ΣΕΙΣΜΟΛΟΓΙΑ. — **Abnormal Nucleation of Subcrustal Events in the Vicinity of Cos Island**, by Academician *A. G. Galanopoulos**.

ABSTRACT

The present paper aims to address the abnormal clustering of subcrustal events with focal depths 100 km and over in the vicinity of the volcanic islands Aegina and in particular Cos, in the northwestern and southwestern cups of the Hellenic volcanic arc.

The earthquake recurrence behavior in the most energetic mantle source of Cos is very well reproduced by Galanopoulos' earthquake recurrence models: $Log(Nc)=a-bt$ and $Log\ (Nc)=k(t+c)^{-p}$.

As a rule, the return period range for a given magnitude and over consists of several seismic cycles or classes of actual repeat times. In each seismic cycle, large events of any possible magnitude may occur. There is no tendency for association of larger events with higher classes of repeat times.

INTRODUCTION

The major area of southern Greece (34° N39°, 20°E29°) is admittedly a subduction area associated with the Hellenic trench. The present paper aims to address the problem of clustering of subcrustal events with focal depths 100 km and over in the vicinity of the volcanic islands Aegina and in particular Cos, in the northwestern and southeastern cups of the Hellenic volcanic arc.

There is no satisfactory explanation of the abnormally high activity of subcrustal origin in the northwestern and southeastern cups of the tertiary volcanic arc (Galanopoulos, 1975). A counterclockwise rotation of the underthrusting African plate (Le Pichon and Angelier, 1979), with the pole of rotation in the Adriatic Sea (40°N, 20°E), may account for the striking nucleation of subcrustal shocks in the neighbourghood of Cos (Galanopoulos and Delibasis, 1983).

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* Α. Γ. ΓΑΛΑΝΟΠΟΥΛΟΥ, **Ἑστίαση μεγάλου πλήθους σεισμῶν ἐνδιαμέσου βάθους στὴν περιοχὴ τῆς νήσου Κῶ.**

DATA USED

The data used for the present paper cover the period 1971-1985. During the study period the configuration of stations in Greece remained stationary and the type of recording devices did not change. In addition, since 1971 the seismic entries in the regional catalogues of the International Seismological Centre (ISC) are adequately homogeneous. All location data and focal depths were taken from the ISC-catalogues.

Surface wave magnitudes were derived from a calibration formula using the number of reporting stations and the distance out to which the related shocks were registered (Galanopoulos and Makropoulos, 1981). The 4 1/2 M_s was adopted as threshold magnitude (Suzuki and Ito, 1980). The seismic energy was calculated by the Gutenberg-Richter's formula (1956):

$$\text{Log } E = 11.8 + 1.5\ M_s.$$

TABLE 1

Subcrustal events ($h \geq 100$km) of magnitude ≥ 4.5 in the major area of southern Greece (34°N39° 20°E29°), 1971-1985

No	Date	Lat. °N	Long. °E	Depth km	Ms	Interevent Time (Days)	
1	1971, Jan. 16	36.6	26.9	157*	5	-	-
2	1971, March 18	36.3	27.0	141*	5 1/4	61	61
3	1971, May 15	35.8	28.3	113	4 1/2	58	-
4	1971, Aug. 11	36.8	24.0	109+	5 3/4	88	-
5	1972, March 16	37.9	23.4	142+	5	217	-
6	1972, Sept. 18	36.0	24.6	103+	4 3/4	186	-
7	1972, Sept. 25	36.5	26.8	163*	5	7	556
8	1972, Dec. 6	37.7	23.9	158+	5	72	-
9	1973, Sept. 12	36 6	27.0	157*	5	280	352
10	1974, April 8	36.6	27.1	149*	5 3/4	146	146
11	1974, May 12	36.7	26.9	149*	5 1/2	96	96
12	1975, Sept. 23	36.6	26.8	156*	5 1/4	499	499
13	1976, Aug. 2	35.6	25.9	117	5 1/4	314	-
14	1976, Aug. 17	36.7	27.1	160*	6	15	329
15	1976, Aug. 18	36.7	27.4	157*	4 1/2	1	1
16	1976, Sept. 18	36.6	27.0	154*	4 1/2	25	25

TABLE 1 (cont.)

No	Date			Lat. °N	Long. °E	Depth km	M_s	Interevent Time (Days)	
17	1976,	Sept.	24	36.1	26.8	159*	4 1/2	12	12
18	1977,	July	12	36.6	27.0	157*	4 3/4	291	291
19	1977,	July	27	36.1	24.8	115+	5	15	-
20	1978,	Oct.	31	36.2	27.0	149*	4 1/2	461	476
21	1978,	Nov.	28	36.0	26.4	114*	5 3/4	28	28
22	1979,	March	11	37.6	23.4	156+	5	103	-
23	1979,	Aug.	26	39.1	22.1	103	4 1/2	168	-
24	1979,	Oct.	21	38.1	23.0	123	4 1/2	56	-
25	1979,	Nov.	2	36.6	25.4	158	4 3/4	12	-
26	1980,	April	28	37.2	24.2	159+	5	178	-
27	1980,	June	11	36.1	27 8	108*	4 1/2	561	561
28	1981,	May	8	35.8	27 2	110	5 3/4	375	-
29	1981,	May	20	36 2	22 6	109	5 1/2	12	-
30	1981,	Nov.	16	36.6	26 8	161*	5 1/4	180	523
31	1982,	Jan.	24	36 6	27.5	146*	4 1/2	69	69
32	1982,	April	18	36.6	27.1	155*	5 3/4	84	84
33	1982,	May	9	35.9	26.3	133	4 3/4	21	-
34	1982,	July	26	36.9	23.7	106+	5	78	-
35	1982,	Nov.	28	36.4	26.2	140*	5 1/2	125	224
36	1983,	Febr.	28	36.3	27.7	107*	4 1/2	92	92
37	1983,	April	23	36 2	26 4	136*	4 3/4	54	54
38	1983,	Sept.	27	36.7	26 9	160*	6 1/2	157	157
39	1983,	Oct	7	38.0	23.3	136+	5 1/4	10	-
40	1983,	Oct.	31	38.1	22.9	120	4 3/4	24	-
41	1984,	Febr.	28	36.2	25.6	158	5 1/2	120	-
42	1984,	June	20	36.7	27.0	166*	5 1/4	113	267
43	1984,	Sept.	23	36.5	26.5	155*	5 1/4	95	95
44	1984,	Oct.	10	36.8	23.5	103+	5 3/4	17	-
45	1984,	Nov.	20	35.6	26.5	120	4 1/2	41	-
46	1984,	Dec.	16	37.1	24.1	138+	5	26	-
47	1984,	Dec.	16	36.3	26.8	147*	4 1/2	0	84
48	1985,	Febr.	3	37.8	23.8	195+	4 1/2	49	-
49	1985,	Febr.	6	36.6	27.7	128*	5 1/2	14	63
50	1985,	Febr.	25	36.4	26.7	157*	5	8	8
51	1985,	April	23	36.3	26.9	137*	4 1/2	57	57
52	1985,	July	14	35.9	26.2	106	5 1/2	82	-
53	1985,	Dec.	3	36.6	26.9	156*	5 1/2	142	224

Shocks from the Methana and Cos sources are denoted in the focal depth by + and *, respectively.

RESULTS AND REMARKS

In the regional catalogues of the International Seismological Centre there are 122 entries of subcrustal events with focal depths 100km and over and $m_b \geq 3$. Of these events 22 are located in the vicinity of Aegina (36°N38°, 23°E25°) and 57 in the vicinity of Cos (36°N37°, 26°E28°). This indicates that ca 65% of the reported subcrustal events that occurred in the major area of Greece stem from the seismic pockets of Aegina and in particular Cos (s. Fig. 1).

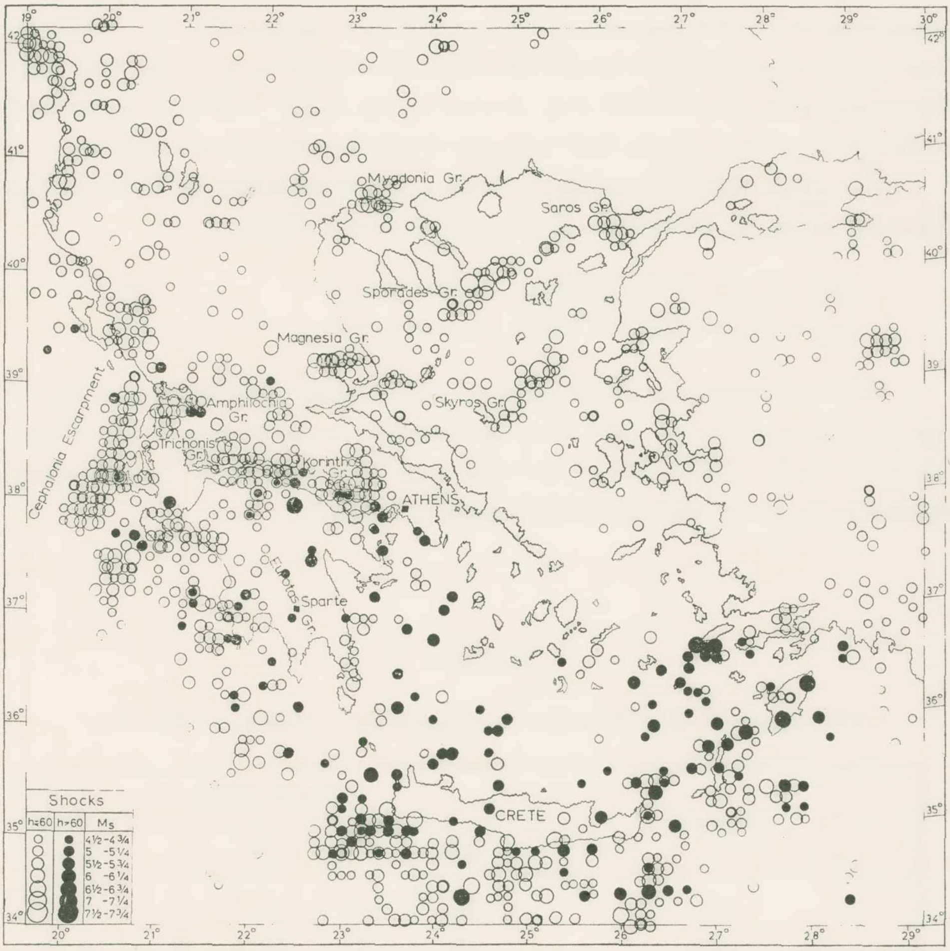

Fig. 1. Distribution pattern of shallow and intermediate focal depth earthquakes with $M_s \geq 4.5$ in the major area of Greece during the period 1971-1985.

The paramount production of the seismic source of Cos is better asserted by the entries of Table 1. Table 1 presents only the subcrustal events of magnitude 4 1/2 and over. The subcrustal events of the whole area considered amount to 53; of these events 12 (23%) stem from the Methana pocket and 29 (55%) from that of Cos.

The sum of the energy released in the 53 events amounts to 71.474×10^{20} ergs; of this amount 7.413×10^{20} (10%) come from the Aegina source and 58.692×10^{20} (82%) from that of Cos.

The focal depths of the mantle shocks of Aegina range from 103 to 195km (on the average 135km). The focal depths of the mantle shocks of Cos range from 107 to 166 km (on the average 148 km). Apparently, the maximum focal depth of the Aegina mantle shocks (195 km), in comparison with that observed in the Cos area (166 km), is due to the larger width of the related contact zone of the oceanic slab with the overriding Aegean microplate.

The magnitude data listed in Table 1 are summarized in Table 2. The following equations fit fairly well the related data of Table 2.

$$\text{Log } (N_c) = 5.9157 - 0.8979 M_s, \quad \text{S.D.} = \pm 0.14 \qquad (1)$$

$$\text{Log } ({}^*N_c) = 5.0602 - 0.7756 M_s, \quad \text{S.D.} = \pm 0.12 \qquad (2)$$

Table 3 shows the distribution of earthquake occurrences per actual repeat time expressed as unit time the average interoccurrence time (Galanopoulos, 1987, 1988a, 1988b), m=103 and *m=189 days. The following equations fit pretty well the related data of Table 3.

TABLE 2

Frequency of Earthquakes in Magnitude Increments M_s=0.5

Frequency	Magnitude M_s				
	4.5	5	5.5	6	6.5
N	20	18	13	1	1
Nc	53	33	15	2	1
*N	11	9	7	1	1
*Nc	29	18	9	2	1

TABLE 3

Distribution of Earthquake Occurrences per Actual Repeat Time Expressed as Unit Time the Average Interoccurrence Time, m=103 and *m=189 Days

Frequency	Repeat Times, t					
	1	2	3	4	5	6
N	34	10	3	2	2	1
N_c	52	18	8	5	5	1
*N	17	6	5	-	-	-
*N_c	28	11	5	-	-	-

$$\text{Log } (N_c)=1.953\text{-}0.3176t, \quad S.D.=\pm 0.0836 \qquad (3a)$$

or $$\text{Log } (N_c)=3.432(t+1)^{-1}, \quad S.D.=\pm 0.0767 \text{ for } t < 6 \qquad (3b)$$

And

$$\text{Log } (^*N_c)=1.850\text{-}0.389t, \quad S.D.=\pm 0.027 \qquad (4a)$$

or $$\text{Log } (^*N_c)=2.954(t+1)^{-1}, \quad S.D.=\pm 0.049 \qquad (4b)$$

The equations (3a) and 4a) give us accurately the return period range of the mantle shocks with $M_s \geq 4.5$, and reproduce satisfactorily the earthquake recurrence behavior observed during the period 1971-1985 in the major area of southern Greece and the very energetic source of Cos, respectively.

TABLE 4

Distribution of Percentage of Earthquake Occurrences in Terms of Actual Interoccurrence Time t,

Percentaqe	Repeat Times, t						
	1	2	3	4	5	6	Total
N	65	19	6	4	4	2	100
*N	61	21	18	-	-	-	100

According to equation (1), to an average recurrence time of 15 years corresponds one $6.59M_s$ event. This event may occur within a time span of about 92(=6.149 ×15) years since 1971. If the equation (3a) holds for longer periods of observation, to an average recurrence interval of 6.149 ×15 years corresponds, under the same assumption for the equation (1), one 7.47M_s event. This event may occur between 92 or less and 566 years [=(1.953:O.3176) ×92]

With the same reasoning, from the equations(2) and (4a), that hold for the very energetic source of Cos, we may expect one 6.52M_s event within a time span of about 71(=4.756 ×15) years since 1971. Under the same assumptions for the equations (2) and (4a), to an average recurrence interval of 4.756 ×15 years corresponds one 7.40Ms event. This event may occur between 71 or less and 338 years [=1.850:0.389) ×71].

It is worth noting the similarity of the results derived for the whole area and the seismic pocket of Cos. This may indicate that the expected 7.5M_s earthquake will occur most probably in the neighborhood of Cos (36°N37°, 26°E28°). There is, then, a 61% probability the expected 7.5M_s earthquake of intermediate focal depth to occur within a time span of 71 year since 1971.

As a rule, the return period range for a given magnitude and over consists of several seismic cycles or clases of actual repeat times. In each seismic cycle, large events of any possible magnitude may occur. There is no tendency for association of larger events with higher classes of repeat times. The rule holds for mantle shocks as well as for crustal shocks.

A C K N O W L E D G M E N T

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ΠΕΡΙΛΗΨΗ

Ἑστίαση μεγάλου πλήθους σεισμῶν ἐνδιαμέσου βάθους στὴν περιοχὴ τῆς νήσου Κῶ

Εἶναι σήμερα γενικῶς ἀποδεκτὸ ὅτι ἡ εὐρύτερη περιοχὴ τῆς νότιας Ἑλλάδας (34°N39°, 20°E29°) εἶναι περιοχὴ συγκλίσεως τῶν πλακῶν Εὐρασίας καὶ Ἀφρικῆς κατὰ μῆκος τῆς Ἑλληνικῆς τάφρου. Ἡ περιοχὴ αὐτὴ χαρακτηρίζεται ἀπὸ ἔντονη σεισμικὴ δράση, τόσο ἐπιφανειακή, ὅσο καὶ ἐνδιαμέσου βάθους.

Δὲν ὑπάρχει ἱκανοποιητικὴ ἐξήγηση γιὰ τὴν ἀνώμαλη ὑψηλὴ σεισμικὴ δράση ἐνδιαμέσου ἑστιακοῦ βάθους στὴ βορειοδυτικὴ καὶ νοτιοανατολικὴ ἄκρη τοῦ Ἑλληνικοῦ ἡφαιστειακοῦ τόξου. Στροφὴ κατὰ τὴν ἀνάδρομη φορὰ τῆς καταδυομένης στὴν Ἑλληνικὴ τάφρο πλάκας τῆς Ἀφρικῆς δικαιολογεῖ ἱκανοποιητικὰ μόνο τὸ κέντρο αὐξημένης σεισμικῆς δράσεως ἐνδιαμέσου ἑστιακοῦ βάθους ποὺ παρουσιάζεται στὸ νοτιοανατολικὸ Αἰγαῖο.

Στοὺς καταλόγους τοῦ Διεθνοῦς Σεισμολογικοῦ Κέντρου, 1971-1985, ἔχουν καταχωρισθεῖ 122 σεισμοὶ μεγέθους 3m_b καὶ ἄνω ποὺ προέρχονται ἀπὸ βάθος ἴσο ἢ μεγαλύτερο τῶν 100 χιλμ. Ἀπὸ τὰ συμβάντα αὐτὰ 27 προέρχονται ἀπὸ τὴν περιοχὴ τῆς Αἴγινας (36°N38°, 23°E25°) καὶ 57 ἀπὸ τὴν περιοχὴ τῆς Κῶ (36°N37°, 26°E28°).

Ἡ μεγαλύτερη σεισμικὴ δράση ἐνδιαμέσου βάθους ποὺ παρατηρεῖται στὴν περιοχὴ τῆς Κῶ φαίνεται καλύτερα ἀπὸ τὴν πλήρη σειρὰ σεισμῶν μεγέθους 4 1/2 M_s καὶ ἄνω. Ἀπὸ τοὺς 53 σεισμοὺς μεγέθους 4 1/2 καὶ ἄνω ποὺ καταγράφηκαν ἀπὸ τὴν εὐρύτερη περιοχὴ τῆς νότιας Ἑλλάδας κατὰ τὴν περίοδο 1971-1985, 12 (ἤτοι 23%) προέρχονταν ἀπὸ τὴν περιοχὴ τῆς Αἴγινας καὶ 29 (ἤτοι 55%) ἀπὸ τὴν περιοχὴ τῆς Κῶ. Ἡ ἐνέργεια ποὺ ἐλευθερώθηκε στὶς περιοχὲς Αἴγινας καὶ Κῶ κατὰ τοὺς σεισμοὺς ἐνδιαμέσου βάθους, μεγέθους 4 1/2 καὶ ἄνω, ἦταν 10% καὶ 82%, ἀντιστοίχως, τῆς συνολικῆς ἐνέργειας ποὺ ἐλευθερώθηκε στὴν ἴδια περίοδο σ' ὁλόκληρη τὴν περιοχὴ τῆς νότιας Ἑλλάδας. Δηλαδὴ τὸ 92% τῆς ἐνέργειας ἀπὸ σεισμοὺς ἐνδιαμέσου βάθους προέρχονται ἀπὸ τοὺς σεισμικοὺς θύλακες Αἴγινας καὶ Κῶ.

Ἡ κατανομὴ τῆς ἀθροιστικῆς συχνότητας τῶν σεισμῶν μεγέθους 4 1/2 καὶ ἄνω, συναρτήσει τοῦ μεγέθους, M_s, καὶ τοῦ χρόνου ἐπαναλήψεως, t, ἐκφρασμένου μὲ μονάδα τὸν μέσο χρόνο ἐπαναλήψεως, m, στὴν εὐρύτερη περιοχὴ τῆς νότιας Ἑλλάδας, N_c, καὶ στὴν ἐνεργὸ περιοχὴ τῆς Κῶ, $^*N_c$, ἀποδίδεται ἱκανοποιητικὰ ἀπὸ τὶς ἀκόλουθες ἐξισώσεις:

$Log(N_c)=5.9175-0.8979\ M_s$, S.D. $= \pm 0.14$ (1)

$Log(*Nc)=5.0602-0.7756\ M_s$, S.D. $= \pm 0.12$ (2)

Ὁμοίως

$Log(N_c)=1.953-0.3176t$, S.D. $= \pm 0.0836$ (3a)

ἢ $Log(N_c)=3.432\ (t+1)^{-1}$, S.D. $= \pm 0.0767$ γιὰ $t<6$ (3b)

καὶ

$Log(*N_c)=1.850-0.839t$, S.D. $= \pm 0.027$ (4a)

ἢ $Log(*N_c)=2.954(t+1)^{-1}$, S.D. $= \pm 0.049$ (4b)

Κατὰ τὴν ἐξίσωση (1) σὲ μιὰ περίοδο παρατηρήσεως 15 ἐτῶν ἀντιστοιχεῖ ἕνας σεισμὸς ἐνδιαμέσου βάθους ($\lesssim$100km) μεγέθους 6.59M_s. Ὁ σεισμὸς αὐτὸς μπορεῖ νὰ συμβεῖ στὴν εὐρύτερη περιοχὴ τῆς νότιας Ἑλλάδας μέσα σὲ διάστημα 92 ἐτῶν μετὰ τὸ 1971. Ἐὰν οἱ ἐξισώσεις (1) καὶ (3a) ἰσχύουν καὶ γιὰ μεγαλύτερες σεισμικὲς περιόδους, σὲ μιὰ μέση περίοδο ἐπαναλήψεως 92 ἐτῶν ἀντιστοιχεῖ ἕνας σεισμὸς ἐνδιαμέσου βάθους ($\lesssim$100km) μεγέθους 7.47 M_s. Ὁ σεισμὸς αὐτὸς μπορεῖ νὰ συμβεῖ μέσα σὲ διάστημα 566 ἐτῶν μετὰ τὸ 1971.

Μὲ τὸ ἴδιο σκεπτικὸ καὶ τὶς ἴδιες ἐκδοχὲς γιὰ τὶς ἐξισώσεις (2) καὶ (4a), θὰ πρέπει νὰ περιμένουμε στὴν περιοχὴ τῆς Κῶ ἕνα σεισμὸ ἐνδιαμέσου βάθους ($\lesssim$100km) μεγέθους 6.52M_s μέσα σὲ διάστημα 71 ἐτῶν, καὶ ἕνα σεισμὸ ἐνδιαμέσου βάθους ($\lesssim$100km) μεγέθους 7.40M_s μέσα σὲ διάστημα 338 ἐτῶν μετὰ τὸ 1971.

Ἡ ὁμοιότητα τῶν ἐξαγομένων γιὰ τὴν εὐρύτερη περιοχὴ τῆς νότιας Ἑλλάδας καὶ γιὰ τὴν πολὺ ἐνεργὸ περιοχὴ τῆς Κῶ ὑποδεικνύει ὅτι ὁ ἀναμενόμενος σεισμὸς ἐνδιαμέσου βάθους ($\lesssim$100km) μεγέθους 7.5M_s περίπου θὰ γίνει μᾶλλον στὴν περιοχὴ τῆς Κῶ. Ὁ σεισμὸς αὐτὸς ἔχει πιθανότητα 61% νὰ συμβεῖ μέσα σὲ διάστημα 71 ἐτῶν, καὶ 100% σὲ διάστημα 338 ἐτῶν μετὰ τὸ 1971.

Κατὰ κανόνα, ὁ μέγιστος χρόνος ἀναμονῆς σεισμῶν ὁρισμένου μεγέθους καὶ ἄνω ἀποτελεῖται ἀπὸ 3 ἢ περισσότερους σεισμικοὺς κύκλους ἢ τάξεις πραγματικῶν χρόνων ἐπαναλήψεως. Σὲ κάθε σεισμικὸ κύκλο μπορεῖ νὰ συμβοῦν σεισμοὶ ὁποιουδήποτε δυνατοῦ μεγέθους. Δὲν ὑπάρχει τάση οἱ σεισμοὶ μεγαλύτερου μεγέθους νὰ παρατηροῦνται σὲ χρόνους ἐπαναλήψεως μεγαλύτερης τάξεως. Ὁ κανόνας αὐτὸς ἰσχύει τόσο γιὰ τοὺς σεισμοὺς τοῦ γήϊνου φλοιοῦ, ὅσο καὶ γιὰ τοὺς σεισμοὺς τοῦ γήϊνου μανδύα.