

DETERMINISTIC AND STOCHASTIC MODELS  
OF THE SEISMIC AND VOLCANIC EVENTS  
IN THE SANTORINI VOLCANO

by

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ABSTRACT

The problem of forecasting future eruptions on Thera volcano has been approached by three models based on its past history. A deterministic model utilizes observations showing that in several circum-Pacific island arcs as well as in the Hellenic arc the onset time of eruption cycles depends on the occurrence time of seismic energy peaks associated with large mantle shocks. In the second model, the observation that Thera is a simple Poissonian volcano, in conjunction with the Bayes' theorem, leads to a probabilistic estimation of the dates of the next eruption onset time. The third model is a particular case of the first one where the occurrence time of the next mantle shock(s) is determined from the observation that the process of occurrence of large mantle shocks in the South Aegean is also Poissonian. All models imply that the next Thera eruptive cycle is not probable to start before the end of the present century.

INTRODUCTION

The Aegean and surrounding regions are very complicated from seismo-tectonic and geophysical point of view (e.g. Papadopoulos et al. 1986). The same is also valid for some characteristics of the Cenozoic magmatism such as its petrochemistry and space-time evolution (Papadopoulos 1989a).

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However, there are certain geophysical features of well-defined properties. One of the most important is the South Aegean calc-alkaline active volcanic arc. The caldera volcano of Thera (Santorini) is the most significant in this arc and one of the most significant in the Eurasian-Melanesian belt.

Thera has repeatedly erupted in post-Minoan times including the present century. Studies concerning its possible activity in the future are of special interest in understanding how the volcano works and in mitigating the volcanic hazard. Only a very limited number of studies on the volcanic hazard and risk in this area have been published so far (Papadopoulos 1985, Fritzas and Papadopoulos 1988).

As far as I know this is the first paper to be presented on forecasting the time of next Thera eruptions. For this purpose three models were tried. The first is a deterministic approach based on the suggestion that the onset time of eruption cycles depends upon the occurrence time of large subcrustal shocks. In the second model, which is purely stochastic, Thera is a simple Poissonian volcano. The third model is a particular version of the first model where the determination of the occurrence time of future subcrustal shocks is based solely on probabilistic terms.

#### THE DATA

All the known post-Minoan Thera eruptions are described by Georgalas (1962) (see also in Simkin et al. 1981, for their Volcanic Explosivity Index). There is evidence, however, that the volcanic eruptions reporting is complete only since about the 16th century (Papadopoulos 1988). The dates of the eruptions which occurred since that time, along with their characteristics, are listed in Table 1. This observational material has been used in the present analysis.

For the time interval 1900-1985 the earthquake catalog of Cominakis and Papazachos (1986) is the data source for intermediate depth earthquakes analyzed in the third model. This catalog seems to be complete in events of surface-wave magnitude  $M_S \geq 6.5$ . From the Bulletin of the Seismological Institute of the National Observatory of Athens it results that intermediate depth events of such a magnitude were not recorded in the time interval 1986-1988.

## A DETERMINISTIC MODEL

The close spatial coincidence of active volcanoes and inclined deep seismic zones has been postulated many years ago (Gutenberg and Richter 1954). Since that time a wide variety of specific associations between deep seismic processes and volcanic activity in convergent plate margins have been proposed. One of the most interesting is the association of particular volcanic eruptions and particular intermediate depth or deep shocks preceding eruptions in several island arcs including Thera in the Hellenic arc (Blot 1980). However, it remains questionable whether such an association is a certain feature of island arcs for reasons explained by Papadopoulos (1986,1987a).

One of the problems of investigating spatio-temporal relationships between tectonic earthquakes and volcanic eruptions in a specified region is the sort of volcanic events which must be considered. For example, volcanic events such as steam or phreatic eruptions, smoke, and emission of "more gas than usual" are inadequate for investigations of this type. Apparently it is desirable to consider only significant volcanic events which reflect directly the occurrence of magmatic processes in the magmatic chambers or even deeper in the roots of the volcanoes. For these purposes, magmatic eruptions which lasted at least 15 days and had a Volcanic Explosivity Index equal to or larger than 1, have been defined as "significant volcanic eruptions" (Papadopoulos 1987b).

In a related paper, Papadopoulos (1987a), analyzed data of large ( $M_S \geq 7$ ) subcrustal earthquakes ( $h > 75$  km), which occurred from 1900 up to 1980, and found that in at least seven subduction zones of the circum-Pacific region periods of frequent volcanic activity with significant eruptions occurring in one to seven volcanoes of a given arc are systematically preceded by seismic energy peaks associated with usually no distant shocks of  $M_S \geq 7.3$  taking place directly beneath the volcanic belt of the same arc at the depth range of 80-190 km. The time lag between one energy peak and the onset of the following volcanic activity ranges between 1 and 18 years but in most cases it does not exceed 12 years. In the same paper it is shown that on the basis of the  $\chi^2$ -test in a  $p \times q$  contingency table the correlation between the time series of large mantle shocks and subsequent eruption cycles is significant at the 99% level. The present author (Papadopoulos 1986) observed that in the South Aegean the occurrence of large intermediate depth shocks at the periods of 1846-1863, 1887-1911 and 1926(July)-1935 were correspondingly followed by the three eruption cycles which occurred on Santorini at 1866-1870, 1925-1926 (January) and 1939-1941 including the minor event of 1950. The time lag is of the order of 15 years which is compatible with that found for the Pacific arcs. From these observations the suggestion that fracturing associated with large subcrustal shocks can cause magma formation or vice-versa is discussed in detail in the author's papers cited above.

The observation that the significant volcanic activity in at least some island arcs may depend on the deep seismicity could contribute toward the investigation of an effective pattern for the long-term forecasting of volcanic eruptions. In the South Aegean it is noticeable that since February 3, 1950, the day of the last Thera activity, neither volcanic activity nor intermediate depth shocks with  $M_s \geq 6.8$  have been reported. Assuming that the model mentioned earlier is correct, then, a new cycle of normal eruptions in Thera must be expected some years after the next large intermediate depth earthquakes beneath the South Aegean.

Under this assumption the problem of forecasting the time of occurrence of the next eruption is equivalent with the problem of forecasting the occurrence time of the next large subcrustal shock(s). In a recent related paper the present author (Papadopoulos 1989b) utilized all the existing data and knowledge on this problem and, on the basis of seismicity observations and statistical considerations, concluded that such shocks are long overdue and that the next event(s) must be expected to occur in certain earthquake nests of the Benioff zone in the next years.

In a next section a purely probabilistic approach of the problem is attempted. This approach along with the deterministic model discussed in previous lines generates a mixed model for the volcanic eruptions forecasting in Thera.

## A STOCHASTIC MODEL

### Theory

Earthquake occurrences can be modelled as a point process, that is a discrete stochastic process describing the positions of the events in time. The prototype of all point processes is the Poisson process which is defined by the three basic properties (e.g. Lomnitz 1974):

- (a) Independence - the number of events in any time interval is independent of the number of events in any other nonoverlapping interval,
- (b) Orderliness - the probability of more than one event occurring in the same time interval is asymptotically negligible,
- (c) Stationarity - the probability of one event occurring in a short time interval  $dt$  is  $\lambda dt$ , where  $\lambda$  is a constant in time .

The probability density function of  $x$ , the number of events per unit time, is the well-known Poisson distribution

$$f(n) = \exp(-\lambda) \lambda^x / x! \quad (1)$$

Equivalently, the distribution of the time intervals  $T$  between successive events is the negative exponential distribution

$$f(T) = \lambda \exp(-\lambda T) \quad (2)$$

The probability of observing  $x$  events in time  $t$ , is

$$P(x) = \exp(-\lambda t) (\lambda t)^x / x! \quad (3)$$

The rejection or adoption of the Poisson or other specific stochastic model depends on the selected time unit for which the numbers of events are counted. For example, Kárník et al. (1983), examined the time distribution of the aftershocks of the  $M_S=6.5$ , July 20, 1978 event in the area of Thessaloniki, North Greece, and concluded that the negative binomial distribution is rejected for one day time unit. On the contrary, this is not rejected for a time unit equal to only one hour.

To secure that the selection of the time unit is as objective as possible, the present author has proposed (Papadopoulos 1989c) that the time unit must be taken equal to the mean return period,  $T_m$ , of events having magnitude equal to or larger than the lower magnitude threshold,  $m$ , in the sample. The Gutenberg-Richter (G-R) magnitude-frequency relation provides estimate of  $T_m$ . An independent estimate of  $T_m$  for large crustal earthquakes may be supplied from geotectonic methods, provided that proper data is available.

One of the most commonly used probabilistic approaches of the earthquake prediction problem is the Bayesian one. Although this is not a procedure on which specific predictions or special precautions can be based, it may still be quite useful for engineering purposes in the sense of long-term earthquake prediction. On the basis of Bayes' theorem in conjunction with the Poisson process model, Ferraes (1985), showed that the posterior Bayesian conditional probability,  $P(T_R / M)$ , of the event  $T_R$  given that an earthquake of magnitude  $M$  has occurred, can be expressed as :

$$P(T_R / M) = \frac{\lambda T_R \exp(-\lambda T_R) [1 - \exp(-\lambda T_R)]}{\sum_{j=1}^k \lambda T_j \exp(-\lambda T_j) [1 - \exp(-\lambda T_j)]} \quad (4)$$

This formula can be used to estimate the inter-arrival times,  $T_j$ , as well as the real time arrival dates for future earthquakes of a given magnitude range. Assuming that the inter-arrival time,  $T$ , has an exponential prior distribution and that we have  $n$  events each with inter-arrival time  $T_1, T_2, \dots, T_n$ , then, the parameter  $\lambda$  of the prior probabilities,  $P(T_j) = 1 - \exp(-\lambda T_j)$ , and conditional probabilities (likelihood function),  $P(M / T_j) = \lambda T_j \exp(-\lambda T_j)$ , is given by

$$\lambda = 1 / \bar{T} \quad (5)$$

with

$$\bar{T} = \frac{\sum_{i=1}^n T_i}{n} \quad (6)$$

The theory outlined above can also be applied to describe in probabilistic terms the expected times of the future volcanic activity in a specific volcano or volcanic belt under the condition that we take into account only the onset time of each eruption cycle regardless of its total duration. It is known that several "simple Poissonian volcanoes" have been recognized in several regions of the world (see short review in Scandone 1983).

The model

To apply the previous theory in the case of Thera eruption cycles, two problems must be solved first:

(1) How many eruption cycles took place in the time interval for which the data is suggested to be complete, that is since the beginning of the 16th century?

(2) Is Thera a simple Poissonian volcano?

The occurrence times of the known eight Thera eruptions since the 16th century A.D. are shown in Table 1. From their time separation it is evident that the events of 1570 (or 1573), 1650, 1707-1711 and 1866-1870 constitute independent eruption cycles. However, the frequent events of the time interval 1925-1950 indicate that probably more than one of the listed events constitute a

unique eruption cycle. On the basis of certain volcanological features, Papadopoulos (1986), suggested that the 1928 and 1950 eruptions were the final events of the 1925-1926 and 1939-1941 activities, respectively. This analysis implies that six eruption cycles occurred in Thera in the examined time interval of 489 years. Nevertheless, in order to obtain as reliable as possible results two alternative procedures have been performed; one for six eruption cycles and another for eight cycles.

To investigate if the volcano is Poissonian or not we have to examine whether the distribution of the eruptions time onset follows the Poisson model. The determination of the probability density function, however, is difficult to be done because (a) of the very small number of events in the sample, and (b) the lack of a reliable way to estimate the mean return period of eruption cycles, that is an objective time unit for which the number of events have to be counted.

To get over these difficulties I have examined how the distribution of the time intervals between successive eruption cycles fits the negative exponential distribution according to the eqn. (2). The examination showed that the data fits the relation (2) (Fig. 1) for  $\lambda_1 = 0.012823$  events /yr determined by the least-squares method. The  $\chi^2$ -test indicates that the Poisson model is adopted at the 0.01 level. In the previous procedure the onset time of the first event is ambiguous and for this reason the date July 1, 1570, has arbitrarily been suggested. The last question we have to answer is: what is the most appropriate value of  $\lambda$  to be taken into consideration? If we simply take  $\lambda = 6 / 489$  we have  $\lambda_2 = 0.01227$  events /yr. Alternatively, the mean of the time intervals,  $\bar{T}$ , is given by (6). Here we have  $\bar{T} = 73.83 (\pm 53.19)$  years. Hence, from (5) we get  $\lambda_3 = 0.013545$  events /yr. Later on, in the Bayesian approach of the problem we have to use the value of  $\bar{T}$  found above. For this reason  $\lambda_3$  is also used in the present analysis. Moreover,  $\lambda_3$  does not deviate practically neither from  $\lambda_1$  nor from  $\lambda_2$ .

Now we can say that the volcano of Thera is Poissonian, at least in the last five centuries, and that the probability of observing  $x$  events in time,  $t$ , is

$$P(x) = \exp(-0.013545t)(0.013545t)^x / x! \quad (7)$$

$1-P(0)$ , which is equal to  $1 - \exp(-0.013545t)$ , gives the probability of observing at least one event in time  $t$ . Table 2 shows values of  $P(0)$ ,  $1-P(0)$ ,  $P(1)$ , and  $P(2)$  for several  $t$  values. From the point of view of forecasting future events in Thera, the most important result in Table 2 is that the probability of observing at least one event in the next 50 years is about 50%, while the probability is being about 74% and 93% for the next 100 and 200 years, respectively.

The Bayesian approach of the problem reveals the real time arrival dates or onset times of the next eruption cycles. Table 3 supplies information on these dates as well as the corresponding Bayesian probabilities and time intervals. Each date is determined by adding each time interval to the year of onset of the last event, which is that of 1939. It is obvious that the highest Bayesian probability corresponds to the year of 2019, while a past date has been "predicted".

Repetition of the same procedure for eight eruption cycles verified that Thera is Poissonian volcano (Fig. 2). The data fits eqn. (2) at the 0.01 level for  $\lambda_1 = 0.0183653$  events /yr determined also in the least-squares sense. For reasons explained earlier the value  $\lambda_3 = 1 / \bar{T} = 1 / 54.36 (\pm 50.65) \text{ yrs} = 0.018396$  events /yr has been adopted instead of  $\lambda_1$  and  $\lambda_2 = 8 / 489 = 0.01636$  events /yr.

After these modifications the probability of observing  $x$  events in time,  $t$ , is being

$$P(x) = \exp(-0.018396t)(0.018396t)^x / x! \quad (8)$$

Table 2 gives values of  $P(0)$ ,  $1-P(0)$ ,  $P(1)$ , and  $P(2)$  for several  $t$  values. Comparison with the corresponding values found

in the case of six eruption cycles shows that in this case  $1-P(0)$  is lower for the same time interval which means that the assumption of eight eruption cycles model increases the probability of observing at least one eruption in a given time interval in the future. This probability is about 60%, 84%, and 97% for the next 50, 100, and 200 years, respectively.

For the Bayesian approach, each of the seven time intervals is added to the year of onset of the last event, that is to 1950. Table 4 gives the real time arrival dates of the next eruption cycle.

#### A MIXED MODEL

Here the first model discussed earlier, the deterministic one, is combined with a probabilistic approach of the expected seismic activity at intermediate depths beneath the South Aegean.

The approach is based on the theory outlined in the previous section. The statistical sample examined is composed by 15 intermediate depth earthquakes ( $h \geq 70$  km) of  $M_S = 6.6-8.0$  which took place in the South Aegean area during the present century, that is in the time interval 1900-1988. The first and last of them occurred on August 11, 1903 and March 31, 1965, respectively.

The G-R relation shows that the mean return period of intermediate depth shocks of  $M_S \geq 6.6$  in the South Aegean is  $T_m = 8$  years (Papadopoulos 1989b). This is the time unit selected to test whether the earthquake process is Poissonian. However, the number of events is too small to obtain a reliable probability density function of the number of events per unit time. To overcome the problem by extending the sample, a technique of largely overlapping time intervals, used by Papadopoulos and Voidomatis (1987) in similar problems, has been applied. Each time interval is equal to 8 years while the time shift is 1 year. The first 8-year interval is 1900-1907, the second is 1901-1908 and the last one is 1981-1988. Totally, 82 intervals have been examined. From the total number of 15 events, 14 were counted 8 times and

one event, that of 1903, was counted only 4 times. This means that 116 events have been counted and that each one of the real 15 events has been counted 7.73 times as an average. The mean rate of real events is  $\lambda_1 = \lambda_2 / 7.73$  where  $\lambda_2 = 116 / 82 = 1.42$  events / yr, that is  $\lambda_1 = 0.18$  events / yr. Considering the mean number of events as the simple ratio of 15 / 89 we take  $\lambda_3 = 0.17$  events / yr.

Observed and theoretical (expected) frequency distributions of the number,  $x$ , of the events analyzed are shown in Fig.3. According to the  $\chi^2$ -test the distribution fits the exponential curve at the 95% confidence level which means that the process is being accepted as a Poissonian one:

$$P(x) = (1.42t)^x \exp(-1.42t) / x! \quad (9)$$

However, the probability of observing a real number of  $x$  events within time  $t$  is given by

$$P(x) = (0.18t)^x \exp(-0.18t) / x! \quad (10)$$

Table 5 gives the probabilities of observing 0,1,2, and at least one event in several time intervals. It is obvious that the probability of observing at least one event of  $M_s \geq 6.6$  in the next 25 years or so is about 99%. This result in conjunction with the first model leads to the conclusion that it is very probable to observe at least one eruption in Thera within the next 40 years approximately, provided that the first model is correct. This is consistent with the Bayesian elaboration of the volcanological data which implies that the years of 2019 and 2030 have the highest Bayesian probabilities to signify the onset time of the next eruption depending on the number of past eruption cycles accepted.

In a Bayesian probabilistic prediction of intermediate shocks of  $M_s = 7.0-8.0$  in the South Aegean, Papadopoulos (1987c), estimated as a rule past dates. This implies that if the first model is practically valid for earthquakes of  $M_s \geq 7$ , then, the time interval extended up to next eruption must be narrowed down.

## CONCLUSIONS AND DISCUSSION

The volcano of Thera has been very active between 1925 and 1950. Since February, 1950, however, it is completely inactive leading thus to a lack of geophysical, geochemical and other observations useful in studying the evolution of the volcano and forecasting its future eruptions. For this reason, the problem has been approached by deterministic and stochastic models based on the past history of the volcano.

The first model, the deterministic one, predicts that the onset time of the next eruptive cycle depends on the time of seismic energy peaks associated with intermediate depth shocks. As shocks of this type are long overdue we expect that such events may take place in the next years. The time lag between seismic and volcanic activity is of the order of 15 years. The next eruptive cycle, therefore, must not be expected before the end of the present century.

According to the second model, which is purely stochastic, Thera is a simple Poissonian volcano the probability of observing at least one eruption increasing with time. For the next 10, 25, and 50 years the corresponding probabilities are about 0.13, 0.29, and 0.49. A Bayesian approach indicates that it is not probable to observe an event before about 1996. Due to the data incompleteness this analysis does not incorporate large magnitude eruptions which occurred before 1500 A.D. Geological record indicates that before the Minoan eruption, dated at about 1400 B.C., another major volcanic event took place at 100,000 years B.P. (e.g. Heiken and McCoy 1984). The problem of incompleteness does not allow us to decide whether the process is Poissonian or time-dependent by taking into account the large magnitude events. Thus, we can say that the Poissonian model seems to be valid at least for eruptions of  $VEI=2-3$  (see Table 1).

From a data set of intermediate depth shocks of  $M_s \geq 6.6$  covering the post-1900 period it results that the earthquake process is Poissonian and that the probability for a new large shock in the next 25 years is about 99%. This means that a new eruptive cycle is very probable to occur in about the next 15-40 years, provided that the first model is correct.

Previous estimations supply information on the expected future eruptive behavior of Thera volcano. This picture is complemented by a qualitative volcanic risk determination which showed that the seismic component of the risk is the most important one not only because of the earthquake phenomena in the area but also because of the serious geotechnical problems in several residential zones mainly along the caldera edge (Fritzas and Papadopoulos

1988). After these developments I feel that future research and administrative activities directed toward the volcanic hazard mitigation must be mainly focused on (1) monitoring of the volcano, (2) elaboration of counter-measures plans, and (3) detailed study of the neotectonic and geotechnical conditions as potential factors of amplification of the seismic motion. The last is an urgent task because (a) the touristic activity in the island is very rapidly developing, and (b) the seismic component of the risk is associated not only with shocks or tremors of volcanic origin but also with tectonic earthquakes in the region of Cyclades, such as the large July 9, 1956 tectonic event of  $M_s=7.5$  in Amorgos Isl. which caused heavy damage, deaths and casualties on Thera.

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Table 1. Thera volcanic eruptions analyzed in this study. For data sources see the text. Key: S=submarine eruption, D=dome extrusion, I=island-forming eruption, E=normal explosion, F=lava flow(s), VEI= Volcanic Explosivity Index.

Date of the volcanic activity	Characters	VEI
1570 or 1573	SDIEF	3
1650 Sept. 26 - Dec. 6	SI	3
1707 May 23 - 1711 Sept. 11	SDIEF	3
1866 Jan. 26 - 1870 Oct. 15	SDIEF	2
1925 Aug. 11 - 1926 Jan. ?	SDEF	2
1928 Jan. 3 - 1928 Mar. 17	DEF	2
1939 Aug. 20 - 1941 July ?	DEF	2
1950 Jan. 10 - 1950 Febr. 2	DEF	2

Table 2. Probabilities of observing 0,1,2, and at least one eruptions in Thera in the next t years. A and B are for the six and eight eruption cycles models, respectively.

t (yrs)	P(0)		P(1)		P(2)		1-P(0)	
	A	B	A	B	A	B	A	B
10	.873	.832	.118	.153	.001	.014	.127	.168
25	.713	.631	.241	.290	.004	.067	.287	.369
50	.508	.399	.344	.367	.117	.169	.492	.601
100	.258	.159	.350	.292	.237	.269	.742	.841
200	.067	.025	.180	.093	.244	.171	.933	.975

Table 3. Bayesian probabilistic prediction of Thera volcanic eruptions on the basis of the six eruption cycles model.

Time interval $T_j$ (yrs)	Bayesian probability	Predicted year of eruption onset
80.25	.276	2019
158.67	.251	2097
59.54	.226	1999
56.67	.217	1996
14.02	.031	(1953)

Table 4. Bayesian probabilistic prediction of Thera volcanic eruptions on the basis of the eight eruption cycles model.

Time interval $T_j$ (yrs)	Bayesian probability	Predicted year of eruption onset
80.25	.272	2030
59.54	.254	2009
56.67	.248	2006
158.67	.156	2108
11.58	.0345	(1961)
11.40	.0336	(1961)
2.40	.0019	(1952)

Table 5. Probabilities of observing 0,1,2, and at least one intermediate depth shocks of  $M_S \geq 6.6$  in the South Aegean in the next  $t$  years.

$t$ (yrs)	$P(0)$	$P(1)$	$P(2)$	$1-P(0)$
1	.835	.150	.014	.165
5	.407	.366	.165	.593
10	.165	.298	.268	.835
15	.067	.181	.245	.933
25	.011	.050	.111	.989

## Figures Legend

Fig. 1. The exponential distribution of time intervals,  $T$ , between successive Thera eruption cycles under the assumption that six cycles occurred from 1500A.D. onwards.

Fig. 2. The exponential distribution of time intervals,  $T$ , between successive Thera eruption cycles under the assumption that eight cycles occurred from 1500A.D. onwards.

Fig. 3. Frequency distribution of the number  $x$ , of post-1900 South Aegean mantle shocks of  $M_s \geq 6.6$  which occurred in 8-year time intervals overlapping by 7 years (the time shift is 1 year). Theoretical and observed frequencies are indicated by black and open circles, respectively.



