CHARACTERISTIC EARTHQUAKES IN THE AEGEAN SOURCE REGIONS

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ABSTRACT

Data from the revised and completed European earthquake catalogue (1901-1985, M>4), were used for the study of cumulative magnitude-frequency distributions $N_c(M)$ in earthquake source regions. The investigated $N_c(M)$ characteristics are: slope b of the log-linear segment and its extreme end, M_a, M_{max} observed, M_c of characteristic earthquakes, M_c - M_a, homogeneity threshold M_h. The Aegean regions display a systematic regional distribution of b and in most of them M_c can be estimated. M_c - M_a can be explained in terms of the prevailing type of sequences and M_c-values indicate the size of dominating faults. The resulting $N_c(M)$ types are compared with theoretical models of seismicity.

ΧΑΡΑΚΤΗΡΙΣΤΙΚΟΙ ΣΕΙΣΜΟΙ ΣΤΗΝ ΠΕΡΙΟΧΗ ΤΟΥ ΑΙΓΑΙΟΥ.

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ΠΕΡΙΛΗΨΗ

Δεδομένα από τους αναθεωρημένους και πλήρεις καταλόγους σεισμών της Ευρώπης (1901-1985, M>4, Karnik 1989) χρησιμοποιήθηκαν για τη μελέτη των αθροιστικών κατανομών $N_c(M)$ των μεγεθών των σεισμών σε σεισμικές περιοχές. Τα χαρακτηριστικά των κατανομών που ερευνήθηκαν είναι: η κλίση, b, της καμπύλης της κατανομής και του μεγίστου ορίου, M_a, το μέγιστο μέγεθος σεισμού, M_{max}, που παρατηρήθηκε, το μέγεθος, M_c, των χαρακτηριστικών σεισμών, η διαφορά M_c - M_a και το ελάχιστο μέγεθος ομοιογένειας, M_h. Οι περιοχές του Αιγαίου δείχνουν συστηματική χωρική κατανομή του b και στις περισσότερες από αυτές το M_c μπορεί να υπολογιστεί. Η διαφορά M_c - M_a μπορεί να εξηγηθεί με βάση τον επικρατούντα τύπο σεισμικών ακολουθιών, ενώ οι τιμές του M_c δείχνουν το μέγεθος των κυρίων ρηγμάτων. Οι τύποι του $N_c(M)$ που βρέθηκαν, συγκρίνονται με θεωρητικά μοντέλα σεισμικότητας.

INTRODUCTION

The relationship between the numbers of earthquakes N with magnitudes M larger than a certain M value belongs to the basic seismicity characteristics of a certain earthquake region. This cumulative $N_c(M)$ distribution has been expressed either in a simplified form

$$\log N_c(M) = a-bM \qquad (1)$$

Table 1. Earthquake regions

Region	Latitude N	Longitude	ΣN	Mmax	b1	b2	Type	Ma	Mc	Mh
a) Earthquake source regions										
Cephalonia	38.00-38.30	20.00E-21.00E	328	7.0	0.79	1.0	DE		(6.1-7.0)	4.3
Athos	39.70-40.60	24.00E-25.60E	71	7.0	0.52	0.8	D		6.9-7.0	4.4
Lesbos	38.70-39.60	24.00E-25.70E	97	7.2	0.64	0.9	D		6.5-7.2	4.4
Dardanelles	40.00-40.80	27.00E-27.90E	47	7.3	0.47		AC			4.6
b) Earthquake regions										
Albania 1	40.11-41.40	18.51E-20.20E	163	6.1	0.90		C	5.8	5.9-6.1	4.3
Albania 2	40.11-42.00 41.41-42.00	20.21E-21.30E 19.81E-20.20E	196	6.7	0.80		DA	6.0	6.5-6.7	4.3
Bulgar 1	41.01-42.80	24.91E-28.00E	95	7.0	0.82		D	6.0	6.8-7.0	4.4
Bulgar 2	42.81-44.00	24.91E-29.90E	31	6.8	0.71	0.8	D	5.5	6.4-6.8	(4.5)
Struma	41.01-44.00	22.01E-24.90E	236	7.8	(0.76)	1.1	E	5.7	7.2-7.8	4.6
Aegean 1	39.00-40.10	19.01E-21.30E	210	6.1	1.10		DC	5.7	5.6-6.1	4.4
Aegean 2	37.00-38.99	19.01E-21.30E	B65	7.0	0.90		D	6.0	6.5-7.0	4.3
Aegean 3	38.60-39.60	21.31E-24.00E	369	6.8	0.85		DA	6.0	6.6-6.8	4.3
Aegean 4	39.61-42.00	21.31E-22.00E	43	6.1	1.11		B	5.3	(6.1)	4.3
Aegean 5	37.70-38.59	21.31E-24.00E	460	6.7	0.89		DC	5.7	6.2-6.7	4.3
Aegean 6	35.70-37.69	21.31E-22.80E	186	6.8	1.08		B	6.0	(6.8)	4.3
Aegean 8	39.61-41.00	22.01E-24.00E	120	6.9	0.68		D	5.9	6.2-6.8	4.3
Aegean 9	39.61-41.00	24.01E-25.70E	71	7.0	(0.53)	0.9	D	5.8	6.9-7.0	4.4
Aegean 10	37.70-39.60	24.01E-25.70E	107	7.2	(0.66)	0.9	DE	5.8	6.6-7.2	4.3
Aegean 11	35.70-37.69	22.81E-25.00E	77	5.6	1.3		DA	5.0	5.4-5.6	4.3
Aegean 12	37.31-38.10	25.01E-28.79E	75	6.8	0.72		A	6.8	(6.8)	4.4
Aegean 13	38.11-38.90	25.71E-27.50E	86	6.6	0.96		B	6.0	(6.6)	4.4
Aegean 14	35.70-37.30	25.01E-28.59E	301	7.3	0.94		B	6.5	(7.3)	4.3
Aegean 15	33.50-35.69	27.01E-31.00E	198	7.1	1.01		0	5.9	6.7-7.1	4.3
Aegean 16	38.91-39.70	25.71E-27.50E	41	7.0	(0.49)	0.8	D	5.7	6.6-7.0	4.3
Crete 1	33.51-35.69	22.00E-24.80E	251	6.4	0.81		CA	6.3	6.4	4.3
Crete 2	33.51-35.69	24.81E-27.00E	297	5.8	1.30		CA	5.7	5.8	4.3
Marmara	39.71-41.00	25.71E-27.99E	82	7.3	0.53		CA	7.2	7.3	4.4
Turkey 1	39.71-41.50	28.00E-31.40E	126	7.1	0.68		CA	6.B	6.8-7.1	4.6
Turkey 2	38.11-39.70	27.51E-28.80E	95	6.4	0.77		CA	6.0	6.0-6.4	4.4
Turkey 3	35.71-37.40	28.60E-34.00E	141	7.0	0.77		D	6.0	6.7-7.0	4.4
Turkey 4	37.41-38.60	28.80E-31.20E	155	6.9	0.88		8	5.9	6.0-6.9	4.4
Turkey 5	38.61-39.70	28.81E-31.20E	144	7.2	0.93		8	5.9	6.0-7.2	4.4
c) Earthquake provinces										
Rodop	Struma, Bulgar 1,2		362	7.8	(0.69)	0.95	DE	5.7	6.8-7.8	4.2
Ionian	Aegean 1,2		1075	7.0	0.92	1.0	D	5.9	6.4-7.0	4.3
Hellen A	Crete 2, Aegean 14,15, Turkey 3		940	7.4	0.95	1.0	DA	6.2	6.7-7.4	4.3
Hellen B	Struma, Aegean 8,9,10,12,13,16		736	7.8	(0.69)	0.9	DC	5.8	6.8-7.8	4.4
Hellen C	Aegean 12,14,15, Turkey 3		718	7.4	0.85	0.9	DC	6.2	6.8-7.4	4.4
Hellen D	Aegean 2,5,6,11, Crete 1		1839	7.0	0.93		DC	5.8	6.4-7.0	4.4
Hellen E	Aegean 2,5,6,11,14,15, Crete 1,2, Turkey 3		2581	7.4	1.00		(AD)	(6.7)	(7.4)	4.4-
	m_A, h ≥ 60 km		267	7.7	0.59		C	6.9	7.4-7.7	4.4

Notes:

Mmax – the largest observed Ms or m during 1901-1985

b_1 – coefficient in formula (1), least squares fit

b_2 – ibid., eye-fitting of the linear segment of Nc(M)

Ma, Mh – upper and lower boundary values of the linear segment

Mc – characteristic earthquakes

or with the use of more complicated formulae attempting to account for observed deviations from linearity of many (log $\Sigma N,M$) distributions. The understanding of the mechanisms which shape the observed $N_c(M)$ distributions has developed over several decades. During the last decade the phenomenon of "characteristic earthquakes" corresponding to the bulge at the extreme end of $N_c(M)$ emerged (see Fig. 1). The first interpretation of the bulge was presented by M. Bath (1981) who considered the log-linear segment of $N_c(M)$ as a distribution of aftershocks of extreme events in a certain active region. Other investigators, such as Carlson et al. (1991), Hong & Rosenblueth (1988), King (1983), Lomnitz-Adler (1985) and Sadovsky et al. (1982) give feasible explanations using mainly models of fracturing of real media under the assumption of a dominating discontinuity (fault) (see also the summary in Karnik and Klima, 1993b). Most theoretical models suffer from the lack of sufficient experimental evidence. It is not so much the absence of observed N(M) distributions as the absence of homogeneous sets of these results. The recent revision and completion of the European- Mediterranean earthquake catalogue (Karnik, 1989) provided the opportunity to investigate $N_c(M)$ distributions for a variety of earthquake regions. Among them the Aegean area of plate collision and subduction attracts attention because it is characterized by the highest earthquake activity within the Mediterranean region. Results on N(M) in this area exist (Papazachos, 1990), however, the $N_c(M)$ problem deserves further discussion.

OBSERVATIONS

The delineation of earthquake source regions is invariably the first task. This procedure depends much on the personal judgement. As a rule clusters of foci or their close groupings are considered as a single earthquake region. The regional tectonic setting and the position of major active faults is taken into account. This approach was followed also in the present study (Karnik, Klima, 1993a).

$N_c(M)$ distributions have been investigated for three different sizes of earthquake source regions. The largest one is the "earthquake province" comprising several earthquake regions governed by a supposedly identical type of earthquake generation (see Table 1). In the second category the "earthquake regions" with one to three clusters of epicentres are included. The smallest "source regions" have been delineated around foci where at least three earthquakes of M>6 1/2 originated during 1901-1985, their size is approximately 50 km x 50 km so that they involve aftershocks.

The statistical information on the region was taken from the revised and completed European catalogue, 1901-1985 (Karnik, 1989). It contains all events of $M_s \geq 4$ for which data have been available. The completeness threshold decreases with time from $M_s=5$ 1/2 to $M_s=4$ and this fact influences M_h in Table 1.

It must be mentioned that for all shallow events (h<60 km) the surface wave magnitude M_s was determined, whereas all events deeper than normal were classified by the body wave magnitude m_B, based on body wave amplitudes recorded by medium-period or broad-

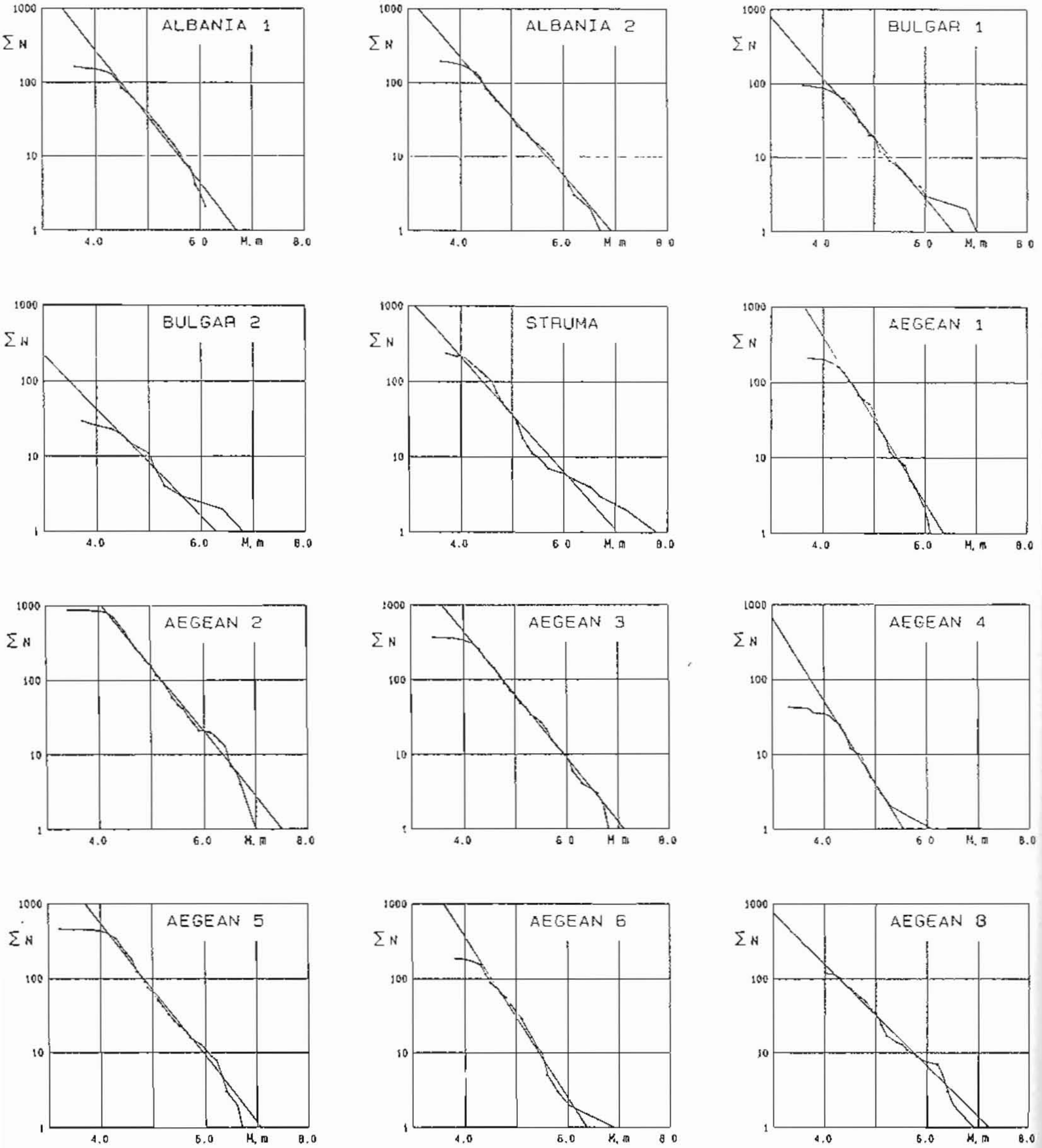
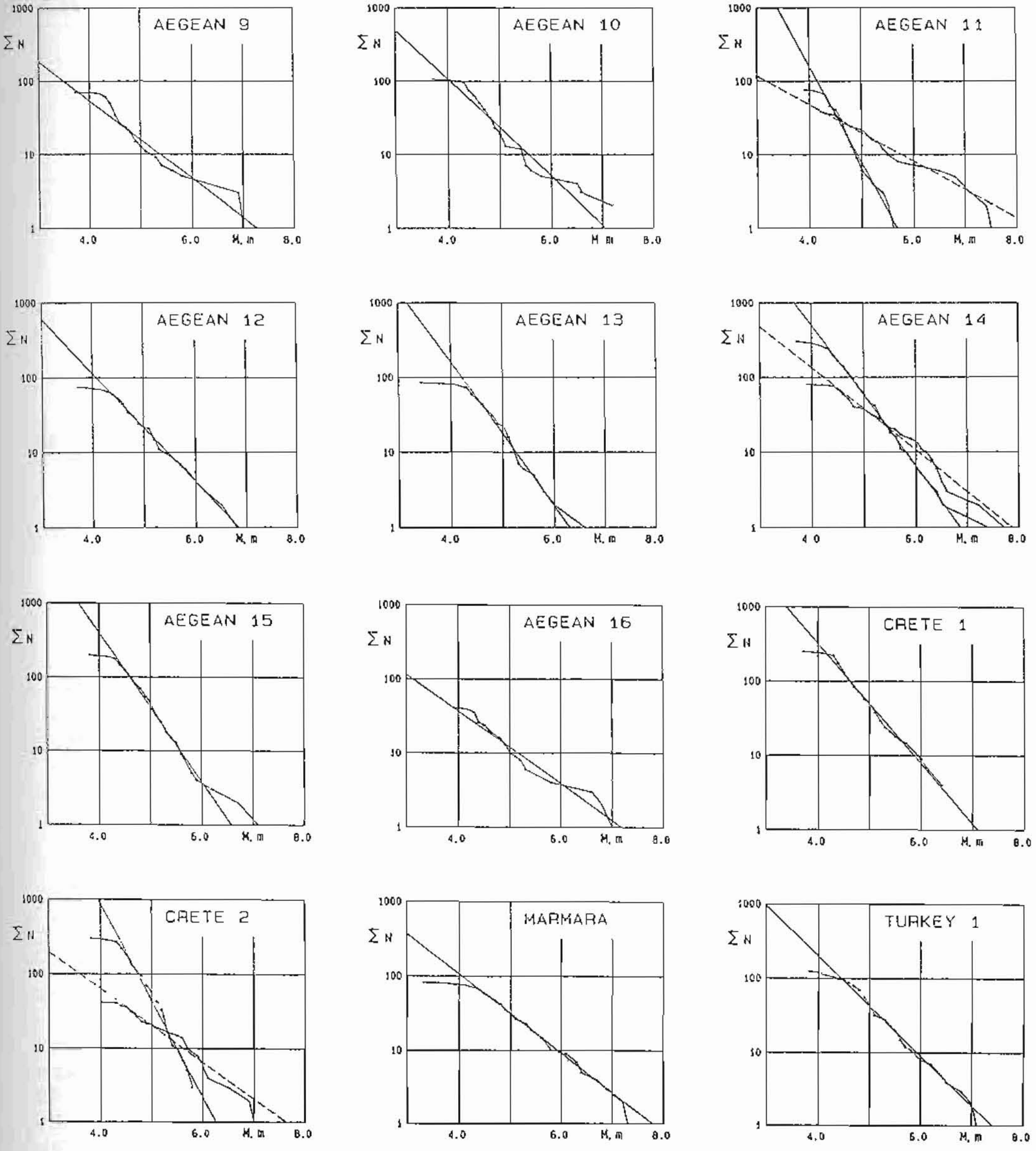

ALBANIA 1
ALBANIA 2
BULGAR 1
BULGAR 2
STRUMA
AEGEAN 1
AEGEAN 2
AEGEAN 3
AEGEAN 4
AEGEAN 5
AEGEAN 6
AEGEAN 8
ΣN
1000
100
10
1
4.0
6.0
M,m
8.0

Fig.1. cont.


AEGEAN 9
AEGEAN 10
AEGEAN 11
AEGEAN 12
AEGEAN 13
AEGEAN 14
AEGEAN 15
AEGEAN 16
CRETE 1
CRETE 2
MARMARA
TURKEY 1
ΣN
1000
100
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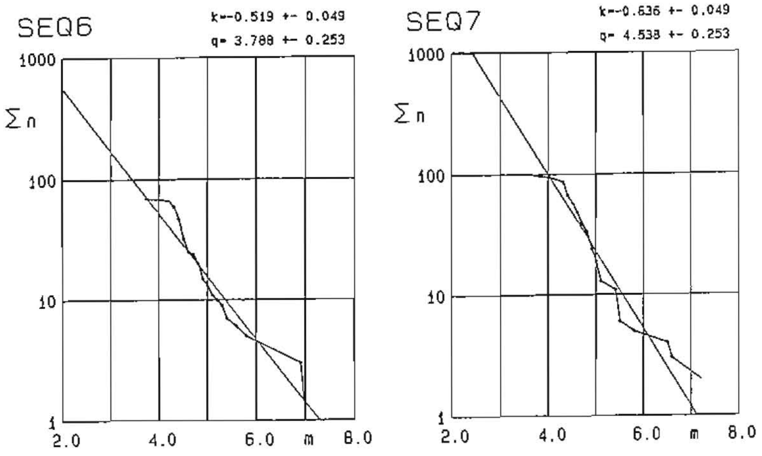
1
4.0
6.0
M, m
8.0

Fig.1. cont.



Athos **Lesbos**

Dardanelles **Cephalonia**

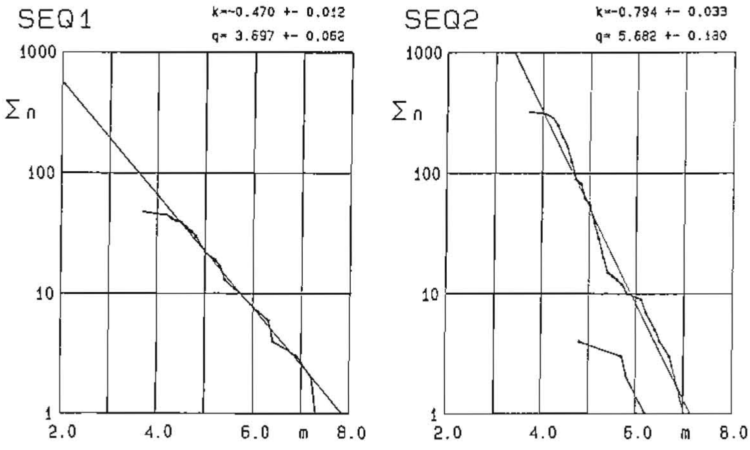


Fig.1. · The cumulative magnitude-frequency relationship - earthquake regions in the Aegean area.

band seismographs. Thus, the $N_c(M_s)$ and $N_c(m_B)$ distributions are not directly comparable without converting m_B to M_s. Since 1963 the m_b(ISC) magnitudes have been assessed for most events. As there is no general equality between m_b, m_B and M_s, m_b(ISC) values were converted to m_B by means of the formula by Abe (1981)

$$m_B = 1.5\ m_b - 2.2 \qquad (2)$$

for events of $h \geq 60$ km.
The IASPEI conversion formula of 1967

$$m_B = 0.56\ M_s + 2.9 \qquad (3)$$

was also used when necessary.

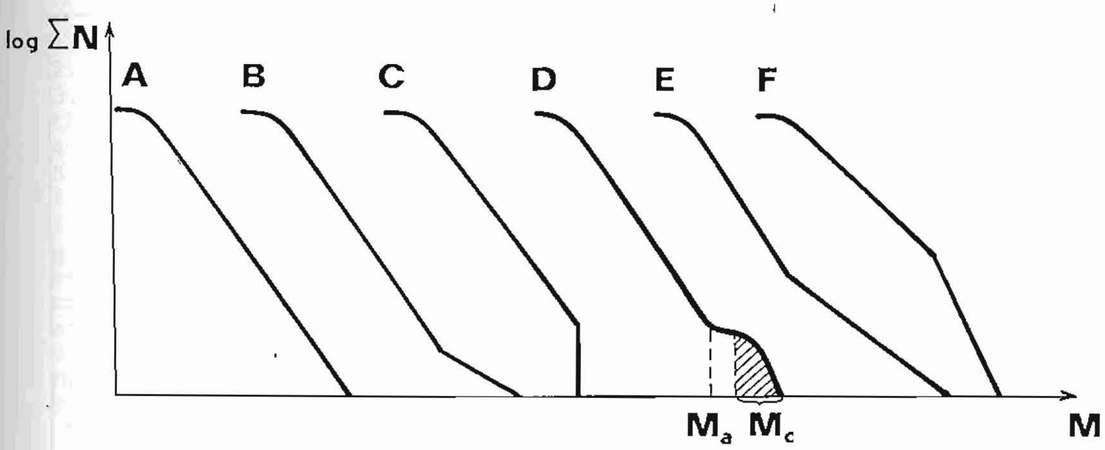


Fig.2. Types of $N_c(M)$ observed in the Mediterranean area (Karnik, Klima, 1993).

CUMULATIVE MAGNITUDE-FREQUENCY DISTRIBUTIONS

The observed shapes of $N_c(M)$ in the Mediterranean area can be grouped into six general types, two of them being quite rare (see Fig. 2). This conclusion is also valid for the Aegean area (see Fig. 1). The existence of a single dominant sequence in a region or of a superposition of two or more earthquake populations influenced the observed shapes of $N_c(M)$. It can be concluded that most ($\log N_c$, M) plots fit formula (1) only within the magnitude range of small and moderate earthquakes above the homogeneity threshold. The deviations from $N_c(M)$ commence at a certain value M_a which depends on the largest M observed (M_{max} obs) and on the distribution type. The coefficients a and b in formula (1) were calculated by the least squares' method excluding ΣN for the largest two magnitudes and ΣN for $M<4.4$. The first limitation guarantees the approximate equality of b from cumulative and interval distributions (Riznichenko, 1964). It also eliminates the upper extreme values of ΣN often deviating from the ($\log N_c$,M) linearity. Thus, the a- and b-values in Table 1 correspond to the linear segment of $N_c(M)$ distributions. For several regions the calculated b-value did not fit the distributions properly, therefore the b-value of the log-linear segment was estimated separately by eye-fitting (see b2 in Table 1). All b-values for shallow earthquakes fall within b = 0.5-1.5. The average b-value calculated as an arithmetic mean from 75 European-Mediterranean regions and 25 provinces equals 0.92; b = 0.90 if the small secondary maximum at b = 1.35 is neglected. The mean value for four regions with earthquakes deeper than normal is $b=0.56$ (m_B).

Earthquake provinces

Earthquake provinces have been formed by combining several earthquake regions into one seismotectonic unit. There are six provinces in the Aegean area (see Table 1):


TURKEY1
TURKEY2
TURKEY3
TURKEY4
TURKEY5
MARMARA
AEGEAN1
AEGEAN2
AEGEAN3
AEGEAN4AEGEAN8
AEGEAN5
AEGEAN6
AEGEAN9
AEGEAN10
AEGEAN11
AEGEAN12
AEGEAN13
AEGEAN14
AEGEAN15
CRETE1
CRETE2
40.
36.
20.
24.
28.
32.

1. The Ionian province comprising the Ionian islands.
2. Hellen A, covering the SE portion of the Hellenic arc.
3. Hellen B, including the "Vardar zone" and its extension into the Aegean Sea.
4. Hellen C, including further extension of Hellen B to SE.
5. Hellen D, covering the western wing of the Hellenic arc.
6. Hellen E, involving the Hellenic arc.

There is a very extensive literature on all aspects of seismicity of the Aegean area and it is impossible to present a representative review in this paper. Most studies have been carried out by Greek seismologists from the institutes in Athens and in Thessaloniki. Recent papers by Greek authors dealing with very similar problems as the present paper are, e.g., those by Hatzidimitriou et al. (1985), Papazachos et al. (1987), Papazachos (1985, 1990, 1992), Kiratzi et al. (1985).

Earthquake regions

There are 24 earthquake regions covering the Aegean area including the western part of Turkey, i.e. the coastal zones of the Aegean Sea. The boundaries of the regions are defined in Table 1. In two regions the extensive intermediate depth activity ($h = 60$-180km), i.e. Crete 2 and Aegean 14, was investigated separately.

Earthquake sources zones

Some regions have been subdivided into smaller units for the study of Mediterranean earthquake sequences with $M_{max}>6\ 1/2$, with identical or very close epicentres. In the Aegean area the following four sources have been selected:

Athos: 39.7°N-40.6°N, 24.0°E-25.6°E (sequences: 8 Nov. 1905, 18 Jan. 1982, 6 Aug. 1983),

Lesbos: 38.7°N-39.6°E, 24.0°E-25.7°E (6 March 1967, 17 Febr. 1968, 19 Dec. 1981),

Cephalonia: 38.0°N-38.3°N, 20.0°N-21.0°E (24 Jan. 1912, 11-12 Aug. 1953),

Dardanelles: 40.0°N-40.8°N, 27.0°E-27.9°E (9 Aug. 1912, 13 Sept. 1912, 18 March 1953).

For all three categories of earthquake source regions $N_c(M)$ distributions were plotted. Examples are given in Fig. 1 and the parameters of $N_c(M)$ are listed in Table 1. All distributions follow one of the generalized types reproduced in Fig. 2. It can be concluded that type D or the types close to D prevail. The D shapes are not fully identical, the relative lack of events in the transitional interval between the log-normal segment and the bulge as well as the bulge itself are evident with different lucidity.

The focal region of Cephalonia produces a D-shape $N_c(M)$, however, the bulge extends over a wide range of M. It is due to a specific situation in the region where peaks of activity are accompanied by the occurrence of doublets, i.e. of two extreme events of a small magnitude difference. This focal behaviour smoothes the bulge of $N_c(M)$. The region of Dardanelles and particularly those of Athos and Lesbos fit well the D-type with M_c= 6.9-7.3, 6.7-7.0 and 6.5-7.2, respectively, all of them can be defined by M_c = 7±0.2. Particularly in the case of Athos, the extremely large differences $M_1 - M_2$ between the main shock and the largest aftershock make the bulge very pronounced. A similar review of events belonging to earthquake regions and provinces confirm that the shape of $N_c(M)$ is mainly influenced by the dispersion of the observed largest magnitudes M_{max} and by the variety of differences $M_1 - M_2$. It is again evident that the simplified Gutenberg-Richter formula fits most N(M) or $N_c(M)$ distributions only within a limited magnitude range. Significant deviations have been observed at both ends. In the low magnitude range both the incompleteness of a sample and the existence of the real low magnitude threshold cause a drop in N. In the high magnitude range the activity of dominant faults determines the upper threshold magnitude values.

VARIATION OF THE b-VALUE

It is questionable to compare the present b-values with the published ones because different authors use a different approach in representing $N_c(M)$ plots. A "representative" b-value can be much influenced by one or two points deviating from a log-linear distribution. In Table 1 most coefficients b1 fit well the log-linear portion of N_c (M), in several cases of a poor fit b2 was estimated by eye-fitting taking into account only the log-linear segment.

The b1- and b2-values in the Aegean area range between 0.7 and 1.3, the arithmetic mean being b = 0.90. A systematic regional distribution can be observed, the largest values of b = 0.9 to 1.3 are linked with the western and southern parts of the Hellenic arc, in the eastern part the b-values are lower and the lowest values (b = 0.5-0.8) can be found in the extension of the Vardar zone into the Aegean Sea and along the western branch of the North Anatolian Fault, i.e. in the Dardanelles and in the Marmara Sea region. This pattern is similar to that observed earlier by Papazachos (1990). Table 1 gives other parameters of $N_c(M)$ distributions, e.g. M_a and M_h, the upper and lower boundary values of the linear segment, and M_c, the observed magnitude range of characteristic earthquakes.

As seen in examples in Fig. 1 not all $N_c(M)$ exhibit a clear D-type distribution. For regions with only one large earthquake sequence the B-type is observed (Fig. 3), it may be considered as an early stage of the D-type. Moreover, there are also regions with a log-linear $N_c(M)$ distribution over the whole range of observations of $M>M_h$ (types A or C). Regionally, this type extends from the Crete through W. Turkey to the Dardanelles-Marmara region. A simple explanation may be that faults of different lengths are responsible for the observed earthquake activity.

SEISMOTECTONIC INTERPRETATION

The observed types of $N_c(M)$ distributions may be explained first of all by the idea of a single dominating fault or a fault segment governing the seismicity of a region. Semi-theoretical and theoretical models by Bath (1981), Schwartz and Coppersmith

(1984), Hong and Rosenbluth (1988), Carlson et al. (1991), and others, prove the physical feasibility of the existence of characteristic earthquakes and of the D-type of $N_c(M)$. Earthquakes are released in a weakened medium where fractures facilitate the stress release. Such areas are mainly located at the present or earlier plate contacts. In these places the ruptures (faults) are of different dimension that predetermine the magnitude of earthquakes. The fault dimensions can be also distributed regularly in the region or some dimensions may be missing and only some may generate earthquakes. Mechanical properties of the strained rock material may establish a certain hierarchy of dimensions of fractures (Sadovsky et al. 1982). In a region with a simple tectonic structure, i.e. with one dominating fault, extreme events of almost identical magnitude will recur forming the bulge on $N_c(M)$. The aftershocks and the background seismicity, linked with small faultlets and secondary faults, form the log-linear portion of $N_c(M)$ with a slope close to b = 0.9-1.0.

In regions involving active faults of different dimensions the resulting $N_c(M)$ of type A may originate by superposition of individual earthquake populations. It must be noted that some faults generate swarms, doublets (or even triplets) of similar M, large aftershock series differing from a simple, but most common case of a main shock of magnitude M_1 followed by a series of aftershocks with the largest one of magnitude M_2, $M_1 - M_2 = 1.0$ in average.

The integral image of seismicity defined by $N_c(M)$, however, is influenced by the delineaton of a single earthquake source. Since M_c is connected with the size (length L) of an earthquake source, the observed M_c-values can be converted into the dimensions of faults (sources) governing earthquake generation in each region. In the Aegean region the empirical formula by Papazachos & Papazachou (1989)

$$\log L(\mathrm{km}) = 0.51\ M_s - 1.85 \qquad (4)$$

is applicable. It follows that for the observed range of M_c=6.0-7.3, the lengths of earthquakes generating faults should be between 16 km and 75 km. It must be noted that similar formulae derived for other regions lead to higher L-values. The knowledge of the existence of a prevailing $N_c(M)$ type D, i.e. of characteristic earthquakes, in most Aegean regions may help in assessing the seismic hazard more accurately. It follows from type D that large earthquakes, just below M_c, have a relatively low probability of occurrence.

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