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THE RELATIONSHIP BETWEEN TECTONIC EARTHQUAKES AND VOLCANIC ERUPTIONS WITH PARTICULAR REFERENCE TO SANTORINI (AEGEAN SEA) AND INDONESIA[1]

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ABSTRACT

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In certain cases tectonic earthquakes can trigger volcanic eruptions; or outbreaks are followed by tectonic shocks within some hundred kilometres of the volcano and within some weeks or months after the beginning of the eruption. For the gradation of the cases which were analysed a space-time parameter, denoted by ϱ, was introduced. At first altogether 47 cases are summarized in Tables I, II and III, respectively. After them almost all known eruptions of the Santorini volcano are treated. Also many eruptions of a number of Indonesian volcanoes are discussed. Finally some reasonable models are presented with the help of which one can give a rather simple geophysical explanation for the relationship in the case of both phreatic-phreatomagmatic and true magmatic eruptions.

The paper is dedicated in honour of Mrs. **Luus van Bemmelen** and Professor Dr. Dr. h. c. **Reinout Willem van Bemmelen.**

INTRODUCTION

During the last decade many investigations were carried out to state the possible relationship between tectonic earthquakes and subsequent volcanic eruptions in the nearer-farther environment of the epicentre. BLOT (1976) has devoted a volume to this relationship with the help of which he succeeded in predicting some eruptions in the New Hebrides region and elsewhere. He concentrated his effort above all to the investigation of the relationship between intermediate (h = 70 to 300 km) and deep (h = 301 to 700 km) shocks and eruptions. His numerous and convincing examples will not be repeated here.

In the present paper the author deals primarily with the connection between shallow (h = 0 to 69 km) tectonic earthquakes and subterranean, submarine and particularly surficial volcanic manifestations. Earthquakes before and after eruptions will be treated alike. For the gradation of the cases a space-time parameter, denoted by ϱ, was introduced (HÉDERVÁRI, 1977-c). As the focal depth and Richter-magnitude of the earthquakes are not exactly known in every case, particularly not for earthquakes that took place before the installation of seismographs, these parameters were not considered, except in Indonesia where the true spatial distance between the volcanoes and the focus (hypocentre) of the tectonic shocks was taken into account instead of the epicentre-to-volcano distance. It can be supposed, however, that an earthquake, having a larger magnitude, may have a greater effect on a volcano than that of a shock having a smaller magnitude and thus less energy. The nature of such triggering effects is not known exactly; however, some reasonable models for the explanation of the established relationship will be discussed briefly later. It can be noted, furthermore, that the relationship is a *special* manifestation of the nature.

There are many cases when earthquakes did *not* trigger eruptions. For instance in 1956 there was a series of strong earthquakes very near the volcano of Santorini (36° 24' N, 25° 24' E), including a shock of magnitude 7.8 on July 9 at 36° 42' N, 25°48' E, from a shallow focus. In spite of this series, the volcano did not erupt. It appears that some kind of geophysical and tectonic circumstances (of unknown nature) must be fulfilled for the realization of a relationship between earthquakes and eruptions or vice versa and these cir-

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cumstances are not always fulfilled. Nevertheless, there are examples when the interaction is without any doubt. Such cases are represented with a low value of parameter ϱ. First of all let us summarize the meaning of this parameter.

THE SPACE-TIME DISTANCE (PROBABILITY-FACTOR)

For the investigation of the interaction between the volcanic and seismic events it is reasonable to apply a *space-time diagram,* that is a Descartes-type coordinate system where the time is indicated on the horizontal axis, and the spatial distance between the epicentre (or hypocentre) of the earthquake and the volcano is indicated on the vertical one. Such a diagram is presented in this paper for Indonesia. In the origo the start of the eruption is indicated. The length of the line that connects the origo with a point which represents a shock, is measured in space-time units, denoted by ϱ. Let d be the spatial distance and τ the temporal distance, then

$$\varrho = \sqrt{d^2+\tau^2}.$$

d is expressed in kilometres and the time-unit, τ, is equal to 4.8 hours, that is 1/5 day. The probability of a physical connection between an earthquake and a volcanic outburst or vice versa is given by the value of ϱ. THE SMALLER THE ϱ, THE GREATER THE PROBABILITY.

EXAMPLES FOR THE VOLCANIC-SEISMIC INTERACTIONS

At first we shall present examples for earthquakes before eruptions (Table I), furthermore earthquakes during and/or after eruptions (Table II), and finally five further cases (Table III), that were discussed in more detail elsewhere (GULYÁS ET AL., 1974).

CASES WHERE THE DATA ARE INCOMPLETE

'...the eruptions of 1597, 1766 and 1947 (of the *hekla*) ...were accompanied by fairly strong earthquakes and followed by destructive earthquakes in the western half of the seismic zone a few months later...' (BJÖRNSSON & EINARSSON, 1974, p. 232).

1784 ... ... e: 64.1° N, 20.5° W (both are approximate data), M = 7.5–8.0, $d \sim$ 100 km, t = + ...days (in the second half or after the great *lakagigur* fissure-eruption of 1783–84) (BJÖRNSSON & EINARSSON, 1977, after their Fig. 5).

According to NEUMANN VAN PADANG (1976), some phreatic eruptions of *butak petarangan* are known and each of them was preceded by strong tectonic earthquakes. Such cases were observed in 1786, in May 1928 and between October 13th and November 3rd, 1939.

On 1907.01.08 a strong tectonic shock took place on the island of Hawaii. The *mauna loa* erupted on the next day.

VAN BEMMELEN (1970) has mentioned that a revival of the activity of *merapi* was observed after the M = 8.1 shock that occurred on 1943.07.23 at 9.5° S, 110° E, from a depth of h = 90 km (d = 220 km).

On 1960.04.29 a shock of tectonic origin took place near the *una una* volcano, SE of the island. This was not followed by an eruption; however, a slight increase in temperature of the solfatara fields and an insignificant increase of activity of solfataras were observed (KATILI ET AL., 1960).

On 1976.02.10 a local, volcanic earthquake swarm has commenced at Dominica, West Indies. Only 12 events were recorded during the following months, but they increased sharply following a regional earthquake of magnitude 5.9, that took place on 1976.03.14. According to Tomblin, the swarm was due to subsurface migration of magma (SEAN I, 1976, p. 7).

According to TAYLOR (1955, p. 1.): *ambrym,* New Hebrides: 'During the twelve months before the eruption marked increase in the frequency of tectonic earthquakes occurred throughout the whole of the New Hebrides region'. 'The greatest concentration of epicentres occurred in the deep, opposite Ambrym volcano'. 'The correlation between tectonic earthquakes and volcanic activity in this instance was so good that it was immediately suspect'. On the following pages he writes: 'The volcanic crises at *manam* and *rabaul* in 1936 and 1937 were preceded by a broad regional increase in seismicity which appears to have reached a peak in 1934'. 'The severe eruption in the GOROPU mountains in 1943 was preceded by an interesting group of three unusual earthquakes in 1939 and 1940 ... Of interest is the fact that the initial earthquake in 1939 had an epicentre less than sixty miles from *lamington*. Thus signs of abnormal stress conditions in this area were present at least ten years before the Lamington eruption'. 'In 1950 *bagana* produced an eruption of unusual severity. In the previous years nine major earthquakes occurred in the off-shore deep, and in the year of the eruption the epicentres moved eastward'. 'The *langila* eruption of 1954 had a group of precursory earthquakes beginning in 1950'. 'Beginning in 1950, an unusual number of submarine earthquakes have been occurring in the Bismarck Sea and along the structural arc which appears to include New Ireland and the Admiralty Islands. This supplies a consistent background for the current activity of *tuluman* ...'. 'In 1888, *ritter*

Remarks:
The symbols used in these tables are as follows:
M: *Richter*-magnitude; m: body-wave magnitude; h: focal depth in kilometres; s: shallow; d: distance between the epicentre and the erupting volcano, given in kilometres; R: distance between the hypocentre and the erupting volcano, expressed in kilometres; ϱ: probability-factor (space-time distance between the events), expressed in space-time units.

Table I
Earthquakes before eruptions.

No.	Date of the earthquake	M	h	d	Start of the eruption	Name of the volcano	ϱ	Remarks
1	1910.07.24	6.5	?	5	1910.07.25	Usu	7.07	
2	1975.11.29	5.7 } 7.2 }	5	39	1975.11.29	Kilauea	39.00	Two shocks
3	1933.06.24	7.5	s	20	1933.07.10	Pematang Bata	82.46	Ph
4	1898.04.10	?	s?	30	1898.05.02	Una Una	114.02	
5	1975.06.10	7.0	s	135	1975.06.14	Tia Tia	136.47	
6	1970.09.14	6.8	46	140	1970.09.18	Akita-Komagatake	141.42	
7	1856.08.23	6.9	s?	35	1856.09.25	Akita-Komagatake	168.67	
8	1926.09.05	6.8	s?	180	1926.09.08	Tokachi	180.62	
9	1973.06.24	7.3	s	160	1973.07.14	Tia Tia	188.68	See: 9
10	1973.06.17	7.4	s	160	1973.07.14	Tia Tia	209.34	
11	1960.05.22	9.5	s	210	1960.05.24	Puyehue	210.24	See: 11 Phm
12	1962.04.23	7.0	25	160	1962.05.09	Tokachi	248.30	
13	1968.05.15	4.5	77	300	1968.05.18 or: 05.21	Fernandina	300.37 301.50	See: 13
14	1835.02.20	<8.0	?	450	1835.02.20	Osorno	450.03	See: 14
15	1976.06.26	6.6	s	215	1976.09.15	Karangetang	458.53	
16	1707.10.28	8.4	?	400	1707.12.16	Fuji Yama	469.07	
17	1835.02.20	>8.0	?	540	1835.02.20	Minchinmavida	540.02	
18	1976.06.25	7.1	s	530	1976.08 . . .	Kadovar	563.03	See: 18
19	1835.02.20	>8.0	?	570	1835.02.20	Corcovado	570.02	
20	1965.04.19	6.3	50	220	1965.08.03-1967.10 . . .	Matsushiro	573.85	See: 20
21	1976.06.07	6.5	s	410	1976.08.31	Taal	590.33	
22	1960.05.22	9.5	s	270	1961.01.25	Calbuco	1269.05	
23	1856.08.23	6.9	?	210	1857.05 . . .	Tokachi	1316.85	See: 23
24	1835.02.20	>8.0	?	570	1835.11.11	Corcovado	1433.22	
25	1902.04.19	8.2	s	2000	1902.04.24	Mt. Pelée	2000.16	
26	1902.04.19	8.2	s	2000	1902.05.01	Soufrière	2000.90	

2: The first shock occurred at $03^h\,36^m$, the second at $04^h\,48^m$, only 44 minutes prior to the start of the outbreak. This latter was the largest Hawaiian earthquake since 1868 and was accompanied by seaward displacement of much of the volcano's south flank. Tsunami, generated by the shock and not by the outbreak, maximum height 14.6 m. Massive ground subsidence and faulting.
3: Ph: phreatic eruption.
9: the volcano had been inactive during 161 years prior to this outbreak.
11: Phm: phreatomagmatic eruption. According to the new magnitude scale (KANAMORI, 1977) this, that is the famous Chilean shock, was the greatest in this century.
13: partial caldera-collapse, accompanied by numerous 'collapse-earthquakes' and the appearance of a gigantic eruption-cloud, 175 km in diameter.
14: the magnitude of the shock was very great, probably over 8.0 on the Richter-scale. The epicentre was near Concepción. No exact data are available.
18: the exact time of the start of the eruption is not known; very beginning of August 1976. Arbitrarily 38 days were chosen as the time-difference between the shock and the start of the outbreak. Note that it was a subsurface activity after a dormancy of 276 years. Another strong shock occurred near the epicentre of the first shock on 1976.10.29. This might also have been associated with the outbreak.
20: subsurface volcanic manifestation without true eruption on the surface, near the extinct volcano Minakami Yama, during the inactive period of the near-by volcano Asama Yama. More than 700,000 small and mediocre earthquakes of volcanic origin were observed from August 3rd, 1965 to the first days of October 1967. Crustal deformations, outbreaks of ground-water, faultings, landslides as well as intensive *earthquake-lights* were observed and the latter were photographed. Disturbances in the local geoelectric, geomagnetic and gravity fields were also stated.
23: the day of the start of the outburst is not known; 260 days were considered as a probable time-difference between the events.

Sources: 1, 5, 6, 7, 8, 9, 10, 12, 13, 14, 16, 17, 19, 23, 25, 26: NAKAMURA (1975); 2: Geotimes 21 (1, 2), 1976 and Bulletin of Volcanic Eruptions 15, 1977; 3: NEUMANN VAN PADANG (1976); 4: KATILI ET AL. (1963); SAPPER (1927); 11, 22: CASERTANO (1976); 15, 21: HÉDERVÁRI (1977-a); 18: HÉDERVÁRI (1977-b); 20: HÉDERVÁRI (1976-c); 24: LAMB 1970).

Table II
Earthquakes during and/or after eruptions.
For the symbols used, see Table I

No.	Date of the earthquake	*M*	*h*	*d*	Start of the eruption	Name of the volcano	*ϱ*	Remarks
27	1914.01.12	6.1	50	10	1914.01.12	Sakurazima	10.31	
28	1963.05.18	6.0	54	10	1963.05.16	Agung	14.14	See: 28
29	1963.05.22	6.0	56	20	1963.05.16	Agung	36.06	See: 29
30	1963.05.18	≈5.0	56	40	1963.05.16	Agung	41.23	See: 30
31	1868.04.02	7.5–7.75	?	60	1868.03.26	Kilauea	69.46	
32	1975.06.14	7.0	s	145	1975.06.14	Tia Tia	145.00	
33	1970.10.16	6.2	37	55	1970.09.18	Akita-Komagata-ke	150.42	
34	1943.02.22	7.5	s	160	1943.02.20	Parícutin	160.31	
35	1976.02.04	7.5	29	170	1976.02.03	Pacaya	170.07	See: 35
36	1868.04.02	7.5–7.75	?	60	1868.01...	Mauna Loa	355.11	See: 36
37	1835.02.20	>8.0	?	450	1835.01.19	Osorno	477.60	
38	1978.01.14	6.5	23	6	1977.10.09	Mihara Yama	485.04	See: 38
39	1926.09.09	6.8	?	180	1926.05.24	Tokachi	569.21	
40	1976.10.29	7.1	s	520	1976.08...	Kadovar	687.68	See: 40
41	1975.11.29	5.7 } 7.2 }	5	100	1975.07.06	Mauna Loa	736.82	Two shocks See: 41
42	1923.09.01	7.9	s	75	1922.12.28	Izu-Oshima	1332.11	See: 42

Remarks:
28: second paroxysm of Agung. The inactive period of Agung prior to the new eruption-cycle of 1963 lasted for about 120 years. Seismological data are from the Catalogue of Epicentres ... for 1963.
29: second paroxysm of Agung.
30: second paroxysm of Agung.
35: 'After the quake (in Guatemala) a broad zone of fumaroles and boiling mudpots developed with an extent of approximately 200 metres by 100 metres' (SEAN, 1976). Lava flow was reported from Santiaguito. The Pacaya-eruption evidently was caused by the mechanical strains that gradually built up in the crust before the earthquake and the shallow magma chamber was thereby deformed.
36: the day of the start of the volcanic activity is not known, 70 days were chosen as a probable value.
38: subsurface activity without true eruption on the surface at 34.73°N, 139.38°E. In the period of 1977.10.09–1977.11.16 more than 332 shocks (of volcanic origin) were observed.
40: the day of the start of the outbreak is not known; very beginning of August 1976. Subsurface activity after a dormancy of 276 years. It was triggered by the shock of 1976.06.25.
41: the shock of 1975.11.29 has triggered an eruption of the near-by volcano, Kilauea (see in Table I as well).
42: this was the tragic Tokyo-earthquake when about 144 000 people lost their lives.

Sources: 27, 31, 32, 33, 36, 39, 42: NAKAMURA (1975); 28, 29, 30: HÉDERVÁRI (1976-b, 1976-c, 34: RICHTER (1958); 35: HÉDERVÁRI (1976-a); 37: LAMB (1970); 38: HÉDERVÁRI (1978); 40: HÉDERVÁRI (1977-b); 41: CENTER FOR SHORT-LIVED PHENOMENA (1975).

Table III
Further examples for volcanic-seismic interrelations.
For the symbols used, see Table II.

No.	Date of the earthquake	*m*	*M*	*R*	Start of the eruption	Name of the volcano	*ϱ*
43	1967.08.06	5.0-5.2		100	1967.08.31	Semeru	160.08
44	1967.05.05	5.3		240	1967.05.07	Slamet	240.21
45	1962.12.22		6.0	150	1963.05.05	Semeru	686.59
46	1965.11.23	5.8		190	1966.04.26	Kelud	793.10
47	1966.06.26	5.4		240	1967.01.12	Merapi	1028.40

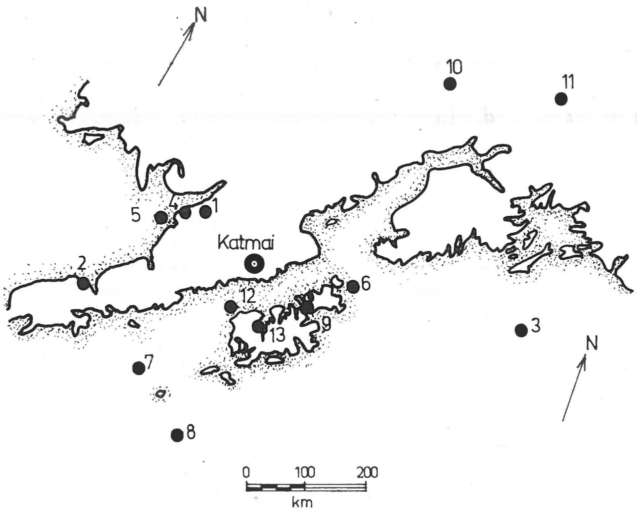

Fig. 1
Distribution of earthquake epicenties around Katmai (Alaska) after the great eruption of 1912.

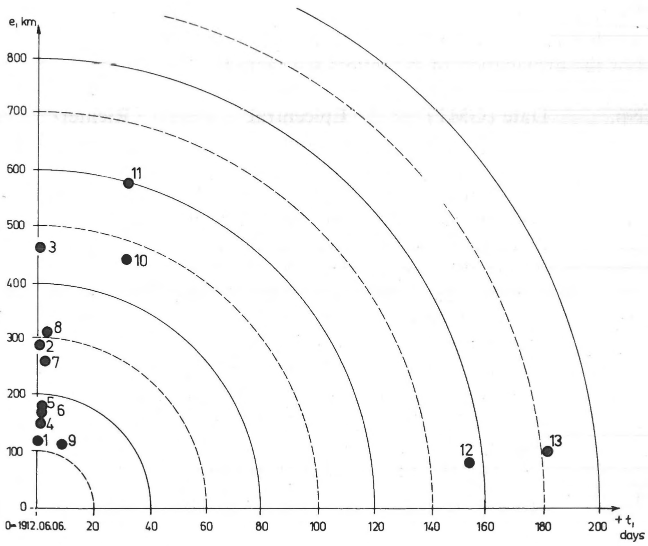

Fig. 2
Space-time diagram of the earthquakes that occurred after the explosive outburst of Katmai. e: epicentral distance in km; t: day after the start of the outbreak.

island produced its catastrophic eruption. ... In 1883 earthquakes were again numerous, possibly as a prelude to the culminating paroxysm of Ritter'. 'Of the *manam* eruptions in recent years in 1936–1937 and 1947 the former appears to have been the more powerful. ... The precursory earthquakes of these two eruptions occurred from origins which are either submarine and coastal or inland'.

'*Conclusion*: The above evidence suggests that the current volcanic activity in the Territory is explainable on the grounds of widespread regional stress conditions which are manifest in an increase in the frequency of tectonic earthquakes. ... This relationship suggests more detailed seismic work as a very promising field for volcanological research'.

According to CARR (1977): 'In the past the two largest eruptions in Central American history (*cosigüina* in 1835 and *santa maria* in 1902) occurred within months after nearby great earthquakes' (p. 657).

EARTHQUAKES RELATED TO THE KATMAI–NOVARUPTA ERUPTION

One of the greatest volcanic catastrophes was the outbreak of the *katmai–novarupta* system of Alaska in 1912. Katmai lies at 58.27° N, 154.98° W and the crater known as Novarupta is at a distance of some 10 km W of it at 58.28° N, 155.25° W. The sequence of the events was treated recently by WARD & MATUMOTO (1967) as follows:

(1) Explosive eruption of pumice and ash, probably from Novarupta;
(2) main ash flow either from fissures at the head of the Valley of Ten Thousand Smokes or also from Novarupta;
(3) some further minor ash eruptions;
(4) collapse of the summit of Katmai and the origin of the caldera as a result of the removal of material from under Katmai either through or near Novarupta.

Three great explosions were distinguishable (VON WOLFF, 1914): June 6, $23^h\ 24^m$ (GMT); June 7, 1^h; and June 7, 9^h, respectively.

The whole sequence was accompanied and followed by vigorous seismic activity. These tectonic shocks are tabulated in Table IV. Data of No. 1 to 11 shocks are given by VON WOLFF (1914); the others by GUTENBERG & RICHTER (1954). Magnitudes are from Gutenberg & Richter as welt as from DUDA (1965). Abbreviations are as follows: *h*: focal depth in km; *s*: shallow; *t*: time-interval between the start of the eruption and the occurrence of the shocks in days; *d*: distance of the epicentre from Katmai in km.

EARTHQUAKES RELATED TO THE ERUPTIONS OF SANTORINI

The world-famous volcano of *Santorini* in the Aegean Sea which completely destroyed a rich Minoan civilisation around 1500 B.C., and resulted in the decline of the Minoan Empire on Crete, has been investigated with particular interest by three members of the *International Research Group on Terrestrial and Cosmic Physics* (KOMLÓS, HÉDERVÁRI & MÉSZÁROS, 1978). The results were presented on the world-congress known as 'Thera and the Aegean World' which was organized by the *Greek Archaeological Society* and was sponsored by Mr. *Petros Nomikos,* Chairman of the Congress, held at Athens, August, 1978. The above mentioned authors (Komlós et al.) have found that *all but one of the*

Table IV
Earthquakes after the Katmai–Novarupta eruption.
For the explanation of the letters see table I

No.	Date (GMT)	Epicentral coordinates	Richter-magnitude	h	t	d
1	1912.06.07.09.56	58.6° N, 156.9° W	6.4	s	1	120
2	1912.06.07.12.23	56.8° N, 158.9° W			1	290
3	1912.06.07.18.24	59.0° N, 147.0° W			1	460
4	1912.06.08.07.36	58.4° N, 157.2° W			2	150
5	1912.06.08.08.48	58.2° N, 158.0° W			2	180
6	1912.06.08.12.59	58.6° N, 152.0° W			2	170
7	1912.06.09.17.14	56.0° N, 156.5° W			3	260
8	1912.06.10.16.06	55.4° N, 154.7° W	7.0	s	4	310
9	1912.06.12.07.04	58.0° N, 153.0° W			6	110
10	1912.07.07.07.57	62.0° N, 152.0° W	7.1	s	31	440
11	1912.07.08.21.54	62.5° N, 148.5° W			32	580
12	1912.11.07.07.40	57.5° N, 155.0° W	7.5	90	154	80
13	1912.12.05.12.28	57.5° N, 154.0° W	7.0	90	182	100

Probability-factor,
$\varrho = \sqrt{d^2 + \tau^2}$,

where τ is the time-unit ($1\ \tau = 4.8$ hours):

No.	ϱ, in space-time units
9	114.0
1	120.1
4	150.3
6	170.3
5	180.3
7	260.4
2	290.0
8	310.6
3	460.0
10	466.5
11	601.7
12	774.1
13	915.5

historically known eruptions of this volcano were associated with tectonic earthquakes that took place within a circle with a radius of some 420 km around Santorini and within about ± 150 days from the start of the eruptions. This statement refers to the 'Minoan' eruptions as well, that took place around 1500 B.C. This eruption was in all likelihood associated with a shock and occurred at a distance of about 165 km of the volcano at 35° N, 26° E with a magnitude of around 6.8. Data of earthquakes were taken over from GALANOPOULOS (1961) and from KÁRNÍK (1968, 1971), respectively, while volcanological data are from GEORGALAS (1962). In our table V, however, only those cases will be enumerated where the time-interval between the start of the eruptions in question and the occurrence of the shocks are known exactly. The symbols are the same as previously. The relationship between seismic and volcanic phenomena was particularly interesting during the 1866.01.31 to 1870.10.15 eruptive cycle of Santorini (KOMLÓS ET AL., 1978). It must be noted, however, that this was a special case and the pattern between seismic and volcanic manifestations was different from this one in the case of other eruptive cycles.

For the period between 1858.01.01 and 1878.01.01 all the earthquakes were considered, provided that they took place within a distance of 420 km measured from Santorini. The eruptive activity was initiated (triggered) by shock No. 6 in our table V. This was a shallow earthquake with an epicentral intensity of 7° measured on the 12° scale of Mercalli & Sieberg. Disregarding this quake all the other shallow ones took place at a distance of d ⩾ 130 km of the volcano. That is during 20 years there had been a practically *aseismic circle* around Santorini with a radius of d ⩾ 130 km. This is consistent with the results obtained by Japanese authors according to which the immediate environment of active volcanoes shows a very reduced seismicity disregarding, of course, the triggering shocks.

Another very interesting feature is that during the eruptive period of 1866–1870 the number of shallow shocks of smaller magnitude showed a remarkable growth relative to the period preceding and following the eruptive cycle (Fig. 3). The cycle began with the occurrence of six shallow shocks with a Richter-magnitude of 5.5 – 6.3. The average energy of the shallow shocks, and their number too, showed a decrease at around the middle of the volcanic cycle, while at the very end of it two $M = 7.5$ earthquakes occurred within some months. After these two powerful shocks there was a long pause until 1873.01.31. *Evidently the internal energy within the crust (and perhaps the uppermost mantle) around Santorini was almost completely exhausted due to the long eruptive cycle as well as the many smaller and the two great earthquakes!* (Here it can be noted that intermediate shocks were not included in this investigation).

For the fast characterization of the probability of the physical (cause-and-effect) relationship between earthquakes and eruptions or vice versa the following arbitrary scale is suggested (note again that at this stage of the study the magnitude of the shocks are not considered):

A:	$\varrho =$	0 – 99	perfectly sure
B:		100 – 199	sure
C:		200 – 299	very probable
D:		300 – 399	probable
E:		400 – 499	a little less probable but possible
F:		500 – 599	still less probable but possible
G:		600 – 699	perhaps possible
H:		700 – 799	a little improbable but not impossible
I:		800 – 899	improbable but not impossible
J:		900 – 999	very improbable but not impossible
K:		1000 or over	perfectly improbable

Table V
Earthquakes associated with the eruptions of Santorini.
For the explanation of the letters see table I.

No.	Start of the eruption	Date of the shock	*d*	*t*	Epicentral coordinates, N	E	Richter-magnitude
1	1650.09.26	1650.09.29	0-15	+3	36.5	25.5	6.1 ?
2	1707.05.23	1707.06.06	415	+14	37.75	21.0	5.4 ?
3	1866.02.01	1865.07.23	320	−192	39.4	26.2	6.0
4		1865.10.11	205	−113	37.75	27.0	5.5
5		1865.11.11	210	−82	38.25	26.25	6.25
6		1866.01.31	0-15	−1	36.4	25.3	6.1
7		1866.02.02	210	+1	38.25	26.25	6.1 ?
8		1866.02.06	135	+5	36.0	24.0	6.1 ?
9		1867.03.07	305	+35	39.1	26.6	6.1
10	1925.08.11	1925.05.14	390	−89	38.5	21.75	4.7
11		1925.06.06	390	−66	38.25	21.75	5.2
12		1926.02.08	240	+181	37.1	27.9	5.1[1])
13	1928.01.23	1927.11.18	210	−66	34.5	25.0	4.9
14		1928.01.22	335	−1	38.5	22.5	5.2
15		1928.04.10	120	+78	37.4	26.1	5.0
16	1939.08.20	1939.07.24	280	−27	37.2	28.3	4.8
17		1939.07.28	230	−23	34.3	25.0	4.8
18		1940.01.06	95	+139	35.7	25.9	5.6
19		1940.02.29	105	+199	35.5	25.5	6.0
20	1950.01.10	1949.09.17	240	−115	37.0	22.75	4.9
21		1949.09.17	195	−115	34.8	26.2	5.1
22		1949.10.04	390	−98	38.5	21.8	4.6
23		1949.10.05	390	−97	38.5	21.8	4.4
24		1949.11.23	245	−48	38.6	26.3	5.2
25		1949.12.07	220	−34	34.7	24.1	4.9
26		1950.02.12	220	+33	34.7	24.1	5.0
27		1950.05.30	175	+140	36.8	27.2	4.8

[1]) This shock occurred after the end of the eruptive cycle by 25 days. In this table only shallow earthquakes were considered. Note that the coordinates of Santorini are 36°24' N, 25°24' E.

Probability-factors:

No.	ϱ, in space-time units	No.	ϱ, in space-time units
6	15.81	5	460.65
1	21.21	11	510.88
8	137.30	10	591.71
7	210.06	4	601.04
17	257.15	21	607.17
26	275.00	23	622.35
25	278.03	20	623.08
16	310.85	22	626.56
14	335.04	18	701.46
24	342.97	27	721.54
9	351.64	12	936.28
13	391.15	19	1000.52
15	408.04	3	1011.93
2	420.86		

EARTHQUAKES RELATED TO THE ERUPTIONS OF INDONESIAN VOLCANOES

A few Indonesian examples have already been discussed, including the very interesting case of Agung. In the following a number of further Indonesian examples will be summarized briefly (Table VI).

In table VI the data of the period of 1913.01.01 to 1949.12.31 are given and they are supplemented by some shocks that were related to the Agung eruption in 1963. The space-time diagram is shown in figure 4.

In the course of this investigation the author has used the

Table VI
Earthquakes associated with the eruptions of Indonesian volcanoes.

Symbols used:
Ph e: phreatic explosions
N e: normal explosions (due to igneous activity)
Sm: submarine eruption
G b: gas bubbles
Ex: extrusion of a lava dome
E c l: eruption in a crater lake
Ts: tsunami (of volcanic origin)
L f: lava flow
E c c: eruption in the central crater
t: time-interval between the eruption and the occurrence of the shock, given in days
–: tectonic earthquake preceding the eruption
+: tectonic earthquake during and/or after the eruption
R: the true spatial distance between the hypocentre of the shock considered and the erupting volcano given in kilometres,
$R = \sqrt{h^2 + e^2}$;
where h is the focal depth in kilometres and e the distance between the epicentre and the volcano in kilometres
d: $M = 5.3 - 5.9$, where M is the Richter magnitude
ϱ: the probability factor expressed in space-time units,
$\varrho = \sqrt{R^2 + \tau^2}$;
where τ is the time-unit (= 4.8 hours).

The numbers, such as 6.1-12, etc., after the name of the volcano considered means the catalogue-number in the Catalogue of Active Volcanoes of the World Including Solfatara Fields, Volume I, Indonesia (edited by Neumann van Padang), Napoli, 1951. No. means the serial number of the earthquake under consideration, according to the value of the probability factor.

Note that in this table only those eruptions were taken into account for which the start of the outbreak was known exactly (year, month and day, respectively). All eruptions between 1913.01.01 and 1949.12.31 were considered. Data of earthquakes are from the *Index Catalogue(s) of Epicentres*; data of eruptions are from Neumann van Padang (quoted above). As a supplement Agung's case was also mentioned and shown in Fig. 5., although its outbreak took place in 1963. Magnitudes of earthquakes are from Duda (1965) Gutenberg & Richter (1954), Richter (1958) and Rothé (1969). Focal depths are usually from the same sources as well as from the *Index Catalogue(s) of Epicentres.*

Volcano	Commencement of the eruption	Type	*t*	*R*	*M*	ϱ	No.
Agung, 6.4-2	1963.03.17	N e	+ 2	54.9	6.0	55.8	1
Agung, 6.4-2	1963.03.17	N e	+ 6	59.5	6.0	66.6	2
Agung, 6.4-2	1963.03.17	N e	+ 2	68.8	?	69.5	3
Pematang Bata, 6.1-27	1933.07.10	Ph e	−12	44.6	< d	74.8	4
Pematang Bata, 6.1-27	1933.07.10	Ph e	−15	44.6	< d	87.3	5
Pematang Bata, 6.1-27	1933.07.10	Ph e	−16	44.6	< d	91.6	6
Lewotobi Lakilaki, 6.4-18	1939.12.17	N e	0	106.4	< d	106.4	7
Lokon-Empung, 6.6-10	1942.09.03	N e	−10	114.8	< d	125.3	8
Raung, 6.3-34	1936.08.22	N e	−26	86.5	< d	156.2	9
Dempo, 6.1-23	1934.04.23	N e	− 5	158.5	< d	160.4	10
Soputan, 6.6-3	1947.08.22	N e	−24	119.6	< d	169.5	11
Sorikmarapi, 6.1-12	1917.05.20	Ph e	+32	227.4	< d	177.7	12
Marapi, 6.1-14	1927.04.28	?	+12	177.2	6.0	187.0	13
Peak of Ternate, 6.8-6	1938.09.08	N e	+29	153.6	< d	211.2	14
Api Siau, 6.7-2	1941.10.30	N e	+19	192.8	< d	215.0	15
Marapi, 6.1-14	1917.06.16	?	+ 5	227.4	< d	228.8	16
Dempo, 6.1-23	1936.11.26	N e	+24	197.8	< d	231.3	17
Ruang, 6.7-1	1946.10.13	N e	+ 1	232.4	< d	232.4	18
Raung, 6.3-34	1938.11.14	?	−16	233.1	6.5	246.4	19
Kerintji, 6.1-17	1938.01.19	Ph e	− 1	250.7	6.5	250.8	20
Soputan, 6.6-3	1947.08.22	N e	−31	197.8	< d	251.3	21
Salak, 6.3-5	1938.01.31	Ph e	− 9	254.0	6.0	258.0	22
Awu, 6.7-4	1931.02.11	E c c, Ex	+35	247.2	6.75	259.8	23
Bromo, 6.3-31	1929.08.07	?	−48	112.4	6.25	265.0	24
Tangkuban Prahu, 6.3-9	1929.05.20	Ph e	−24	237.3	< d	265.9	25
Bromo, 6.3-31	1922.06.10	?	−31	217.5	< d	267.1	26
Dempo, 6.1-23	1934.02.20	N e	− 1	281.9	< d	282.0	27
Banua Wuhu, 6.7-3	1918.07.18	N e	+24	262.1	< d	288.3	28
Kawah Idjen, 6.3-35	1917.02.25	Ph e, E c l	−36	232.6	< d	293.8	29

Ruang, 6.7-1	1946.10.13	N e	+15	286.9	< d	296.5	30
Banua Wahu, 6.7-3	1918.07.18	N e	+28	262.1	8.25	297.1	31
Awu, 6.7-4	1931.03.18	E c c, E x	+35	240.3	7.0	297.2	32
Banua Wahu, 6.7-3	1918.07.18	N e	+32	262.1	< d	299.5	33
Nila, 6.5-6	1932.03.13	Ph e	+31	257.1	< d	300.2	34
Nila, 6.5-6	1932.03.13	Ph e	+13	296.8	< d	303.9	35
Banua Wahu, 6.7-3	1918.07.18	N e	+34	262.1	< d	307.1	36
Bromo, 6.3-31	1948.02.15	?	+ 4	306.8	< d	307.4	37
Awu, 6.7-4	1922.06.20	Ph e	+ 4	262.1	< d	312.4	38
Soputan, 6.6-3	1947.08.22	N e	−55	148.7	< d	312.6	39
Nila, 6.5-6	1932.03.13	Ph e	+38	257.1	< d	319.7	40
Awu,, 6.7-4	1931.02.11	E c c, Ex	+16	321.7	< d	323.6	41
Dempo, 6.1-23	1934.04.23	N e	+30	286.9	< d	323.7	42
Soputan, 6.6-3	1947.08.22	N e	−53	197.8	< d	330.7	43
Bromo, 6.3-31	1939.06.24	?	−44	257.1	< d	338.4	44
Dempo, 6.1-23	1926.04.22	N e	+69	36.2	< d	346.9	45
Bromo, 6.3-31	1948.02.15	?	+51	247.2	< d	355.2	46
Raung, 6.3-34	1945.01.20	N e	−11	232.6	< d	355.8	47
Anak Krakatau, 6.2	1927.06.??	Sm, G b	−57	217.5	< d	358.5	48
Api Siau, 6.7-2	1947.12.01	N e	−38	351.6	< d	361.7	49
Anak Krakatau, 6.2	1927.06.??	Sm, G b	−48	272.0	< d	362.8	50
Api Siau, 6.7-2	1947.12.01	N e	−72	91.2	< d	371.4	51
Galunggung, 6.3-14	1918.07.17	N e, Ex	+26	351.6	< d	374.8	52
Awu, 6.7-4	1922.06.20	Ph e	+23	386.4	< d	386.9	53
Tangkuban Prahu, 6.3-9	1929.05.20	Ph e	+78	44.6	< d	392.5	54
Slamet, 6.3-18	1929.06.06	N e	−41	341.6	< d	398.4	55
Banua Wahu, 6.7-3	1918.07.18	N e	−40	346.6	< d	400.1	56
Raung, 6.3-34	1937.10.27	N e	−30	371.4	7.2	400.6	57
Soputan, 6.6-3	1947.08.22	N e	−70	197.8	< d	402.0	58
Awu, 6.7-4	1922.06.20	Ph e	+ 7	386.4	< d	403.2	59
Soputan, 6.6-3	1947.08.22	N e	−71	199.1	7.2	407.0	60
Api Siau, 6.7-2	1941.10.30	N e	+ 9	437.9	7.3	440.2	61
Pematang Bata, 6.1-27	1933.07.10	Ph e	+31	416.3	d	444.2	62
Papandajan, 6.3-10	1923.03.11	Ph e	+62	321.7	< d	446.7	63
Galunggung, 6.3-14	1918.07.17	N e, Ex	+45	386.4	< d	447.1	64
Papandajan, 6.3-10	1923.03.11	Ph e	+65	321.7	< d	457.3	65
Galunggung, 6.3-14	1918.07.17	Ne, Ex	+49	386.4	< d	457.5	66
Dieng, 6.3-20	1944.12.04	Ph e	−81	291.8	6.75	499.2	67
Kawah Idjen, 6.3-35	1936.11.05	Ph e, E c l	−101	105.3	< d	515.9	68
Api Siau, 6.7-2	1941.10.30	N e	− 43	474.7	7.1	521.6	69
Banua Wahu, 6.7-3	1918.07.18	N e	+ 96	281.9	< d	556.7	70
Paluweh, 6.4-15	1928.08.04	N e, Ex, Ts	+116	59.9	6.9	583.1	71
Api Siau, 6.7-2	1941.10.30	N e	− 71	478.8	5.75	596.1	72
Anak Krakatau, 6.2	1927.12.29	Sm	−112	220.7	6.25	601.9	73
Agung, 6.4-2	1963.02.17	N e	− 1	612.2	d	612.2	74
Anak Krakatau, 6.2	1927.12.29	Sm	−129	134.1	< d	658.8	75
Merapi, 6.3-25	1948.09.29	N e, L f	− 2	662.9	< d	663.0	76
Agung, 6.4-2	1963.02.17	N e	− 24	691.2	< d	701.6	77
Raung, 6.3-34	1937.10.27	N e	− 77	691.1	7.2	791.2	78

Remarks:

1: In total 85 earthquakes were taken into account. Some improbable cases (intermediate or deep earthquakes after phreatic eruptions) were omitted. Similarly, intermediate or deep shocks following true magmatic eruptions were also neglected.
2: No. 19: h = 90 km.
3: No. 20: h = 100 km.
4: No. 22: h = 150 km.
5: No. 48 and 50: the eruption of Anak Krakatau was visible on the surface of the sea from 1927.12.29. Gas bubbles, as indicators of the commencement of the submarine activity were observed as early as June 1927, however. As the start of this bubble-activity is not known exactly therefore a medium value for *t* was applied. Practically Anak Krakatau is one of the most active volcanoes of the world. Hence further eruptions after its birth on 1927.12.29 were not elaborated and considered because their number is too high.
6: No. 69: h = 190 km.
7: No. 72: h = 200 km.
8: No. 74: h = 561 km.
9: No. 76: h = 638 km.
10: No. 77: h = 599 km.
11: No. 78: h = 610 km.
12: earthquakes of shallow origin denoted as n (normal) or s (shallow) in the catalogues used were considered as shocks with h = 33 km if the more exact focal depth was not given in the catalogues.

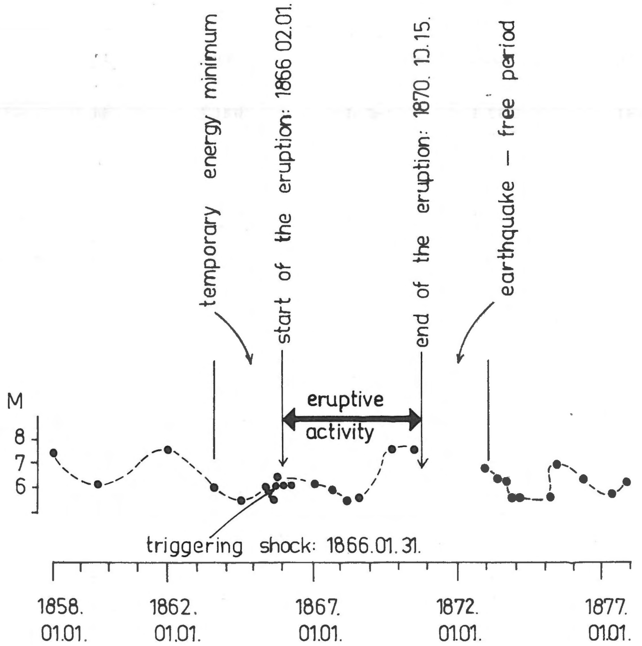

Fig. 3
Variation of seismic energy release in association with the activity of Santorini after 1866.01.31. M: Richter magnitude.

data of altogether 129 eruptions of 27 Indonesian volcanoes (Agung is not included). All earthquakes within a circle of a radius of 700 kilometres of the volcanoes in question were considered provided that they occurred within about 4 months before or after the start of the outbreaks.

STATISTICAL ANALYSIS OF THE INDONESIAN EXAMPLES

In table VI altogether 78 cases were listed. Their distribution is shown in table VII.

It can be seen that 67 cases out of the 78 belonged to the categories of A, B, C, D and E, respectively. The physical relationship between tectonic earthquakes and volcanic eruptions is more frequent in the case of normal eruptions (due to igneous activity) than in the case of phreatic outbursts. The ratio is 43 : 20. The maximum number of the cases are seen in category D (probable). Category C (very probable) stands in second place. The number of 'perfectly sure' cases (category A) is relatively low, and just half of them is represented by phreatic eruptions.

MODELS FOR THE EXPLANATION OF THE RELATIONSHIP

Concerning the cases of Puyehue and Pematang Bata, we wish to quote some sentences from VITALIANO & VITALIANO (1971, p. 103):

We have to do with '... two different cases of the same type of relationship, not two different types of relationships. Puyehue and Pematang Bata ... have apparently been triggered *directly* by earthquakes. In this connection it is important to make distinction between 'trigger' and 'cause'. A gun will fire when the trigger is pulled, but only if it is loaded; the trigger determines *when* the bullet will be fired, not *why*. The 1960 Puyehue eruption, like that of Pematang Bata, has been attributed to the fact that the earthquake allowed ground water to come in contact with magma. However, inasmuch as Puyehue lies directly on the Reloncavi fault on which earthquake movement occurred, and some lava was erupted too, it has also been suggested that the magma chamber might actually have been squeezed as a result of the earthquake. In any case, Puyehue and Pematang Bata both must have been 'loaded' with hot magma, and the earthquake merely created the circumstances which made an eruption occur when it did'.

CASERTANO (1976), expressing the relationship in the cases of Puyhue and Calbuco, has written as follows: 'I think that the quakes may have caused, also by forming or reactivating faults, a sudden decrease of pressure in the magmatic zones of each erupting volcano. These depressions gave rise to the ascent of the magma and triggered the eruptions. The fact that the earthquake had triggered eruptions only of these two volcanoes (and in different times) and not also the others on the same line (Osorno, Nilahue and so on) depends on the peculiar conditions of each one'.

In the Agung's case it seems to be likely that the release of seismic energy immediately after the second paroxysm might have been the result of a considerable change in the loading of the uppermost layers of the ground, due to the removal of a very remarkable quantity of mass in the form of lava, nuée ardente deposits and other pyroclastics (at least 300 millions of tons!) (HÉDERVÁRI, 1976-b). In all likelihood the same considerations may be valid for the Katmai–Novarupta eruption as well.

Generally speaking the following explanations can be suggested:

(1) *Phreatic eruptions after earthquakes.* The model is due to NEUMANN VAN PADANG (1976). The surface water sank along the fault planes to the still very hot, though extinct magma chamber; and these fault planes have their origin by the preceding tectonic earthquake. By this process the explosions of water-vapour can take place in the depth which lead to the commencement of a phreatic or phreatomagmatic eruption.

(2) *Tectonic earthquakes (of shallow origin) after phreatic eruptions.* The author's view is as follows. The subsurface steam-explosions can promote the release of stored mechanical stresses in the environment of the volcano, leading thus to the occurrence of tectonic shocks within some days, or weeks, after the start of the outbreak. The mass-displacements in the case of phreatomagmatic eruptions, near the magmatic hearth and the pipe can also promote the release of seismic stresses provided that the tectonic preconditions are already given in

Table VII
Statistics of the Indonesian examples (on the basis of table VI)

Category and limits for ϱ	Phreatic eruptions with or without eruption in a crater lake	Normal explosions with or without extrusion of a lava dome	Submarine activity	Eruption in the central crater with or without extrusion of a lava dome	Others or unknown	Total
A (0 – 99)	3	3	–	–	–	6
B (100 – 199)	1	5	–	–	1	7
C (200 – 299)	4	10	–	2	4	20
D (300 – 399)	6	10	2	1	3	22
E (400 – 499)	5	7	–	–	–	12
F (500 – 599)	1	4	–	–	–	5
G (600 – 699)	–	2	2	–	–	4
H (700 – 799)	–	2	–	–	–	2
Total:	20	43	4	3	8	78

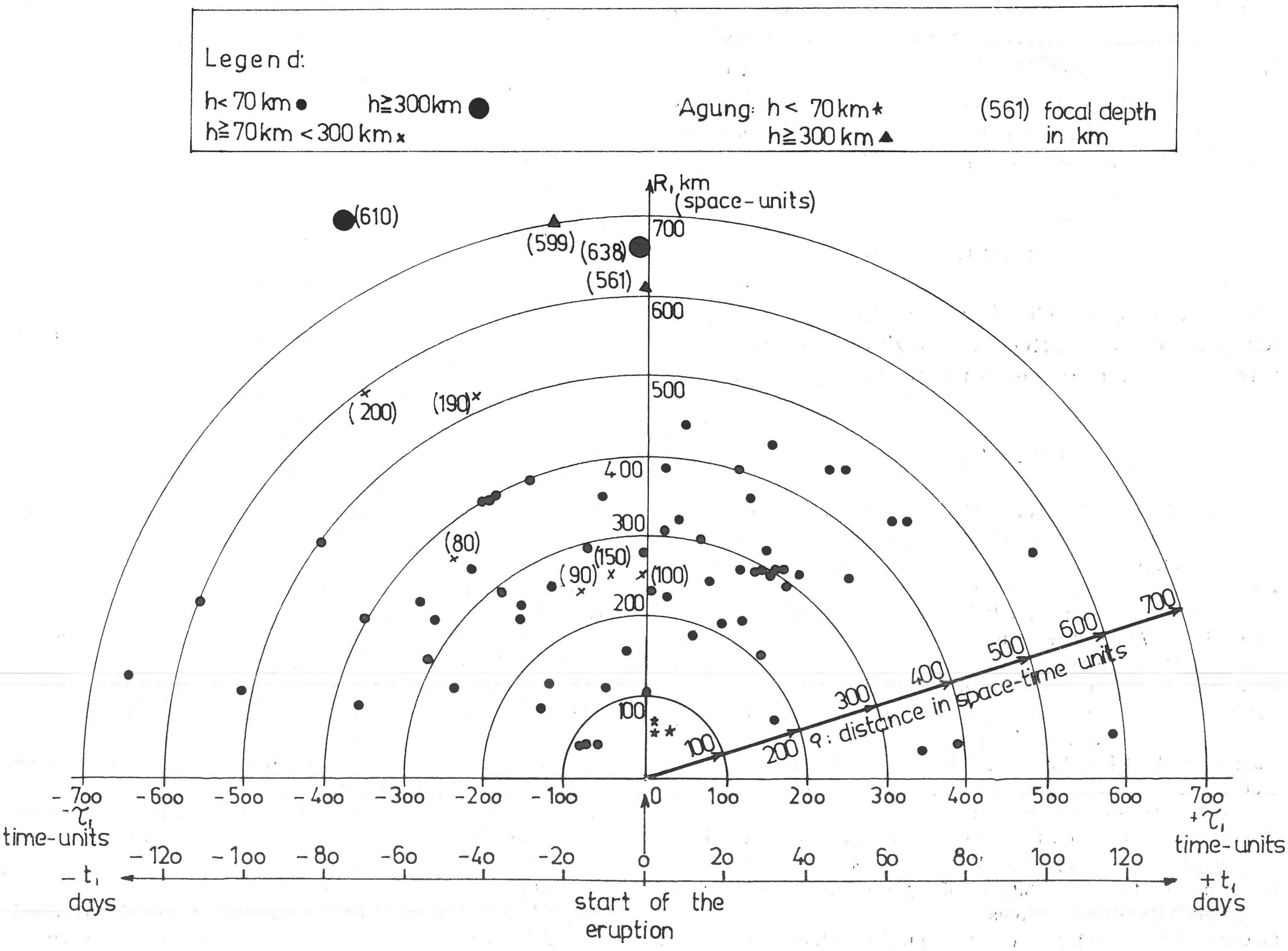

Fig. 4
Space-time diagram of the earthquakes associated with the eruptions of Indonesian volcanoes. For explanation see text.

the area. In this case the volcanic activity can serve as a secondary effect that hastens the occurrence of the earthquake.

(3) *Tectonic shocks before, during and after true magmatic eruptions.* NAKAMURA (1971, 1975) has explained them by the following considerations: as the crustal strain gradually builds up toward the earthquake, the volcano's (shallow) magma chamber is also deformed and contracts to some degree. Then the magma in the reservoir is squeezed up and thus causes an eruption, which, once started, may proceed as a self-moving machine. Later, when the earthquake occurs, the strain that squeezed up the magma is released. The head of the magma falls off resulting the end of the eruption, in case it has still continued.

Let us add some further ideas to the Nakamura-model. It is well-known that *before* the outburst there are some deformations within the volcanic mount itself due to the pressure of the emerging magma on the walls of the pipe. *After* the eruption the reverse process can be supposed, that is the deformations change their sign. Instead of swelling of the mount, a small-scale contraction takes place owing to the decrease of pressure within the pipe. This second process may perhaps also create further mechanical stresses within the uppermost layers of the earth, near the ground-surface and in the nearer-farther environment of the volcano in question and through this process the phenomenon promotes the release of seismic energy which was stored *previously* in the rocks.

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