

PREDICTION OF LARGE AFTERSHOCKS:
AN APPLICATION FOR THE AREA OF GREECE

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ABSTRACT

Matsuura (1986) studied quantitatively the temporal features of the aftershock activity following some large earthquakes. The earthquakes concerned were accompanied by large aftershocks which triggered their own aftershock activities.

Aftershock activity shows an appreciable deviation from the modified Omori's formula before the occurrence of a large aftershock.

The present study is an application of this method for the area of Greece. The method tested for some recent seismic sequences in Greece, seems that it works well enough.

This method is a useful tool for the possibility of predicting the occurrence of a large aftershock which might be as large and disastrous as the main shock, if we keep watch on the change of the aftershock activity immediately following the main shock.

Introduction

Seismicity pattern is one of the most promising subjects in earthquake prediction studies, because it brings information about physical conditions of the source region of an impending large earthquake. Seismic quiescence in a source region preceding a large earthquake has often been reported (e.g. UTSU, 1968; MOGI, 1968b, 1969). Another remarkable precursor is foreshocks.

However, it is very difficult to recognize those seismicity changes as precursors before the earthquake occurs. Many precursory changes of seismicity were found after the occurrence of a large earthquake. That is the so called

'post prediction", which is far easier than true prediction. For example it is always easy to identify foreshocks after the occurrence of the main shock but they are indistinguishable, in real prediction, from clusters of shocks which would not lead to large shocks. Seismicity shows such a wide variation that is very difficult to represent its temporal features quantitatively, except for the case of aftershock activities.

It is widely accepted that the occurrence rate of aftershocks $n(t)$ obeys the modified Omori formula (UTSU, 1961)

$$n(t) = \frac{K}{(t+c)^p} \quad (1)$$

where t is the lapse time from the main shock. Aftershocks are usually much smaller than the main shock and not followed by secondary aftershocks. However, sometimes a large aftershock occurs. Such a large aftershock is followed by its own aftershocks (secondary aftershock). Hereafter, "large aftershock" means this type of remarkable aftershock.

Since the temporal characteristics of normal aftershock sequences can be represented quantitatively by modified Omori formula, MATSU'URA (1986) proposed a method to examine whether there is any anomalous change in aftershock activity before the occurrence of a large aftershock. If any change is recognized and its common features are known, it is not only useful for prediction of such a large aftershock which might cause additional disaster, but also important to reveal the generating process of such a large aftershock or an earthquake in general.

Method

The conventional way to estimate the parameters, K , c , and p in (1) is from a $\log n(t)$ vs $\log (t)$ plot. Since $n(t)$ is not a directly observed quantity, it is calculated from the number of aftershocks in a certain unit of time. In this way, several aftershocks are represented by only one datum point, and to obtain the three parameters it is needed a great number of aftershocks.

Ogata (OGATA, 1983) proposed the maximum likelihood method for the estimation of these parameters. According to this method, the likelihood is defined as

$$L(K, c, p; t_1, t_2, \dots, t_N) = \prod_{i=1}^N n(t_i) \exp\left\{-\int_{t_i}^T n(s) ds\right\} \quad (2)$$

when the i -th aftershock occurred at time t_i , all N aftershocks were observed from time S to T , and $n(t)$ is the same as (1).

The logarithmic form can be written as follows.

$$\ln L(K, c, p; t) = \sum_{i=1}^N \ln \{n(t_i)\} - \int_0^T n(s) ds \quad (3)$$

It is useful to plot the cumulative number of aftershocks against the frequency-linearized time r (OGATA and SHIMAZAKI, 1984) in order to check the fit between the modified Omori formula and the temporal pattern of aftershock occurrence. The frequency-linearized time (FLT) is defined as

$$r = \int_0^t n(s) ds \quad (4)$$

which is equal to the calculated cumulative number of aftershock using the estimated parameters in (1). The time interval between two successive aftershocks is equal to the unit time of r . Therefore, if an aftershock sequence is perfectly expressed by (1) the cumulative number of aftershocks increases linearly with r (fig.1 (a)). Figure 1 after MATSU'URA (MATSU'URA, 1984) shows schematically the variations of aftershock activity with time.

Generally, when one aftershock sequence contains some large aftershocks accompanied by their secondary aftershocks, the modified Omori formula becomes

$$n(t) = \sum_{i=0}^M H(t-T_i) \cdot \frac{K_i}{(t-T_i+c_i)^{p_i}} \quad (5)$$

where $H(t)$ is a unit step function, M is the number of large aftershocks having their own aftershocks, and $T_0(r)$ and T_i are the origin time of the main shock and the i -th large aftershock, respectively.

Data

The present study is an application of MATSU'URA'S method to four recent earthquake sequences which occurred in the area of Greece. For studying these sequences, lists of aftershocks has been carefully made from the National Observatory, Seismological Institute monthly bulletins. The results of the method for the four sequences are the following.

1) The Gulf of Korinth earthquake of 1981

On February 24, 1981 the surrounding areas of the gulf of Korinth, including Athens were struck by an earthquake of $M_L=6.2$. After a few hours the largest aftershock of $M_L=5.9$ occurred. March 4 a large aftershock of $M_L=5.8$ occurred causing extend damages on Plateae and Karporeli.

For studying this sequence a list of aftershock has been carefully made. In order to be sure for the homogene-

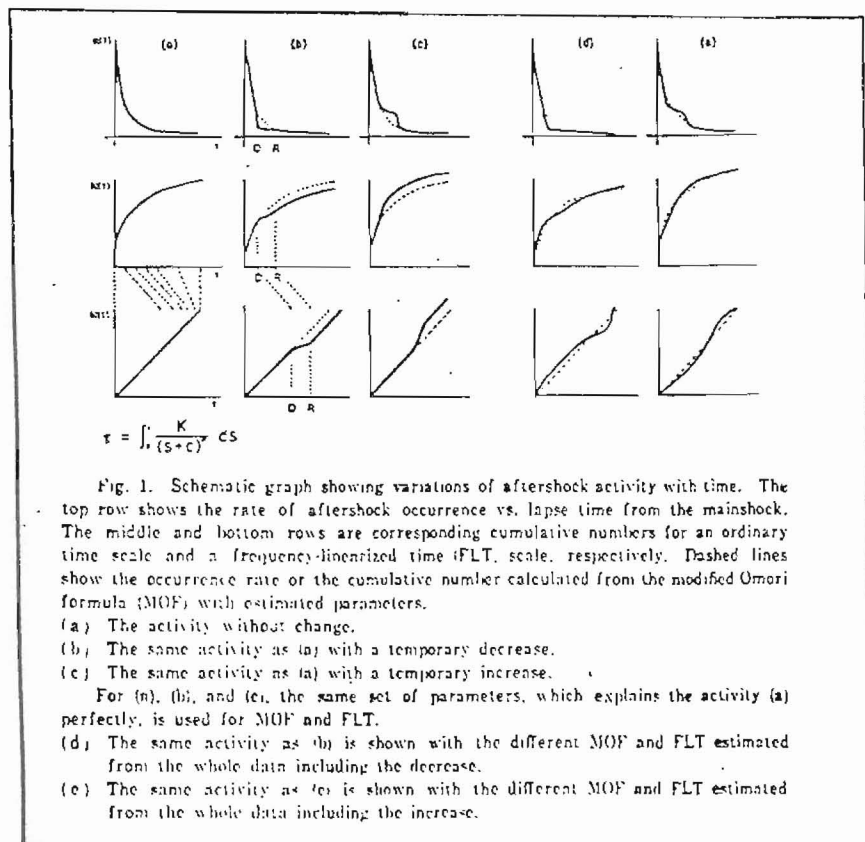


Fig. 1. Schematic graph showing variations of aftershock activity with time. The top row shows the rate of aftershock occurrence vs. lapse time from the mainshock. The middle and bottom rows are corresponding cumulative numbers for an ordinary time scale and a frequency-linearized time (FLT scale, respectively. Dashed lines show the occurrence rate or the cumulative number calculated from the modified Omori formula (MOF) with estimated parameters.

(a) The activity without change.

(b) The same activity as (a) with a temporary decrease.

(c) The same activity as (a) with a temporary increase.

For (a), (b), and (c), the same set of parameters, which explains the activity (a) perfectly, is used for MOF and FLT.

(d) The same activity as (b) is shown with the different MOF and FLT estimated from the whole data including the decrease.

(e) The same activity as (c) is shown with the different MOF and FLT estimated from the whole data including the increase.

Fig. 1: After MATSU'URA (1986)

ity of the data it has been $M_L=3.5$ as threshold magnitude. It did not examine the case of the largest aftershock because of the very high number of aftershocks immediately after the main shock.

In the five days 4.78833 interval from the main shock, the data deviate largely from the single Omori formula before the aftershock of March 4. In this case the short quiescence and the following foreshock-like high activity are observed before, the large aftershock (fig. 2 a,b). The Omori's law for the time interval from the main shock up to 8 days is

$$n(t) = \frac{27.0}{(t+0.126)^{0.943}} \quad (6)$$

and up to 5,68 days

$$n(t) = \frac{38.9}{(t+0.379)^{1.438}} \quad (7)$$

ii) The north Aegean sea earthquake of 1981

On December 19, 1981 the northern Aegean sea earthquake (hereafter is called first shock) of $M_L=6.3$ occurred. After one month, when aftershock activity was still observed, the Chalkidiki earthquake (the second shock) of $M_L=6.4$ occurred on January 18, 1982, abutting on the source region of the first shock.

This is one of the best examples for studying changes in aftershock activity with a large aftershock. Since the shock was large enough, there is a high probability that preparatory processes for the second shock which started after the occurrence of the first shock changed physical conditions in the whole or a large part of the aftershock area of the first shock.

To study this sequence a list of aftershock with threshold magnitude $M_L=3.5$ it was made. Also in this case the quiescence and the following foreshock activity are observed before the second shock (fig. 3 a,b)

The parameters of the Omori law for the time interval from the first shock to 31 days (the second shock) are

$$n(t) = \frac{10.4}{(t+0.018)^{0.8}} \quad (8)$$

and from the beginning to quiescence (4 days)

$$n(t) = \frac{10.2}{(t+0.051)^{1.09}} \quad (9)$$

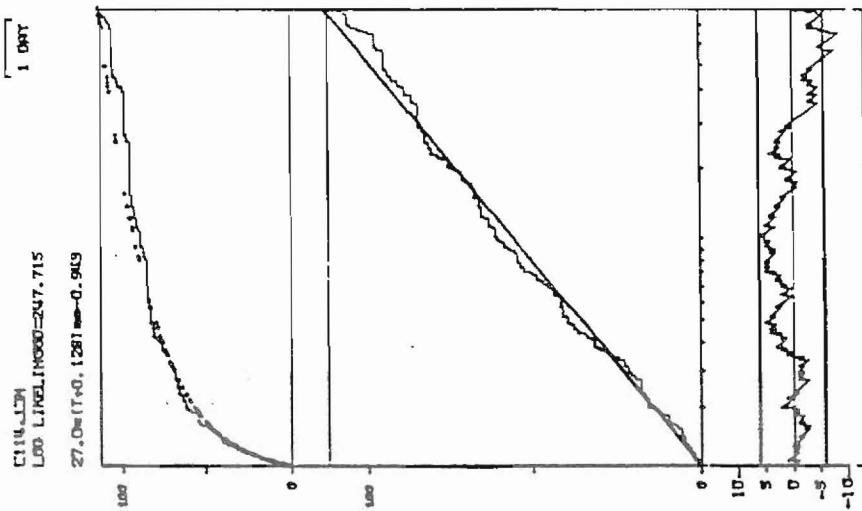


Fig. 2a From all data

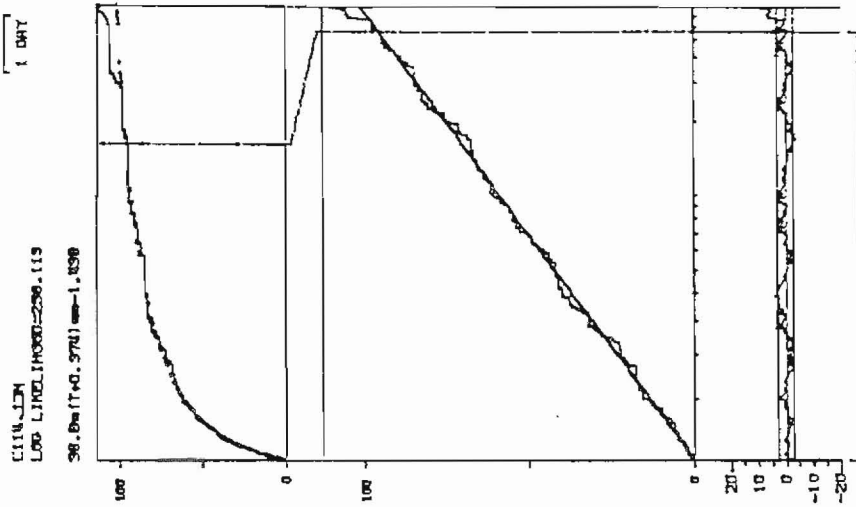


Fig. 2b From data up $t=5.68$ days

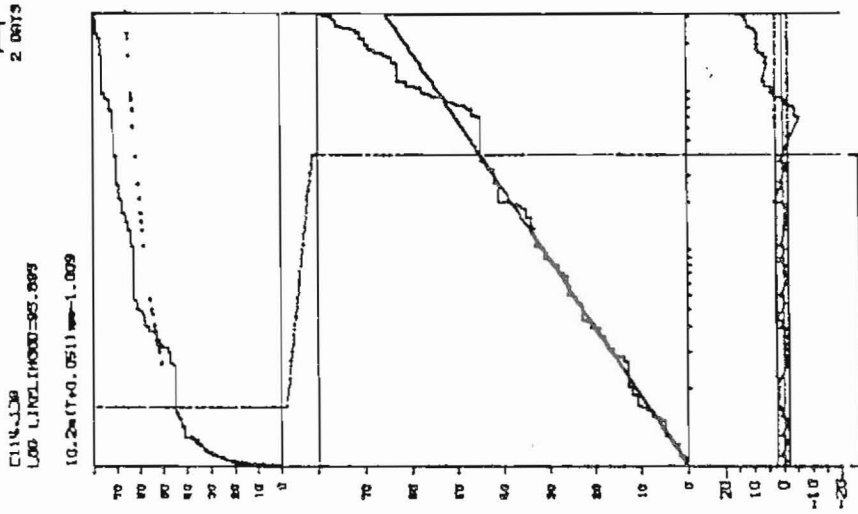


Fig. 3b From data up t=4 days

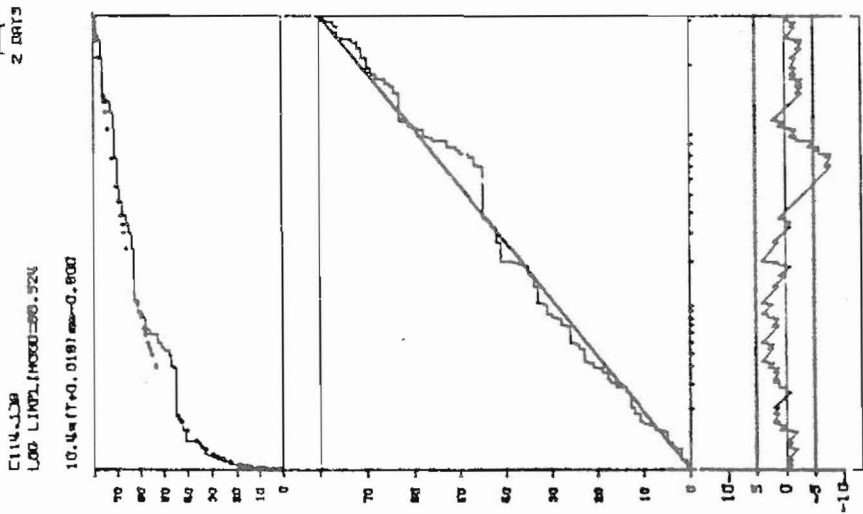


Fig. 3a From all data

iii) Kefalonia earthquake of 1983

On January 17, 1983 an earthquake of $M_L=6.2$ occurred West of Kefalonia island. The largest aftershock occurred on March 23, with magnitude $M_L=5.7$. The time interval between the main shock and the largest aftershock was two months.

To study this sequence list of aftershocks with magnitude threshold $M_L=3.7$ it was chosen. Also in this case, the quiescence and the following foreshock like activity is the characteristic behavior of the aftershock sequence (fig. 4 a,b).

The parameter of the Omori's law for the time interval 0.129-64 days are

$$n(t) = \frac{63.8}{(t+0.69)^{1.08}} \quad (10)$$

and for the time interval 0.129 to eleven days

$$n(t) = \frac{143.4}{(t+1.354)^{1.572}} \quad (11)$$

iv) The Central Aegean sea, earthquake sequence 1986.

On March 25, 1986 an earthquake (hereafter called first shock) occurred with magnitude $M_L=5.2$. After four days, on March 29, 1986 an earthquake (second shock) occurred in the same area. To study this earthquake sequence of homogenous list of aftershocks with threshold magnitude $M_L=3.1$ was made.

Two days after the main shock a quiescence began. In two more days a recovery of the seismic activity was started (fig. 5).

The parameters of the Omori law for the two times intervals (0 - 2 days and 0 - 4 days) are

$$n(t) = \frac{7.7}{(t+0.008)^{0.481}} \quad (12)$$

$$n(t) = \frac{7.7}{(t+0.016)^{0.556}} \quad (13)$$

Conclusion

This study confirms some of the conclusions of MATSU'URA; Thus an anomalous pattern has been found in aftershock activities prior to large aftershocks which are followed by secondary aftershocks. Before the occurrence of such a large aftershock a period of seismic quiescence is observed. Then the aftershock activity recovers to the normal level or in-

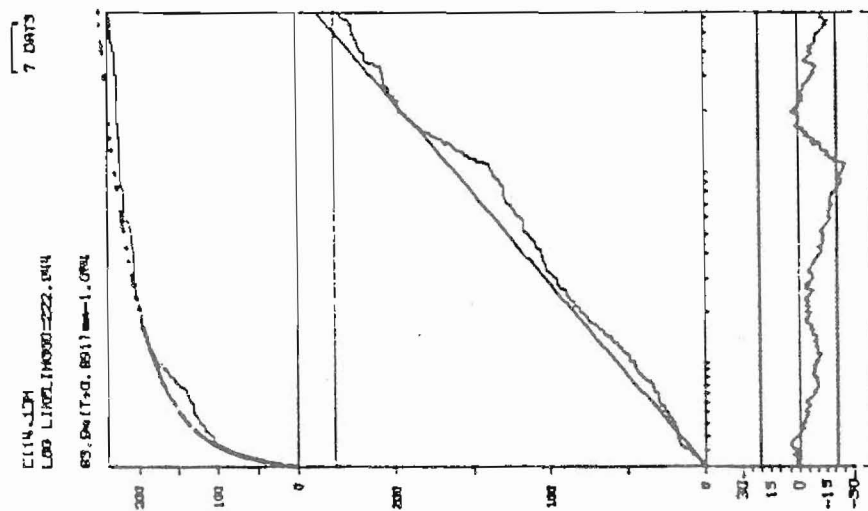


Fig. 4a From all data

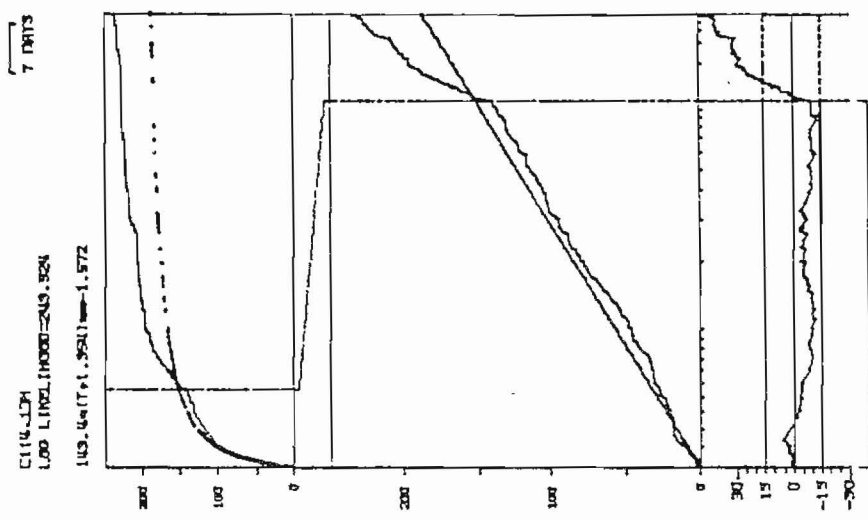


Fig. 4b From data up to $t=11.2$ days

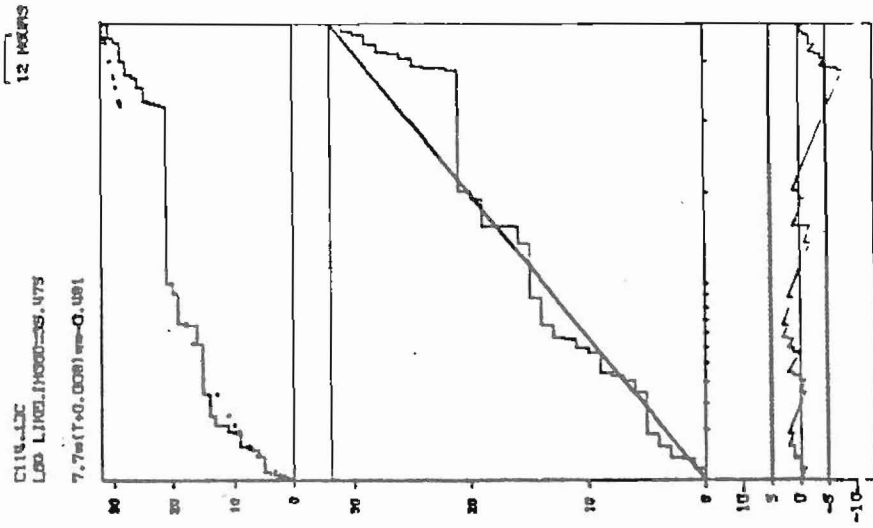


Fig. 5a From all data

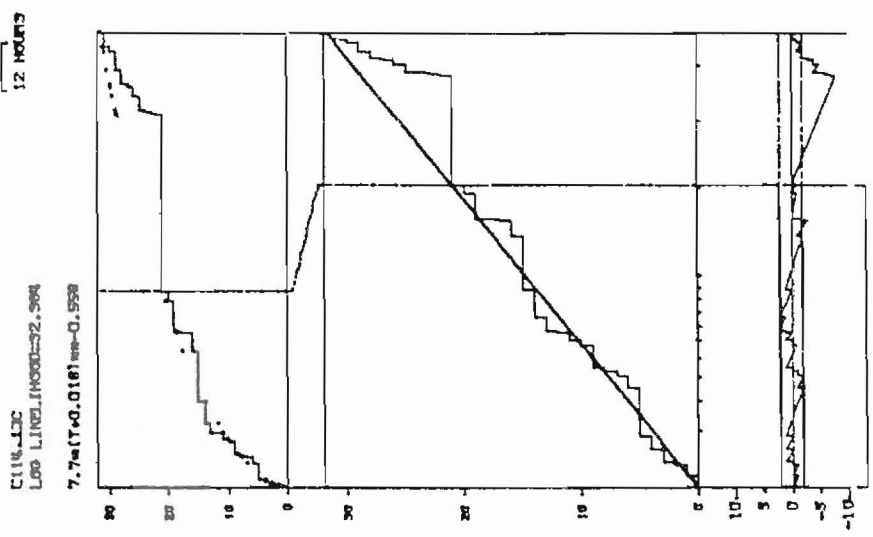


Fig. 5b From data up to t=2 days

creases beyond it prior to the large aftershock.

Based on this feature, prediction of a large aftershock is possible when a real-time watch of the aftershock activity change is performing. However, an accurate prediction of two occurrence time and of the size of the forthcoming large aftershock is impossible by this method.

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