Temporal patterns of modern aftershock sequences
along the Dead Sea Transform

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Abstract

Earthquake aftershock sequences differ in productivity, depth, frequency, rate of decay, and spatial and temporal. As a result, they appear in various combinations of peak and follow-up events. Among the physical parameters known to control these variations are crustal geothermal gradient, sedimentary thickness and mainshock magnitude. The short-term relations among events composing earthquake sequences, in terms of their magnitudes and temporal evolution, have traditionally been described by three empirical laws, namely the Gutenberg-Richter (G-R) frequency-magnitude relation, Bath’s law of the difference between main- and after-shock magnitudes, and Omori's law which describes the commonly observed temporal aftershock rate decay pattern. Based on the catalog of the Israel Seismic Network, these relations are used to analyze three earthquake sequences that followed $M_L > 5.0$ peak events along the Dead Sea Transform (the 1993 and 1995 Gulf of Elat sequences and the 2004 northern Dead Sea sequence). The data sets were selected within time windows of 1-2 years and spatial windows that are large enough to encompass the entire near-field triggered event series. This analysis showed (i) that among the two Gulf of Elat sequences, the typical mainshock-aftershock 1995 had a faster short term decay rate, but the two had comparable decay rate afterwards, and (ii) that the 2004 sequence apparently had a pronouncedly low productivity and fast decay rate compared with the Gulf of Elat sequences. These observations suggest that the temporal evolution of earthquake sequences along the DST is primarily controlled by the specific local structural-mechanic setting in each case, thus producing either mainshock-aftershock or fault-array earthquake sequences. In addition, it is possible that earthquake sequences in the Dead Sea basin are moderated in terms of productivity and temporal extent due to the exceptionally thick sedimentary cover there.
1 Introduction

Sequences of aftershocks typically follow moderate to large earthquakes and occur in regions that surround the main rupture. However, the fact that there are no universally accepted definitions for the various types of earthquake sequences (aftershocks, foreshocks, swarms; Frohlich, 1987; Kisslinger, 1996; Utsu, 2002), reflects their great variability in time, space, productivity, depth, frequency and rate of decay. Various time-frequency relations have been observed (Utsu, 2002), e.g., a mainshock-aftershock sequence (no foreshocks, outstanding mainshock), a foreshock-mainshock-aftershock sequence, an earthquake swarm (no outstanding mainshock) or series of successive mainshock-aftershock sequences. Time-space relations often show (Kisslinger, 1996) that aftershocks during an initial period (up to about two days) tend to occur on the same section of the fault that slipped during the mainshock, that the following aftershocks occur on the same segment but beyond the initial slip patch and that later aftershocks occur on other faults that were triggered by the mainshock. Earthquake sequences tend to be more productive, to occur at greater depths and to decay at a slower rate in low heat flow (cold) regions (Kisslinger, 1996; Magistrale, 2002; McGuire et al., 2005), while sequences without clear distinction between main- and aftershocks were reported to typically characterize geothermal and volcanic areas (Mogi, 1967; Utsu, 2002).

The short-term relations between earthquakes, their magnitudes and their aftershock sequences have traditionally been described by three empirical scaling laws:

(i) The Gutenberg-Richter (G-R) frequency-magnitude (power law) relation (Gutenberg and Richter, 1954), which states that the number of earthquakes of magnitude equal or greater than $m$, $N(\geq m)$, in a specific region and time interval, is approximated by the relation

$$N(\geq m) = 10^{a-bm}$$

The value of $b$ is mostly in the range 0.8 to 1.2 and the constant $a$ gives the logarithm of the number of earthquakes with magnitude greater than 0. In terms of the G-R parameters, aftershock sequences do not differ from mainshocks.

(ii) Bath’s law (Bath, 1965), according to which the difference between a mainshock magnitude $m_{MS}$ and the largest aftershock magnitude $m_{AS}$ is approximately a constant which is independent of $m_{MS}$,

$$\Delta m = m_{MS} - m_{AS}^{\text{max}} \approx 1.2$$
Overall, however, $\Delta m$ varies widely from 0 to 3 or more (Utsu, 2002). A modified version of Bath’s law (Scherbakov and Turcotte, 2004) extrapolates the G-R relation for aftershocks, to give

$$N(\geq m) = 10^{b(m_{MS} - \Delta m^* - m)}$$

Where $\Delta m^*$ is the magnitude difference between the mainshock and the largest aftershock and is approximately constant.

(iii) The Omori law, which states that a main earthquake is immediately followed by a sequence of aftershocks whose frequency of occurrence decays at a rate proportional to $t^{-p}$, where $p \sim 1$ (Omori, 1894). A modified version of Omori’s law (Utsu, 1961) states that the number of aftershocks as a function of time is given by

$$n(t) = \frac{K}{(c + t)^p}$$

Where $t$ is time since the mainshock, and $c$ and $K$ are time constants. The parameter $c$ reflects the earliest part of the sequence and accounts for the observed fact that the earliest aftershocks do not follow a steady decay rate. Rather, their rate increases in the first minutes to hours, then begins to decrease (Kisslinger, 1996). A connection between Omori law aftershock rate decay and stress fluctuation of a random Brownian motion type was proposed by Kagan and Knopoff (1987). Finally, the modified Omori's law is just one optional description of aftershock decay rates, and they may also be described by exponential and other functions (Gross and Kisslinger, 1994).

By combining these three relations, Shcherbakov et al. (2004) suggested a generalized Omori’s law for aftershocks that gives their rate of occurrence with magnitudes greater than $m$ as a function of time $t$, the G-R $b$-value, the mainshock-aftershock magnitude difference $\Delta m^*$, the mainshock magnitude $m_{MS}$, $c(m)$ and $p$,

$$n(t) = \frac{(p - 1)10^{b(m_{MS} - \Delta m^* - m)}}{c^{1-p}(c + t)^p}$$

By testing this relation on mainshock-aftershock sequences in California, Shcherbakov et al. (2004) found that the characteristic time $c(m)$ scales with the lower magnitude cut-off $m$ and the mainshock magnitude $m_{MS}$ and increases when $m$ decreases. As a result, the rate of seismic activity for lower magnitudes remains at a nearly constant level before starting to decrease. Overall, the modified Omori’s law can be used to forecast the rate of aftershock
occurrence if the mainshock magnitude is known and assuming the seismogenic parameters $b, p$ and $\Delta m^*$

2 Earthquake sequences along the Dead Sea Transform

The rate and magnitude of seismic activity along the Dead Sea Transform (DST) since the initiation of recording by the Israel Seismic Network (ISN) in the early 1980's supply only a few cases where aftershock statistics can be applied, mostly in the Gulf of Elat (GOE; Fig. 1). Seismicity in the GOE during the 12 years prior to the large ($M_w$7.2) 1995 Nuweiba earthquake was clustered in space and time (Fig. 2), with the release of seismic energy mostly localized at two major fault step zones (El Isa et al. 1984; Alamri 1991; Shamir and Shapira 1994; Shamir et al., 2003). The 1983 and 1990-91 sequences (peak magnitudes $M_L$=5.2 and 4.3, respectively) were mostly confined to the northern Gulf (Elat basin), while the 1993 sequence (peak magnitude $M_L$=5.8) occurred in its central part (Aragonese basin). No similar activity was reported in the Gulf in previous decades (the regional catalog is considered complete for $M_L \geq$4.8 since 1900 and for $M_L \geq$4.0 since 1940). Of these, the 1993 sequence and the 1995 aftershock sequence of the Nuweiba earthquake were selected for statistical analysis, for reasons of magnitude and epicenter location accuracy.

Elsewhere along the southern DST (Mt. Hermon to Red Sea), only the earthquake sequence that followed the Feb. 2004, northern Dead Sea (NDS) basin earthquake ($M_L$5.2) could be potentially considered an aftershock sequence.

In this study, the Gutenberg-Richter power law frequency-magnitude distribution and a modified Omori's Law fit to the event rate decay are calculated for each sequence. Since there is no universally accepted definition of aftershocks, data for each sequence were selected within spatial windows (Table 1) related to the mainshock rupture length (GOE 1995) or an estimate of the epicenter spread (GOE 1993, NDS 2004), considering the tectonic setting (i.e. an elongated transform zone) and allowing also for location errors. Temporal windows were selected to be long enough to span each earthquake sequence. The magnitudes of the peak event ("mainshock") ($m_{MS}$) and the next largest event ($M_{MS}^{max}$), their difference ($\Delta m$) and the number of events used for the analysis ($n$) are also listed in Table 1.
Table 1: Time-space-magnitude parameters for the three analyzed earthquake sequences. The two values for the $\Delta m$ value of the NDS 2004 sequences refer to near field/far field events, respectively.

<table>
<thead>
<tr>
<th></th>
<th>GOE 1993</th>
<th>GOE 1995</th>
<th>NDS 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x^{EW}, \Delta y^{NS}$ (km)</td>
<td>58x160</td>
<td>80x160</td>
<td>18x80</td>
</tr>
<tr>
<td>$\Delta t$ (days since MS)</td>
<td>390</td>
<td>730</td>
<td>346</td>
</tr>
<tr>
<td>$m_{MS}$</td>
<td>5.8 (MI)</td>
<td>7.2 (Mw)</td>
<td>5.2 (MI)</td>
</tr>
<tr>
<td>$m_{AS}^{max}$</td>
<td>5.6</td>
<td>5.6</td>
<td>4.7</td>
</tr>
<tr>
<td>$\Delta m$</td>
<td>0.2</td>
<td>1.6</td>
<td>0.5/1.5</td>
</tr>
<tr>
<td>$n$</td>
<td>1278</td>
<td>2195</td>
<td>40</td>
</tr>
</tbody>
</table>

**Gulf of Elat, 1993 (GOE93)**

The August 1993 Gulf of Elat earthquake sequence was mainly concentrated in the Aragonese basin (Fig. 2), and included two peak events (ML=5.8 and 5.6) in the first day, followed by 497 events of $M_L \geq 3.0$ in the following year, within the spatial window selected in this study. These earthquakes reflect the activation of a complex fault array in the southern part of the Aragonese Basin, located at a major tensile left-step along the DST (Ben Avraham et al., 1979). The spatial data window encompasses the width of the Gulf and is ~3 times as long as the Gulf-parallel epicentral distribution.

A fundamental problem in any analysis of GOE seismicity is its location outside the ISN and at the suture between four seismic networks (Israel, Jordan, Egypt, Saudi Arabia) with differing network coverage and data availability. Epicenter determinations are particularly sensitive to availability of data from the seismic networks of Saudi Arabia, as demonstrated for the 1993 sequence by comparison of Figs. 2 and 3. The 1993 sequence is the only one for which data from all four networks was available and is therefore the best located.
Figure 1: Bathymetry, mapped faults and schematic fault structure (inset) of the Gulf of Elat/Aqaba (after Hall & Ben-Avraham 1978; Ben-Avraham et al. 1979a; Ben-Avraham 1985; Ben-Avraham & Tibor 1993). Epicenter and focal mechanism of the 1995 Nuweiba earthquake after Shamir et al., 2003
Figure 2: Earthquake sequences in the Gulf of Elat, 1983-1993 (Shamir and Shapira, 1994). Peak events are emphasized.
In terms of the epicenter distribution and the temporal magnitude decrease (Fig. 4), the 1993 sequence cannot be classified as a typical mainshock-aftershock sequence, as it is not geometrically related to a mainshock segment, has two peak events (M\textsubscript{L} 5.8 and 5.6) and a small $\Delta m$ value of 0.2. It is also not an earthquake swarm in the volcanic/geothermal sense. Fig. 5a shows the frequency-magnitude relation for events of magnitude 4.0 and higher and Fig. 5b the temporal change in daily event rate and the modified Omori’s law fit to that rate decay.

**Figure 3:** Epicenter distribution of the 1993 Gulf of Elat sequence based only on the seismic networks of Israel, Jordan and Egypt. Compare with Fig. 2, where data from the Saudi Seismic Network was also used for the 1993 sequence (blue).
Figure 4: Temporal magnitude change for the 1993 Gulf of Elat earthquake sequence.

Figure 5: (a) Frequency-magnitude relation \( (M_I \geq 4.0) \), and (b) temporal change in daily event rate and the modified Omori's law fit to that rate decay.
**Nuweiba earthquake, 1995 (GOE95)**

The Nuweiba earthquake (November 22, 1995; $M_w = 7.2$), the largest seismic event along the Dead Sea Transform (DST) in at least 175 yr, ruptured 45–50 km along the Aragonese segment of the left-stepping strike-slip fault system occupying the gulf of Elat/Aqaba (Fig. 1). It was followed by an intense aftershock sequence that included more than 800 events of $M_L \geq 3.0$ within the following 2 years.

The epicenter distribution for the Nuweiba aftershock sequence (GII, 2007; Shamir, 1996; Hofstetter et al., 2003; Shamir et al., 2003; Fig. 6) was determined based on the seismic networks of Israel, Jordan and Egypt, and thus suffers from inaccuracy due to insufficient station coverage. Generally, the epicenters were mostly concentrated in the pull-apart basins to the northwest and southeast of the mainshock rupture segment, but the degree to which they occurred along that segment cannot be determined.

Another deficiency of this data base is the incompleteness of the catalog, both with respect to $M_L \leq \sim 3.5$ events (due to their distance from ISN) and with respect to $M_L \approx 5–6$ events during the first 1-2 days due to overlapping recording. For the available data, the temporal magnitude distribution (Fig. 7) shows an $M_w$ difference of 1.6 between the mainshock and the largest recorded aftershock.

The frequency-magnitude relation for $M_L \geq 4.0$ aftershocks during the 730 days following the Nuweiba earthquake is shown in Fig. 8a, and the temporal change in daily event rate and the modified Omori's law fit to that rate decay in Fig. 8b.
Figure 6: Aftershock sequence of the 1995 Nuweiba earthquake, Gulf of Elat, based on the seismic networks of Israel, Jordan and Egypt.
Figure 7: Temporal magnitude distribution of the aftershock sequence of the 1995 Nuweiba earthquake.

Figure 8: (a) Frequency-magnitude relation ($M_L \geq 4.0$), and (b) temporal change of daily event rate and the modified Omori's law fit to that rate decay for the Nuweiba earthquake aftershock sequence.
The northern Dead Sea basin, 2004 (NDS04)

An $M_L=5.2$ earthquake struck the northeastern Dead Sea basin in February 2004, the largest in this region since the 1927, $M_L\sim6.2$ (Shapira et al., 1992), Jericho earthquake. During the year following the 2004 event, 46 events of magnitude $M_L \geq 2.0$ occurred within the spatial window shown in Fig. 9. This temporal sequence consists of a main near-field cluster in the northern Dead Sea and two minor sequences, ~30 km to the south (central Dead Sea) and north (Fazael valley). Although this sequence (let alone its near-field cluster) is too small for a robust statistical analysis, its frequency and temporal behavior may provide some insight with regard to the earthquake activity in the Dead Sea basin. As indicated by the fault plane solution of the peak event (Fig. 9), it did not occur along the eastern DST segment trending N-S, nor did the near-field aftershock sequence occur along any of the potential nodal planes. In addition, the magnitude difference between the peak event and the second largest "aftershock" is only 0.5 (Fig. 10). Therefore, the NDS04 sequence is not a typical mainshock-aftershock sequence but apparently a series of triggered events on a fault array that is yet to be resolved (Shamir, 2006).

The frequency-magnitude relation for $M_L \geq 2.0$ earthquakes during the year following the NDS04 peak event is shown in Fig. 11a, and the temporal change in daily event rate and the modified Omori's law fit to that rate decay in Fig. 11b. Note, however, that these results should be considered cautiously due to the small number of events in this data set and the rate of earthquake occurrence of 0-1 per day (as suggested also by the b-value of 0.58).

Table 2: Parameters of the frequency-magnitude (G-R) relation and the Omori's law fit to the event rate decay for the three analyzed data sets

<table>
<thead>
<tr>
<th></th>
<th>GOE 1993</th>
<th>GOE 1995</th>
<th>NDS 2004</th>
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<tbody>
<tr>
<td>G-R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>5.468</td>
<td>7.806</td>
<td>3.204</td>
</tr>
<tr>
<td>b</td>
<td>0.939</td>
<td>1.273</td>
<td>0.707</td>
</tr>
<tr>
<td>Omori's law</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>264.7</td>
<td>197.11</td>
<td>40.8</td>
</tr>
<tr>
<td>c</td>
<td>1.63</td>
<td>0.205</td>
<td>1.66</td>
</tr>
<tr>
<td>p</td>
<td>0.89</td>
<td>0.72</td>
<td>1.50</td>
</tr>
</tbody>
</table>
Figure 9. Epicenters of the 2004 north Dead Sea earthquake sequence. Location is based on the Israel and Jordan seismic networks. Fault plane solution after Shamir, 2006.
Figure 10: Temporal magnitude distribution of the 2004 northern Dead Sea earthquake sequence

Figure 11: (a) Frequency-magnitude relation ($M_L \geq 2.0$), and (b) temporal change of daily event rate and the modified Omori's law fit to that rate decay for the 2004 northern Dead Sea sequence.
4 Discussion and Conclusions

Based on the catalog of the Israel Seismic Network (GII, 2007), three earthquake sequences associated with three $M_L > 5.0$ peak events along the Dead Sea Transform were analyzed in terms of the Gutenberg-Richter frequency-magnitude relation and the modified Omori’s law for aftershock decay rate. The data sets were selected within time windows of 1-2 years and spatial windows that are large enough to encompass the entire near-field triggered event series.

The temporal evolution of the 1993 and 1995 Gulf of Elat sequences was previously examined by Rabinowitz and Steinberg (1998). They found close $p$ values (0.9 and 0.75 for the 1993 and 1995 sequences, respectively) but different $A$ (9.6 and 15) and $c$ values (0.045 and 0.053). Their analysis, however, was based on a time window of only 3 months for the 1995 Nuweiba earthquake (Mw=7.2) and on spatial windows that span the entire Gulf of Elat. An inherent problem associated with analyzing Gulf of Elat seismicity is catalog incompleteness; however, based on the frequency-magnitude relations for these sequences (Figs. 5a and 8a) it can be concluded that this does not significantly bias the statistical results. A notable difference is found in the $c$ parameters of the Omori’s law fit for these sequences. If this time parameter is not a constant but rather scales with the lower cutoff and the mainshock magnitude, as suggested by Shcherbakov et al. (2004), then this is related to their different mainshock magnitudes.

In order to compare the evolution of event rate for the analyzed sequences independently of their specific durations and daily rates, their Omori’s law curves were normalized with respect to their rate at $t=0$ ($A/c^p$) and plotted on a log scale (Fig. 12) against normalized time (relative to the time window length $t_{\text{max}}$). Tests with varying time windows show the following:

(i) The short term decay of the NDS-04 sequence is highly sensitive to $t_{\text{max}}$. A shorter $t_{\text{max}}$ brings the decay rate closer to the GOE-93 short term decay rate.

(ii) The overall relatively fast temporal decay of NDS-04 is insensitive to $t_{\text{max}}$.

(iii) The relative configuration of GOE-93 and GOE-95 is not sensitive to $t_{\text{max}}$ variations of either sequence.

Two major characteristics of the analyzed sequences emerge from this comparison:

(1) The temporal decay rate of the Dead Sea sequence is significantly faster than those of the Gulf of Elat sequences. Thus, for example, at $t=0.5$ $t_{\text{max}}$, the NDS04 event rate is
down to 0.09% of its initial value while the GOE95 and GOE93 rates are 0.45% and 1.5% of their initial values, respectively.

The apparent low productivity and fast decay rate of the NDS04 sequence obviously cannot be explained by high heat flow, a connection suggested by previous studies of aftershock sequences (e.g. Kisslinger, 1996; Magistrale, 2002; McGuire et al., 2005). On the other hand, Ben Zion and Lyakhovsky (2006), based on a 3-layer viscoelastic lithospheric model using damage rheology, suggested that low event productivity and fast decay rates characterize aftershock sequences in a crust containing a thick sedimentary cover. The thickness of the syn-tectonic sedimentary fill in the northern Dead Sea basin is about 4km (Ginzburg and Ben Avraham, 1997) and the entire depth to the basement may reach 8-9km. In the Gulf of Elat, 2-3km of sediments were recorded seismically without reaching basement (Ben Avraham et al., 1979), but the sedimentary record cannot be much thicker considering that the Gulf began opening around 20 my ago. Thus these significant thickness differences could play an important role in creating different decay rates and productivity for the respective sequences.

Figure 12: Normalized daily event rate as a function of normalized time for the three analyzed earthquake sequences.
The short-term (up to \( t \sim 0.1 \, t_{\text{max}} \)) event rate decay of the GOE95 was substantially faster than that of GOE93 (as expressed by the lower \( c \) parameter of the former). Following that initial phase, the two Gulf of Elat sequences had the same decay rate. Since these sequences overlapped spatially, the parameters of heat flow and sediment thickness can be excluded from their comparison, and the difference in short-term decay rate was apparently related primarily to the difference in structural setting: The GOE95 sequence initiated along the Nuweiba mainshock rupture segment, then spread to the complex fault systems to the north (Elat basin) and south (Aragonese basin); the GOE93 sequence, on the other hand, did not follow a major mainshock and reflects mostly the activity of the south Aragonese fault system. It is therefore concluded that the initial fast decay rate of the GOE95 sequence represents the initial spread of aftershocks along the Nuweiba mainshock segment. In the medium- and long term, the two sequences activated the same fault systems and thus have similar decay rates.

In summary, while the data base available for analysis of earthquake sequences along the DST is limited by the small number of medium-large events, epicenter location problems and catalog incompleteness, it seems that the temporal evolution of earthquake sequences along the DST is primarily controlled by the specific structural-mechanical conditions in each case. These, in turn, determine whether a typical mainshock-aftershock sequence (GOE95) or a fault-array sequence (GOE93, NDS2004) will develop, with the former apparently characterized by a faster short-term decay rate. However, even for similar sequence types these characteristics may vary with location, as demonstrated by the differences in productivity and decay rate for the two fault-array sequences GOE93 and NDS2004. Thus, it is speculated that earthquake sequences in the Dead Sea basin could be moderated relative to Gulf of Elat sequences due to the exceptionally thick sedimentary cover there.
Acknowledgments

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References


Geophysical Institute of Israel (GII), 2007. Catalog of earthquakes in Israel and adjacent areas.


Aftershock sequences of the earthquakes offshore north of the Dead Sea have been examined in this study, focusing on their productivity and spatial-temporal patterns. The productivity of the sequences is measured by the Gutenberg-Richter relation (Gutenberg and Richter, 1954), which relates the number of earthquakes to their magnitudes. The Omori law (Omori, 1894) and Bath's law (Bath, 1961) are used to analyze the decay rate of event frequency and the relationship between the magnitude of the mainshock and the frequency of aftershocks. The spatial distribution of the earthquakes is studied using the Bath's law to estimate the source parameters of the fault-plane and the earthquake mechanism.

The study also examines the relationship between the productivity of the sequences and the tectonic setting of the Dead Sea region. The results show that the productivity of the sequences is influenced by the tectonic structure and the depth of the fault-plane. The productivity is higher in areas with more complex tectonic settings and deeper fault-depths. The study provides insights into the seismic activity of the Dead Sea region and its implications for earthquake risk assessment.
ה突出יות בבזים של סדרות עכשווים של קשתי משינה
לאורות טרנספורם אים המלה

ג' שמיר

מונש עלدت ההידוג לניירכון לערידות אדם

ירחלים, אפריל 2008

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