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The Aegean Sea (Greece) Earthquake Sequence of 25 March 1986: An Application of the ν-Value Method for Earthquake Prediction

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Abstract. A technique based on the ν-value, which is defined by $(\bar{\tau})^2/\overline{\tau^2}$, where τ is the time interval between two adjacent earthquakes and indicates the pattern of time sequences of earthquakes, has been applied to the 25 March 1986 Aegean Sea (Greece) earthquake ($M_L = 5.2$) in an attempt to discover temporal changes in seismicity. The analysis of several earthquake sequences revealed that low ν-values preceded the occurrence of relatively large earthquakes. The ν-value technique may be used for monitoring the seismicity changes.

Key words. Earthquake prediction, seismicity changes, ν-value.

1. Introduction

Changes in the pattern of seismic activity, such as foreshocks and temporary changes in the b value prior to the occurrence of large earthquake, have been shown to be very useful for earthquake prediction. The identification, however, of foreshocks and their relation to the magnitude and time of the main shock is not so clear and discrimination cannot usually be made until the mainshock occurs. Several prediction algorithms essentially using the number of earthquakes occurring in a certain time window and the distribution of time intervals of earthquakes, have been proposed by Keilis-Borok *et al.* (1978, 1980a, b) and tested by Sauber and Talwani (1980) for identifying foreshocks.

Mogi (1967) concluded that the type of earthquake sequence depends mainly on the structural state of the Earth's crust and the space distribution of the applied stresses. Three kinds of sequence patterns, namely, successive, periodical, and random, can be found in most earthquake catalogs, and may reflect the relationship between the tectonic stresses and stress releases during earthquakes.

In view of earthquake prediction, Matsumura (1982, 1984) developed a new method for describing seismicity patterns in the space and time domain, and proposed a new parameter, the 'ν-value', which is closely related to the apparent interaction between two successive earthquakes. This parameter is derived on the basis of the Weibull distribution and the values characterize the earthquake sequence as being periodical ($\nu > 0.5$), clustered ($\nu < 0.5$), or random ($\nu = 0.5$).

In this study, the earthquake sequence of 25 March 1986 which occurred in the northern Aegean Sea, has been analyzed by using the ν-value method to examine whether the large seismic events of this sequence were predictable.

2. The 'ν-Value' Model – Theoretical Considerations

In the following analysis, it is assumed that the occurrence of earthquakes is treated as a probabilistic phenomenon. A crucial problem in reliability analysis is the determination of the probabilistic distribution of failure-occurrence time, which, in our case, corresponds to the earthquake occurrence. The Weibull distribution function, which is widely applied to quality-control research, has been used by Hagiwara (1974) to estimate the probability of earthquake occurrence on the basis of crustal strain data in the south Kanto District of Japan. Based on this model, Matsumura (1982, 1984) defined the ν-parameter to make an unbiased assessment of possible time-dependent changes in seismicity patterns. A brief description of the ν-value model is made here, following Hagiwara (1974) and Matsumura (1984).

The conditional probability that the rupture (i.e. earthquake) will occur in a time interval between t and $t + \Delta t$, is defined by $\lambda(t)\,\Delta t$, where $\lambda(t)$ is the hazard rate and is given by

$$\lambda(t) = \lambda_1 t^{p-1} \quad (\lambda_1 > 0, p > 0). \tag{1}$$

The reliability function $R(t)$ is

$$R(t) = \exp\left\{-\int_0^t \lambda(t)\,\mathrm{d}t\right\} = \exp\{-\lambda_1 t^p/p\} \tag{2}$$

and the corresponding density function $f(t)$ is

$$f(t) = -\,\mathrm{d}R(t)/\mathrm{d}t = \lambda_1 t^{p-1} \exp\{-\lambda_1 t^p/p\} \tag{3}$$

The mean time interval $\bar{\tau}$ between $t = 0$ and the time at which the earthquake occurs, is obtained as

$$\bar{\tau} = \int_0^t tf(t)\,\mathrm{d}t = (p/\lambda_1)^{1/p}\,\Gamma(1+1/p), \tag{4}$$

where Γ is a gamma function.

The mean-square time $\overline{\tau^2}$ is given by

$$\overline{\tau^2} = \int_0^t t^2 f(t)\,\mathrm{d}t = (p/\lambda_1)^{2/p}\,\Gamma(1+2/p) \tag{5}$$

Dividing the square of Equation (4) by Equation (5), we obtain the ν parameter.

$$\nu \equiv \{\Gamma(1+1/p)\}^2 \,/\, \Gamma(1+2/p) = (\bar{\tau})^2 \,/\, \overline{\tau^2} \tag{6}$$

Based on the ν-values, the earthquake occurrence patterns are classified into the following three categories: successive $(0<\nu<0.5)$, random $(\nu = 0.5)$, and periodic $(0.5<\nu<1.0)$.

The parameters λ_1 and p of the Weibull distribution (Equation (1)), are related to the seismic activity and seismic pattern, respectively. From Equation (6), it is evident that the ν-value is a function only of p.

3. The Earthquake Sequence of 25 March 1986

On 25 March 1986, a moderate earthquake of local magnitude $M_L = 5.2$ occurred in the northern part of the Aegean Sea (38.38°N, 25.13°E) and was followed by another one, of magnitude $M_L = 5.3$, four days later.

During the time period from the occurrence of the first seismic event of 25 March until the end of July 1986, six more significant events with $M_L > 4.5$ and more than three hundred smaller events with $M_L > 2.7$ occurred. All these shocks are recorded by the permanent seismic network of the Seismological Institute of the National Observatory of Athens. Figure 1 shows the hypocenter distribution, and Table I summarizes the

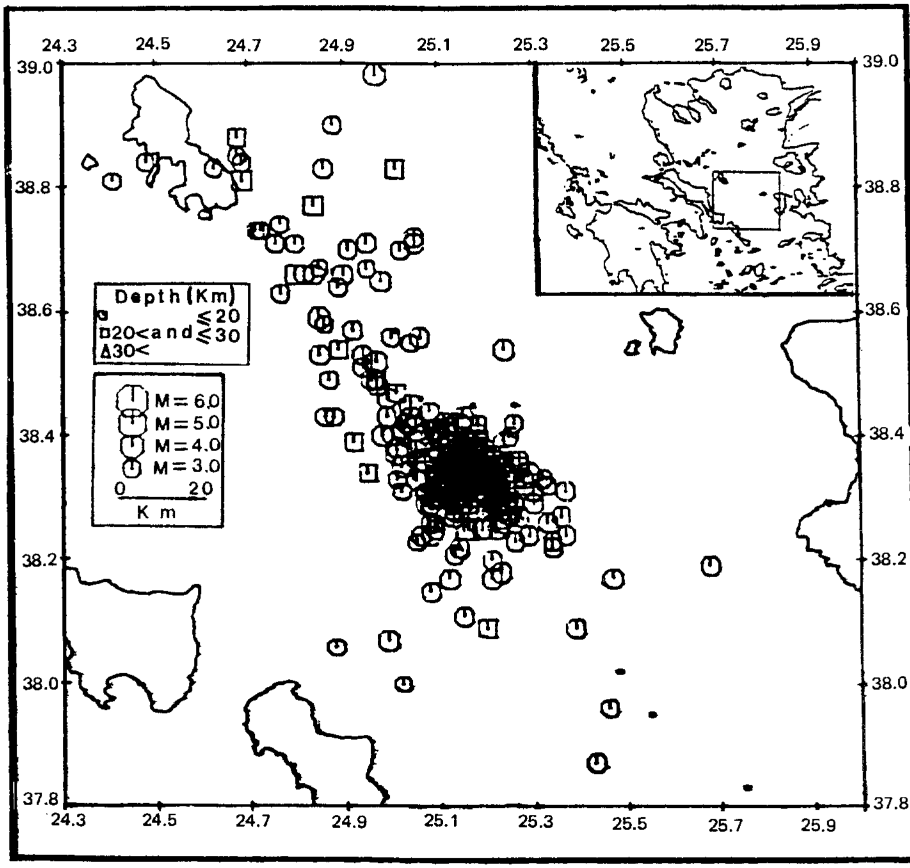

Fig. 1. Epicenters of the Aegean sea sequence ($M_L > 2.7$) compiled by the Seismological Institute of the National Observatory of Athens, for the period 25 March 1986 through to the end of July 1986.

Table I. The parameters of the seven large shocks

Event No.	Date		Origin time	Lat. (°)N	Long. (°)E	Depth (km)	M_L
1	1986	Mar.	25:01:41:36.9	38.38	25.13	16	5.2
2	1986	Mar.	29:18:36:39.6	38.37	25.18	16	5.3
3	1986	Apr.	3:23:32:19.8	38.36	25.14	12	4.9
4	1986	Apr.	25:05:00:48.4	38.39	25.17	22	4.7
5	1986	Jun.	3:06:16:30:7	38.35	25.12	13	4.7
6	1986	Jun.	4:08:06:05.8	38.34	25.07	19	4.6
7	1986	Jun.	17:17:54:21.6	38.34	25.10	17	4.8

seismic parameters of the largest events of the sequence. The occurrence frequency, of all the events of this sequence, as a function of time, is shown in Figure 2, where the arrows indicate the occurrence time of the significant events.

It is worth noting that in the adjacent area defined by 37.8°N–39.0°N and 24.5°E–25.7°E, no earthquakes with $M_L > 6.0$ occurred from 479 BC until 1900 (Papazachos and Comninakis, 1982), and then only one event, with $M_L = 5.3$, took place on 14 January 1949 (Makropoulos *et al.*, 1986). Thus, this part of the Aegean Sea may be regarded as being in seismic quiescence, at least for the present century.

The existence of the two large events with local magnitudes of 5.2 and 5.3, allow us to consider that the earthquake sequence has been processed by twin earthquakes.

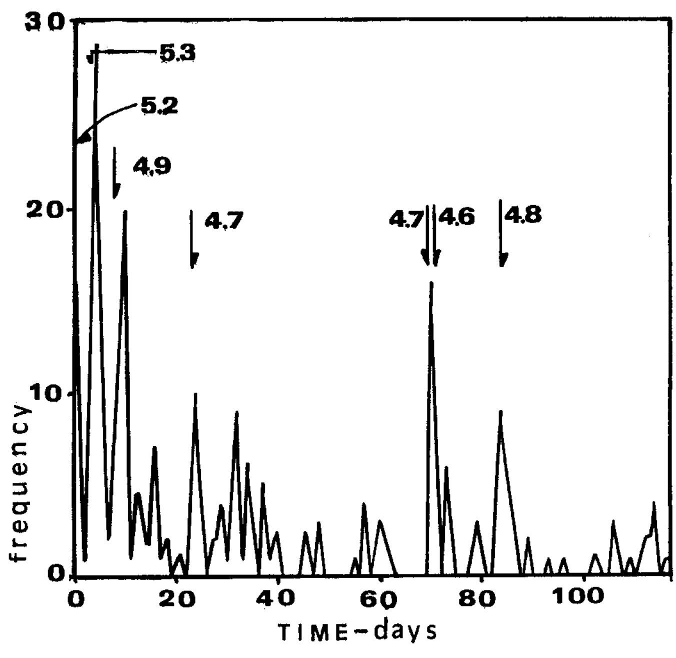

Fig. 2. Plot between the frequency of the shocks and time. The occurrence of the seven large shocks are also shown.

Moreover, the total number of aftershocks with a local magnitude greater than 2.7, is not so large according to the statistical model proposed by Drakopoulos (1971) for the area of Greece. These characteristic lead us to examine whether the significant events of the seismic sequence were predictable by using the ν-value method.

4. Data Analysis

This study deals with the seismic sequence which occurred in the 'a-posteriori' defined area (37.80°N–39.00°N, 24.50°E–25.70°E) during a time period of four years (from July 1982 till July 1986). In total, 413 events occurred during this time period.

The ν-value has been computed on the basis of a number of successive earthquakes comprising a certain group. This group is successively moved by a window of events until the end of the aftershock sequence.

The ν-values have been determined for every 30 earthquakes which are moved by a window of 10 events. Figure 3 shows the obtained results. In this figure, a point was plotted at the time of the last event within the window and it is observed that, prior to March 1986, the ν-value fluctuates slowly, in the range 0.4 and 0.6, showing a nearly random occurrence. Before the occurrence of the first shock of 25 March 1986, and during the seismic activity, the ν-value is characterized by abrupt changes in the range between 0.05 and 0.5, showing successive occurrence.

The ν-values have also been computed for the time period after January 1986 by using different parameters to correlate the previously obtained small ν-values with the

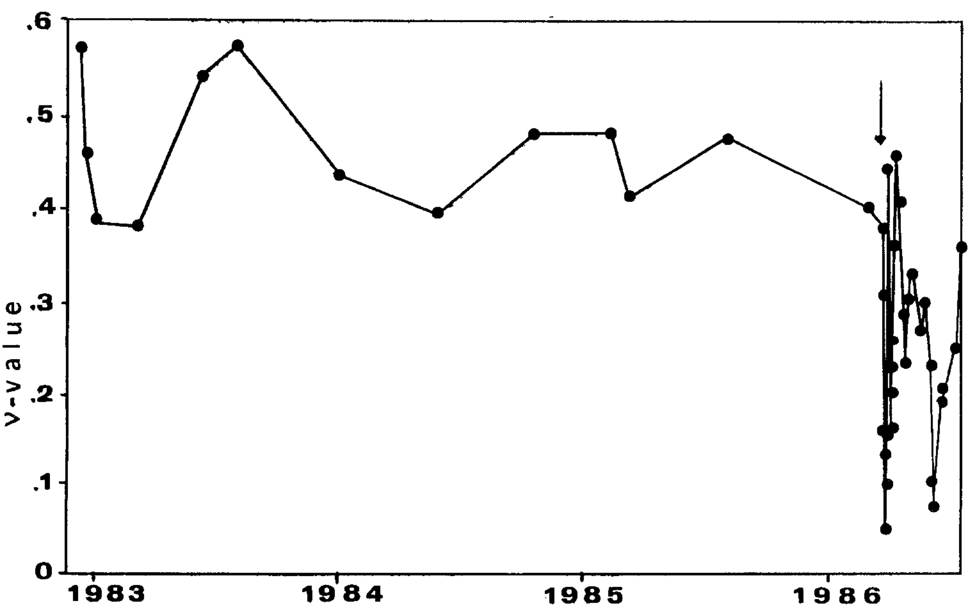

Fig. 3. Changes of the ν-value for the period December 1982 through to July 1986. The ν-values were calculated for groups of 30 successive shocks which are moved by a window of 10 shocks. The vertical arrow shows the beginning of the sequence (25 March 1986).

occurrence of seven significant events in the sequence. The calculations were performed by using group numbers 20 and 30 and moving window number 10, 5. Figures 4 to 7 show the obtained results. The vertical arrows indicate the occurrence time of the large events with the corresponding local magnitudes.

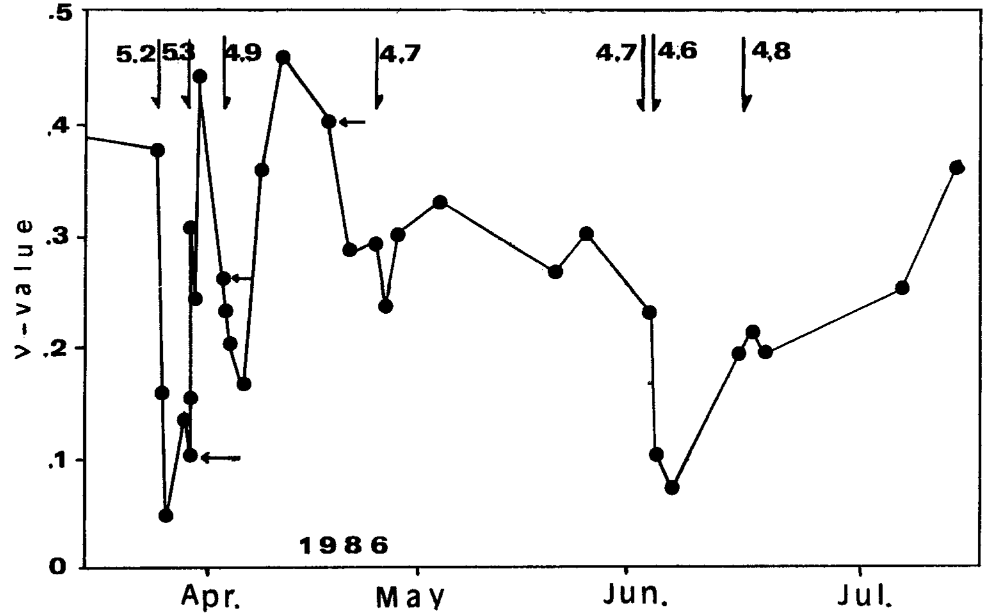

Fig. 4. Changes of ν-value for the period March through July 1986. The ν-values were calculated for groups of 30 successive shocks which are moved by a window of 10 shocks.

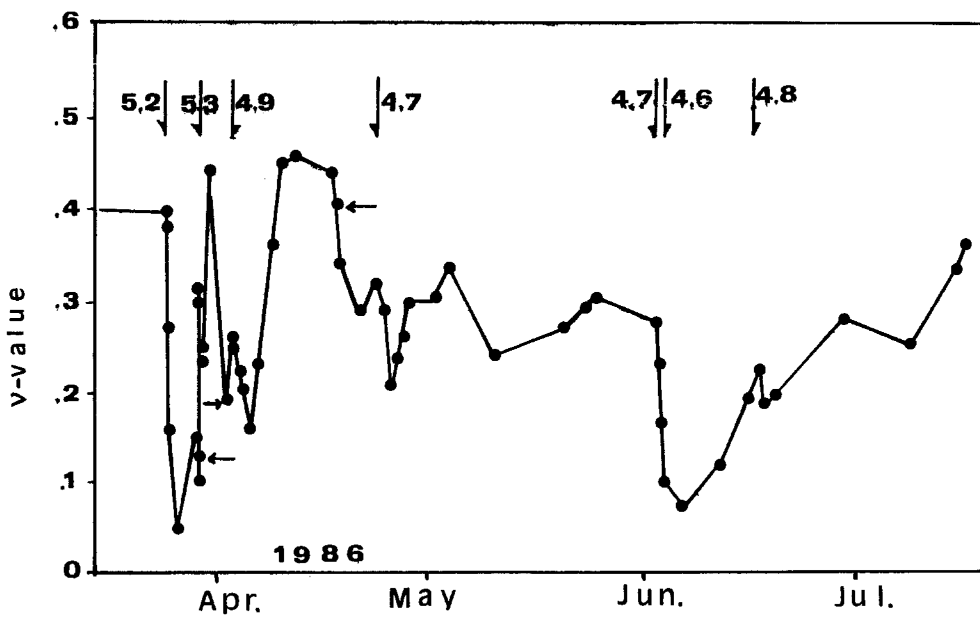

Fig. 5. Changes of ν-value for the period March through July 1986. The ν-values were calculated for groups of 30 successive shocks which are moved by a window of 5 shocks.

As the examined seven large events belong in the same seismic sequence and occurred during a short time period (less than 3 months), we try to distinguish whether the decreases of the ν-values are caused by foreshocks preceding or by aftershocks following these large events. Thus, the elapsed time is calculated, i.e. the time between

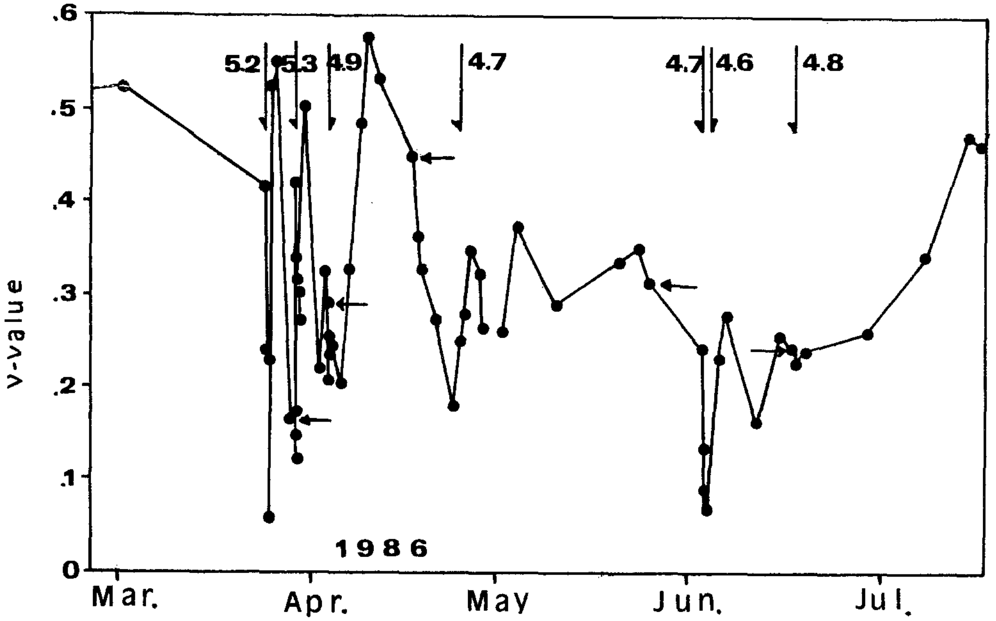

Fig. 6. Changes of ν-value for the period March through July 1986. The ν-values were calculated for groups of 20 successive shocks which are moved by a window of 10 shocks.

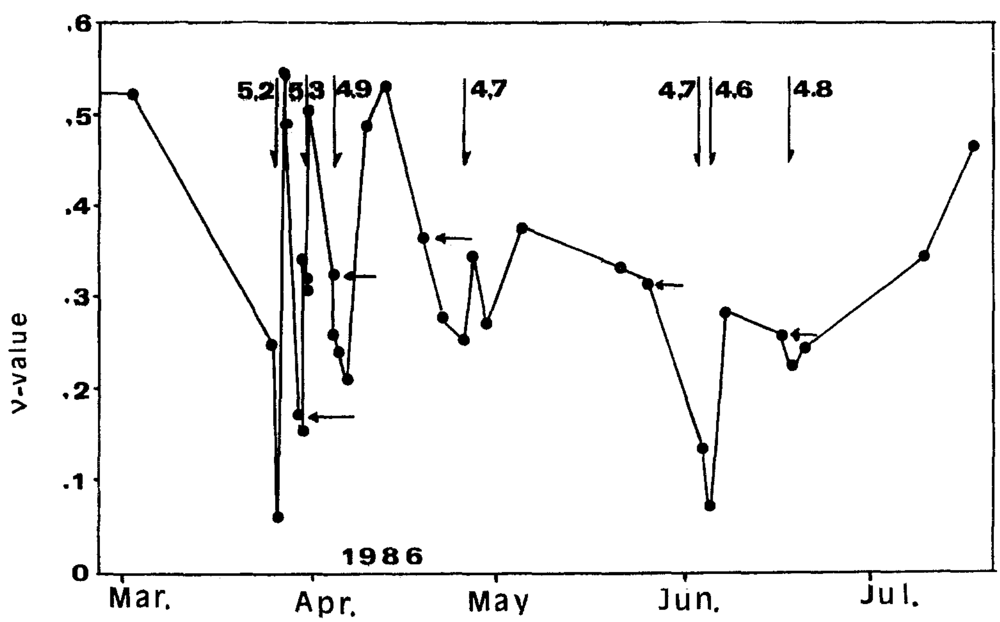

Fig. 7. Changes of ν-value for the period March 1986 through July 1986. The ν-values were calculated for groups of 20 successive shocks which are moved by a window of 5 shocks.

the plotted point from which a continuous ν-value decrease is obvious and the occurrence of the next large shock. Table II summarizes the results for all the examined cases. The symbol (−) means that the elapsed time was not possible to calculate because there was no clear ν-value decrease, as defined above. For event No. 6 (4 July, $M_L = 4.6$), this was also not possible, as this event occurred soon after event No. 5 (3 July, $M_L = 4.7$) and the elapsed time was hidden into the aftershocks of the previous event.

From Table II and Figure 2, it is concluded that only the elapsed time for event No. 4 is clearly correlated with aftershock activity of the previous shock.

It is also worthwhile examining the efficiency of this method for earthquake prediction. Utsu (1977) has proposed two kinds of probabilities relating to earthquake prediction: one is that a prediction will be successful and the other is that an earthquake will be predicted. The first one is a ratio of the number of shocks which were successfully predicted to the total number of small ν-values and the second one is the ratio of the number of earthquakes which were successfully predicted to the total number of earthquakes under consideration.

Table III summarizes the rates of successful predictions and predicted earthquakes. The assumption is that the prediction that an earthquake will occur within 150 hours was issued just after the point from which a clear ν-value decrease was found. The rates given in Table III seem to be reasonably successful for a single precursory phenomenon.

5. Discussion and Conclusions

The ν-values, which relate with the time pattern of an earthquake sequence and characterize the earthquake occurrence as being clustered, random, or periodic, were calculated and the decreases were examined for the Aegean Sea earthquake sequence of 25 March, 1986.

The results show that almost all the significant events of this earthquake sequence were preceded by small ν-values.

The probabilities of successful prediction and predicted earthquakes are calculated

Table II. The elapsed time, unit is hour, which is calculated between the plotted point from which a continuous ν-value decrease is obvious (horizontal arrow) and the occurrence of the next large shock (continuous arrow). Sequential event numbered from 1 to 7 correspond to the events of Table I. The four cases correspond to Figures 4, 5, 6 and 7.

Case	Event No.						
	1	2	3	4	5	6	7
30,10	–	16	16	160	–	–	–
30, 5	–	16	32	144	–	–	–
20,10	–	18	6	150	190	–	5
20, 5	–	20	32	200	180	–	25

Table III. Rates of successful prediction and predicted earthquakes for precursory ν-value indicating successive occurrences of seismic sequences. (a) The number of shocks that are preceded by anomalously small ν-values ($\nu < 0.3$). (b) The total number of anomalously small ν-values ($\nu < 0.3$). (c) The seven large shocks listed in Table I. (The four cases correspond to Figures 3b, 4, 5 and 6.)

Case	Rate of successful prediction	Rate of predicted earthquakes
30,10	2/7 (29%)	2/7 (29%)
30, 5	3/10 (30%)	3/7 (43%)
20,10	5/12 (42%)	5/7 (71%)
20, 5	4/9 (44%)	4/7 (57%)

for the events of this sequence. These probabilities seem to depend upon the number of successive earthquakes comprising a certain group.

Although Matsumura (1982, 1984) and Hamada (1987) used microearthquakes to investigate changes in the seismicity pattern by means of the ν-value, the obtained results by this study show that the ν-value model could be applied for earthquake sequences with a higher lower-limit of magnitudes.

The results show that the interaction between successive shocks is worth investigating as a tool in earthquake prediction, although evaluation of the ν-value method in the present method is not sufficient because of the limited amount of data.

Until now, none of the precursors reported is sufficient in practical prediction, if it is used alone. Therefore, a realistic approach to this aim is to take into consideration such precursors and, among them, the ν-value.

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