Volcanic-type Microearthquake Activity in Melos, Greece

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Riassunto. — Uno sciame di terremoti cominciò improvvisamente il 26 Agosto 1971 nell'isola di Melos (Grecia) e durò circa cinque giorni. La maggior parte degli eventi avvenne ad una profondità di poco superiore ai 5 km. La distribuzione della frequenza dei terremoti in funzione degli intervalli $S-P$, indica alcuni picchi che evidenziano l'attività principale in alcune aree molto piccole. Il valore b di questo sciame (1.2) sta tra quello dei terremoti tettonici e quello dei terremoti vulcanici, per cui l'attività osservata comprende una mescolanza di scosse vulcaniche e tettoniche in una struttura molto eterogenea con sollecitazioni localmente concentrate. Questo tipo di sciame può essere indice di processi magmatici che non sono riusciti a raggiungere la superficie sotto forma di eruzioni vulcaniche o di processi idrotermici i quali liberano improvvise tensioni tettoniche. Il presente studio aumenta il numero delle regioni per le quali gli sciami di terremoti vengono associati ad aree di vulcanismo antico o recente. Ricerche particolareggiate sugli sciami di terremoti che avvengono specialmente in aree vulcaniche di vulcanismo recente, sono molto importanti dal punto di vista della Sismologia e della Vulcanologia, perché possono offrire un mezzo per rivelare processi vulcanici, idrotermici o magmatici.

Summary. — An earthquake swarm broke out at the 26 of August, 1971 in Melos island (Greece) and lasted for about five days. The majority of events were shallower than 5 km. The frequency distribution of earthquakes as a function of $S-P$ intervals indicates some peaks and so the main activity in certain very small areas is clear. The b-value of this swarm (1.2) is intermediate between that of tectonic earthquakes and that of volcanic ones and so the observed activity imply a mixture of tectonic and volcanic shocks in a highly heterogeneous structure with locally concentrated stresses. This type of swarm may be indicative of magmatic processes

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that failed to reach the surface as volcanic eruptions or of hydrothermal processes that trigger tectonic strain release. The present study increases the number of regions for which earthquake swarms are associated with areas of historic of recent volcanism. Detailed researches on earthquake swarms especially those occurring in volcanic areas of recent volcanism are very important from the standpoint of Seismology and Volcanology, because they may offer a means of detecting volcanic, hydrothermal, or magmatic processes.

1. – Introduction

Volcanic earthquakes are rare events in Greece whose the general seismicity level is rather high. This circumstance makes the more interesting the occurrece of volcanic shocks in any area of the country given their capability of contributing data relevant for characterising local features of the volcanic seismicity in Greece. It was this potentiality which drew our attention to the swarm having started on the 26th August, 1971 in the Melos island.

A supplementary impetus about this study was given by the fact that two days after the beginning of the swarm a mobile station started to operate very close to the epicenters. So it was possible to record in three days a large number of material even for the weaker tremors. However, as the local instrumental information while of rather good quality (with exception of the magnitude determination of the main portion of microshocks) was coming only from one station, except the 76 larger events the contemplated research was severely limited, in particular by the lack of information on the space and magnitude distribution of microevents. Despite this serious handicap and the fact that occurred only very small events, some useful results were obtained and they are to be reported in what follows.

Researches on earthquake swarms especially those occuring in volcanic areas of recent volcanism are very important from the standpoint of Seismology and Volcanology because they may lead to some empirical relations in connection with volcanic phenomena such as impending eruptions or magmatic processes in progress beneath the volcano and its vicinity. Earthquake swarms with shallow hypocenters often occur before eruptions or may accompany them; others may be attributed to magmatic activity that failed to reach the surface.

Swarms (sequences of events closely grouped in time and space but without one outstanding main-shock) have occurred as forerunners, for example to most of the major volcanic eruptions in the Losser Antilles ([12]). Some of them, were not associated with volcanism, but were accompanied by increased activity of hot springs and fumaroles. Others like the famous Matsushiro swarm of 1965-1967 were located near volcanoes that apparently have been dormant or extinct for ten thousands of years or more ([8]). Thus although many swarms occur in volcanic regions and are associated with volcanic eruptions, some apparently do not. A causal relationship between swarms and magmatic, volcanic, or hydrothermal activity still remains unresoved although has been suggested.

Among the several possible mechanisms of swarm generation three of the more appealing mechanisms are related to volcanism. In one case magmatic activity acts as a concentrated source of stress ([13]) in the second, volcanoes are the loci of heterogeneous materials ([17]). In the third likely mechanism localized sourses of high fluid pressures may lower the effective strength and act essentially as concentrated sourses of stress (Mckenzie personal communication). Magmas or hydrothermal processes are possible sources of high fluid pressures near volcanoes. Such a mechanism undoubtedly was a causative agent in the Denver series of earthquakes ([3]) and may be in the Matsushiro swarm ([9]).

It must be added here that the swarm of Melos in 1971 belong to a small scale earthquake swarm manifested for a few days with a sequence of extremely shallow microearthquakes but it was indeed a remarkable event for the volcanic arc in Greece.

2. – Volcanics of the Aegean region and geology of Melos

Magnetic anomalies occur in the Aegean Sea and these are caused by magnetized rocks that have been intruded by volcanism ([15]).

Spatial distribution of volcanism in the Aegean region is closely related to the boundaries of two small plates — the Aegean and Turkish plates — whose relative motion has recently been elucidated by earthquake fault plane solutions ([5]).

Volcanic centres are located most abundantly in the northeastern corner of the Aegean plate. In the southwest (fig. 1) an important feature is the chain of centres stretching from Krommyonia volcano, near Korinth, to the Bodrum peninsula of southwestern Turkey. This

Fig. 1 – Distribution of volcanic rocks of Tertiary and Quaternary age (solid black) within the Aegean region (after Paraskevopoulos, 1956).

chain of island volcanoes, usually termed the south Aegean volcanic arc [11] displays many of the features of typical island arc.

The lavas of the south western Aegean arc (Korinthos to Melos group) closely resemble those of Pacific Island arcs and continental margins in mineralogy and major element chemistry [10]. It is characterized by the development of hydrous minerals. In some circum-Pacific volcanic arcs, correlations have been made between the composition of lavas and the depth to the Benioff zone beneath the volcanoes.

Basaltic lavas are very rare among of the south western Aegean arc and Islands of Northeastern Aegean. Frequency of chemical

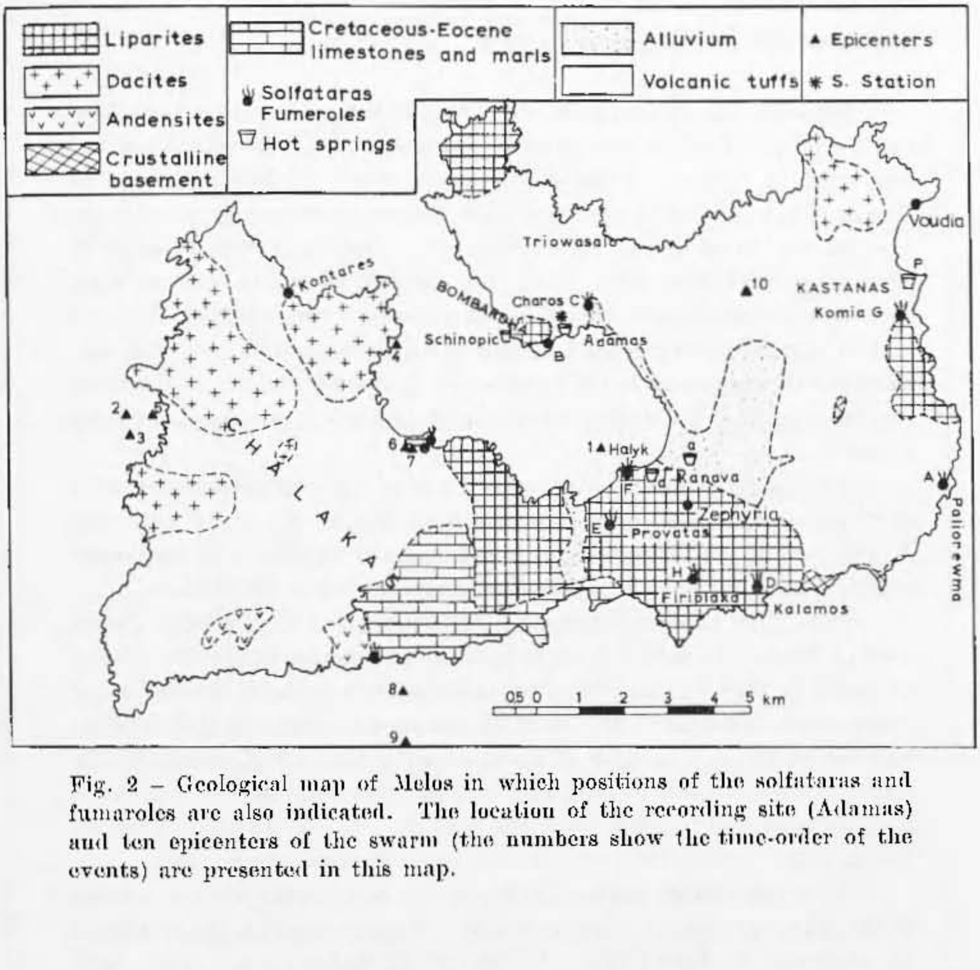

Fig. 2 – Geological map of Melos in which positions of the solfataras and fumaroles are also indicated. The location of the recording site (Adamas) and ten epicenters of the swarm (the numbers show the time-order of the events) are presented in this map.

analyses cited by Paraskevopoulos (1956), suggests that the most abundant rock types of both localities fall within the range andesite-dacite and this may indicate andesitic parent magmas for the two groups of volcanics.

A geological map of Melos is presented in fig. 2 in which positions of the solfataras and fumaroles are also indicated. The general picture of the volcanic activity is that solfataric and fumarolic activity is present at different places mostly in the eastern part of Melos. Solfataras and fumaroles with some temperatures escape, from many crevices and openings and muriated hot springs are found in some parts of the Melos (4).

3. – History of swarms in Greece

Although the general seismicity level in Greece is rather high, volcanic earthquakes are rare events. Also tectonic type swarms occur very rare in Greece. From a systematic study of 140 sequences in Greece, Drakopoulos (1) classified only 4 cases as swarm-type. In the 4 cases the *b*–value was higher than 1.2. Generally it is believed in agreement with new data, that the number of small scale swarms occurred in Greece-both tectonic and volcanic type-is higher, but the lack of portable seismographs was the main factor for not having detailed data. Of course earthquake sequences do not fall strictly in the three classes according to Mogi's classificarion but are gradational between them.

Minakami (6) describes several types of swarms associated with continental volcanoes: type *A* events with depths of 1 to 10 km; type *B* very small events with very shallow focal depths; and explosion earthquakes that have compressional first motion at all stations.

Since 1910 another interesting earthquake swarm has been generated in Melos. In table I, you can see the felt shocks during the swarm, in Melos in 1918 but according to information from local people, many other shocks were also felt. So if we compare the ratio of the recorded number to the felt number of shocks during the recent swarm to the larger number of felt shocks, higher intensities and larger duration of activity observed in 1918, we think that may be the number of microearthquakes during 1918 was of the order of some thousands.

Since the swarm during 1918 and the earthquake swarm studied in this paper probably occur on the ocean floor, none of the activity could be observed at first hand. Anyway it is rather certain that both swarms are of volcanic and not of tectonic feature.

4. – Instrumentation

The "Special Purpose Seismograph" Model 15015 is a short-Period, portable, self-contained, single-component seismograph suitable for survey or monitoring applications.

The size and weight of the system is such that it can be hand carried transported in the trunk of an automobile, or as baggage on a commercial airliner. The maximum magnification at 1 CPS is 10^6 and

Table I. – Felt Shocks during the swarm in 1918 (Melos)

Date	Time	Geogr. Coordin. N	E	Intens. I	Magn. M	Remarks
1918						
Mar. 20	21:18	36 3/4	24 1/2	IV-V		Felt in Plaka
» 20	21:26		»	IV-V		»
» 21	02:05		»	IV-V		»
» 21	06:12		»	IV-V		»
Juny 7	22:30		»	VI-VII		»
» 7	22:31		»	VI-VII		»
» 29	00:02		»	V		Many shocks from 00h till 03h
July 1	08:20		»	VI		Felt in Plaka
» 16	14:35		»	III		5 felt shocks
» 16	20:04	35.9	25.2	VI		Felt in Plaka, Heraklion, Hierapetra, Seriphos.
Sept. 11	20:27	36.7	24.1	VI	3.8	Felt in Plaka, Siphnos, Seriphos.
» 11	20:28		»	IV	4.6	Felt in Syra
» 11	21:03		»	VI	4.6	Felt in Melos, Siphnos, Seriphos.
» 11	21:13		»	V	3.9	Felt in Melos, Siphnos, Seriphos.
» 11	21:59		»	III	3.5	Felt in Plaka (Melos)
» 11	22:06		»	III	3.5	»
» 12	02:49		»	III	3.1	»
» 12	06:09		»	III	3.1	»
» 12	07:23		»	III	3.1	»
» 12	11:42		»	VI	4.8	»
» 12	15:59		»	III	3.5	»
» 12	17:55		»	III	4.2	»
» 29	00:40		»	IV	4.6	Ios, Melos
» 30	03:30		»	III	3.9	Melos
» 30	04:33		»	III	3.6	»
1918						
Sept. 30	04:34		»	III	4.5	Melos
» 30	07:25		»	III	3.9	»
» 30	07:28	36.7	24.1	IV		Melos
		35.0	24.0(ISS)	V-VI	5.2	Melos
			»	IV		Seriphos, Siphnos
			»	III		Naxos, Syra
			»	II-III		Kythera
Sept. 30	08:20		»	III		Melos
» 30	08:27		»	III	3.5	»
» 30	09:12		»	III		»
» 30	09:32		»	III		»
» 30	09:35		»	III		»
» 30	09:44		»	IV	4.3	Melos
» 30	10:54		»	III	3.2	»
» 30	16:26		»	III	3.2	»
Oct. 2	07:27		»		4.4	»
» 2	11:03		»	III	3.5	»
» 10	22:13		»	III		»
» 11	00:02		»	IV	3.3	Seriphos
» 18	20:30		»	IV		Siphnos
Dec. 13	21:04		»	IV	3.4	Seriphos
			»	III		Melos.

the frequency response is 0.01 to 15 CPS (depends on seismometer and filter). The recording time is 12 hours. During the time of recording microearthquakes in Melos the drum speed was 5 minutes per revolution and the speed on records was 90 mm/min.

The portable short-period seismometer, model 18300 has been designed for use in field operations where a small light-weight, short-period seismometer is desired. The seismometer during the field work in Melos was operated in vertical position but it may be also operated in horizontal position. Its period is adjustable from 1.33 ro 0.91 second (0.75 to 1.1 CPS). This seismometer is a very stable instrument. When properly installed it may be expected to operate without further adjustment.

The solid-state Amplifier model 25220 consists of three basic parts: a broad band (dc to 20 KHZ) low-noise preamplifier with a fixed gain of 325, an operational amplifier to further increase the gain of the overall amplifier in addition to shaping the frequency response curve, and dc–to–dc converter to permit isolation of input, output and power grounds.

In addition to greater sensitivity, microearthquake recording systems are more portable and need far less power than standard field instruments. The resulting freedom in site selection was used in Melos to reduce epicentral distances to a few kilometers or less which is a significant advantage in locating shocks and in studying the statistical properties of the activity.

5. – Data.

The first step in analysis of the records by portable seismograph was the elimination from consideration of some intervals of time when the noise level was high.

This study emphasized shocks with S—P intervals less than about 1.7 seconds corresponding to hypocentral distances less than 10 km. In most cases the distances were much less. Thus with only a single vertical-component seismograph, it is possible to study microseismicity on a scale of a few kms. Of course there are improved methods for location based on networks, arrays, multicomponent seismographs, and on various data-processing techniques; but the advandages of these must be weighed against the extreme simplicity of the single-component technique which reduces analysis to mere counting of events with small

Table II. – FELT SHOCKS IN ADAMAS OF MELOS DURING THE RECENT SWARM (AUG. 1971)

Date	Time	Date	Time	Date	Time
1971		1971		1971	
Aug 26	21:20	Aug 28	02:25	Aug 29	01:15
Aug 27	00:30	»	02:45	»	04:28
»	02:30	»	02:50	»	04:53
»	02:55	»	03:00	»	07:02
»	06:05	»	03:20	»	07:13
»	08:10	»	04:00	»	07:15
»	09:50	»	05:07	»	09:42
»	10:00	»	05:53	»	09:45
»	10:45	»	06:40	»	09:47
»	10:50	»	06:50	»	09:58
»	11:00	»	06:59	»	10:28
»	12:05	»	07:13	»	10:37
»	14:00	»	07:15	»	11:56
»	17:00	»	09:45	»	11:57
»	17:25	»	09:46	1971	
»	17:45	»	09:47	Aug 30	05:45
»	21:40	»	09:58	»	06:18
»	21:47	»	11:56	»	06:37
»	22:45	»	11:57	»	07:30
»	22:46	»	16:15	»	07:32
1971		»	20:21	»	07:40
Aug 28	00:20	»	22:20	»	07:43
»	00:21	»	22:29	»	07:44
»	00:25	»	23:15	»	07:46
»	00:37	»	23:23	»	07:56
»	00:38	»	23:24	1971	
»	00:47	1971		Aug 31	11:20
»	02:05	Aug 29	00:20	»	11:34
»	02:20	»	00:26	»	11:36
»	02:21	»	01:06	»	11:37
				»	11:38
				»	12:30

S—P intervals and provides immediate results for planning the subsequent field program.

The instrument was not operated at full gain (db) on account of noise level. The station fall geographically (36°44′44″ N, 24°26′38″ E) near the center of the epicenters (Fig. 2). This site was chosen for a variety of reasons including proximity to fault traces, to the large number of previously felt earthquakes, accessibility etc. A wide variety of some noise sources was encountered.

Complexity of geological condition in Melos and the looseness of superficial layers affect very much the serious decay of high frequency

Table III. – Shocks recorded by VAM station with P–to–P amplitude $a > 2.5$

Date	Time	M_L	Date	Time	M_L
1971 Aug. 26	20:49	2.0	1971 Aug. 28	02:27	2.1
»	21:41	2.1	»	02:47	2.9
»	22:55	2.1	»	03:19	2.3
»	23:03	2.0	»	05:08	2.0
»	23:09	2.0	»	05:53	2.4
»	23:10	2.0	»	05:56	2.2
»	23:12	2.2	»	06:40	2.0
»	23:24	2.0	»	06:41	2.2
»	23:46	2.0	»	06:53	2.2
»	23:55	2.2	»	07:00	2.1
1971 Aug. 27	01:45	2.0	»	13:15	2.0
»	01:51	2.5	»	16:44	2.3
»	02:17	2.0	»	22:22	3.1
»	02:18	2.6	»	22:29	2.5
»	02:19	2.9	»	23:15	3.0
»	02:30	2.1	»	23:23	2.9
»	02:36	2.0	»	23:27	2.0
»	03:05	2.5	»	23:28	2.2
»	03:10	2.2	»	23:29	2.0
»	03:13	2.4	1971 Aug. 29	00:35	2.1
»	03:16	2.3	»	01:08	2.4
»	03:19	2.4	»	01:16	2.6
»	03:25	2.9	»	01:18	2.3
»	03:36	2.1	»	02:25	2.0
»	03:46	2.1	»	03:13	2.4
»	03:48	2.0	»	04:54	3.2
»	03:52	2.9	»	05:03	2.7
»	04:29	2.2	»	07:15	2.1
»	04:44	2.7	»	09:45	3.2
»	06:08	2.5	»	09:46	2.7
»	12:06	2.0	»	10:38	2.1
»	16:59	2.1	1971		
»	21:40	2.1	Aug. 30	05:59	2.5
»	22:44	2.4	»	07:34	2.3
1971 Aug. 28	00:20	2.0	»	20:06	3.2
»	00:24	2.1	»	20:07	2.4
»	00:37	2.3	1971		
»	02:19	2.8	Aug. 31	02:24	2.3
			»	14:31	2.2
			»	17:29	2.0

waves. The seismic frequency of these earthquakes depends also on the nature of geological formations on which the seismometrical observations were placed.

A series of about 1000 earthquakes were recorded by the portable seismograph in which felt quakes also were included, some of them being accompanied with rumblings. The earthquake swarm lasted for five days and the daily seismic frequency of felt earthquakes in Adamas during the five days was 17, 31, 22, 10 and 6, respectively (table II).

The main portion of events was also felt in Zephyria, Thiorychia, Kalamos, Voudia, Apollonia etc. (Map. fig. 2).

The hourly count of microshocks after the installation of the portable seismograph is shown in fig. 3. As it is obvious from this figure the rate of the activity change from 0 to 89 events per hour. Some of the events in the sharp peaks of August 28 and 29 were probably aftershocks of two main shocks which occurred at 22 h: 22 min. and 04h: 54 min. and they had magnitudes 3.1 and 3.2 correspodingly. This is supported from the exponentially decaying (fig. 3) plus some detailed activity plots.

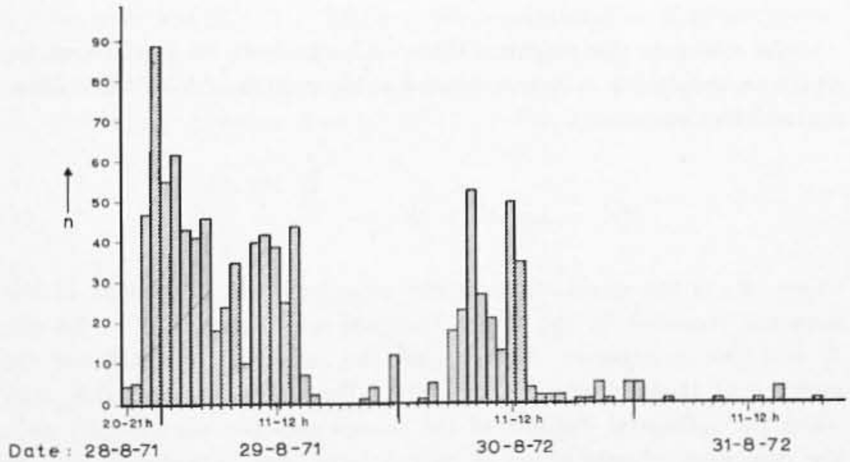

Fig. 3 – Time distribution of microaftershock activity during the last 3 days.

It was evident from the seismograms that the small hypocentral depths harmonize well with the remarkable attenuation of amplitude according to the epicentral distance. The apparent feature of the larger earthquakes on the seismogram of VAM do not differ from those of the tectonic origin of extremely shallow depth recorded from the same epicentral distance.

Except of 76 events with P—P amplitude in the vertical component of VAM station larger than or equal to 2.5 mm there were nearly 17 events with P—P amplitudes in VAM between 1.5 and 2.4 but we didn't use these to the b–value determination because there were doubts abour their epicentral distances.

The procedure of the epicenter determination for the largest 10 events was workable using some stations from the network of Greece.

One important advantage of the epicenters calculated in this study is that all events are very close to the mobile station and all events were very shallow. Thus although any one epicenter may be in a small error for a variety of reasons (poor station distribution etc.) the small pattern developed by the whole swarm is tectonically significant, mainly because all the events occurred within a distance of 10 km from the mobile station.

6. – Magnitude determination

To calculate the magnitude M'_L of each shock of the swarm for which an amplitude A' was measured at the station of VAM the following relation was used:

$$M_L' = \log A' + \overline{M}_L - \frac{\sum_{i=1}^{n} \log Ai}{n} \qquad [1]$$

where $\overline{M}_L$ is the mean value of the magnitudes of all shocks of the sequence recorded by the Wood-Anderson seismograph ($T = 0.8$ sec, $V = 2{,}800$) in Athens. Ai and n are the amplitude at VAM and the number of these shocks respectively. This method is reliable only when the epicentral distance of the shocks does not vary largely as is the case here. Some errors of course have been introduced but the general conclusions of the present study are not affected largely. Finally we have found the equation:

$$M_L = 1.57 + \log A' \qquad [2]$$

where A' is the double amplitude as measured on the vertical component of VAM seismograph (Sprengnether type $V = 44{,}000$ $T = 0.5$ sec.).

We were sure about the epicentral distances only for shocks with P—P amplitudes from VAM $A \geq 2.5$ (76 events). So we calculated magnitudes only for these events by using the formula [2] (see table III).

Under these limitations the smallest magnitude used for b-value determination was $M_L = 2.0$ (see also about b–value).

The computation of magnitude from records of the portable seismograph is quite impossible due to its dependence upon an amplitude versus distance relation, the difficulties of instrument calibration, the effect of the frequency response of the instruments used here, the use of a vertical component instrument only etc.

7. – b-VALUE

The slope, or b–value, of the frequency-magnitude relationship:

$$\log N = A - bM \qquad [3]$$

where A and b are constants was determined. The uncertainty in this determination was around two tenths (0.2), since the number of earthquakes used was only 76. The b–value as calculated by the least square method using only the larger 76 events was 1.22 (fig. 4) which is intermediate between that of tectonic earthquakes (b = 0.6 to 1.0) and that of volcanic earthquakes (b = 1.8 to 2.6). This b–value plus the nature

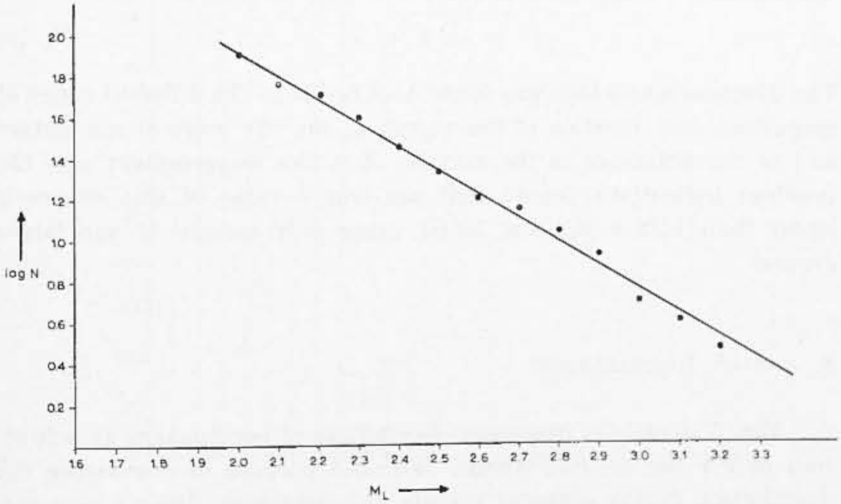

Fig. 4 – Cumulative frequency function of the magnitude during the activity of the swarm.

of the earthquakes observed imply a mixture of tectonic and volcanic shocks in a highly heterogeneous structure with locally concentrated stresses. This value is higher, but not necessarily significantly higher, than typical b–values for earthquakes and for aftershocks in many areas of the world.

Suzuki (14) showed that the b–value is independent of the source–receiver distance provided the attenuation function does not depend on magnitude. As a result the b– value can be calculated without knowing the magnitude of the events.

Using recordings of 10 hours from the portable seismograph the frequency versus amplitude relation was studied although this procedure in its application was difficult. A log–log plot of frequency versus amplitude approaches a straight line with an m value of 2.4 ($b = 1.4$)

$$\log N = a - m \log A \qquad [4]$$

Where N is the number of earthquakes with trace amplitude between A and $A + dA$.

The previous procedure may introduce a bias toward a lower b–value. Immediately following the large shocks the probable aftershock activity may saturate the seismogram, making a complete count of the smaller aftershocks impossible. An underestimate of the number of smaller events will bias the b toward a lower value. When we estimate m and b from the same sample of data it must be valid:

$$m = b + 1 \qquad [5]$$

The disagreement which was found here is due to the different range of magnitude and duration of the sample in the two ways of calculation and to the difference in the sample. But this disagreement plus the previous indications denote that the true b–value of this swarm is larger than 1.22 which was found using only sample of the larger events.

8. – S—P Distribution

Fig. 5 shows the frequency distribution of earthquakes as a function of 0.1 sec S—P intervals. For the purpose of comparing the distribution during different periods, the data were divided into successive not equal samples and the S—P interval versus frequency relations for four different periods are illustrated (fig. 6). Only the events with trace amplitudes of 2 mm or larger were selected and counted in order to eliminate the influence of the fluctuation in noise level. From figures 5 and 6 we observe that the $S - P$ interval fluctuates between 0.3 to 1.7 sec. That means that the focal depth of all the earthquakes is less than 5 km. It is also concluded that the epicentral distances were smaller than 10 km. Main maximum in frequency

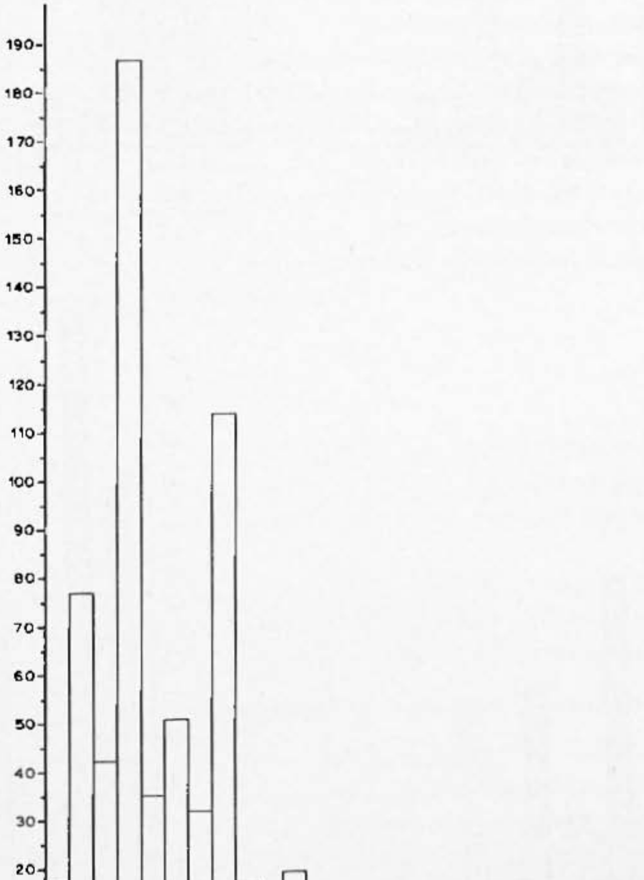

Fig. 5 – Distribution of observed $S - P$ times during all the period of operation of the portable seismograph.

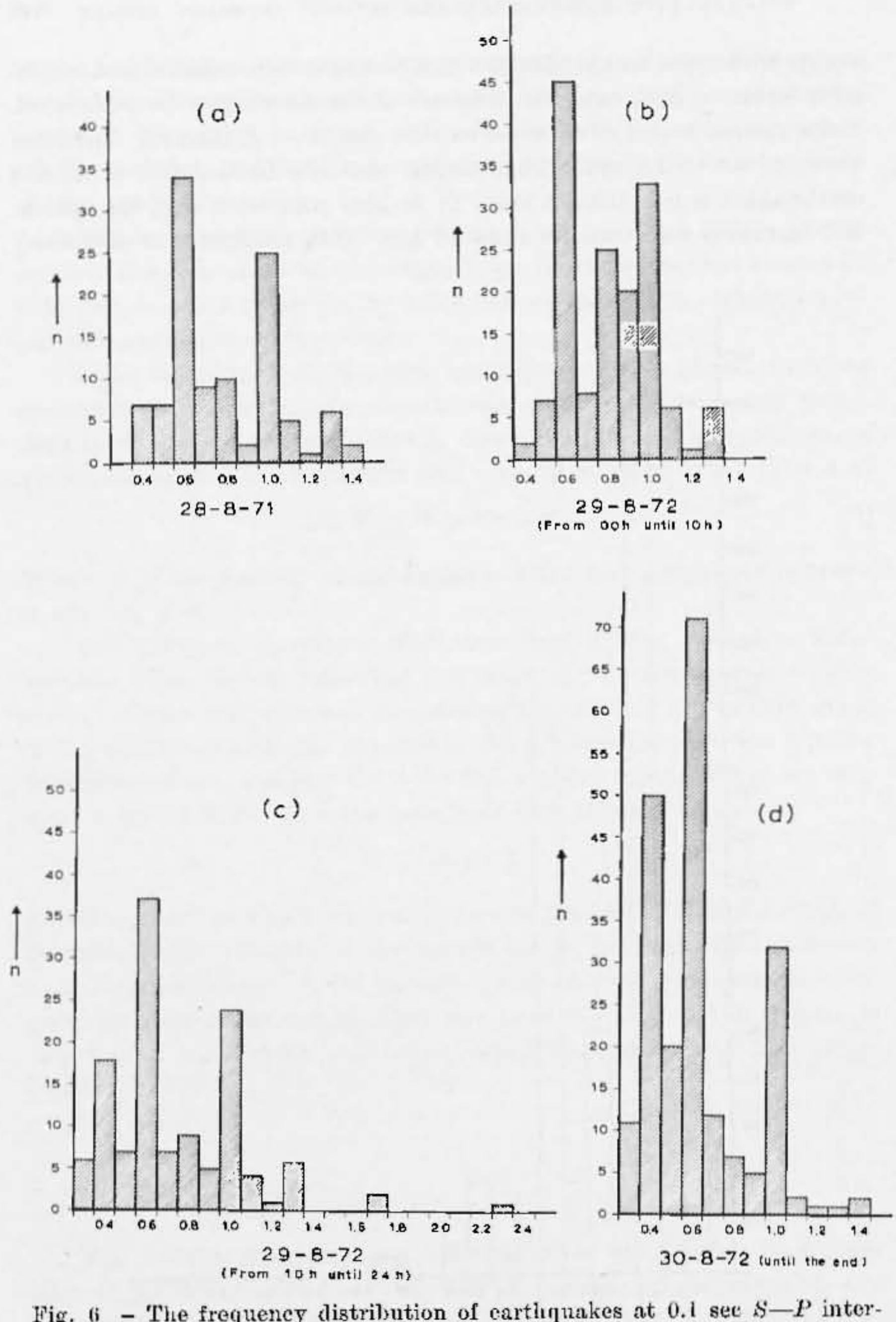

Fig. 6 – The frequency distribution of earthquakes at 0.1 sec $S—P$ interval. The data are divided into 4 successive (but not equal) periods from (a) through (d). Individual groups of data indicate that the observed earthquake activity is localized in time and space.

occur at S—P interval of 0.6 sec in all cases. Other secondary maximum occurs at 1.0 sec.

There is not any substantial systematic difference in the different time-intervals such as to conclude any migration of the epicenters from the seismograph either in the vertical or in the horizontal direction. We can just say that a larger percentage of the shocks during the last day of the observation were in nearest distances to the station. The strong peaks at 0.6 and 1.0 sec indicate systematic short-term increases in seismicity in limited small areas. It is also concluded that several peaks in activity are clear and are limited to certain small areas. The peaked nature of the S—P distribution can be easily explained by the existence of a non–uniform distribution of activity within the zone.

As the S—P interval increases the number of recorded events falls off sharply as the ground amplitude and hence detectability, decreases with distance from the source. In fact, the distribution follows the amplitude versus distance relation given by Richter in his definition of local earthquake magnitude.

9. – Discussion

All the earthquakes of the table III recorded in VAM are between 26 Aug. and 31 of Aug. (duration of 5 days). By examining the seismograms of VAM before and after these dates we didn't find any earthquakes from this region.

Records by the portable seismograph started at 18h of 28 of Aug. and the seismograph was operated continuously up to the evening of 31 of Aug. (duration of its operation 74 hours). The average rate during the recording period by the portable seismograph is $\frac{960}{74} = 13$ shocks/hour while the maximum rate was 89 shocks/hour (fig. 3). So if we adopt that the activity of the swarm was at the same level during the 26,27 and 28 of Aug., we may conclude that in 5 days occured nearly 1,800 volcanic micro and ultramicroearthquakes in Melos.

If we consider that the rate of the shocks recorded by the portable seismograph to shocks recorded by VAM station is approximately constant, that means that shocks of different magnitude are randomly distributed in time, we may write,

$$\frac{P_{tot}}{V_{tot}} = \frac{P_{att}}{V_{att}} \qquad [6]$$

Where

P_{tot} = total number of shocks recorded by port. seismograph

V_{tot} = total number of shocks recorded by VAM station

P_{aft} = total number of shocks recorded by port. seism. after its installation.

V_{aft} = total number of shocks recorded by VAM after the inst. of port. seismograph.

From the formula [6] we have

$$P_{tot} = \frac{P_{aft}}{V_{aft}} V_{tot} = \frac{960}{25} \times 75 = 2880$$

V_{aft} is seen from fig. 7.

So by this method we may conclude that nearly 3,000 volcanic micro and ultramicroearthquakes occurred in Melos from 26 up to 31 of Aug. 1971 and this seems to be more probable. If we adopt this number (3,000) and we take into consideration that we may extrapolate the relation,

$$\log N = 4.22 - 1.22 \, M_L \qquad [7]$$

to very small magnitudes, we may find the minimum magnitude detected by the portable seismograph under the conditions of its operation in Melos. It was found $M_{L\min} = 0.4$.

If the above number of the occurred shocks is correct, the mean rate of occurrence per hour was 25 events and so by comparison to the mean rate of 13 events/hour valid for the 3 last days of activity, we think that during the first 2 days the frequency of shocks was much higher. This conclusion is also supported from the table of felt earthquakes and from the recorded events in VAM (fig. 7).

One significant observation made in this figure is that all the four events with $M_L \geqslant 3.0$ of this activity occurred after the installation of the portable seismograph e.g. in the second half of the activity. From the same figure we can see that the maximum magnitude observed per 6 hours is larger generally during the second half of the activity. Taking into consideration the above observations, we may concluded that the value of b doesn't remain constant with time as it has been concluded for aftershock sequences (2).

It is believed that if it was possible to calculate b–values by using all the data, the b–value should be 0.2–0.3 higher than the reported 1.22 here as it was found previously by using records from the portable seismograph.

A first interpretation of the intermediate *b*–value for this swarm is that a mixture of tectonic events and *B*–type volcanic earthquakes have been recorded. Further consideration suggests the existence of a locally concentrated stress distribution that may be caused both by the heterogeneity of the materials near the volcanic range and by a

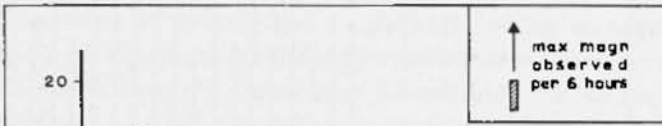

Fig. 7 – Histogram showing the number of recorded events per 6 hours in VAM and the maximum magnitude observed per 6 hours.

stress concentration as a result of movement of magma. Mogi (7) in his model experiments pointed out that the *b*–value of the elastic shocks generated in very porous and extremely heterogeneous pumise is clearly larger (1.2 to 1.7) than the *b*–value for shocks in granite and andesite specimens (0.6 to 1.0).

To investigate the question of the existence of secondary aftershock series, the observed seismic activity was examined in time intervals of 10 minutes. One representative section of a record written on August

29 converted to activity plot in fig. 8. By such representative figures we saw that in some cases it was clear that the general level of microaftershock activity is not significantly influenced by the occurrence

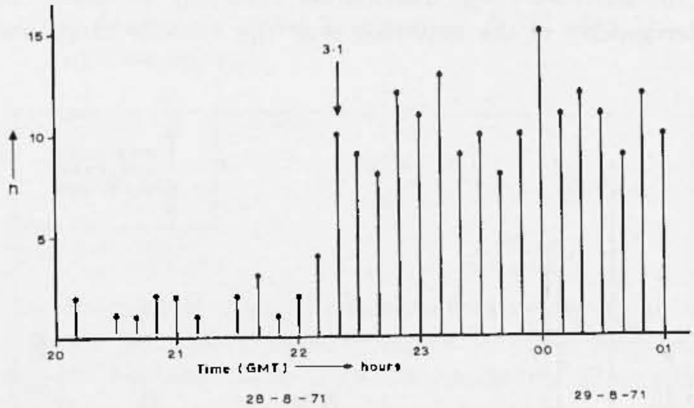

Fig. 8 - Detailed activity plot as a function of time.

of $M_L \geq 3.0$ shocks. But in most cases (example fig. 8) the microaftershocks cluster in time about the larger shocks and give strong evidence of triggering small aftershock sequences. In conclusion we can say that of 4 shocks with M_L greater than or equal to 3.0, 3 events gave strong evidence of triggering a secondary aftershock sequence.

The initial motions of the explosion earthquakes are usually clearly recorded on the seismograms and their directions are push and "upward" motions without exception in all directions from the source [6]. On account of the loose material and other reasons, the noise level in Melos was generally very high and prevented us from having extremely high magnification. Therefore we had not precise knowledge about the distribution of the initial motion of small earthquakes although the epicentral distances were very small, in other words, the initial motions of small earthquakes were in most cases disturbed by around noise. The direction of the initial motion was not stable in Melos during the time of occurrence of the shocks. In other words in the portable seismograph the up and down initial motions are distributed not systematically.

10. – Conclusions and synopsis

Swarm-type sequences occur very rare in Greece and this circumstance plus the postulated fact that the microearthquake activity is a valuable tool in comparing the seismicity of many volcanic regions, drew our attention for this investigation. The present study increases the number of regions for which earthquake swarms are associated with areas of historic or recent volcanism.

The activity of Melos (Greece) although belong to a small scale earthquake swarm, manifested for five days with a sequence of extremely shallow microearthquakes, may be attributed to magmatic activity that failed to reach the surface or more probably to nonmagmatic mechanism for producing concentrations or inhomogeneities in stress.

Since from S—P graphs it was concluded that the hypocenters are extremely shallow and concentrate in limited areas, it is natural that the amplitudes of events attenuate remarkably according to the epicentral distance as it is clear in the seismograms.

Magnitude determination was possible only for the 76 larger events. There are strong indications that the real b–value of this swarm was higher than 1.22 (value calculated from a limited sample of larger events). So the true b–value plus the nature of the earthquakes imply a mixture of tectonic and volcanic shocks in a highly heterogeneous structure with locally concentrated stresses.

Up and down initial motions are distributed randomly.

The average rate per hour of events detected by the portable seismograph was 13, while the maximum observed rate was 89 events/hour. Under simple natural assumptions, it was found that the minimum magnitude detected by the portable seismograph was $M_L = 0.4$ and the average rate per hour in the whole duration of activity was approximately 25.

It is also concluded that during the first 3 days the frequency of microshocks was much higher than the frequency during the second half of activity but all the events with $M_L \geqslant 3.0$ occurred during the second half of the activity and so we may conclude that the value of b doesn't remain constant with time.

The microaftershocks sometimes clustered but in other cases didn't cluster in time about the larger events. It was impossible by the present investigation to propose or to support strongly some hypotheses of swarm generation.

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