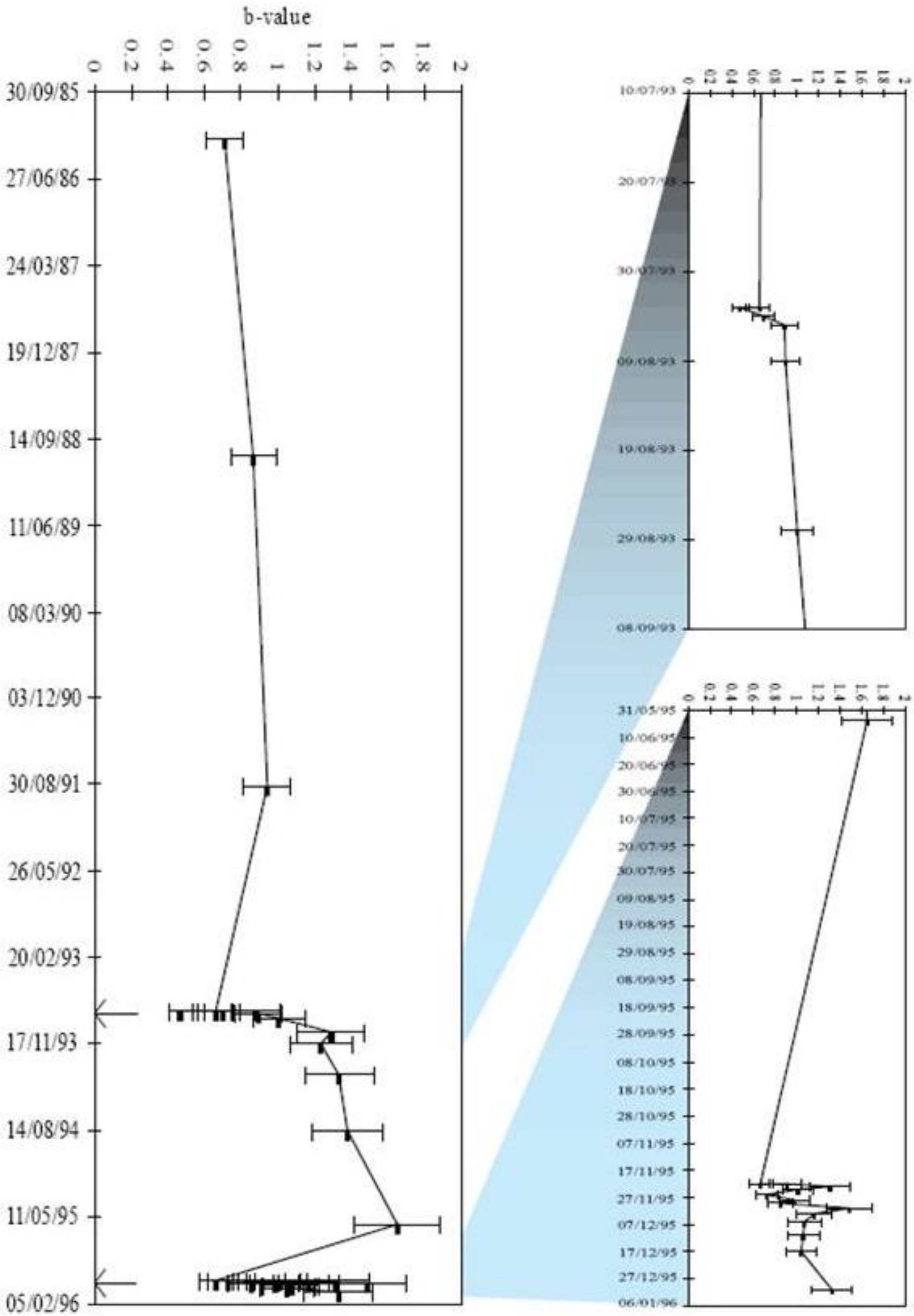

Figure 4. Variation of *b*-value for the Gulf of Aqaba. Magnitude threshold 3.0, the *b*-value estimated using a window length '50 events' which slides by 10 events, and Equation 2 is employed to obtain *b*-value. The standard error in *b*-value is indicated by vertical bar. Arrows indicate the time of occurrence of earthquakes > 5.9 M_D.

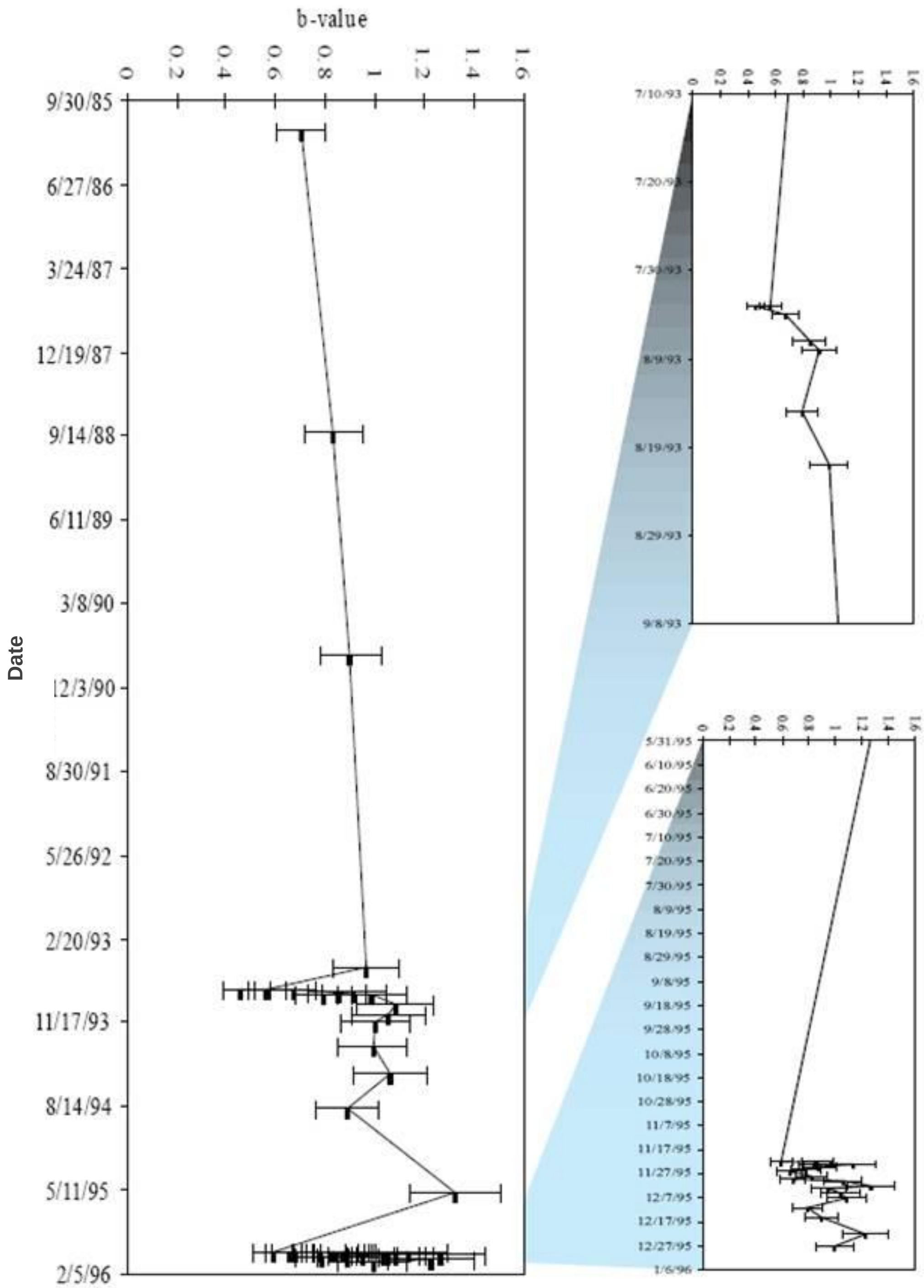

Figure 5. Variation of *b*-value for the Gulf of Aqaba. Magnitude threshold 3.0, the *b*-value estimated using a window length '30 events' which slides by 5 events, and Equation 2 is employed to obtain *b*-value. The standard error in *b*-value is indicated by vertical bar. Arrows indicate the time of occurrence of earthquakes > 5.9 M_D.

b-Value prior the 1995 earthquake

Figure 3 shows the time variation of *b*-value before the 1995 earthquake in the Gulf of Aqabah. The *b*-value was 0.70 ± 0.10 in 1985 and rose gradually till it reached 0.98 before the 1993 earthquake. This value dropped immediately after the 1993 earthquake and then rose sharply till it reached the value of 1.31 ± 0.19 on 3 November

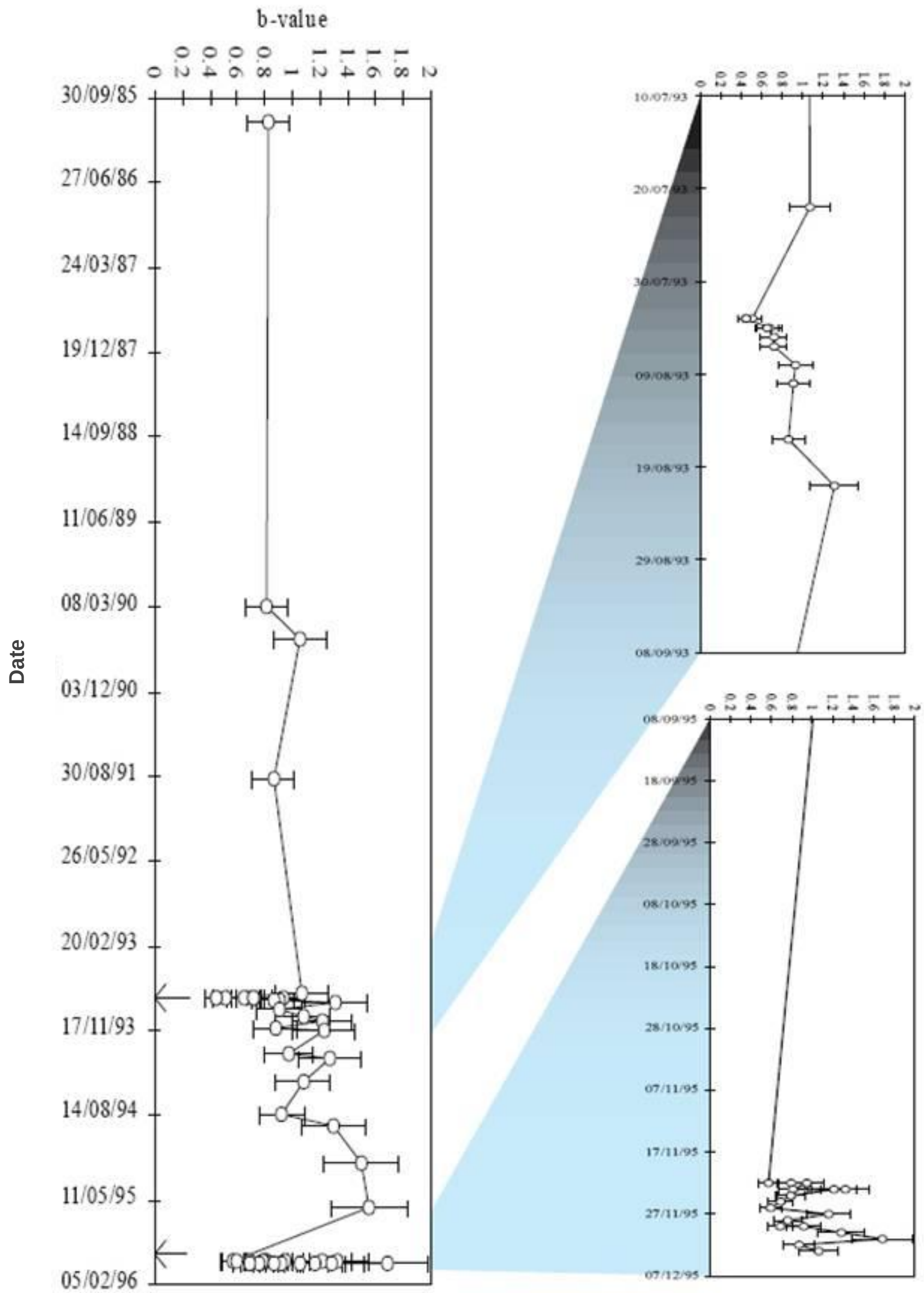

Figure 6. Variation of *b*-value for the Gulf of Aqaba. Magnitude threshold 2.8. The *b*-value estimated using a window length of '30 events' which slides by 5 events. Equation 2 is employed to obtain *b*-value. The standard error in *b*-value is indicated by vertical bar. Arrows indicate the time of occurrence of earthquakes > 5.9 M_D.

1993 when an earthquake occurred with the duration magnitude of 5.6 and then the *b*-value slightly dropped to 1.24 ± 0.18. This value rose again sharply to 1.46 ± 0.21 before 22 November 1995 which witnessed the largest earthquake that occurred instrumentally in the Gulf of Aqabah with the magnitude of 6.2.

After the 1995 earthquake, the value dropped to 0.65 ± 0.09 and then rose and dropped irregularly affected by the enormous numbers of the aftershocks in the next few days till it had stabilized at the end of the observation period to 1.05 ± 0.15.

The *b*-value seems to increase gradually reaching its

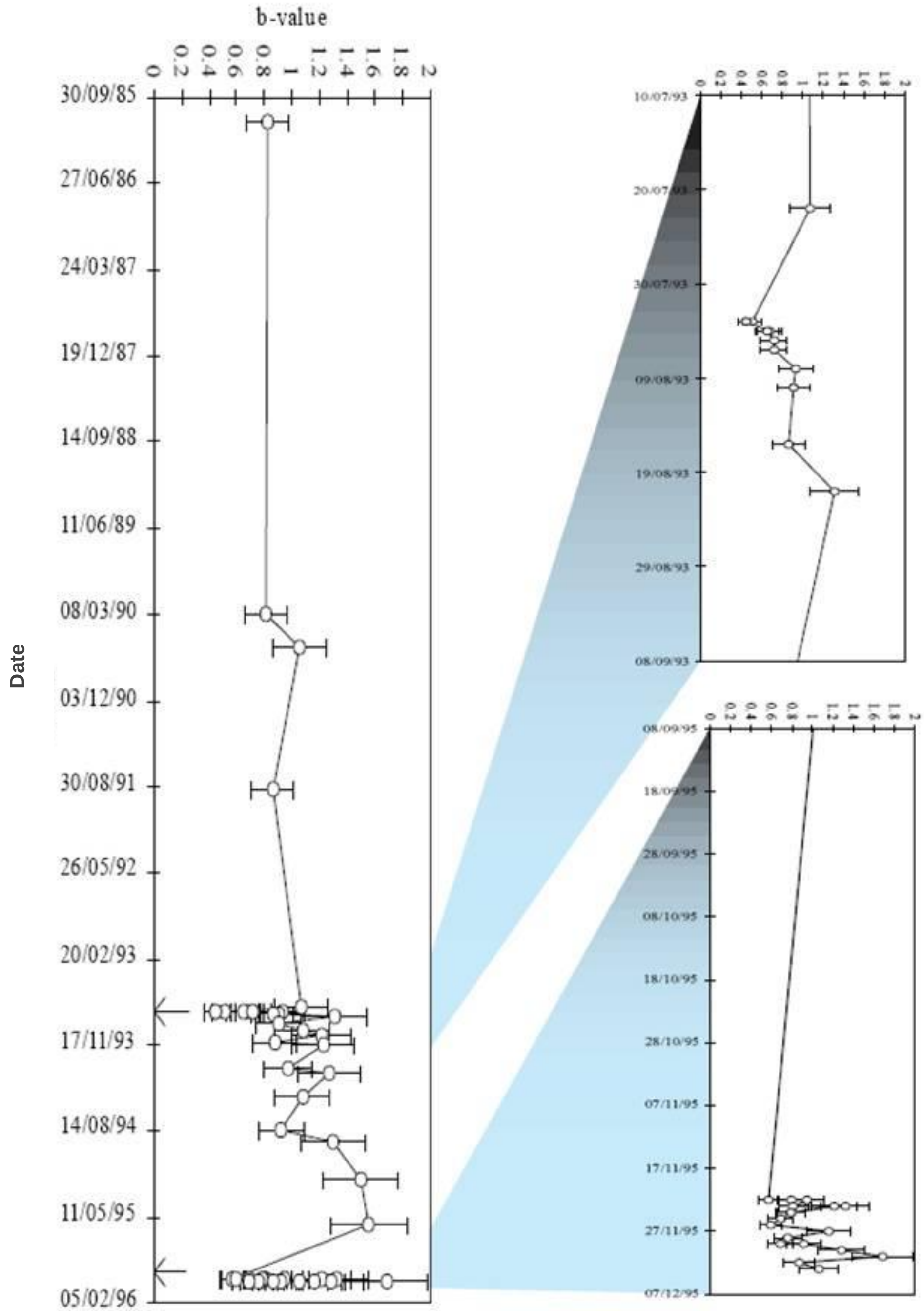

Figure 7. Variation of *b*-value for the Gulf of Aqaba using Equation 2 (dashed line) and equation 3 (full line). The *b*-value estimated using a window length '50 events' which slides by 10 events. The standard error in *b*-value is indicated by vertical bar. Arrows indicate the time of occurrence of earthquakes > 5.9 M_D.

maximum value before the 1995 earthquake. The decrease in *b*-value seems to be a reflection of the occurrence of the large earthquakes which occurred on the 3rd of August, 1993 with magnitude of 6.0 and on the 3rd of November, 1993 with magnitude of 5.6.

When Equation 3 was applied to estimate the *b*-value, the *b*-value gave almost the same results as Equation 2 (Figure 7). An average *b*-value difference of 13% was found between two methods. This difference is a small when compared with that (30%) of Frohlich and Davis (1993) who made a comparison of the *b*-value obtained using various methods on four teleseismic catalogues.

Mogi (1963) has classified earthquake sequences into three types: type I: in the case of a homogeneous

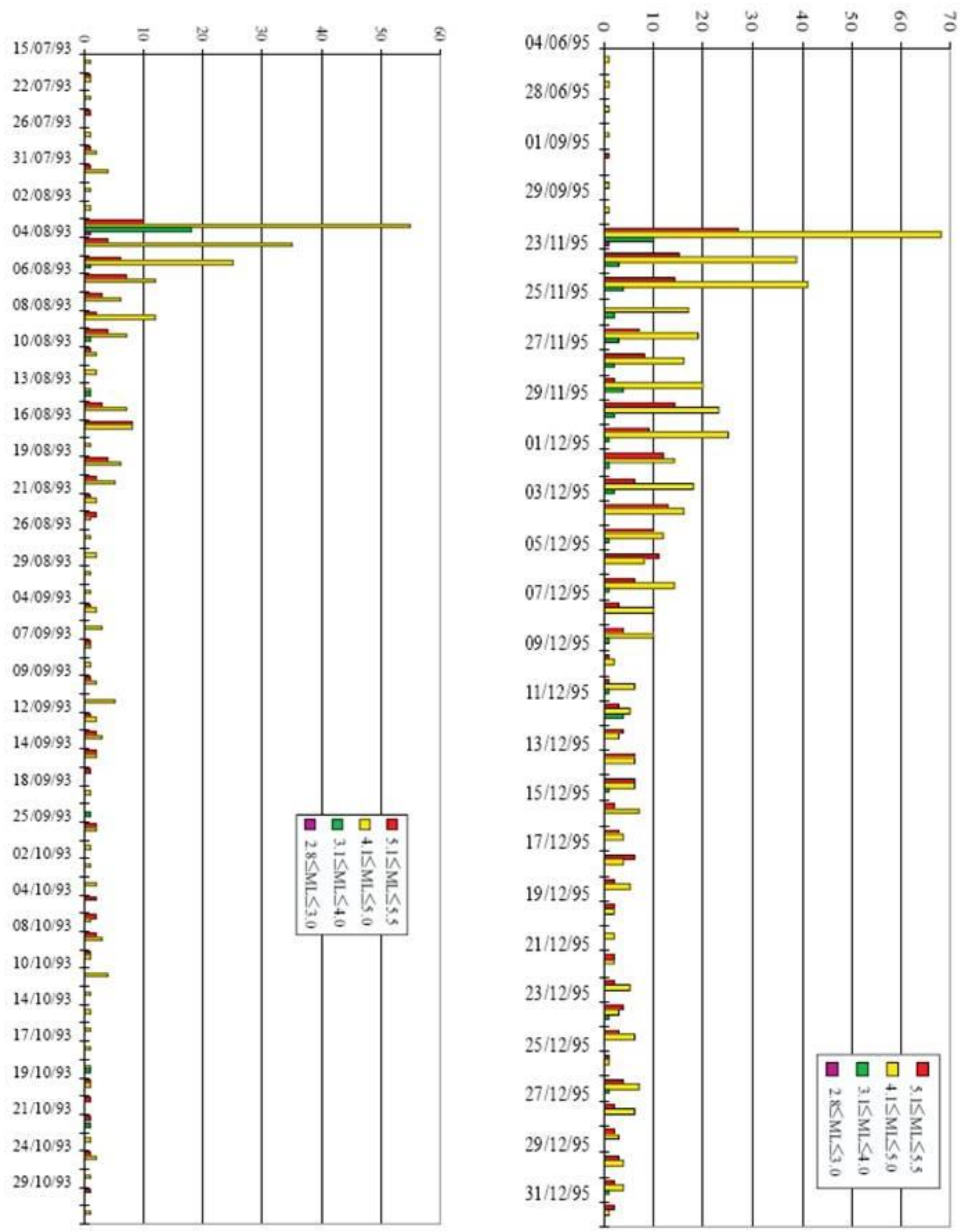

Figure 8. Diagram showing the number of earthquakes and magnitude as a function of time.

material and uniformly applied stress, a mainshock occurs without any foreshock and is followed by numerous aftershocks; type II: when the material has a rather heterogeneous structure and/or the applied stress is not uniform, small shocks occur prior to mainshock and many aftershocks occur following the mainshock; type III: when the structure of the material is extremely heterogeneous and/or the applied stress has considerable concentration, a swarm type of activity occurs when the number of shocks and their magnitude increases gradually and then decreases after some times without notable mainshock throughout the entire sequence.

It has been observed that earthquakes occurring in the Gulf of Aqabah belongs to types I, II, and III. The 1995 earthquake, lacking foreshocks and having numerous aftershocks can therefore be classified as type I (Figure 8). The 1993 earthquake was preceded by many foreshocks and followed by numerous aftershocks therefore it can be classified as type II (Figure 8). The 1983 sequence followed the same pattern of the 1993 sequence, therefore, it can be classified as type II. The 1990 swarm can be classified as type III, because there was no notable mainshock throughout the entire sequence. The difference in magnitude between the two largest events in the swarm is also 0.4. This also applied to the 1991 swarm where the largest two events were of the same magnitude.

The 1985 earthquake was not preceded by any foreshocks and not followed by any aftershocks. Therefore, it can be classified as isolated type (Ma et al., 1990).

It has been observed that the normal earthquake occurrence in the Gulf of Aqabah belongs to types I, II and III. This observation indicates that the variation in the *b*-value in the Gulf of Aqabah increased sharply before a type I of earthquake sequence as happened before the 1995 earthquake (Figures 3 to 7). It also indicates moderate and steady increase in the *b*-value before a type II of earthquake sequence as it is the case with the 1993 earthquake (Figures 3 to 7).

Smith (1981, 1986) and Wyss et al. (1990) have observed that the intermediate-term quiescence is often connected with an increasing *b*-value. However, a large increase of this value (1.46 ± 0.21) has been observed in the 1995 Gulf of Aqabah earthquake sequence accompanied by quiescence which has been referred to by Al-Shaabi (1998). While the increase of the *b*-value was not great (0.98 ± 0.14) before the 1993 earthquake which was not accompanied by the quiescence but preceded by foreshock activity.

Imoto (1991) has classified the temporal variation of the *b*-value into three groups: increase, decrease and no change. But in the Gulf of Aqabah, it has been observed that there is only one type, namely, increase before large earthquakes (Figures 3 to 7). The *b*-value was around 0.98 before the 1993 sequence and 1.05 after the 1995 sequence. This may indicate the main stress in the Gulf of Aqabah after the active term has decreased.

Conclusions

It can be concluded from this study that the occurrence of a period of high *b*-values before a large earthquake has been observed in the Gulf of Aqabah, as found in subregions of New Zealand, California and Venezuela. The b-value increased sharply before the mainshock-aftershock sequence type which was accompanied by a period of quiescence, meanwhile it indicates moderate and steady increase in its value before the foreshock-mainshock-aftershock type. Thus, our results provide additional evidence in support of the observation of Smith (1986), that the *b*-value is a medium-term precursor for earthquakes. Hence, this study suggests that monitoring of the temporal variation in *b*-values for the Gulf of Aqabah may prove to be a useful method for earthquake prediction.

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