THE STATISTICS OF LARGE EARTHQUAKE MAGNITUDE AND AN EVALUATION OF GREEK SEISMICITY

by

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ABSTRACT

The problem of the upper bound to earthquake magnitude occurrence is examined. It is demonstrated using simple frequency-magnitude and energy-magnitude laws, that it is possible to include an upper bound as an unknown parameter, and to calculate its value both analytically and graphically. It is shown that a finite upper bound to earthquake magnitude is necessary to preserve a finite rate of energy release. This upper bound is expressed in terms of the mean annual release of energy and the parameter b of the frequency-magnitude law.

The third type asymptotic distribution of extreme values of Gumbel, which includes the upper bound as a parameter, is then determined using Marquardt's algorithm. The methods of Extreme-Values and strain energy release are then analytically related and both methods tested on the high seismicity of the circum-Pacific belt. Uncertainties on the extreme value parameters and related predictions are obtained using an error matrix, and uncertainties on the parameters from strain energy release are also determined. Both methods give similar results and are applicable to the estimation of seismic risk.

These methods are then applied to evaluate Greek seismicity and seismic risk. Greek earthquakes are relocated and magnitudes determined to produce a homogeneous catalogue using mainly instrumental data since 1901. Tectonic models of Greece are examined using the new hypocentres. Seismic risk maps are presented and these contour maps show the maximum expected earthquake magnitudes and accelerations in the next T years at stated probability levels.

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CONTENTS

CHAPTER I

INTRODUCTION

As a result of increasingly complex industrial, commercial and residential developments, which cause centres of population to spread in ever widening circles, reliable estimations of seismic risk and seismic hazard, and developments of means of mapping them, are among the research problems in seismology which most urgently require answers.

Definition of seismic risk as "the probability of occurrence of an earthquake in the future" (Lomnitz, 1974), implies a degree of future uncertainty. Hence principles of probabilistic forecasting and decision making are essential in any seismic risk analysis. Models of seismic risk usually consist of:

i) empirical formulae based on available macroseismic data,

ii) statistical distribution laws for earthquake occurrence in time and magnitude, and

iii) attenuation laws describing the decay of seismic ground motion with focal distance.

1.1 General statement of problem

The distribution of earthquake magnitudes in time and in size is generally investigated by:

i) Using the whole available data - whole process.

ii) Using only the extreme value magnitudes - part process.

When models of the first category are applied to the experimental data, like the linear frequency-magnitude model of Gutenberg and Richter (1944), it becomes clear that they do not represent the real process for the large earthquakes. Most of the proposed alternative expressions such as the quadratic or truncated frequency-magnitude formulae (Merz and Cornell, 1973, Cornell and Vanmarcke, 1969) do not recognize the inescapable existence of an upper bound to the magnitude that can be generated in a region (Esteva, 1976).

To implement earthquake-resistant design codes, it is usually necessary to know the maximum dynamic load to which a structure might be subject during its design life, or alternatively, the most probable return period of a specified design load. The inclusion of an upper bound to earthquake magnitude as an unknown parameter in a statistical model leads to more reliable estimates, especially for large earthquakes, because it is closer to the real process than that represented by the unlimited or truncated models.

One of the objectives of this study is to investigate the regional upper bound for earthquake magnitude. This is first attempted by using the strain energy release in the region, calculated from the linear energy-magnitude law, combined with analytic expressions for the upper bound to magnitude.

In all the statistical models which use the whole process, inclusion of low magnitudes, which usually are incomplete and inhomogeneous, can bias the estimation of the prediction parameters. On the other hand, in earthquake engineering applications, the need to consider extreme value distributions separately from the statistics of the whole process is of primary importance. Thus, another prime objective of this study is to investigate the usefulness of the distribution of Extreme-Values, which Gumbel (1966) has called the third type asymptotic distribution of extremes, for estimating the seismic risk and return periods of largest earthquakes. This type of distribution is chosen because it holds for initial distributions which are limited towards the largest values, and it contains the upper bound of the distribution as an unknown parameter.

The theory of Extreme-Value statistics is formulated under the assumptions:

i) the prevailing conditions are valid in the future and,

ii) the observed extreme values are independent of each other.

For the case of earthquake occurrence, our experience shows that earthquakes do not occur at the same level of magnitude and frequency all over the world. Practically 99% of all earthquakes occur along plate boundaries. Less than 3% of the earth's seismic energy release occurs on the midoceanic rises or in the interior of plates (Lomnitz, 1974).

Although aftershocks following large earthquakes are the most outstanding example of dependent events, Gumbel (1966) suggests that the influence of interdependence may vanish for largest values of a variate. Lomnitz (1966) points out that large earthquakes are indeed characterized by a high degree of randomness and independence in time.

It is then reasonable to assume for a specific region and sampling period that the behaviour of the largest earthquakes will usually be similar to that of the near past; although the distribution will vary over geological epochs. Consequently the theory of Extreme-Value statistics can be applied to establish a prediction procedure for the largest earthquake magnitude of the next n years, by using the past N years' earthquake data in a given region.

These two objectives form the first part of this thesis.

In the second part, the objective is to evaluate the seismicity and seismic risk of Greece, using the methods already developed, which by then will be seen to give reliable estimates of the future seismic activity of a region. The evaluation is obtained by estimating both the return periods for specified magnitudes and also the expected magnitudes and accelerations within a period of time, all at a given probability level. The results are finally presented by mapping the geographic variation of earthquake risk in terms of maximum magnitude earthquakes and maximum ground motion accelerations expected to occur in the next T years.

1.2 Specific problems and research goals

In any seismic risk analysis estimation of the uncertainties in the predictions is a vital factor for the final judgement of the results. A specific goal is then to develop a technique to compute the errors on the parameters of the third type asymptotic distribution, and on all related predictions, using an error matrix. A second goal is to explore any physical meaning of these parameters by linking them with the physical release of strain energy. This is attempted by relating physical quantities such as mean annual energy release, derived from the linear frequency-magnitude and energy-magnitude laws, with the same quantities obtained using the parameters of the third type asymptote. The strain energy release and the third type asymptotic distribution methods are then tested on the seismicity of the circum-Pacific belt, and then applied to the seismicity of Greece.

Seismically, Greece is one of the most active countries in the world and the most active country in Europe. About 3 to 4% of the seismic energy release in the world is contributed by Europe, and half of this by Greece (Galanopoulos, 1971a). The long documented seismic history of Greece reports many catastrophes due to earthquakes (Galanopoulos 1961, Lomnitz 1974). However, demands of statistical seismology for data which is as accurate and homogeneous as possible, implies that instrumentally recorded events are preferable. The present century is the only available period with data of sufficient reliability for our purposes. Even so, because the worldwide density of stations has increased markedly from decade to decade, the completeness of a sample of earthquake data is strongly dependent not only on the geographic area but also on the particular time interval covered. In order to achieve a more accurate picture of seismic risk for Greece, an important aspect of this study must be the preparation of an homogeneous earthquake catalogue by relocating all the events for which there is sufficient data. For this purpose all earthquakes for the period 1917-1963 are selected from International and Greek sources and the hypocentral parameters will be recalculated, and the completeness of the data tested.

The calculation of seismic risk, either in terms of strain energy release or acceleration, velocity etc. depends critically on the magnitude of the earthquakes considered and so homogeneous magnitudes are necessary. This requirement can be best fulfilled if the magnitudes are determined from the same instruments which ideally should have been operating all the time. Thus a complementary aspect of relocation is the calculation of magnitudes for every single earthquake which appears in the new catalogue.

Uppsala Wiechert amplitudes from Uppsala seismological bulletins will be used to determine surface-wave magnitude up to 1954, whereas from 1955 onwards, the Uppsala and Kiruna amplitudes from modern instruments will be used.

Thus, the sample of extremes that eventually forms the final basis for statistical analysis of the earthquake risk in Greece consists of the set of annual maxima of magnitudes and accelerations which are drawn as required from the new catalogue. The final product will be detailed maps and evaluations of seismic risk in Greece.

CHAPTER II

REVIEW OF STATISTICAL MODELS

2.1 Introduction

The earthquake phenomenon has been analysed for many years in terms of specific characteristics such as its location, magnitude and focal depth. The set of these characteristics of historical earthquakes is called the "seismicity" of the region. With the development of the hypothesis of sea-floor spreading, however, the earthquake phenomenon and seismic activity in general began to be regarded as a global process. Since then, the generation and propagation of seismic energy from source to the site are among the earthquake's diverse seismic properties which have been studied with rising interest.

The occurrence of earthquakes in space and time falls under the general category of stochastic processes, that is, mathematical models of a given physical system that changes in accordance with the laws of probability (Lomnitz, 1974). Hence, statistical models have to be used, and the validity of the model checked by its concordance with past observations.

The aim of this chapter is to review some of the existing statistical models of the occurrence of earthquakes in time, magnitude and attenuation which includes acceleration, velocity and displacement. Emphasis is given to the Extreme-Value models, of which the third-type asymptotic distribution will be one of the main subjects of this study.

2.2 Statistical models using the whole process

2.2.1 Occurrence models

a) Simple Poisson model

Let us consider the earthquake as an event which occurs along a time axis. This model assumes that one event in a given magnitude range and in any given volume of the earth crust is equally likely to be found in any unit time interval along the time axis, and it is independent of any other event. The probability of finding n events in time t, if the mean rate of occurrence k is known, follows the Poisson probability law:

$$P(n,kt)=\frac{e^{-kt}(kt)^n}{n!} \qquad (2\text{-}1)$$

The mean and the variance of the Poisson distribution are both equal to the mean rate k.

According to the Poisson model, the probability of observing no events within a time t, that is of finding a time larger than t without events, is:

$$P(0,t)=e^{-kt} \qquad (2\text{-}2)$$

Then the probability of finding a time equal or less than t with no events is:

$$P(t)=1-e^{-kt}, 0<t<\infty \qquad (2\text{-}3)$$

This time interval is the waiting time or return period between two consecutive events. The corresponding probability density function is:

$$P'(t)=ke^{-kt}, t>0 \qquad (2\text{-}4)$$

with mean $1/k$ and variance $1/k^2$, where $P'(t)$ denotes the derivative of $P(t)$ with respect to time.

There are cases where the Poisson model seems to give satisfactory results, at least for main events or when dealing with large shocks throughout the world (Cornell and Kallberg, 1969, Sacuiu and Zorilescu, 1970). But many authors, for example, Knopoff (1964) and Vere-Jones (1970) find, after testing different regions in the world, that the Poisson model is inadequate and does not explain the time distribution of low magnitude events, because it ignores the tendency for these events to cluster in space and time. In addition to this, the Poisson model assumes that the distribution of the waiting time between events does not depend on knowledge of the time elapsed since the last one, that is the occurrence of a certain magnitude is completely independent of the occurrence of any other.

b) Clustering models

In order to improve the simple Poisson model the basic assumption of independence of events, especially at low magnitudes, has to be checked. Thus, in the case of simple dependence, the Markov model may be used, whereas the non-Markovian process may be the alternative approach for complex dependence.

(1) Markov model

The basic idea of using the Markov model for earthquake occurrence comes from the fact that according to the Elastic Rebound Theory (Reid, 1911), there is a storage of strain energy that has to build up before a new event takes place.

According to the Markov model, the probability of a future event depends on the past history of events so that (Oliveira, 1974):

$$P(n_k, t_k | n_o, t_o; n_1 t_1; \ldots n_{k-1}, t_{k-1}) = P(n_k, t_k | n_{k-1}, t_{k-1}) \qquad (2\text{-}5)$$

n_i, t_i being the number of events n_i to occur in the time interval t_i; or the probability of being in a state*k, after considering all the

*States of the process are the regions in which a multidimensional continuum is divided. For example, the variables: energy, number of earthquakes, latitude, longitude, depth and time, define a 6-dimensional space: the earthquake state space (Lomnitz, 1974).

states from zero up to k, depends only on the probability of being in the state k-1. This is a first order Markov chain characterized by the transition probability:

$$P(n_k, t_k | n_{k-1}, t_{k-1})$$

Authors like Shah and Vagliente (1972), Vagliente (1973), Benjamin and Cornell (1970) have emphasised the usefulness of Markov simulation but also some weaknesses of this model due to the difficulty in setting the initial conditions and because it requires complicated numerical treatment.

(2) Non-Markovian models

Applicability of some of these general models is discussed by Vere-Jones (1970). These models assume that earthquakes occur in clusters, and that the number of events in each cluster is stochastically independent of its origin time.

In these models the conditional probability of an event taking place during the interval (t,t+dt), given that the cluster consists of N shocks is equal (Esteva, 1976) to:

$$P(N,t) = N\ell(t)\,dt \qquad (2\text{-}6)$$

where

$$\ell(t) = \partial L(t)/\partial t \qquad (2\text{-}7)$$

L(t) being the cumulative distribution function of the time of an event corresponding to a given cluster, measured from the cluster origin time.

Most of these models are based on information about earthquakes with magnitudes above relatively low thresholds, recorded during time intervals of at most ten years, and as Esteva (1976) points out, the degree of clustering observed, and the distribution of times between clusters, cannot be extrapolated to higher magnitude thresholds and longer time interval without further study.

2.2.2 Magnitude models

The usual expression relating earthquake magnitudes with their rates of occurrence is due to Gutenberg and Richter (1944). This relationship is called "magnitude-frequency formula" and states that in a certain region and in a given period of time:

$$\log N(m) = a - bm \tag{2-8}*$$

where N(m) is the mean number of earthquakes per unit volume and per unit time having magnitude greater than m, and a and b are zone-dependent constants. a depends on the period of observation and on the level of seismicity of the region, and consequently, varies widely from region to region, while b remains within a relatively narrow range.

Equation (2-8) can be normalized to yield the frequency distribution of magnitudes in a region. Thus, for m=0 equation (2-8) becomes:

$$\log N(0) = a \tag{2-9}$$

and normalization is achieved by dividing through by N(0):

$$\log\left[1-F(m)\right] = \log\frac{N(m)}{N(0)} = bm \tag{2-10}$$

which yields:

$$1-F(m) = e^{-\beta m} (m \geq 0) \tag{2-11}$$

or

$$F(m) = 1-e^{-\beta m} (m \geq 0) \tag{2-12}$$

where $\beta = b/\log e = 1/\bar{m}$, and F(m) is the cumulative probability distribution of earthquake magnitudes. The frequency distribution f(m) is the first derivative of F(m):

$$f(m) = \beta e^{-\beta m} (m \geq 0) \tag{2-13}$$

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*Throughout this study the log is used for $\log_{10}$ whereas the expression ℓn is used for $\log_e$.

Experimental data show that the linear form (2-8) does not hold for very large earthquakes. Thus, alternative expressions to (2-8) have been proposed, attempting to represent more adequately the observed magnitude-recurrence data. Cornell and Vanmarcke (1969) impose a limitation or upper bound to the exponential distribution of magnitudes (2-13), by introducing a truncating factor $k(m_1)$ where m_I is the largest possible Richter's magnitude, the value of which for the world has been suggested as 8.5 to 9.0 (Richter, 1958). Thus, equation (2-13) becomes:

$$f(m)=k(m_1)\beta e^{-\beta m}, 0 \leq m \leq m_1 \qquad (2-14)$$

Sacuiu and Zorilescu (1970) and Merz and Cornell (1973) introduce a quadratic term for the magnitude into equation (2-8).

Most of the expressions, however, fail to recognize the existence of an upper bound to the magnitude that can be generated in a given region, the existence of which is inescapable (Esteva, 1976).

2.2.3 Attenuation model

The attenuation of seismic energy as it propagates from source to the site is a very important consideration for any seismic risk analysis. Attenuation models relate the changes of the characteristics of earthquake ground motion with distance. Seismic attenuation laws have been determined using the maximum acceleration, velocity and displacement. Esteva and Rosenblueth (1964) after considering data from earthquakes, the propagation of elastic waves and the definition of magnitude, proposed the general formula:

$$Y=b_1 e^{b_2 m} R^{-b_3} \qquad (2-15)$$

where Y, the peak ground motion, is connected with the magnitude m and the focal distance R; b_1, b_2, and b_3 are constants and their values depend on the type of Y considered. In Chapter VII, Table 7-7 summarizes some of the proposed formulae. Because of the limited number of strong-motion records and especially because most of these records come from the same area, these expressions often amount to modifications of the general formula (2-15) and allow for local conditions rather than large regional differences.

2.3 Extreme-Value theory fitting, using the part process

The previous models which use the whole process have a common "weak" point; there is a lack of accuracy, homogeneity and completeness of data sets used, at low magnitudes. These properties are very important for any statistical treatment and mainly depend on the sophistication of the instruments and networks used to record the earthquakes. Even now, after seventy years of continuous development, the problem still remains for smaller earthquakes. Another difficulty of applying the previous models is that in most cases the initial distribution function is not known. From the point of view of earthquake risk, however, the quantity usually needed is the maximum dynamic load to which a structure will be subject during its design life or, alternatively, the most probable return-period of a specified design load. Thus, what is of primary importance in earthquake engineering implies a need to consider the extreme value distribution separately from the statistics of the whole process.

The statistical theory which seems to overcome most of the above-mentioned problems is the Extreme-Value Theory. This theory following Gumbel's developments and applications to flood analysis (Gumbel, 1935, 1966) has attracted widespread interest and has been adapted by geophysicists for hydrological computations, climatic evaluations (Jenkinson 1955, Gringorten 1963b, Krumbein and Lieblein, 1956), as well as for analysis of earthquake events and seismic risk determination (Nordquist, 1945, Dick 1965, Epstein and Lomnitz 1966, Kárnik and Hubnerova 1968, Milne and Davenport 1969, Schenkova and Kárnik 1970, Stepp 1971, Shakal and Willis 1972, Curtis 1973, Yegulalp and Kuo 1974, Yegulalp 1974, Schenkova and Schenk 1975, Lilwall 1976, Willmore and Burton 1976, Schenkova and Kárnik 1976, 1978, Kárnik and Schenkova 1977, Burton 1978a, 1978b).

Some of the more important practical advantages of the Extreme-Value method are (Lomnitz 1974):

i) The extreme values of a geophysical variate are better known, more homogeneous in time, and more accurately determined than the average events in a time series of data.

ii) The method does not require a detailed knowledge of the parent distribution. The distribution of extremes depends only on the tail of the distribution of the variate, and certain important distributions behave in a similar way at large values; for example, the normal, exponential and log normal distributions.

While details of the theory and many references to basic original contributions will be found in the previous papers, it will be useful to summarize the main results. With regard to the largest value (a similar formulation applies to the smallest value) the problem is formulated as follows:

Suppose we have a sample consisting of N independent extremes, each being the largest of sample of size n, where n is large, drawn from the same parent population. The series of extremes then forms a distribution called the Extreme-Value distribution. For the case of annual extremes, n is equal to 365 days, and N is equal to period in years considered.

Suppose Y to be the largest earthquake occurring in a year; and define

$$y=\max(m_1,m_2,\ldots m_N) \qquad (2\text{-}16)$$

where the m_i form a sequence of annual maximum earthquakes drawn at random from the cumulative distribution F(m). Then the probability that Y will be the largest among N independent samples is:

$$\begin{aligned}\phi_N(y)&=P(Y\leqslant y)=P(\text{all } m_i\leqslant y)\\ &=P(m_1\leqslant y,m_2\leqslant y,\ldots,m_N\leqslant y)\end{aligned} \qquad (2\text{-}17)$$

Since the m_i are independent events, the probability of the largest event can be written using the multiplication rule as:

$$\begin{aligned}\phi_N(y)&=P(Y\leqslant y)=P(m_1\leqslant y)P(m_2\leqslant y)\ldots P(m_N\leqslant y)\\ &=F_{m_1}(y)F_{m_2}(y)\ldots F_{m_N}(y) \text{ and}\\ \phi_N(y)&=F_m^N(y)\end{aligned} \qquad (2\text{-}18)$$

The probability of a value to be equal or larger than y is

$$1-\phi_N(y)$$

and its reciprocal

$$T_N(y)=\frac{1}{1-\phi_N(y)} \qquad (2\text{-}19)$$

is the return period of y, which is the mean number of intervals required for a largest value greater than or equal to y to be observed.

If K year extreme intervals have to be used, the distribution $\phi_K(y)$ is related to $\phi_1(y)$ for the one year intervals by the formula:

$$\phi_K(y)=\phi_1^K(y) \qquad (2\text{-}20)$$

2.3.1 The three asymptotic distributions

Irrespective of the parent distribution, the distribution from which the extremes are sampled, the limiting extreme-value distribution (Davis 1970, p.205) must take one of three forms. These we will call first, second and third type asymptotic distributions of Gumbel (1966). Each of these assumes a specific behaviour for absolute large values of the variable (Gumbel, 1963). The three asymptotic distributions are:

$$\text{I} \qquad \phi^{(1)}(x)=\exp\left[-\exp(-a(x-u))\right], \quad a>o \qquad (2\text{-}20)$$

$$\text{II} \qquad \phi^{(2)}(x)=\exp\left[-\left(\frac{u-\varepsilon}{x-\varepsilon}\right)^{k}\right], \quad k>o,\ x\geqslant\varepsilon,\ u>\varepsilon\geqslant 0 \qquad (2\text{-}21)$$

$$\text{III} \qquad \phi^{(3)}(x)=\exp\left[-\left(\frac{\omega-x}{\omega-u}\right)^{k}\right], \quad k>0,\ x\leqslant\omega, u<\omega \qquad (2\text{-}22)$$

and if we introduce the reduced variable y as:

$$y= -\ln\left[-\ln\phi(x)\right] \qquad (2\text{-}23)$$

these become:

$$y_{I}=a(x-u) \text{ with sign of } \frac{d^2x}{dy^2}=0 \qquad (2\text{-}24)$$

$$y_{II}=k\ell n(x-\varepsilon) + \text{const with sign of } \frac{d^2x}{dy^2}>0 \qquad (2\text{-}25)$$

$$y_{III}=\text{const}-k\ell n(\omega-x) \text{ with sign of } \frac{d^2x}{dy^2}<0 \qquad (2\text{-}26)$$

The first type asymptotic distribution (2-20) holds for initial distributions unlimited in both directions (exponential or normal), but tends to zero exponentially in the tails. The second type arises when the initial distribution is bounded below and exponentially approaches zero in the upper tail. The third type results when the initial distribution is bounded towards the right. The second type asymptotic distribution is therefore ruled out, and only the third type asymptotic distribution, and for comparative reasons the first type, will be employed in the analysis of extreme magnitude earthquakes in this thesis.

2.3.2 Mathematical meaning of the parameters

a) For the first type asymptotic distribution:

<u>a</u> is the extremal intensity function

<u>u</u> is the characteristic largest value with the property

$$\phi^{(1)}(u) = \frac{1}{e}$$

and at the same time u is the mode of the largest values.

b) For the third type asymptotic distribution

<u>ω</u> is the upper limit with the property

$$\phi^{(3)}(\omega) = 1$$

<u>k</u> is the shape parameter and

<u>u</u> is again the characteristic largest value with

$$\phi^{(3)}(u) = \frac{1}{e}$$

but not the mode as in the first type asymptote.

The two asymptotic distributions have the common property

$$\phi^{(1)}(u) = \phi^{(3)}(u) = \frac{1}{e} \qquad (2\text{-}27)$$

Therefore, approximately 36% of the observations in all cases should be situated before the value x = u.

2.3.3 Physical meaning of the parameters

a) For the first type asymptotic distribution

1/a is a measure of dispersion of the extreme values of magnitude from the mode u where

u is the most probable observed annual (if the time interval is one year) maximum magnitude. For u we have (see 2.3.6):

$$u = \frac{a}{b}$$

where a and b are the constants of the frequency-magnitude or Gutenberg-Richter's law.

b) For the third asymptotic distribution

ω is the upper limit of the distribution (ie the largest earthquake magnitude that may occur in the area under consideration). Such an upper limit is likely to be a function of maximum source size in the Earth's crust and upper mantle (Yegulalp and Kuo, 1974).

u is the maximum magnitude which because of (2-27) is exceeded in the long run about 63% of the time.

k is the shape parameter because its reciprocal 1/k is a measure of the curvature of the asymptotic distribution curve. The value of k shows how quickly the curve approaches the upper limit.

2.3.4 Probability papers - plotting positions

a) Probability papers

Probability papers are constructed to obtain approximate straight lines for the observed (cumulative) frequencies for an assumed distribution. These papers were first suggested by Powell (1943) and prepared by Gumbel (1945), and give a simple graphical method of testing the fit between theory and observations. The choice of a probability paper is identical with the choice of a distribution. Generally, the probability paper is a rectangular grid where the observed variate x is plotted as ordinate and the reduced variate y as abscissa, both in linear scales. In addition, the probability $\phi(x)$ is plotted on a scale parallel to the scale of y, and the return period T(x) on an upper line parallel to the abscissa, going to the right. The scales $\phi(x)$ and T(x) are not linear.

Consider, for example, the first type asymptotic distribution of extremes:

$$\phi(x)=\exp\left[-\exp(-a(x-u))\right] \tag{2-28}$$

or taking the double logarithm

$$F(x)=-\ell n\left[-\ell n\phi(x)\right]=a(x-u)=y \tag{2-29}$$

then F(x) is a linear function of x and plots as a straight line on extreme probability paper.

b) Plotting position

In order to use the probability papers, the N annual extremes x_i are arranged in ascending size such that $x_1 \leqslant x_2 \leqslant \ldots \leqslant x_N$ and a probability value $\phi(x_i)$ has to be assigned to each extreme x_i. The value of $\phi(x_i)$ is determined from the N observed extremes in such a way that

$$0<\phi(x_1)<\phi(x_N)<1 \tag{2-30}$$

Gumbel (1954) has proposed the formula

$$\phi_N(x_i)=\frac{i}{N+1} \tag{2-31}$$

where i is the ordered value from a sample of size N. This formula gives an approximation to the expected probability for the ordered observations regardless of the initial distribution.

Kimball (1960) and Gringorten (1963a) have discussed alternative plotting positions and inherent bias in the various options. These plotting positions are:

$$\phi(x_i)=(i-\tfrac{1}{2})/N, \qquad (2\text{-}32)$$

$$\phi(x_i)=(i-\tfrac{3}{8})/(N+\tfrac{1}{4}), \qquad (2\text{-}33)$$

or

$$\phi(x_i)=(i-0.44)/(N+0.12) \qquad (2\text{-}34)$$

All these plotting formulae can be expressed by the general formula

$$\phi(x_i)=(i-a)/(N+1-2a) \qquad (2\text{-}35)$$

and the problem of selecting a suitable formula reduces to the problem of finding a suitable value of a. The equations (2-31) to (2-34) are derived from (2-35) for $a=0$, $a=\frac{1}{2}$, $a=\frac{3}{8}$, and $a=0.44$.

The plotting position (2-32) is used by Jenkinson (1955) for the analysis of meteorological data. Kimball (1960) shows that this position produces a bias for the largest of the annual extremes which is opposite in direction to that of Gumbel's (2-31), which as Knopoff and Kagan (1978) show also produces a significant bias. Gringorten (1963a) shows that as N becomes large, a approaches the value of

$$a=1-e^{-\gamma}=0.439 \qquad (2\text{-}36)$$

where γ, Euler's constant, is equal to 0.577..., and he suggests that (2-34) is most suitable for the double exponential Gumbel's first type asymptotic distribution. This function minimizes the bias in the long-return period end of the distribution. Hence, Gringorten formula is chosen in this study because we are more interested in obtaining best fit for the high magnitudes and long return periods at the right end of the distribution.

2.3.5 Estimation of the parameters

a) The first type asymptotic distribution

(1) Maximum likelihood method

Kimball (1946) estimates the parameters a and u of the first type asymptotic distribution (2-20), by the maximum likelihood method using complicated successive approximations. Stepp (1971) also uses this method for the earthquake risk analysis in the Puget Sound area (USA). The basic principle of the method is to maximize the product:

$$P=\prod_{i=1}^{N} f(x_i;u,a) \tag{2-37}$$

With respect to u and a, where $f(x)=\phi'(x)$ is the probability function and N the sample size. If we use the logarithm, then (2-37) becomes:

$$L=\sum_{i=1}^{N} \log f(x_i;u,a) \tag{2-38}$$

The conditions of maxima L with respect to u and a are:

$$\frac{\partial L}{\partial u}=0 \text{ and } \frac{\partial L}{\partial a}=0 \tag{2-39}$$

By simultaneously solving these equations using successive approximations one can get the maximum likelihood estimates of u and a.

The maximum likelihood method applied to ordered extremes, weights the lower extremes of the series (Kimball 1946) relatively much more than the upper extremes. However, when treating annual earthquake extremes, known to be incomplete especially at the low magnitudes, this property of the maximum likelihood method may influence the final estimates.

(2) Least-squares method

The advantage of probability paper is the transformation of the theoretical curve $\phi(x)$, x into a straight line. The linear reduction

$$y=a(x-u) \text{ or } x=u+\frac{1}{a}y \qquad (2\text{-}40)$$

for which any probability paper is designed also allows the classical method of least-squares to be used. This method is used for the estimation of u and a throughout this study.

b) The third type asymptotic distribution

(1) Method of moments

The parameters ω, u, and k of the third type asymptotic distribution (eq 2-22), may be estimated with the help of the first three sample moments (Gumbel 1966, Yegulalp and Kuo 1974).

Equation (2-22), with the transformation

$$z=\frac{\omega-x}{\omega-u}\ ,\ x\leqq\omega \qquad (2\text{-}41)$$

becomes

$$\phi(x)=e^{-z^{k}} \qquad (2\text{-}42)$$

Then, the reduced moment of order z^{ℓ} is:

$$\overline{z^{\ell}}=-\int_{0}^{\omega}z^{\ell/k}de^{-z}=\frac{\ell}{k}\Gamma\left(\frac{\ell}{k}\right) \qquad (2\text{-}43)^{*}$$

Hence

$$\overline{(\omega-x)^{\ell}}=(\omega-u)^{\ell}\Gamma\left(1+\frac{\ell}{k}\right) \qquad (2\text{-}44)$$

---

*Γ(x) is called Gamma Function and defined as:

$$\Gamma(x)=\begin{cases}\int_{0}^{\infty}e^{-t}t^{x-1}dt, & \text{for } x>0\\ \lim\limits_{n\to\infty}\dfrac{n!n^{x-1}}{x(x+1)(x+2)\ldots(x+n-1)}, & \text{for } x\neq 0,-1,-2,\ldots\end{cases}$$

The three moments can be obtained from equation (2-44) by substituting 1, 2, 3 for ℓ respectively.

Then, the estimators of the parameters can be found from tables (Gumbel, 1966 p.282).

The estimation of the parameters can also be obtained with the help of the first two moments and the largest observed earthquake magnitude in a period of N years. Thus, it is possible to avoid the third moment which has a large variance and the disadvantage of the previous consideration which does not assure that the upper limit ω is larger than the largest earthquake magnitude observed in N years. An estimated upper limit for the largest magnitudes, which is smaller than the largest observed value, does not make sense.

The estimators of ω, u, and k can also be found from the tables of k and N (Gumbel, 1963).

(2) Method of least-squares

Because the previous method needs all the values of x_i to be available and because earthquake catalogues are, in practice, incomplete, Yegulalp and Kuo (1974) decided to approach the problem using the least-squares method. The main points of this method are:

If $x_1, x_2, \ldots x_N$ are the observed maximum magnitudes in a given region, and $P_1, P_2, \ldots P_N$ are the corresponding plotting positions, then the problem consists of minimizing the sum of squares of the differences between the theoretical and observed maximum magnitudes:

$$n = \sum_{i=1}^{r} (x_i - x_i')^2, \text{ for } \omega>0,\ 0<u<\omega, k>0 \qquad (2\text{-}45)$$

where

$$x_i' = \omega - (\omega - u)\left[-\ell n \phi(x_i)\right]^{1/k} \qquad (2\text{-}46)$$

The necessary and sufficient conditions to minimize n are:

$$\frac{\partial n}{\partial \omega} = \frac{\partial n}{\partial u} = \frac{\partial n}{\partial (1/k)} = 0 \qquad (2\text{-}47)$$

and

$$\frac{\partial^2 n}{\partial \omega^2}, \frac{\partial^2 n}{\partial \omega \partial u}, \frac{\partial^2 n}{\partial u^2}, \frac{\partial^2 n}{\partial (1/k)^2}, \frac{\partial^2 n}{\partial \omega \partial (1/k)}, \frac{\partial^2 n}{\partial u \partial (1/k)} > 0 \qquad (2\text{-}48)$$

for $\omega > o$, $o < u < \omega$, $k > o$

Thus, estimators of ω, u, and k can be obtained by satisfying these conditions.

While this method avoids rather than takes into account the incompleteness of earthquake catalogues, it does not consider the other important factor of accuracy of earthquake magnitudes. Thus we need more powerful estimation methods which allow weights to be assigned to each individual extreme. The variance-covariance, or error matrix, for the parameters should also be examined. Given the uncertainties of the parameters, we can then examine the stability of the system and accordingly the usefulness of this procedure when applied to forecasting. This is attempted in the present study (Chapter IV).

2.3.6 Useful relations for forecasting procedure

a) For the first type asymptotic distribution

Epstein and Lomnitz (1966) show that assuming a Poisson distribution for the number of earthquakes with magnitude exceeding zero in a year, and if m, the magnitude, is a random variable distributed with cumulative distribution function:

$$F(m) = 1 - e^{-\beta m}, \quad m \geqslant 0 \qquad (2\text{-}49)$$

then, the largest annual earthquake magnitude is distributed with the cumulative distribution function:

$$G(m)=\exp\left[-a\exp(-\beta m)\right], \ m\geq 0 \tag{2-50}$$

But equation (2-50) corresponds to equation (2-20)which is the first asymptotic distribution of largest values. From (2-20) taking the logarithm twice, we have:

$$\ell n\left[-\ell n\phi(x)\right]= ua-ax \tag{2-51}$$

and if we note that:

$$\exp\left[-a(x-u)\right]$$

is the expected number of earthquakes, N_x in a given year which have magnitude exceeding x, it follows that:

$$\ell nN_x=ua-ax \tag{2-52}$$

Comparison between (2-52) and the widely used Gutenberg-Richter's empirical formula

$$\log N_x=a'-bx \tag{2-53}$$

gives $$a'=ua/\ell n10 \tag{2-54}$$

and $$b=a/\ell n10 \tag{2-55}$$

from which $$\frac{a'}{b} = u \tag{2-56}$$

which is the mode or most probable annual maximum magnitude.

The same authors have derived the following relations:
The modal earthquake magnitude in a T years period is

$$\tilde{m}_T = u + \frac{\ell nT}{a} \text{ or (Curtis, 1973) } \tilde{m}_T = \frac{a'}{b} + \frac{\log T}{b} \quad (2\text{-}57)$$

The value m_p of the annual maximum magnitude which is exceeded with probability p is

$$m_p = u - \frac{\ell n\left[-\ell n(1-p)\right]}{a} \text{ or } m_p = \frac{a'}{b} - \frac{\log\left[-\ell n(1-p)\right]}{b} \quad (2\text{-}58)$$

The value m_{pr} of the maximum magnitude which is exceeded with probability p in an r year period is

$$m_{pr} = m_p + \frac{\ell nr}{a} \text{ or } m_{pr} = m_p + \frac{\log r}{b} \quad (2\text{-}59)$$

Finally, the probability P_{mr} of occurrence of an earthquake of magnitude greater than m in an r year period is:

$$P_{mr} = 1 - \exp\left[-r\exp(-a(m-u))\right]$$

or

$$P_{mr} = 1 - \exp\left[-10^{a'} r\exp(-bm\ell n10)\right] \quad (2\text{-}60)$$

b) For the third type asymptotic distribution

While for the first type asymptote the characteristic largest value, u, coincides with the mode of the distribution, in the third type asymptote this property does not exist because of the asymmetry of the distribution.

Thus, the mode of the third type asymptote is (Gumbel, 1966, p 286)

$$\tilde{m} = \omega-(\omega-u)(1-\frac{1}{k})^{1/k} \quad (2\text{-}61)$$

which for the next T years will be (Yegulalp, 1974):

$$\tilde{m}_T = \omega-(\omega-u)\left[(1-\frac{1}{k})/T\right]^{1/k} \quad (2\text{-}62)$$

From the method of moments, (eq 2-44 for ℓ=1), the expected annual largest magnitude $\bar{m}$ is:

$$\bar{m} = E(m) = \omega-(\omega-u)\Gamma(1 + \frac{1}{k}) \quad (2\text{-}63)$$

and the expected largest magnitude for the next T years, $E(m_T)$, will be:

$$\bar{m}_T = E(m_T) = \omega-(\omega-u)\Gamma(1 + \frac{1}{k})T^{1/k} \quad (2\text{-}64)$$

In addition to these point estimates, Yegulalp (1974) considers the interval in which the largest earthquakes of the next T years will lie with a given probability a, by solving the equations:

$$1 - \frac{a}{2} = \exp\left[-T((\omega-m_{up})/(\omega-u))^k\right] \quad (2\text{-}65)$$

and

$$\frac{a}{2} = \exp\left[-T((\omega-m_\ell)/(\omega-u))^k\right] \quad (2\text{-}66)$$

where m_{up} and m_ℓ are the upper and lower bounds respectively. Thus we have:

$$m_{up} = \omega-(\omega-u)\left[-\frac{1}{T}\ln(1 - \frac{a}{2})\right]^{1/k} \quad (2\text{-}67)$$

and

$$m_\ell = \omega-(\omega-u)\left[-\frac{1}{T}\ln(\frac{a}{2})\right]^{1/k} \quad (2\text{-}68)$$

2.3.7 Applications of the Extreme-Value theory to Seismic risk problems

Nordquist (1945) was the first to apply the theory of extreme values for the estimation of the probability of occurrence of maximum magnitude earthquakes. He demonstrates that the theory is applicable to the seismic hazard problem. Using world data for 1904 to 1939 from Gutenberg and Richter (1941), and data from Southern California, he shows that the probability of occurrence of maximum magnitude earthquakes obeys fairly well the first type asymptotic distribution of the largest values. Dick (1965) applied the theory to New Zealand earthquake data for 1942-1961. Since 1966, when Epstein and Lomnitz pointed out the relation among the first type asymptote parameters and the Gutenberg-Richter's frequency-magnitude constants (see 2.3.6), many authors have published papers using the first type asymptote [Lomnitz (1966, 1974), Kárnik and Hubnerova (1968), Milne and Davenport (1969), Schenkova and Kárnik (1970), Kárnik (1971), Shakal and Willis (1972), Curtis (1973), Schenkova and Schenk (1975), Rikitake (1976), Scenkova and Kárnik (1976)].

Yegulalp and Kuo (1966) approach the occurrence of maximum magnitude earthquakes by considering the third type asymptotic distribution. They use World Seismicity data for 1904-1952 from Gutenberg-Richter (1954), and find that the regional occurrence of maximum magnitude earthquakes favours the third rather than the first type asymptotic distribution. Makjanic (1972) proposes that the distribution of the intensities of earthquakes felt at Zagreb also follows the third type asymptotic distribution. He found an intensity of 8.83 on the Mercalli, Cancani, Sieberg (MCS) scale, to be the upper limit for intensities at that city. In a second paper by Yegulalp and Kuo (1974) the early results are improved by applying a test of predictability. They predict the magnitude corresponding to the return periods 2, 3, 5 and 13 years for data in the interval 1953-1965 by using previously estimated parameters. Comparison between the number of exceedances with these observed for the same magnitude show remarkably good agreement. The establishment of a forecasting procedure for largest earthquake magnitudes is also attempted by Yegulalp (1974). Using Yegulalp and Kuo's method for estimation of the parameters ω, u and k, Lilwall (1976) and Willmore and Burton (1976) analyse the seismicity and seismic hazard in the UK, and Kárnik and Schenkova (1977) in the Balkan earthquake provinces.

Burton (1978a and b) analysed the seismicity of UK and the European area using Marquardt's technique of estimating the parameters and their uncertainties (Marquardt, 1963). This technique is further developed in the present work (Chapter IV).

2.4 Summary

The review of the statistical models which use the whole process reveals several weak points caused by the inclusion of low magnitude data, such as lack of completeness, accuracy and homogeneity. The Extreme-Value theory using only extreme magnitudes, which are more complete and accurate, seems to overcome most of these problems. The first type asymptotic distribution assumes that the distribution of extremes is unlimited in both directions, whereas, the third type asymptotic distribution is limited towards the right. Since, for the earthquake magnitude, such an upper bound must be set by the strength of the crustal rocks (Richter, 1958), the third type asymptotic distribution will be used for the seismic risk analysis in this study. It will be compared with the first type asymptotic distribution and the energy release methods (Chapter IV). First, in the next chapter, the upper bound for the earthquake magnitude will be analysed in terms of energy release.

CHAPTER III

THE UPPER BOUND FOR EARTHQUAKE MAGNITUDE

3.1 Statement of the problem

Since 1944 when Gutenberg and Richter obtained their well-known empirical frequency-magnitude relation (see equation 2-8), the magnitude, m, of an earthquake has been recognised to be as important a parameter as the location and depth. Furthermore the relation

$$\log E = A + Bm \qquad (3\text{-}1)$$

with A and B constants, has shown the physical meaning of magnitude to be a measure of the energy E, released during an earthquake of magnitude m. However, as in paragraph 2.2.2 is pointed out, cases where discrepancies between data and the simple frequency-magnitude law (2-8) become apparent especially for low or very high magnitude ranges, and expressions alternative to (2-8) have been proposed.

Richter (1958) considering the behaviour of the frequency-magnitude experimental data, affirmed that "a physical upper bound to the largest possible magnitude must be set by the strength of the crustal rocks, in terms of the maximum strain which they are competent to support without yielding". Yegulalp and Kuo (1974) have asserted that "it is apparent on physical grounds that there must exist an upper limit to the occurrence of a maximum magnitude earthquake in each region".

But while the alternative expressions are in general agreement with the observations, they do not identify what this upper bound is, nor do they include this upper bound as an unknown parameter in the resulting distribution function. However, the more or less arbitrary introduction of an upper bound, similar to those above (eq 2-14), without considering the dependency of such an upper bound on some physical parameters characterising the region contributes to errors in the evaluation of the other parameters of the distribution.

In the next paragraph will be demonstrated that using the simple Gutenberg-Richter relation (2-8) it is possible to include an upper bound for magnitude of earthquakes, that this is necessary, and furthermore the value of such an upper bound for a given region will be found.

3.2 Energy release and the upper bound for earthquake magnitude

3.2.1 Mathematical consideration

Let: M_1 be the most probable annual maximum magnitude (mode)

M_2 be the magnitude which corresponds to the annual rate of energy release, and

M_3 the upper bound for the earthquake magnitude in the same region.

From the relations (2-8) and (3-1) we have:

$$\ell nN = a' - b'm \rightarrow N = e^{a'-b'm} \tag{3-2}$$

and

$$\ell nE = A' + B'm \rightarrow E = e^{A'+B'm} \tag{3-3}$$

where $a' = a\ell n10$, $b' = b\ell n10$, $A' = A\ell n10$ and $B' = B\ell n10$ (3-4)

The number of earthquakes per year with magnitude range dm is:

$$N(m) - N(m + dm) = e^{a'-b'm} - e^{a'-b'(m+dm)}$$

or

$$dN(m) = b'e^{a'-b'm}dm \tag{3-5}$$

The annual energy release for all earthquakes with magnitude in the range dm, $\bar{E}$, is then:

$$d\bar{E} = e^{A'+B'm}.b'e^{a'-b'm}dm \tag{3-6}$$

and the total energy release, TE, is

$$TE = \int_{M_o}^{M_3} \bar{E}(m)\,dm = b'\int_{M_o}^{M_3} e^{A'+B'm} \cdot e^{a'-b'm}\,dm$$

$$= b'e^{a'+A'} \cdot \frac{1}{B'-b'} \cdot e^{(B'-b')m}\Big|_{M_o}^{M_3} \tag{3-7}$$

where M_o is the earthquake magnitude threshold.

Equation (3-7) is equivalent to

$$TE = \frac{b'}{B'-b'} \cdot e^{a'+A'} \left[e^{(B'-b')M_3} - e^{(B'-b')M_o}\right] \tag{3-8}$$

Usually $b \sim 1$ and $B = 1.44$ for surface wave magnitude M_s used in this study (Bath, 1958), so $B-b \sim 0.5$. Hence, only case when $B > b$, which is almost always observed, will be considered hereafter.

Using the definition of M_2 equation (3-8) becomes:

$$TE \equiv e^{A'+B'M_2} = \frac{b'}{B'-b'}\left[e^{a'+A'+(B'-b')M_3} - e^{a'+A'(B'-b')M_o}\right] \tag{3-9}$$

and if we notice (eq 2-56) that:

$$\frac{a'}{b'} = \frac{a}{b} = M_1 \tag{3-10}$$

from equation (3-9) we have:

$$e^{B'M_2} = \frac{b'}{B'-b'} \cdot e^{M_1 b'}\left[e^{(B'-b')M_3} - e^{(B'-b')M_o}\right] \tag{3-11}$$

As $M_o \to -\infty$ (unlimited to the left) equation (3-11) becomes:

$$e^{B'M_2} = \frac{b'}{B'-b'} \cdot e^{M_1 b'} \cdot e^{(B'-b')M_3} \tag{3-12}$$

or equivalently:

$$B'M_2 = \ell n(\frac{b'}{B'-b'}) + M_1 b' + (B'-b')M_3 \qquad (3\text{-}13)$$

From (3-13) by solving for M_2 and M_3 we get:

$$M_2 = \frac{b'}{B'} M_1 + \frac{B'-b'}{B'} M_3 + \frac{1}{B'} \ell n(\frac{b'}{B'-b'}) \qquad (3\text{-}14)$$

and

$$M_3 = \frac{1}{B'-b'}\left[B'M_2 - b'M_1 - \ell n(\frac{b'}{B'-b'})\right] \qquad (3\text{-}15)$$

Because the mean rate of energy release (M_2) is finite (Knopoff and Kagan, 1978) the M_3 from the equation (3-15), must be finite.

The relations (3-14) and (3-15), because of (3-4) become:

$$M_2 = \frac{1}{B}\left[bM_1 + (B-b)M_3 + \log(\frac{b}{B-b})\right] \qquad (3\text{-}16)$$

and

$$M_3 = \frac{1}{B-b}\left[BM_2 - bM_1 - \log(\frac{b}{B-b})\right] \qquad (3\text{-}17)$$

Thus:

$$M_3 = C_1(b)M_2 + C_2(b)M_1 + C_3(b) \qquad (3\text{-}18)$$

where

$$C_1(b) = \frac{B}{B-b},\ C_2(b) = -\frac{b}{B-b},\ \text{and } C_3(b) = -\frac{1}{B-b}\log(\frac{b}{B-b}) \qquad (3\text{-}19)$$

In addition to the previous relations it can be shown that:

$$M_3 - M_2 = C_1(b)M_2 - M_2 + C_2(b)M_1 + C_3(b) \qquad (3\text{-}20)$$

$$= [C_1(b) - 1]M_2 + C_2(b)M_1 + C_3(b)$$

and because

$$C_1(b) - 1 = -C_2(b) \qquad (3\text{-}21)$$

it follows that:

$$M_3 - M_2 = -C_2(b)\left[M_2 - M_1\right] + C_3(b) \qquad (3\text{-}22)$$

similarly,

$$M_3 - M_1 = C_1(b)\left[M_2 - M_1\right] + C_3(b) \qquad (3\text{-}23)$$

From the previous consideration, several features are significant. The first feature to note is that a finite upper bound to the largest earthquake magnitude is necessary to preserve a finite rate of energy release. This is inescapable even if the usual linear frequency-magnitude law applies for a given region. A second significant feature comes from equation (3-18). The upper bound M_3 is a function of the most probable annual maximum magnitude M_1, and the mean annual rate of energy release M_2. Furthermore, M_3 depends on the b value which characterizes the region from seismotectonic point of view. The relation between M_3 and b coupled with the property of b being different from region to region (Duda, 1965), leads to the conclusion that each region must also have its own upper bound for earthquake magnitudes expected to occur within that region.

Thus, for a given region having the a and b of equation (2-8) and calculating the mean annual rate of energy released simply by dividing the total energy released ΣE, for a given period, T, with that period (ie $\Sigma E/T$) we can calculate M_2 and M_1 from equations (3-1) and (3-10) respectively. Equation (3-18) can then be used to estimate the maximum magnitude earthquate, M_3, which may occur within that region. From the above equations the uncertainties of M_1, M_2, and M_3 can also be estimated.

The stationarity of M_3 is, of course, related to the stationarity of the parameters a and b. Generally, the larger the number of earthquakes available for analysis, the more reliable are the estimates of a and b (Duda, 1965) and consequently of M_3.

3.2.2 Graphical method of estimating M_2 and M_3

The graphical method of estimating M_2 and M_3 for a given region consists of plotting the cumulative energy released as a function of time. It is based on the assumption that the rate of total energy accumulation and release in a given region with similar geological structure, remains fairly constant, provided that the period of observation is long enough to average out existing periodicities. Because it is intuitively evident that the strain producing forces do not change within a time span of a few hundred years, it is reasonable to assume that in a given region, the rate of strain or energy accumulation and the possibilities of energy storage per unit volume are everywhere similar within the region. Hence the total amount of energy that may be accumulated and released remains fairly constant.

Therefore, from the graph of cumulative energy released as a function of time (see Figure 3-1), we can derive:

i) the rate of energy released as the slope of the line, SS', which connects the starting point S (0.0 energy), with the final S', (E total). If the time interval is taken to be one year (ΔT = 1 year), then the slope ($\Delta E/\Delta T$) represents the annual rate of energy released, and the corresponding magnitude will be M_2.

ii) Since the total energy that may be accumulated and released in a given region is constant, the two lines, BB' and CC' of maximum and minimum energy released, that is the lines which pass through the end, BB', and beginning, CC', points of the active periods, PP', should run parallel to each other and to the SS'. Thus the vertical

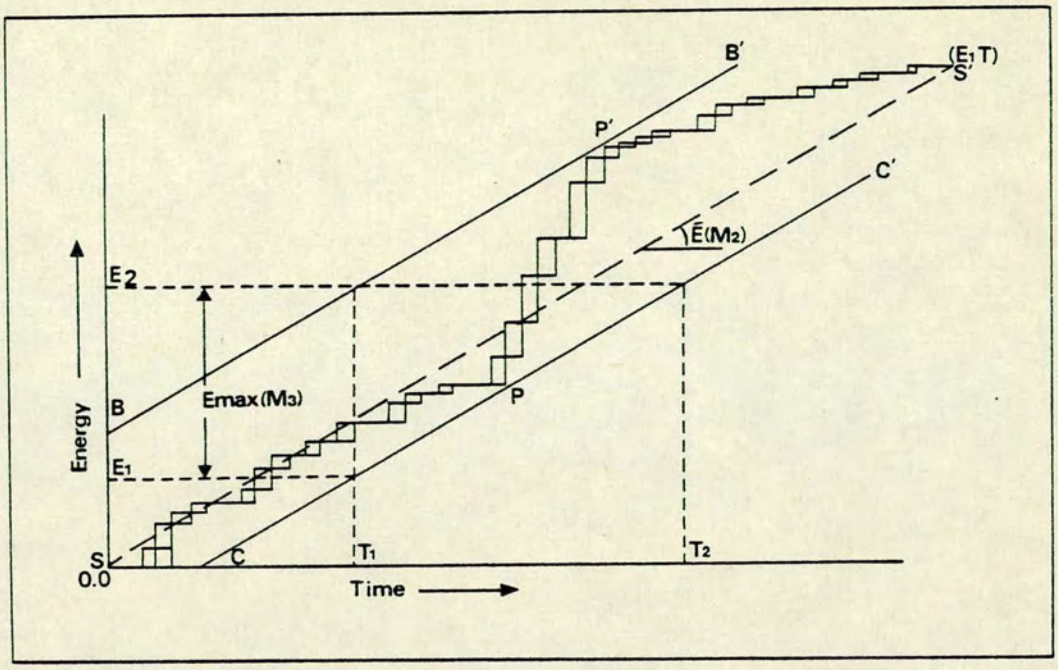


Fig 3-1 Explanatory diagram for graphical representation of the energy release method of calculating upper bound magnitude and mean annual energy release.

SOUTH AMERICA

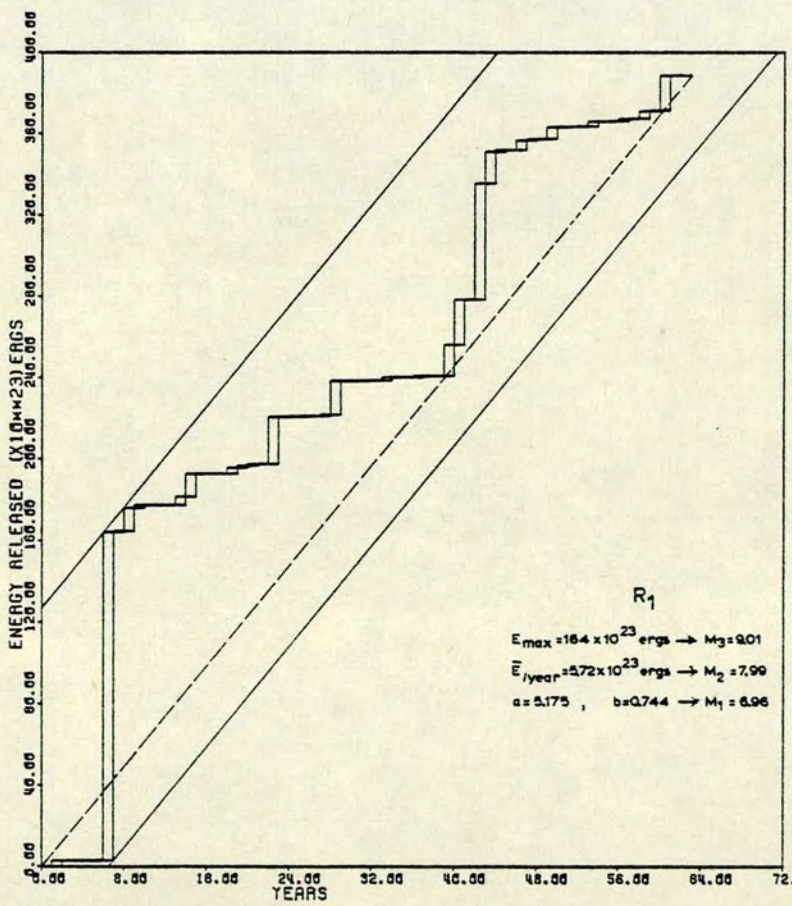


Fig 3-2 Cumulative energy release as a function of time for Region 1, and period 1897-1964. The insert shows the values of maximum possible energy release Emax, mean annual energy release $\overline{E}$/year, and the values of a and b of the frequency-magnitude formula. The magnitudes which correspond to Emax, $\overline{E}$/year, and annual mode (a/b) are also listed.

distance, E_1E_2, of these two enveloping parallel lines, indicates the total amount of energy that may be released in the region. Hence, the vertical distance (energy) E_1E_2 is the upper limit for the energy that can be observed in the region E_{max}, if the accumulated energy can be released by a single earthquake. The corresponding magnitude of such an earthquake must correspond to M_3.

iii) The horizontal distance T_1T_2, between the two parallel lines BB' and CC' indicates the minimum time, Tr, required for the accumulation of the maximum energy if there were no earthquakes in the meantime. This time interval will be called the "waiting time".

3.2.3 Testing the two methods

In order to test both analytical and graphical methods, the circum-Pacific belt is chosen. This region is seismically the most active in the world. Only 24% of the earth's seismic energy release occurs outside of it (Duda, 1965).

Data used are those compiled by Duda (1965) and his catalogue supplies the most reliable data now available for large earthquakes ($M \geqslant 7.0$) and seems homogeneous over the whole world for the magnitudes and period considered.

Following Duda's subdivision, the circum-Pacific belt is divided into eight subregions as follows:

(1) Region 1 (South America)

(2) Region 2 (North America)

(3) Region 3 (Aleutians, Alaska)

(4) Region 4 (Japan, Kurile, Kamchatka)

(5) Region 5 (New Guinea, Banda Sea, Celebes, Moluccas, Philippines)

(6) Region 6 (New Hebrides, Solomon, New Guinea)

(7) Region 7 (New Zealand, Tonga, Kermadec) and

(8) Region 8 (Caroline, Marianas)

The last subregion (Region 8) is rejected because of insufficient data.

For each of the seven remaining subregions, the constants a and b of the frequency-magnitude relation (2-8) and the annual energy release using equation (3-1) with constants A = 12.24 and B = 1.44 (Båth, 1958) are calculated for shallow and shallow plus intermediate earthquakes. The period considered is from 1897 to 1964. The values of a and b and their standard deviations σ_a and σ_b are calculated by the least squares method.

Tables 3-1 and 3-2 tabulate the values of a, σ_a, b, σ_b, total energy released within the whole period TE, mean annual energy released TE/year, M_1, ΔM_1, M_2, ΔM_2 as well as the values of M_3 for both analytical M_{3A}, ΔM_{3A}, and graphical M_{3G} methods for each subregion for shallow and shallow plus intermediate earthquakes respectively. Both tables also contain the ratios M_2/M_1, M_3/M_1, the waiting time TR, and the difference betwen M_3 and M_2 for each region. Table 3-2 also includes the same parameters for Greece for the period 1952-1972 (Galanopoulos, 1972a) Turkey for the period 1918-1973 (Alsan et al., 1975), and for the world as a whole for the period 1897-1970 (Båth, 1973). For Turkey and the world, the graphs of energy released as a function of time published by these authors are used to obtain M_3, whereas for Greece only the analytical method is applied. The results of the graphical method used for Greece from 1950-1972 are from Galanopoulos (1972a) who used a graph of strain released as a function of time, to calculate M_3. The graphical method for regions and periods noted by the captions is illustrated in Figures 3-2 to 3-11.

3.2.4 Results and discussion

a) General features

Figures 3-2 to 3-11 and table 3-1 and 3-2 reveal several general features. The first is that as the energy release decreases and gets closer to the lower parallel bound, the possibility of having a large earthquake increases and vice versa. Thus, the lower (upper) parallel bound is

Table 3-1

Parameters computed from shallow earthquakes

Region	a	b	M_1	TE*/year	M_2	M_{3A}	M_{3G}	M_2/M_1	M_{3A}/M_1	M_{3A}/M_2	$M_{3A}-M_2$	Tr(years)
(1) South America	5.18 ±.58	0.74 ±.08	6.96 ±.05	5.72	7.99 ±.13	9.05 ±.32	9.01	1.15	1.30	1.13	1.06	27
(2) North America	8.40 ±.62	1.15 ±.07	7.29 ±.04	4.50	7.93 ±.09	8.87 ±.56	9.00	1.09	1.22	1.12	0.94	31
(3) Aleutians-Alaska	5.86 ±.68	0.85 ±.08	6.89 ±.05	3.70	7.86 ±.12	9.03 ±.37	8.97	1.14	1.31	1.15	1.17	21
(4) Japan, Kuril, Kamchatka	8.14 ±.51	1.10 ±.06	7.40 ±.03	8.50	8.11 ±.09	9.19 ±.48	8.91	1.10	1.24	1.13	1.08	25
(5) N. Gun. Bunda Sea, Celebes	9.17 ±.62	1.24 ±.07	7.39 ±.03	6.10	8.02 ±.09	9.04 ±.83	8.92	1.09	1.22	1.13	1.02	19
(6) N. Hebr. Solom. N. Guinea	9.27 ±.81	1.27 ±.10	7.27 ±.04	2.99	7.80 ±.06	8.61 ±.84	8.70	1.08	1.18	1.10	0.81	16
(7) N. Zeal., Tonga, Kermadec	6.52 ±.54	0.94 ±.07	6.93 ±.04	2.99	7.80 ±.16	8.96 ±.54	8.93	1.12	1.29	1.15	1.16	41

* Units are 10^{23} erg

Table 3-2

Parameters computed from shallow plus intermediate earthquakes

Region	a	b	M_1	TE*/year	M_2	M_{3A}	M_{3G}	M_2/M_1	M_{3A}/M_1	M_{3A}/M_2	$M_{3A}-M_2$	Tr(years)
(1) South America	7.54 ±.49	1.04 ±.06	7.24 ±.04	6.44	8.03 ±.12	9.18 ±.54	9.10	1.11	1.27	1.14	1.15	25
(2) North America	8.74 ±.81	1.19 ±.10	7.34 ±.03	4.74	7.94 ±.10	8.86 ±.55	9.00	1.08	1.21	1.12	0.92	33
(3) Aleutians-Alaska	6.73 ±.53	0.95 ±.07	7.07 ±.04	4.06	7.89 ±.11	9.01 ±.41	8.78	1.12	1.27	1.14	1.12	20
(4) Japan, Kuril, Kamchatka	8.42 ±.55	1.12 ±.07	7.52 ±.03	10.43	8.18 ±.07	9.11 ±.42	8.96	1.09	1.21	1.11	0.93	14
(5) N. Gun. Bunda Sea, Celebes	8.23 ±.37	1.10 ±.05	7.48 ±.03	8.62	8.12 ±.06	9.00 ±.36	9.04	1.09	1.20	1.11	0.88	22
(6) N. Hebr. Solom. N. Guinea	10.29 ±.44	1.40 ±.06	7.35 ±.04	4.19	7.90 ±.05	8.83 ±2.80	8.83	1.07	1.20	1.12	0.93	21
(7) N. Zeal., Tonga, Kermadec	7.36 ±.31	1.04 ±.04	7.08 ±.03	3.63	7.86 ±.13	9.03 ±.55	8.97	1.11	1.27	1.15	1.17	30
Greece (1950-1972)	6.89 ±.14	1.05 ±.02	6.58 ±.05	1.37	7.45 ±.12	8.60 ±.57	8.52	1.13	1.31	1.15	1.15	30
Turkey (1913-1973)	4.11 ±.07	0.68 ±.01	6.04 ±.05	0.33	7.19 ±.09	8.11 ±.23	7.95	1.18	1.34	1.14	0.92	14
World (1897-1970)	10.44 ±.80	1.29 ±.10	8.09 ±.03	44.00	8.68 ±.04	9.24 ±.53	9.52					18

* Units are 10^{23} erg

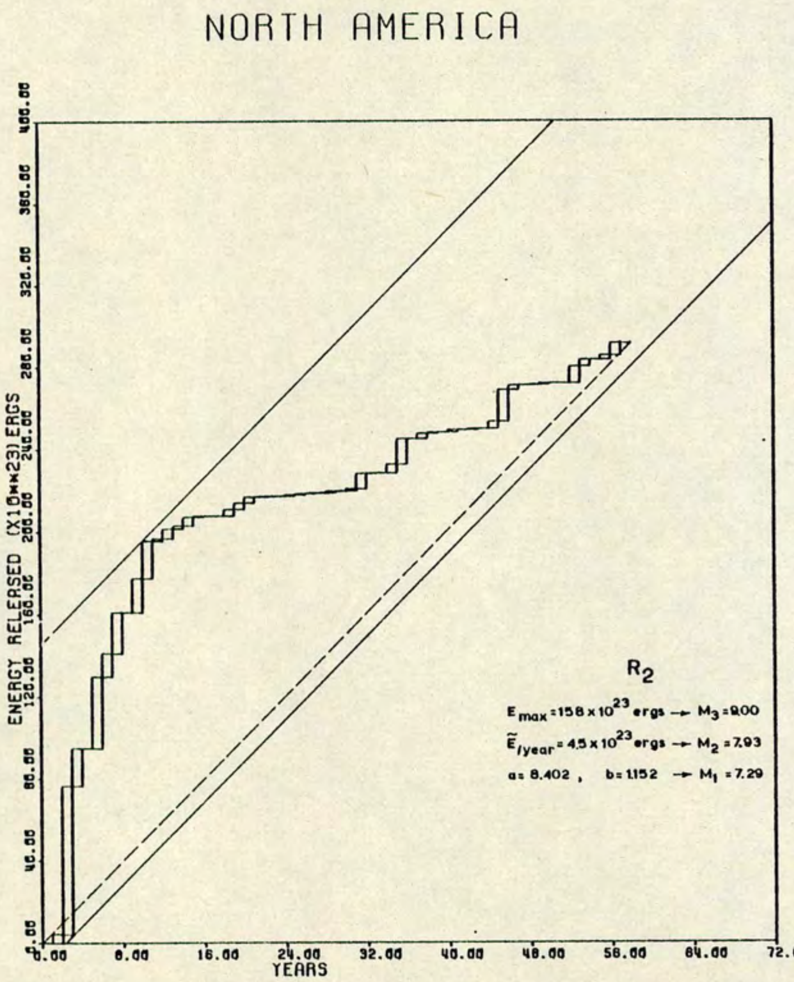


Fig 3-3 Cumulative energy release as a function of time for Region 2, and period 1897-1964. For explanation of the insert see Fig 3-2.

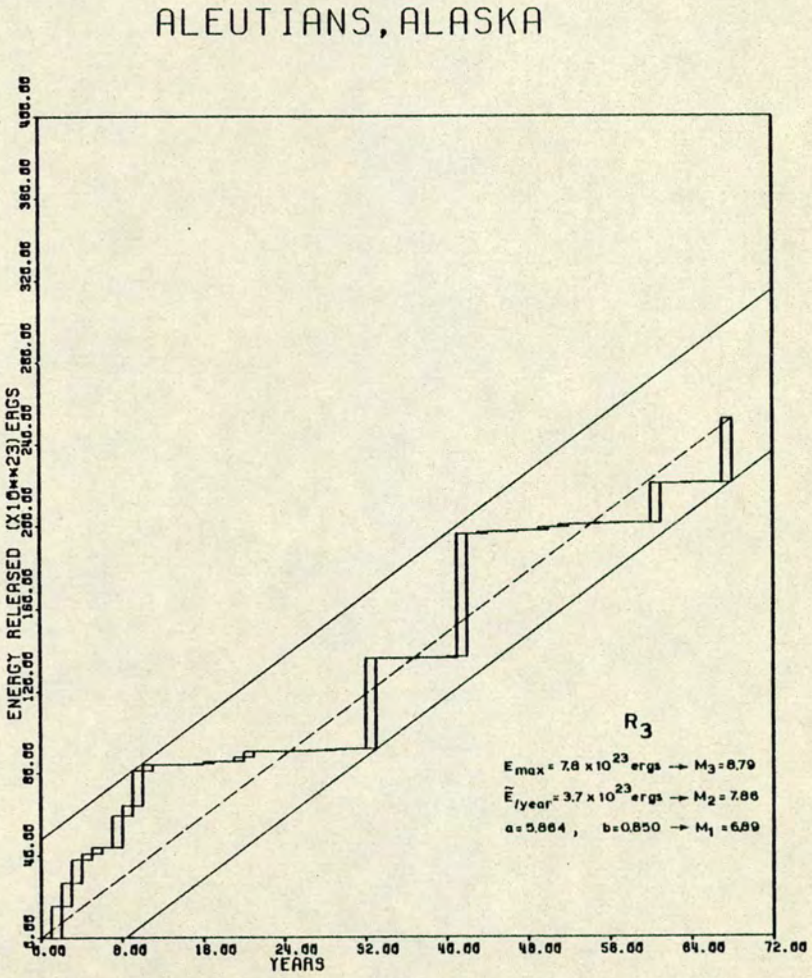


Fig 3-4 Cumulative energy release as a function of time for Region 3, and period 1897-1964. For explanation of the insert see Fig 3-2.

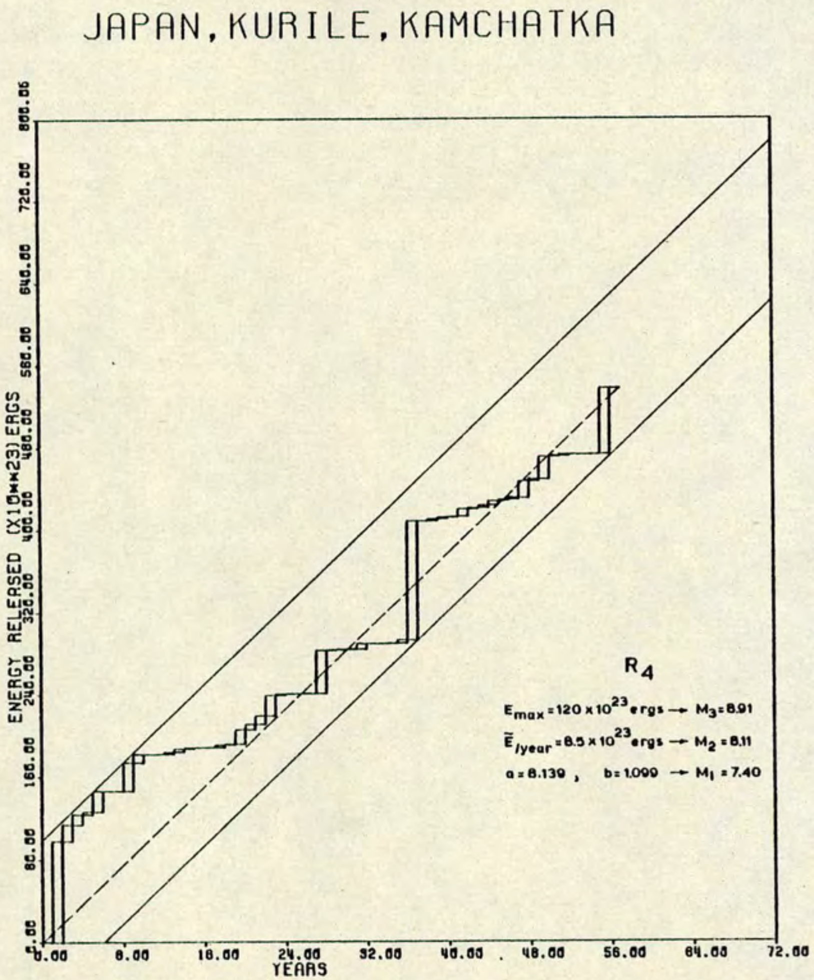


Fig 3-5 Cumulative energy release as a function of time for Region 4, and period 1897-1964. For explanation of the insert see Fig 3-2.

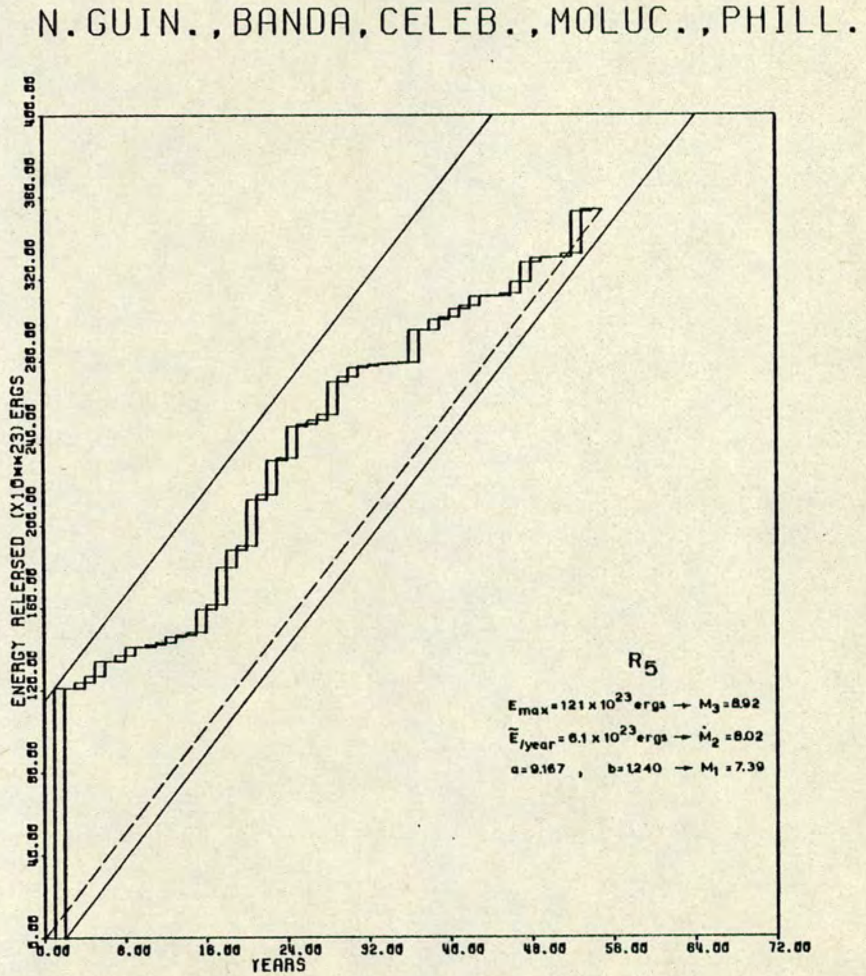


Fig 3-6 Cumulative energy release as a function of time for Region 5, and period 1897-1964. For explanation of the insert see Fig 3-2.

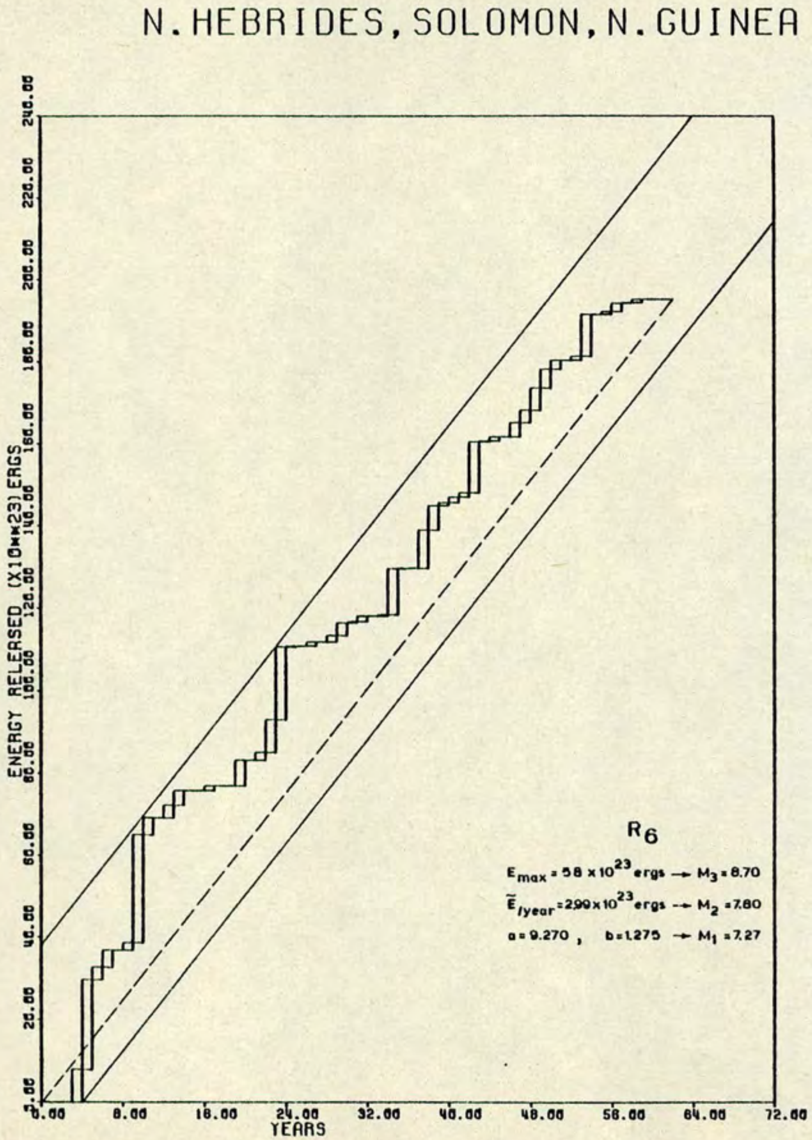


Fig 3-7 Cumulative energy release as a function of time for Region 6, and period 1897-1964. For explanation of the insert see Fig 3-2.

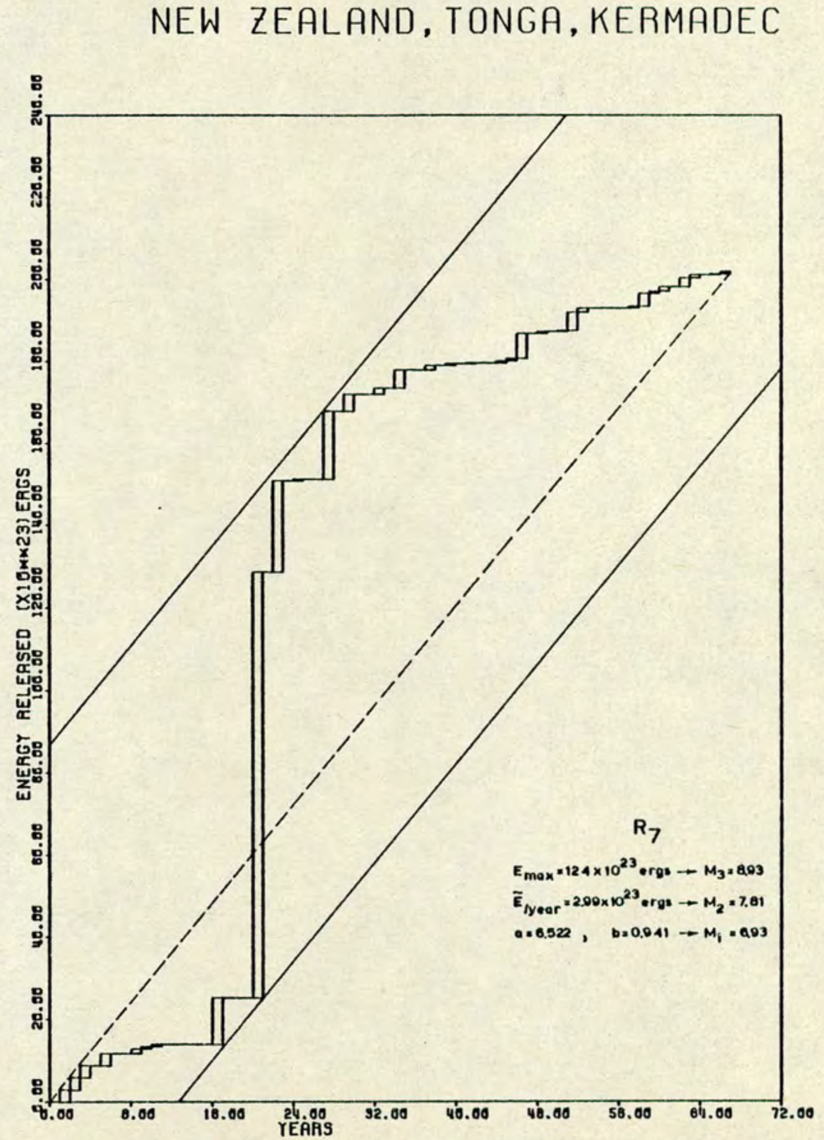


Fig 3-8 Cumulative energy release as a function of time for Region 7, and period 1897-1964. For explanation of the insert see Fig 3-2.

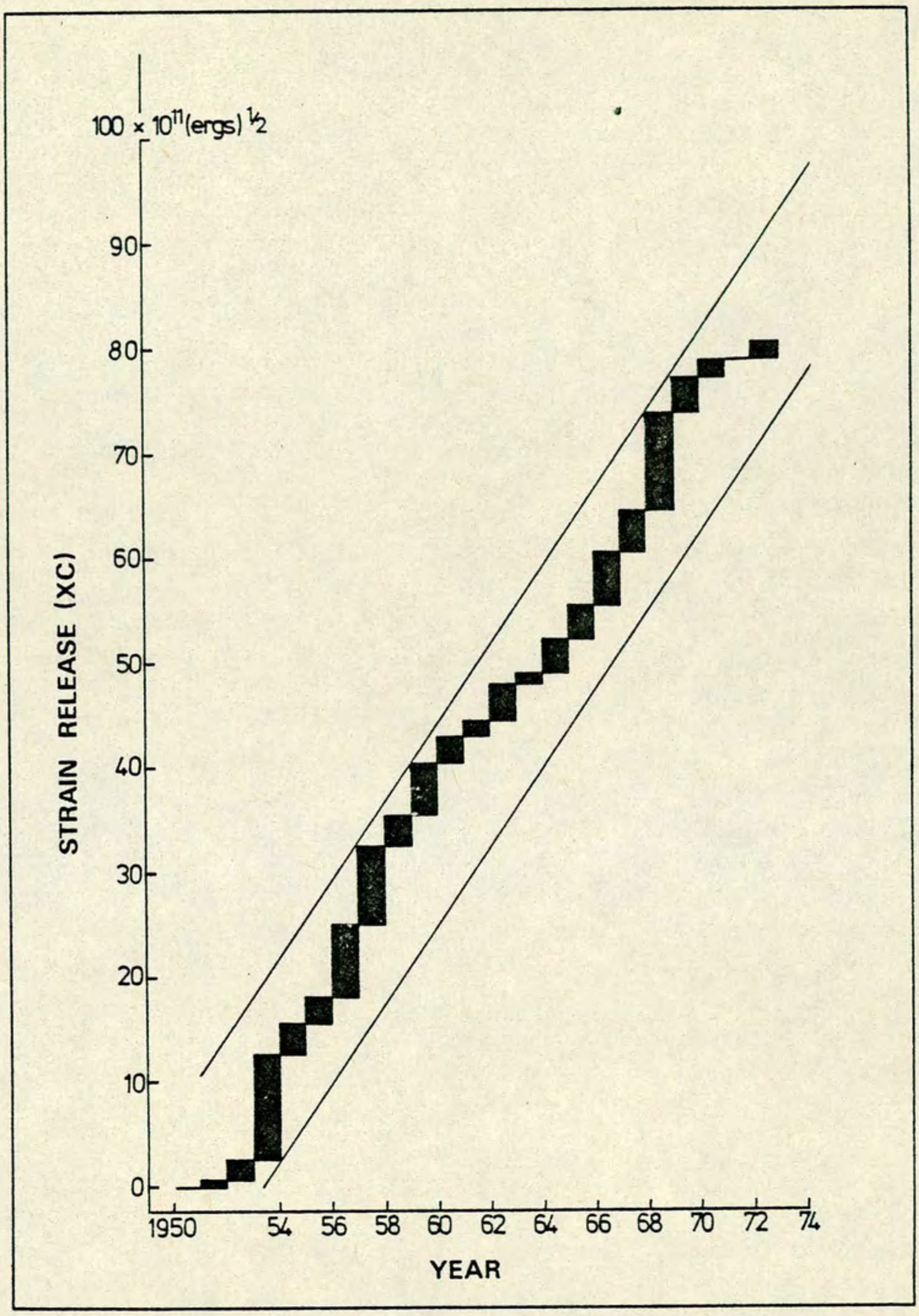


Fig 3-9 Cumulative strain energy release as a function of time for Greece for the period 1950-1972 (after Galanopoulos, 1972a).

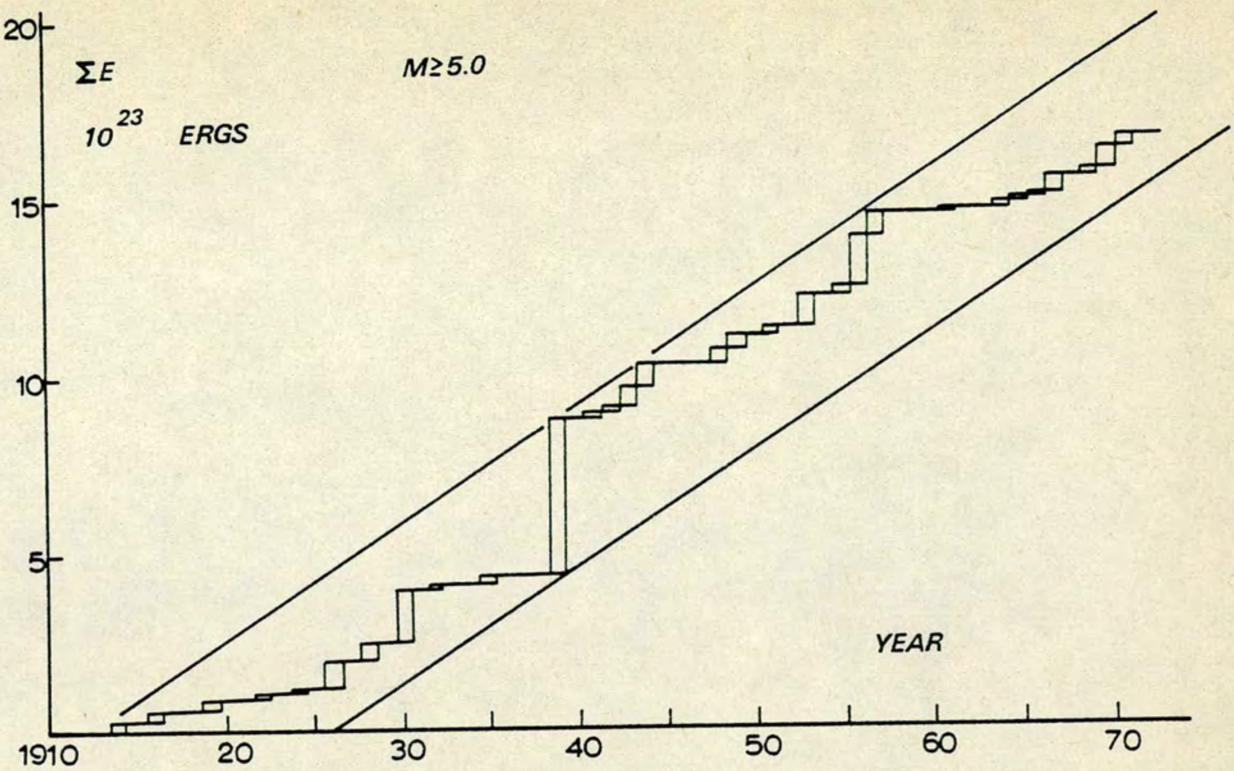


Fig 3-10 Cumulative energy release as a function of time for Turkey for the period 1913-1973 (after Alsan et al, 1975).

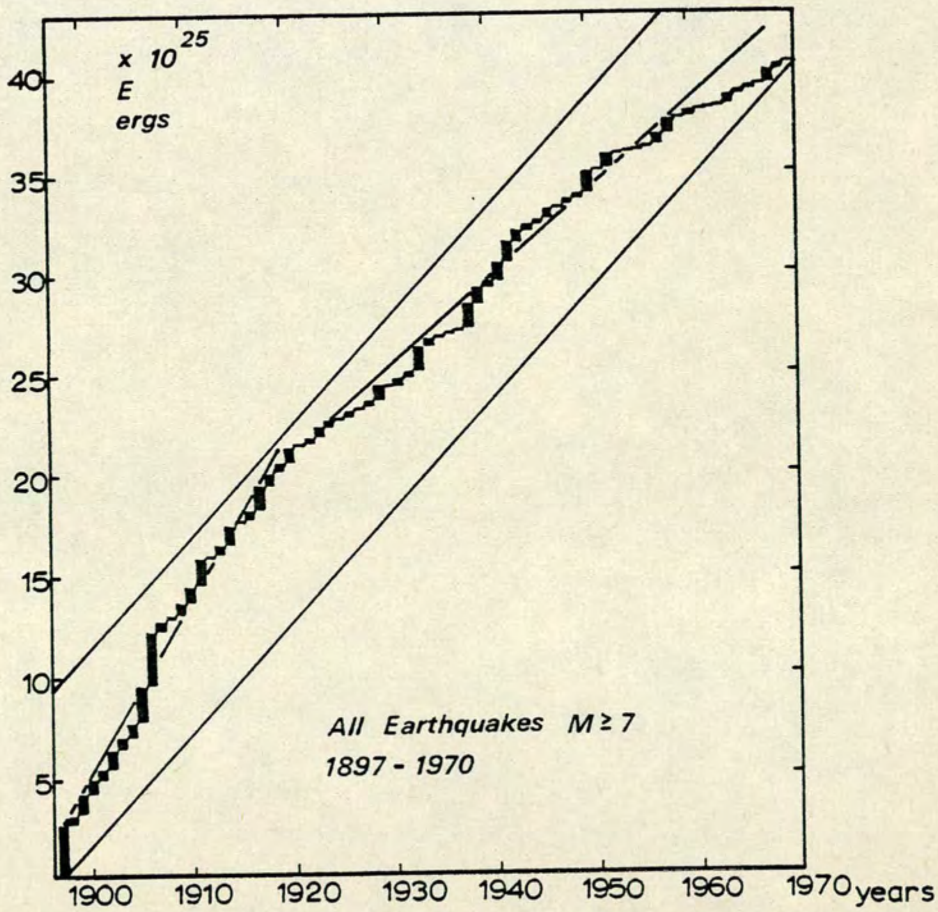


Fig 3-11 Cumulative energy release as a function of time for the world, for the period 1897-1970 (after Båth, 1973).

the bound of higher (lower) seismic risk for the region, because it is the line of maximum (minimum) storage of energy which may be released. Then, the maximum possible energy to be released in a year is the difference between E_{max} and the level of energy which already has been released during the recent past. The second feature to note is that on graphs like these the energy of large events dominates because of the logarithmic nature of equation (3-1). For the circum-Pacific belt, for example, it is clear that the very active period of the first decades of the present century dominates the analysis of the seismic behaviour of this part of the world.

A third significant feature is the very good agreement between M_3 obtained from analytical and graphical methods. This agreement shows that the assumption that the vertical distance between the two parallel lines is equivalent to the maximum possible energy which may be released, is a realistic one.

Probably the most significant feature is the close relation between M_1, M_2, and M_3. From table 3-1 for shallow earthquakes we can derive the following relations:

$$
\begin{aligned}
M_2 &= (1.11 \pm 0.04)M_1, \\
M_3 &= (1.25 \pm 0.05)M_1, \\
M_3 &= (1.13 \pm 0.02)M_2, \text{ and} \\
M_3 - M_2 &= 1.03 \pm 0.13.
\end{aligned}
\qquad (3.24)
$$

When the same procedure is applied to the parameters of Table 3-2 for shallow plus intermediate earthquakes, we find exactly the same proportionality

$$
\begin{aligned}
M_2 &= (1.11 \pm 0.06)M_1, \\
M_3 &= (1.25 \pm 0.07)M_1, \\
M_3 &= (1.13 \pm 0.03)M_2 \text{ and} \\
M_3 - M_2 &= 1.04 \pm 0.13.
\end{aligned}
\qquad (3\text{-}25)
$$

The fact that the relations (3-24) and (3-25) are almost identical may be due to the same mechanism, characterizing both shallow and intermediate earthquakes in the depth range 0-400 km (Båth and Duda, 1963).

Because Duda's subdivision is based on the distribution and number of shallow earthquakes rather than on tectonic evidence, the relations (3-24) and (3-25) seem to be valid for tectonically very different regions and for a wide range of magnitudes. Considering the ease with which M_1 and M_3 may be derived for a region, equations (3-24) and (3-25) will be of great assistance for regional seismic risk considerations, particularly if, as seems likely, they have a universal character.

b) Regional features

(1) Circum-Pacific belt

From figures 3-2 to 3-8 it is clear that for all the circum-Pacific belt subregions after the high seismic activity during the first two decades of this century, a general pattern of decreasing activity is apparent. The fact that in 1965 in almost all cases the level of energy released is close to the lower bound means that a period of increasing seismic activity may be about to start. This, in fact, seems to be the case. Looking back to the international data file, for the period 1965-1974, we can see that:

Region 1	has experienced	27	quakes	with	magnitude	range	7.0 to 8.1
Region 2	"	13	"	"	"	"	7.0 to 8.5
Region 3	"	13	"	"	"	"	7.0 to 7.9
Region 4	"	27	"	"	"	"	7.0 to 8.1
Region 5	"	35	"	"	"	"	7.0 to 8.1
Region 6	"	49	"	"	"	"	7.0 to 8.1
Region 7	"	12	"	"	"	"	7.0 to 7.9

The waiting time Tr (see 3.2.2c) for shallow earthquakes is as follows:

Region 1 : 27 years

Region 2 : 31 years

Region 3 : 21 years

Region 4 : 15 years

Region 5 : 19 years

Region 6 : 16 years and

Region 7 : 41 years

The two most active regions are situated diagonally opposite each other. These are the north-western part (Region 4) and south-eastern part (Region 1) of the circum-Pacific belt, with M_3 = 9.2 and M_3 = 9.1 respectively. Region 4 also has the shorter waiting time which means that a period of 15 years without any large earthquake is enough to accumulate energy for an earthquake with magnitude as big as 9.2.

(2) Greece and Turkey

From Figures 3-9 (Greece) and Figure 3-10 (Turkey) and Table 3-2 we can conclude the following.

The difference in b values for these two seismically very active neighbouring countries shows that we expect to have a larger proportion of strong earthquakes in Turkey (smaller b value) than in Greece, but the maximum expected earthquake is more likely to occur in Greece (M_3 = 8.6) than in Turkey (M_3 = 8.1). For both regions a new active period may be about to start. Values of the expected annual maximum and for mean rate of annual energy release, for both Greece and Turkey, are also tabulated in Table 3-2.

(3) World

Table 3-2 also contains the parameters for shallow and intermediate earthquakes for the world as a whole. Since these earthquakes occurred in a broad variety of tectonic plates, the parameters b and M_1 are only of theoretical interest. M_{3G}, however, which does not depend on the value of b, has a very significant meaning. It is an indication of the global upper bound for earthquake magnitudes, and gives a value of 9.5.

3.3 Summary

The analytical method, which uses the simple frequency-magnitude law, demonstrates the necessary existence of an upper limit to maximum magnitude earthquakes, and from both analytical and graphical methods it is possible to estimate the size of such an upper limit. As this size depends on the values of b, which are different from region to region, each region must also have its own upper limit. Thus, earthquake magnitude statistical models must include this upper limit as an unknown parameter, in order to be as close to reality as possible. The advantage of the methods described is the easy way of getting the size of the upper limit M_3, simply by having the M_1 and M_2 through the relations (3-15) or (3-17).

The two methods are tested in the circum-Pacific belt using Duda's catalogue and subdivision. The results show a very good agreement between M_3 obtained from both analytical and graphical methods.

The empirically obtained relations (3-24) and (3-25) are almost identical which may be due to the fact that shallow and intermediate earthquakes have the same mechanism in the depth range 0-400 km (Båth and Duda, 1963). If the close relation between M_1, M_2, and M_3 derived from tectonically very different regions has a universal character, equations (3-24) and (3-25) will be of great assistance for regional seismic risk considerations. The upper bound to magnitude and the annual rate of energy release differ by one magnitude unit.

From the regional features it is concluded that the two most active regions in the circum-Pacific belt are Region 4 (Japan, Kurile, Kamchatka) and Region 1 (South America). These regions are situated diagonally opposite to each other and they have an upper bound of M_3 = 9.2 and M_3 = 9.1 respectively. Region 4 also has the shorter waiting time (15 years). In almost all the circum- Pacific belt a general pattern of decreasing activity is observed. However, since the cumulative energy release is in all cases close to the lower bound (maximum energy storage) a period of increasing seismic activity started after 1965.

For Greece, Turkey, using published graphs, it is found that the upper bound to earthquake magnitude is M_3 = 8.6 and M_3 = 8.1 respectively.

For the world as a whole, an upper bound with the value of M_3 = 9.5 is found to indicate the global upper bound for earthquake magnitudes.

In the next chapter, the problem of the upper bound for earthquake magnitude is analysed with the Extreme-Value statistical models, the third type asypmtotic distribution of which seems to fulfil almost all the conditions necessary to be a useful tool in obtaining estimates of the frequencies and recurrence times for large magnitude earthquakes. A method of estimating the parameters, which allows variance-covariance matrix for the parameters to be calculated is described. Thus, comparisons between parameters obtained by the analytical and graphical methods of this chapter, and the same parameters from the Extreme-Value statistics method are made, and relations between the simple frequency-magnitude law and third type asymptote results are established.

CHAPTER IV

THIRD TYPE ASYMPTOTIC DISTRIBUTION OF GUMBEL AND STRAIN ENERGY RELEASE RELATIONS

4.1 Introduction

A method of determining the parameters of Gumbel's third type asymptotic distribution is described in this chapter, and these parameters are then related to physical strain energy release.

4.1.1 Uncertainties - weights

The need for a statistical model which includes the largest expected earthquake magnitude in a given region as an unknown parameter arises from the arguments in Chapter III. Hence the third type asymptotic distribution of Gumbel, being such a statistical model, is used for seismic risk evaluation in many regional seismic studies. But when reviewing these studies, it soon becomes apparent that none of them considers the uncertainties in the parameters involved, nor are the uncertainties of the data used taken into account. However, these factors are very important for any statistical treatment.

In this chapter it is demonstrated that using the non-linear least-squares fitting method, it is possible to calculate the uncertainties of the estimated parameters by extending it to obtain variance-covariance or error, matrices. The method described in this chapter also allows weight for each individual extreme magnitude to be assigned. Thus, the calculated parameters with their uncertainties may constitute an improved basis for seismic risk estimations.

4.1.2 Relations between parameters of strain energy release and the third type asymptote

The physical meaning of the parameters of the first type asymptote is related to that of the parameters of the frequency-magnitude formula as shown by Epstein and Lomnitz (1966) (see paragraph 2.3.6). The lack of any relation between the parameters of the third asymptote, and the parameters of other formulae with clear physical meaning (eg frequency-magnitude), has previously meant that no physical interpretation of these parameters has been attempted.

Although a direct comparison between the parameters of the non-linear third type asymptote and those of these linear formulae cannot be made, it is still possible to use the procedure of Chapter III to relate these parameters with the parameters of strain energy release such as M_1, M_2, and M_3. So, the parameters of the third type asymptote can be expressed in terms of physical quantities like M_1, M_2, and M_3.

4.1.3 Testing region

The circum-Pacific belt is again chosen as a region for testing both the method and the relations between the expressions which correspond to those of M_1, M_2, and M_3 derived in Chapter III. It is then demonstrated that using the third type asymptotic distribution of Gumbel, with the uncertainties of the parameters computed, it is possible to establish a forecasting procedure for the maximum magnitude earthquakes likely to occur in the most seismically active region in the world.

4.2 Estimation of the parameters

4.2.1 Non-linear least-squares methods

Because of non-linearity in the parameters ω, u and k of the third type asymptotic distribution of Gumbel (see paragraph 2.3)

$$\phi(x) = \exp\left[-\left(\frac{\omega-x}{\omega-u}\right)^k\right] \qquad (4-1)$$

the conventional linear least-squares method cannot be directly applied to estimate them. The problem is approached by using the non-linear least-squares method. The data input consists of earthquake maximum magnitudes and some additional requirements are met by this method. These requirements are:

i) to allow weight for each individual earthquake magnitude

ii) To take into account the years for which earthquake magnitudes are absent or not available, and

iii) to compute the variance-covariance or error matrices from which the uncertainties of the parameters can be calculated.

The non-linear least-squares methods such as grid search, gradient search, linearization of fitting function etc, are like the least-squares methods based on the following two principles:

i) A measure of goodness of fit between the data and postulated curve, χ^2, can be defined as:

$$\chi^2 = \sum_{i=1}^{N} \left[\frac{1}{\sigma_i^2} \left[y_i - y(x_i) \right]^2 \right] \tag{4-2}$$

where σ_i are the uncertainties in the N data points y_i

ii) According to the method of least-squares, the optimum values of the parameters a_j are obtained by minimizing χ^2 with respect to each of the parameters simultaneously. This gives

$$\frac{\partial}{\partial a_j} \chi^2 = \frac{\partial}{\partial a_j} \sum_{i=1}^{N} \left[\frac{1}{\sigma_i^2} \left[y_i - y(x_i) \right]^2 \right] = 0, \; j = 1,n \tag{4-3}$$

where n is the number of parameters.

It is generally not convenient to derive an analytical expression for calculating the parameters of a non-linear function y(x). Instead, χ^2 must be considered a continuous function of the n parameters a_j, describing a hypersurface in n-dimensional space, and the space must be searched for the minimum of χ^2.

There are a number of ways of finding this minimum value: by searching parameter space using a grid or gradient search, approximate analytical methods such as parabolic extrapolation of χ^2, or linearization of the fitting function using a Taylor expansion. The gradient search method and the method of linearizing the function are combined in the algorithm chosen in this study.

One disadvantage inherent in the analytical methods is that while they converge quite rapidly to the point of minimum χ^2 from points nearby, they cannot be relied on to approach the minimum with any accuracy from a point outside the region where the χ^2 hypersurface is approximately parabolic. In contrast, the gradient search is ideally suited for approaching the minimum from far away, but it does not converge rapidly when in the immediate vicinity of the minimum. Therefore we need an algorithm which behaves like a gradient search for the first portion of a search and behaves like an analytical solution as the search converges. Such an algorithm eventually chosen is the Marquardt algorithm.

4.2.2 The Marquardt (1963) algorithm

The main features of this algorithm (Bevington 1969) are obtained as follows.

Expand the fitting function y(x) to first order in a Taylor expansion as a function of the parameters a_j

$$y(x) = y_o(x) + \sum_{j=1}^{n} \left[\frac{\partial y_o(x)}{\partial a_j} \delta a_j \right] \qquad (4\text{-}4)$$

where $y_o(x)$ is the value of the fitting function at the starting point x.

This gives a function which is linear in the parameter increments δa_j. To this approximation, χ^2 can be expressed explicitly as a function of the parameter increments δa_j:

$$\chi^2 = \sum_{i=1}^{n} \left[\frac{1}{\sigma_i^2} \left[y_i - y_o(x_i) - \sum_{j=1}^{n} \left[\frac{\partial y_o(x_i)}{\partial a_j} \delta a_j \right] \right]^2 \right] \quad (4\text{-}5)$$

Following the method of linear least-squares, χ^2 is minimised with respect to each of the parameter increments δa_j by setting the derivatives equal to 0,

$$\frac{\partial \chi^2}{\partial \delta a_k} = -2 \sum_{i=1}^{N} \left[\frac{1}{\sigma_i^2} \left[y_i - y_o(x_i) - \sum_{j=1}^{n} \left[\frac{\partial y_o(x_i)}{\partial a_j} \delta a_j \right] \right] \frac{\partial y_o(x_i)}{\partial a_k} \right] = 0 \quad (4\text{-}6)$$

This yields a set of n simultaneous equations, which we can treat as a matrix equation

$$b_k = \sum_{j=1}^{n} (\delta a_j A_{jk}), \; k = 1,n$$

or

$$b = \delta a A, \quad (4\text{-}7)$$

where b is a row matrix whose elements are

$$b_k = \sum_{i=1}^{N} \left[\frac{1}{\sigma_i^2} \left[y_i - y_o(x_i) \right] \frac{\partial y_o(x_i)}{\partial a_k} \right] \quad (4\text{-}8)$$

and A is a symmetric matrix of order n whose elements are

$$A_{jk} = \sum_{i=1}^{N} \left[\frac{1}{\sigma_i^2} \frac{\partial y_o(x_i)}{\partial a_j} \frac{\partial y_o(x_i)}{\partial a_k} \right] \quad (4\text{-}9)$$

and this is called the curvature matrix because of its relationship to the curvature of χ^2 in parameter space.

The Marquardt algorithm combines the gradient search with the method of linearizing the fitting function by increasing the diagonal terms of the curvature matrix A by a factor which controls the interpolation of the algorithm between the two extremes. Thus equation (4-7) becomes

$$b = \delta a A'$$

$$A'_{jk} = \begin{cases} A_{jk}(\mu+1) & \text{for } j = k \\ A_{jk} & \text{for } j \neq k \end{cases} \qquad (4\text{-}10)$$

If μ is very small (near to the minimum), equations (4-10) are similar to the solution of equations (4-7) developed from a Taylor's expansion. If μ is very large (far from the minimum), the diagonal terms of the curvature matrix dominate, and the matrix equation degenerates in n separate equations

$$b_j = \mu \delta a_j A_{jj} \qquad (4\text{-}11)$$

which yields increments δa_j in the same direction as the gradients b_j of equation (4-8) but with lengths scaled by A_{jj} and reduced by a factor of μ.

The solution for the parameter increments δa_j follows from equation (4-10)

$$\delta a_j = \sum_{k=1}^{n} (b_k E'_{jk}) \qquad (4\text{-}12)$$

where b_k are given in equation (4-8) and the matrix E' is the inverse of the matrix A whose elements are given in equations (4-9).

Thus when the starting points are far away from the point of minimum χ^2 the gradient search method brings them quite rapidly near to it, and when this method starts to suffer markedly as the search approaches the minimum, the linearization of fitting function method, more suitable for points nearby, continues the trial until the minimum χ^2 has been reached.

Finally, the uncertainties of the parameters can be obtained from the inverse of the curvature matrix which, in the limits of the approximation we have made, is

$$\sigma^2 a_j = E'_{jj} \qquad (4\text{-}13)$$

E' is called the error matrix because it contains most of the information needed to estimate the errors. For n = 3 it becomes:

$$\begin{bmatrix} \text{Var } a_1 & \text{Cov } a_1a_2 & \text{Cov } a_1a_3 \\ \text{Cov } a_2a_1 & \text{Var } a_2 & \text{Cov } a_2a_3 \\ \text{Cov } a_3a_1 & \text{Cov } a_3a_2 & \text{Var } a_3 \end{bmatrix} \qquad (4\text{-}14)$$

4.2.3 Computations

For the purpose of this study a computer program has been written using the previous algorithm. A full description of the computation procedure and a complete annotated listing of this program is given in Appendix A.

4.3 Prediction Uncertainties

In section 2.3.6 the most probable maximum modal magnitude, $\tilde{m}(n)$, for the next n years, and the interval in which the maximum magnitude will lie with a given probability level 'α', were found to be:

$$\tilde{m}(n) \simeq \omega - (\omega - u)\left[(1 - \frac{1}{k})/n\right]^{1/k} \qquad (4\text{-}15)$$

$$m_{up}(n) \simeq \omega - (\omega - u)\left[-\frac{1}{n}\ln(1 - \frac{\alpha}{2})\right]^{1/k} \qquad (4\text{-}16)$$

and

$$m_{\ell}(n) \simeq \omega - (\omega - u)\left[-\frac{1}{n}\ln(\frac{\alpha}{2})\right]^{1/k} \qquad (4\text{-}17)$$

where $\tilde{m}(n)$ is the mode of the next n years and $m_{up}(n)$ and $m_{\ell}(n)$ the upper and lower bounds, or the interval, at probability level α.

It is obvious that, using equations (4-16) and (4-17), the $m_{up}(n)$ and $m_{\ell}(n)$ tend towards ω as $n \to \infty$. Thus the upper bound, $m_{up}(n)$ cannot exceed the parameter ω, despite the lack of precision in estimates of ω(Burton, 1978b). However, we can overcome this disadvantage by assigning uncertainties to the upper and lower bounds. It is possible to use the approximation formula:

$$\sigma^2(m) \simeq \sigma^2\omega\left[\frac{\partial m}{\partial \omega}\right]^2 + \sigma^2 u\left[\frac{\partial m}{\partial u}\right]^2 + \sigma^2(1/k)\left[\frac{\partial m}{\partial(1/k)}\right]^2 + 2\sigma^2\omega u\left[\frac{\partial m}{\partial u}\right]\left[\frac{\partial m}{\partial u}\right] + \ldots \quad (4\text{-}18)$$

where σ^2 is the variance or covariance of the parameter involved, and the partial derivatives of equations (4-18) are calculated according to the particular form of prediction formula for m(n). Using equations (4-18) for the uncertainties of the bounds, it can be shown that

$$\sigma^2\left[m_{up}(n)\right], \ \sigma^2\left[m_{\ell}(n)\right] \underset{n \to \infty}{\to} \sigma^2(\omega) \quad (4\text{-}19)$$

All the partial derivatives of the equations (4-16) and (4-17) with respect to u and 1/k tend to zero, because of a factor $\frac{1}{n}$, whereas the partial derivatives with respect to ω tend to unity. Making use of the variance covariance matrix of (4-14), it is possible to use equation (4-18) and to assign uncertainties on (4-16) and (4-17) which have the advantage that they include the probability level as a parameter.

A full description of the above calculation, as well as a computer program which has been written for this purpose, are also included in the main program (Appendix A).

4.4 Energy release and the third type asymptotic distribution

Because the third type asymptotic distribution is a three-parameter curve, its parameters cannot be directly related to those of linear frequency-magnitude or energy-magnitude formulae. However, it is possible to compare results derived from the expressions used to describe the same physical quantities, such as most probable expected maximum magnitude, or annual energy release etc. So relations among the parameters of the different models can be established.

4.4.1 The mode

For the third type asymptotic distribution, the most probable annual maximum or annual mode, $\tilde{x}$, is given (see eq 2-61) as:

$$\tilde{x} = \omega - (\omega - u)(1 - 1/k)^{1/k} \qquad (4\text{-}20)$$

The same quantity, using the whole available data set is $M_1 = a/b$. Then $\tilde{x}$ may be compared with M_1, that is

$$M_1 = \frac{a}{b} \simeq \tilde{x} = \omega - (\omega - u)(1 - 1/k)^{1/k} , \qquad (4\text{-}21)$$

which for the T year mode (see eq 2-42 and 2-47) becomes

$$M_T = \frac{a}{b} + \frac{\log T}{b} \simeq \tilde{x}_T = \omega - (\omega - u)\left[(1 - 1/k)/T\right]^{1/k} \qquad (4\text{-}22)$$

4.4.2 The mean annual energy release

The expected yearly number of events, N_x, over some magnitude x, is connected with its return period T_x, (Epstein and Lomnitz, 1966) by the relation

$$N_x = \frac{1}{T_x} \qquad (4\text{-}23)$$

For the third type asymptotic distribution we have from equations (4-22) and (4-23):

$$\left(\frac{\omega - x}{\omega - u}\right) = \left(\frac{1-1/k}{T_x}\right)^{1/k} = \left[(1 - 1/k)N_x\right]^{1/k} \qquad (4\text{-}24)$$

and

$$N_x = \left(\frac{\omega - x}{\omega - u}\right)^k / (1 - \frac{1}{k}) \qquad (4\text{-}25)$$

Equation (4-25) for $x = \tilde{x}$ becomes: $N_{\tilde{x}} = 1$, because the annual mode is the earthquake magnitude which is expected to be exceeded once in a given year.

The number of earthquakes with magnitude in the range dx in a given year is:

$$dN_x = \frac{k}{(1 - 1/k)} \cdot \frac{1}{(\omega - u)^k} (\omega - x)^{k-1} dx \qquad (4\text{-}26)$$

and the annual energy release, E_{dx}, for all earthquakes with magnitude in the range dx is

$$E_{dx} = e^{A+Bx} dN_x$$

$$= e^{A+Bx} \cdot \frac{k}{(1 - 1/k)} \cdot \frac{1}{(\omega - u)^k} \cdot (\omega - x)^{k-1} dx$$

$$(4\text{-}27)$$

where A and B are the constants of the energy-magnitude equation

$$\ell nE = A + Bx \qquad (4\text{-}28)$$

Then the total annual energy release, TE, from (4-27) becomes

$$TE = \int_{-\infty}^{\omega} e^{A+Bx} dN = \int_{-\infty}^{\omega} e^{A+Bx} . C. (\omega - x)^{k-1} dx \qquad (4\text{-}29)$$

where

$$\epsilon = \frac{k}{(1 - 1/k)} \cdot \frac{1}{(\omega - u)^k} \tag{4-30}$$

or

$$TE = C.e^A \int_{-\infty}^{\omega} e^{Bx}(\omega - x)^{k-1} dx \tag{4-31}$$

If we put

$$\omega - x = y \rightarrow x = \omega - y \tag{4-32}$$

then, by noting that

$$\begin{aligned} x &\rightarrow -\infty, \quad y \rightarrow \infty \\ x &\rightarrow \omega, \quad y \rightarrow 0 \\ dx &= -dy \end{aligned} \tag{4-33}$$

and

$$e^{Bx} = e^{B\omega} \cdot e^{-By}$$

the equation (4-31) becomes

$$TE = C.e^{A+B\omega} \int_{0}^{\infty} y^{k-1} e^{-By} dy. \tag{4-34}$$

But

$$\int_{0}^{\infty} y^{k-1} e^{-By} dy = \frac{\Gamma(k)}{B^k} \; (B > 0,\ k - 1 > -1) \tag{4-35}$$

where $\Gamma(k)$ is the Gamma-function of k. Equation (4-34) becomes:

$$TE = C.e^{A+B\omega} \cdot \frac{\Gamma(k)}{B^k} \equiv e^{A+BX_2} \tag{4-36}$$

where X_2 is the magnitude which corresponds to this TE. By re-substituting C from equation (4-30) we have:

$$\frac{k^2}{k-1} \cdot \frac{1}{(\omega - u)^k} \cdot e^A . e^{B\omega} . \frac{\Gamma(k)}{B^k} \equiv e^A . e^{BX_2} \qquad (4\text{-}37)$$

or

$$e^{BX_2} = \frac{k^2}{(k-1)} \cdot \frac{\Gamma(k)}{(\omega - u)^k . B^k} \cdot e^{B\omega} \qquad (4\text{-}38)$$

Taking logarithms on both sides of (4-38) and solving for X_2 we have:

$$X_2 = \omega - \frac{k \ell n B}{B} + \frac{1}{B} \ \ell n \left[\frac{k^2}{k-1} \cdot \frac{\Gamma(k)}{(\omega - u)^k} \right] \qquad (4\text{-}39)$$

If we use Båth's (1958) energy-magnitude constants in equation (4-28) this gives $B = 1.44 \ell n 10$, and equation (4-39) finally becomes

$$X_2 = \omega - 0.3615k + \frac{1}{1.44} \log \left[\frac{k^2}{k-1} \cdot \frac{\Gamma(k)}{(\omega - u)^k} \right] \qquad (4\text{-}40)$$

Then, the M_2 which corresponds to the mean annual energy release by using the whole data set (see paragraphs 3.2.1 and 3.2.2), should be comparable with X_2, which is the same magnitude derived from the third type asymptotic distribution parameters. That is:

$$M_2 = \frac{1}{B}\left[bM_1 + (B-b)M_3 + \log\left(\frac{b}{B-b}\right) \right] \simeq X_2 = \omega - 0.3615k + \frac{1}{1.44} \log \left[\frac{k^2}{k-1} \cdot \frac{\Gamma(k)}{(\omega - u)^k} \right]$$

(4-41)

4.4.3 The upper limit

The M_3 upper limit for earthquake magnitudes, which is derived from the whole process, should be comparable with ω of the third type asymptotic distribution.

4.5 Testing the Third Type Asymptotic Distribution Method

4.5.1 Data

Verification of the relations (4-21) and (4-41) depends on the agreement of the results when these two models are applied to the same area. The circum-Pacific belt is again chosen as the testing area. Periods of investigation are from 1897 to 1964, as in Chapter III, and from 1897 to 1975 inclusive. This is the longest time span available.

For the above periods of investigation the data sets used are:

i) those compiled by Duda (1965)

ii) Gutenberg and Richter's (1954) catalogue, for years in which no earthquakes have been reported in Duda's catalogue, and

iii) since 1956 from the Institute of Geological Sciences seismicity file (Burton 1978c).

4.5.2 Data treatment

a) Missing years

For each of the seven subregions of the circum-Pacific belt, the largest yearly observed earthquake magnitude is taken and these are ranked in increasing size. Then the plotting position of the ith observation, x_i, is defined as:

$$p_i = \frac{i - 0.44}{N + 0.12} \tag{4-42}$$

where i is the rank, counted from below, and N is the total number of observations.

The couples (p_i, x_i) can be plotted on Gumbel's probability paper.

Here the parameters are computed with the help of the least-squares methods described in paragraphs 2.3.5 (first type) and 4.2.1 (third type). However, even for these very active regions, there are "missing years" without recorded earthquakes. This is due to the threshold of the magnitudes recorded in the catalogues, or to the instruments' detectability during operation. So the problem of filling the missing years arises, and this becomes even greater as the method is applied to smaller or less active regions.

It is possible to reduce the number of missing years by taking instead of one year extremes, two or more year extremes. Equation (2-20) converts back to one year maxima. But although this method may reduce the number of missing years, it still does not ensure that there will be no such intervals. An alternative solution may be the filling of all these empty intervals with a specific magnitude, for example with the magnitude which corresponds to intensity I = V (Schenkova and Kárnik, 1976, 1978). However, as the number of these artificially created maximum values becomes large the curve is forced to pass through them because of their cumulative weight. Furthermore, as these points are clustered at one part of the distribution, they may influence the slope of the curve and, consequently, the estimation of the parameters.

In this study Yegulalp and Kuo's (1974) consideration is adopted. If during N years there are j missing extremes, the first actual observed extreme is ranked as j + 1, assuming the first j of the N observations are not available. The advantages of this approach are:

i) The rank of the remaining magnitudes is the same as it would be if there were no missing years, provided that during these missing years, no earthquake with magnitude greater than the first actual observed magnitude occurred.

ii) It allows the completeness of the data set to be taken into account since this method of treatment does not disturb the distribution of the actual observed magnitudes. Thus, magnitudes which prove to be incompletely reported, see Chapter V, can be omitted from the calculations without affecting the distribution of the remaining extremes.

b) Weighting the data

One of the refinements which the method of estimation of the parameters allows, is the possibility of assigning weight, or uncertainty to each individual extreme magnitude. Such an uncertainty may simply reflect the date of the observations, the size of the earthquakes and the sensitivity of instruments used, or general improvement in magnitude determiation during this century.

The main sources for Duda's catalogue are Gutenberg's (1956) work for the period 1897-1903, and Gutenberg and Richter's (1954) catalogue for the period 1904-1952. For both periods the magnitudes are those revised by Richter (1958).

Considering the comments (Gutenberg, 1954, page 609, and Gutenberg and Richter, 1954, page 10) about the accuracy of the magnitudes listed, in these two works, and also because Duda's magnitudes are those of Richter (1958) converted from unified magnitude m, to the surface wave magnitude Ms, the system used for weighting the annual extremes chosen in this study is:

Period (Duda's original source)		Standard deviation assigned
1. 1897-1903 (Gutenberg, 1956) and 1904-1917 (Gutenberg and Richter, 1954)	:	± 0.6
2. 1904-1917 (Duda's addition of 146 events)	:	± 0.4
3. 1918-1953 (Gutenberg and Richter, 1954)		
3a. when a magnitude is assigned to the tenth of a unit	:	± 0.3

3b. when it is assigned to the nearest quarter	:	± 0.4
3c. when as in 3a with the addition of ±	:	± 0.4
3d. when as in 3b with the addition of ±	:	± 0.5
4. 1954-1975 (Duda and IGS file)	:	± 0.3

4.5.3 Results and discussion

a) The parameters

The estimated parameters with their uncertainties for both first and third type asymptotic distributions are tabulated in Tables 4-1 and 4-2 respectively. These include the seven subregions of the circum-Pacific belt for sampling periods 1897 to 1964 and 1897 to 1975. Figures 4-1a to 4-7b, inclusive, show the two distribution curves and the observed annual maximum magnitudes.

In both tables there are two additional columns. One contains the number of missing annual extremes, labelled "missing years", and the other, "chi-square", contains the difference between the reduced chi-square for the first, ρ_1, and the same quantity for the third type asymptotic distribution, ρ_3. The reduced chi-square ρ, for F degrees of freedom, given by χ^2/F, is taken as a measure of goodness of fit.

Tables 4-1 and 4-2 and figures 4-1a to 4-7b inclusive, show several significant features. First feature to note is that for each region the characteristic value u, with the probability $\phi(u) = 1/e$ of not being exceeded during a year, is well determined.

Secondly, when the data in a region shows little curvature, and $\lambda = 1/k$ is small, and therefore ω is high, as in regions 1, 5, and 6, then these parameters are accompanied by large uncertainties. This may indicate that the time span proves insufficient to establish curvature. In fact, when comparing the two tables, it is apparent that as the sampling duration lengthens, and the observational data improves, the values usually tend to stabilize.

Table 4-1

Estimated Parameters of Asymptotic distributions (1897-1964)

Region	Third type						First type				Missing	chi square
	ω	σ_ω	u	σ_u	$\lambda=\frac{1}{k}$	σ_λ	υ	σ_υ	$\frac{1}{a}$	$\sigma\frac{1}{a}$	years	$\rho_1-\rho_3$
(1) South America	10.16	1.13	7.08	0.04	0.197	0.091	7.08	0.04	0.477	0.028	8	+0.094
(2) North America	9.14	0.51	7.14	0.04	0.320	0.110	7.11	0.03	0.501	0.031	3	+0.186
(3) Aleutians, Alaska	9.66	0.63	6.78	0.04	0.260	0.083	6.84	0.04	0.486	0.029	13	+0.216
(4) Japan Kurile Kamchatka	9.30	0.34	7.38	0.03	0.327	0.076	7.34	0.03	0.437	0.024	2	+0.348
(5) New Guinea, Banda Sea Celebes, Moluccas Philippines	10.00	1.11	7.42	0.03	0.194	0.098	7.40	0.03	0.425	0.027	2	+0.069
(6) New Hebrides Solomon New Guinea	9.44	1.11	7.23	0.03	0.220	0.125	7.22	0.04	0.397	0.031	6	+0.060
(7) New Zealand Tonga Kermadec	8.95	0.35	6.89	0.04	0.357	0.091	6.95	0.04	0.441	0.027	10	+0.316
(8) World	9.23	0.25	8.17	0.03	0.358	0.056	8.12	0.03	0.285	0.025	0	+0.299

Table 4-2

Estimated Parameters of Asymptotic distributions ($1897-1975_{sep}$)

Region	Third type						First type				chi square	Missing years	Observed Maximum
	ω	σ_ω	u	σ_u	$\lambda=\frac{1}{k}$	σ_λ	υ	σ_υ	$\frac{1}{a}$	$\frac{\sigma 1}{a}$	$\rho_1-\rho_3$		
(1) South America	9.92	0.94	7.09	0.03	0.208	0.086	7.10	0.03	0.457	0.025	+0.101	10	8.9
(2) North America	9.01	0.39	7.11	0.03	0.352	0.094	7.10	0.03	0.471	0.027	+0.257	6	8.6
(3) Aleutians, Alaska	9.77	0.69	6.79	0.04	0.235	0.077	6.85	0.04	0.469	0.027	+0.178	16	8.7
(4) Japan Kurile Kamchatka	9.33	0.34	7.38	0.03	0.307	0.069	7.34	0.03	0.429	0.022	+0.329	2	8.9
(5) New Guinea Banda Sea, Celebes Maluccas, Philippines	9.58	0.72	7.41	0.03	0.235	0.097	7.38	0.03	0.414	0.025	+0.091	4	8.7
(6) New Hebrides Solomon New Guinea	9.56	1.14	7.25	0.03	0.198	0.112	7.24	0.03	0.381	0.027	+0.050	6	8.6
(7) New Zealand Tonga Kermadec	8.91	0.33	6.87	0.04	0.359	0.089	6.95	0.04	0.429	0.025	+0.294	14	8.7
World	9.13	0.15	8.12	0.03	0.395	0.054	8.07	0.03	0.299	0.022	+0.326	0	8.9

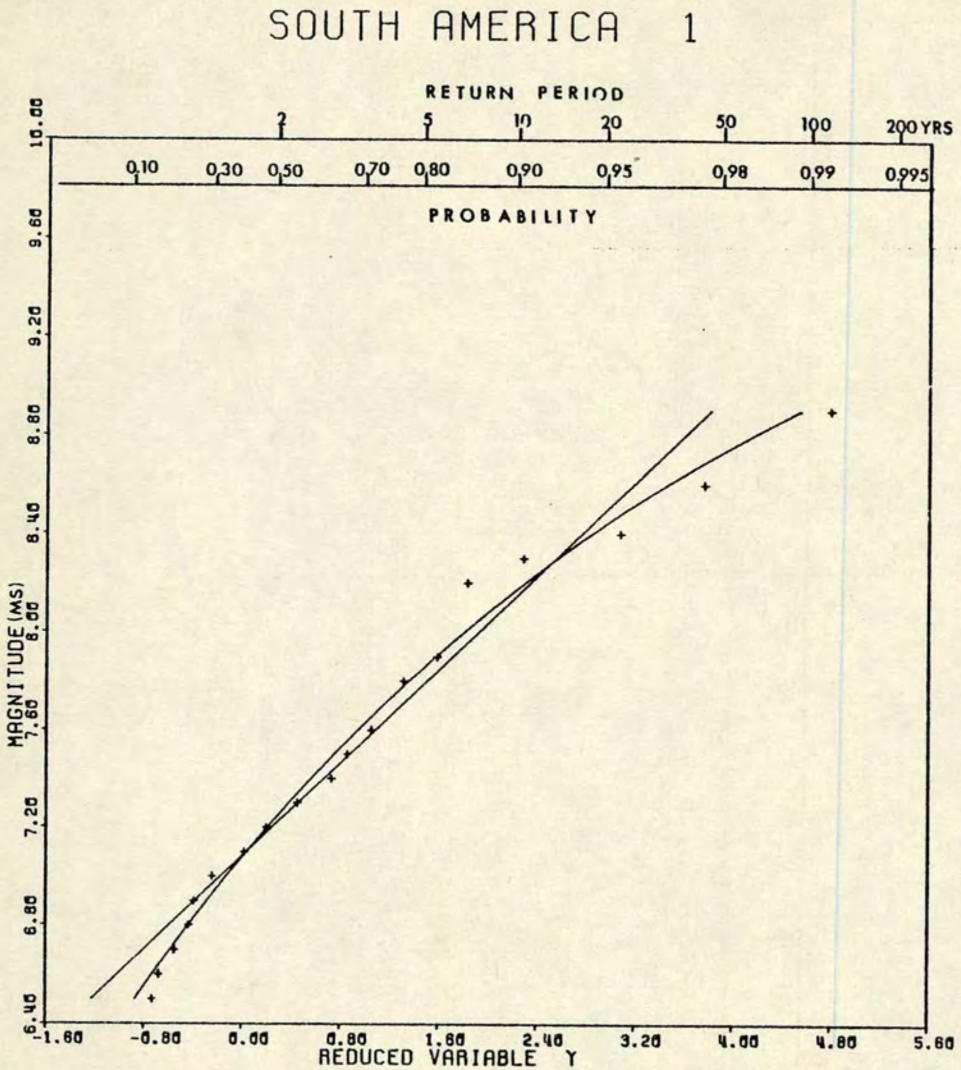


Fig 4-1a Asymptotic distribution curves of extreme values of magnitude for Region 1, for the period 1897-1964. Straight line indicates the first type of extreme value distribution, curved line indicates the third type, + indicates observed annual maximum magnitude. Subsidiary x axis represents the probability of a magnitude being an annual extreme, and its return period in years.

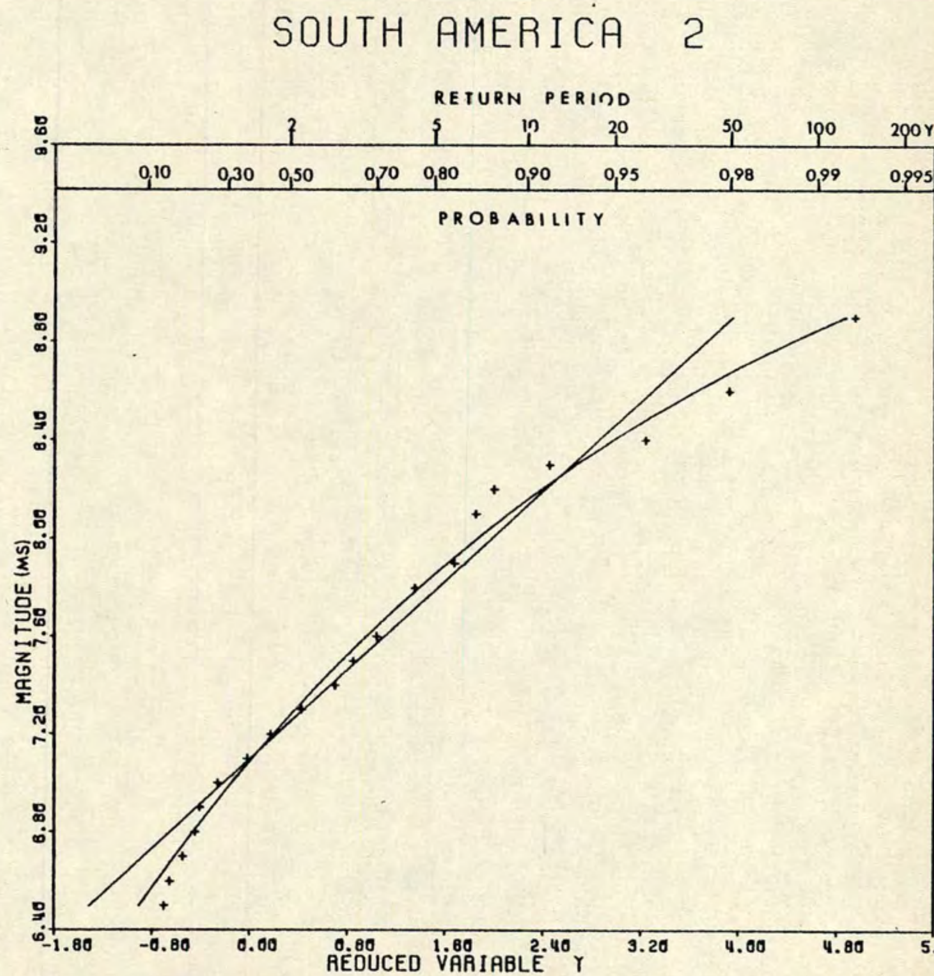


Fig 4-1b Asymptotic distribution curves of extreme values of magnitude for Region 1, for the period 1897-1975. (Explanation of symbols as in Fig 4-1a).

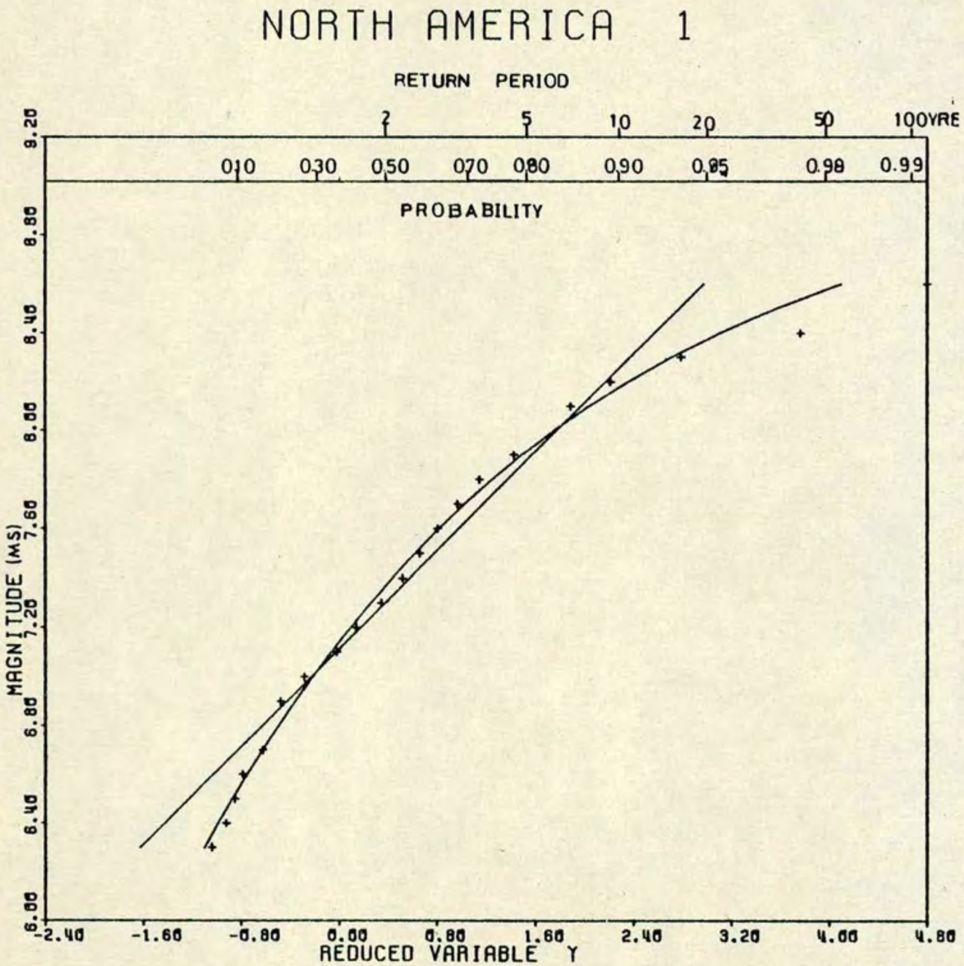


Fig 4-2a Asymptotic distribution curves of extreme values of magnitude for Region 2, for the period 1897-1964. (Explanation of symbols as in Fig 4-1a).

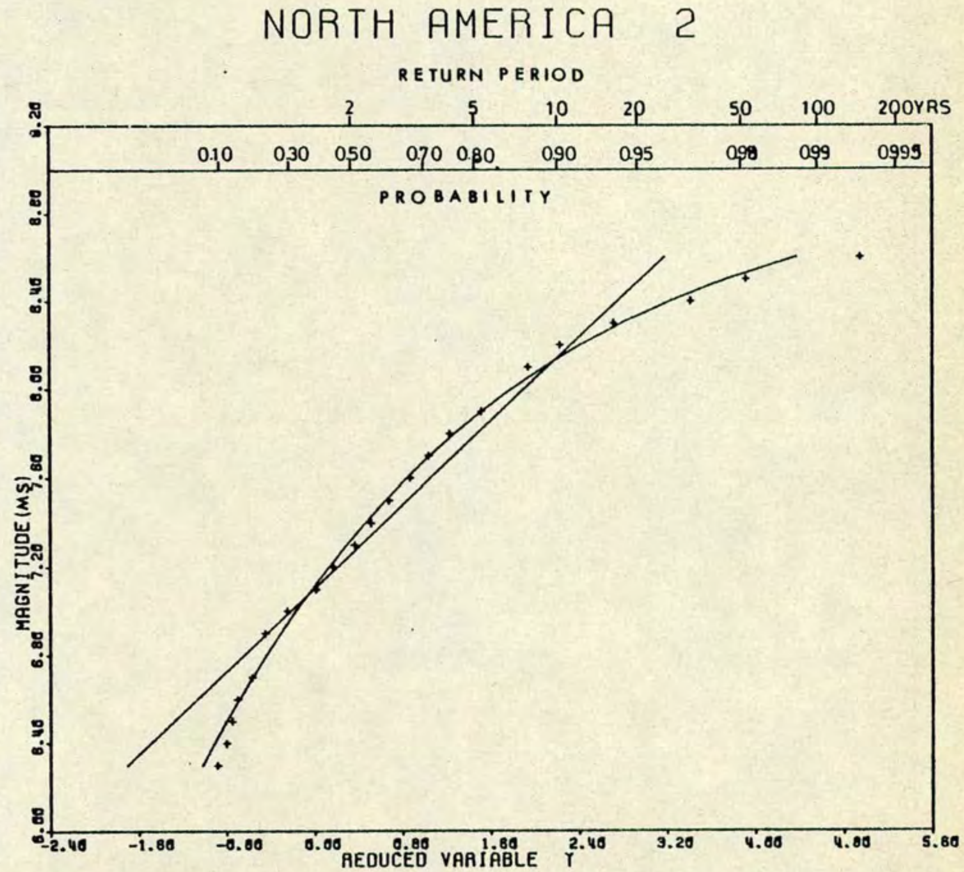


Fig 4-2b Asymptotic distribution curves of extreme values of magnitude for Region 2, for the period 1897-1975. (Explanation of symbols as in Fig 4-1a).

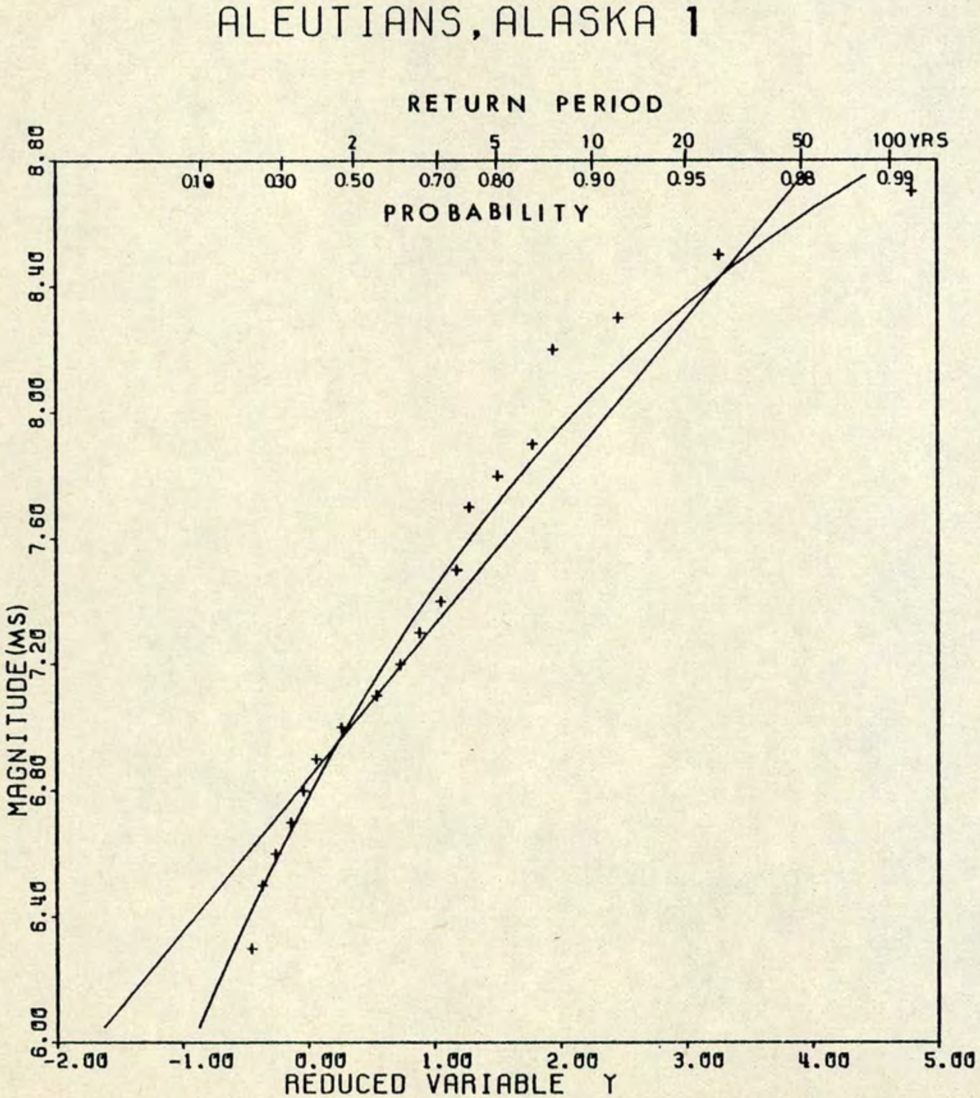


Fig 4-3a Asymptotic distribution curves of extreme values of magnitude for Region 3, for the period 1897-1964. (Explanation of symbols as in Fig 4-1a).

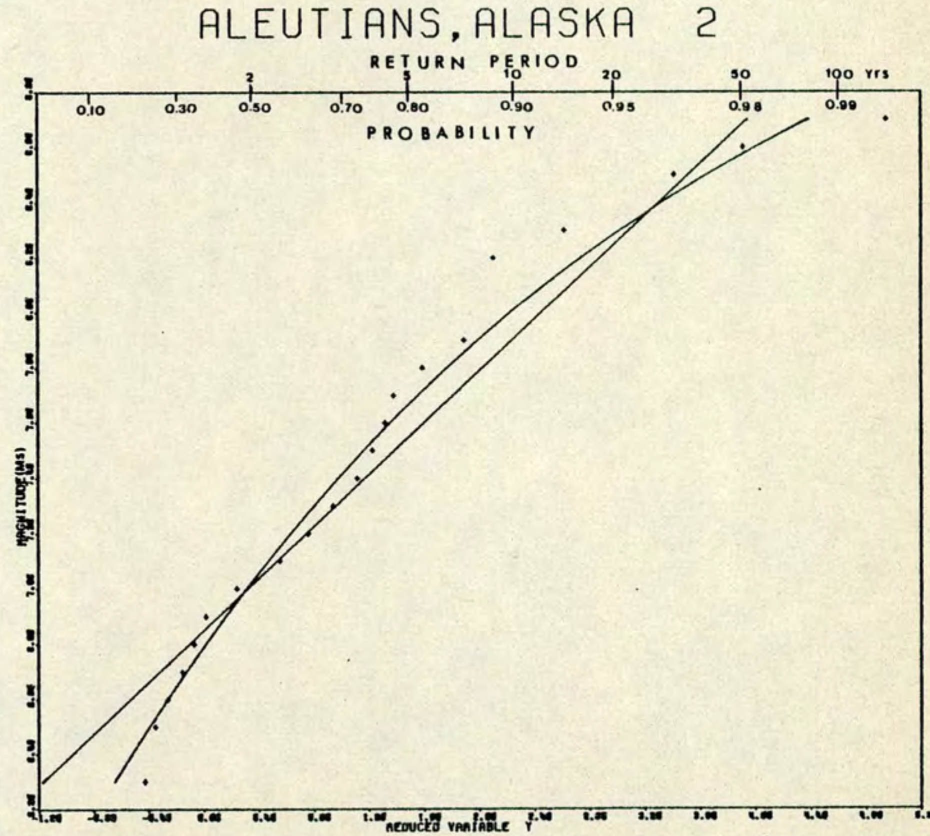


Fig 4-3b Asymptotic distribution curves of extreme values of magnitude for Region 3, for the period 1897-1975. (Explanation of symbols as in Fig 4-1a).

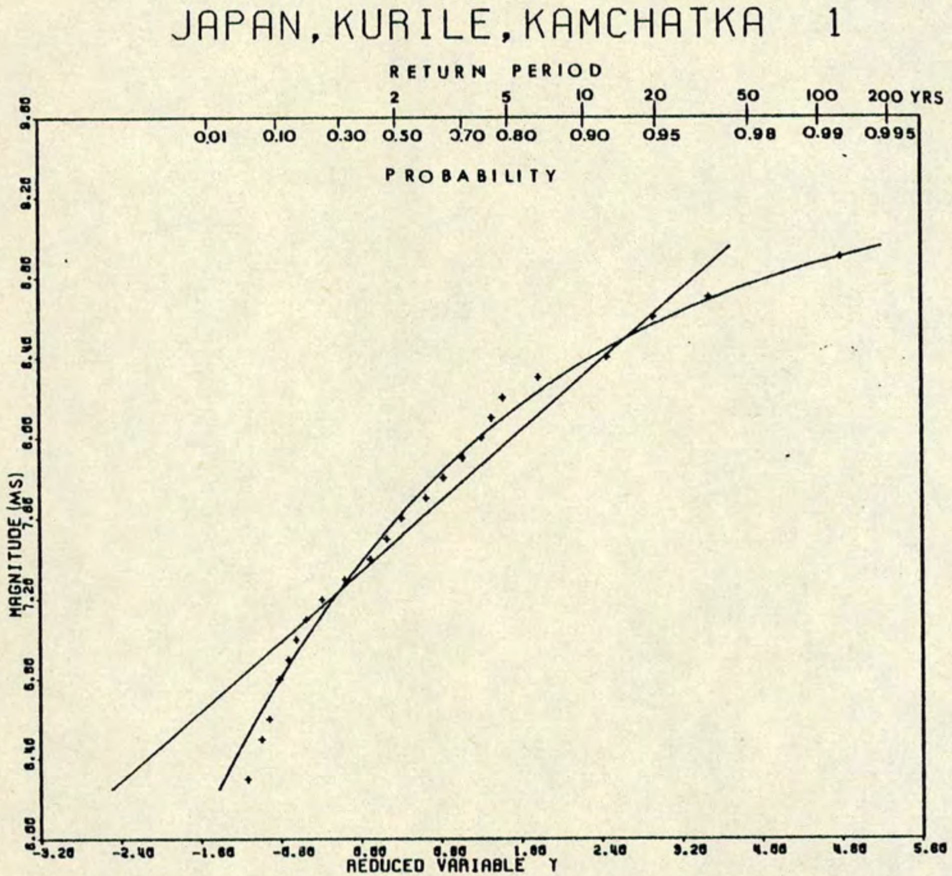


Fig 4-4a Asymptotic distribution curves of extreme values of magnitude for Region 4, for the period 1897-1964. (Explanation of symbols as in Fig 4-1a).

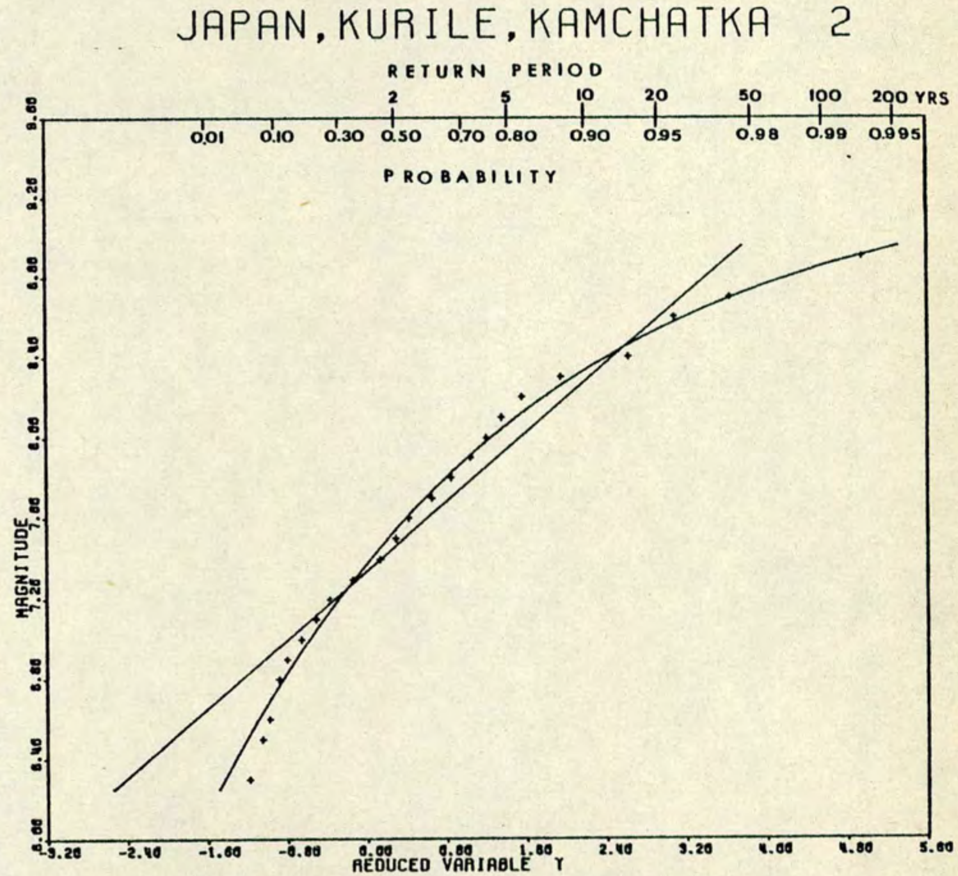


Fig 4-4b Asymptotic distribution curves of extreme values of magnitude for Region 4, for the period 1897-1975. (Explanation of symbols as in Fig 4-1a).

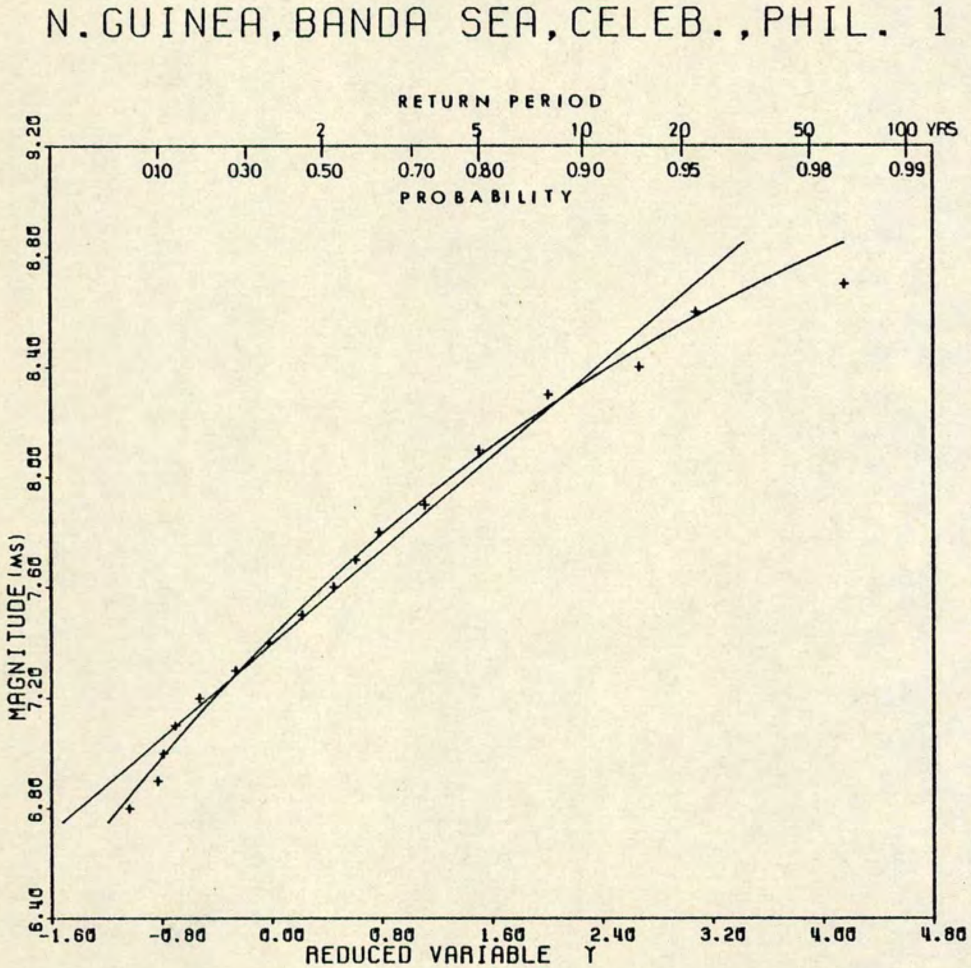


Fig 4-5a Asymptotic distribution curves of extreme values of magnitude for Region 5, for the period 1897-1964. (Explanation of symbols as in Fig 4-1a).

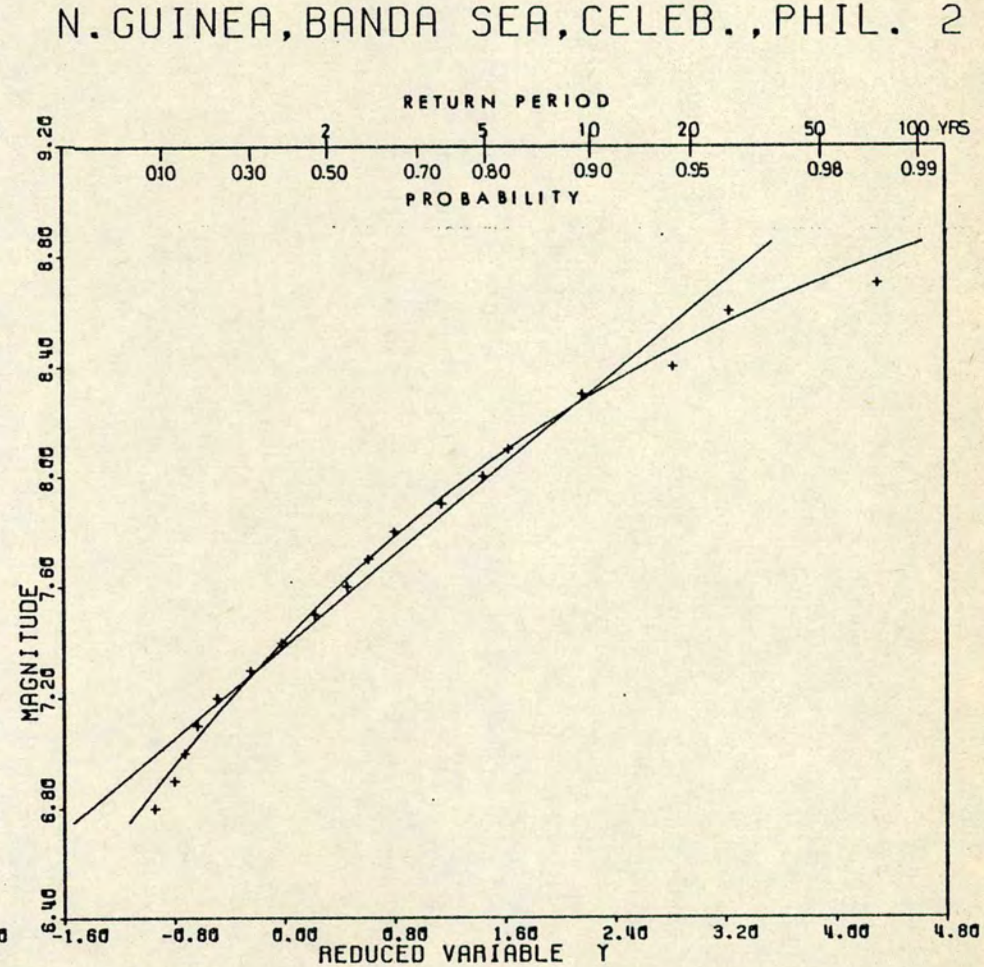


Fig 4-5b Asymptotic distribution curves of extreme values of magnitude for Region 5, for the period 1897-1975. (Explanation of symbols as in Fig 4-1a).

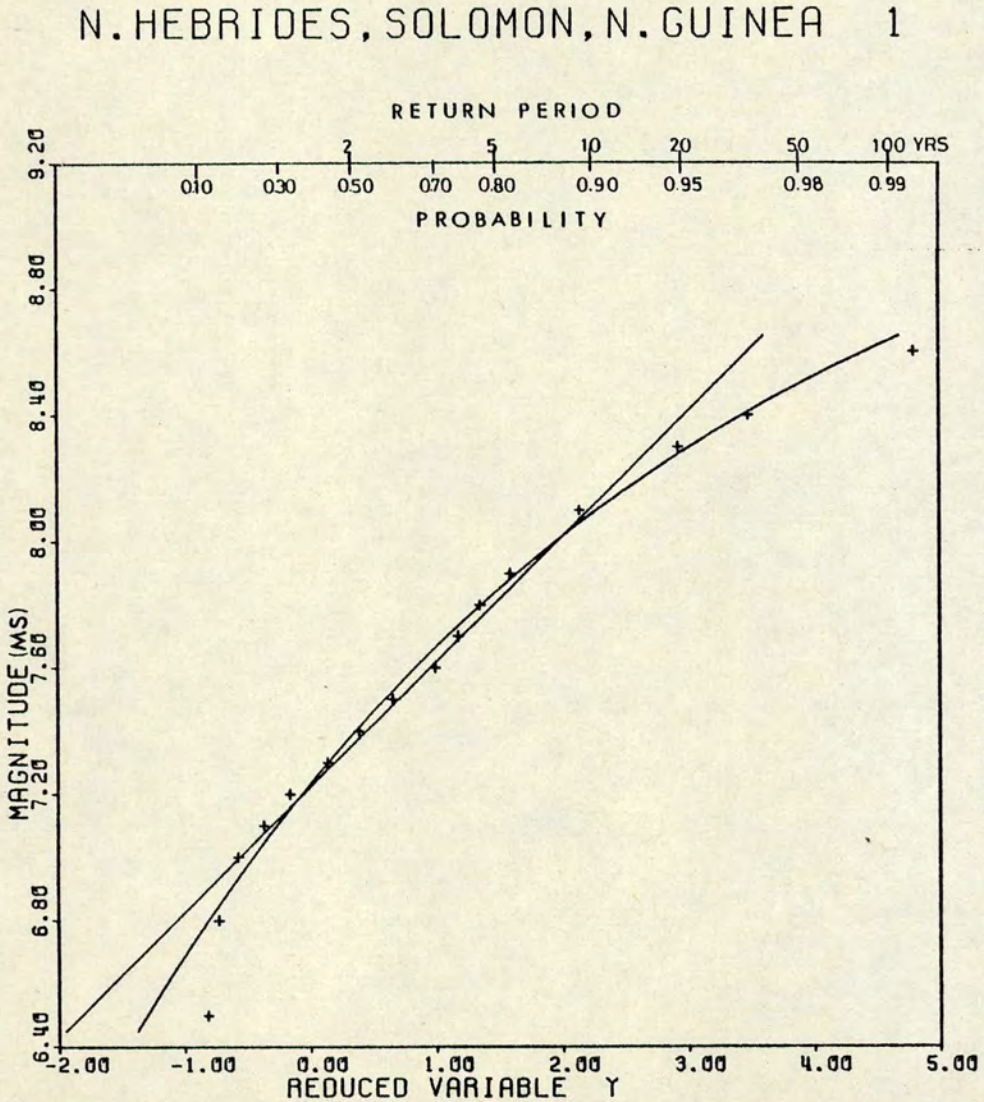


Fig 4-6a Asymptotic distribution curves of extreme values of magnitude for Region 6, for the period 1897-1964. (Explanation of symbols as in Fig 4-1a).

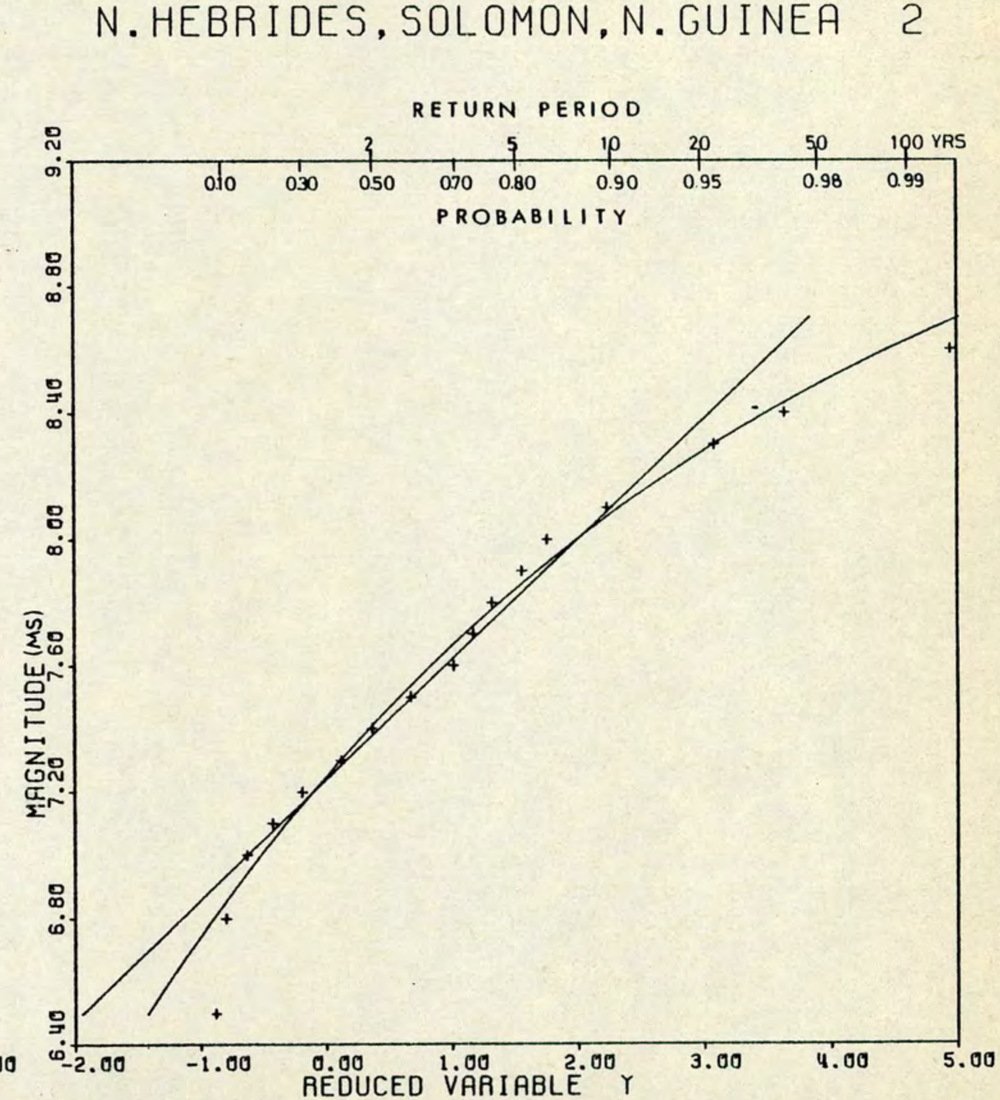


Fig 4-6b Asymptotic distribution curves of extreme values of magnitude for Region 6, for the period 1897-1975. (Explanation of symbols as in Fig 4-1a).

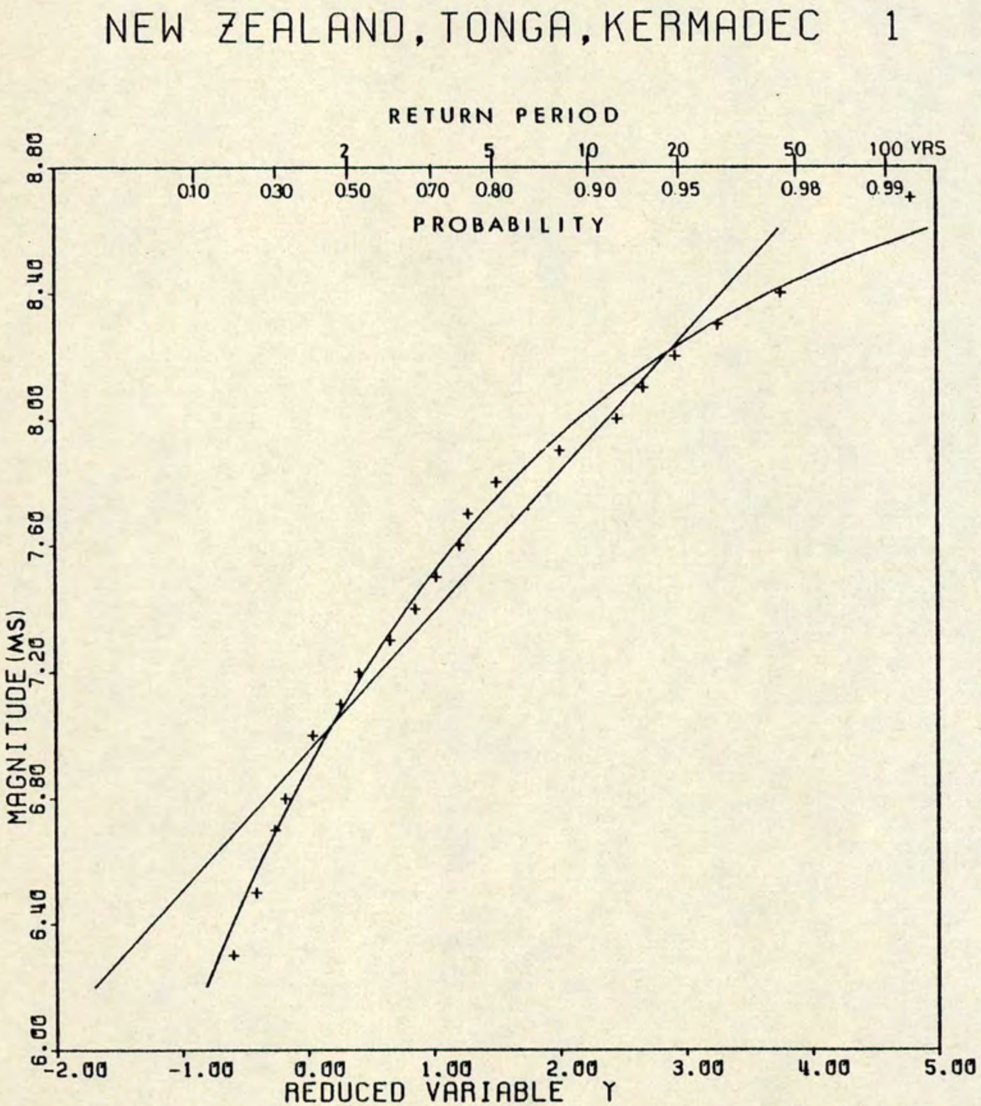


Fig 4-7a Asymptotic distribution curves of extreme values of magnitude for Region 7, for the period 1897-1964. (Explanation of symbols as in Fig 4-1a).

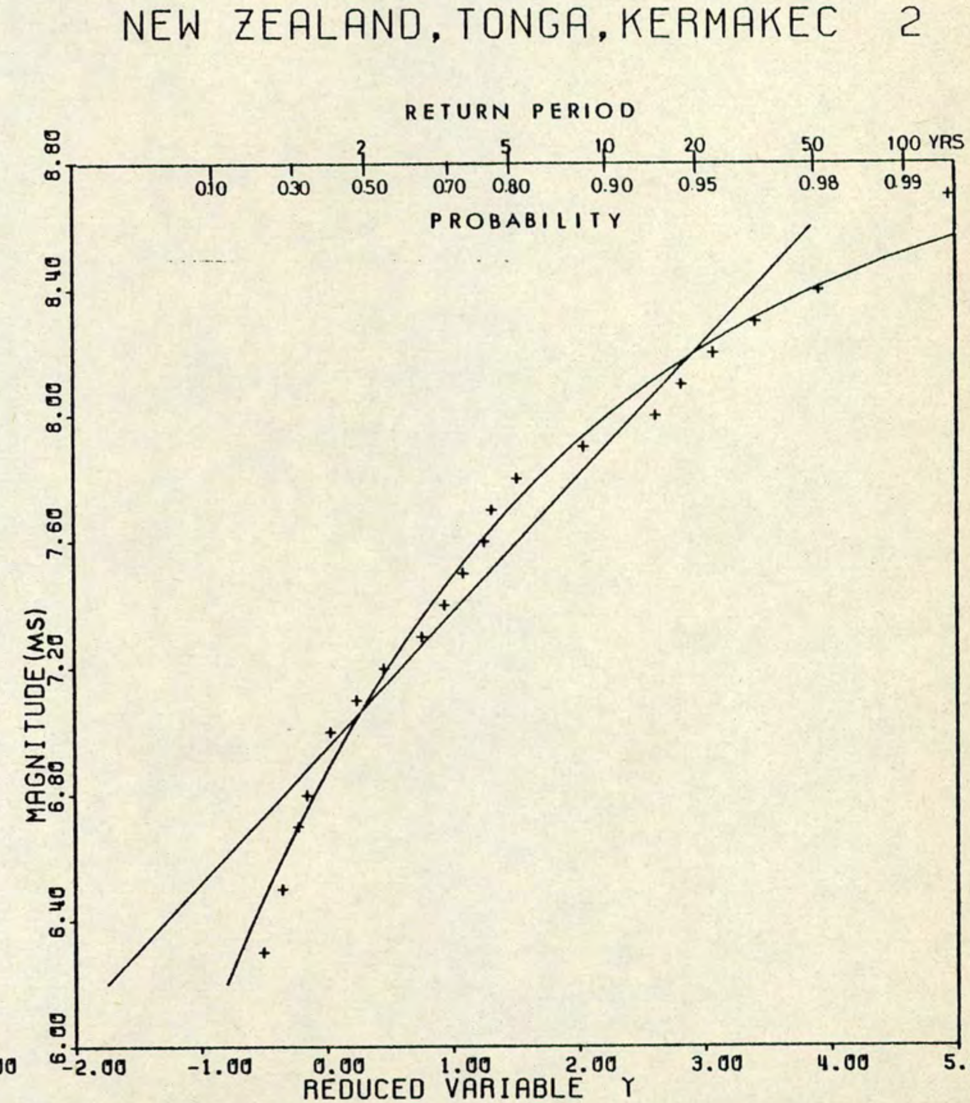


Fig 4-7b Asymptotic distribution curves of extreme values of magnitude for Region 7, for the period 1897-1975. (Explanation of symbols as in Fig 4-1a).

On the other hand, although the absolute values of ω for almost all the regions are higher in both tables than that for the world as a whole, when their uncertainties are considered, all regions have a common range for ω corresponding to the one for the world (9.0-9.5).

These regions are the most seismically active in the world, with observed earthquakes with magnitude as high as 8.9 (Regions 1 and 4), and largest earthquakes with magnitude at least 8.6 (Regions 2 and 6). This range of 9-9.5 as an upper bound to future events seems to be realistic.

Furthermore, the regional asymptotic distribution curves are clearly upper bounded by the asymptotic curve for the world. This is well shown in figures 4-8a and 4-8b where all the regional curves are plotted along with the curve for the world.

They are lower bounded by the curve of Region 7 (New Zealand, Tonga, Kermadec), which is the least active region of the seven subregions, having the smallest number of shallow earthquakes.

The most significant feature which tables 4-1 and 4-2 reveal may be that in all regions the reduced chi-square of the first type asymptote fit is greater than that of the third asymptotic distribution. The minimum difference of $\rho_1 - \rho_2$, is 0.05 for Region 6 which has also the minimum value for λ (minimum curvature). The significance of such a small difference in the two distributions fitted can be seen in figure 4-6b for Region 6, and in figure 4-5a for Region 5 ($\rho_1 - \rho_2 = 0.07$). The maximum difference between ρ_1 and ρ_3 is 0.348 for Region 4 which shows a well-formed third asymptotic distribution curve.

From the above features it can be concluded that the third type asymptotic distribution is preferable as a general model for the statistical behaviour of the occurrence of maximum magnitude earthquakes. With the help of the parameter uncertainties now computed, it is possible to establish a more realistic forecasting procedure based on more information about the

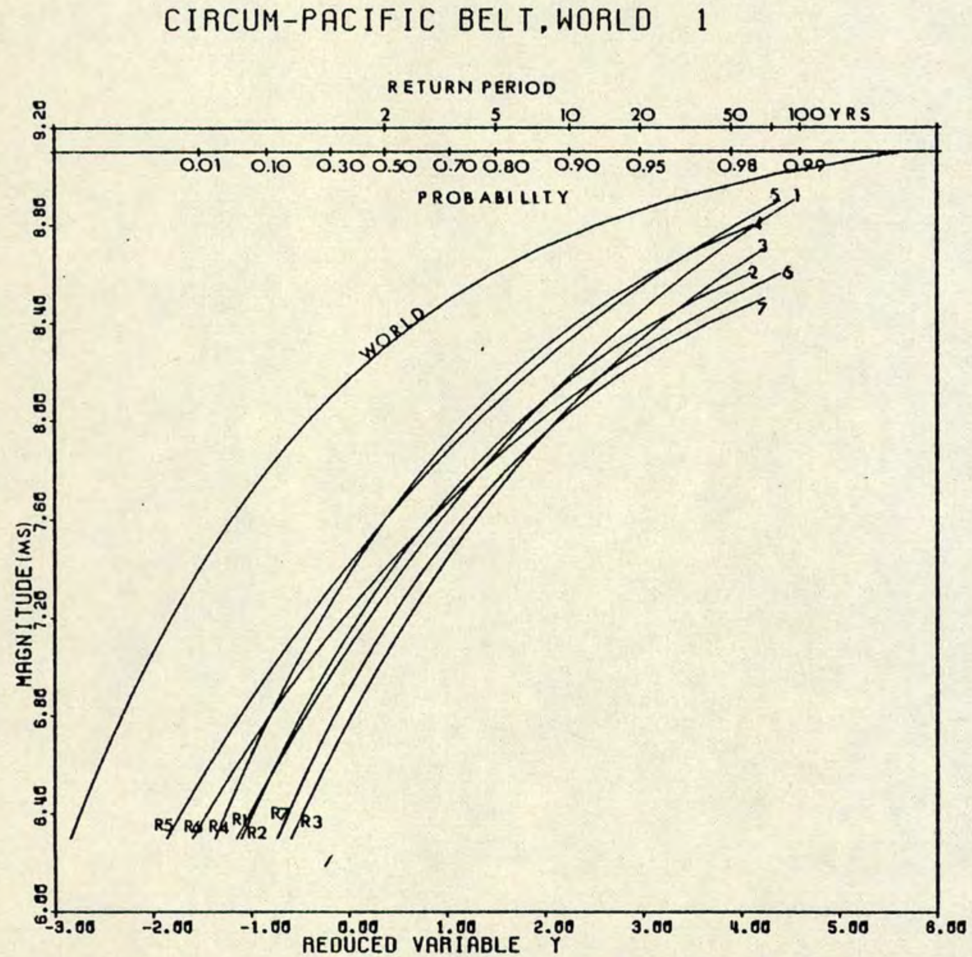


Fig 4-8a Asymptotic distribution curves of extreme values of magnitude for the circum-Pacific belt and the world as a whole, for the period 1897-1964. (Explanation of symbols as in Fig 4-1a).

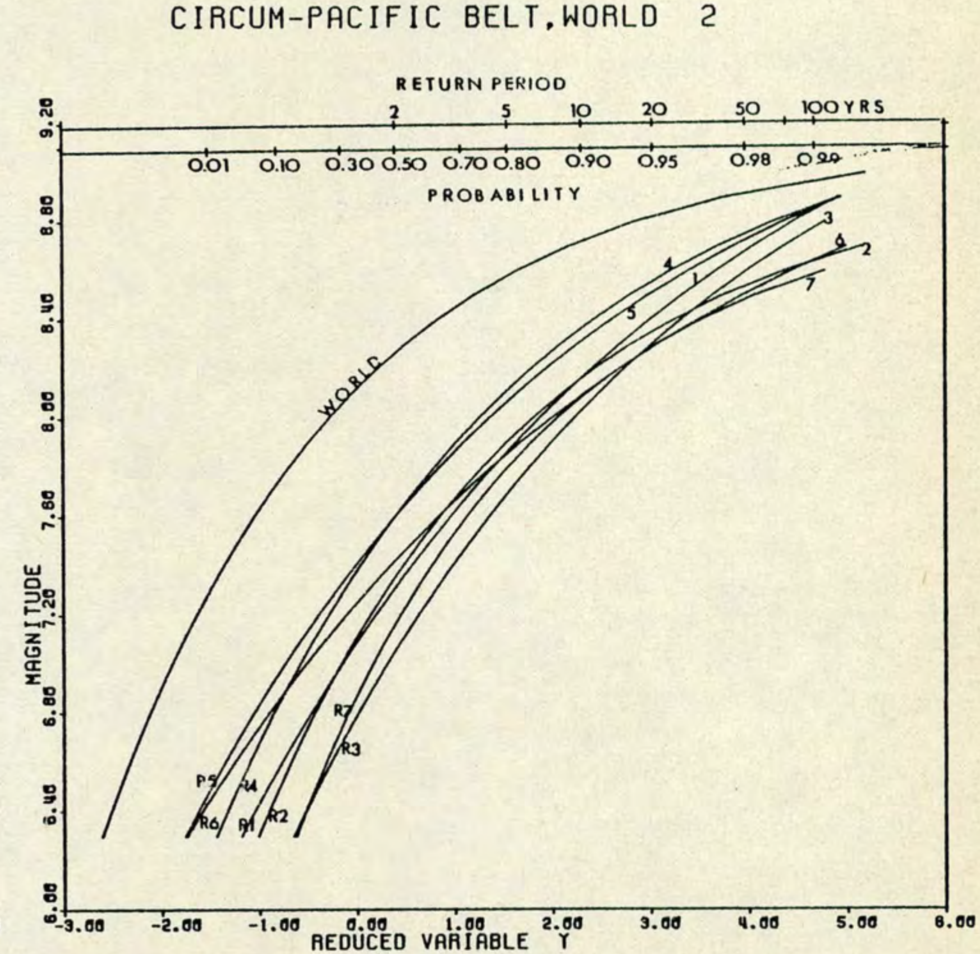


Fig 4-8b Asymptotic distribution curves of extreme values of magnitude for the circum-Pacific belt and the world as a whole, for the period 1897-1975. (Explanation of symbols as in Fig 4-1a).

data sample.

b) Statistical stability of the system

Because one of the basic assumptions for this model is that the future seismic behaviour of a region will be similar to that in the past, the statistical stability of the system must be examined. Only if stability exists, is it possible to make valuable applications of the procedures derived using the calculated parameters.

As a test parameter the most expected maximum magnitude, mode, with return period 75 years, M_{75} is chosen. This approximates to the time span of the largest sample period. The results for sample periods of 35, 45, 55 and 75 years along with the range in which the M_{75} will lie with 95% probability level are tabulated in Table 4-3. These are calculated using equations (4-16) and (4-17).

As expected for these regions characterized by continuous high seismic activity, it is clear from Table 4-3 that statistical stability is effectively achieved over the whole range of the intervals chosen. This stability tends to increase as the sample period lengthens and the mode, M_{75}, becomes stable.

c) Regional features

In view of the statistical stability of the data sample, the parameters derived from the longest available period (ie 1897-1975) may now be used to predict future occurrence of maximum magnitude earthquakes. Because the prediction should be made for a period comparable with the longest available period, Table 4-4 contains the mode which is expected to be exceeded at least once during the next 1, 10, 20, 50 and 100 years for each of the seven sub-regions and for the world as a whole. The range of this magnitude at the 95% probability level is included.

In addition to these quantities, it is possible to determine uncertainties in them using the variance-covariance matrices and equation (4-16).

In fact, negative covariance of ω and λ exists and so predicted

Table 4-3

Test of Statistical Stability

$\tilde{M}(75)$

Region \ Sample period (years)	35	45	55	65	75
1	9.2±1.3*	9.1±1.4	9.0±1.1	8.9±1.0	8.9±1.0
2	8.9±1.0	8.8±1.1	8.7±0.8	8.7±0.7	8.7±0.8
3	8.7±0.9	8.9±1.2	8.8±0.9	8.8±0.9	8.8±1.0
4	9.0±0.8	8.9±0.8	8.9±0.9	8.9±0.9	8.9±0.7
5	9.0±0.9	9.0±0.8	8.9±1.0	8.9±0.9	8.9±1.0
6	8.8±0.9	8.9±1.0	8.7±1.0	8.7±1.1	8.7±1.2
7	8.8±1.0	8.8±0.9	8.7±0.9	8.6±0.9	8.6±0.6

* The uncertainties are the ranges in which the mode with return period T = 75 years ($\tilde{M}75$) will lie with probability 95%. (See equation 4-16).

Table 4-4

Predicted most probable largest earthquake magnitude (mode)
and upper and lower bounds of the interval in which the maximum magnitude will lie
with probability 95% for return periods 1, 10, 20, 50 and 100 years

Region \ Return Period (years)		1			10			20			50			100		
		L. Bound	Mode	U. Bound	L. Bound	Mode	U. Bound	L. Bound	Mode	U. Bound	L. Bound	Mode	U. Bound	L. Bound	Mode	U. Bound
(1) South America	a	6.2±.1	7.2±.1	8.7±.1	7.7±.1	8.3±.1	9.2±.3	8.0±.1	8.5±.1	9.3±.3	8.3±.1	8.8±.1	9.5±.4	8.6±.1	9.0±.2	9.5±.5
	b	6.2±.1	7.2±.1	8.6±.1	7.7±.1	8.3±.1	9.2±.2	8.0±.1	8.5±.1	9.2±.3	8.3±.1	8.7±.1	9.4±.4	8.5±.1	8.9±.1	9.4±.4
(2) North America	a	6.1±.2	7.4±.1	8.5±.1	7.7±.1	8.3±.1	8.9±.3	8.0±.1	8.5±.1	8.9±.3	8.3±.1	8.6±.2	9.0±.3	8.4±.1	8.7±.2	9.0±.4
	b	6.0±.2	7.4±.1	8.5±.1	7.7±.1	8.3±.1	8.8±.2	8.0±.1	8.4±.1	8.8±.2	8.3±.1	8.6±.1	8.9±.3	8.4±.1	8.7±.2	8.9±.3
(3) Aleutians, Alaska	a	5.6±.2	7.0±.1	8.5±.1	7.5±.1	8.2±.1	9.1±.2	7.8±.1	8.4±.1	9.2±.3	8.2±.1	8.7±.1	9.3±.3	8.4±.1	8.9±.2	9.3±.3
	b	5.7±.2	7.0±.1	8.5±.1	7.5±.1	8.2±.1	9.0±.2	7.8±.1	8.4±.1	9.1±.3	8.2±.1	8.7±.1	9.3±.3	8.4±.1	8.8±.1	9.3±.3
Japan (4) Kurile Kamchatka	a	6.4±.1	7.6±.1	8.7±.1	8.0±.1	8.5±.1	9.0±.2	8.2±.1	8.7±.1	9.1±.2	8.5±.2	8.8±.1	9.1±.2	8.7±.1	8.9±.1	9.2±.2
	b	6.4±.1	7.6±.1	8.7±.1	7.9±.1	8.5±.1	9.0±.2	8.2±.1	8.6±.1	9.1±.2	8.5±.1	8.8±.1	9.1±.2	8.6±.1	8.9±.1	9.2±.2
N Guinea, Banda Sea (5) Celebes, Moluccas Philippines	a	6.7±.1	7.5±.1	8.7±.2	7.9±.1	8.5±.1	9.2±.3	8.2±.1	8.6±.1	9.3±.4	8.5±.1	8.8±.2	9.4±.4	8.6±.1	9.0±.2	9.5±.5
	b	6.6±.1	7.5±.1	8.7±.1	7.9±.1	8.4±.1	9.1±.2	8.1±.1	8.6±.1	9.1±.3	8.4±.1	8.8±.1	9.2±.3	8.6±.1	8.9±.1	9.3±.4
N. Hebrides (6) Solomon N. Guinea	a	6.5±.1	7.4±.1	8.5±.2	7.7±.1	8.2±.1	8.9±.4	7.9±.1	8.4±.1	8.9±.4	8.2±.1	8.6±.2	9.0±.5	8.4±.1	8.7±.3	9.1±.6
	b	6.6±.1	7.4±.1	8.4±.2	7.7±.1	8.2±.1	8.9±.3	7.9±.1	8.4±.1	8.9±.4	8.2±.1	8.5±.2	9.0±.5	8.4±.1	8.7±.2	9.1±.5
N. Zealand (7) Tonga Kermadec	a	5.7±.2	7.2±.1	8.4±.1	7.6±.1	8.2±.1	8.7±.2	7.8±.1	8.4±.1	8.8±.2	8.2±.1	8.5±.1	8.8±.3	8.3±.1	8.6±.2	8.8±.3
	b	5.7±.2	7.2±.1	8.4±.1	7.5±.1	8.2±.1	8.7±.2	7.8±.1	8.3±.1	8.7±.2	8.1±.1	8.5±.1	8.8±.2	8.3±.1	8.6±.1	8.8±.2
World	a	7.5±.1	8.3±.1	8.9±.1	8.5±.1	8.8±.1	9.1±.1	8.6±.1	8.9±.1	9.1±.2	8.8±.1	9.0±.1	9.1±.2	8.9±.1	9.0±.1	9.2±.2
	b	7.4±.1	8.3±.1	8.9±.1	8.5±.1	8.8±.1	9.0±.1	8.6±.1	8.9±.1	9.2±.1	8.7±.1	9.0±.1	9.1±.1	8.8±.1	9.0±.1	9.1±.1

a: Using parameters estimated from sample period: 1897-1964

b: Using parameters estimated from sample period: $1897\text{-}1975_{sep.}$

magnitudes are generally well determined with small uncertainty even when there are relatively large uncertainties in the parameters ω and λ. The observed maximum magnitude earthquake within each region is shown in the last column of Table 4-2 to illustrate this point.

From Table 4-4 several features concerning the future seismicity of the circum-Pacific belt are apparent.

i) The annual mode for all the regions is greater than m = 7.0 with the maximum for Region 4 (Japan, Kurile, Kamchatka) as high as m = 7.6.

ii) During the next 10 years a maximum magnitude earthquake which will exceed m = 8.2 is expected in almost every region in the circum-Pacific belt. This may be as high as m = 8.5 for Region 4. Likewise, for the next 20 years a maximum magnitude earthquake is expected which may exceed 8.3 (Regions 6 and 7), 8.4 (Regions 2 and 3), 8.5 (Regions 1 and 5) and 8.6 (Region 4).

iii) The regions in which events with predicted maximum magnitude expected to exceed 8.8 - 8.9 during the next 100 years are: Region 1, Region 4 and Region 5. These regions are situated in the north-western (Region 4 and Region 5) and south-eastern (Region 1) part of the circum-Pacific belt, diagonally opposite each other. This is comparable with the results of paragraph 3.2.4 using the strain energy release method.

iv) From figures 4-1a to 4-7b it can be seen that the return period, and the number of exceedences over the next 100 years, for an earthquake with magnitude 8.0 or greater in each of the seven subregions is as follows:

Region 1: 7 years, 14-15 occurrences

Region 2: 6.5 years, 15-16 occurrences

Region 3: 10 years, 10 occurrences

Region 4: 4 years, 25 occurrences

Region 5: 4.5 years, 22-23 occurrences

Region 6: 8 years, 12-13 occurrences

Region 7: 10 years, 10 occurrences

v) Kanamori (1978) points out that the surface-wave magnitude scale saturates for great earthquakes with faults of length greater than 60km. In the circum-Pacific belt he found four "giant" earthquakes which, in his newly introduced magnitude scale M_w have magnitudes exceeding M_w = 9.0. These are:

the 1960 Chilean earthquake	(22.5.1960)	with magnitude	M_w=9.6 (Ms=8.3)- Region 1
the 1964 Alaskan "	(28.3.1064)	" "	M_w=9.2 (Ms=8.4)- Region 3
the 1957 Aleutian "	(09.3.1957)	" "	M_w=9.1 (Ms=8.25)-Region 3
the 1952 Kamchatka "	(04.11.1952)		M_w=9.0 (Ms=8.4)- Region 4

Comparison of M_w with surface-wave magnitude Ms, for earthquakes with a smaller fault dimension shows that M_w agrees reasonably well with Ms.

To examine the effect which the exclusion of such a high magnitude may have on the results of the statistical analysis, the annual extremes, including the new magnitude 9.6 for the Chile earthquake of 1960, are taken and re-analysed for Region 1. It is found that:

$$\omega = 11.05 \pm 0.34, \; u = 7.07 \pm 0.03 \text{ and } \lambda = 0.158 \pm 0.018,$$

and the values of the mode in 1, 20, 50, and 100 years using these new parameters are:

$$\tilde{m}_1 = 7.2\pm0.1 \;,\; \tilde{m}_{10} = 8.4\pm0.1 \;,\; \tilde{m}_{50} = 8.9\pm0.2 \;,\text{ and } \tilde{m}_{100} = 9.2\pm0.2 \;.$$

Comparing the above results with those of Table 4-4 it is apparent that the new predicted magnitudes do not differ significantly from the magnitudes which were derived without using M_w for the 1960 annual maximum. Considering that Region 1 includes the most dramatic single adjustment to magnitude, that is, from $M_s = 8.3$ to $M_w = 9.6$, it seems that these few cases of saturation do not produce any significant bias in the prediction procedure using the third type asymptotic distribution.

4.6 Comparing the results from energy release and third type asymptotic distribution methods

The validity of the established relations, equations (4-21) and (4-41), among the parameters of the frequency-magnitude and energy-magnitude laws, and those of the third type asymptote can be verified by comparing the results for the same quantity derived using the two different procedures.

For each of the seven subregions both the mode and the magnitude which corresponds to the mean annual energy release, are calculated using equations 4-20 and 4-40 respectively. These are tabulated in Table 4-5 along with the upper limit ω. In the same table the values of M_1, M_2 and M_3, calculated in Chapter III (Table 3-2), are listed for each subregion. Then a comparison can be made between M_1 and $\tilde{x}$, M_2 and X_2, whereas M_3 must be within the range of ω.

Table 4-5 reveals some of the most significant features of this study. From the remarkably similar results for M_1 and $\tilde{x}$, as well as for M_2 and X_2 we can draw several conclusions.

i) The relations obtained here among the parameters of the two different procedures used to describe the same phenomenon, are valid over a wide range of seismo-tectonic environments.

ii) These relations give a physical link to all the parameters of the third type asymptotic distribution. Equation (4-41) links the parameters with the mean annual energy release in the region under investigation, and equation (4-21) with the a and b of the magnitude-frequency formula.

Table 4-5

Comparison between the parameters derived from the strain energy release and third type asymptote methods

Region code	M_1	$\tilde{x}$	M_2	X_2	M_3	$\omega \pm \delta\omega$	ρ_3
1	7.25	7.21	8.03	8.13	9.10	10.16±1.2	0.07
2	7.34	7.37	7.94	8.07	9.00	9.14±0.5	0.03
3	7.07	7.00	7.89	8.02	8.78	9.66±0.6	0.09
4	7.52	7.61	8.20	8.28	8.96	9.30±0.4	0.07
5	7.48	7.53	8.12	8.23	9.04	10.00±1.1	0.02
6	7.35	7.35	7.90	7.98	8.83	9.44±1.1	0.08
7	7.08	7.19	7.86	7.91	8.97	8.95±0.4	0.05
World	8.09	8.30	8.68	8.62	9.52	9.23±0.25	0.03

iii) In all regions except the third, the values of M_3 are within the range of $\omega \pm \delta\omega$. However, the case of Region 3 has its own significance. From Table 4-5 it can be seen that Region 3 has the maximum value for the chi-square fit of all seven regions, that is, relatively the worst fit. But this region has also the worst fit when Duda (1965) plots the regional recurrence curves using the frequency-magnitude formula. He points out that "this may be caused by the superposition of two natural populations of earthquakes". The third type asymptotic distribution for this region might be similarly influenced by such a seismic feature producing this relatively poor fit.

Comparing the regional seismicity resulting from both the methods of paragraphs 3.2.4 and 4.5.3 shows that the corresponding seismic pictures are almost identical.

Finally, the remarkably similar results which are obtained from these two methods in a region with the most complete data set, like the circum-Pacific belt, suggests that the third type asymptotic distribution method will be of great assistance for forecasting procedures in less active regions where only the extreme earthquake magnitudes may be known.

4.7 Conclusions

The objectives of this chapter were:

i) to investigate the usefulness of the third type asymptotic distribution of extremes for predicting earthquake risk, and

ii) to relate the parameters of that asymptote with those of the frequency-magnitude and energy-magnitude laws, in order to explore their physical meaning and obtain a link with the physical release of strain energy.

Towards the first objective, a specific goal was to develop a computing procedure which would determine uncertainties in the parameters computed. It is assumed that an error analysis is vital to any seismic risk analysis.

Using Marquardt's algorithm which is based upon the non-linear least-squares fitting, the covariance matrix among the three parameters has been obtained.

This computing procedure allows several important factors to be taken into account, such as an assigned weight for each individual extreme magnitude, the number of missing years may be considered and incompletely reported data may be omitted without disturbing the distribution of the observed maximum magnitudes.

The variance-covariance matrix among the parameters shows that the characteristic largest value u is the most precisely known parameter. The variance for ω and λ are usually large. This indicates that the upper limit to earthquake magnitude and the curvature of the distribution are often difficult to resolve with high precision.

The negative covariance between the upper limit and curvature implies that they are not independent parameters (Burton, 1978b). Yegulalp and Kuo (1974) also note that there is a correlation between these two parameters. Thus, it can be concluded that among the parameters of the third type asymptote only the characteristic value u is independent.

It is observed that when the data shows little curvature λ, and, therefore, a high value of ω, these parameters are usually accompanied by larger uncertainties than usual, which may indicate that the time span is insufficient to establish curvature. However, the existence of negative covariance between them leads to seismic risk calculations with reasonable uncertainties. Uncertainties have been computed for the upper and lower bounds within which the predicted quantities will lie at a given probability level.

Comparison between the first and third type asymptotic distribution shows that in all cases the third has a better fit to the data than the first. This is reasonable because the third type asymptote is closer to the real process: it takes into account the existence of an upper magnitude threshold. It can be concluded that the third type asymptote is usually preferable as a general model for the statistical behaviour of the occurrence of maximum magnitude earthquakes.

The second objective is achieved by relating the third asymptote's parameters to the parameters of the frequency-magnitude and energy-magnitude laws. In particular, the X_2 (eq 4-41) gives the mean annual rate of energy release in the region in terms of the Gumbel parameters.

A second feature is the remarkably similar results which are obtained when the two different procedures, that is whole process and part process, are used to describe the same phenomenon in the same area.

Finally, the centres of highest seismic activity in the circum-Pacific belt are diagonally opposite each other, and this presumably relates to the tectonic movement of the Pacific plate (Duda, 1965). The seismicity of this region is expected to generate a maximum magnitude which may exceed $m = 8.2$ in almost every region in the circum-Pacific belt during the next 10 years. Regions 1, 4, and 5 are the regions in which an earthquake with magnitude $m = 8.8$ to 8.9 is expected to be exceeded at least once during the next 100 years.

From the results obtained in this chapter it is apparent that the energy release method developed in Chapter III and the third type asymptotic distribution described here, are capable of describing the seismic feature of a region. The method of calculating the uncertainties in the parameters and in the prediction quantities shows that the third type asymptotic distribution method can be a useful model for prediction procedure. Thus, in the next part of this study these methods will be applied to Greek seismicity in an attempt to evaluate the seismic risk of the area. This area, although it has a seismicity lower than the circum-Pacific belt, is seismically the most active area in Europe. Before this can be done, an earthquake catalogue of the area is presented which will be the main source for the ensueing risk evaluation.

CHAPTER V

AN EARTHQUAKE CATALOGUE FOR THE AREA OF GREECE ($N_{33}^{42.5}$, E_{19}^{29})SINCE 1901

5.1 Introduction

Among the demands of modern seismology for seismic hazard or zoning considerations, is the existence of an earthquake data set as accurate, homogeneous and complete as possible. Thus, although Greece has the seismic privilege to be the most active area of Europe, and its long history can report catastrophes due to earthquakes as far back as 2100 B.C. (Sieberg, 1932; Galanopoulos, 1961), the requirements for accuracy and completeness restrict usage to mainly instrumentally recorded events. Therefore, the earliest starting point for a statistical treatment founded on instrumental measurements is the beginning of the present century, whereas the whole seismic history remains a vital background factor for the seismic behaviour of the region.

The steady improvement of number and quality of seismological stations from decade to decade, however, makes it almost impossible to prepare a catalogue which would be equally complete and accurate over the whole period of instrumental observations. With the data available, homogeneity can only be achieved by consistent treatment of all source parameters.

For Greece, such an effort is attempted in the present study by recalculating all source parameters, when there are enough data to justify this treatment, by using single and joint epicentre determination methods of calculating source parameters. Magnitudes are recalculated according to a consistent scheme for the longest possible part of the period under consideration. The results, then, are tested for completeness and compared with the ISS original locations and with macro-seismic epicentres.

5.2 Previous work in Greek earthquake cataloguing

Although the need for earthquake cataloguing was recognized in Greece as early as the middle of the nineteenth century, and a number of Greek earthquake catalogues have existed since 1879 (Schmidt, 1879, for 1840-1878; Galanopoulos, 1953, for 1879-1892; Annales de l'Observatoire National d'Athènes from 1893 up to 1936; and monthly and annual bulletins since 1949), the first systematic attempt to accumulate and classify all earthquakes over a certain magnitude (M⩾5) was made by Galanopoulos in 1960. By careful examination of all available sources, he published details of a large number of earthquakes with macroseismic information which occurred in the period 1801-1958. This catalogue and a more recent version for the period 1700-1960 (Galanopoulos, 1963) which includes a long list of further references, are the basis for most of the later publications concerning Greek seismicity.

In 1969, Kárnik, in his publication for Europe (1901-1955), made the first attempt to present an earthquake catalogue with magnitude determinations. The basic sources for Greek epicentres came from the previous Galanopoulos publications as well as from Gutenberg and Richter (1954). In this catalogue there are four types of magnitudes: (a) M_{LH} for earthquakes with depths 1-5 km or 5-60 km (sup. and n respectively); (b) M_B for depths 60-300 km; (c) M in brackets for magnitudes converted from macroseismic parameters I_o and r; and (d) M when this magnitude is taken from national catalogues and corrected for differences between it and his M_{LH} standards.

In 1970 the UNDP/UNESCO Survey of the Seismicity of the Balkan Region began, and it gave first priority to the compilation of an earthquake catalogue. This catalogue (Shebalin, Karnik and Hadžievski, 1974) represents a "collection of main earthquake parameters" as pointed out in its preface. It covers the period 1901-1970 and contains earthquakes with $M \geq 4$ or $I_o \geq VI$. Basic sources for Greece were lists of earthquake parameters from Galanopoulos (1960, 1963), Kárnik (1969, 1971), and Papazachos and Comninakis (1971), coupled with International Summaries and Catalogues.

The UNESCO's catalogue has been widely used for many investigations for the Balkan region because it is the most complete in terms of the number of earthquake entries. It is useful to briefly describe the procedure used for earthquake parameter determinations by quoting from its introduction and explanatory text.

i) Origin time

"The estimation of the origin time was based mainly on results reported by ISS, BCIS, ISC, etc., and for the beginning of the century from reported P-arrivals and macroseismic observations. The final estimation was, usually, taken as average for all the accessible determinations" (page 51).

ii) Epicentre coordinates

"As a base for determinations of normal epicentres ($h < 60$km) in the catalogue the macroseismic data were chosen. For the intermediate shocks ($60 \leqslant h \leqslant 300$) the position of epicentres were taken from instrumental determinations. For the aftershocks, the coordinates of the main shock were repeated" (pages 52, 53).

iii) Focal depth

"For the whole investigated period (1901-1970), the only possibility for the determination of focal depth of 'normal' shocks was the use of macroseismic data. All instrumental determinations of focal depth of 'normal' shocks published by ISS, BCIS, etc., for the period before 1965 were neglected. Since 1965 the instrumental determinations of h made by ISC and CGS (NEIS), became the source of information. The determination of focal depth for intermediate sources was based mainly on the instrumental data" (pages 56, 57).

iv) Magnitude

"The M_{LH} (Karnik et al., 1962) was taken as the basic one for 'normal' shocks. Generally the instrumental determinations of M_{LH} made by Karnik (1969) were used for the period 1901-1963. For $M_B = 4 - 5$ the published M_B from ISC and US were taken, because for this interval $M_B \approx M_{LH}$ can be assumed. In the total absence of instrumental data, the magnitude corresponding to M_{LH} was determined from macroseismic data. For intermediate shocks the magnitudes M_B determined by Karnik (1964) were used or, exceptionally, were taken from international summaries" (pages 58, 59).

This catalogue will be referred to as UNS from now on.

The first attempt to relocate epicentres reported by the International Seismological Summary (ISS), using the single-event method and the computer program SPEEDY of Douglas, Young and Lilwall (1974) for the Marmara region in north-west Turkey, which is included in our area of investigation, was made by Crampin and Üçer (1975). They relocated all sixty earthquakes which took place within this area from 1913-1963. Without applying any station adjustment the relocated epicentres were significantly different from the ISS locations, with an average shift of 40 km for events before 1957, and 5 km for events from 1956-1963 when the ISS epicentres were calculated by computer.

Alsan, Tezuçan and Båth (1975) published the first computerized earthquake catalogue for the whole of Turkey. This catalogue, in order to provide better continuity with corresponding catalogues, includes events from beyond the Turkish borders. Because the same criterion is also applied in the present study, there is an overlapping zone of 33.5°N-42.0°N, 25.5°E-29.0°E. For the relocation of epicentre parameters, a computer program based on the single-event method was used. This program was developed in 1972 at the BCIS (Rothé et al., 1972).

Magnitudes were redetermined using Swedish station amplitudes. Üçer et al. (1975) point out that the shift from ISS locations for the first decade after 1918 gives an average change in position of 137 km. This average shift is lessened for the later events being 42 km for the decade 1948-1958, whereas for the period 1959-1963 it is less than 10 km. This catalogue will be referred to as ATB (ie the initials of the authors).

Finally, Galanopoulos (1977) includes the most recent catalogue of Greek earthquakes. This catalogue contains a list of earthquakes since 1902 with $M \geqslant 5\frac{1}{2}$. It is a compilation from his previous work (1960, 1963), Kárník (1969), Gutenberg and Richter (1954), UNS and ATB, and since 1961 all earthquake parameters, except magnitude, are those calculated by ISS and the International Seismological Centre (ISC). All magnitudes are averaged surface wave magnitudes, determined using macro and microseismic information.

It is apparent that none of the existing catalogues for Greece as a whole fulfil the important objective of homogeneity either for locations or for magnitudes. All of them have inconsistencies because they are compiled from many different sources. Furthermore, the ISS locations are influenced by the period in which the events were recorded and by changes in travel-time models used (see below), as is apparent from the work of Crampin and Üçer (1975) for the Marmara area and Ucer et al. (1975) for the results of ATB.

5.3 The ISS epicentres: reasons for inaccuracies

The only Bulletins which tabulate phase arrival and epicentres from 1917 until 1963 are those of the International Seismological Summary. ISS used different travel-time tables during the whole period (Turner-Zoppritz from 1917 until 1929, Jeffreys-Bullen revised tables from

1930-1936, and since then Jeffreys-Bullen with ellipticity corrections).

Epicentres were determined by hand-operated mechanical calculators, except for the last seven years when an electronic computer was used, and although the full scale least-squares procedure used was similar to the computer procedure used today, it frequently adopted old locations to fresh sets of arrivals to reduce the prodigious amount of work (Crampin and Üçer, 1975).

The lack of adequate travel-time tables for the whole period and the technique of adopting old locations, leads to inaccuracies in ISS epicentre determinations. Even for recent events (ie since 1954) the use of the world-wide travel-time tables, without station adjustments for the particular region, (acceptable when making international routine calculations), makes the ISS locations less precise than is possible. These inaccuracies can be allowed for by relocating using consistent travel times, coupled with station adjustments to account for station, travel-time, network and source effects. An attempt to eliminate these inaccuracies is made in this study.

5.4 Data sources

5.4.1 Relocation

Because both SPEEDY and JED programs (Douglas, Young and Lilwall, 1974) which are used for the relocation procedure, are designed for first arrival readings (ie P-waves), the following data sources are used:

i) For the period 1913-1917, the monthly bulletins of the British Association for the Advancement of Science.

ii) For 1918-1963, the bulletins of the ISS.

iii) For 1964-1976, the bulletins of the ISC.

Arrival data were collected for those earthquakes with epicentres not only within Greek territory but slightly beyond.

The area of investigation is limited to latitudes 33^{o}N to 42.5^{o}N and longitudes 19^{o}E to 29^{o}E north of the 38^{o}N parallel and 30^{o}E south of it, in order to cover the Dodecanese Islands.

An attempt to recalculate events prior to 1917 using source (i) was not successful because of the poor quality and quantity of the readings reported as first arrivals. The stations were too widely spread and too limited in number. For the period 1964-1975, where data from source (iii) is available, several test recomputations showed that the shift between the new and old location was on an average less than 10 km to within the 95% confidence limits. Furthermore ISC gives standard deviations in origin time, coordinates and focal depth determinations, which indicate the quality of the solution given. Therefore no recomputations for this period are made.

Earthquakes for the period 1917-1963 inclusive are relocated here, using first arrival data from source (ii) exclusively. For the 605 earthquakes which are relocated, 45,000 first arrivals (cards) were punched and used as input to both programs.

5.4.2 Magnitude

In order to determine the surface-wave magnitude, M (see 5.7) the following data sources are used:

i) For the period 1908-1959, the annual bulletins of the Seismological Institute at Uppsala (SIU) for readings of Uppsala station (UPP).

ii) For 1951-1955, the annual bulletins of SIU for readings of Kiruna station (KIR).

iii) For 1956-1963, the monthly bulletins of SIU for all the Swedish network.

iv) For 1901-1970, the UNS catalogue.

v) For 1964-1976, the ISC magnitude determinations.

vi) For 1976-1978, the United States National Earthquake Information Centre (NEIC) magnitude determinations.

5.5 Earthquake-relocation procedure

Earthquakes are today generally located by one of two methods. The first method is called the "single-event" or Geiger's method (Geiger, 1910); the second is the Joint Epicentre Determination (JED) method (Douglas, 1967).

5.5.1 Methods and computer programs chosen for relocation

The computer programs SPEEDY and JED written by Douglas, Young and Lilwall (1974) are used to relocate the source parameters of Greek earthquakes. Both programs are designed to accept first-arrival readings only, and a set of travel-time tables. In this study the ISS first arrivals and Herrin's "68" travel-time tables are the main input data to both programs. SPEEDY is a "single-event" based program, whereas JED is a "group-event" based program. A detailed description of the two methods can be found in Lilwall (1969).

Although JED is a more accurate method of epicentre determination than "single-event" methods, it is a very costly process in terms of computing time. So JED is used here as the first step of the relocation procedure to determine a set of station adjustments which are then retained. Thus, having a set of station adjustments derived from a group of major and well-recorded events using JED, the "single-event" based program SPEEDY can then be used, and these adjustments applied to the travel-time of other events.

5.5.2 Procedure used

Applying station adjustments to travel-times in a "single-event" location, assumes that the corrections for a particular station are constant for all epicentres. This is not necessarily the case for the large area of Greece, which has a very complicated tectonic structure. The whole area was initially divided into three regions, but not divided in time:

Region A: Western Greece (west of $22^{o}E$), with mainly shallow earthquakes.

Region B: Southern Greece (south of $38^{o}N$), with the majority of intermediate earthquakes.

Region C: Central and Northern Greece (the remaining part of Greece).

For Region A, 19 well-recorded events (minimum number of stations 65, average number 121) were relocated using SPEEDY. This facilitated the selection of a master event, which was restrained in a subsequent JED relocation of the same 19 events. A set of station adjustments, corresponding to the earthquakes of region A were obtained for 260 stations which had recorded more than 5 events. These adjustments were subsequently used in individual SPEEDY relocations of the 19 events, including the previous master event. This resulted in a new slightly changed position for the master event (in all cases the shift was less than 5 km). The master event was then restrained at its new position and a final set of adjustments for the region determined by JED. This procedure was repeated for the other two regions.

Before applying station adjustments in all subsequent relocations, the effectiveness of these "terms" in the precision of the final solution was checked. This check was made using the latest and presumably more accurate set of data from 1957 until 1963.

As a measure of calculated precision the 95% confidence area around the epicentre has been chosen (Flinn, 1965). The 202 events of this period were relocated using SPEEDY both with and without station adjustments. Table 5-1 tabulates the results and shows that 174 of the total 202 events (86.1%), relocated using station adjustments, have smaller 95% confidence areas than those to which adjustments were not applied. The 17.8% overall average improvement is surprisingly high considering the quality of the data set used. It is expected that as the quality of first arrivals increases, and the number of stations omitted because of bad readings decreases, the application of station adjustments should improve the precision and accuracy of epicentre parameters, although the difference in confidence areas should decrease. In fact, the 28 cases of larger confidence areas are almost all associated with poor quality first arrivals. The application of station adjustments results in some stations which have been truncated in the first solution being included in later solutions, if these stations correspond to poor quality first arrivals the confidence area may increase; but because of the larger number of stations, the solution will probably be less subject to station network bias.

Table 5-1

Contribution of station adjustments into final earthquake location

Region	No of events	No of improved cases ($A_w < A_o$)*	Percentage of improved %	No of worst cases ($A_w \geq A_o$)	Percentage of worst %	Average improved $(1 - \frac{A_w}{A_o})$
A	71	62	87.3	9	18.3	22.1
B	48	37	77.1	11	22.9	11.2
C	83	75	90.4	8	9.6	20.1
TOTAL	202	174	86.1	28	13.9	17.8

* A_w : 95% confidence area with station adjustments

A_o : 95% confidence area without station adjustments

It was also found that the differences in type, sensitivity and accuracy of the instrument used during the whole period combined with the uneven distribution of the stations, to minimize the effect of the station adjustment to a more accurate location. So, the final procedure chosen divides the data both geographically and in time as follows. First, the whole region was divided into two subregions: A + C = R_1 and B = R_2. This is done not only in order to save computing time, but also because A and C subregions show similarities in earthquake depths. The vast majority of earthquakes in subregions A and C have their origin in the upper crust, whereas region B includes the vast majority of intermediate earthquakes (ie h>60 km). Secondly, the time-span of each group is chosen short enough to avoid large differences in station distribution and instrumental characteristics, but long enough to include at least one or two large and well-recorded events with as much macroseismic information as possible, the latter being the main criterion because of the need for a restrained master event. After 1953, when the quality of stations and first arrivals remarkably improved and macroseismic and microseismic locations, in most cases, became close to each other, the limit in number of events within a group and first arrivals, put by JED and computer storage capability, governs the choice.

The periods chosen are: 1917-1925, 1926-1930, 1931-1935, 1936-1940, 1941-1945, 1946-1949, 1950-1952, 1953, 1954-1956, 1957-1958, 1959, 1960-1969, and 1962-1963. Consequently, 26 (2 x 13) runs of JED were necessary, and 605 earthquakes have been relocated for the period 1917-1963.

For each of the 26 groups a master event has to be chosen and restrained. The criterion for choosing a master event for a group is that this event must have the best solution, that is the smallest 95% confidence area derived from SPEEDY with station adjustments applied, coupled with supporting macroseismic information. However, especially for shallow earthquakes when discrepancies exist, more weight is given to the macroseismic hypocentre than the SPEEDY epicentre. Table 5-2 lists the epicentres of the 26 master events chosen, along with their uncertainties; Intensities and macroseismic epicentres taken from UNS are also included.

Table 5-2

The 26 Master events used for the relocation procedure

Date	Lat °N	Lon °E	Depth Km	No Obs.	Period	Region	Intensity	Macroseismic Epicentre
13.11.24	39.2±0.2	20.9±0.1	85±20	29	1917-1925	R1	7	(39.3 20.7)
06.07.25	37.8±0.1	21.9±0.1	70±20	53	1917-1925	R2	7	(37.8 22.1)
30.08.26	36.8±0.1	23.2±0.1	26±12	75	1926-1929	R2	8	(36¾ 23¼)
18.04.28	42.3±0.1	25.3±0.1	7± 4	95	1926-1929	R1	10	(42.2 25.1)
26.09.32	40.4±0.1	23.8±0.1	5± 4	134	1930-1934	R1	10	(40.5 23¾)
09.11.34	36.5±0.1	25.4±0.1	132±14	64	1930-1934	R2	-	-
04.01.35	40.8±0.1	27.5±0.1	13±10	84	1935-1940	R2	9	(40.5 27.5)
20.07.38	38.3±0.1	23.7±0.1	42±15	81	1935-1940	R1	8	(38.5 23.8)
27.08.42	41.6±0.1	20.5±0.1	12± 7	50	1941-1946	R1	8	(41.7 20.5)
02.09.45	34.4±0.1	28.6±0.1	62± 9	68	1941-1946	R2	-	-
30.06.48	39.0±0.1	20.5±0.1	36±11	96	1947-1949	R1	9	(38.8 20.5)
23.07.49	38.7±0.1	26.3±0.1	17± 7	124	1947-1949	R2	9	(38.5 26.3)
05.04.51	37.5±0.1	20.3±0.1	41±14	78	1950-1952	R1	-	-
17.12.52	34.5±0.1	24.2±0.1	17± 9	232	1950-1952	R2	-	-
07.02.53	34.8±0.1	24.1±0.1	33± 9	138	1953	R2	-	-
11.08.53	38.4±0.1	20.7±0.1	11± 6	244	1953	R1	10	(38.2 20.7)
03.01.55	39.2±0.1	22.3±0.1	41± 9	100	1954-1956	R1	7	(39.2 22.1)
16.07.55	37.7±0.1	27.2±0.1	31± 9	232	1954-1956	R2	8	(37.5 27.1)
24.04.57	36.4±0.1	28.6±0.1	69± 5	255	1957-1958	R2	-	-
27.11.57	39.4±0.1	22.7±0.1	42± 5	111	1957-1958	R1	6	(39.2 22.6)
25.04.59	37.0±0.1	28.6±0.1	35± 7	149	1959	R2	8	(37.0 28.7)
07.10.59	41.0±0.1	19.8±0.1	28± 4	161	1959	R1	8	(41.0 19.8)
26.05.60	40.6±0.1	20.6±0.1	20± 4	194	1960-1961	R1	9	(40.6 20.7)
23.05.61	36.8±0.1	28.4±0.1	74± 5	212	1960-1961	R2	8	(36.5 28.6)
28.04.62	36.2±0.1	26.8±0.1	56± 5	173	1962-1963	R2	-	-
28.08.62	37.8±0.1	22.9±0.1	95± 3	226	1962-1963	R1	7	(37.7 22.6)

For the remaining events of the group, and in those cases where SPEEDY failed to give reliable depth determinations, depths were restrained to values derived from (M, I_o, h)-relations of Shebalin et al (1974), using self-determined magnitudes described below.

5.6 Magnitude determination

For magnitude determination of Greek earthquakes, the method used by Alsan, Tezucan and Båth (ATB) for Turkish earthquakes (ATB - 1975) is adopted for the following reasons:

i) Swedish annual and monthly bulletins with ground amplitudes are available from 1908.

ii) The majority of ATB catalogue earthquakes are within the common Aegean area (ie 35.5°N - 42.5°N, 25.5°E - 30.0°E). Thus the converting equations derived for that region are also valid for Greece (see below). This common area is tectonically the most complicated, the remaining parts being characterised by containing the vast majority of shallow earthquakes.

iii) For both Turkish and Greek earthquakes, the dominating surface-wave periods of Swedish records are around 10-15 sec., and hence the validity of converting equations becomes even stronger.

iv) The uniform way of magnitude determinations for these seismically very active neighbouring countries in which there is no seismicity boundaries, enables further and larger scale investigations to be made.

5.6.1 Magnitude scale chosen

The only instrument which has been in operation during the whole period of investigation, with almost unchanged characteristics, is the Uppsala's Wiechert seismograph. There are far too few cases where the Wiechert has recorded body phases to justify calculations of the body wave magnitude M_b alone, so the surface-wave magnitude M is chosen as the standard magnitude required for the whole period. The value of M is calculated from

$$M = \log \frac{A}{T} + 1.66 \log\Delta^{\circ} + 3.3 \qquad (5\text{-}1)$$

where T is the period in the range 10-30 seconds, A the ground amplitude in microns, and Δ the epicentral distance in degrees (ATB, 1975). Values of M generally exhibit greater stability than M_b values when only one or few stations are available (Båth, 1969).

5.6.2 Magnitude determination procedure

A detailed description of the procedure used can be found in the ATB catalogue. The basic steps and conversion equations used for magnitude determinations of the Greek earthquakes are as follows.

The ATB procedure is applied and the magnitude is taken as the average of M from Uppsala (UPP) derived from long-period Benioff instruments, and M from Kiruna (KIR), derived from Galitzin instruments. For a consistent calculation of M over the whole period of investigation, the following regression equations, derived from parallel recordings on the instruments since 1955 are used:

$$\left.\begin{aligned} &M(UPP) = 1.01M(KIR) - 0.17 \quad \text{for } N = 221 \\ \text{and} \quad &M(KIR) = 0.91M(UPP) + 0.58 \quad \text{for } N = 221 \end{aligned}\right\} \qquad (5\text{-}2)$$

where N is the number of pairs of observations (ie number of earthquakes). Then, the average $\overline{M}$, in terms of M(UPP) or in M(KIR) alone, is:

$$\overline{M} = \tfrac{1}{2}\left[M(UPP) + M(KIR)\right] = 0.95M(UPP) + 0.29 = 1.01M(KIR) - 0.08 \qquad (5\text{-}3)$$

Likewise:

$$\overline{M} = 0.85M(W) + 1.04 \quad \text{for } N = 51 \qquad (5\text{-}4)$$

where M(W) is the Wiechert magnitude.

When surface-wave records are unavailable, then:

$$\overline{M}_b = \tfrac{1}{2}\left[M_b(UPP) + M_b(KIR)\right] \qquad (5\text{-}5)$$

where M_b is determined from short-period vertical-component P-wave records, using the formula

$$M_b = \log \frac{A}{T} + q(\Delta,h) \qquad (5\text{-}6)$$

where the calibrating term $q(\Delta,h)$ is taken from Gutenberg and Richter (1956).

The regression equation of $\overline{M}$ on $\overline{M}_b$ is:

$$\overline{M} = 1.46\overline{M}_b - 2.91 \text{ for } N = 63 \text{ and } h \leqslant 45 \text{ km} \qquad (5\text{-}7)$$

When only M_b(UPP) or M_b(KIR) is available, then:

$$\left.\begin{array}{ll} \overline{M} = 1.30M_b(UPP) - 1.91 & \text{for } N = 90 \\ \overline{M} = 1.45M_b(KIR) - 3.04 & \text{for } N = 66 \end{array}\right\} \qquad (5\text{-}8)$$

Equations (5-2) to (5-8) are taken from the ATB catalogue and applied to earthquakes from 1908 until 1968.

The ISC took over the service from ISS in 1964 and started to determine body-wave magnitudes M_b, with continuously decreasing magnitude threshold. A regression equation $\overline{M}$ and M_b (ISC) is derived for the five overlapping years 1964-1968 so that the smaller Greek earthquakes, which are too distant from the Swedish network to ensure detection, are included without sacrificing the achieved homogeneity. This is:

$$\overline{M} = 1.37M_b(ISC) - 1.74 \text{ for } N = 187 \qquad (5\text{-}9)$$

with a standard deviation on $\overline{M}$ of ±0.27.

It is necessary to check if any systematic bias exists in magnitude determinations from the Swedish network. A regression between M_b(ISC) values and M for the same events reported from all available agencies is derived for the period 1964 to 1975. This is:

$$M = 1.31M_b(\text{ISC}) - 1.41 \text{ for } N = 126 \qquad (5\text{-}10)$$

with a standard deviation on M of ±0.41.

These two lines plotted in Figure 5-1 are almost identical, so any disadvantage caused by using only a local network is diminished.

Equations (5-9) and (5-10) have their own limitations for extrapolation because the values of M_b used are not greater than 6.1 to 6.3, the vast majority being between M_b = 4.4 - 5.5.

In the ATB catalogue the corresponding equation to (5-9) is:

$$\overline{M} = 1.55(\text{ISC}) - 2.49 \text{ for } N = 110 \qquad (5\text{-}11)$$

This equation is very similar to equation (5-9), especially in the range M_b = 4.3 - 5.5 for which the conversion equations (5-2) to (5-8) are needed. This is probably because the overlapping area of the two investigations includes the Aegean Sea, which is seismically very active, resulting in similar conversion equations for both regions.

The number of observations may be used as an additional check on calculated magnitude, especially for events with $M \leq 5$. The number of observations, N', serves as a measure of recording distance and so M depends on log N. For the period 1964-1968, the following equation is derived:

$$\overline{M} = 1.51 \log N' + 2.04 \text{ for } N = 187 \qquad (5\text{-}12)$$

with a standard deviation on the calculated M of ±0.34, whereas for M_b (ISC) the corresponding equation is:

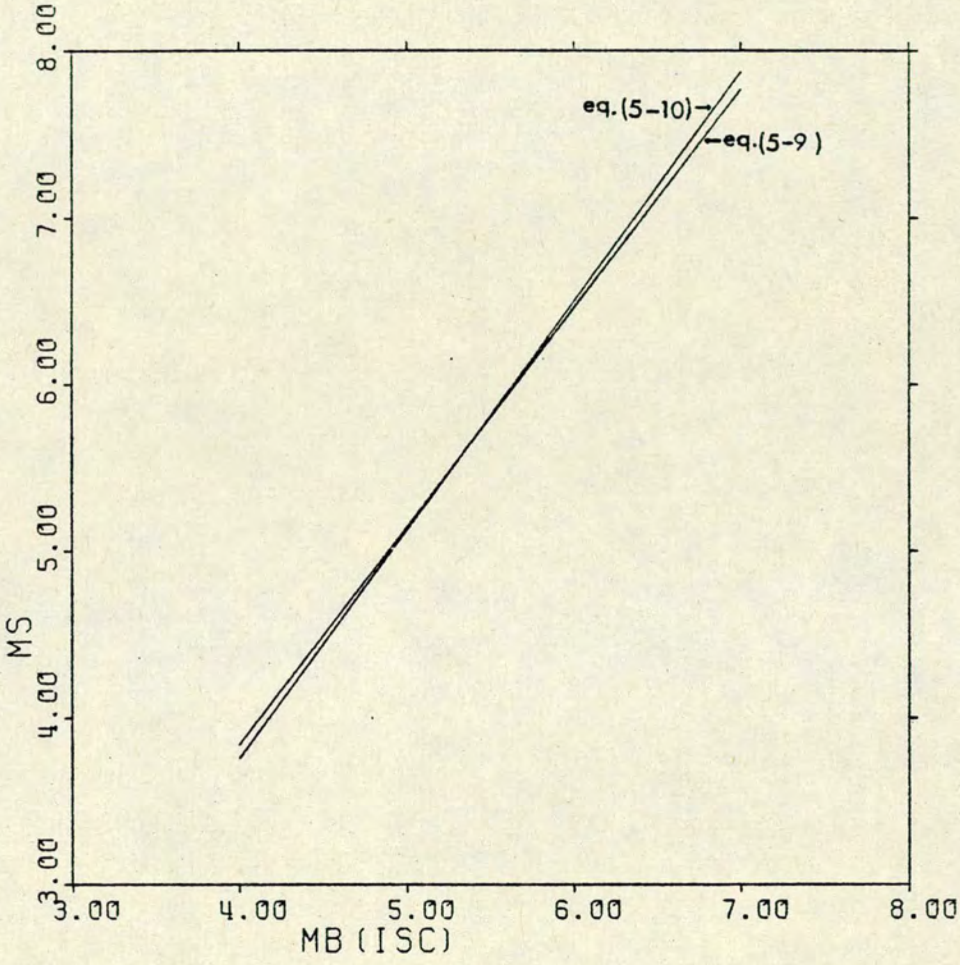


Fig 5-1 Surface-wave magnitudes Ms of Greek earthquakes (derived from amplitudes of the Swedish network and reported from other agencies), versus body-wave magnitude Mb (reported by ISC), for the same events (eq 5-9 and 5-10 in the text respectively).

$$M_b(ISC) = 0.94 \log N' + 3.06 \text{ for } N = 187 \qquad (5\text{-}13)$$

with a standard deviation on the M of ±0.24.

Although the values of the coefficients of these equations certainly depend on the years used, equation (5-12) is used as an additional check for small earthquakes (ie $M \leqslant 5$) since 1964.

5.7 Completeness of the catalogue

The consistent method of calculation of all source parameters, including magnitude, is designed to give a high degree of homogeneity of data included in the present catalogue. But like any other catalogue, its completeness depends upon data availability, and this is far from homogeneous, the usual bias being against small shocks, particularly in the earliest years. This inhomogeneity can be assessed by finding the magnitude above which the catalogue can be considered as homogeneous and reasonably complete, or alternatively by assigning time intervals in which a certain magnitude range is likely to be completely reported.

5.7.1 Temporal plot of grouped events

Table 5-3 and Figure 5-2 illustrate incompleteness in the data available for Greece. Figure 5-2 shows the number of earthquakes per decade. (The last group covers the period 1971-1977). Events are grouped in six magnitude ranges: $M \leqslant 4.7$, $4.8 < M \leqslant 5.2$, $5.3 \leqslant M \leqslant 5.7$, $5.8 < M \leqslant 6.2$, $6.3 \leqslant M \leqslant 6.7$, and $M \geqslant 6.8$; and they are plotted along with the total number of events per decade. The numerical data corresponding to Figure 5-2 are listed in Table 5-3, for the complete period from 1901-1977 (earthquakes for 1901-1907 are taken from the UNS catalogue).

The first feature to note from Figure 5-2 is that there is no reason to question the completeness of the large earthquakes with magnitude greater than 5.8. The fluctuation in the number of magnitude 5.8 and larger earthquakes recorded per decade, shows no trend in the 77-year sample period from

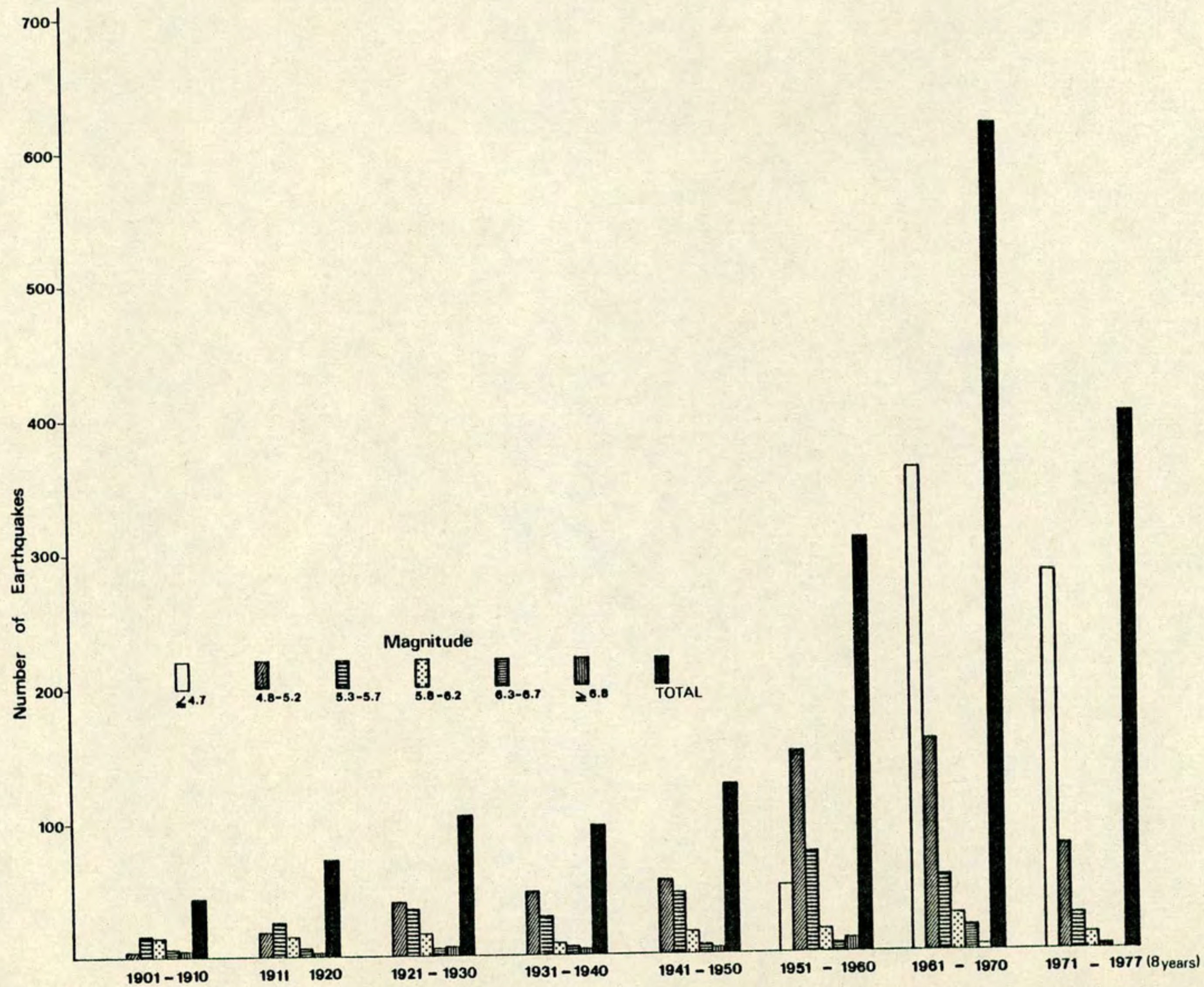


Fig 5-2 Reported Greek earthquakes grouped in six magnitude ranges for each decade since 1901.

1901 to 1977. Events of magnitude M = 5.8 are well recorded because they have an average 20μ ground amplitudes in Uppsala's Wiechert seismograph.

Table 5-3

Number of earthquakes in the area of Greece reported in each decade since 1901

Period	M≤4.7	4.8≤M≤5.2	5.3≤M<5.7	5.8≤M≤6.2	6.3≤M≤6.7	M≥6.8	Total
1901 - 1910	0	4	17	13	5	4	43
1911 - 1920	0	19	27	16	6	3	71
1921 - 1930	0	40	37	17	4	6	104
1931 - 1940	0	48	29	9	6	4	96
1941 - 1950	0	55	46	16	6	3	126
1951 - 1960	48	149	74	18	7	10	306
1961 - 1970	360	158	56	28	9	3	614
1971 - 1977	282	79	28	7	3	0	399
	690	552	314	124	46	33	1759

It is likely that these earthquakes have been completely recorded by the Swedish network for at least the past 70 years.

Secondly, for earthquakes with 5.3 ≤ M < 5.7, there is a gradual increase in the number of shocks throughout the whole period. Two interpretations can be given for this behaviour. First is that completeness of data increases with an increasing sample period, and second, that the observed behaviour is due to the statistical fluctuation of activity. Although the first interpretation cannot be rejected on the basis of figure 5-2 alone, the fact that in our magnitude determinations the Uppsala's Wiechert ground amplitude reports are used from 1908 to 1951, coupled with its unchanged characteristics, supports the possibility of a temporal trend in activity for this range of magnitudes. For these moderate earthquakes Drakopoulos (1976a)also postulates a trend in activity, deduced from observations of intensities reported in the UNS catalogue for Greece. However the lower part of the range (5.3-5.4) is apparently influenced by the time in which it was recorded. It is likely that earthquakes with magnitude $M \geq 5.5$ are completely reported during the past 60 to 70 years.

A third important feature of Figure 5-2 is that the most significant jump in the total number of reported events occurs for the last three periods (1951-1977). Although the first decade (1951-1960) was very active (17 earthquakes with $M \geq 6.3$, whereas the average number for the remaining period was 9 earthquakes), the huge increment in the total number is due to the contribution of smaller events with $M \leq 5.2$. Since 1951 the use of Uppsala and Kiruna's more sensitive instruments affects the threshold of magnitude detectability which, with the use of the ISC determinations and conversion formula (5-9) is, finally, down to M = 4.0.

5.7.2 Analysis of sample completeness

The previous analysis suggests that the present catalogue is severely incomplete below magnitude M = 5.5 before 1950. But earthquakes with magnitudes less than 5.5 may represent maximum annual magnitude earthquakes. The inclusion of such earthquakes for years in which the reporting is incomplete may affect the results of an extreme value statistical treatment, or any other statistical analysis of the data. An analytical method of assigning time intervals in which a certain magnitude class is likely to be completely reported is needed, and Stepp's (1971) method is chosen here. This method is based on the behaviour of the mean rates of occurrence $\lambda(M)=N(M)/\text{year}$, where N is the number of events with magnitudes within the class of magnitude M.

Each magnitude class is modelled as a point process in time. The variance of the estimate of a sample mean is inversely proportional to the number of observations in the sample.

The variance of the sample mean, is obtained by assuming that the earthquake sequence can be modelled by the Poisson distribution. If k_1, $k_2, \ldots k_n$ are the number of quakes per unit time interval, then an unbiased estimate of the mean rate per unit time interval of this sample is (Hamilton, 1964, p 90):

$$\lambda = \frac{1}{n} \sum_{i=1}^{n} k_i \qquad (5\text{-}14)$$

and its variance is

$$\sigma_\lambda^2 = \frac{\lambda}{n} \qquad (5\text{-}15)$$

That is, the variance is equal to the mean where n is the number of unit time intervals. Taking the unit time to be one year gives:

$$\sigma_\lambda = \sqrt{\lambda/T} \qquad (5\text{-}16)$$

as the standard deviation of the estimate of the mean, where T is the sample length.

Assuming stationarity, the mean, variance and other moments of each observation stay the same, and we expect that σ_λ behaves as $1/\sqrt{T}$ in the sub-interval in which the mean rate of occurrence in a magnitude class is constant. Departure from $1/\sqrt{T}$ behaviour, that is from the line parallel to $\sigma_\lambda = 1/\sqrt{T}$ through the points (σ_λ, T) of a magnitude class, for a stable mean rate of occurrence, means that either the sub-interval is not long enough to give a good estimate of the mean or that these sub-intervals include periods in which reports are incomplete.

Table 5-4 tabulates the rates of earthquake occurrence as a function of time interval (λ = N/T) for each of the five chosen magnitude classes, $4.2 \leq M \leq 4.7$, $4.8 \leq M \leq 5.2$, $5.3 \leq M \leq 5.7$, $5.8 < M \leq 6.2$ and $M \geq 6.3$. The difference from the previous magnitude division (see 5.8.1) being the reduction of the two higher classes to one, because there is no question about the

Table 5-4

Values of λ and σ_λ for five classes of magnitude and time interval T

Period	T Years	$1/\sqrt{T}$	$4.2 \leq M \leq 4.7$			$4.8 \leq M \leq 5.2$			$5.3 \leq M \leq 5.7$			$5.8 \leq M \leq 6.2$			$M \geq 6.3$		
			N	$\lambda = \frac{N}{T}$	σ_λ	N	$\lambda = \frac{N}{T}$	σ_λ	N	$\lambda = \frac{N}{T}$	σ_λ	N	$\lambda = \frac{N}{T}$	σ_λ	N	$\lambda = \frac{N}{T}$	σ_λ
1977-1973	5	0.45	210	42.0	2.90	60	12.0	1.55	20	4.0	0.89	5	1.0	0.45	2	0.40	0.28
1977-1968	10	0.32	422	42.2	2.05	134	13.4	1.66	51	5.1	0.71	19	1.9	0.44	5	0.50	0.22
1977-1963	15	0.26	630	42.0	1.67	212	14.1	0.97	76	5.1	0.58	31	2.1	0.37	12	0.80	0.23
1977-1958	20	0.22	669	33.5	1.29	275	13.7	0.83	103	5.2	0.51	41	2.1	0.32	18	0.90	0.21
1977-1953	25	0.20	687	27.5	1.05	367	14.7	0.77	147	5.9	0.48	52	2.1	0.29	31	1.24	0.22
1977-1948	30	0.18	690	23.0	0.88	413	13.8	0.68	170	5.7	0.44	56	1.9	0.25	37	1.23	0.20
1977-1943	35	0.17	690	19.7	0.75	413	12.3	0.59	194	5.6	0.40	61	1.7	0.22	40	1.14	0.18
1977-1938	40	0.16	690	17.3	0.66	454	11.4	0.53	211	5.3	0.36	74	1.9	0.21	42	1.05	0.16
1977-1933	45	0.15	690	15.3	0.58	476	10.6	0.48	223	5.0	0.33	75	1.7	0.19	48	1.07	0.15
1977-1928	50	0.14	690	13.8	0.53	503	10.1	0.45	245	4.9	0.31	84	1.7	0.18	55	1.10	0.15
1977-1923	55	0.13	690	12.5	0.48	521	9.5	0.42	261	4.8	0.29	90	1.7	0.17	59	1.07	0.14
1977-1918	60	0.13	690	11.5	0.44	540	9.0	0.39	282	4.7	0.28	100	1.7	0.17	62	1.03	0.13
1977-1913	65	0.12	690	10.6	0.40	546	8.4	0.36	292	4.5	0.26	109	1.7	0.16	64	0.99	0.12
1977-1908	70	0.12	690	9.8	0.37	551	7.9	0.33	300	4.3	0.25	115	1.6	0.15	71	1.01	0.12
1977-1903	75	0.11	690	9.2	0.35	552	7.4	0.31	313	4.2	0.24	122	1.6	0.15	78	1.04	0.12
1977-1901	77	0.11	690	8.9	0.34	552	7.2	0.30	314	4.1	0.23	124	1.6	0.14	79	1.03	0.11

completeness for events of $M \geq 6.3$ for the whole period. N is the cumulative number of earthquakes in the time interval T. For each rate λ, the standard deviation σ_λ, is computed using equation (5-16). Values of σ_λ for the five magnitude classes as a function of sample length are plotted on Figure 5-3. The "reference-line" $\sigma_\lambda = 1/\sqrt{T}$ is plotted in the top right-hand corner of this figure.

Figures 5-3 and Table 5-4 reveal several features relevant to the statistical treatment of our earthquake catalogue. First, the postulated behaviour of σ_λ is observed, at least over a sub-interval of the total 77-year period interval, for all magnitude classes. Secondly, a minimum time interval is required to reach a stable estimate of the mean recurrence rate. This interval is a function of magnitude class, being successively longer with each higher maximum magnitude class. For earthquakes with magnitude $4.2 \leq M \leq 4.7$, 5 to 10 years of homogeneous observations are sufficient to establish a stable mean rate; for a maximum magnitude of 5.2 the minimum observation period is between 10 to 15 years. A stable estimate of the mean recurrence rate of maximum magnitude 5.7 is obtained in about 15 to 20 years, and for maximum magnitude 6.2 in about 30 to 40 years, while for magnitude greater than 6.3 an interval of about 40-50 years of homogeneous observations is required for a stable estimate of the mean recurrence rate. Thirdly, departure of observed values of σ_λ from $1/\sqrt{T}$ behaviour with increasing sample length occurs for all magnitudes except those greater than 6.3. The latter departure, can again be explained by incomplete reporting of earthquakes as early data are incorporated into the sample. An alternative explanation is that this is caused by a trend towards increasing frequency in the data. However if the latter is the case, departure from $1/\sqrt{T}$ behaviour would be expected to occur at the same time in all magnitude classes. The fact that Figure 5-3 does not show a certain departure at the same time for all classes, gives rise to the explanation that there is not an overall

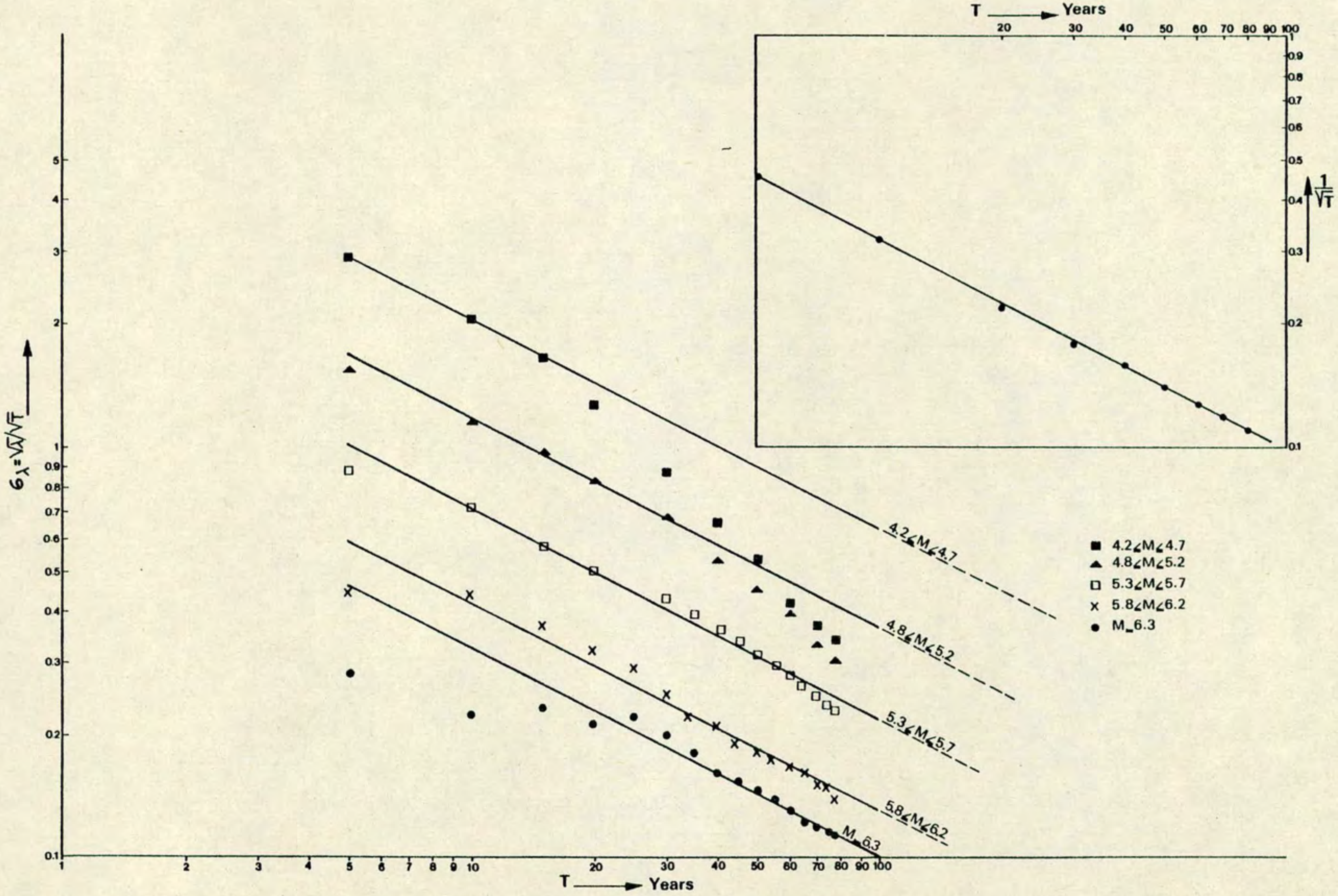


Fig 5-3 Completeness: standard deviation of the estimate of the mean of the annual number of events as a function of sample length. The insert shows the "reference line" $\sigma_\lambda = 1\sqrt{T}$ to which the lines must be parallel (see paragraph 5.7.2).

trend of activity, and confirms that departure is due to incomplete reporting.

It is concluded that maximum magnitude 4.7 events are completely reported only during the most recent 15 year interval, events with 4.8≤M≤5.2 during the most recent 30 year interval, events with 5.3≤M≤5.7 during at least the past 60 years. The period in which events with magnitude 5.7≤M≤6.2 are completely reported is during the past 67 years, whereas events with M≥6.3 are completely reported over the whole 77 year sample interval. Table 5-5 summarises the results after applying Stepp's test for completeness.

Table 5-5

Results from test of completeness for Greece (1901-1977)

Magnitude class	Time required for stable mean recurrence rate (years)	Period of completely reported events
4.2 ≤ M ≤ 4.7	5 - 10	15 (1977-1963)
4.8 ≤ M ≤ 5.2	10 - 15	30 (1977-1948)
5.3 ≤ M ≤ 5.7	15 - 20	60 (1977-1918)
5.8 ≤ M ≤ 6.2	30 - 40	67 (1977-1911)
M ≥ 6.3	40 - 50	77 (1977-1901)

The results of Table 5-5 show that it is possible to create an artificially homogeneous data sample by determining intervals over which earthquakes in different magnitude classes are completely reported. So we can avoid the problem of estimating the recurrence rates from the whole available data sample which for uncorrected data results in the estimated recurrence rates of large earthquakes being overestimated, the recurrence rates for small earthquakes being underestimated.

5.8 Comparing the results

Appendix B contains the complete list of Greek earthquakes since 1901 along with the explanatory text. There are 1806 earthquakes for which magnitudes are assigned using the procedure described in paragraph 5.6 . For the earliest period 1901 until 1907 no ground amplitudes are available, and so only the 32 largest earthquakes with all parameters adopted from the UNS-catalogue are included. UNS's determinations are adopted because its magnitudes for large earthquakes usually closely resemble our determinations. Since 1917 the recalculated locations are detailed along with the total shift in distance (km), and azimuth (degr.), from the ISS locations.

As a comparison between ISS and recalculated locations, the average total shift as a function of the period recorded and the percentage of earthquakes which shifted, are calculated and plotted on Figures 5-4 and 5-5 respectively.

The first feature to note is that the largest annual average shifts are obtained for the first decade after 1917, and the average change in position for 78 earthquakes is 165 km. In the second decade the average shift for 95 shocks is 72 km. In the following third and fourth decades and the remaining seven years (1957-1963) with 84, 182 and 166 shocks, the average shifts decrease rapidly with values of 59 km, 35 km and 17 km respectively. The second significant feature is that changes in epicentres from the ISS locations are more than 40 km for 40% of the total number of recalculated quakes, and more than 50 km for 34%.

The method chosen to relocate the events, by using as master events earthquakes with as much macroseismic information as possible, coupled with station adjustments derived from each group of events, strengthens the possibility that these large changes reflect the degree of inaccuracies in ISS locations, especially for the early events. The fact that these changes rapidly decrease from decade to decade, as more stations report arrivals,

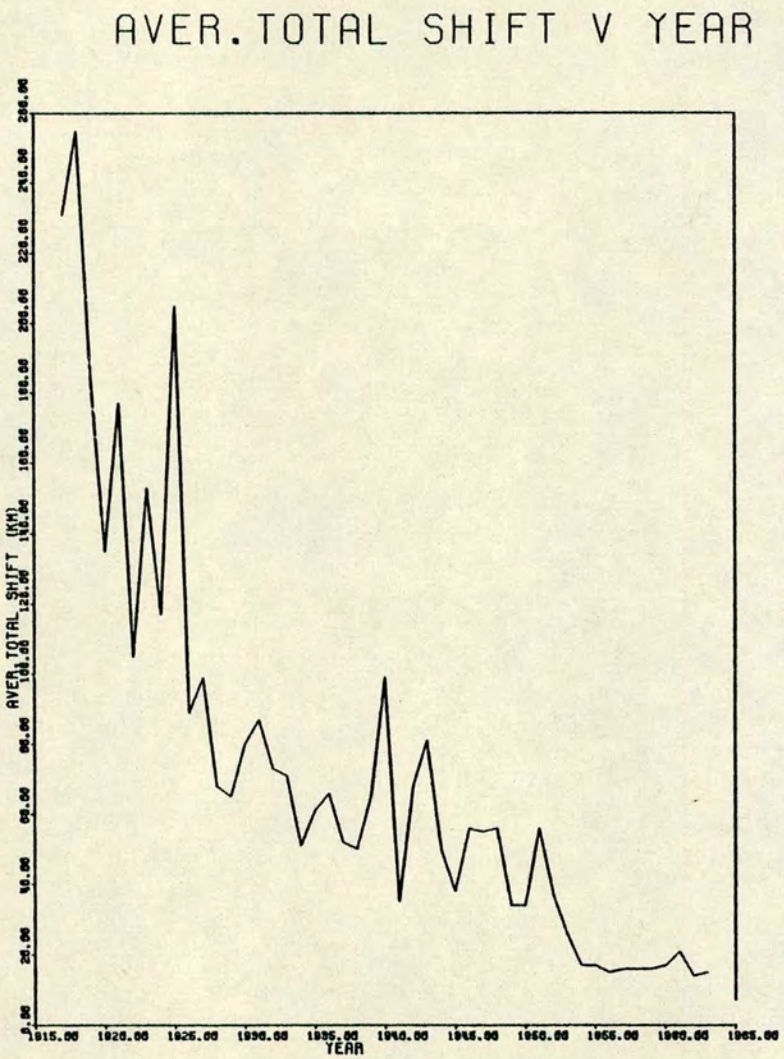


Fig 5-4 Mislocation errors: average total epicentre shift in distance (km) from ISS location to the recalculated location, as a function of the period recorded.

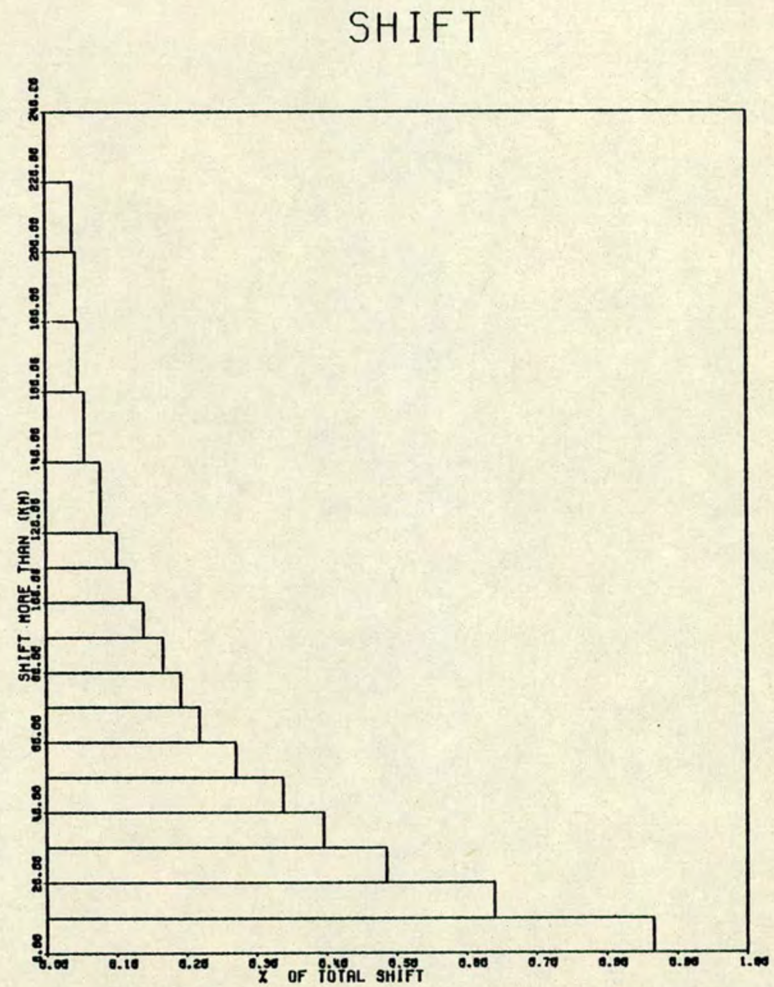


Fig 5-5 Mislocation errors: percentage of total epicentre shift in distance (km) from ISS location to the recalculated location exceeding a certain shift.

supports this explanation. As a further test, Table 5-6 tabulates the 39 worst cases (largest shifts) in which the UNS catalogue gives different locations, usually based on macroseismic information, along with the total shifts from the ISS and UNS locations. The average shift from UNS locations, for the same events is only 39.9 km. Again this supports the explanation that these large shifts are due to ISS mislocations for reasons discussed in paragraph 5.3.

Figure 5-6 plots the shift in distance versus change in azimuth for each relocated earthquake showing that except for five of the earliest events (24.12.1917, 27.12.1917, 09.02.1918, 22.03.1919, and 10.05.1921) which have an azimuthal change around 220^{o}- 240^{o}, there is no correlation between the shift in direction and the shift in distance. These five earthquakes were previously located in the north-eastern part of Greeece, but macroseismic information (Galanopoulos 1961, UNS 1974) shows that the new locations are very close to macroseismic epicentres (see also Table 5-6).

Differences in locations between ISS and the new epicentres certainly reflect differences in the methods used. But while for the earlier events it is obvious that ISS mislocations are due to different travel-time models used, or because of adoption of old positions for later events, the 17 km average total shift found for the latest period (1956-1963), using many more stations all around the world with very sensitive instruments, is a significant figure. During this period, the major differences between JED and ISS methods of event location are the different travel-time tables used, and the station adjustments which JED applies to the first arrivals.

However, Crampin and Üçer (1975) using Jeffreys-Bullen travel times and the SPEEDY program without station adjustments point out that for the Marmara Sea area the average shift in position for the period 1956 to 1963 is about 5 km from the ISS locations. On the other hand, in the ATB catalogue for Turkey (Alsan et al, 1975) when "Herrin" travel-time tables are

Table 5-6

Cases of large shifts from ISS and UNS locations

DATE	Shift from ISS locations		Shift from UNS locations	
	in distance(km)	in azimuth(deg)	in distance(km)	in azimuth(deg)
14.03.1917	232.4	305.7	42.4	142.3
24.12.1917	410.8	241.3	18.0	17.4
09.02.1918	445.4	237.5	63.4	62.6
22.08.1919	580.6	233.3	203.2	197.6
29.11.1920	126.2	60.0	67.5	84.0
30.03.1921	254.7	283.0	47.2	221.0
10.05.1921	415.5	237.7	26.6	303.7
10.08.1921	157.4	10.8	58.6	68.6
13.09.1921	98.6	22.3	24.1	275.5
14.09.1921	157.6	204.9	54.8	184.6
09.02.1922	144.7	187.6	24.9	113.9
20.05.1923	135.8	213.7	40.1	232.3
01.08.1923	129.8	106.0	49.4	137.9
13.11.1924	117.9	138.7	21.1	122.7
12.04.1925	598.9	307.2	66.9	201.4
01.09.1925	226.3	225.6	51.3	162.9
26.02.1926	140.5	286.5	33.4	80.2
26.06.1926	123.8	312.2	54.4	300.9
05.07.1926	134.7	218.7	40.0	278.1
30.08.1926	83.5	170.1	7.5	331.9
01.07.1927	87.7	188.8	14.5	80.5
18.04.1928	90.6	314.7	35.8	77.2
28.04.1928	91.9	291.7	25.4	116.3
11.09.1931	154.3	9.4	20.5	293.1
23.09.1931	226.3	347.8	37.5	128.7
26.09.1932	105.6	0.0	28.8	0.0
01.06.1933	221.8	7.23	20.8	7.23
02.07.1933	325.7	358.0	79.4	264.7
03.09.1935	161.7	5.2	41.1	97.6
08.08.1936	130.3	15.6	54.5	28.3
03.06.1938	66.1	226.5	2.1	238.7
18.09.1938	116.5	268.8	30.4	354.9
23.02.1940	81.6	323.7	23.4	267.3
14.02.1943	114.7	333.2	24.9	2.1
27.05.1944	147.3	222.7	37.3	311.3
04.06.1947	58.9	22.2	11.6	341.1
29.11.1947	104.0	353.8	12.8	286.5
10.08.1948	174.5	2.3	46.3	279.9
17.09.1949	62.8	72.3	14.7	303.9

Average total shift ISS: 185.6 km

Average total shift UNS: 39.9 km

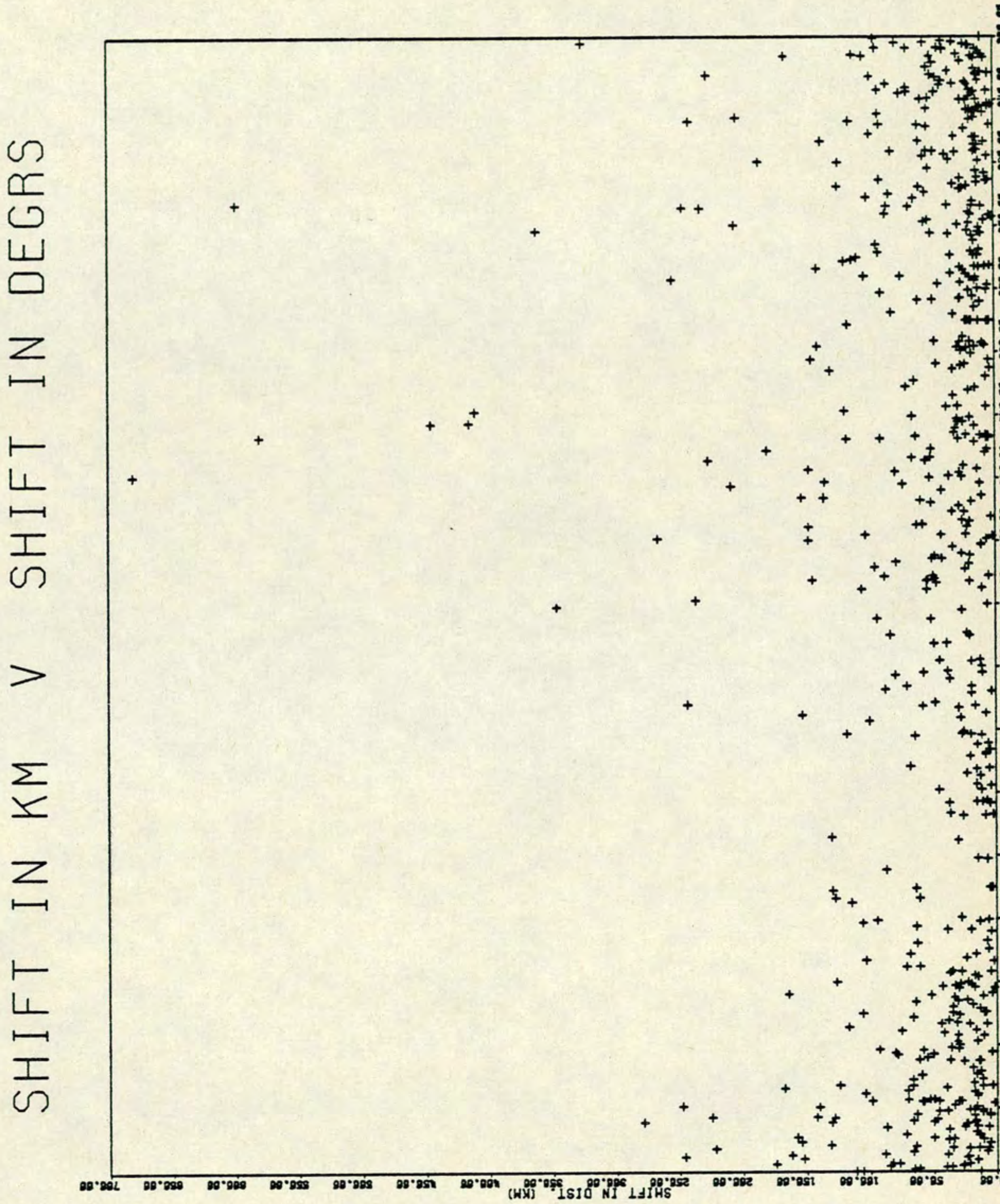


Fig 5-6 Mislocation errors: shift in distance (km) versus change in azimuth (degr.) for the relocated events compared to the ISS locations.

used, it is concluded that there are no significant differences between ISC locations, calculated with Jeffreys-Bullen travel-time tables, and their locations.

It seems reasonable to conclude that a significant part of the 17 km shift in position found for the period since 1956 is due to the station adjustments applied to the first arrival data by the JED method. In fact, for the 202 earthquakes of this period which are located using SPEEDY, with and without station adjustments, the changes in relative position (ie, distance between the two positions of the same event with and without station adjustments) have an average shift of 8.6 km.

The results of these tests show that the relocated epicentres are significantly different from those of ISS with the average shift decreasing from decade to decade since 1917. Even for the most recent period of investigation since 1956 there is still a significant change in position, with an average shift of 17 km.

5.9 Summary

Because none of the existing earthquake catalogues for Greece ($N_{33}^{42.5}$, E_{19}^{29}) fulfil the demands of modern seismology for accuracy, homogeneity and completeness, this chapter has attempted to reduce these inaccuracies as far as available data permits.

Considering the data available for recalculation of source parameters, the catalogue presented here contains:

i) Earthquakes for which all parameters are calculated using the JED method (Period: 1917-1963).

ii) Earthquakes for which magnitudes are determined using the Swedish network ground amplitude records (Period: 1908-1977).

iii) Earthquakes adopted from the UNS catalogue for all parameters, because neither first arrival nor ground amplitude data is available (Period: 1901-1907).

iv) Earthquakes for which magnitude determinations are possible but not recalculations of the other parameters because of limited number of arrivals. For these earthquakes, parameters other than magnitude are adopted from other sources after special investigation for as much macroseismic information as possible (Period: 1908-1977).

The last two cases are included in the catalogue for completeness. Although the accuracy of the adopted earthquakes is not known, the criterion for adoption using macroseismic information eliminates large errors in location.

For all these earthquakes magnitudes are determined using the same procedure as for the rest of the data sample, and so magnitude homogeneity is retained.

When Stepp's test of completeness is applied, the results show that only earthquakes with magnitude greater than 6.3 are completely reported during the whole period of investigation (1901-1977), whereas earthquakes with a maximum magnitude $M \leq 4.7$ are completely reported only during the most recent 15 years (1963-1977). The time required for stable mean recurrence rate is found to be 40-50 years of homogeneous observations for magnitude greater than 6.3, whereas for earthquakes with magnitude between 4.2 and 4.7, only 5 to 10 years of homogeneous observations are sufficient to establish a stable mean recurrence rate.

The JED method chosen to relocate the events has the advantage of using master events, which coupled with its capability of detecting source, travel-times, network and station bias and the facility to combine these into a single "term" (ie station adjustment), guarantees the highest possible accuracy for the relocated earthquake epicentres. The consistent treatment of all available data, particularly magnitude determinations, ensures a high degree of homogeneity for the whole period of investigation.

Completeness of the catalogue is limited by data availability, but using the results of Table 5-4, it is possible to determine intervals over which earthquakes in different magnitude classes are completely reported.

Finally, because the accuracy of the following seismic risk investigation is related to the earthquake catalogue used, comparisons between ISS original locations and those of the present catalogue are worthwhile.

The comparison tests show that ISS locations are severely biased. These large average total shifts imply that it is not possible to describe the detailed seismicity of Greece by just using the ISS data sample for the whole period. This earthquake catalogue for Greece has a high degree of homogeneity, accuracy and completeness, and permits more detailed seismotectonic studies to be made on the basis of a long, instrumentally recorded data sample.

In the next chapter existing tectonic models will be tested to see if they are in accord with the recalculated parameters of the earthquakes. This will then be followed by the application of the statistical techniques of the first part of this thesis to the new earthquake catalogue to estimate seismic risk for Greece.

CHAPTER VI

GREEK TECTONICS AND SEISMICITY

6.1 Introduction

The spatial distribution of earthquakes in a region shows its present active tectonics, and the size of earthquake magnitudes is a measure of the degree of the activity. Hence, maps with the spatial distribution of the epicentres can reveal the tectonic features of the region with as much precision as the accuracy of the earthquake parameters used.

Greece and the adjacent areas (ie the Greek mainland, the Aegean Sea and western Turkey) have the highest seismic activity in the whole Mediterranean and European area (Kárnik, 1969; Galanopoulos, 1971a). The high seismic activity shows that this area is tectonically very active. This, coupled with the fact that it is a part of the Alpine-Himalayan zone, which is the only continental region where large scale shortening is now taking place (McKenzie, 1978), makes it a region of great interest for geologists and geophysicists.

In this chapter, an attempt is made to examine the validity of existing tectonic models using the recalculated parameters of the earthquakes in the area (Appendix B). Furthermore, using the recalculated depths and radial vertical distance-depth cross-sections, three dimensional isodepth contouring maps are produced. These maps reveal several significant features of the tectonic process in the region.

6.2 Morphologic, geologic and geophysic feature of the area

The main morphologic and geologic features of the area of Greece and the adjacent areas are, from south to north (see Fig. 6-1):

1. the Mediterranean ridge (or chain)
2. the Hellenic trench (or trough)

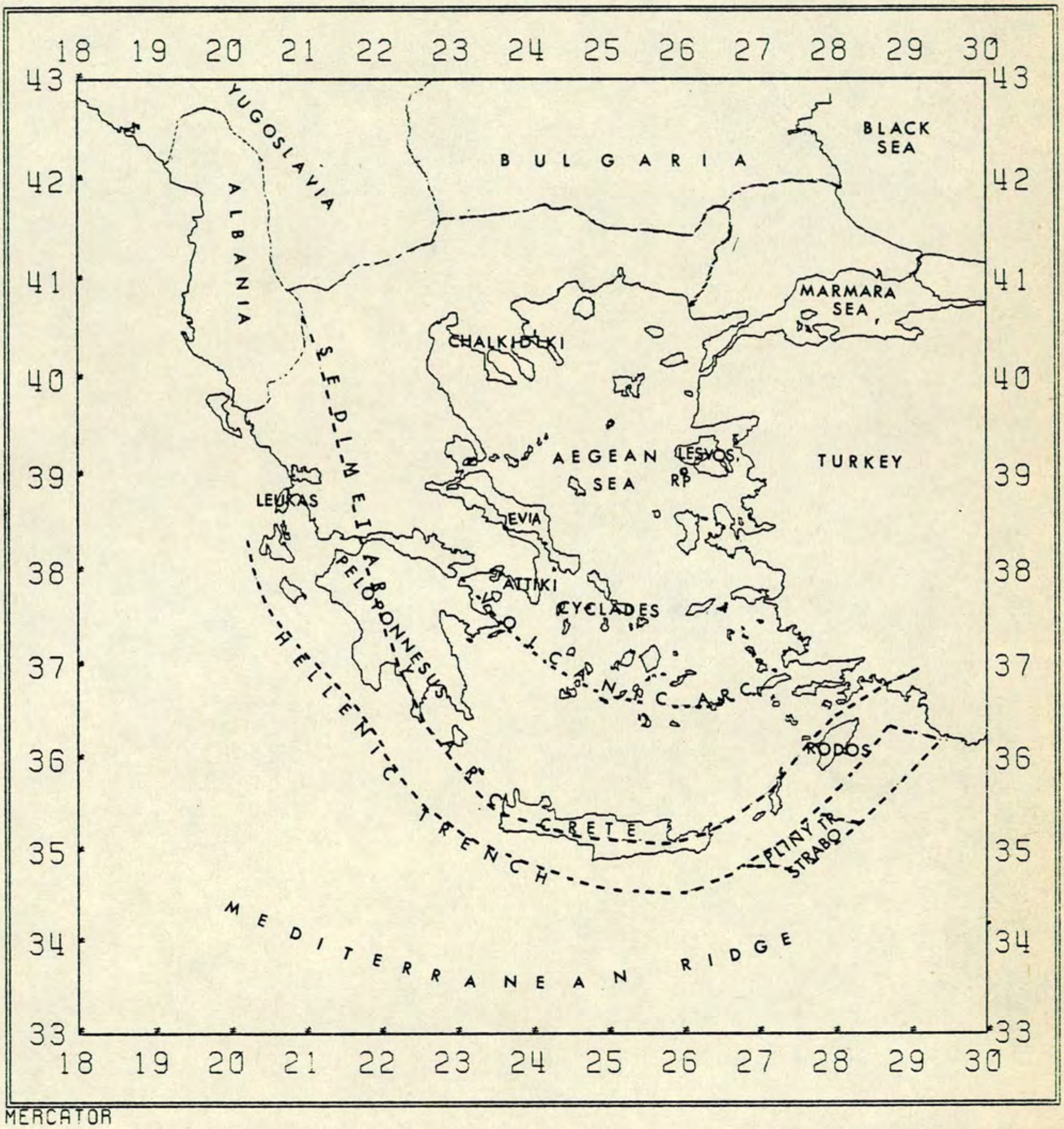


Fig 6-1 Summary map of the Aegean region, showing morphologic and geologic trends in a schematic way.

3. the Hellenic arc, and

4. the northern Aegean Sea.

The Mediterranean ridge has irregular topography and extends from the Ionian Sea to Cyprus. It is not a mid-ocean ridge, and Finetti (1976) investigating its tectonic features in detail suggests the name "east Mediterranean chain".

The Hellenic trench consists of a series of depressions to a depth of 5100 m which parallels the Hellenic arc.

The Hellenic arc is formed by the outer sedimentary arc, a link between the southern Dinarides and the Turkish Taurides, and the inner volcanic arc which parallels the sedimentary arc. Between these two arcs is the Cretan trough with water depth to about 2000 m. The outer sedimentary arc consists of Paleozoic to Tertiary rocks folded and faulted in several phases of the Alpine orogeny, while the inner volcanic arc consists of recent andencitic volcanism at Santorini, Nisyros, Milos and Kos.

The Aegean Sea immediately north of the volcanic arc is a rather stable block of folded Paleozoic and granitoïd masses. The extreme north includes the northern Aegean trough with water depth to about 1500 m, the northeast extension of which is probably the small depression of the Marmara Sea (Papazachos and Comninakis, 1976).

Greece was surveyed gravimetrically and magnetically in the years 1971-1973 (Makris, 1975). Along the Greek mainland the Bouguer anomalies have negative values with a gravity minimum of -140 mGal situated at the Pindos Mountains. The Aegean Sea is characterized by positive Bouguer anomalies with a maximum of +175 mGal at the central trough of the Cretan Sea (Makris, 1975), while in the central and northern Aegean it is about +50 mGal. A belt of negative free-air anomalies down to -200 mGal follows the Hellenic trench, while the Bouguer anomalies are positive up to +180 mGal (Morelli et al, 1975).

Positive magnetic anomalies have been determined in several parts of the Aegean Sea. The strongest of these anomalies have been observed along the volcanic arc, in the northern Aegean trough and in the Cretan trough (Vogt and Higgs, 1969; Makris, 1973). The magnetic field is undisturbed in the Mediterranean Sea south of Crete (Vogt and Higgs, 1969).

Heat flow is relatively high in the Aegean Sea floor ($\sim$2.1 HFU) in the volcanic arc of the southern Aegean and Jongsma (1974), has interpreted it as due to underthrusting of oceanic crust.

Seismic refraction studies and experiments (Papazachos, 1969; Makris, 1973, 1976a) have indicated that the crust thins from about 50 km below the Peloponnesus and the Pindus Mountains toward the Aegean (25-30 km) and that the central part of the Cretan Sea crust is only 20 km thick (Makris, 1976b; see Fig. 6-2).

6.3 Principle tectonic models for Greece and the adjacent areas

By definition (McKenzie and Parker, 1967), seismic belts mark the boundaries of stable plates, and focal mechanisms indicate the relative motions of adjacent plates. Focal-mechanism studies (Constantinescu et al, 1966; Papazachos and Delibasis, 1969; McKenzie, 1970, 1972; Ritsema, 1974) suggest southerly to westerly thrusting of the arc over the Mediterranean.

McKenzie (1970, 1972) was the first to delineate a small, rapidly moving plate, which contains the Aegean, part of Greece, Crete and part of western Turkey (see Fig 6-3). He called it the "Aegean plate". The south-western boundaries were well defined, and earthquake fault plane solutions show that the motion between the Aegean and African plates is in a north-south direction. The northern boundary was defined by extensional and transform faults, and he concluded that it was a continuation of the North Anatolia fault (but see below). The boundary with the other

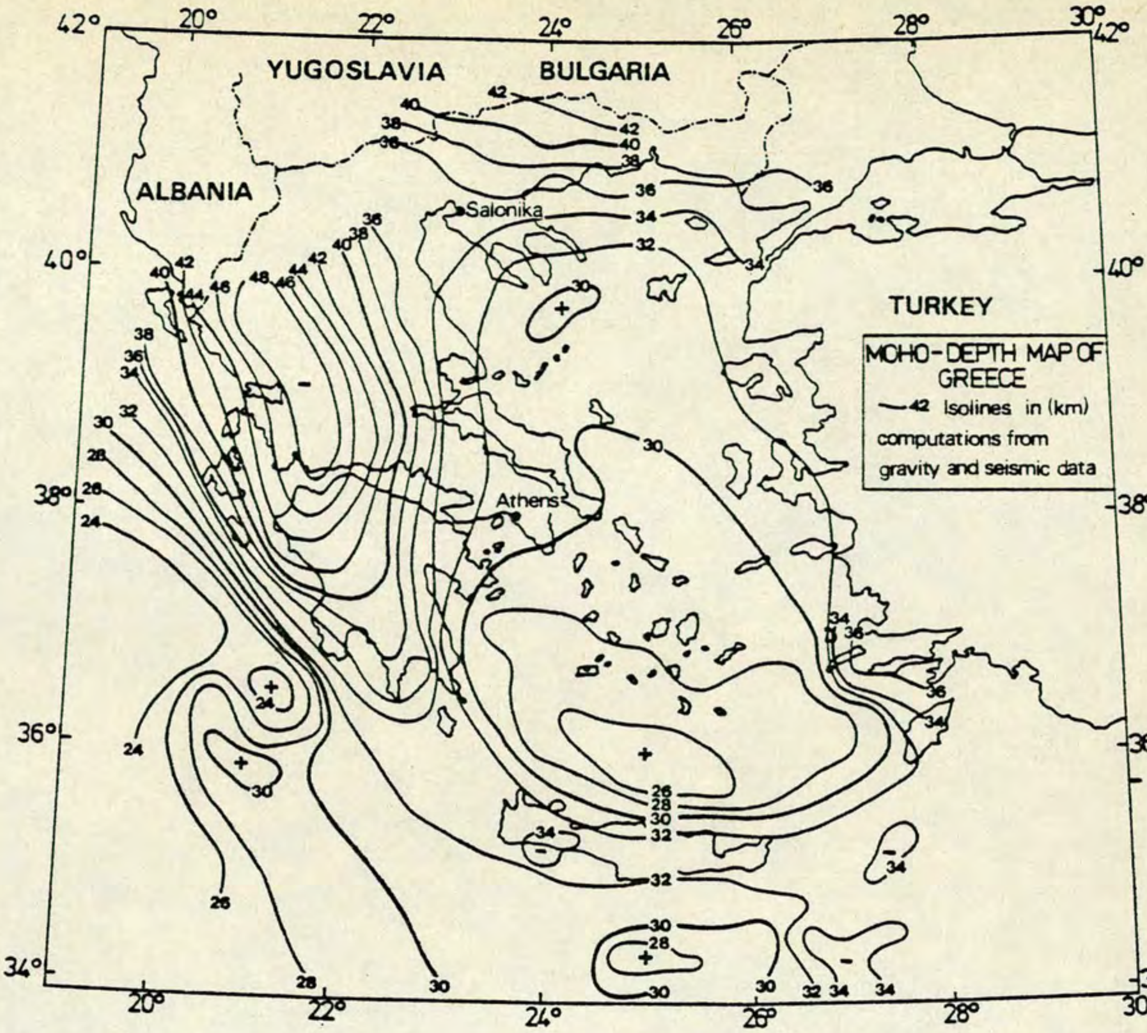


Fig 6-2 Contour map of the Moho discontinuity from gravity and seismic data (after Makris, 1973).

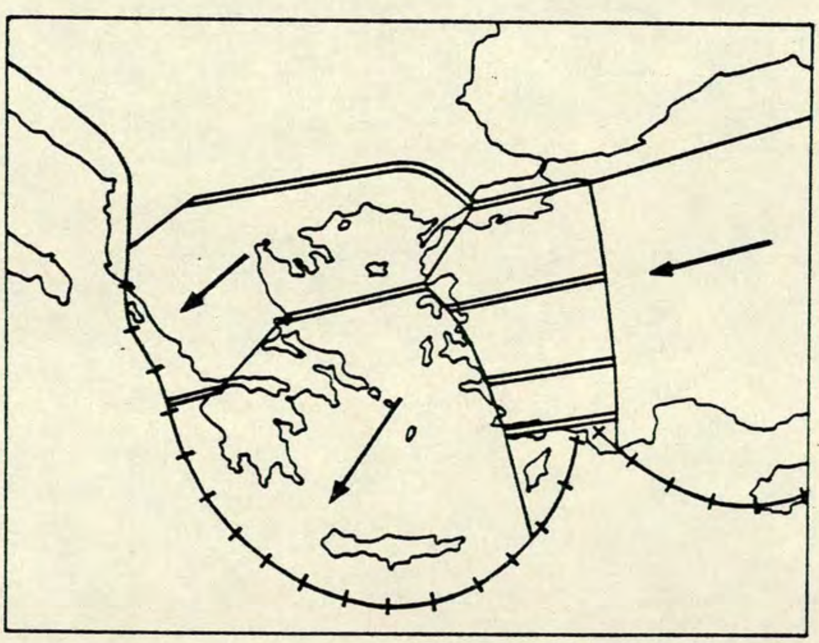


Fig 6-3 Sketch of plate boundaries and motions in the Aegean area obtained from seismicity and fault plane solutions (after McKenzie, 1972).

plate, the "Turkish plate", was poorly defined.

After McKenzie's work, contemporary plate tectonics in the area, and its problems, were discussed by Lort (1971), Papazachos and Comninakis (1971, 1976, 1978), Galanopoulos (1972b, 1973, 1974, 1975), Comninakis and Papazachos(1972, 1976), Alvarez (1973), Dewew et al (1973), Papazachos (1973, 1974, 1976a, 1976b, 1977), Makris (1973, 1975, 1976a, 1976b, 1978), Gregersen (1977) and others. The common point of almost all these studies is that the African plate underthrusts Greece and the adjacent areas along the Hellenic arc. The mean dipping angle is about 35° (Papazachos and Comninakis, 1971; Galanopoulos, 1973; Agarwal et al, 1976; Gregersen, 1977). However, McKenzie's model has been critized by a number of authors (Papazachos, 1973, 1976a, 1976b, 1977; Crampin and Üçer, 1975; Mercier et al, 1976) for its simplicity and its definition of its northern and western boundaries.

From the definition of the boundaries of a plate (see above), it is difficult to talk about truly stable aseismic microplates in this region. All the maps of spatial distribution of epicentres show that several small aseismic blocks exist. Hence, most geologists and geophysicists now prefer the name "Aegean area" rather than "plate" because of its real complexity.

As Figure 6-3 shows, the northern boundary of McKenzie's plate consists of transform faults, but Mercier et al (1976), after extensive investigations in central Greece, found no evidence of a transform fault. The continuation of that northern boundary towards the North Anatolia fault has also been debated (Papazachos, 1976a, 1977; Crampin and Üçer, 1975).

Papazachos (1976a) using focal mechanisms and the spatial distribution of earthquakes in the northern Aegean, has concluded that there is an amphitheatrical Benioff-zone which, although less well defined compared with the similar one in the south Aegean, is dipping towards a thrust region which includes the northernmost part of the Aegean and part of the Marmara area.

A different model for the Aegean area has been suggested by Makris (1976b, 1978). According to his model, the deformation of the region is the surface expression of a hot mantle plume which extends to the base of the lithosphere and has been mobilized through compressional processes that forced the lithosphere to sink into the asthenosphere. The model is based on refractional-seismic data from which a low velocity of the compressional waves of 7.7 km/sec for the upper mantle has been determined, on gravity measurements, which show that density lower than normal is extending to the base of the lithosphere, and on the high values of heat flow in the Aegean area.

This model explains that the crustal thickening along the Hellenic arc is due to the crustal down-buckling which is thickening at the compressional front. This collision is responsible for the high seismicity along the arc. The Hellenic trench is the result of the upwards movement of the Aegean crust which is forced to override part of the Ionian-East Mediterranean crust and lithosphere towards Africa. This movement causes a subduction zone to develop at the collision front. According to this model, the deep seismicity is caused by crust and upper mantle fragments dislocated from their original positions and subducted into the soft, low Q asthenosphere. Thus more complicated Benioff-zones develop, which differ from the Benioff-zones of the Pacific, because the interaction is between continental-continental or continental-subcontinental blocks.

Recently, McKenzie (1978) published another model for the Aegean Sea and surrounding regions. This model is a modification of the previous one of Fig 6-3. It is based on new fault plane solutions of earthquakes taken from USGS and NOAA, Landsat photographs, and seismic refraction records. The main points of this model are the following:

i) Rapid extension is taking place in the northern and eastern parts of the Aegean Sea region, whereas the southern part is relatively inactive.

ii) From the fact that the pre-Miocene geology of the islands of the Aegean closely resembles that of Greece and Turkey, and from the thin ($\sim$30 km) crust of the southern part of the Aegean compared with the thick ($\sim$50 km) crust beneath Greece and Turkey (see also Fig. 6-2), it is concluded that the thin crust of the Aegean has been produced by stretching the orogeny belt by a factor of two since the Miocene. This stretching can account for the high heat flow, while the sinking slab produced by subduction along the Hellenic arc maintains the motion.

iii) In north-western Greece and Albania, where he found both thrust and normal faults, while his data did not show any sinking slab, the term "blob" of cold mantle detaching from the lower half of the lithosphere is introduced. These blobs are produced by thermal instability when the lithosphere is thickened by thrusting.

iv) The direction of relative motion between the southern Aegean region and Africa determined from fault plane solutions is 211^{o}E.

v) The new information suggests that the North Anatolia Fault does not extend beneath the Aegean, and that the motions are taken up on several structures with components of normal faulting.

vi) There is no evidence to support the suggestion made in his previous model (1972) that the Anatolian Trough is connected to the Gulf of Corinth.

The main differences between his previous model (Fig 6-3) and the new one are summarized in Fig 6-4, taken from his recent paper (Mackenzie, 1978, Fig 18).

Fig 6-4 Summary of the present deformation of theAegean area after McKenzie (1978). (Long curved lines show normal faults. Lines with open semicircles show thrust faults. Solid dots mark epicentres of shocks for which mechanisms are used. Arrows show the direction of motion obtained from fault plane solutions. The long heavy arrow shows the direction of relative motion between the Aegean and Africa. Heavy Vs mark sites of recent volcanism.)

McKenzie (1978) also comments that "the theory of plate tectonics is of little value in regions such as northern Greece and Turkey where the deformation is spread over a zone". Dewey and Sengor (1978) also point out that plate tectonics is not useful in the Aegean area where normal faulting is not confined to a narrow zone. These two comments and the wide criticism which McKenzie directed against almost all the proposed models for the region may reflect the real complexity of the Aegean area.

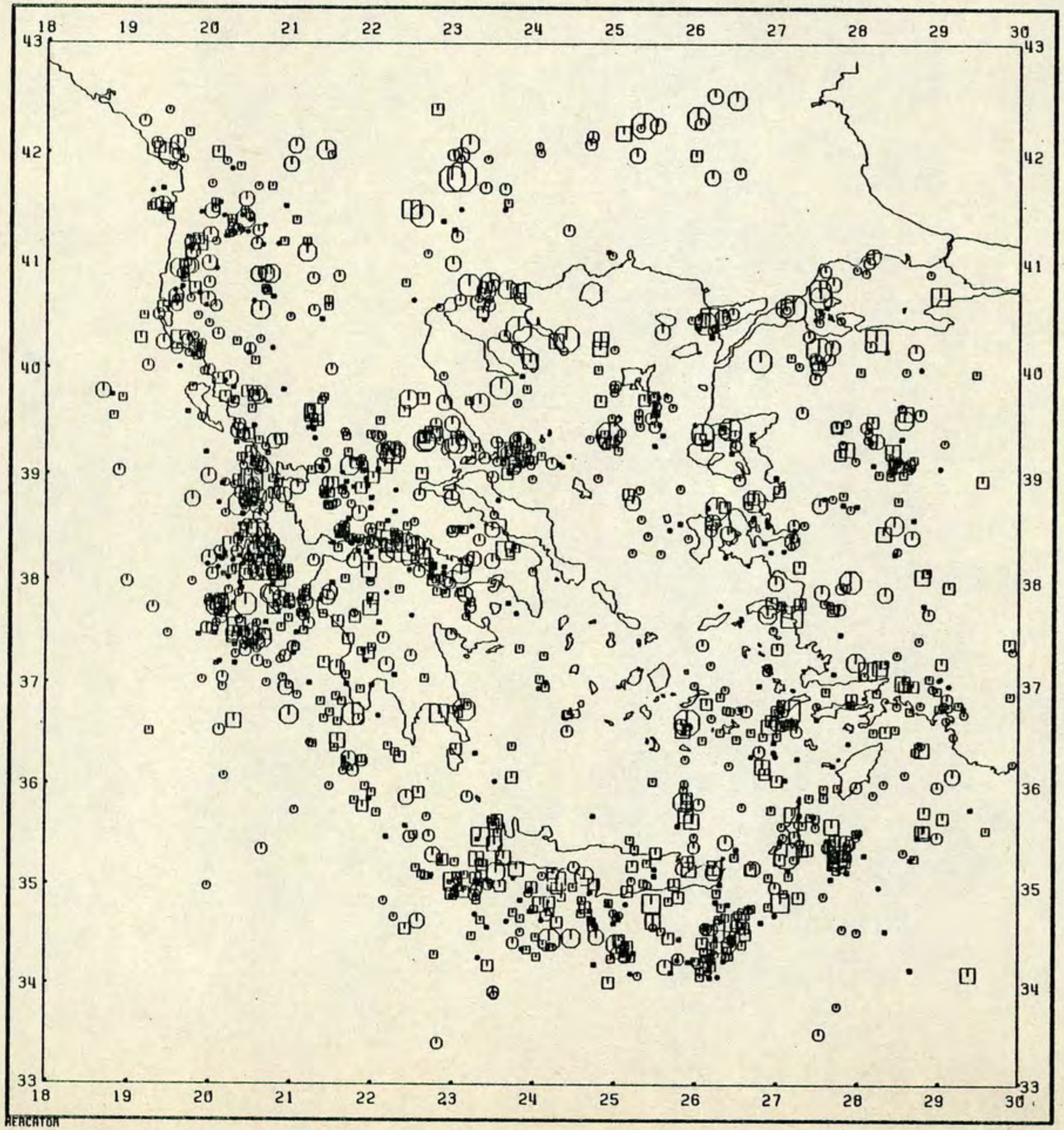
6.4 Spatial distribution of the epicentres

6.4.1 Shallow earthquakes (h<60 km)

Figure 6-5 is a map of the epicentres of shallow earthquakes for Greece and the adjacent areas (33.5°N to 42.5°N, 18.5°E to 29.5°E) for the period 1901-1978, based on the recalculated parameters (1917-1963) and those of UNS and ISC. A total of 1492 events is mapped which, because of the consistent treatment (see Chapter V), is believed to represent the most complete, accurate and homogeneous data sample available for this purpose.

Comparing this map with similar ones previously published, it is apparent that, although the general pattern of all maps is the same because of the high activity of the region, a better delineation of the seismic zones is achieved. A well defined seismic belt which runs parallel to the Hellenic Arc, and contains the majority of shallow earthquakes, can be seen in Figure 6-5. To the north, this zone runs well within Albania in an almost north-south direction, whereas its south-east part joins the diffused zone of Asia Minor (the west coast of Turkey).

A second well defined zone with a ENE-WSW trend runs from Leukas Island, where it meets the first zone, and through central Greece reaching the east coast of Greece near Volos. After that, it is divided into two less well defined branches. One turns to the north and covers the



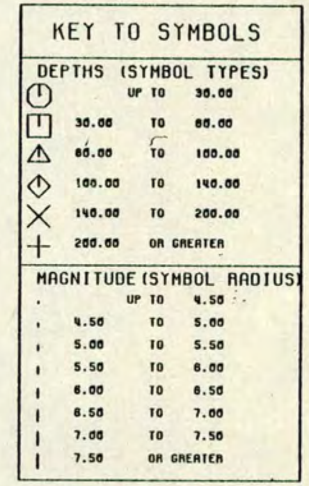


Fig 6-5 Spatial distribution of the epicentres of shallow depth earthquakes for Greece since 1901.

Chalkidiki peninsula, and the other continues through the Sporades Islands and, in an east-west direction, joins Asia Minor after reaching the north coast of Lesvos Island. However, this branch seems to be divided near the eastern Sporades, and a new narrow zone is developed with an almost north-south direction, which passes through the west coast of Limnos Island and ends, quite sharply, near the south coast of Thassos Island. From the distribution of shallow earthquakes in the northeast part of the region (Marmara area), it is not clear whether the North Anatolian Fault extends towards the Aegean Sea, or diverts into western Turkey, or both.

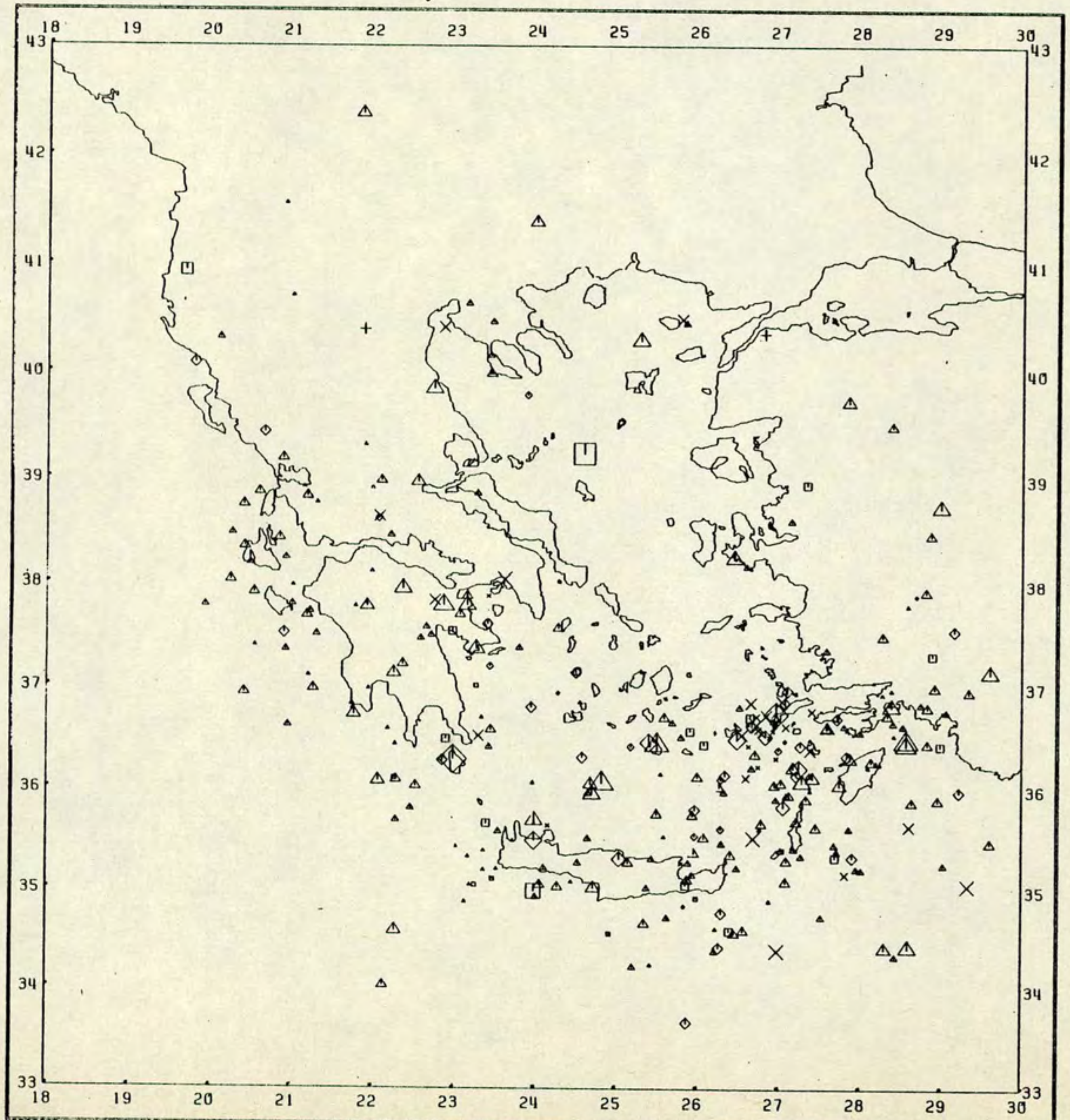
A third well defined zone is that which follows the Saronikos and Corinth gulfs. This zone at the west end and, in the middle of the gulf of Patras, is curved, and joins the previous zone (central Greece) in a north-south direction, rather than continuing and meeting the arcuated first zone (along the Hellenic arc).

From Figure 6-5, it is clear that at least three well defined aseismic blocks exist: the attikocycladic block, which is part of what McKenzie (1972) calls the "Aegean plate", the block formed by north-eastern Greece and the aseismic block in central Greece around the Ptolemais basin. The existence of these aseismic blocks indicates that it is difficult to talk about a simple plate model for the region. It means that the lithosphere is very fragmented, which is illustrated by the existence of these several small aseismic blocks.

6.4.2 Intermediate earthquakes (h>60 km)

Figure 6-6 is a map of the spatial distribution of the intermediate depth earthquakes. Different symbols are used for the different depth ranges, and the size of the symbols is proportional to magnitude ranges, as the caption of the figure describes.

From Figure 6-6 it can be seen that most of the earthquakes with



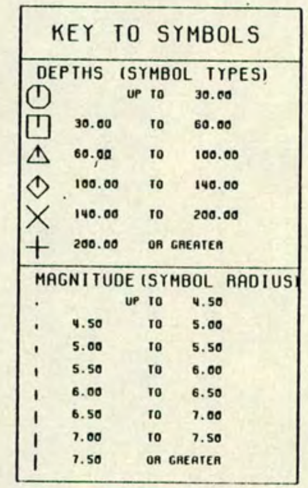


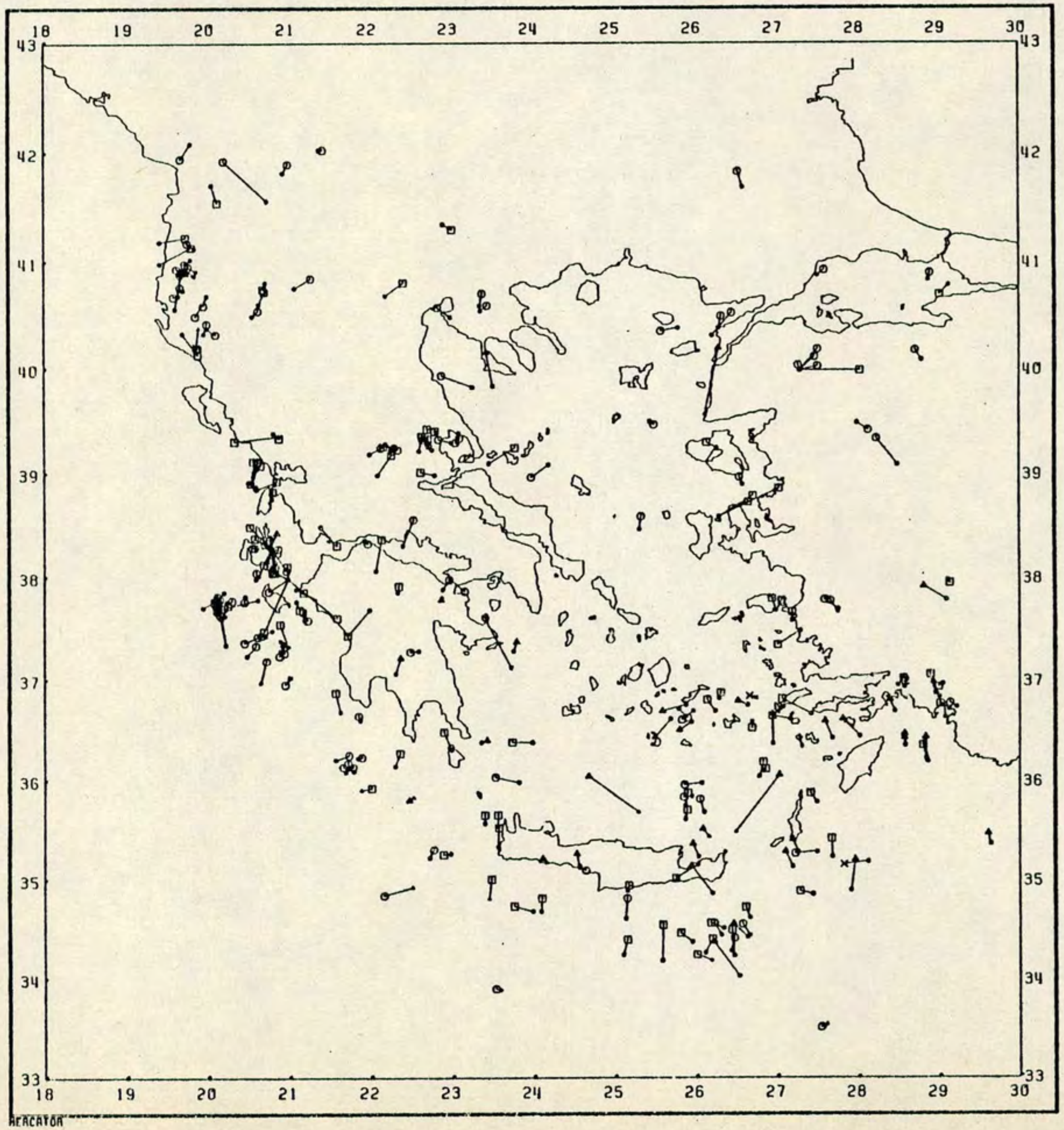
Fig 6-6 Spatial distribution of the epicentres of intermediate depth earthquakes for Greece since 1901.

depth h < 100 km are associated with the Hellenic arc.

In previously published maps, nearly all large intermediate earthquakes in the area of Greece were limited to the region south of 38.5°N (Drakopoulos, 1976b). However, from Figure 6-6 it is clear that there is a significant number of intermediate earthquakes in the north part of the region which had been reported as shallow. From both Figures 6-5 and 6-6 it can be seen that the distribution of the hypocentres is not well represented by a simple dipping Benioff zone, either to the south or to the north. Most parts have both shallow and intermediate earthquakes, without any clear or systematic change in depth as the distance from the Hellenic arc lengthens towards the volcanic arc.

Figure 6-7 shows the shift in position and depth for the earthquakes which occurred during the last ten years of the recalculated period (1953-1963). Two sizes of symbols are used. The smaller size symbols show the locations taken from the ISS data file, while the larger ones show the recalculated locations. The different symbols for different depth ranges are the same as in Figures 6-5 and 6-6, where depths for the ISS locations are those of UNS's catalogue because ISS usually did not calculate depth values.

From Figure 6-7 it can be seen that the majority of the recalculated depths for intermediate earthquakes along the Hellenic arc have shallower depths than those of UNS, especially in the southwest part of Crete. In that part of the Hellenic arc, no earthquake with a depth greater than 100 km is found. The opposite is the case for the southeast part of the arc (eastern Crete, Karpathos, Rodos) and the volcanic arc. Generally a tendency of increasing depths is observed. This may be due to the fact that UNS's depth determinations were based upon macroseismic information using relations among I, M and h (UNS, 1974). As is pointed out in the UNS catalogue the intermediate depth earthquakes seem to have a very big



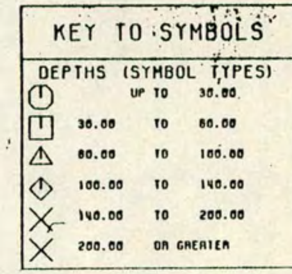
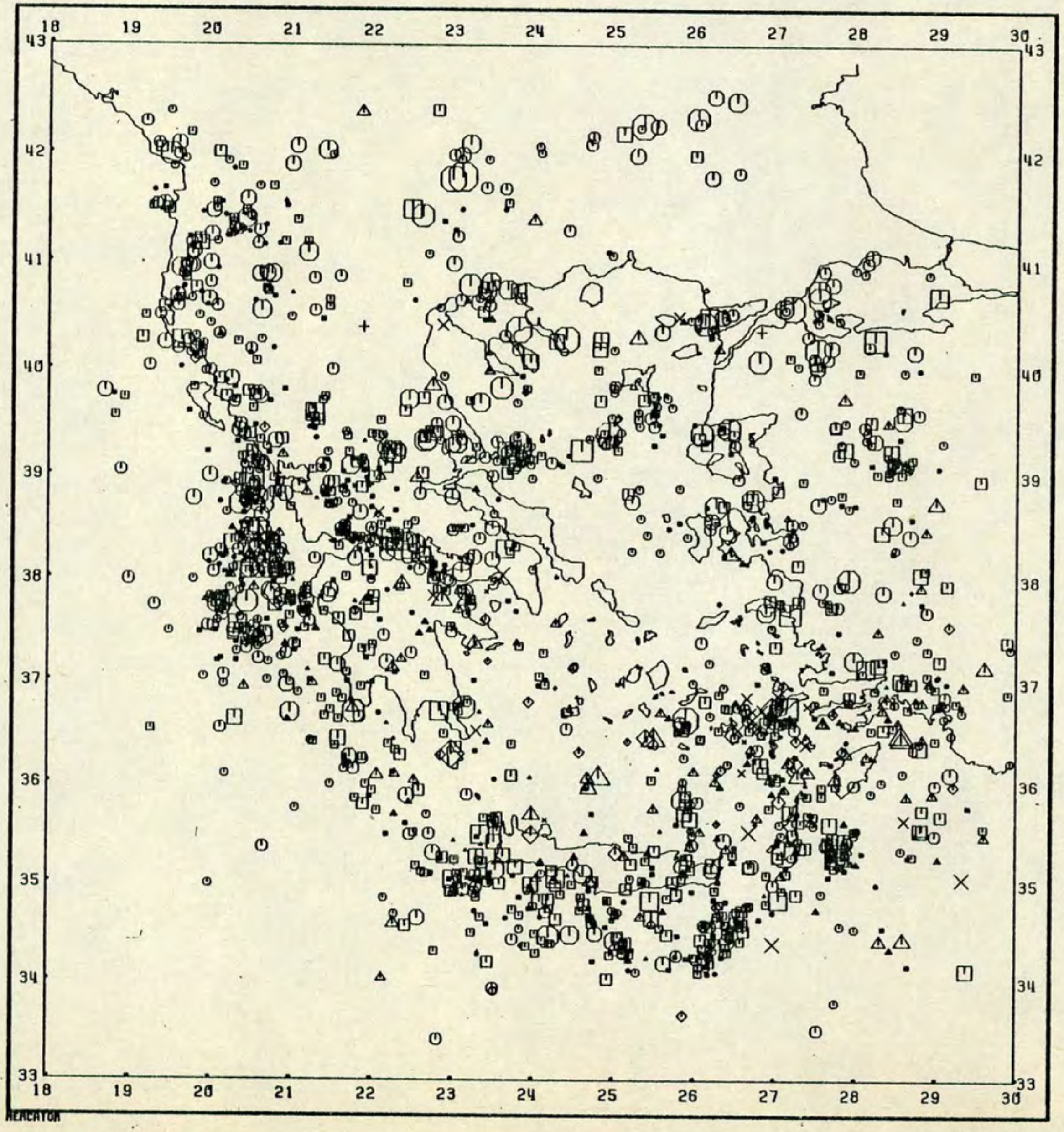


Fig 6-7 Shift in position and changes in depth between the recalculated and ISS locations for earthquakes of the period 1953-1963. Large depth symbols show the recalculated positions, small depth symbols show the positions reported by ISS.



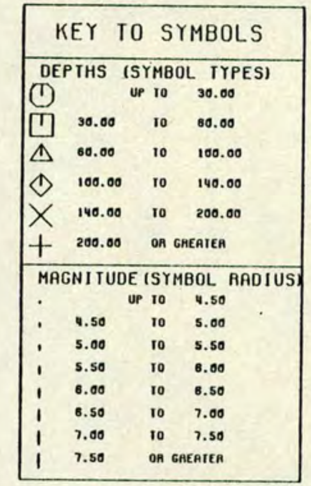


Fig 6-8 Spatial distribution of all earthquakes for Greece since 1901.

vertical extension combined with the inclination of the main rupture, especially for the Aegean Sea. In such cases all the instrumental data forces us to treat the earthquakes as of intermediate depth, but all the macroseismic data presents them as shallow. The spatial distribution of all earthquakes for the period under investigation is mapped in Figure 6-8.

6.5 Isodepth maps from radial vertical cross-sections

6.5.1 Procedure

Using the parameters of the new earthquake catalogue, two and three-dimensional isodepth maps are produced in an attempt to examine the validity of the existing models, and to distinguish places where further work must be done, rather than to present another model. These maps result from continuous radial vertical cross-sections using the following procedure:

i) The approximate centre of the volcanic arc is chosen as a reference point. Its coordinates are 38.9°N, 26.0°E.

ii) Radial vertical planes are drawn with a common axis to the one passing through the reference point, and differing by an azimuth of 10° (36 vertical planes).

iii) In each plane the epicentral distance from the centre versus focal depth is plotted for all earthquakes within $\pm$ 10° azimuth from that plane. Thus, 36 radial vertical cross-sections are produced, each of which overlaps the one adjacent by an azimuth of 10°.

iv) For each of these 36 cross-sections, a smooth curve following the lower part (deeper earthquakes) of the projected events is drawn. Earthquakes which have a depth less than 50 km are excluded. Thus, the coordinates of the points taken from these curves, that is distance from the reference point and depth, constitute the data to be contoured. Figures 6-9a to 6-9f illustrate this procedure.

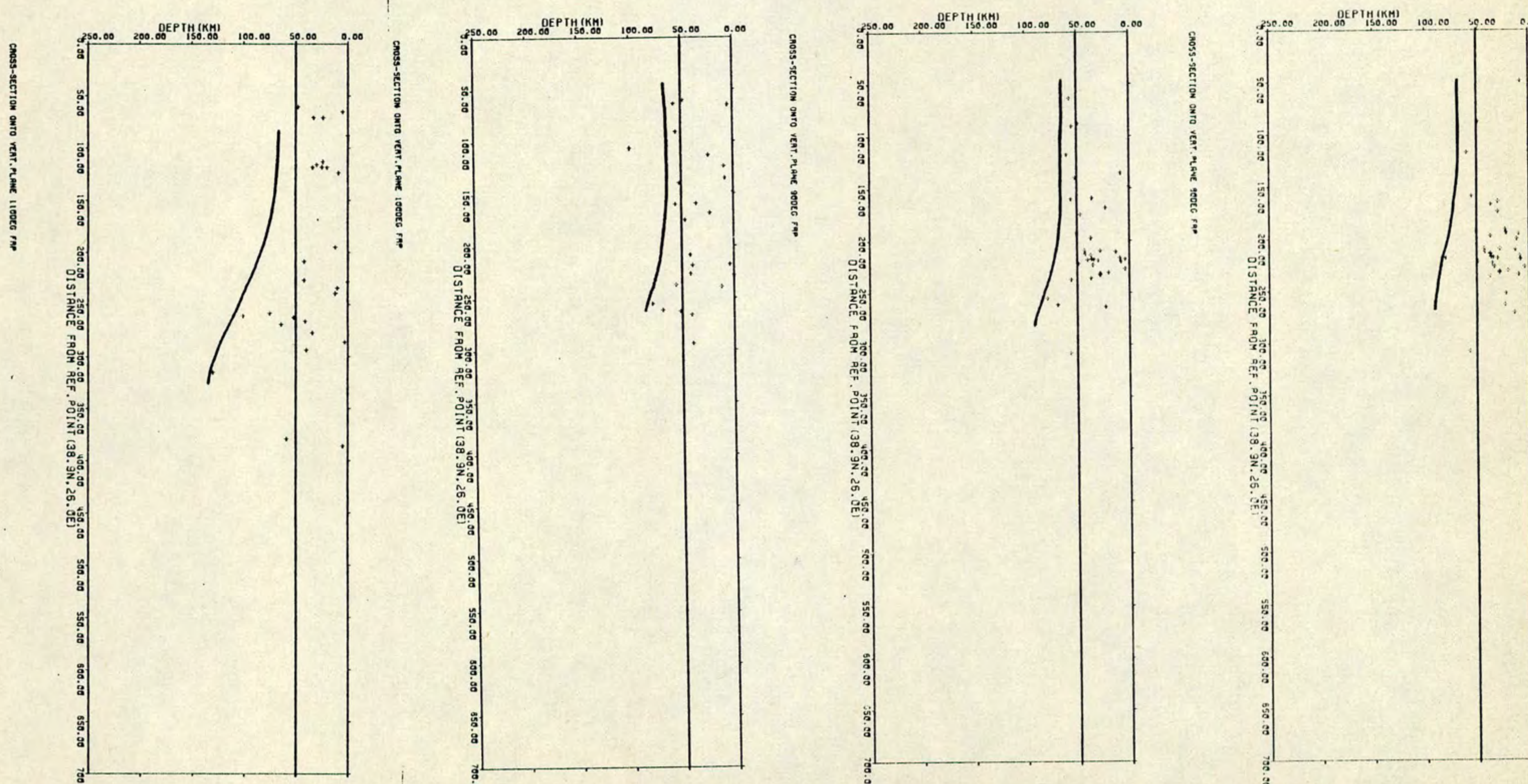


Fig 6-9a Four vertical radial planes passing through the reference point (38.9°N, 26.0°E). The hypocentres projected onto each plane have azimuths between ±10° from the plane. Heavy lines are those from which the points for the isodepth maps are taken.

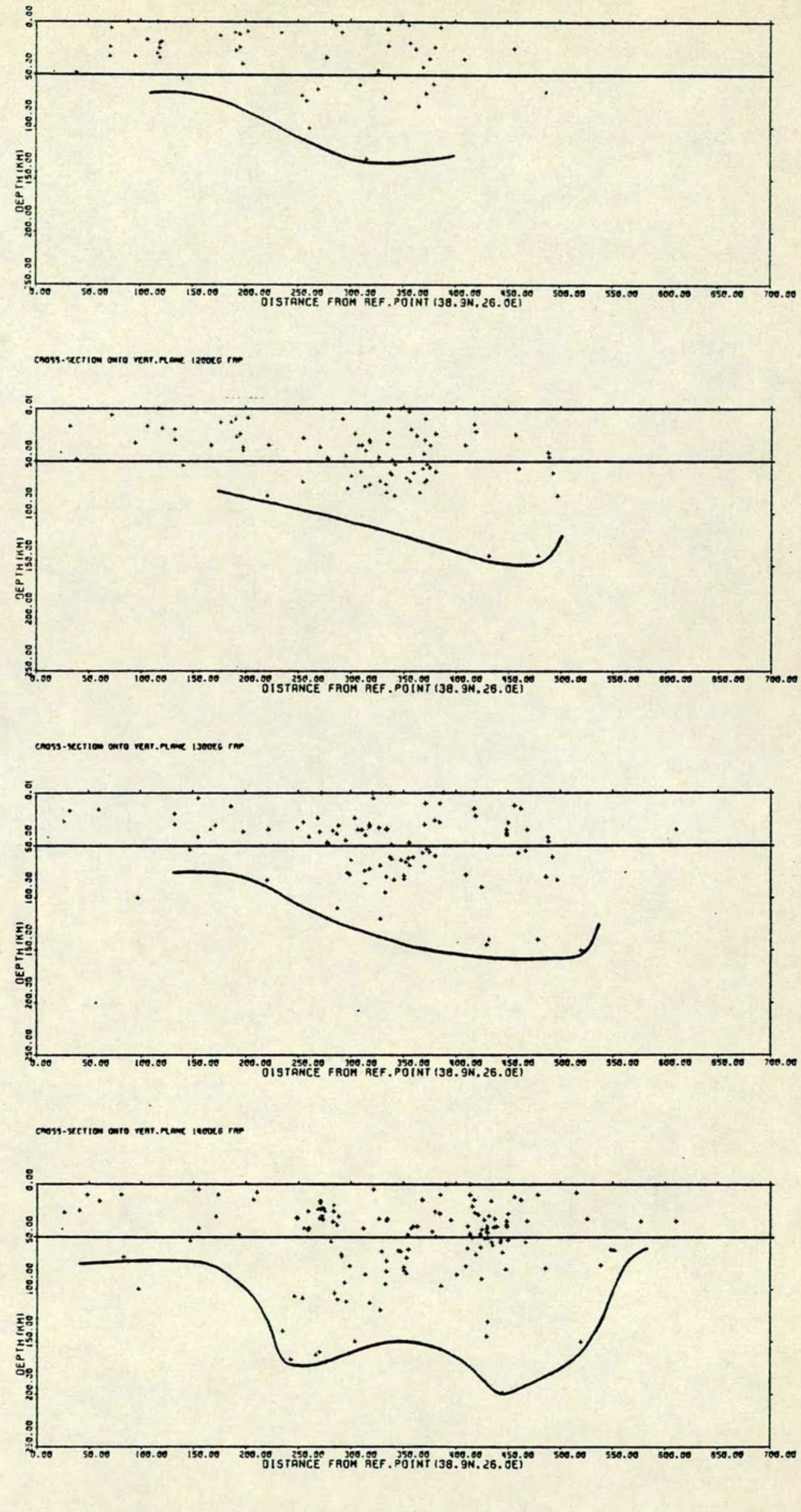
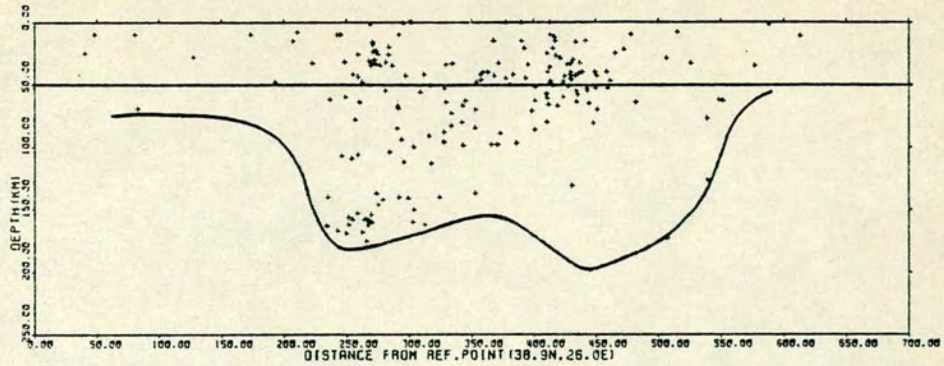
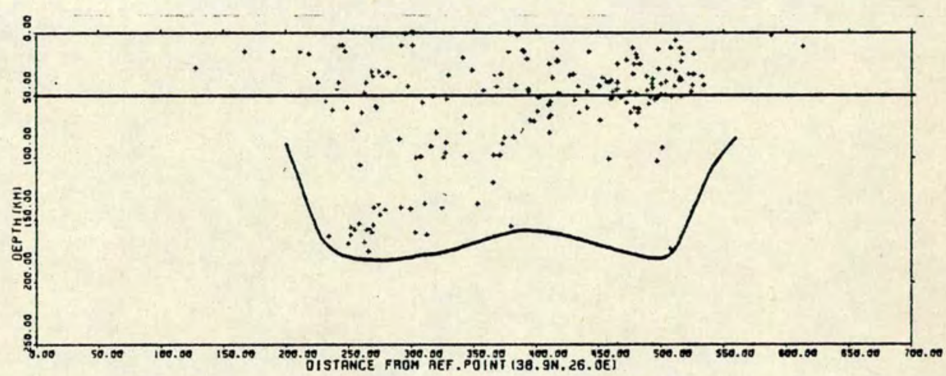


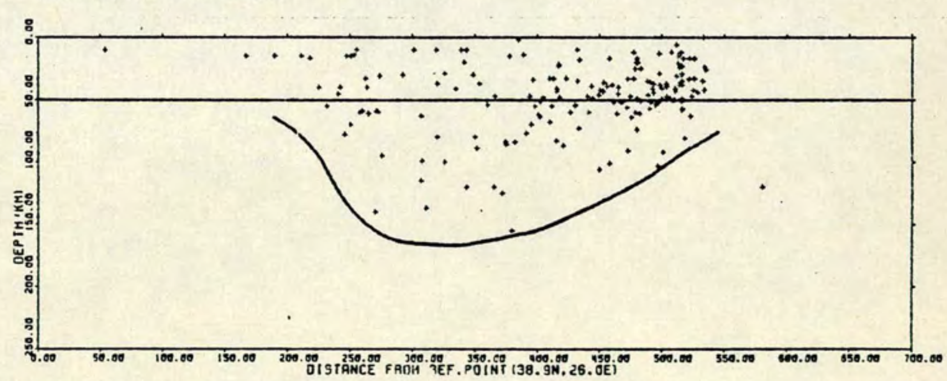
Fig 6-9b For explanation see caption of Fig 6-9a.



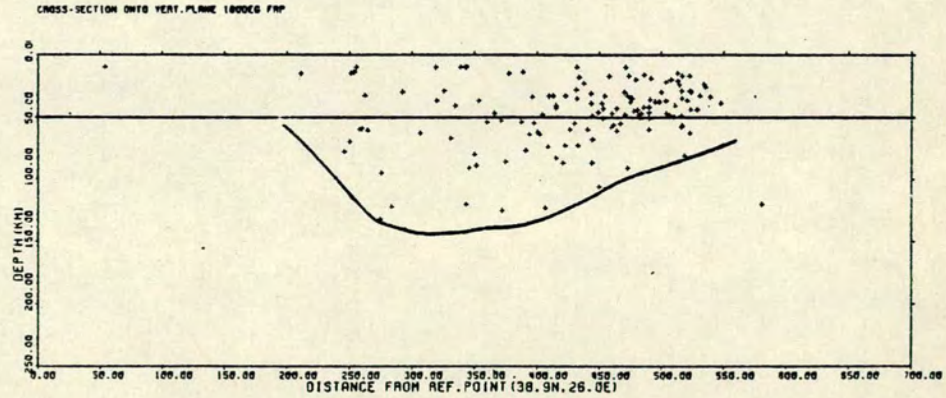
CROSS-SECTION ONTO VERT.PLANE 160DEG FRP



CROSS-SECTION ONTO VERT.PLANE 170DEG FRP

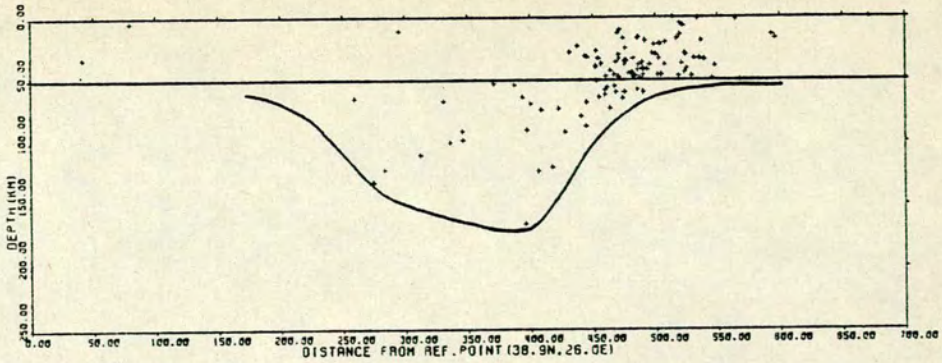


CROSS-SECTION ONTO VERT.PLANE 180DEG FRP

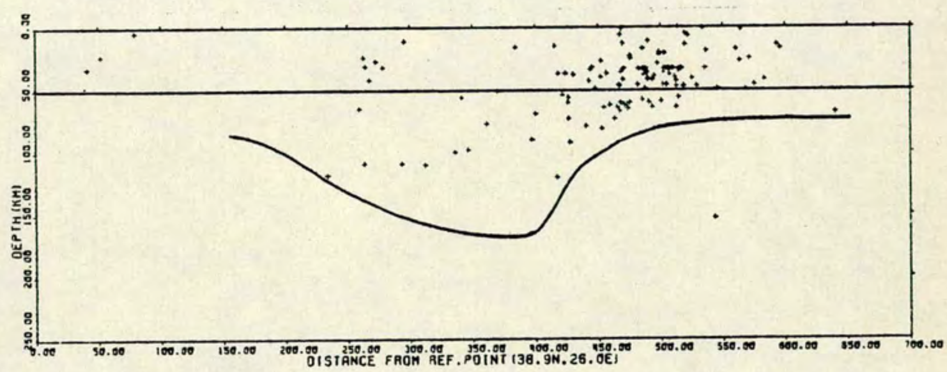


CROSS-SECTION ONTO VERT.PLANE 190DEG FRP

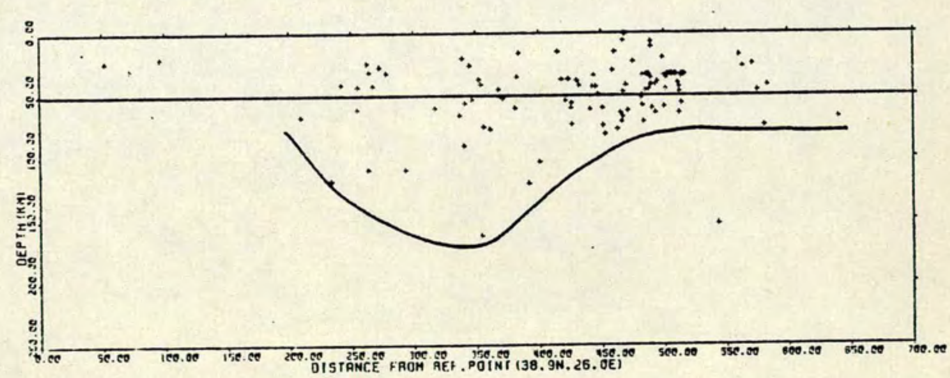
Fig 6-9c For explanation see caption of Fig 6-9a.



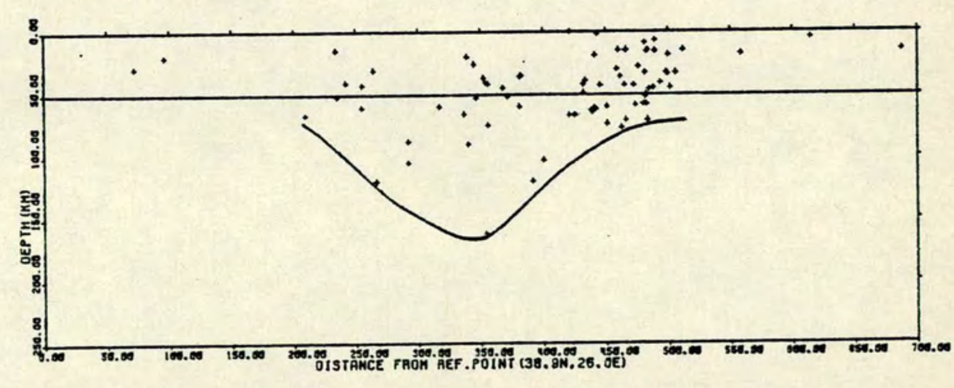
CROSS-SECTION ONTO VERT.PLANE 200DEG FRP



CROSS-SECTION ONTO VERT.PLANE 210DEG FRP

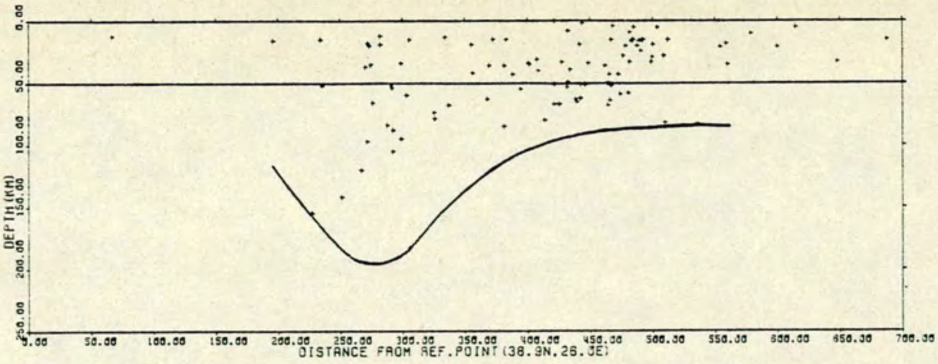


CROSS-SECTION ONTO VERT.PLANE 220DEG FRP

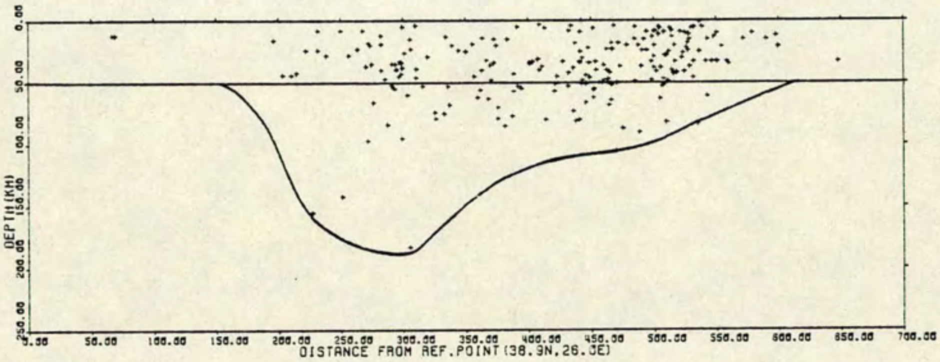


CROSS-SECTION ONTO VERT.PLANE 230DEG FRP

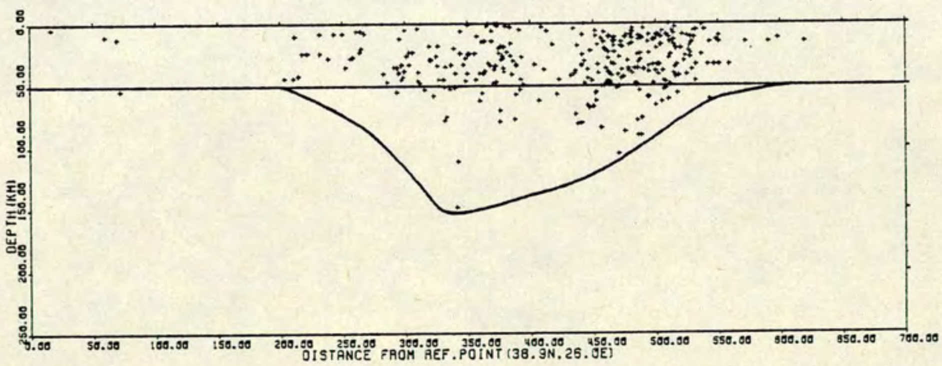
Fig 6-9d For explanation see caption of Fig 6-9a.



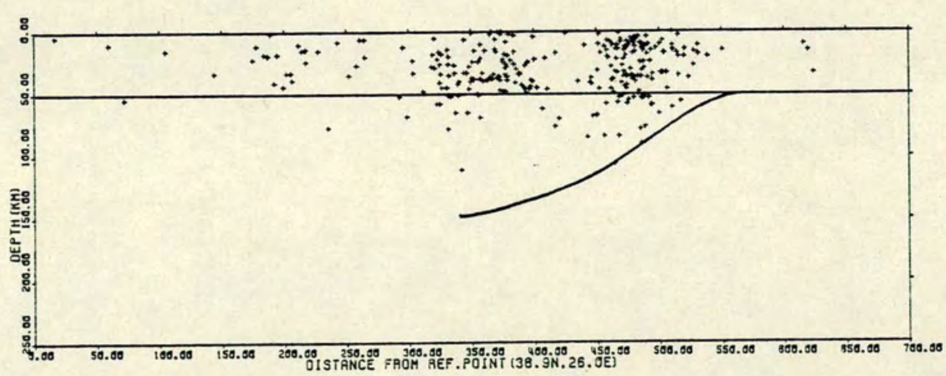
CROSS-SECTION ONTO VERT.PLANE 240DEG FRP



CROSS-SECTION ONTO VERT.PLANE 250DEG FRP

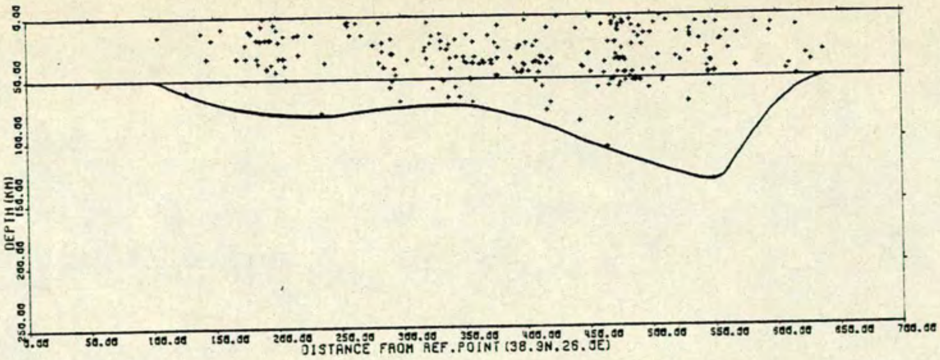


CROSS-SECTION ONTO VERT.PLANE 260DEG FRP

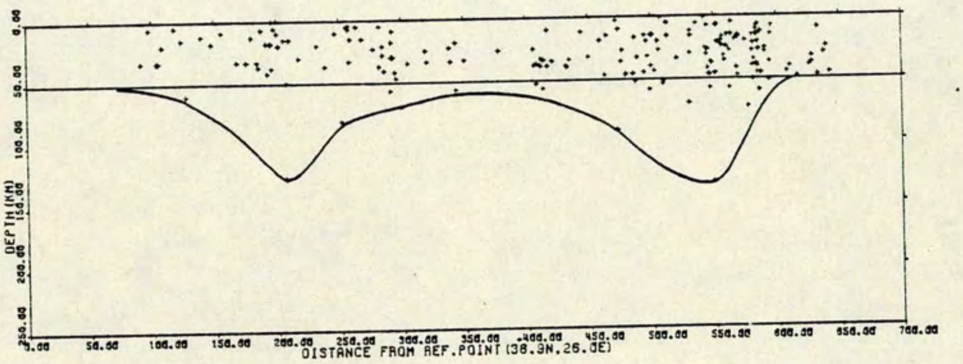


CROSS-SECTION ONTO VERT.PLANE 270DEG FRP

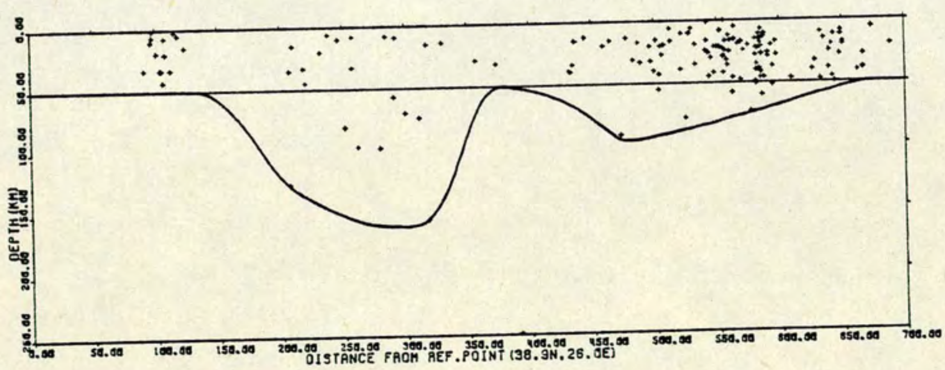
Fig 6-9e For explanation see caption of Fig 6-9a.



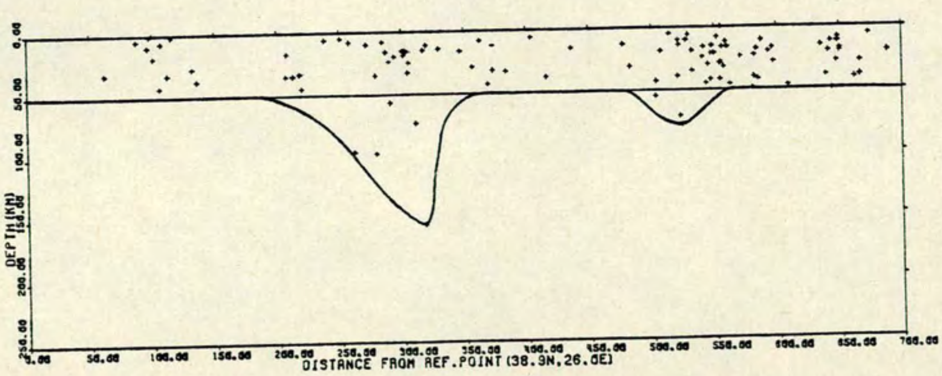
CROSS-SECTION ONTO VERT.PLANE 280DEG FRP



CROSS-SECTION ONTO VERT.PLANE 290DEG FRP



CROSS-SECTION ONTO VERT.PLANE 300DEG FRP



CROSS-SECTION ONTO VERT.PLANE 310DEG FRP

Fig 6-9f For explanation see caption of Fig 6-9a.

6.5.2 Results and discussion

Figures 6-10 and 6-11a to 6-11h, resulting from the previously described procedure, show the following features:

a) The Hellenic trench

All the tectonic models of the region agree that the Hellenic arc is a collision front between Africa and the Aegean area and that Africa underthrusts the Aegean area causing a subduction zone to develop at the collision front. This subduction zone is easily seen in all the figures.

The isodepth of 85-115 km runs almost parallel to the Hellenic trench, with increasing depth towards the two ends. In the north-western end of the trench this isodepth continues to the north, and runs well into Albania, where it has not previously been mapped.

An isodepth of 115-145 km is developed in the convex north-western end of the Hellenic trench which includes the north-western part of Greece, Corfu Island and the southwest coast of Albania. From the isodepths alone it is difficult to conclude if there is a "blob" (McKenzie, 1978) or a poorly defined Benioff zone (Papazachos and Comninakis, 1976), or if this thickening is caused by the existence of the rigid Apullian block beneath the sea to the west, which is stronger than the heavily deformed belts of Albania and Greece (McKenzie, 1978). However, the clear continuation of this arcuated zone north of Leukas Island and the existence of thrust faults (see Fig 6-4), may suggest that subduction is taking place. This area is certainly among those where much more work is needed in order to understand the present tectonic process.

At the south-eastern end of the Hellenic trench (east of Crete) the depth distribution shows that the subduction zone continues and meets western Turkey and Cyprus, through the Pliny and Strabo trenches, rather than the coast of western Turkey near Rodos Island. From the isodepth

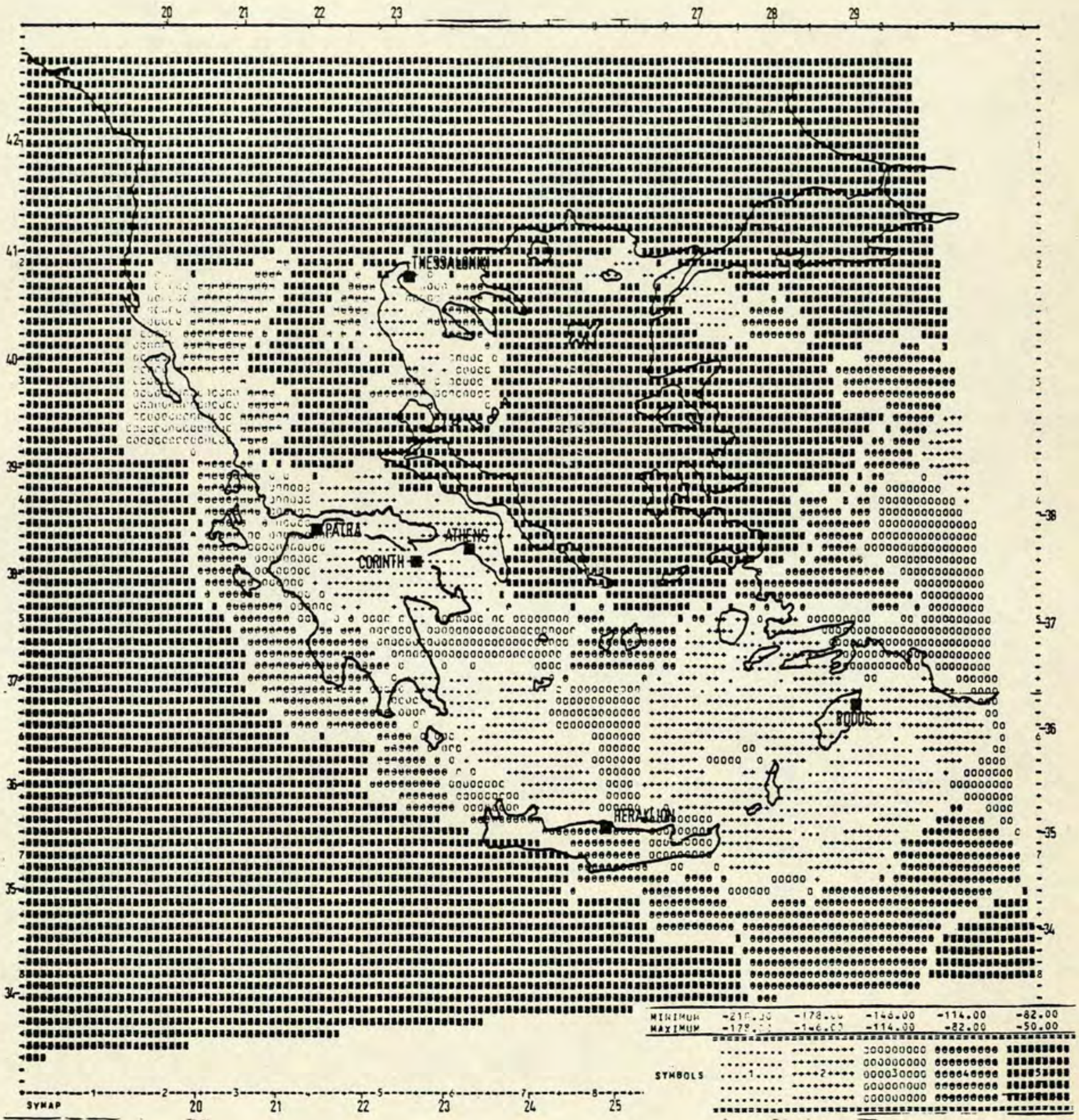


Fig 6-10 Isodepth map for Greek earthquakes obtained using radial vertical cross-sections shown in Figs 6-9a - 6-9f. Symbols for focal depth ranges are indicated in the insert.

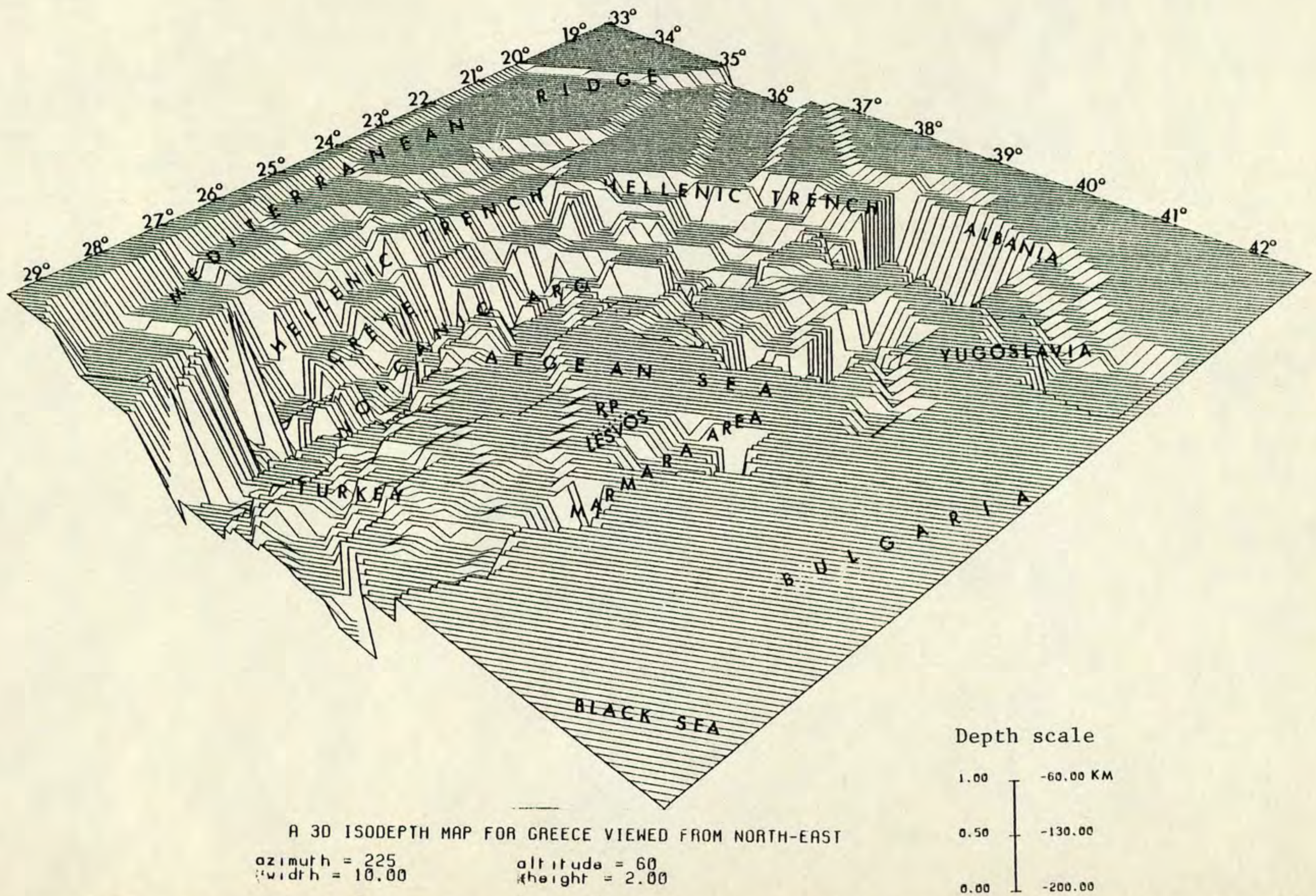
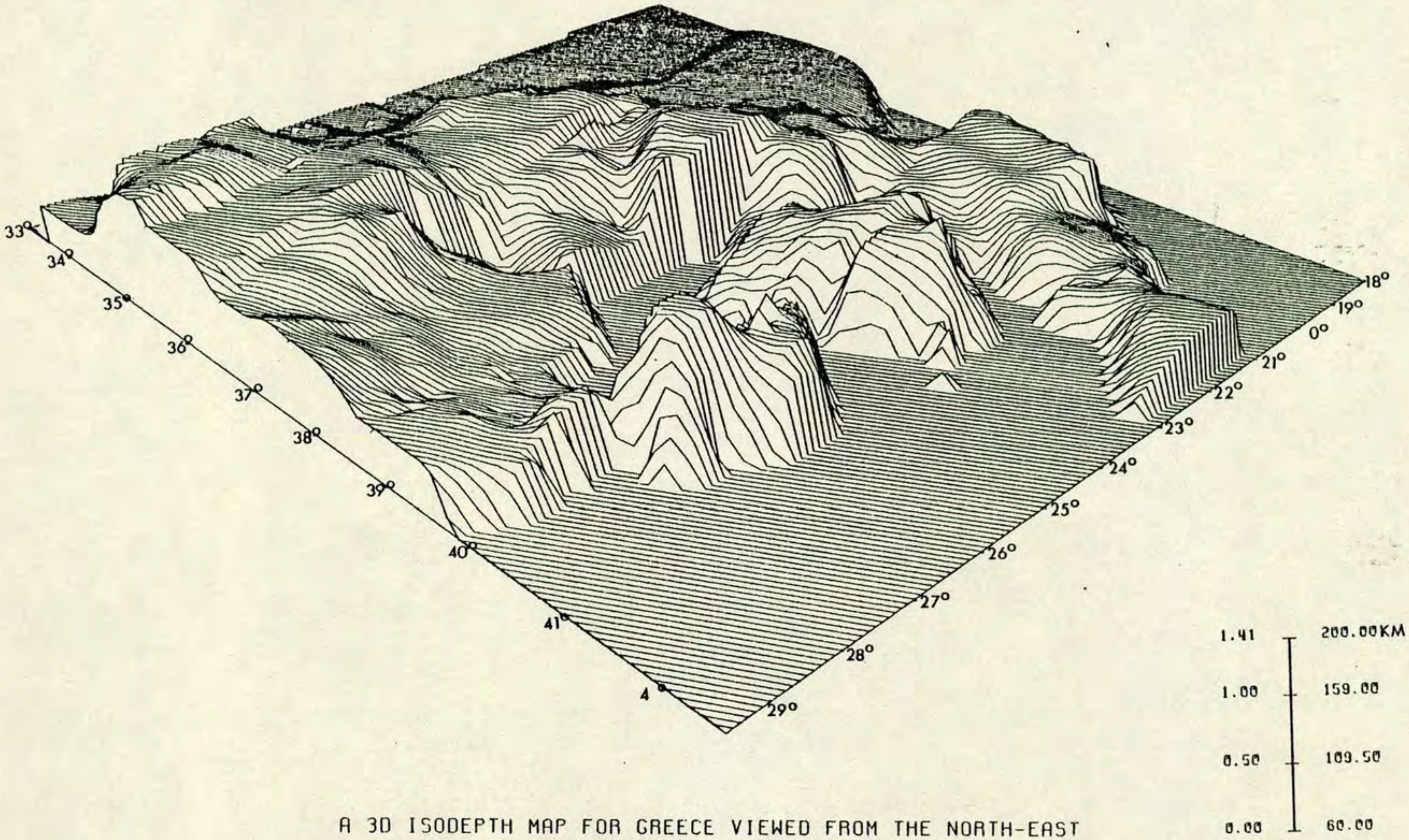


Fig 6-11a Three dimensional isodepth maps for Greek earthquakes obtained using vertical cross-sections shown in Figs 6-9a - 6-9f. The depth scale in km is indicated in the insert. R.P: reference point for all cross-sectional diagrams.



A 3D ISODEPTH MAP FOR GREECE VIEWED FROM THE NORTH-EAST

azimuth = 225 altitude = 45
*width = 10.00 *height = 2.00
smoothings = -1.00

* before foreshortening 30/08/78

Fig 6-11b For explanation see caption of Fig 6-11a.

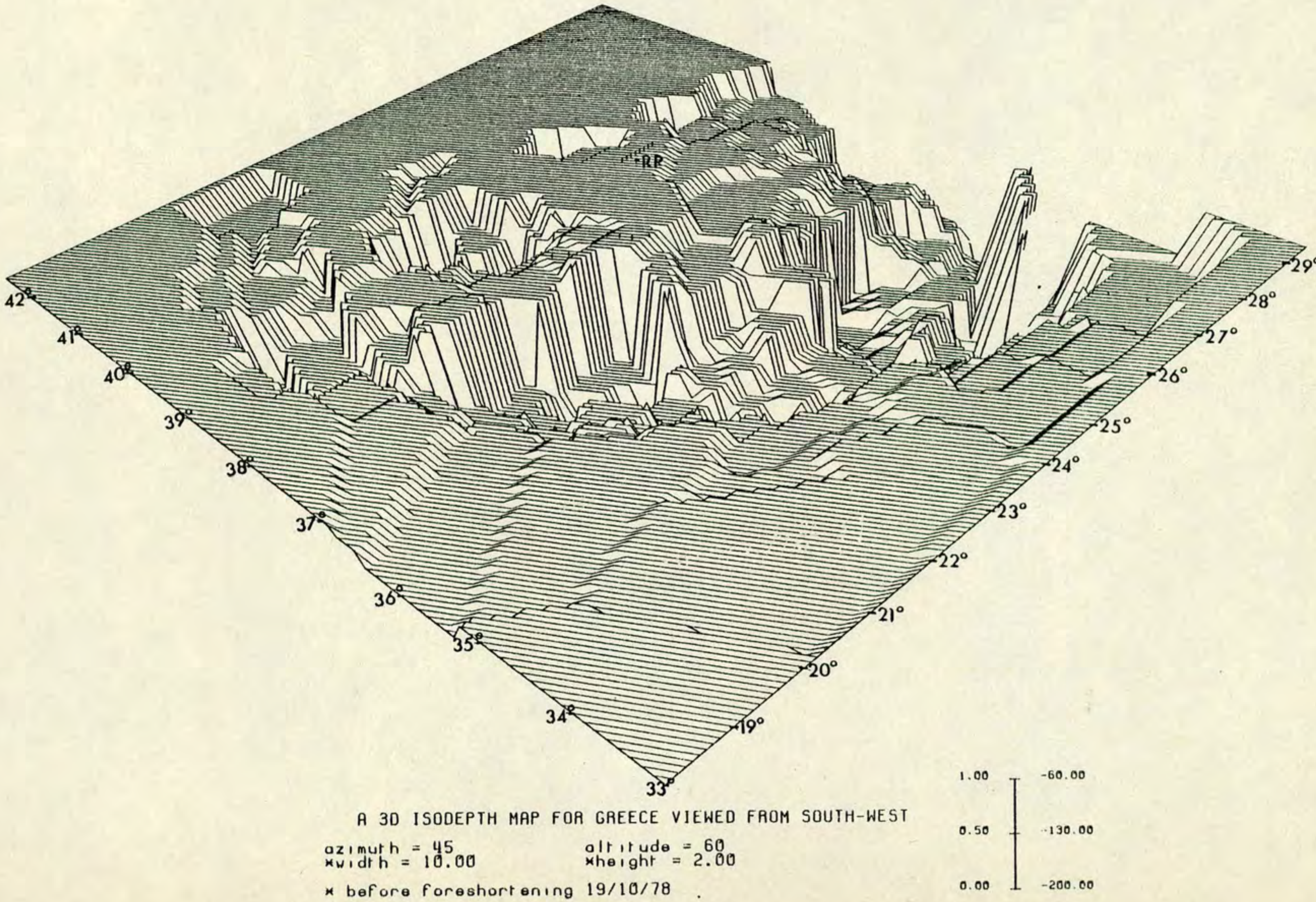
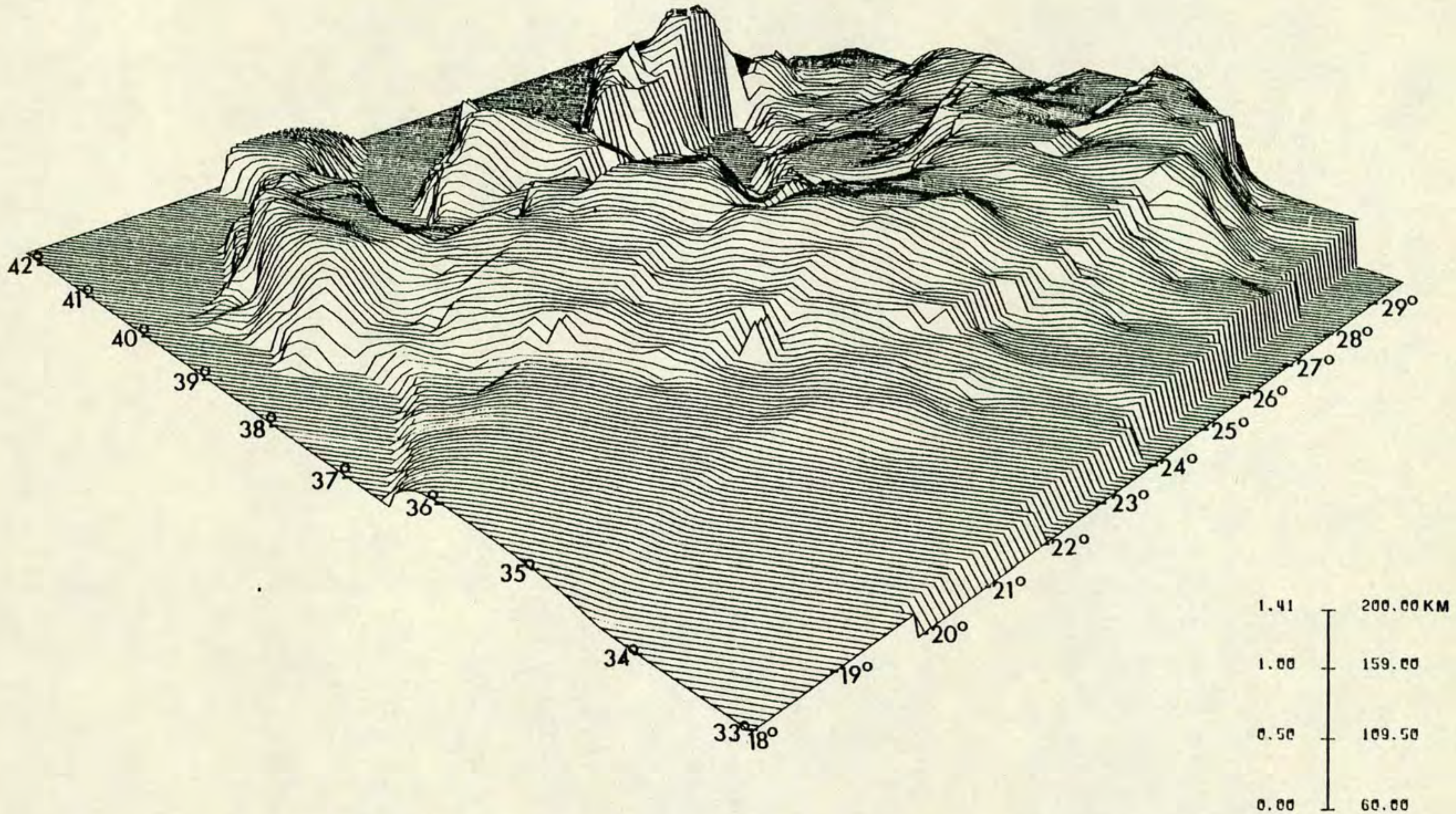


Fig 6-11c For explanation see caption of Fig 6-11a.



A 3D ISODEPTH MAP FOR GREECE VIEWED FROM THE SOUTH-WEST

azimuth = 45　　altitude = 45
*width = 10.00　　*height = 2.00
smoothings = -1.00

* before foreshortening 30/08/78

Fig 6-11d For explanation see caption of Fig 6-11a

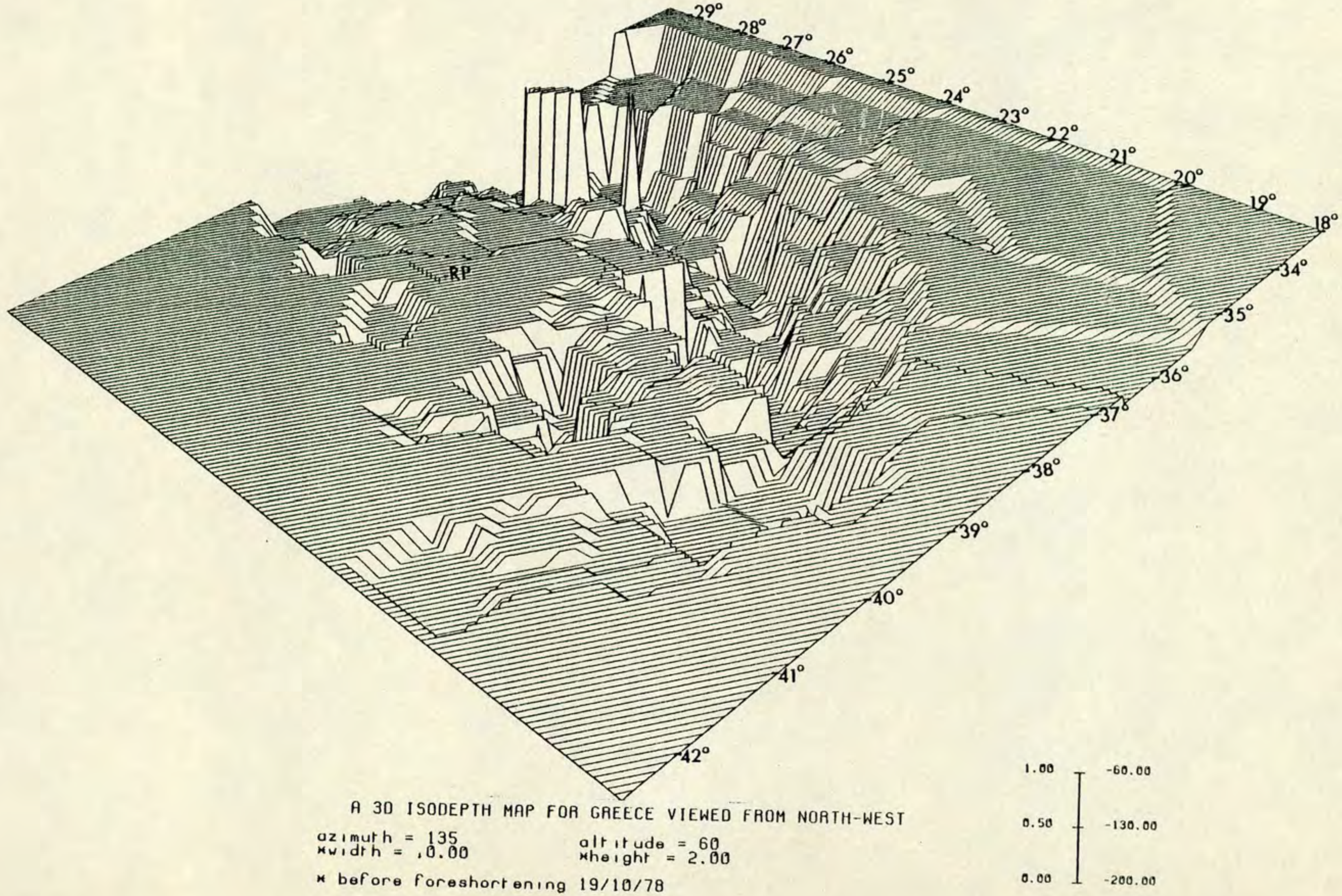
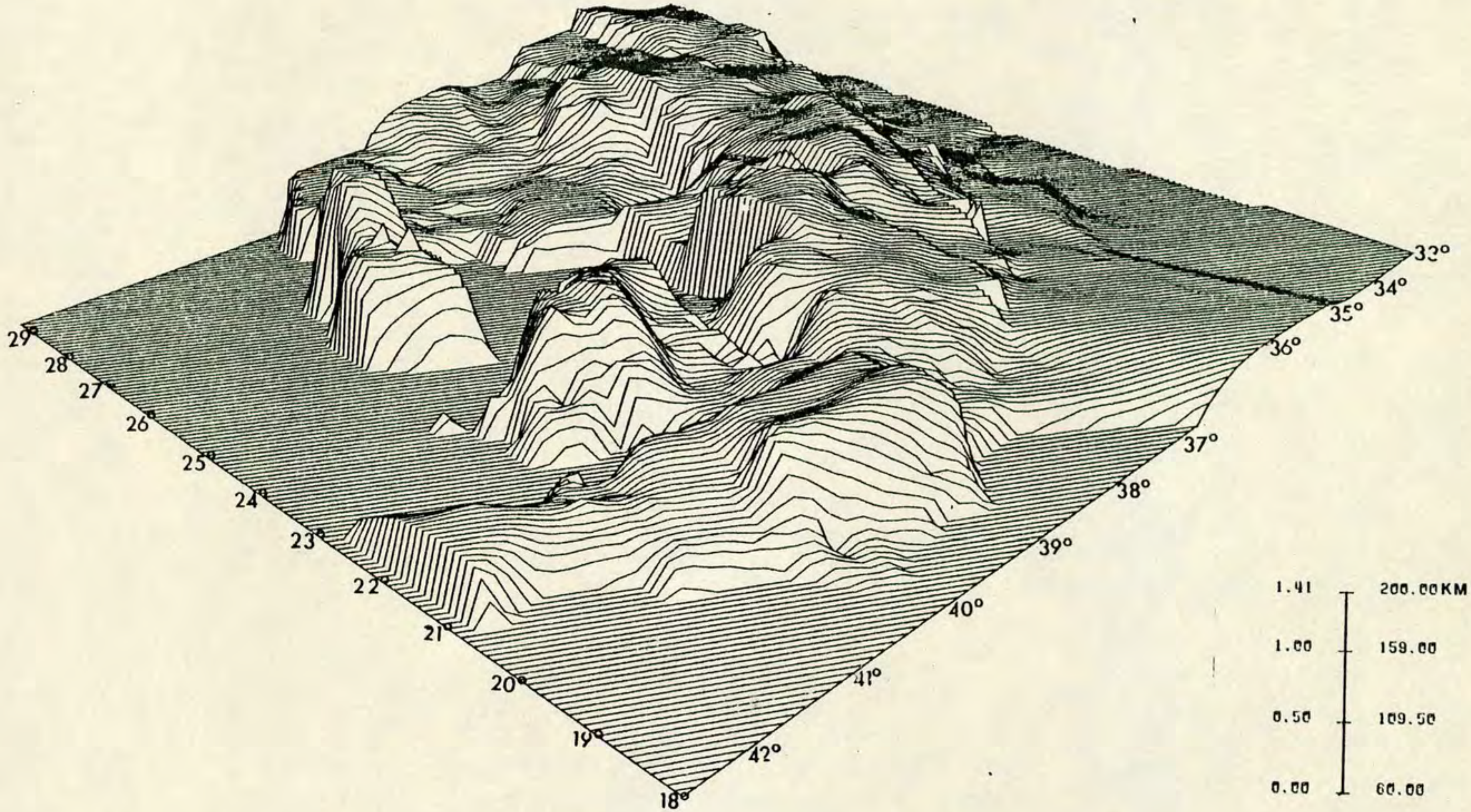


Fig 6-11e For explanation see caption of Fig 6-11a.



A 3D ISODEPTH MAP FOR GREECE VIEWED FROM THE NORTH-WEST

azimuth = 135 altitude = 45
*width = 10.00 *height = 2.00
smoothings = -1.00

* before foreshortening 30/08/78

Fig 6-11f For explanation see caption of Fig 6-11a.

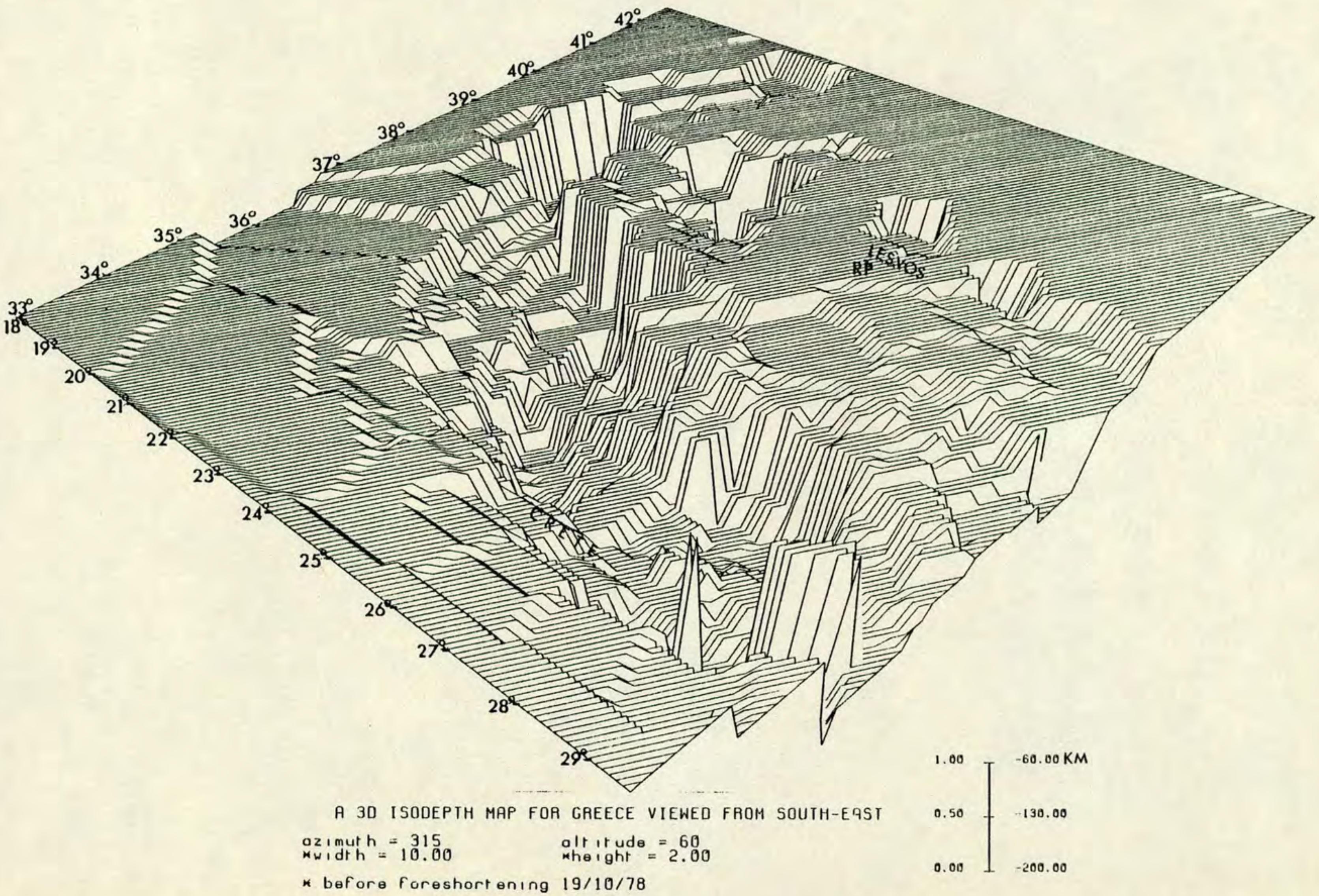
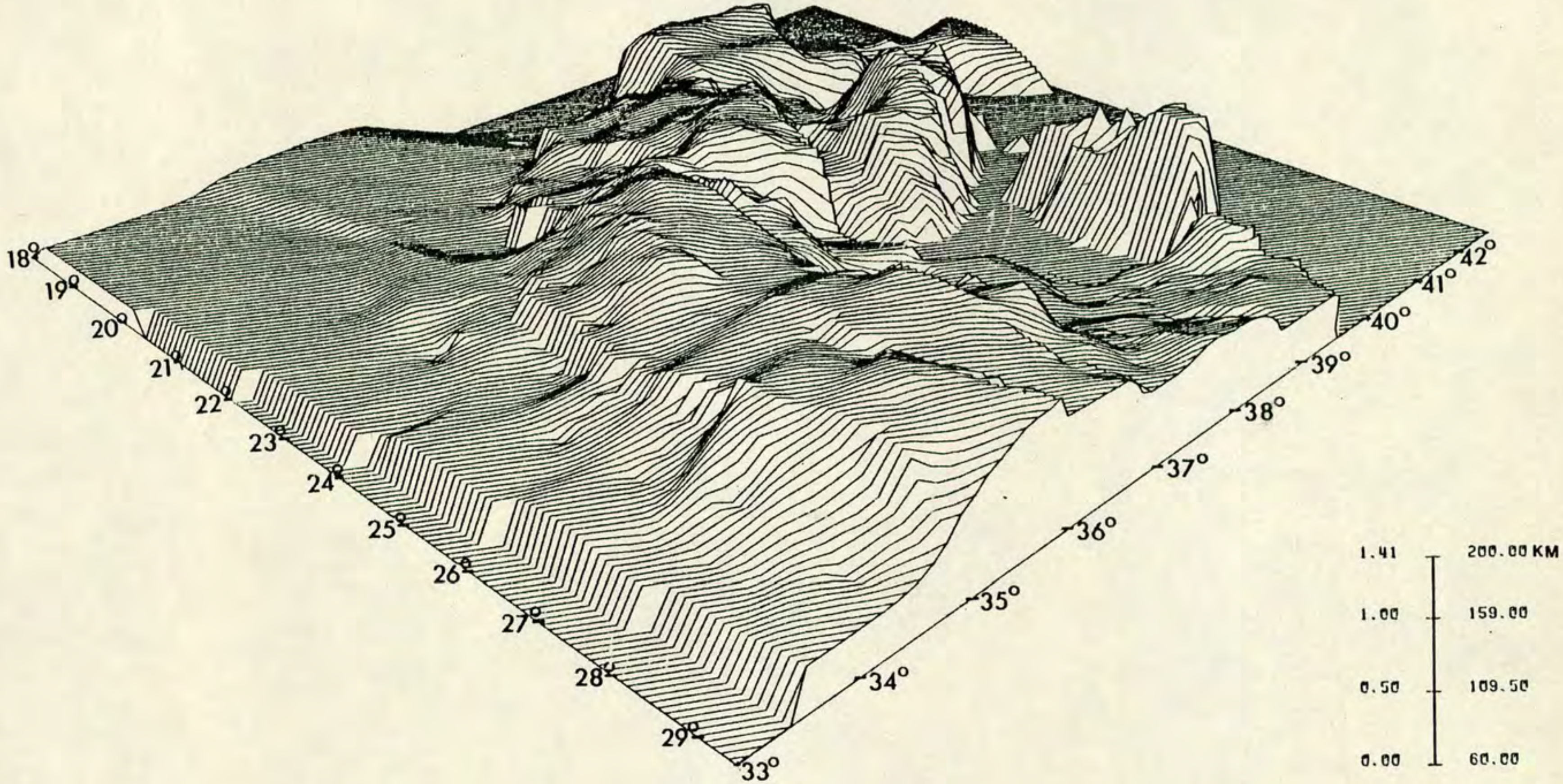


Fig 6-11g For explanation see caption of Fig 6-11a.



A 3D ISODEPTH MAP FOR GREECE VIEWED FROM THE SOUTH-EAST

azimuth = 315 altitude = 45
*width = 10.00 *height = 2.00
smoothings = -1.00

* before foreshortening 30/08/78

Fig 6-11h For explanation see caption of Fig 6-11a.

maps it is apparent that south of Rodos the most extensive and deepest seismicity of the whole area is found, and earthquakes with depths within 180-210 km dominate the area.

Although the majority of the intermediate shocks are related to the subduction zone now occurring along the Hellenic arc, from the isodepth maps it can be seen that there is no clear increase in depth with distance from the thrust zone, and the distribution of deeper earthquakes does not follow the volcanic arc. Thus, it is difficult to define a simple Benioff zone in the southern part of the Aegean region.

The less active part of the arc is between the Peloponnesus and western Crete, but if the relative motion between the Aegean area and Africa is in a southwest direction, as the results of McKenzie's fault plane solution shows (big arrow in Fig 6-4), this part of the arc should be the most active. Furthermore, the dip of the slab of subduction in that direction should be greater beneath southern Greece than beneath the south-eastern part of the Aegean. McKenzie (1978) points out that this may indicate a seismic gap or changes in direction during the period of subduction. Only further work on determining the history of deformation behind the Hellenic arc may explain the relative movements along this arc.

b) The Aegean area

In the southern part of the Aegean area there are four places with maximum isodepths:

i) The north-western part of the Peloponnesus, the Saronikos gulf and the eastern part of the Corinth gulf. Papazachos (1977) interprets the existence of thrust faulting for three intermediate earthquakes, and their difference from the surrounding shallow earthquakes in this region, as due to a sinking slab from the Ionian Sea to the Aegean. However, McKenzie's fault plane solutions (1978), and field mapping of Mercier et al (1976), show that most of the deformation in this area is produced by normal faulting (see also Fig 6-4).

ii) The south-eastern part of the Peloponnesus.

iii) South of Rodos Island, and

iv) West of Kos Island.

The general picture of the south part of the region is an arcuated distribution but with no clear increasing depths with distance from the trench, the deepest part of the region being the part south of Rodos which probably continues towards western Turkey.

The main feature in the central part of the Aegean area, is that central Greece and the Aegean Sea are characterised by shallow seismic activity. This, coupled with the existence of two aseismic blocks (see 6.4.1), shows that there is no subcrustal evidence that the Northern Anatolian fault is connected with the seismic zone of central Greece, or the gulf of Corinth.

In the northern part of the Aegean the features are more complicated than elsewhere. The intermediate shocks are fewer than in the southern part. The fact that thrust and normal faulting exist (Ritsema, 1974; Papazachos, 1976a), and the low depth seismicity of the region, lead Papazachos (1976a) to suggest a northerly sinking slab produced by a subduction zone in the northern Aegean. McKenzie (1978) points out that there is no evidence of thrusting on the scale required for such a suggestion, and that these shocks may lie within material subducted at a trench which is no longer active. From the depth distribution alone none of these hypotheses can be rejected. This is another region for which more geophysical data is necessary for a better understanding of its deep tectonic process.

6.6 Summary

The new earthquake catalogue and the spatial and depth distribution maps based on it reveal that Greece, and the adjacent areas of the Aegean are tectonically more complicated than had previously been recognised. The seismicity of the region is mainly due to the collision between the underthrusting African plate and the Aegean area along the Hellenic arc. Using the parameters of the new catalogue, a better delineation of the seismic activity of the region is achieved, and the spatial and depth distribution of earthquakes show that none of the proposed tectonic models completely explain the observed activity over the whole area.

The existence of small aseismic blocks of which three are well defined shows that the lithosphere is very fragmented, and the region can not be modelled by a simple plate. The earthquake depth distribution and the clear continuation of the seismic activity within Albania along the Hellenic arc may suggest that in the north-western end of the Hellenic trench subduction is taking place. At the south-eastern end of this trench the depth distribution shows that the subduction zone continues and meets Turkey much further south than the existing models suggest. It is difficult to define a simple Benioff zone either in the south part or in the north part of the Aegean Sea, because there is no clear increase in depth with distance from the thrust zone, and the distribution of deeper earthquakes does not follow the volcanic arc. To fully understand the tectonic process further work is still necessary, especially in the following places:

i) The north-western part of the Hellenic arc (north-western Greece, south-western coast of Albania).

ii) The south-eastern end of the arc (Eastern Crete, Karpathos and Rodos Islands).

iii) The northern Aegean Sea and north-western part of Turkey (Marmara Sea area).

In the next Chapter, the seismic risk of Greece will be examined using the earthquake parameters of the new catalogue, the Extreme-Value statistical method of the third type asymptotic distribution combined with strain energy release method already described. Special emphasis will be given to six of the largest cities of Greece.

CHAPTER VII

GREEK SEISMIC RISK EVALUATION

7.1 Introduction

Several attempts have been made to map seismicity and seismic risk of Greece. Galanopoulos (1968) calculated the seismic risk expression in recurrence rates of shallow earthquakes with $m > 5\frac{1}{2}$, 6, $6\frac{1}{2}$, and 7 in each square degree of Greece. Comninakis (1975) defined the seismic risk in terms of the most probable annual maximum magnitude from the a and b values per $\frac{1}{4}$ square degree and for the sample period 1911 to 1970. Algermissen et al (1976) used the UNS catalogue to compile seismic risk maps of the Balkan region, depicting acceleration and velocity with 70% probability of not being exceeded in 25 and 200 year periods.

However, the calculation of seismic risk in terms of expected magnitude, acceleration, velocity or displacement, depends critically on the time span considered, and also on the earthquake parameters used. If the time span is not sufficient to establish stable estimates of risk, then ensueing risk maps will differ for different periods of observation. Thus, comparison between the two seismic maps of Galanopoulos (1968) and Comninakis (1975) shows contradictory results for the area of the north Aegean, because the first map was compiled before the strong activity in the north Aegean during 1965-1967. On the other hand, any uncertainty or significant revision in magnitude produces a related uncertainty in, or requires a recalculation of, the seismic risk parameters.

The new earthquake catalogue for Greece is used in this chapter to evaluate Greek seismic risk in terms of magnitude, by using both the energy release and third type asymptotic distribution methods. The results are presented in the form of contour maps of annual and 80-year most probable maximum magnitudes, and magnitudes with 70% probability of not being exceeded in the next 50 and 100 years. Risk calculations are then made in terms of acceleration using an "average formula" for acceleration attenuation which is derived from most of the commonly used formulae. An attempt to apply the third asymptotic distribution method to the annual maximum observed accelerations, results in poor convergence with values of $\lambda \to 0.0$, which shows that this asymptotic curve tends to the first type asymptotic distribution. Thus the risk in terms of acceleration is computed using the first type asymptotic distribution only, and contour maps of acceleration with 70% probability of not being exceeded in the next 50, 100, and 200 years, illustrate the results.

Seismic risk for six of the heavily industrial and highly populated centres of Greece is examined in more detail.

7.2 Data, and cities for seismic risk estimation

The new earthquake catalogue of Appendix B is used for the seismic risk evaluation of Greece as a whole and for the six following cities of Greece:

Athens	:	37.97°N, 23.72°E
Thessaloniki	:	40.64°N, 22.93°E
Patra	:	38.23°N, 21.75°E
Corinth	:	37.92°N, 22.93°E
Heraklion	:	35.35°N, 25.18°E
Rodos	:	36.43°N, 28.27°E

For each of these cities the distribution of shallow plus intermediate earthquakes for a radius of 100 km and 150 km from their centres, is taken and analysed, with both energy release and Extreme-Value methods. These radii are chosen in order to obtain estimates of the seismic risk more applicable to normal and tall structures. Normal size buildings are mainly subject to the seismic risk associated with strong local earthquakes with high frequency seismic waves (N $\geqslant$ 3c/sec), whereas tall buildings with longer resonant periods can be seriously affected by more distant earthquakes.

7.3 Seismic risk based on the magnitude distribution

Table 7-1 tabulates the three parameters of the third type asymptotic distribution, along with their uncertainties and the reduced chi-square. These parameters are calculated using annual extreme magnitudes and the method described in Chapter IV. The column "missing years" contains the number of years without reported earthquakes.

The results for M_1, M_2 and M_3 using the method of energy release, which is described in Chapter III, and the comparable quantities derived from the parameters of Table 7-1 using the equations (4-21) and (4-41) are tabulated in Table 7-2. Figures 7-1a to 7-7d illustrate both methods.

7.3.1 Comparison of the methods applied

The first feature to note from Tables 7-1 and 7-2 is the close relation between the results of the two different methods. In places in which the cumulative energy release graphs include at least one well defined cycle of periodicity, as in Figures 7-2a and 7-2 c (Athens for 100 km and 150 km radii), Figures 7-5a and 7-5c (Corinth), Figure 7-4a (Patra for 100 km radius), the parameters of the third type asymptotic distribution are well defined, and they have small uncertainties. In places where it is not clear if the periodic cycle is completed, as in Figures 7-3a and 7-3c (Thessaloniki) and Figure 7-7a (Rodos for 100 km radius), the parameters are accompanied by larger uncertainties.

A second feature is that in almost all cases the magnitude distribution has a remarkably good third type asymptotic behaviour. This is apparent from the figures of the third type asymptotic curves and the observed data

Table 7-1

Estimated parameters of the third type asymptote

Place	ω	σ_ω	u	σ_u	λ	σ_λ	Reduced chi-square	Missing years
Athens (100)	6.80	±0.39	2.98	±0.52	0.595	±0.193	0.027	47
Athens (150)	7.35	±0.58	4.19	±0.21	0.402	±0.151	0.042	38
Thessaloniki (100)	8.19	±1.17	2.39	±0.77	0.363	±0.169	0.232	58
Thessaloniki (150)	8.57	±0.83	3.58	±0.30	0.346	±0.119	0.159	45
Patra (100)	6.69	±0.46	4.12	±0.26	0.504	±0.206	0.035	40
Patra (150)	8.23	±0.99	5.12	±0.07	0.238	±0.111	0.039	21
Corinth (100)	6.75	±0.32	3.66	±0.41	0.671	±0.220	0.046	43
Corinth (150)	7.15	±0.44	4.68	±0.11	0.432	±0.147	0.074	29
Heraklion (100)	7.86	±1.17	3.73	±0.32	0.291	±0.158	0.128	46
Heraklion (150)	8.93	±1.97	4.87	±0.09	0.176	±0.117	0.046	27
Rodos (100)	9.23	±3.29	3.88	±0.31	0.170	±0.158	0.146	48
Rodos (150)	9.39	±2.02	4.53	±0.12	0.176	±0.062	0.046	38
Greece	8.73	±0.65	6.21	±0.04	0.236	±0.073	0.023	0

Table 7-2

Estimated parameters of the energy release method. X_1, X_2 and ω are from equations (4-21), (4-41) and Table 7-1.

Place	M_1	X_1	M_2	X_2	M_3	ω	Waiting time (years)
Athens (100)	4.2 ±.1	4.5 ±.1	5.7 ±.1	5.9 ±.1	6.7 ±.3	6.8 ±.4	33
Athens (150)	4.6 ±.1	4.8 ±.1	6.0 ±.1	6.1 ±.1	7.1 ±.3	7.4 ±.6	34
Thessaloniki (100)	3.7 ±.2	3.4 ±.4	6.0 ±.2	6.3 ±.2	7.3 ±.4	8.2 ±1.17	58
Thessaloniki (150)	4.3 ±.1	4.3 ±.2	6.6 ±.1	6.7 ±.2	7.9 ±.4	8.6 ±.8	61
Patra (100)	4.7 ±.1	4.9 ±.1	5.7 ±.1	5.8 ±.2	6.9 ±.3	6.7 ±.5	45
Patra (150)	5.2 ±.1	5.3 ±.1	6.3 ±.1	6.4 ±.1	7.5 ±.4	8.2 ±1.0	49
Corinth (100)	4.7 ±.1	5.2 ±.2	5.8 ±.1	6.1 ±.3	6.9 ±.3	6.8 ±.3	36
Corinth (150)	5.0 ±.1	5.3 ±.1	6.1 ±.1	6.2 ±.2	7.1 ±.3	7.2 ±.4	29
Heraklion (100)	4.3 ±.1	4.2 ±.2	5.9 ±.1	5.9 ±.2	7.1 ±.4	7.9 ±1.9	54
Heraklion (150)	5.0 ±.1	5.0 ±.1	6.3 ±.1	6.3 ±.2	7.5 ±.4	8.9 ±1.9	52
Rodos (100)	4.4 ±.1	4.1 ±.3	6.0 ±.1	6.1 ±.3	7.2 ±.4	9.2 ±3.3	64
Rodos (150)	4.8 ±.1	4.7 ±.1	6.4 ±.1	6.5 ±.2	7.5 ±.4	9.4 ±2.0	39
Greece	6.2 ±.1	6.4 ±.1	7.1 ±.1	7.2 ±.1	8.2 ±.4	8.7 ±.6	33

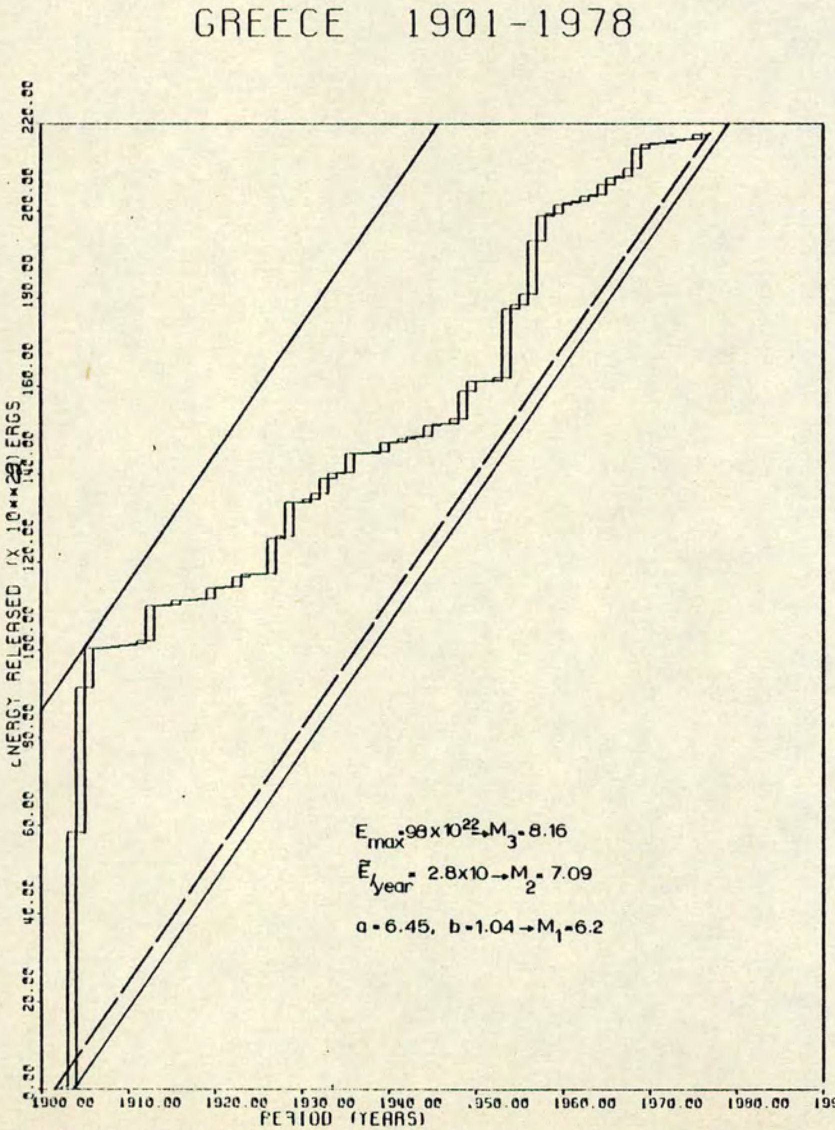


Fig 7-1a Cumulative energy release as a function of time for Greece (1901-1978).

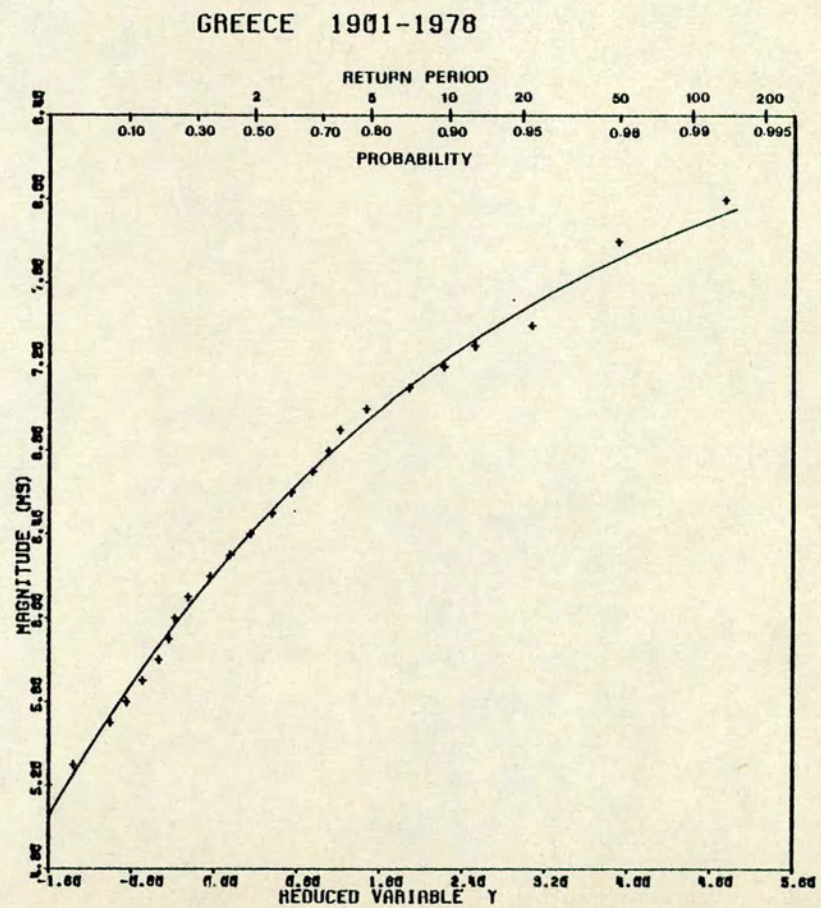


Fig 7-1b Third type asymptotic distribution curve for Greece (1901-1978), + indicates observed annual maximum magnitude.

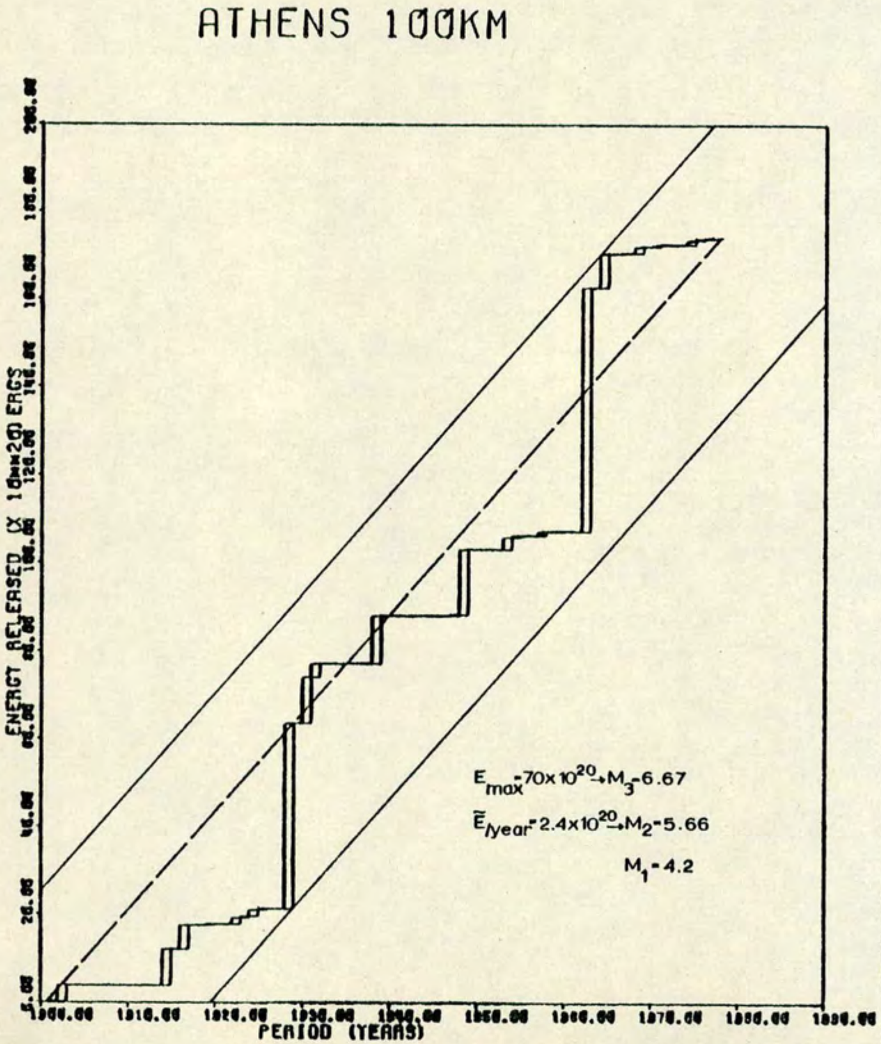


Fig 7-2a Cumulative energy release as a function of time for an area of 100km radius from the city of Athens (1901-1978).

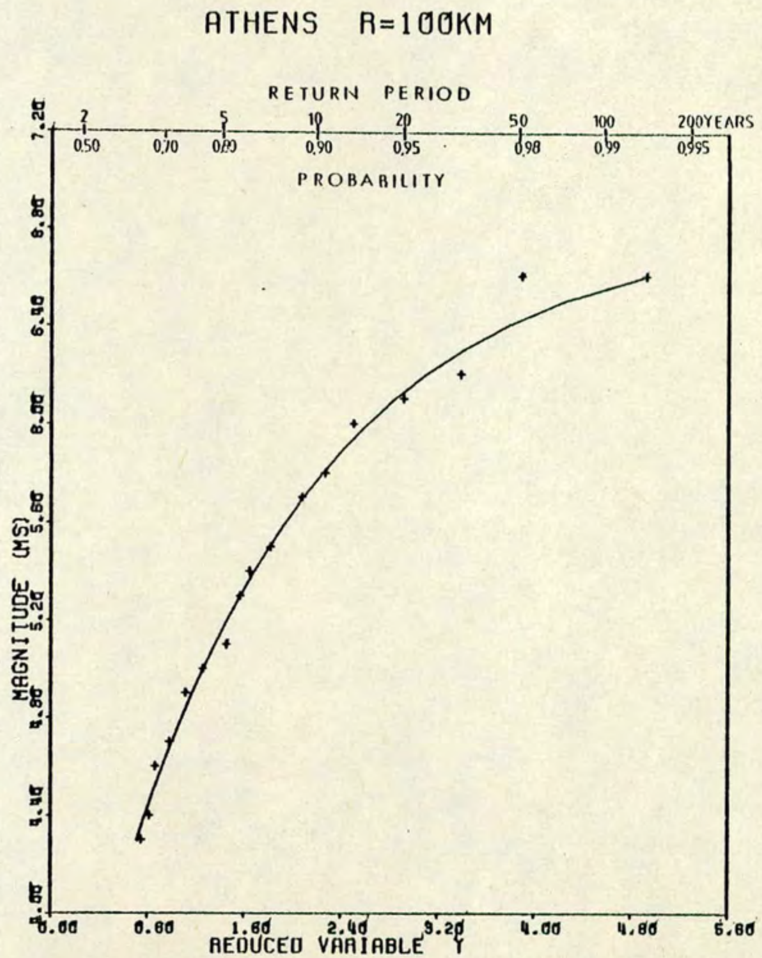


Fig 7-2b Third type asymptotic distribution curve for an area of 100km radius from the city of Athens (1901-1978).

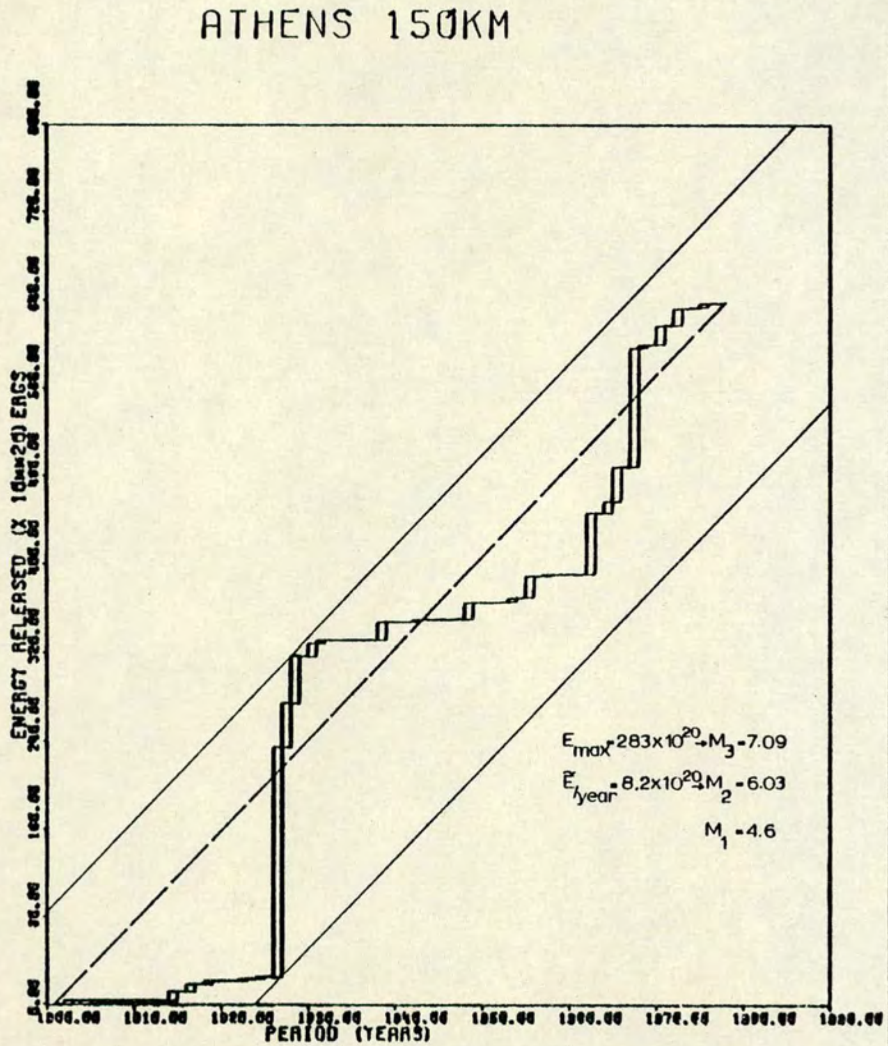


Fig 7-2c Cumulative energy release as a function of time for an area of 150km radius from the city of Athens (1901-1978).

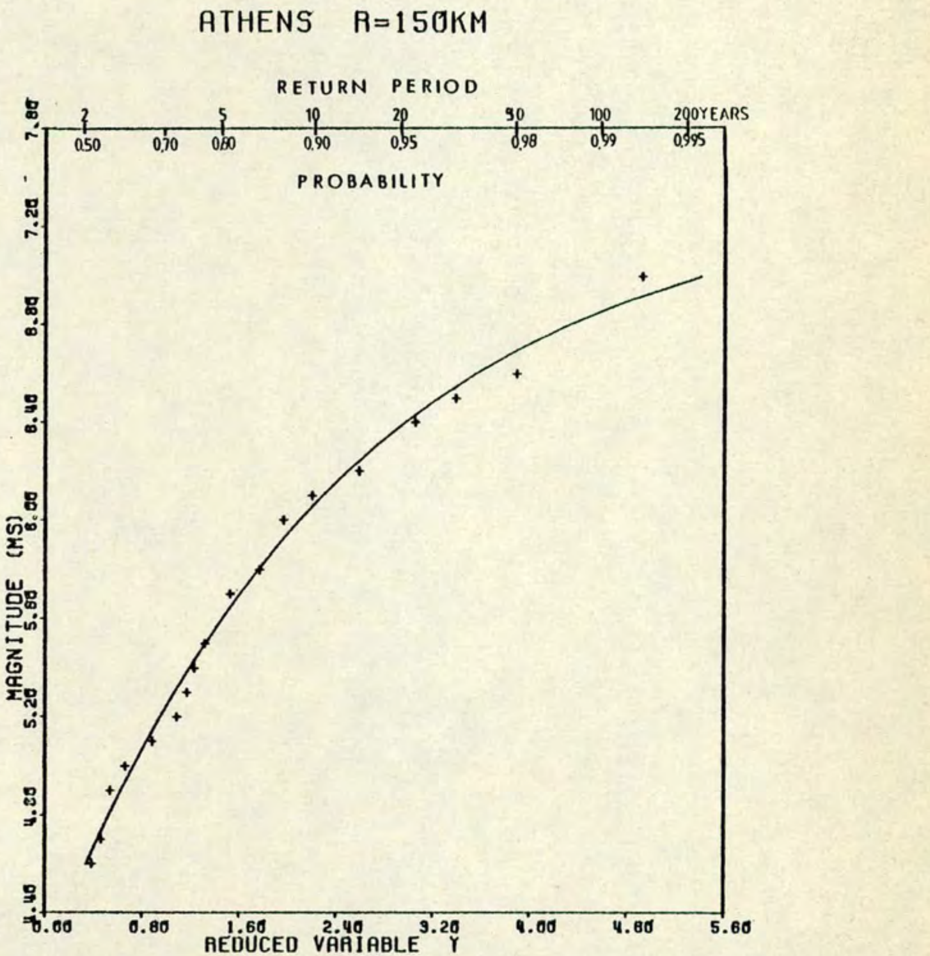


Fig 7-2d Third type asymptotic distribution curve for an area of 150km radius from the city of Athens (1901-1978).

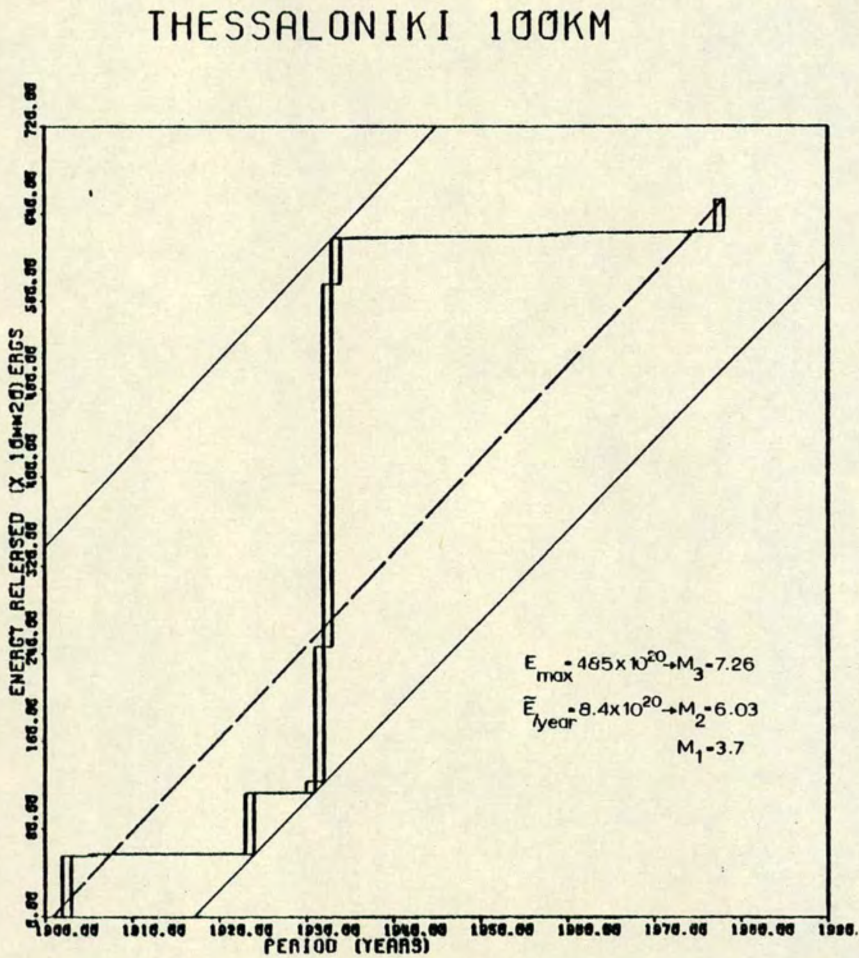


Fig 7-3a Cumulative energy release as a function of time for an area of 100km radius from the city of Thessaloniki (1901-1978).

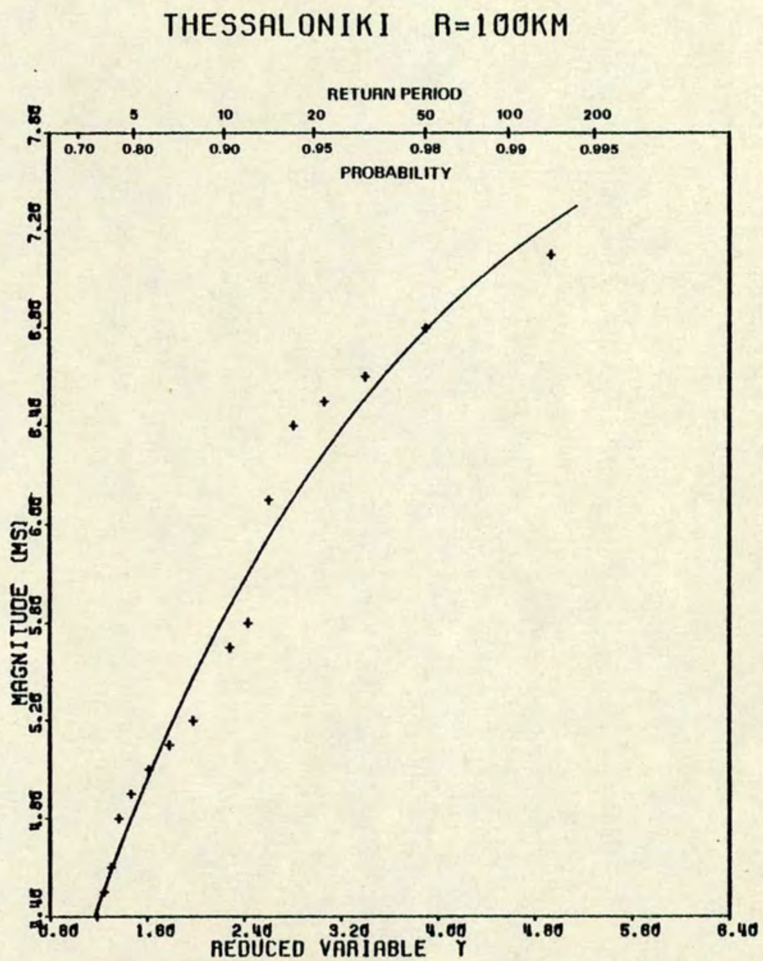


Fig 7-3b Third type asymptotic distribution curve for an area of 100km radius from the city of Thessaloniki (1901-1978).

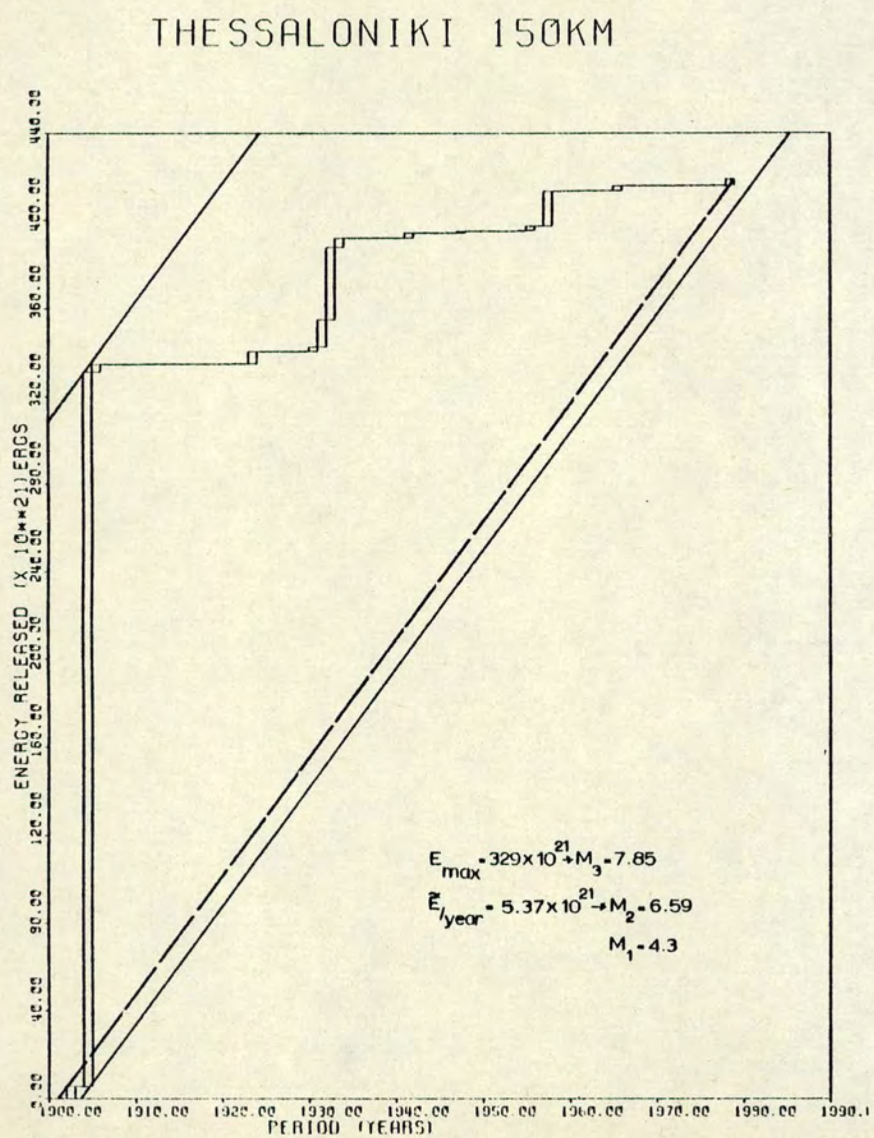


Fig 7-3c Cumulative energy release as a function of time for an area of 150km radius from the city of Thessaloniki (1901-1978).

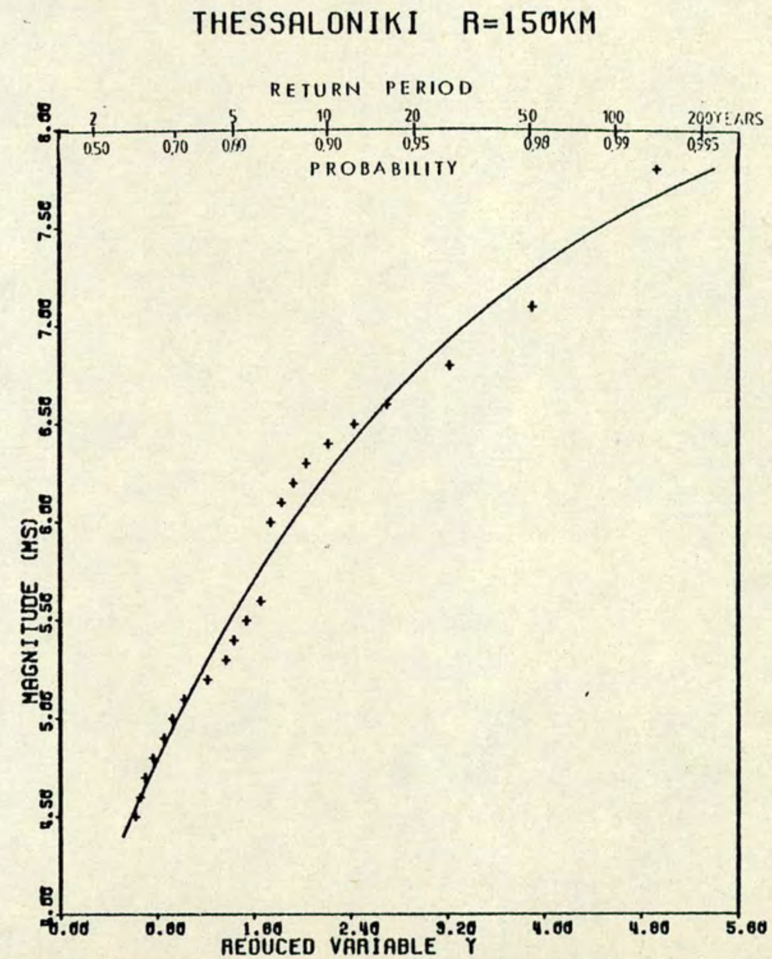


Fig 7-3d Third type asymptotic distribution curve for an area of 150km radius from the city of Thessaloniki (1901-1978).

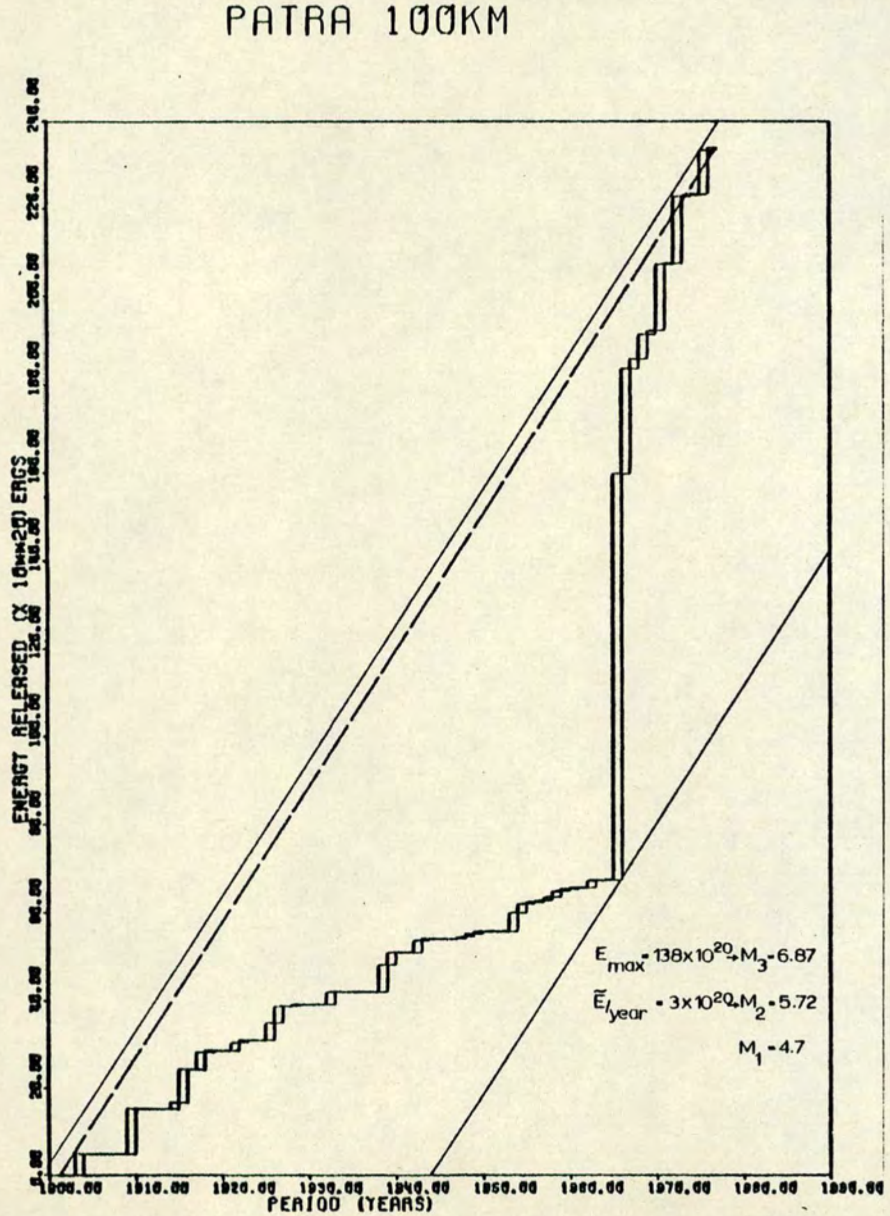


Fig 7-4a Cumulative energy release as a function of time for an area of 100km radius from the city of Patra (1901-1978)

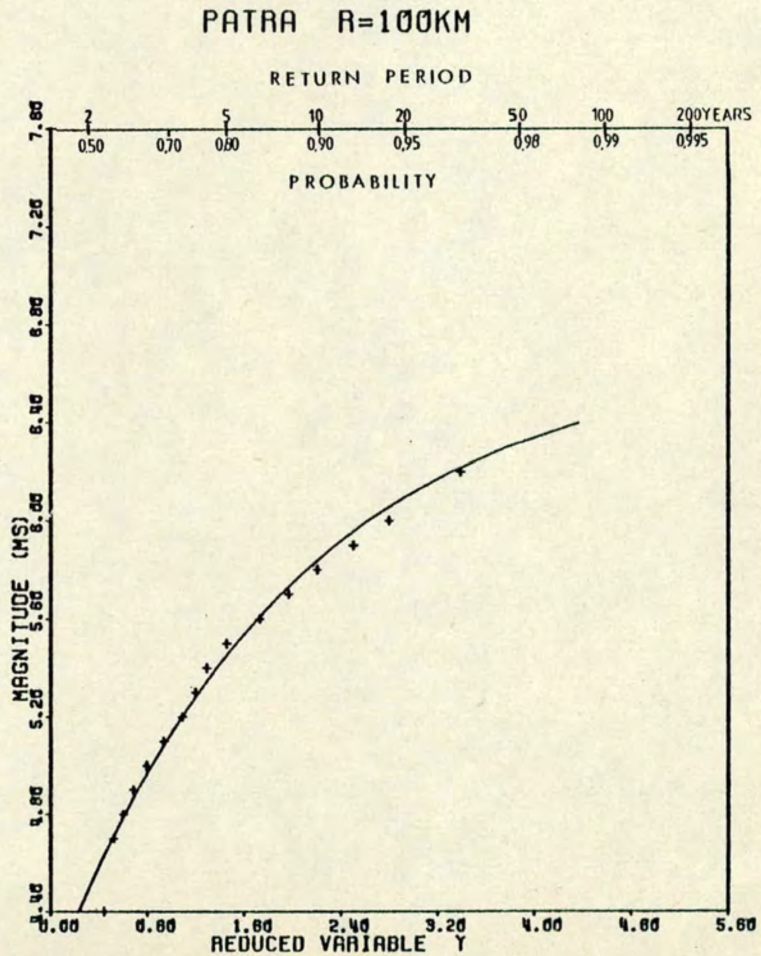


Fig 7-4b Third type asymptotic distribution curve for an area of 100km radius from the city of Patra (1901-1978).

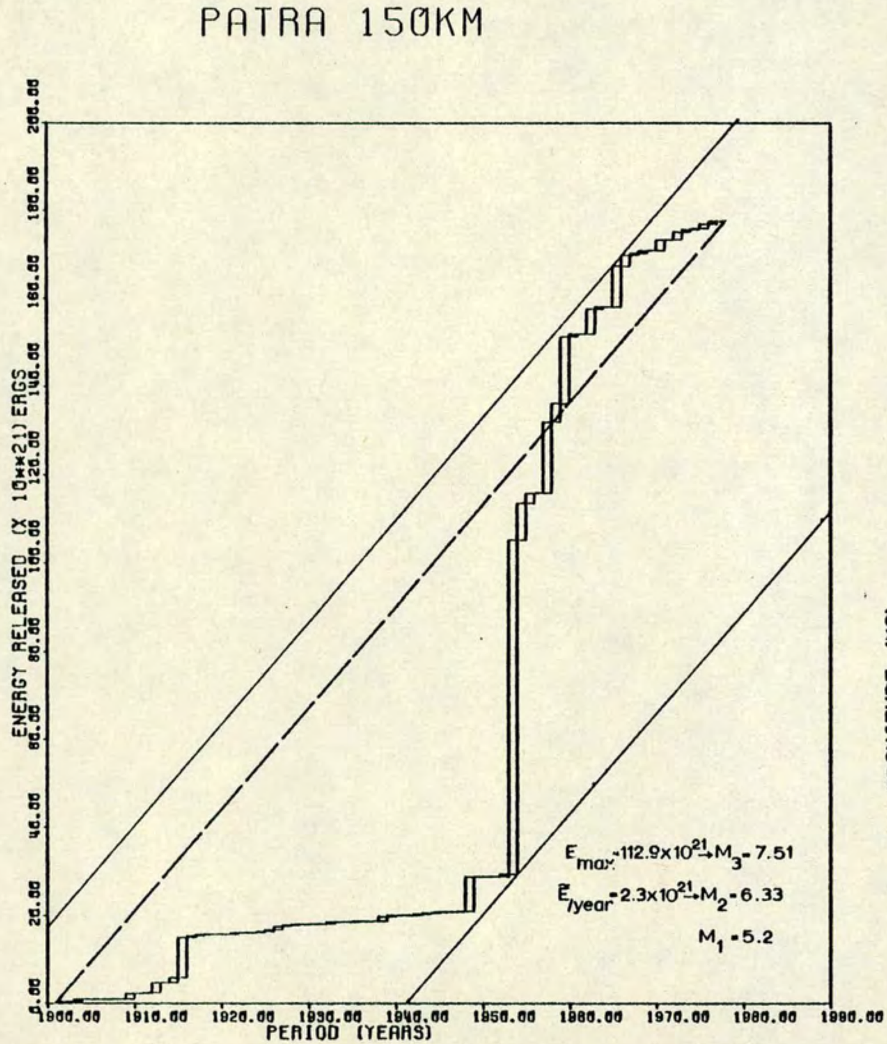


Fig 7-4c Cumulative energy release as a function of time for an area of 150km radius from the city of Patra (1901-1978).

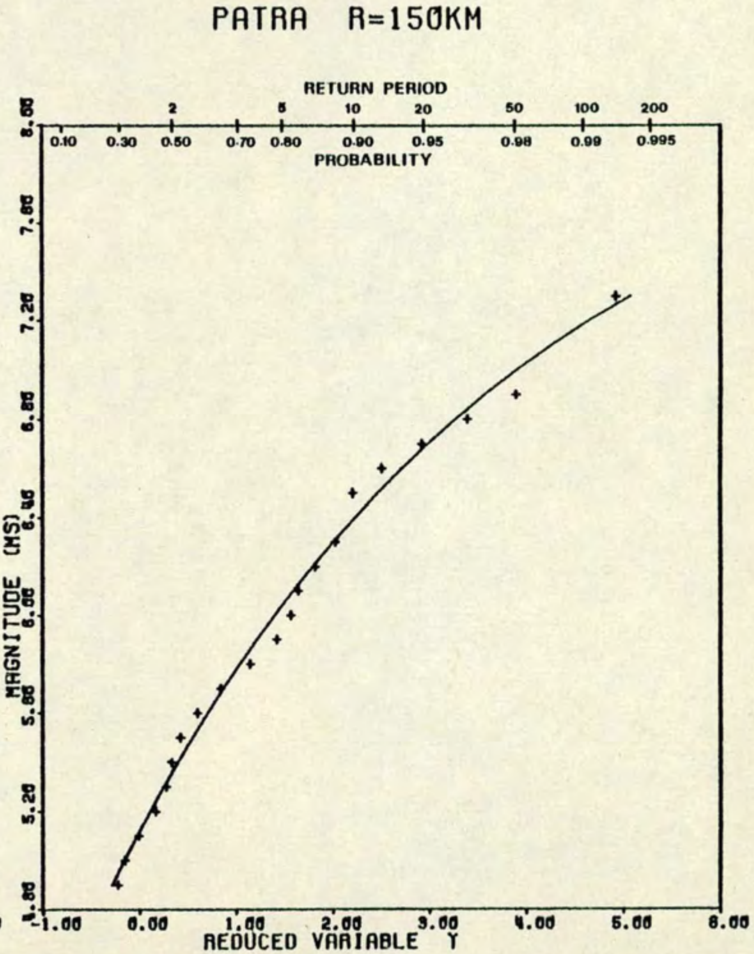


Fig 7-4d Third type asymptotic distribution curve for an area of 150km radius from the city of Patra (1901-1978).

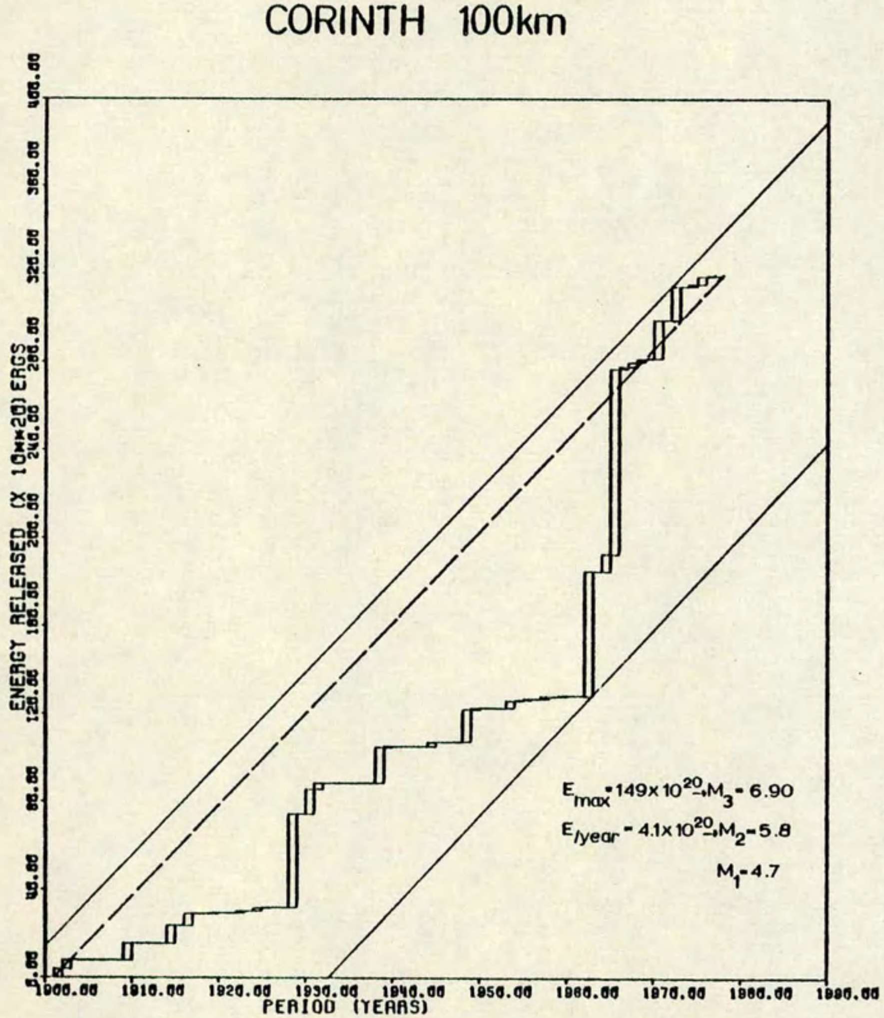


Fig 7-5a Cumulative energy release as a function of time for an area of 100km radius from the city of Corinth (1901-1978).

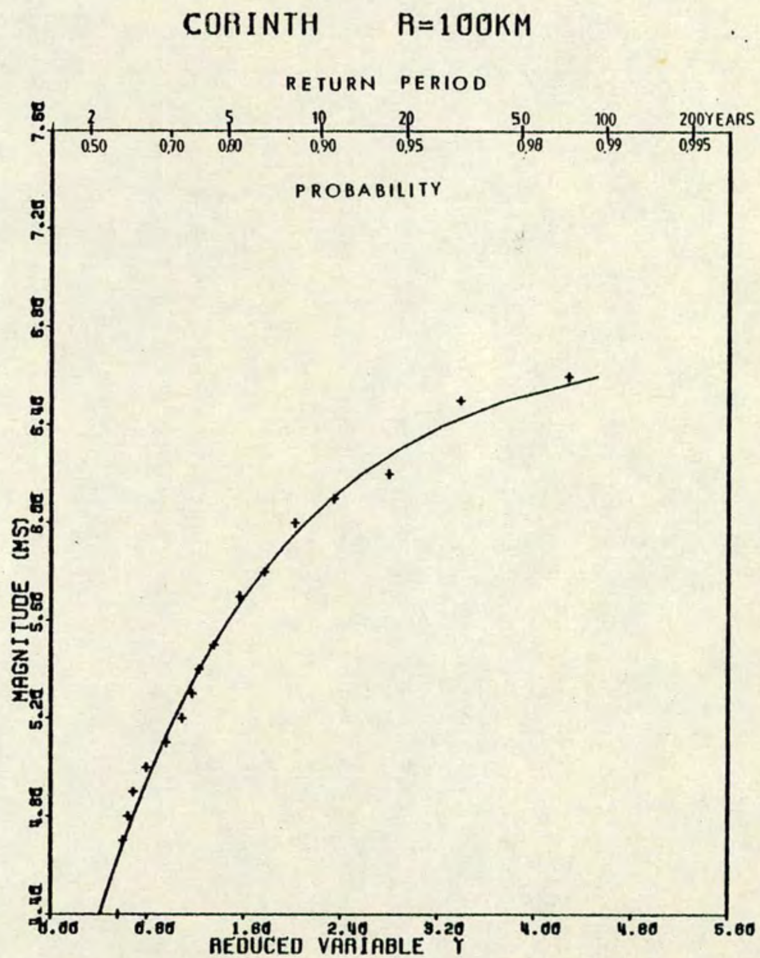


Fig 7-5b Third type asymptotic distribution curve for an area of 100km radius from the city of Corinth (1901-1978).

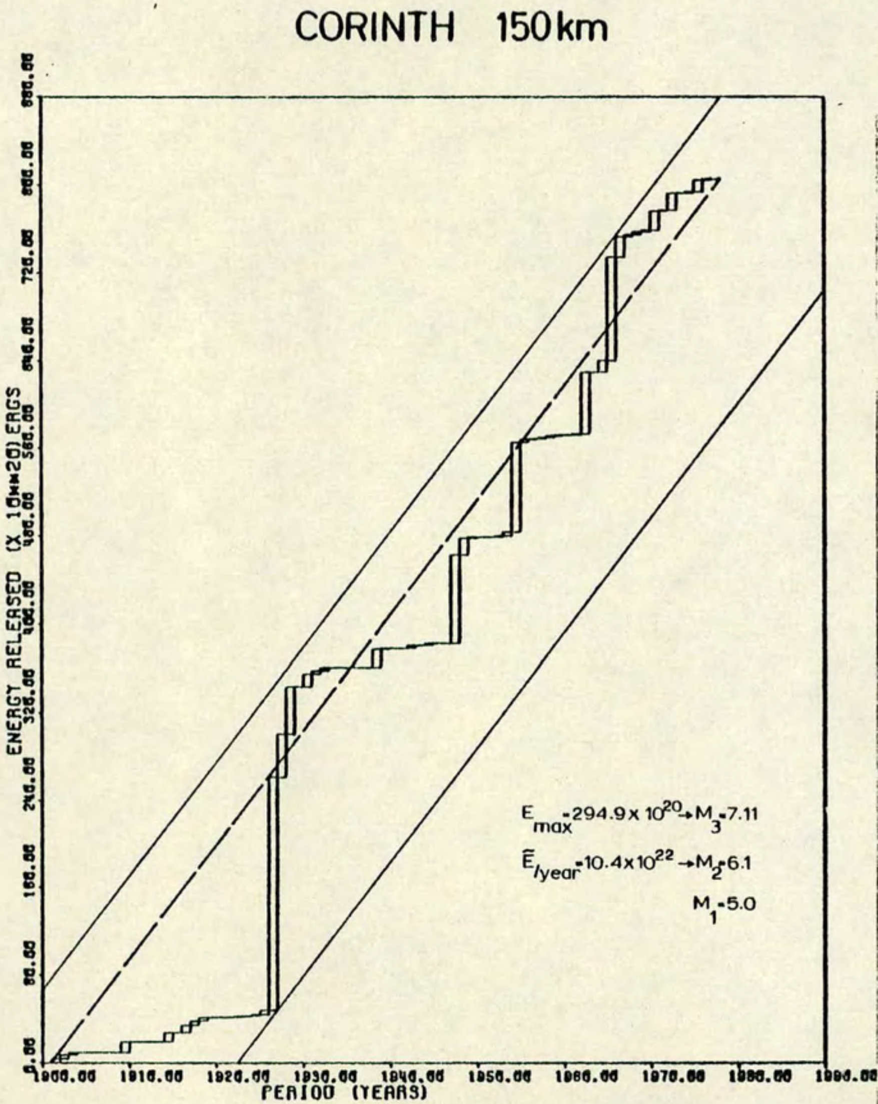


Fig 7-5c Cumulative energy release as a function of time for an area of 150km radius from the city of Corinth (1901-1978).

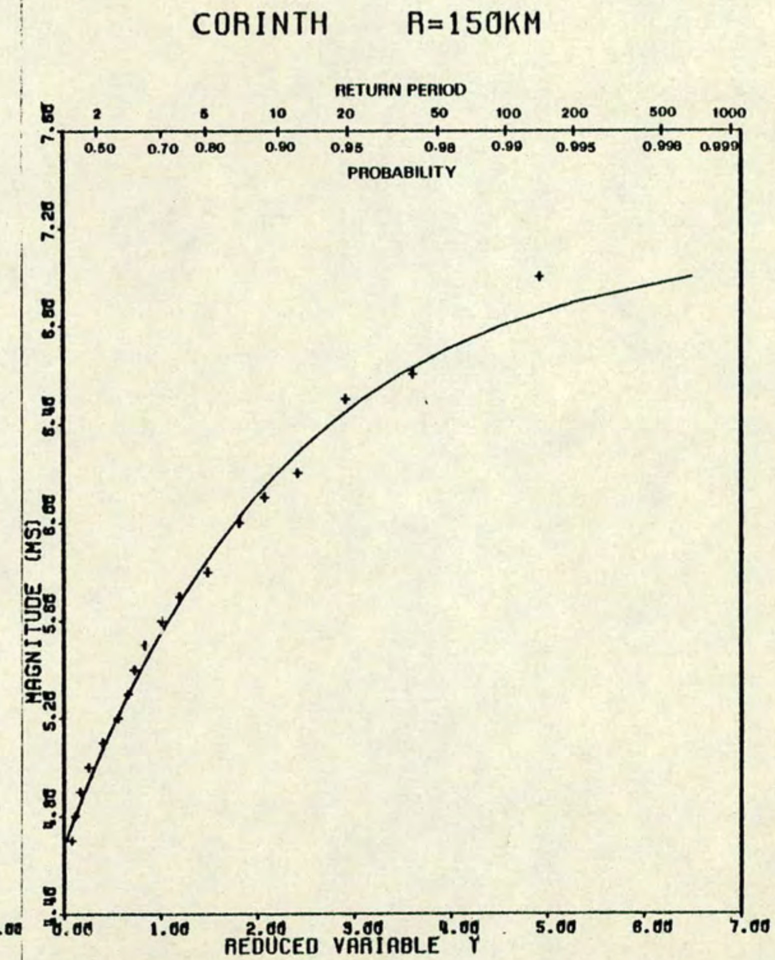


Fig 7-5d Third type asymptotic distribution curve for an area of 150km radius from the city of Corinth (1901-1978).

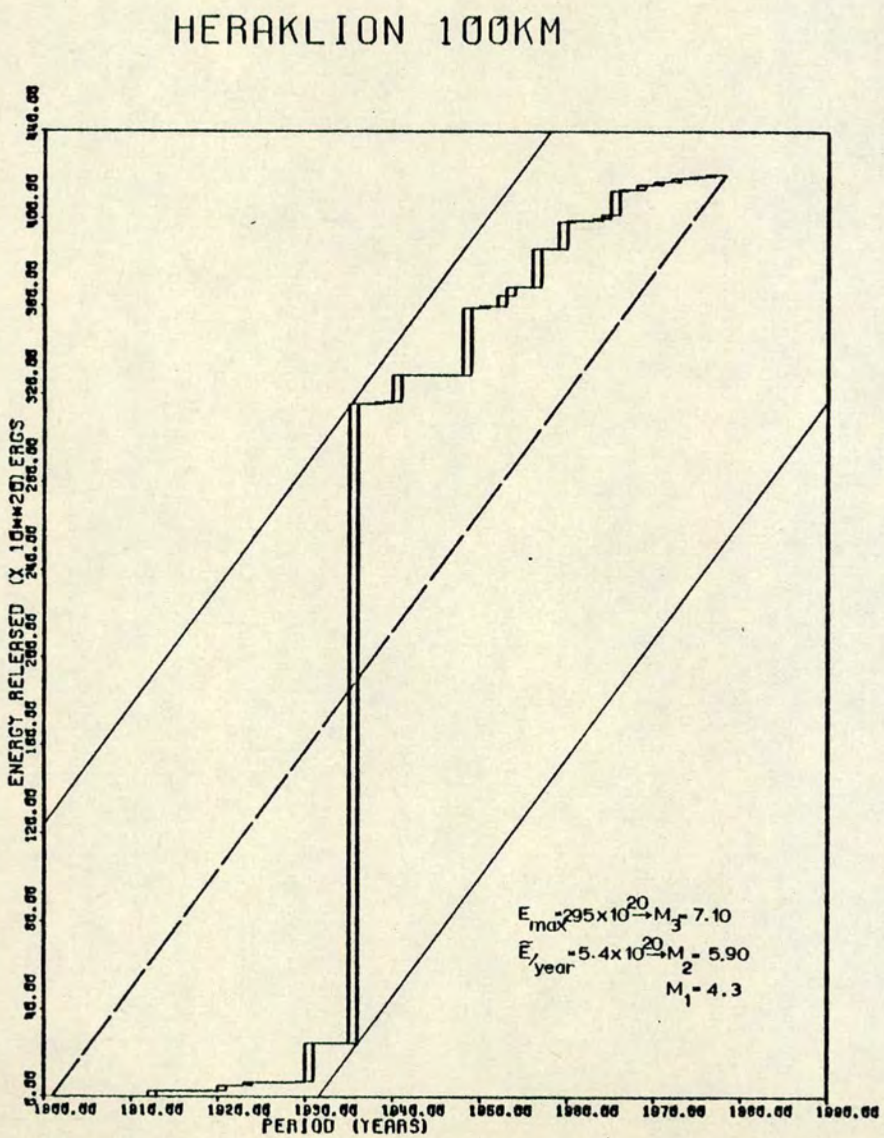


Fig 7-6a Cumulative energy release as a function of time for an area of 100km radius from the city of Heraklion (1901-1978).

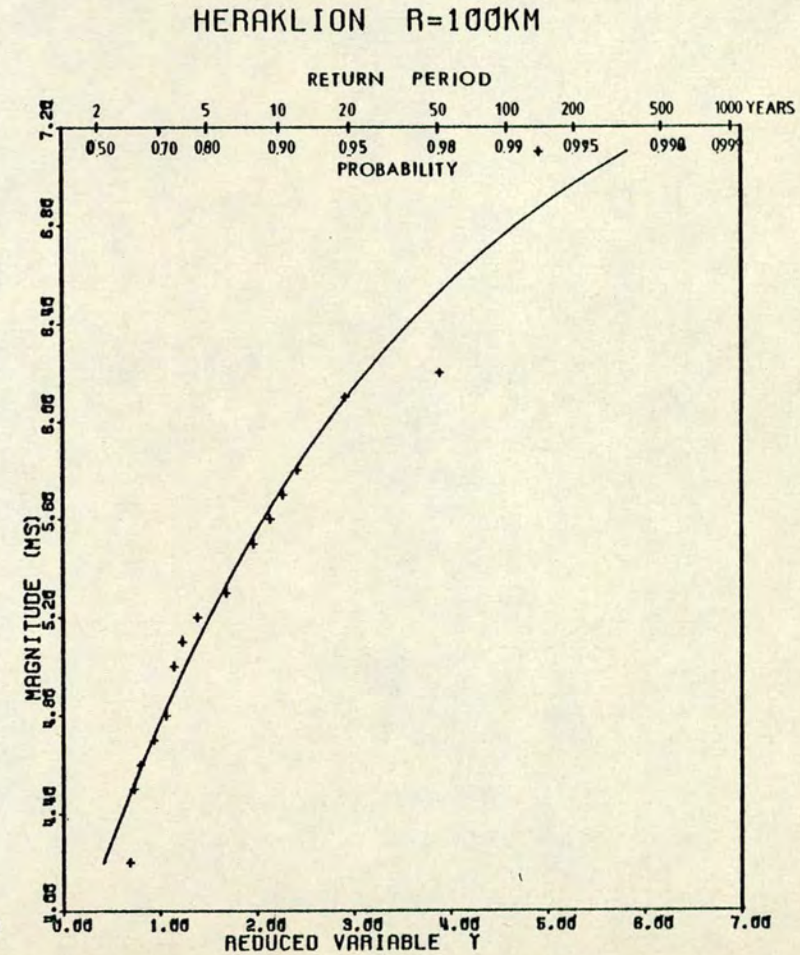


Fig 7-6b Third type asymptotic distribution curve for an area of 100km radius from the city of Heraklion (1901-1978).

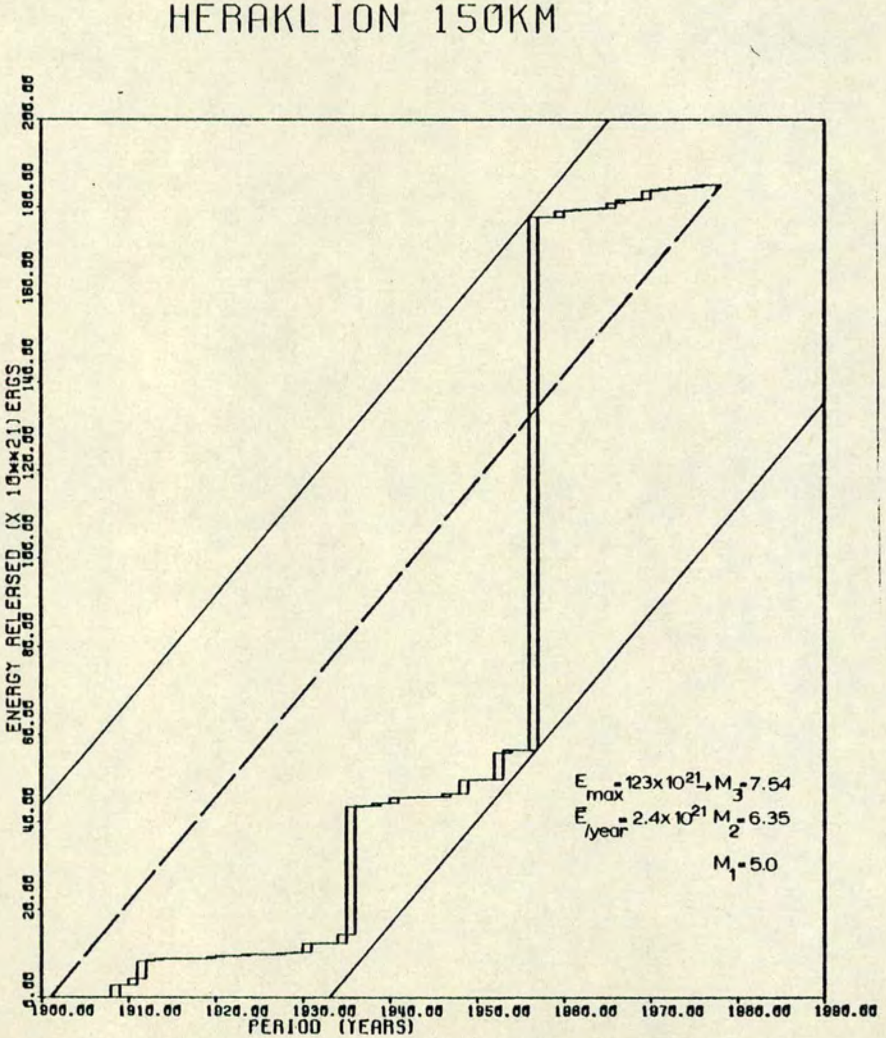


Fig 7-6c Cumulative energy release as a function of time for an area of 150km radius from the city of Heraklion (1901-1978).

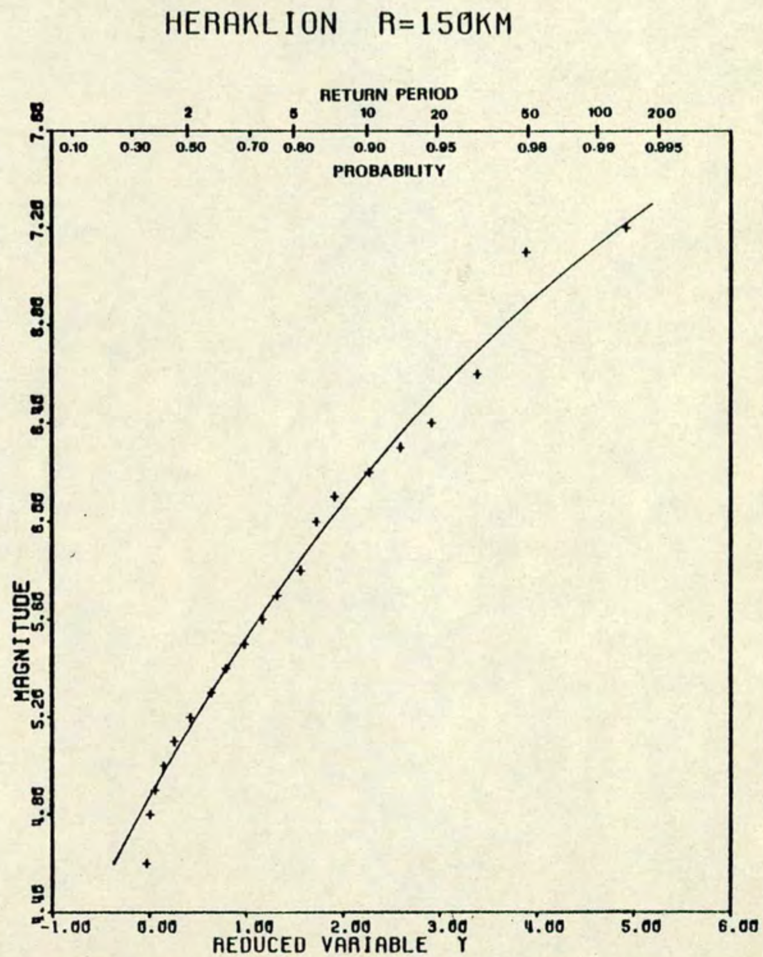


Fig 7-6d Third type asymptotic distribution curve for an area of 150km radius from the city of Heraklion (1901-1978).

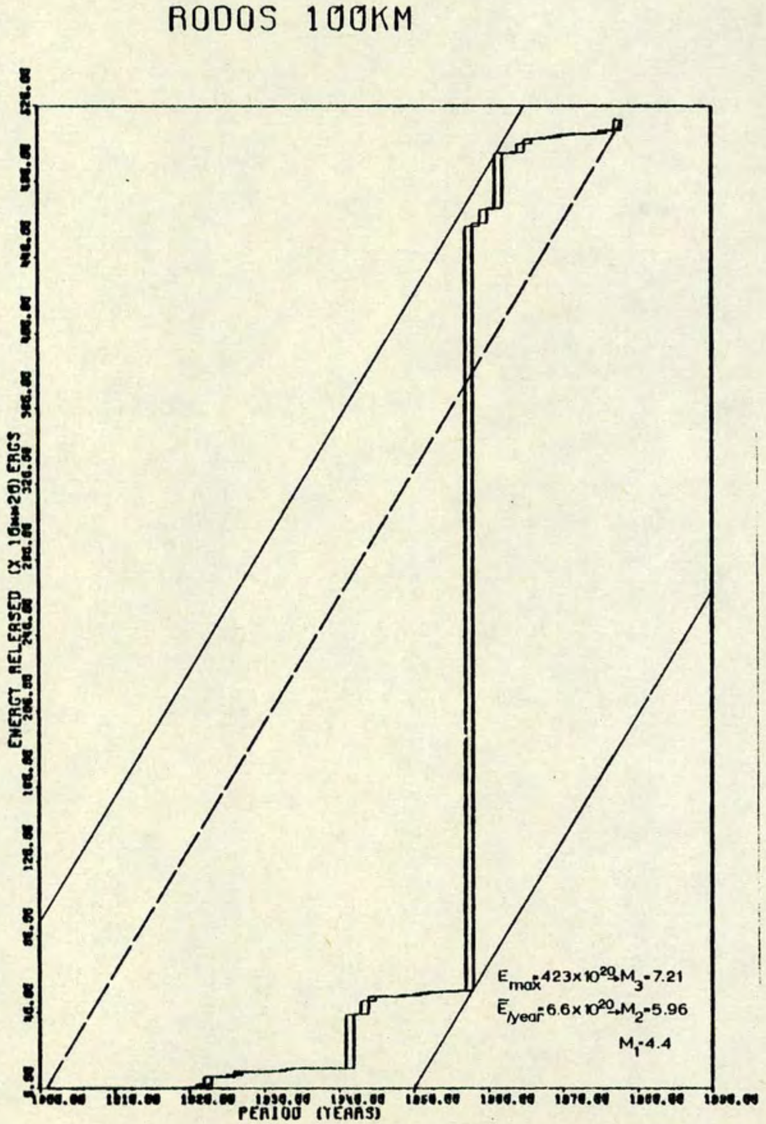


Fig 7-7a Cumulative energy release as a function of time for an area of 100km radius from the city of Rodos (1901-1978).

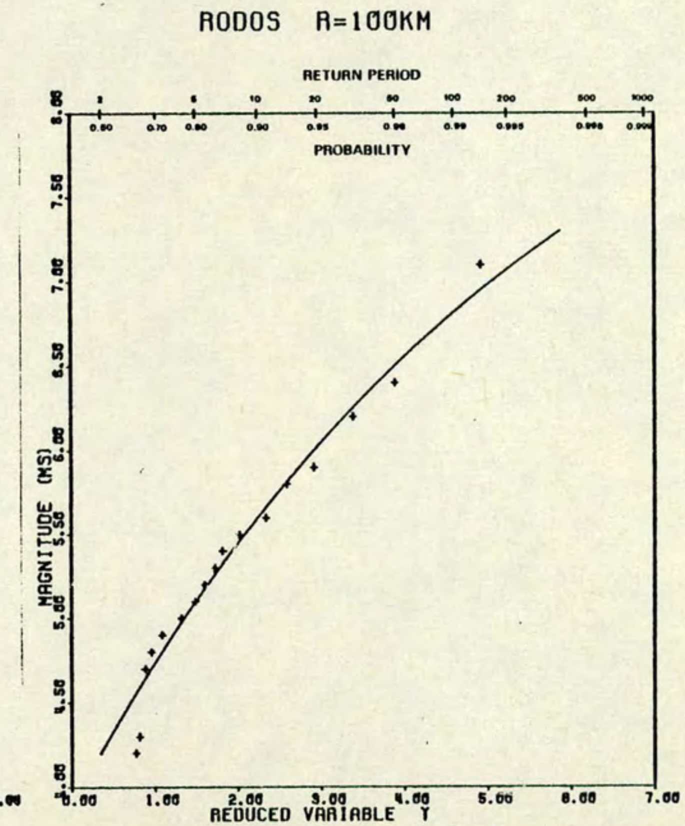


Fig 7-7b Third type asymptotic distribution curve for an area of 100km radius from the city of Rodos (1901-1978).

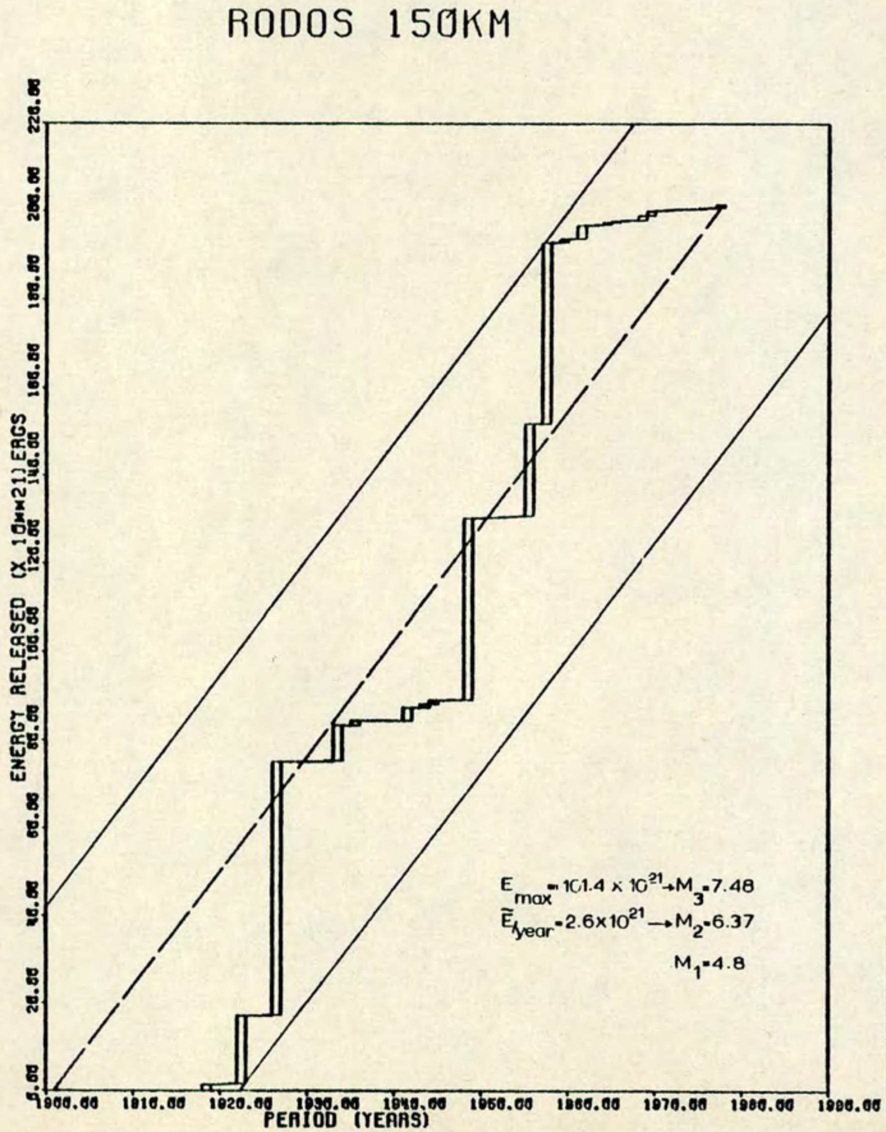


Fig 7-7c Cumulative energy release as a function of time for an area of 150km radius from the city of Rodos (1901-1978).

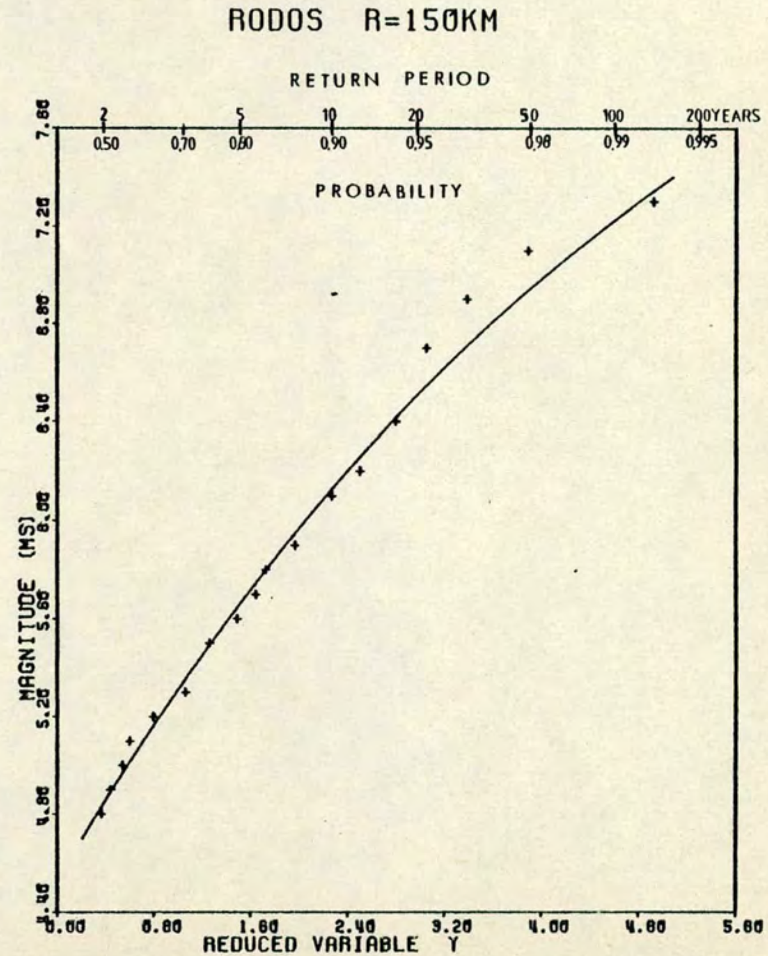


Fig 7-7d Third type asymptotic distribution curve for an area of 150km radius from the city of Rodos (1901-1978).

points in Figures 7-2 to 7-7, as well as from the small values of chi-square (Table 7-1).

From Table 7-1 and Figures 7-3b and 7-3d, it can be seen that Thessaloniki has the largest chi-square values and poorest fit for both 100 km and 150 km radii. The distribution of the observed data points, however, may suggest that this is caused by the superposition of two natural populations of earthquakes, as in Figure 4-3a and 4-3b for the Aleutians and Alaska region. In fact, the area around Thessaloniki, in the north Aegean area, is tectonically much more debated than any other part of Greece (see paragraph 6.3).

7.3.2 Seismic risk evaluation - magnitude

From the parameters of the third type asymptotic distribution, the return period in years for earthquake magnitudes m = 5.0 to m = 8.0, with a step of $\Delta m = 0.5$, are calculated and listed in Table 7-3. The uncertainties can be computed from equation (4-1) using the formula

$$\sigma^2\phi = \sigma^2\omega\left(\frac{\partial\phi}{\partial\omega}\right)^2 + \sigma^2 u\left(\frac{\partial\phi}{\partial u}\right) + \sigma^2\lambda\left(\frac{\partial\phi}{\partial\lambda}\right)^2 + 2\sigma^2\omega u\left(\frac{\partial\phi}{\partial\omega}\right)\left(\frac{\partial\phi}{\partial u}\right) + \dots \qquad (7\text{-}1)$$

and the complete variance-covariance matrix (4-14) for the parameters at each place. Then, the uncertainties for the different return periods for the given place can be derived from equation (2-19).

Tables 7-4 and 7-5 tabulate the number of exceedances during the next 50 and 100 years for each of the magnitudes previously listed in Table 7-3. The results for Greece and the city of Athens are discussed here in detail, whereas, the values of all parameters for the remaining five places are also tabulated in the same tables and plotted as for the special cases of Greece and the city of Athens.

a) Greece

For the area of Greece the upper bound for earthquake magnitudes

Table 7-3

Return period (years) for given magnitudes (M_s)

Place \ M_s	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Athens (100)	4.1	6.6	14.3	71.1	-	-	-
Athens (150)	2.6	4.3	8.7	26.0	222.9	-	-
Thessaloniki (100)	5.7	8.7	15.0	30.0	77.8	343.6	-
Thessaloniki (150)	3.2	4.6	7.3	13.2	28.8	86.2	530.6
Patra (100)	2.8	5.2	14.3	184.1	-	-	-
Patra (150)	1.4	2.3	4.6	12.3	49.8	442.2	-
Corinth (100)	2.9	4.4	8.7	42.9	-	-	-
Corinth (150)	1.9	3.1	6.4	22.5	654.0	-	-
Heraklion (100)	4.1	7.4	16.0	46.1	222.2	-	-
Heraklion (150)	1.8	3.2	6.9	19.1	69.3	378.8	-
Rodos (100)	4.4	8.6	18.9	49.3	156.4	664.3	-
Rodos (150)	2.6	4.1	8.3	19.8	57.3	216.1	-
Greece	1.0	1.1	1.3	2.4	5.5	21.9	198.4

Table 7-4

Number of exceedances during the next
50 years v. Magnitude (M_s)

City \ M_s	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Athens (100)	12-13	7-8	3-4	0-1			
Athens (150)	19-20	11-12	5-6	1-2	-	-	-
Thessaloniki (100)	8-9	5-6	3-4	1-2	0.1	-	-
Thessaloniki (150)	15-16	10-11	6-7	3-4	1-2	0-1	-
Patra (100)	17-18	9-10	3-4	0.1	-	-	-
Patra (150)	34-35	22-22	10-11	4-5	1-2	-	-
Corinth (100)	17-18	11-12	5-6	1-2	-	-	-
Corinth (150)	25-26	16-17	7-8	2-3	-	-	-
Heraklion (100)	12-13	6-7	3-4	1-2	0-1	-	-
Heraklion (150)	28-29	15-16	7-8	2-3	0-1	-	-
Rodos (100)	11-12	5-6	2-3	1-2	-	-	-
Rodos (150)	19-20	12-13	6-7	2-3	0-1	-	-
Greece	49-50	47-48	37-38	20-21	9-10	2-3	0-1

Table 7-5

Number of exceedances during the next 100 years

v. Magnitude (M_s)

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	Maximum Observed (78 years)
Athens (100)	24-25	15-16	7-8	1-2	-	-	-	6.6
Athens (150)	38-39	23-24	11-12	3-4	0.1	-	-	7.0
Thessaloniki (100)	17-18	11-12	6-7	3-4	1-2	-	-	7.1
Thessaloniki (150)	31-32	21-22	13-14	7-8	3-4	0-1	0-1	7.8
Petra (100)	35-36	19-20	7-8	0-1	-	-	-	6.6
Petra (150)	68-69	43-44	21-22	8-9	2-3	0-1	-	7.3
Corinth (100)	34-35	22-23	11-12	2-3	-	-	-	6.6
Corinth (150)	51-52	32-33	15-16	4-5	0.1	-	-	7.0
Heraklion (100)	24-25	13-14	6-7	2-3	0.1	-	-	7.1
Heraklion (150)	56-57	31-32	14-15	5-6	1-2	0.1	-	7.2
Rodos (100)	22-23	11-12	5-6	2-3	0-1	-	-	7.1
Rodos (150)	38-39	24-25	12-13	5-6	1-2	0-1	-	7.3
Greece	99-100	94-95	75-76	40-41	18-19	4-5	0-1	8.0

is found to be

$$8.16 \pm 0.43 \text{ or } 8.73 \pm 0.65$$

for the energy release and third type asymptotic distribution methods respectively. During the 78 years of instrumental data the maximum earthquake magnitude had a value of 8.0 (11.8.1903). Galanopoulos (1972a) using the graphical method for strain energy release (see Fig 3-10) estimated the upper bound and found a value of m = 8½. Considering the seismic history of the area (Galanopoulos, 1960, 1961; Richter, 1958; Lomnitz, 1974) the value of m = 8.73 ± 0.65 as an upper bound for surface-wave magnitude is acceptable. The "waiting time" (see paragraph 3.2.2) for an earthquake equal to the upper bound is 33 years (Fig 7-1a).

The most probable annual maximum (mode) is m = 6.4 ± 0.1. Galanopoulos (1972a) and Comninakis (1975), using the frequency-magnitude law, estimated the mode as 6.5 and 6.4 respectively.

The annual rate of energy release corresponds to an earthquake with magnitude m = 7.2 ± 0.1 (Table 7-2 and Figure 7-1a).

Table 7-3 shows that in Greece an earthquake with magnitude greater than or equal to 5.5 is expected to be the annual maximum magnitude almost every year (return period = 1.06 years). The period required for an earthquake with magnitude greater than or equal to 7.0 to be observed as an annual maximum is 5.5 years, whereas an interval of about 200 years is needed for an earthquake with magnitude greater than or equal to the largest observed in the region (11.8.1903, m = 8.0) to be an annual extreme magnitude. However, the return period for an earthquake with magnitude 7.5 is only 22 years.

Table 7-6 contains the number of exceedances of given maximum magnitude earthquakes which is predicted for Greece, along with the number observed, during the 78 year sample period. This shows that for both low

Table 7-6

Predicted and Observed number of exceedances

Magn m ⩾	Greece			Athens (R = 100km)			Athens (R = 150km)		
	No of exceedances			No of exceedances			No of exceedances		
	Predicted		Observed	Predicted		Observed	Predicted		Observed
	50 years	100 years	78 years	50 years	100 years	78 years	50 years	100 years	78 years
5.0	49-50	99-100	78	11-14	24-25	22	19-20	38-39	36
5.5	47-48	94-95	76	7-8	15-16	12	11-12	23-24	24
6.0	37-38	75-76	63	3-4	7-8	6	5-6	11-12	14
6.5	20-21	40-41	36	0-1	1-2	2	1-2	3-4	4
7.0	9-10	18-19	19	-	-	-	-	0-1	1
7.5	2-3	4-5	5	-	-	-	-	-	-
8.0	0.1	0-1	1	-	-	-	-	-	-

and high magnitudes the predicted numbers agree with the maximum magnitudes observed. The close agreement between observed and predicted extreme magnitudes not only illustrates the plausibility of the method, but also shows that the sample period considered is long enough for stable estimates.

b) Athens (37.97°N, 23.72°E)

For the city of Athens the upper bound for earthquake magnitude has the value of

$$m = 6.80 \pm 0.39 \text{ (100 km) or } m = 7.35 \pm 0.58 \text{ (150 km)}$$

The "waiting times" for these magnitudes are 33 and 34 years respectively (Fig 7-2a and 7-2c). During the 78 year sample period the maximum observed earthquake magnitudes were 6.6 (28.08.1962) and 7.0 (30.08.1926) within a distance of 100 km and 150 km from Athens. The most probable annual maximum magnitude within the same distance is: 4.5 ± 0.1 and 4.8 ± 0.1 respectively. The mean annual rates of energy release correspond to earthquakes with magnitudes 5.7 ± 0.1 and 6.0 ± 0.1. The same quantities from the third type asymptotic distribution analysis have the values of 5.9 ± 0.1 and 6.0 ± 0.1. From Table 7-6 it can be seen that for both radii there is also a remarkably good agreement between predicted and observed number of exceedances over the whole range of magnitude.

However, the example of Athens has its own unusual significance. It shows that although the number of missing years is greater than the number of observed extremes, the assumption that the first observed extreme is ranked as j + 1, assuming the first j of the N observations are not available (see paragraph 4.5.2 (a)), leads to realistic results from the third type asymptotic distribution method.

7.4 Seismic risk based on peak acceleration of ground motion

7.4.1 Choosing the acceleration-distance formula

Since 1964 when Esteva and Rosenblueth proposed a general formula (2-15) for ground motion, most of the existing formulae are modifications of (2-15) rather than different models of the changes of the characteristics of earthquake ground motion with distance. The main reason for this is a lack of large numbers of strong motion records necessary for regional studies.

Table 7-7 tabulates some of the best known attenuation formulae in terms of maximum acceleration with remarks on their validity. From Figure 7-8, where these formulae are plotted for m = 7.5 and h = 10 km, it is apparent that they present a large dispersion and can not be universally accepted. Thus, for the estimation of seismic risk in terms of maximum acceleration for Greece, it is thought that an average formula derived from the relations of Table 7-7 may be a more reliable way to approach the problem. The validity of such a formula can then be evaluated by the degree of its concordance with the existing local strong motion records. From the formulae of Table 7-7 the "average formula" for maximum acceleration is found, by trial and error, to be:

$$A = 2164\, e^{0.70m} (R + 20)^{-1.80} \text{ cm/sec}^2 \qquad (7\text{-}2)$$

with uncertainties $\Delta b_2 = \pm\ 0.03$ and $\Delta b_3 = \pm\ 0.02$. This formula is also plotted in Figure 7-8. To demonstrate the validity of this formula the upper, lower and average values for the whole range of the eight curves, and for epicentral distances from 10 km to 120 km for m = 7.5 and h = 10 km, are tabulated in Table 7-8 along with the values from equation (7-2).

The next step is to check the proposed formula with observations from the existing Greek strong motion records. Since 1972, when the first accelerograph was installed in Greece, there are eight accelerograms

Table 7-7

Maximum acceleration formulae from which the "average formula" (7-2) is derived

1. $A = 1080.e^{0.5M}.(R+25)^{-1.32}$	Donovan, 1973	in cm/sec^2, more than 20 f soil overlying the rock
2. $A = 6.6 \cdot 10^{-2} \cdot 10^{0.4M_L}.R^{-1.39}$	Orphal and Lahoud, 1974	in g, hard rock. $\Delta b_2 = \pm 0.076$, $\Delta b_3 = \pm 0.063$
3. $A = 5600 \cdot e^{0.8M}.(R+40)^{-2}$	Esteva, 1974	in cm/sec^2, hard rock
4. $A = 5000 \cdot e^{0.8M}.(R+40)^{-2}$	Shah et al, 1975	in cm/sec^2, hard rock
5. $A = 1230\ e^{0.8M}(R+13)^{-2}$	Ahorner and Rosenhaur, 1975	in cm/sec^2, hard rock
6. $A = 1.03h^{0.6} \cdot 10^{0.54M} \cdot R^{-1.5}$	Båth, 1975	in cm/sec^2
7. $\log A = 2.308-1637\log(R+30)+0.411M$	Katayama, 1974	in cm/sec^2
8. $\log A_p = M+\log A(R)-\log A_o(M,s,p,v)$	Trifunac, 1976	in cm/sec^2 p: conf. level, s: type of soil, v: component

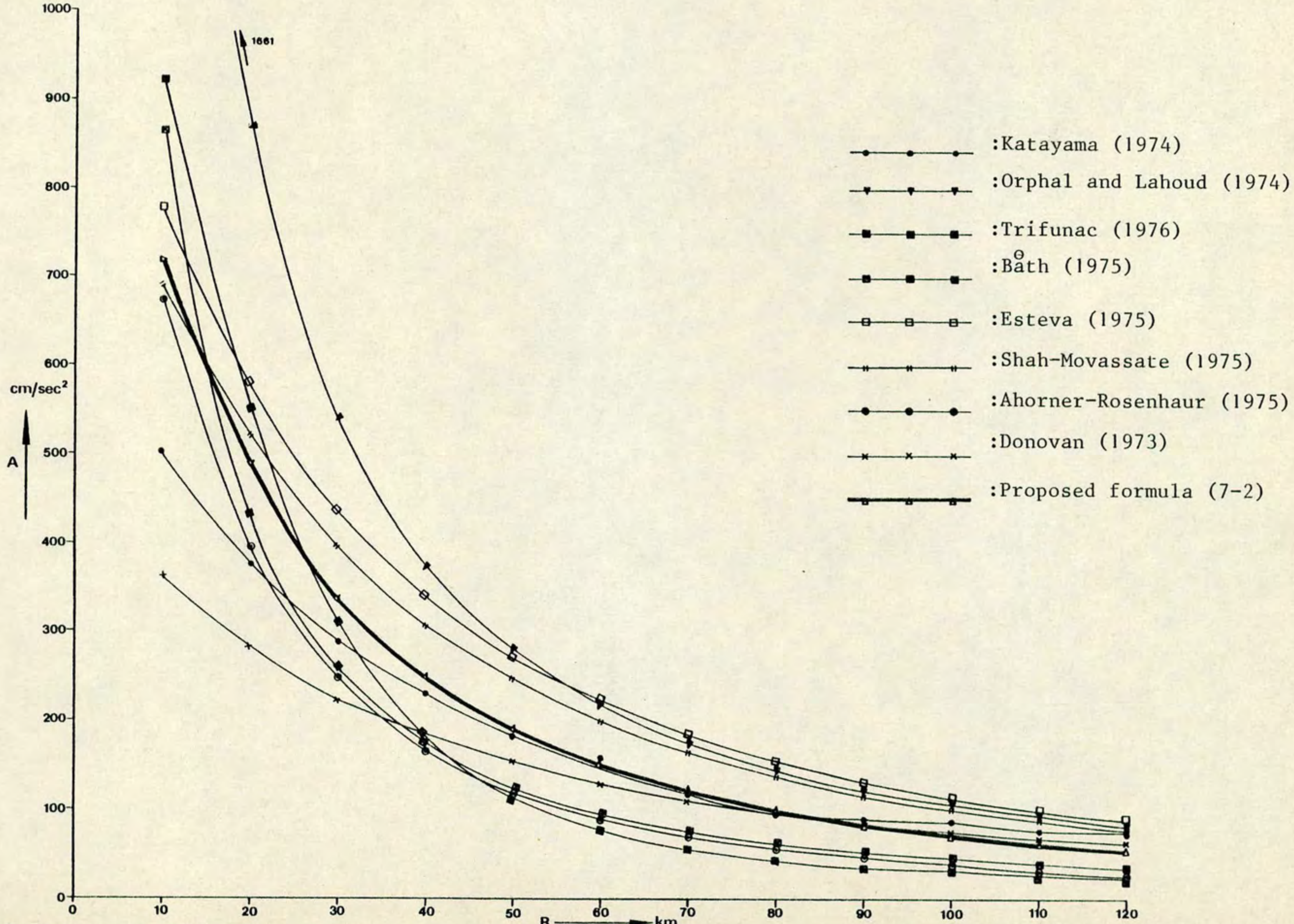


Fig 7-8 Peak acceleration as a function of epicentral distance using m=7.5 and h=10km, for the eight acceleration attenuation formulae of Table 7-7 and the derived average formula (7-2).

Table 7-8a

Values of maximum acceleration (cm/sec^2) for epicentral distance R(km) and derived from the formulae of Table 7-7, using M=7.5 and h=10km

Formula		10km	20km	30km	40km	50km	60km	70km	80km	90km	100km	110km	120km
Esteva	1975	771	581	440	342	273	222	184	155	132	114	100	88
Båth	1975	865	435	259	174	126	97	77	64	53	45	40	35
Donavan	1973	-	-	253	181	151	128	111	98	87	78	70	64
Orphal et al	1974	1661	878	542	375	280	218	177	148	125	108	95	84
Shah et al	1975	688	519	393	305	244	198	164	138	118	102	89	78
Ahorner et al	1975	673	397	249	168	121	91	71	57	46	39	33	28
Trifunac (p=0.5, s=2, h≤15)	1976	922	546	310	180	112	78	58	45	38	34	30	27
Katayama	1974	501	380	288	229	186	151	128	109	95	85	74	68

Table 7-8b

Range and averages of acceleration values (cm/sec^2) v distance (km) bracketed by the eight formulae of Table 7-8a, and comparable values derived from the proposed formula of equation 7-2.

Upper - Lower	922-673	581-397	440-249	342-168	280-112	222-78	184-58	155-45	132-38	115-34	98-30	88-27
Average	798±125	490±92	345±100	255±87	196±84	150±72	121±63	100±55	85±47	75±40	64±34	58±30
Proposed formula	716±215	486±148	340±105	250±79	191±61	151±48	123±40	102±33	86±28	74±24	64±21	56±19

available. Table 7-9 contains the maximum recorded accelerations for these shocks taken from Drakopoulos (1976b), whereas the other parameters are from the catalogue presented in this study. The last column gives the values of the maximum acceleration derived from equation(7-2). From this table it can be seen that values from the "average formula" (7-2) agree with mo t of the observed values of maximum acceleration.

7.4.2 Method used to fit the maximum acceleration data

Equation (7-2) is applied to each earthquake, and the ranked annual maximum accelerations form the data sample for the Extreme-Value method, similarly to that used for maximum magnitudes. An attempt to apply the third type asymptotic distribution to the annual maximum accelerations results in poor convergence with values of ω as high as 10 g and values of λ close to 0.0. However, when the curvature parameter λ tends to zero, then the third type asymptotic curve becomes the first type asymptotic distribution.

An explanation for this may be that the value of peak acceleration from equation (7-2) depends not only on the magnitude, but also on the focal distance from the point of interest. Because of the nature of attenuation (Fig 7-8) which is rapid for focal distances less than 40 km, and slow towards the longest distances for which the strong motion is highly attenuated, the data points are concentrated at low values of acceleration with occasional high values for near earthquakes. In this situation the straight line (first asymptote) seems to fit the data better than the three parameter curve of the third asymptote, and so the first type asymptote is applied to the extreme accelerations for Greece.

7.4.3 Procedure used to evaluate the seismic risk in T years at a given probability level

The seismic risk of the six selected places is calculated using

Table 7-9

Observed peak accelerations from strong motion records of Greek earthquakes compared with the values predicted by equation 7-2

Date	Origin time h:m:s	Station	M_s	R_{km}	A observed cm/sec^2	A from 7-2 cm/sec^2
1972 Sep. 17	14:07:15.3	Argostolion	5.9	29	170	122
1972 Oct. 30	14:32:10.7	Argostolion	5.4	28	110	90
1973 Nov. 4	15:52:12.6	Leukas	5.9	20	180	175
1973 Nov. 4	16:11:38.7	Leukas	4.9	20	80	87
1974 Jan. 29	15:12:44.8	Patra	4.3	30	40	38
1975 Apr. 4	05:16:16.5	Patra	5.7	56	58	48
1975 May 13	00:22:53.0	Xylokastron	4.6	46	74	30
1975 Oct. 12	08:23:12.6	Corinth	5.0	35	33	47

equation (2-59) in terms of maximum acceleration A_{PT}, with 70% probability of not being exceeded in a T year period. That is:

$$A_{PT} = A_{P1} + \frac{\ell nT}{a} = u - \frac{\ell n\left[-\ell n(1-P)\right]}{a} + \frac{\ell nT}{a} \qquad (7\text{-}3)$$

where A_{P1} is the annual maximum acceleration which is exceeded with probability P, u and a are the parameters of the first type asymptotic distribution using P = 0.30 (1 - P = 0.70 probability to be the largest acceleration value in a T year period). Table 7-10 tabulates A_{PT} for 25, 50, 100 and 200 year periods.

Using the same procedure, the maximum expected velocity and displacement for the same probability and periods is also tabulated in Table 7-10. These values are derived using the equation of Orphal and Lahoud (1974):

$$V = 7.26 \cdot 10^{-1} \cdot 10^{0.52m} \cdot R^{-1.39} \quad \text{cm/sec} \qquad (7\text{-}4)$$

$$D = 4.71 \cdot 10^{-2} \cdot 10^{0.57m} \cdot R^{-1.18} \quad \text{cm} \qquad (7\text{-}5)$$

For these places, the magnitude m_{TP} with the probability P of being the maximum during a T year period can also be derived from equation (2-20). That is:

$$P_T(m) = P_1^T(m) = \exp\left[-T\left(\frac{\omega-m}{\omega-u}\right)^{1/\lambda}\right] \qquad (7\text{-}6)$$

and

$$m_{TP} = \omega - (\omega-u)(-\ell nP_T)^{\lambda}/T^{\lambda} \qquad (7\text{-}7)$$

Then the return period RP in years from equation (7-6) is

$$RP = \frac{1}{1 - P^{1/T}} \qquad (7\text{-}8)$$

which for P = 0.70 and T = 25, 50, 100, and 200 years corresponds to: RP = 70, 140, 280, and 560 years. This means that a magnitude with 70% probability of not being exceeded in 25 years has a return period equal to 70 years. These values are also tabulated in Table 7-10.

7.4.4 Seismic risk evaluation - acceleration

From Table 7-10 it can be seen that the maximum acceleration for the short-term (25 years) risk and for the long-term (200 years) risk expected in the cities of Thessaloniki and Corinth is $A \simeq 120\ cm/sec^2$ and $180\ cm/sec^2$ respectively. The same cities also have the highest values for the expected velocities and displacements, although these values are not necessarily associated with the same earthquake.

The difference between the risk determined from the extreme magnitudes and accelerations at a particular place reflects the fact that in the attenuation models, the focal distance of each earthquake is taken into account. Thus, Athens and Corinth have almost the same seismic risk in terms of expected magnitude, but they differ significantly in terms of expected acceleration, velocity, and displacement. Because these two places are characterized by similar earthquake depth distribution and are near each other ($\sim$ 50 km), the difference shows that the seismic risk in the city of Athens is due to relatively more distant earthquakes than in the city of Corinth.

On the other hand, the cities of Heraklion and Rodos are characterized by intermediate depth earthquakes and have the lowest seismic risk in terms of expected maximum accelerations although the expected earthquakes may have large magnitudes.

7.5 Spatial distribution of seismic risk in Greece $\left[N_{33}^{42.5}, E_{19}^{29}\right]$

7.5.1 Contour maps of seismic risk - Procedure used

Close agreement is obtained between the observed and the predicted extreme magnitude occurrences for Greece as a whole, and for the six

Table 7-10

Amplitudes which have 70% probability of not being exceeded in T years

Amplitude of:	Magnitude*				Acceleration (cm/sec^2)				Velocity (cm/sec)				Displacement (cm)			
Period (years):	25	50	100	200	25	50	100	200	25	50	100	200	25	50	100	200
Athens	6.50 0.16	6.60 0.21	6.67 0.25	6.71 0.30	79.93	92.39	104.85	117.32	6.89	8.01	9.12	10.24	1.98	2.31	2.63	2.95
Thessaloniki	6.95 0.25	7.22 0.32	7.44 0.35	7.61 0.43	122.47	143.16	163.85	184.54	11.95	14.05	16.15	18.25	3.25	3.82	4.39	4.97
Patra	6.39 0.18	6.48 0.25	6.54 0.28	6.58 0.31	102.40	117.16	131.92	146.68	8.10	9.30	10.51	11.71	2.11	2.42	2.74	3.05
Corinth	6.57 0.16	6.64 0.20	6.68 0.24	6.70 0.29	117.87	136.27	154.67	173.07	10.21	11.88	13.54	15.20	2.62	3.04	3.46	3.89
Heraklion	6.66 0.19	6.88 0.23	7.06 0.27	7.21 0.35	55.93	63.73	71.52	79.32	4.94	5.69	6.44	7.19	1.46	1.69	1.92	2.15
Rodos	6.65 0.25	6.94 0.31	7.19 0.40	7.42 0.45	63.88	73.15	82.41	91.68	6.38	7.42	8.46	9.50	1.90	2.22	2.54	2.86

* Magnitude values are thosefor distance within 100 km from the cities, derived from the third type asymptote.

selected places, using the Extreme-Value method. Thus, a more detailed evaluation of seismic risk in terms of maximum magnitudes and acceleration for every part of Greece may be attempted, and contour maps of the distribution of the seismic risk can be prepared.

Greece is divided into cells of 0.5^{o} Latitude x 0.5^{o} Longitude, and a mesh of grid points with spacing of 0.5^{o} Lat, 0.5^{o} Lon, is created for the whole area. All earthquakes occurring within a circle of 1^{o} radius, with its centre at a particular grid point, are then collected from the new earthquake catalogue, and their annual maximum observed magnitudes are analysed with the third type asymptotic distribution. With a similar computing procedure, but for radius of 2^{o}, the first type asymptotic distribution is applied to the maximum accelerations. For every grid point the parameters and their uncertainties are computed. Each set of parameters corresponds to an area which overlaps the adjacent one by about 3/4 or 7/8 of the area, respectively. Using equations (2-61), (2-62), and (7-7), the annual and 80 year mode, and the maximum magnitude which is expected with 70% probability of not being exceeded in 50 and 100 years, are then estimated and contoured. Similarly, the parameters of the first type asymptote are used in equation (7-3) producing contour maps of seismic risk in terms of acceleration with 70% probability of not being exceeded in 50, 100, and 200 years.

For these calculations the computer program used in the calculations of Chapter IV is extended and listed in Appendix A. For the contours, the General Purpose Contouring Programme (GPCP) of Edinburgh Regional Computing Centre (ERCC) is used.

7.5.2 Results and discussion

a) Magnitude distribution

Figures 7-9 to 7-12 show the distribution of seismic risk in terms of maximum expected magnitudes. The values in Figures 7-11 and 7-12

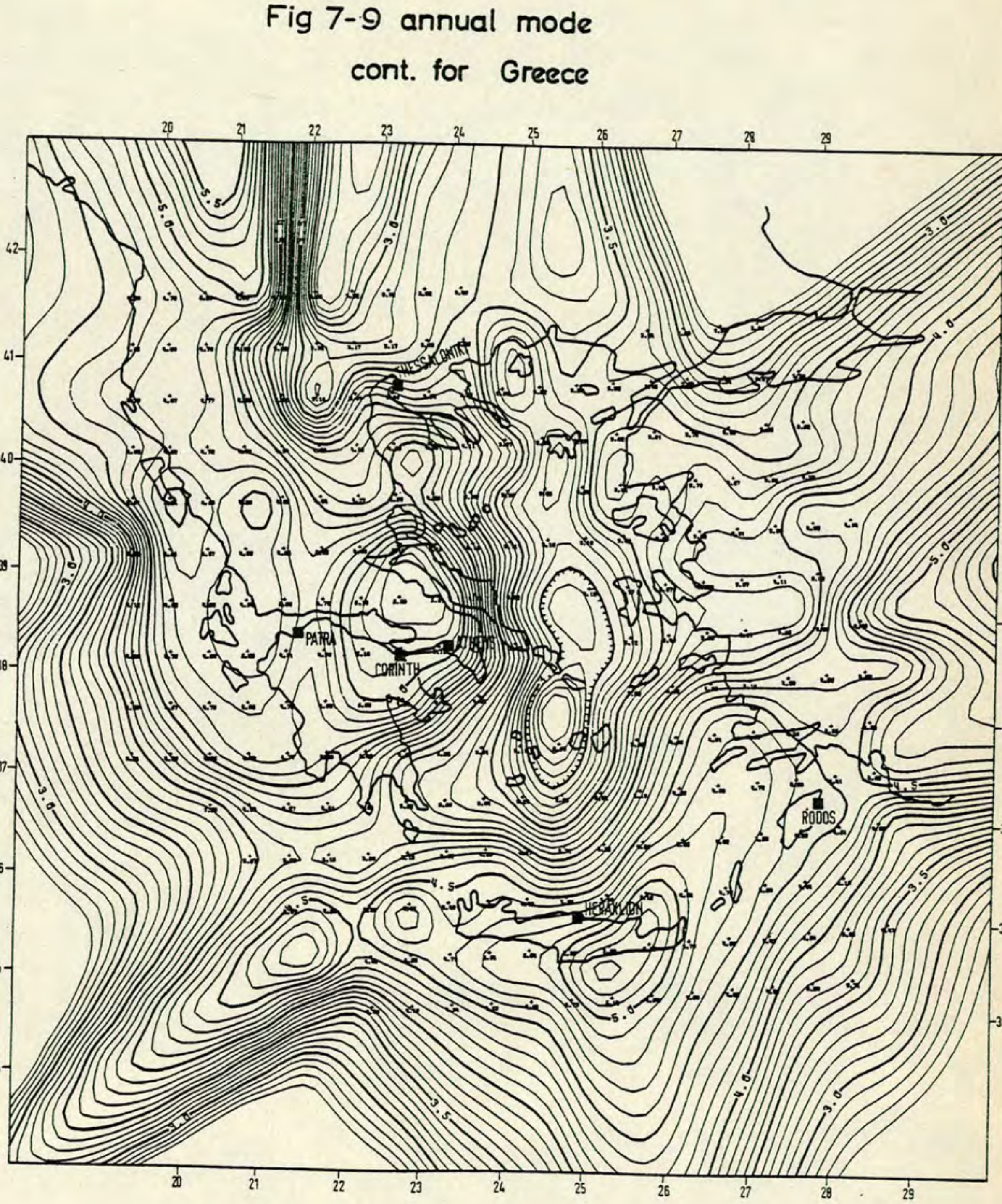


Fig 7-9 Most probable annual maximum earthquake magnitude (mode) for Greece.

Fig 7-10 80 year mode cont.
for Greece

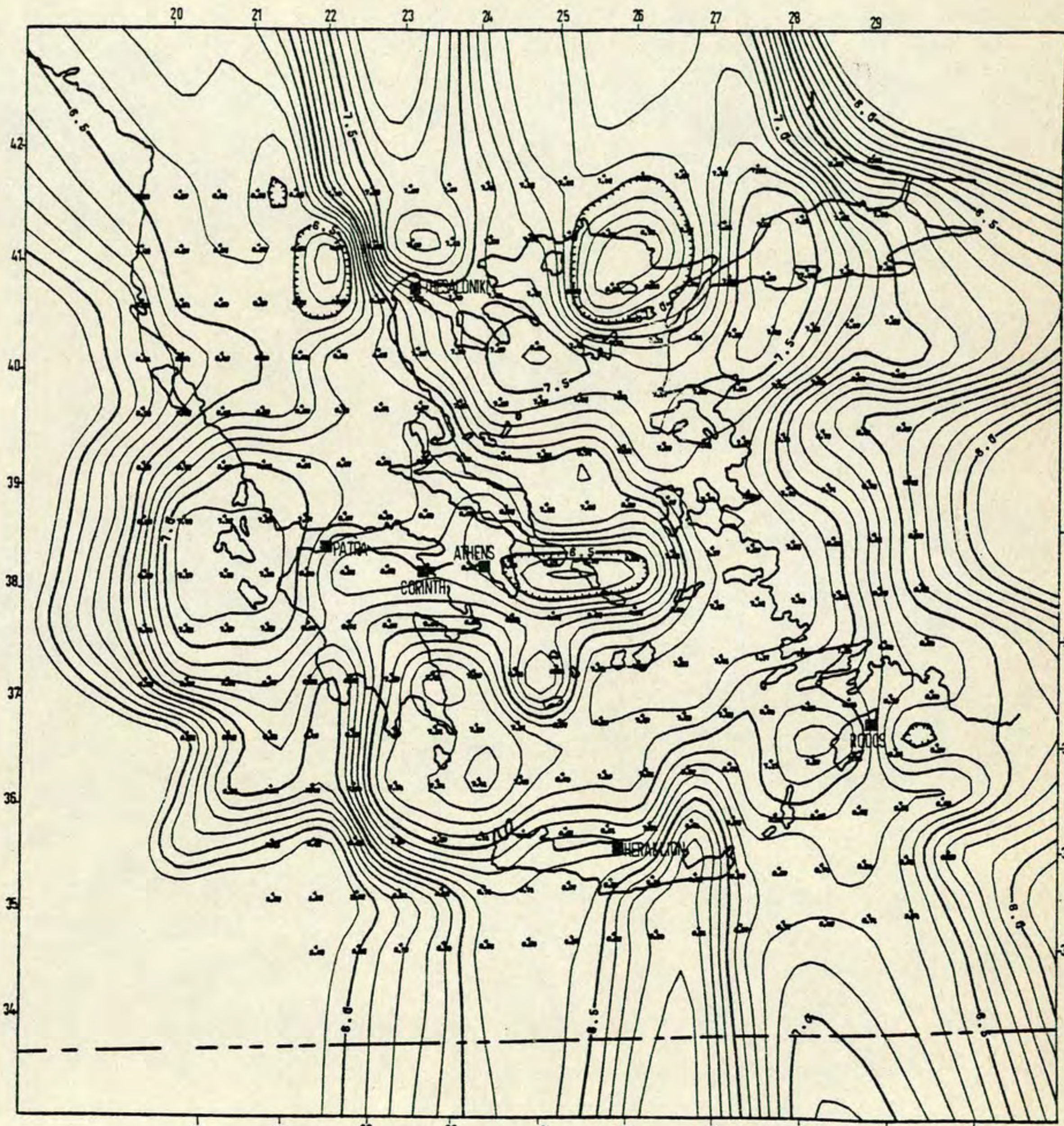


Fig 7-10 80 year most probable maximum earthquake magnitude for Greece.

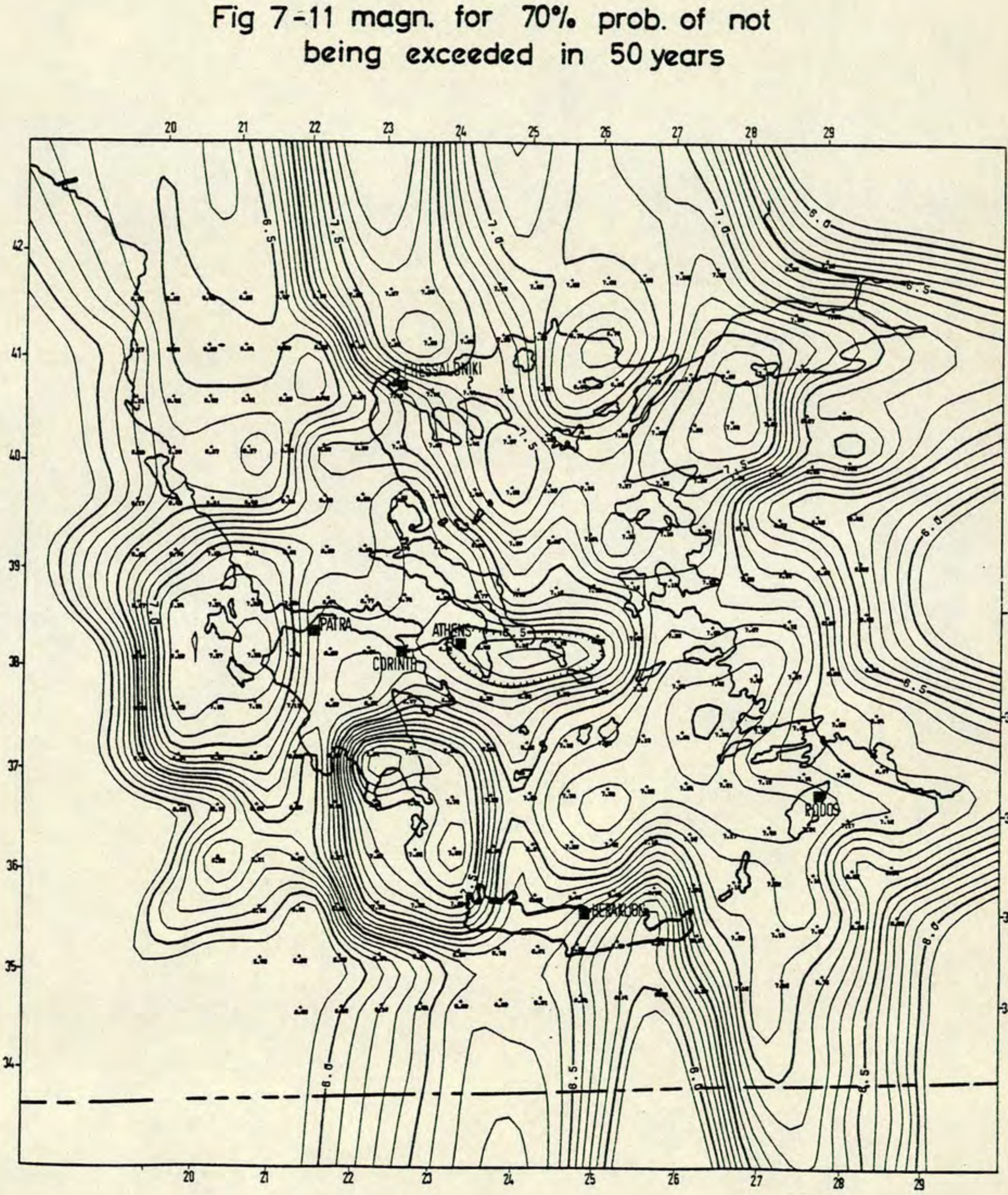


Fig 7-11 Maximum expected earthquake magnitude with 70% probability of not being exceeded in 50 years for Greece.

Fig 7-12 magn. with 70% prob. of not being exceeded in 100 years

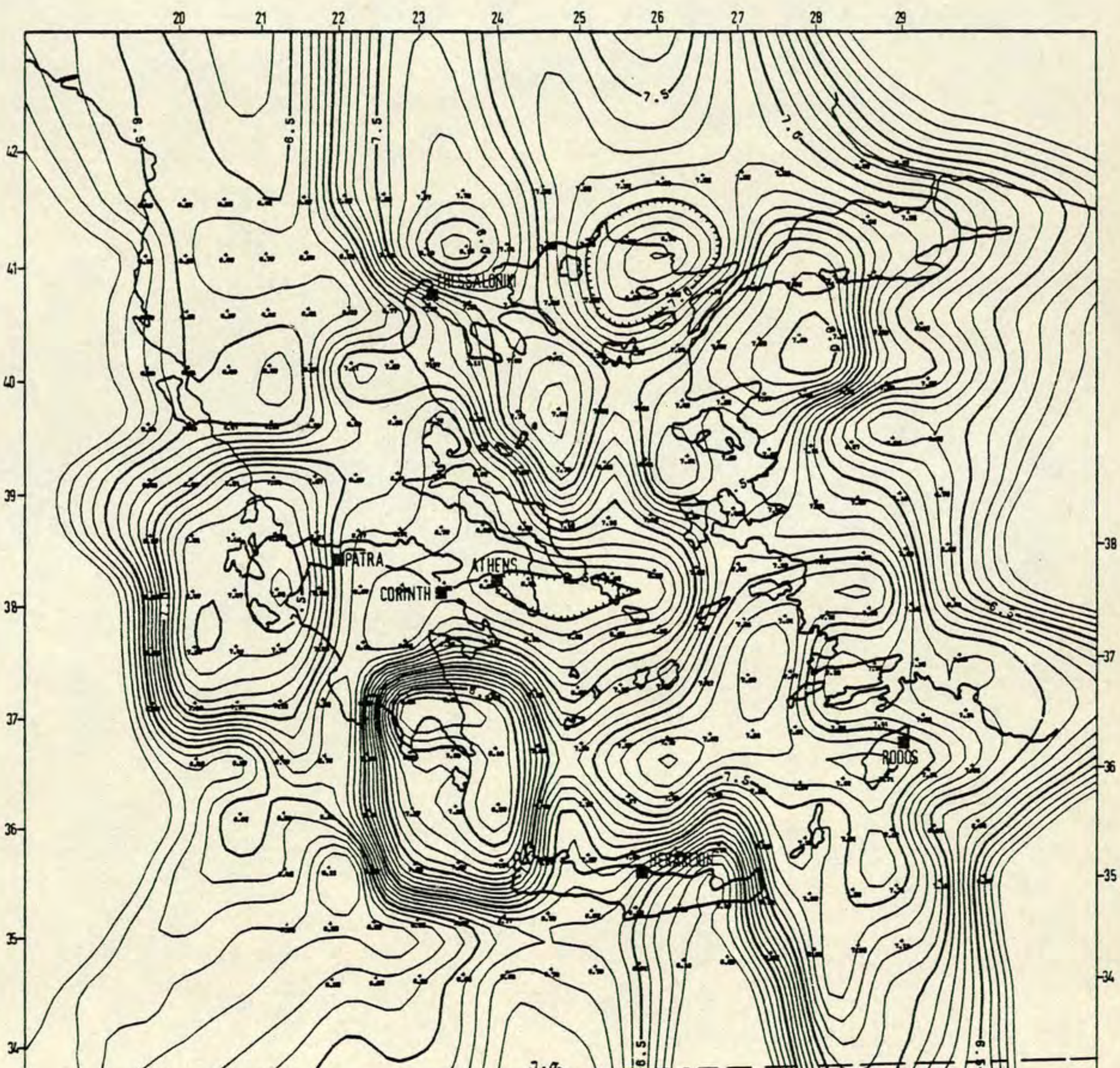


Fig 7-12 Maximum expected earthquake magnitude with 70% probability of not being exceeded in 100 years for Greece.

correspond to return periods of 140 and 280 years (eq 7-8), and these combined with Figures 7-9 and 7-10 allow the short-term (annual mode) and long-term risk in every part of the area to be evaluated.

Comparing these figures shows that the values of maximum annual magnitude are significantly different from the values for the 80 year mode, and the two overall pictures are also different in regional detail. The reason for this is that every place has its own distribution curvature for magnitude occurrence, which shows how quickly the distribution approaches the upper bound. Places in which the distribution of maximum magnitudes has greater curvature (larger value of λ), than other places, show greater difference between the regional contour maps of the annual and 80-year modes. As longer return periods are considered these differences become small, because the expected magnitudes are close to the upper bound and so the overall pictures are then similar. Figures 7-9 to 7-12 illustrate this point.

Figure 7-10 describes the most expected maximum magnitude during a period of 80 years. Because this period is almost equal to the time span of the data used (1901-1978), Figure 7-10 is the figure most easily compared with the observed distribution in Figure 6-8. The two figures are very similar.

The three main aseismic blocks discussed tectonically in paragraph 6.4.1 are clearly defined in Figure 7-10 as the areas of the lowest seismic risk in Greece. Areas with high values of maximum expected magnitudes are also areas where the observed magnitudes have large values. It is expected that during the next 80 years earthquakes with magnitude $\geqslant 7.5$ will occur at least once in the area of the Greek-Yugoslavia borders, the Chalkidiki peninsula, and the Marmara Sea in north-western Turkey. These areas have experienced earthquakes with magnitudes $m = 7.8$ (4.4.1904), $m = 7.4$ (8.11.1905), and $m = 7.4$ (18.3.1953) respectively.

Figures 7-11 and 7-12 which describe the risk in terms of maximum magnitude with 70% probability of not being exceeded in 50 and 100 years show a similar picture of seismicity. This is because these values correspond to return periods of about 140 and 280 years, and so they become close to their own upper bound with only small changes with increasing return periods. In both figures, an area with high risk, which in Figure 7-10 was poorly defined, becomes clear. It is the area of the south-eastern part of the Peloponnesus and Kithera Island. This area has experienced the largest intermediate depth earthquake with magnitude m = 8.0 (11.8.1903, h = 120 km).

In the next 100 years there is a probability of 70% that the maximum expected earthquake magnitude will not be greater than m = 8.0 in any of these high risk areas and consequently in the whole area of Greece.

b) Acceleration distribution

The seismic risk in terms of values of maximum acceleration with 70% probability to be the largest during the next 50, 100, and 200 years is described in Figures 7-13 to 7-15.

The overall picture of these three figures show an almost identical pattern. This is expected because it is apparent from equation (7-3) that the values of maximum acceleration, with a given probability of not being exceeded up to a certain time, increase as a linear function of the logarithm of time. So as the time increases, the acceleration value at a particular point increases proportionally to its previous value, and therefore the shape of the isovalue lines does not change.

Comparing the figures which show the risk in terms of maximum magnitude with those of maximum acceleration, the pictures differ significantly mainly in the places where intermediate earthquakes dominate. This is expected because in the strong motion attenuation formulae, the focal distance from the point of interest is an important factor in calculations of the

Fig 7-13 acceleration with 70% prob of not being exceeded in 50 years

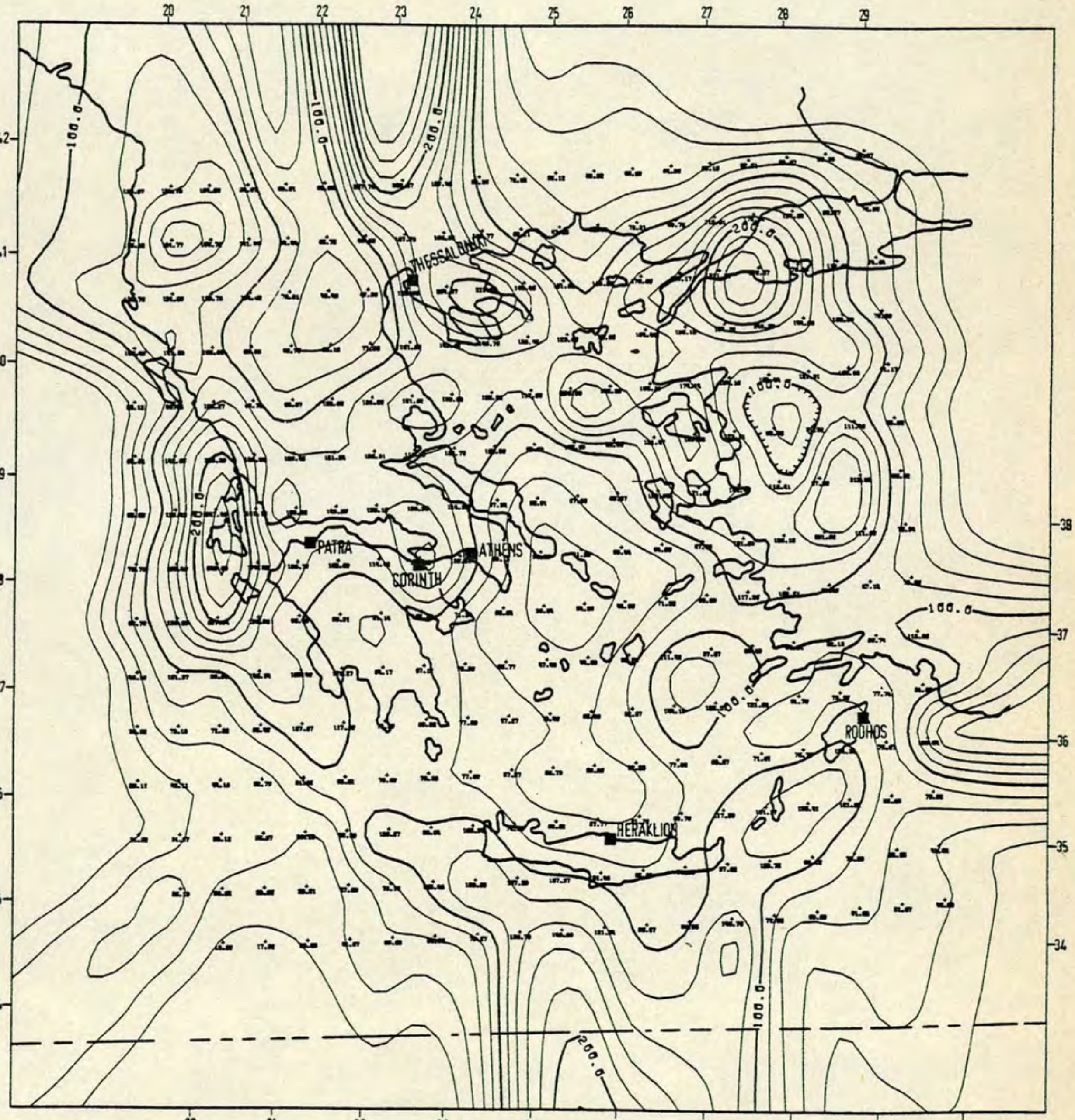


Fig 7-13 Maximum expected acceleration with 70% probability of not being exceeded in 50 years for Greece.

Fig 7-14 acceleration with 70% prob of not being exceeded in 100 years

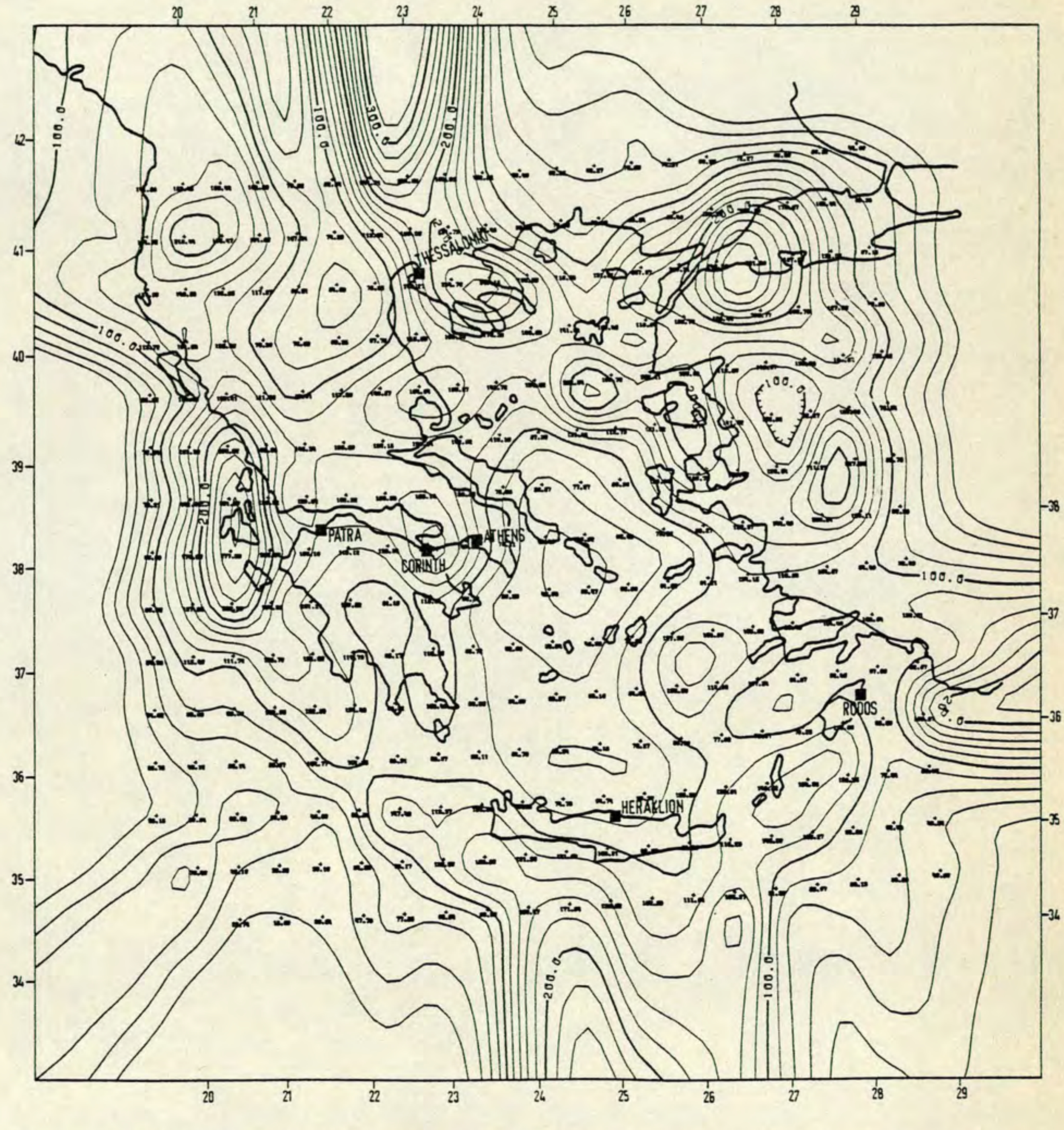


Fig 7-14 Maximum expected acceleration with 70% probability of not being exceeded in 100 years for Greece.

Fig 7-15 acceleration with 70% prob of not being exceeded in 200 years

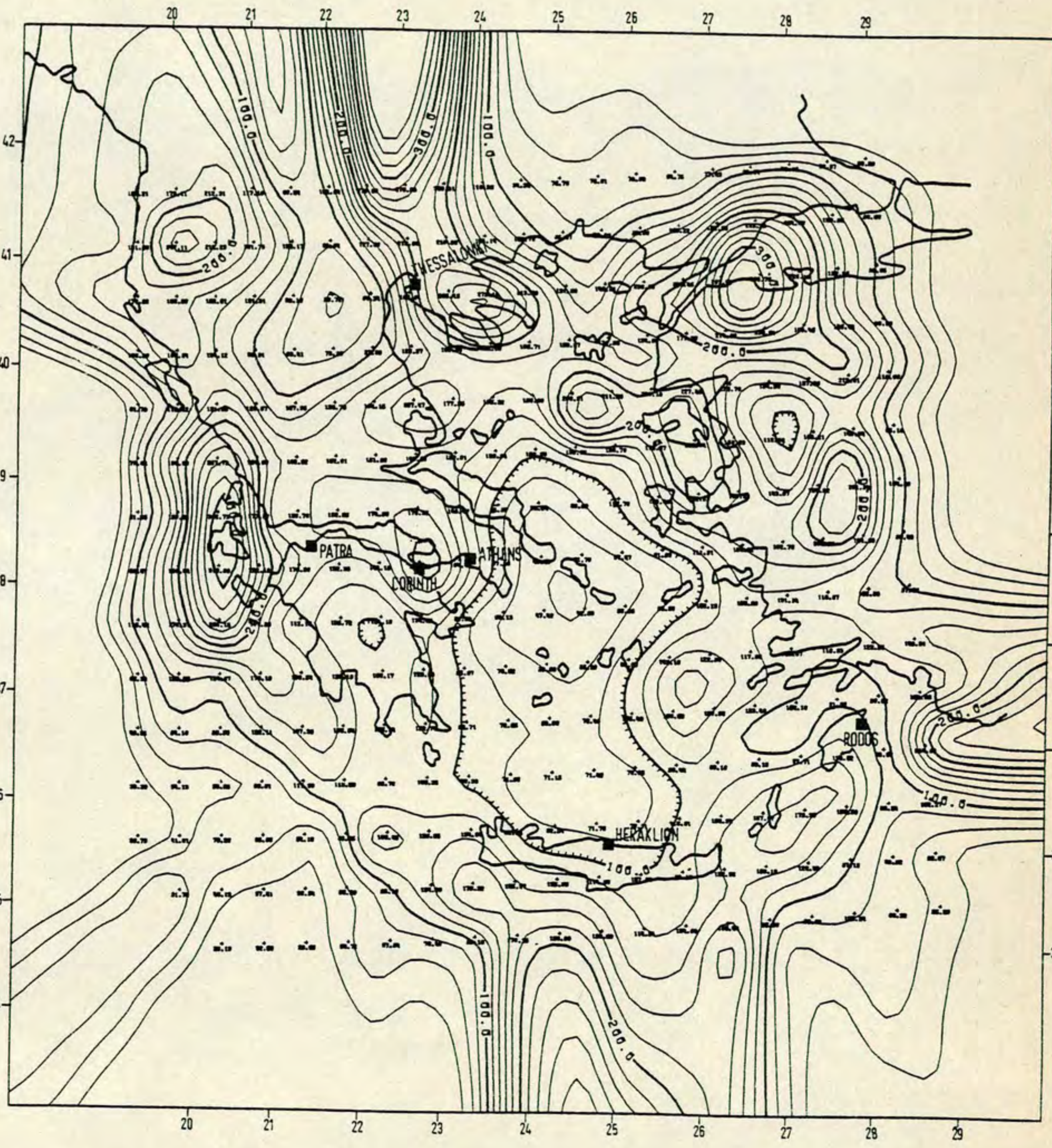


Fig 7-15 Maximum expected acceleration with 70% probability of not being exceeded in 200 years for Greece.

final maximum acceleration observed at that point. Thus, from Figures 7-13 to 7-15 two new high risk areas are well defined. These are the areas around Cephalonia and Leukas Islands, and around Lesvos and the eastern Sporades Islands, with values of maximum accelerations at the 70% probability level for the next 50 years approximately equal to 200 cm/sec^2 (0.2g).

The areas where an acceleration of 0.3 g is expected to be the maximum acceleration at the 70% probability level in the next 200 years are the Marmara Sea area, and the area around Cephalonia and Leukas Islands.

As a part of the UNESCO Survey of the Seismicity of the Balkan region, maximum acceleration risk maps were prepared by a group of seismologists at the U.S. Geological Survey, Denver, Colorado Centre (Algermissen et al, 1976). These maps depict acceleration and velocity with 70% probability of not being exceeded in 25 and 200 year periods using data from the UNS's catalogue, and attenuation formulae derived from those of Schnabel and Seed (1973). Comparing the 200 year map for accelerations with Figure 7-15, the values of Algermissen et al's map are significantly larger than those of Figure 7-15. The main reason for the high values found in the previous work, for exampe A = 0.6g around Cephalonia Island, seems to be the way the attenuation formulae were applied. They modified Schnabel and Seed's formula in such a way that it can be applied for two depth intervals, 15 and 110 km. Then all earthquakes with a depth less than 50 km were considered to have occurred at a depth of 15 km, and earthquakes with a depth more than 50 km were considered to have occurred at 110 km. However, the vast majority of earthquakes in Greece, as the recalculated depth parameter shows, have their origin at a shallow depth. 1492 out of a total of 1805 earthquakes have a depth less than 50 km, with an average depth of 28-35km. Thus, the above considerations may lead to serious overestimation of the values computed. Drakopoulos (1976b)also points out that Algermissen et al's values for the maximum acceleration appear to be relatively high for

Greece.

Considering the computing procedure followed here, that is every individual parameter is taken into account, and the agreement between the observed and calculated values of maximum accelerations, using equation (7-2), Figures 7-13 to 7-15 present an improved evaluation of the seismic risk in terms of maximum acceleration in Greece.

7.6 Summary

The objective of this Chapter was to evaluate seismic risk in Greece, and at six selected cities, in terms of both maximum expected magnitude and accelerations.

Assessing seismic risk in terms of maximum magnitudes is achieved by applying the method of strain energy release and the method of the third type asymptotic distribution. The results obtained show that where the energy release graphs include at least one well defined cycle of periodicity then the parameters of the third type asymptotic distribution have small uncertainties. From the figures presented, and the values of chi-square, it is shown that in all places analysed the magnitude distribution is well fitted by third type asymptotic behaviour.

From Table 7-6, where the predicted number of exceedances for different magnitudes is compared with those observed during the sample period (1901-1978), the close agreement also shows that the third type asymptotic distribution method, with the assumption made for missing years, reveals the seismic picture of a region.

The seismic risk for the selected cities is obtained in terms of both the return period for earthquakes with magnitude from $m = 5.0$ to $m = 8.0$, and also the number of expected exceedances of these magnitudes during the next 50 and 100 years.

The value of $m = 8.73 \pm 0.65$ is found as an upper bound for earthquake magnitudes of Greece, and this is in agreement with the seismic history of the area. An earthquake with magnitude equal to or greater than $m = 5.5$ is expected as an annual extreme almost every year. An earthquake with magnitude equal to or greater than $m = 7.5$ is expected to occur in Greece every 22 years, whereas the return period for an earthquake with magnitude greater than $m = 8.0$, observed once in Greece (11.9.1903), is about 200 years.

For Athens the upper bound magnitude is $m = 6.8 \pm 0.4$ within an area of 100 km radius from the city, whereas the most probable annual maximum magnitude is $m = 4.51 \pm 0.08$.

Seismic risk is then obtained in terms of maximum accelerations. There is no universally accepted formula of strong motion attenuation, and the existing formulae show large dispersion in terms of maximum acceleration, and so an average formula is derived from the eight published formulae of Table 7-7. This formula agrees fairly well with the observed values of maximum acceleration recorded in Greece. An attempt to use the third type asymptotic method for maximum accelerations, however, results in poor convergence with values of $\lambda \approx 0.0$ and an unacceptable upper limit $\omega \approx 10g$. A possible explanation for this may be the tendency of the observed maximum accelerations to cluster towards the two ends of the distribution as a result of the nature of the attenuation of the motion with focal distance. The first type asymptotic distribution appears to be a better representation of the distribution of the maximum accelerations.

Seismic risk in terms of maximum expected acceleration at a 70% probability level for the six places are tabulated in Table 7-8. The same table also contains the results for maximum velocities and displacement derived using the same procedure with equations (7-4) and (7-5) respectively. To complete the seismic picture, values of the maximum expected magnitude, at the same probability level, are also included in the table.

The same detailed evaluation is applied to the whole area of Greece by dividing it into cells of 0.5° Lat x 0.5° Lon. These methods are then applied at each grid point for an area extending to 1^{o} radius from it, and the following values are calculated: the annual and 80 year mode, maximum magnitude at the 70% probability level of not being exceeded in 50 and 100 years, and maximum acceleration for the 70% probability level of not being exceeded in 50, 100 and 200 years. These values are then contoured, and the maps derived (Fig 7-9 to 7-15) illustrate the spatial distribution of seismic risk within Greece.

A common feature in all these maps is the existence of three well defined aseismic blocks. These are: the atticocycladic block, the ptolemais basin block and the block formed by the north-eastern part of Greece. These aseismic blocks of low seismic risk correlate with the tectonics described in the previous chapter and indicate that the region can not be modelled by a simple tectonic plate. Also well defined are areas of high seismic risk which correlate with the tectonically most active areas, and these are:

i) Along the Hellenic arc: Greek-Albania-Yugoslavia borders, Leukas and Chephalonia Islands in the Ionian Sea, and the south-eastern end of the arc around Rodos Island.

ii) The western end of the Northern Anatolian fault in the Marmara Sea area and

iii) The northern Aegean Sea: Chalkidiki peninsula and Sporades Islands.

CHAPTER VIII

SUMMARY AND FINAL CONCLUSIONS

The objectives of this study were:

i) to examine the upper bound for earthquake magnitude occurrence,

ii) to investigate the usefulness of the third type asymptotic distribution for predicting earthquake risk, and

iii) to evaluate the seismicity and seismic risk of Greece.

The first two objectives are studied in the first part of this thesis and the third is achieved in the second part.

Reviewing the existing statistical models for earthquake occurrence and magnitude distribution shows that Extreme-Value methods have some important practical advantages compared to the methods which use the whole process. Because the sample consists of extreme values only, they are more complete, accurate and homogeneous than the entire range of events, and so Extreme-Value methods avoid some weak points of the othermethods, particularly those caused by the inclusion of low magnitudes.

Experimental data shows that the linear frequency-magnitude formula does not hold for very large earthquakes. However, most of the proposed alternative expressions fail to recognize the existence of an upper bound to the magnitude that can be generated in a given region, or do not include this upper bound as an unknown parameter in the resulting distribution function. When the problem of the upper bound for earthquake magnitude was examined, it was demonstrated using simple frequency-magnitude and energy-magnitude laws that it is possible to include such an upper bound as an unknown parameter, and to calculate its value both analytically and graphically. It was also shown that a finite upper bound to the earthquake magnitude is necessary to preserve a finite rate of energy release. From the analytical method this upper bound is found to be a function of the mode M_1, the mean rate of annual energy release M_2, and the parameter b of the frequency-magnitude law. Because each region has its own value of b (Duda, 1965), each region must also have its own upper bound to the magnitude of earthquakes which can occur within the region.

The graphical and analytical methods of strain energy release are tested in the most seismically active region in the world, that is, the circum-Pacific belt. The results show remarkably good agreement for the values found for the upper bound from both methods. The empirically obtained relations between M_1 and M_2 show that the upper bound M_3, and the annual mean rate of energy release M_2, differ by one magnitude unit.

The advantage of the Extreme-Value methods, combined with the necessity for the existence of an upper bound to the earthquake magnitude occurrence, shows that the third type asymptotic distribution of extreme values, which includes the upper bound as a parameter, is a statistical model with which realistic predictions for large events can be obtained.

The second objective was then to investigate the applicability of the third type asymptotic distribution method. Because it is assumed that an error analysis is vital to any seismic risk analysis, a specific goal towards this objective was to develop a technique capable of computing the errors of the distribution parameters calculated and of all prediction quantities. A computer program using Marquardt's algorithm, written to do this, and the parameters with their error matrix obtained, reveal that:

i) The characteristic largest value u is the most precisely known parameter.

ii) The variances for ω and λ are usually large and the existence of negative covariance between them shows that they are not independent.

iii) When the data shows little curvature λ, and therefore a high value for ω, these parameters are usually accompanied by large uncertainties. However, this negative covariance leads to seismic risk calculations with acceptable uncertainties.

To explore the physical meaning of the parameters of the third type asymptote they are linked with the physical release of strain energy through M_1, M_2, and M_3. The circum-Pacific belt was again chosen as the testing area. Remarkably similar results were then obtained from these two different procedures, strain energy release and extreme values, showing that the third type asymptotic distribution is practical for prediction purposes. The first type asymptotic distribution was also applied to the same area and the values of chi-square show that in all cases the third type asymptote gives a better fit to the data, and so it is preferable as a general model for the statistical behaviour of the occurrence of maximum magnitude earthquakes.

Strain energy release and third type asymptotic distribution methods when applied to the circum-Pacific belt show that the centres of highest seismic activity are diagonally opposite each other. These are: South America and Japan, Kurile and Kamchatka. This presumably relates to the tectonic movement of the Pacific plate (Duda, 1965).

In the second part of this study the final objective was achieved by applying these methods to the relatively lower seismicity of Greece. Because the results of any statistical method depend on the quality of data used, a specific goal towards the evaluation of Greek seismic risk was the preparation of an earthquake catalogue as accurate and homogeneous as possible.

The Joint Epicentre Determination (JED) technique of calculating earthquake hypocentres was used to recalculate all the source parameters for the period 1917-1963. The recalculated positions are significantly different from those reported by the ISS with the average shift decreasing from decade to decade since 1917. The large average total shifts imply that it is not possible to describe the detailed seismicity of Greece by simply using the ISS data for the whole period.

Homogeneity of the earthquake magnitudes was achieved by recomputing them according to a consistent scheme for the longest possible part of the period under consideration (1907-1978). The recomputation for the period 1907-1968 was made by using ground amplitudes for Greek earthquakes reported by the Swedish network and regression equations derived from parallel recordings of Swedish instruments. For 1968 onwards, regression equations were used to convert the body-wave magnitudes M_b reported by ISC into surface wave magnitudes M_s of the Swedish network.

When Stepp's test of completeness was applied, the results show that only earthquakes with magnitude $m \geqslant 6.3$ are completely reported during the whole period of investigation, whereas earthquakes with a maximum magnitude $4.2 \leqslant m \leqslant 4.7$ are completely reported only during the most recent 15 years. The time required for estimates of the mean recurrence rate to become stable was found to be 40-50 years of homogeneous observations for magnitudes $\geqslant$ 6.3, whereas for earthquakes with magnitudes in the range $4.2 \leqslant m \leqslant 4.7$ only 5 to 10 are required.

The catalogue presented in this study has a high degree of homogeneity and accuracy permitting more detailed seismotectonic studies to be made on the basis of a long instrumentally recorded data sample. The existing tectonic models of Greece were examined and their accordance with the recalculated parameters of the earthquakes was tested. From the maps describing the spatial and depth distribution of the recalculated earthquakes it is clear that the area is tectonically more complicated than had previously been recognised. None of the proposed tectonic models explain the observed seismic activity sufficiently over the whole area. Places where further work is necessary to understand fully the present tectonic process are:

i) the north-western part of the Hellenic arc (north-western Greece and Albania),

ii) the south-eastern part of the Hellenic arc (eastern Crete, Karpathos and Rodos Islands), and

iii) the northern Aegean Sea and north-western part of Turkey.

Finally, within the framework of Greek local tectonics, the evaluation of seismic risk was achieved by applying the statistical techniques of the first part of this study to the new earthquake catalogue. The evaluation was made in terms of maximum expected magnitude and acceleration. To obtain the maximum magnitude distribution both the strain energy release and the third type asymptotic distribution methods were applied. However, the first type asymptotic distribution is better than the third for representing the observed distribution of maximum accelerations. A possible explanation for this may be found in the tendency for most maximum accelerations to lie within the linear part of the acceleration attenuation curve, because the attenuation of ground motion only varies non-linearly for unusually short focal distances. For the seismic risk analysis derived in terms of acceleration an average formula for the attenuation of maximum acceleration was derived from most of the commonly used formulae. This formula gives values which agree with the observed maximum accelerations recorded from eight Greek earthquakes.

Greece as a whole and six heavily industrial and highly populated centres were first selected for a detailed evaluation of seismic risk. The risk values obtained are consistent with the observed values during the period of investigation. For Greece the upper bound for earthquake magnitude is 8.73 ± 0.65. The return period for an earthquake of magnitude equal or greater than the maximum observed $m = 8.0$ is about 200 years. The most probable annual maximum magnitude is $m = 6.41 \pm 0.04$. In an area with

100km radius from the city of Athens, the upper bound is equal to m = 6.8 ± 0.4, the most probable annual maximum $\tilde{m}$ = 4.51 ± 0.08. All regions are well fitted by the third type asymptotic behaviour, and there is close agreement in detail between the predicted and observed number of exceedances of maximum magnitudes for Greece and Athens.

A detailed spatial seismic risk evaluation was obtained for the whole area of Greece by dividing it into cells of 0.5° Lat. and 0.5° Lon. The maximum expected magnitude and acceleration was evaluated at each grid point by applying the third and first type asymptotic distribution methods respectively. These results are presented as contour maps and using these the seismic risk at any locality can be evaluated. The common feature in all these maps is the existence of three well-defined aseismic blocks; these are:

i) the attikocycladic block,

ii) the block around the Ptolemais basin and,

iii) the block formed by the north-eastern part of Greece.

Also well defined are areas of high seismic risk; these are:

i) the Greek-Yugoslavia borders,

ii) the Chalkidiki peninsula and part of the north Aegean Sea,

iii) the north-western part of Turkey,

iv) the Cephalonia and Leukas Islands and,

v) the Eastern Sporades and Lesvos Islands area.

APPENDIX A

COMPUTER PROGRAM LISTING

Risk Analysis Program (RAP)

This program is written in Fortran IV. Its purpose is to compute the parameters, and their uncertainties, of the first and third type asymptotic distribution of extreme values of the following variables: magnitude, acceleration, velocity or displacement. Using these parameters it then estimates prediction parameters and calculates probability levels.

The computer procedure is

i) It creates a mesh of equally spaced grid points in the area of interest.

ii) It selects all the earthquakes within an area with specified radius from each grid point, finds the annual maximum magnitude, acceleration, velocity or displacement, and ranks them considering the first observed maximum as being the j + 1th where j is the number of missing years.

iii) For each data set derived from the previous step, it applies the least-squares method and calculates the parameters and their uncertainties. For the first type asymptotic distribution (eq 2-20) the regression equation is:

$$m = u + \frac{1}{a} y \tag{A-1}$$

and the parameters are computed using the linear least squares method (subroutine LINFIT). For the third type asymptotic distribution (eq 2-22) the regression equation is:

$$m = \omega - (\omega - u) \left[(-\ell n(\phi(m))) \right]^{\lambda} \tag{A-2}$$

where $\phi(m)$ is the plotting position of m given by the equation (2-35). The parameters are then computed using Marquardt's (1963) algorithm as described in paragraph 4.2.2 (subroutine CURFIT).

iv) With the parameters and uncertainties computed it calculates prediction parameters such as: annual mode (eq 2-56 or 2-61), T year mode (eq 2-57 or 2-62), upper and lower bounds (eq 2-66 and 2-68), extreme values with given probability P of not being exceeded in T years (eq 2-59 or 7-7).

The listing of the program starts with a comprehensive block of comment cards.

```
C     THIS PROGRAM COMPUTES THE PARAMETERS AND THEIR UNCERTAINTIES
C     OF THE FIRST AND THIRD TYPE ASYMPTOTIC DISTRIBUTION OF EXTREMES.
C     USING THESE PARAMETERS AND THE ERROR MATRIX IT COMPUTES PREDICTION
C     PARAMETERS SUCH AS : ANNUAL MODE,T-YEARS MODE,MAXIMUM EXPECTED
C     MAGNITUDE OR ACCELERATION OF NOT BEING EXCEEDED IN T YEARS,AT A
C     STATED PROBABILITY LEVEL.IT ALSO COMPUTES UPPER AND LOWER BOUNDS
C     FOR MAXIMUM EXPECTED MAGNITUDES,ACCELERATIONS,VELOCITIES,OR
C     DISPLACEMENTS FOR GIVEN PROBABILITY LEVELS.
C
C     THE PARAMETERS OF THE THIRD TYPE ASYMPTOTE ARE COMPUTED USING
C     MARQURDT'S(1963) ALGORITHM,BY LINEARISING THE FITTING FUNCTION:
C
C         M=W-(W-U)*((-ALOG(P(M))))**LAMDA    SUBROUTINE CURVFIT.
C
C     STARTING WITH INITIAL TRIAL VALUES OF W,U,AND LAMDA (A(1),A(2),A(3))
C     THE GOODNESS OF FIT TO THE N OBSERVALS IS MESURED BY THE REDUCED
C     CHI-SQUARE WHICH IS MINIMISED WITH RESPECT TO EACH PARAMETER,
C     LEADING TO THE LINEAR MATRIX EQUATION:
C
C                 BETA=DELTAA(I)*ALFA
C
C     THE UNCERTAINTIES ON A(1),A(2),AND A(3) ARE THEN CALCULATED FROM
C
C                 DELTAA(I)=BETA*E
C
C     WHERE E IS THE INVERSE MARTIX OF ALFA. E IS THE ERROR MATRIX AND
C     ITS  ELEMENTS ARE THE VARIANCE AND COVARIANCE OF THE PARAMETERS W,
C     U,  AND LAMDA.
C
C     THE PARAMETERS OF THE FIRST TYPE ASYMPTOTE ARE COMPUTED USING
C     LINEAR LEAST-SQUARES METHOD WITH THE FITTING FUNCTION:
C
C                     M=U+1/A*Y
C
C      WHERE
C             Y=-ALOG(-ALOG(P(M))) : THE REDUCED VARIABLE.
C
C     DESCRIPTION OF THE INPUT DATA
C
C
C     DATA STREAM  5  (CARDS 1-3 AND EARTHQUAKES DATA FILE )
C
C     FIRST CARD        :  FORMAT(6F6.2)
C
C     EMIN  :  BOTTOM LATITUDE OF THE AREA OF INVESTIGATION
C     EMAX  :  TOP    LATITUDE
C     BMIN  :  LEFT   LONGITUDE
C     BMAX  :  RIGHT  LONGITUDE
C     DEB   :  STEP OF SHIFT IN LAT  AND LON
C     SIZE  :  RADIUS IN DEGREES OF THE AREA FROM EACH GRID POINT
C
C     SECOND CARD       :  FORMAT(7I5)
C
C     1) IDENT :
```

```
C                =1    FOR MAXIMUM ACCELERATION DISTRIBUTION
C                =2    FOR MAXIMUM VELOCITY
C                =3    FOR MAXIMUM DISPLACEMENT
C                =4    FOR MAXIMUM MAGNITUDE
C
C     2) MODE  :
C              =-1    WEIGHT=1/X(I)
C              =0     EQUAL WEIGHTS IN ALL THE INPUT DATA
C              =1     WEIGHT=1/SIGMAX(I)
C
C     3-4)      MAXT-MINT    :PERIOD OF INVESTIGATION
C      5-6)     LIST1,LIST2 OPTIONS FOR PRINTOUT ( 0 OR 1 FOR FULL PRINTOUT )
C     7)      INT :
C                =1 FOR THE FIRST TYPE ASYMPTOTE
C                =2 FOR THE THIRD TYPE ASYMPTOTE
C
C    THIRD CARD        FORMAT(2F6.2)
C
C      EMMIN     :  MINIMUM MAGNITUDE TO BE CONCIDERED
C      PROB      :  PROBABILITY LEVEL AT WHICH  THE PREDICTION PARAMETER
C                   IS EXPECTED TO BE EXCEEDED IN T YEARS
C
C      AFTER THESE CARDS THE EARTHQUAKE DATA FILE FOLLOWS.IT CONTAINS YEAR,

C     ORIGIN TIME,LAT,LON,DEPTH,AND MAGNITUDE.
C
C     DATA STREAM  3  (CARDS 1-3)
C
C     EACH OF THESE CARDS CONTAINS THE INITIAL VALUE AND THE ST.
C     DEVIATION OF THE PARAMETER A(I).
C
C     FIRST CARD  : W+OR-DELTAW
C     DECOND CARD : U+OR-DELTAU
C     THIRD CARD  :LAMDA+OR-DELTALAMDA
C     FORMAT(2F7.3)
C
C
C
      READ 101, EMIN,EMAX,BMIN,BMAX,DEB,SIZE
      READ 102, IDENT,MODE,MINT,MAXT,LIST2,LIST1,INT
      READ 101, EMMIN,PROB
C
      DIMENSION A(11,37,85),GY(85),YM(85),Y(85),RY(4),Q(6),TITLE(4)
     1,PRO(85),YML(85),A1(5),DELTAA1(5),SIGMAA1(5),YFIT(85),
     2 SIGMAB(10),DERIV(10),ARRAY(10,10),B(10),SIGMAG(10),WEITH(85),
     3 ALPHA(10,10),BETA(10),SIGYML(85),YT(10),YPD(10)
      PI=3.141592
      RAD=180./PI
      DEBY=1./DEB
      FLAMDA=0.001
      NTERMS=3
      DO 11 J=1,NTERMS
      READ(3,103) A1(J),DELTAA1(J)
  103 FORMAT(2F7.3)
```

```
   11 CONTINUE
      AA1=A1(1)
      AA2=A1(2)
      AA3=A1(3)
      IA=(EMAX-EMIN)*DEBY+1.
      JA=(BMAX-BMIN)*DEBY+1.
      KA=MAXT-MINT+1
      PRINT 2
      PRINT 5000
      DO 10  I=1,IA
      DO 10  J=1,JA
      DO 10  K=1,KA
   10 A(I,J,K)=0.
      NO=0
   20 READ 200,IYEAR,TITLE,O3,EN,BO,IDEPTH,EM
      IF(EM.EQ.0.)  GO TO 90
      IF(IYEAR.LT.MINT.OR.IYEAR.GT.MAXT)  GO TO 20
      IF(EM.LT.EMMIN)  GO TO 20
      NO=NO+1
      DEPTH=IDEPTH
      ENL=EMAX
      DO 15 I=1,IA
      E1=ENL-SIZE
      E2=ENL+SIZE
      IF(EN.GE.E2)  GO TO 15
      IF(EN.LT.E1)  GO TO 15
      BOY=BMIN
      DO 25  J=1,JA
      B1=BOY-SIZE
      B2=BOY+SIZE
      IF(BO.LT.B1)  GO TO 25
      IF(BO.GE.B2)  GO TO 25
            CALL DIRCOS(EN ,BO ,AE,BE,CE)
            CALL DIRCOS(ENL,BOY,AP,BP,CP)
      S=(AE-AP)**2+(BE-BP)**2+(CE-CP)**2

      IF(S.GT.0.)  GO TO 27
      DIST=1.0
      GO TO 28
   27 S=1.-S*0.5
      S=SQRT(1.-S*S)/S
      DIST=ATAN(S)*RAD*111.11
      RS=SIZE*111.11
      IF(DIST.GT.RS)  GO TO 25
   28 R=SQRT(DIST*DIST+DEPTH*DEPTH)
      GO TO (21,22,23,24), IDENT
C
C     THE FOLLOWING FORMULA USED FOR ACCELERATION.
C
C    A=2164*EXP(EM*0.7)*(R+20)**-1.80 SEE TEXT EQUATION 7-2
   21 US=-1.80
      AMP=2164.*EXP(EM*0.7)*(R+20.)**US
      GO TO 26
C
```

```
C       THE FOLLOWING FORMULA USED FOR VELOCITY,
C       D.L.ORPHAL AND J.A.LAHOUD, BSSA,VOL:64
C
   22 US=-1.34
      AMP=0.726*10.**(0.52*EM)*(R**US)
      GO TO 26
C
C       ... AND FOR DISPLACEMENT CALCULATION
C
   23 US=-1.18
      AMP=0.0471*10.**(EM*0.57)*(R**US)
      GO TO 26
   24 AMP=EM
   26 K=IYEAR-MINT+1
      IF(AMP.GT.A(I,J,K))  A(I,J,K)=AMP
      IF(LIST1.EQ.0)  GO TO 25
C      PRINT 2100,K,IYEAR,TITLE,O3,EN,BO,IDEPTH,EM,
C     1DIST,R,AMP,A(I,J,K)
   25 BOY=BOY+DEB
   15 ENL=ENL-DEB
      GO TO 20
   90 PRINT 900, NO
      GO TO (110,120,130,140), IDENT
  110 PRINT 1500
      GO TO 150
  120 PRINT 1600
      GO TO 150
  130 PRINT 1700
      GO TO 150
  140 PRINT 1800
  150 CONTINUE
      PRINT 250, RS
      PRINT 1
      RYEAR=25.
      PROB=ALOG(-ALOG(1.-PROB))
      DO 55  I=1,4
      RY(I)=ALOG(RYEAR)
   55 RYEAR=RYEAR*2.
      ENL=EMAX
      DO 50  I=1,IA
      BOY=BMIN
      DO 60  J=1,JA
      PRINT 400, ENL,BOY
      L=0
      DO 70  K=1,KA
      IF(A(I,J,K).EQ.0.)  GO TO 70
      L=L+1
   70 YM(K)=A(I,J,K)
      IF(L.LT.17)     GO TO 60
      SK=L+1
      LL=SK-1
      IF(LIST2.GT.0)  PRINT 800
            CALL RANK (K,YM,Y)
      M=KA-L
```

```
      L=0
      DO 95  K=1,KA
      LYEAR=MINT+K-1
      IF(A(I,J,K).EQ.0.)  GO TO 95
      L=L+1
      SJ=(MAXT-MINT+1)-SK+1+L-0.44
      PRO1=SJ/(MAXT-MINT+1.12)
      GY(L)=-ALOG(-ALOG(PRO1))
      M=M+1
      PRO(L)=PRO1
      YML1=Y(M)
      YM(L)=YML1
      YML(L)=YML1
      GYK=GY(L)
      IF(LIST2.EQ.0)  GO TO 95
      PRINT 950, K,LYEAR,A(I,J,K),YML1,GYK,PRO1,L
   95 CONTINUE
      PRINT 350, L,MINT,LYEAR
      DO 56 II=1,LL
      SIGYML(II)=0.3
   56 CONTINUE
      GO TO (12,13),INT
C
   12  CALL LINFIT(GY,YM,SIGYML,L,MODE,ALFA,SIGMAA,BHTA,SIGMAB,R)
      YMOD=ALFA
      YP=ALFA-(PROB*BHTA)
      PRINT 2
      KYEAR=1
      PRINT 1300, YMOD,YP,KYEAR
      KYEAR=25
      DO 75  N=1,4
      RB=RY(N)*BHTA
      YT(N)=YMOD+RB
      YPD(N)=YP+RB
C      PRINT 1400, YT,YPD,KYEAR
   75 KYEAR=KYEAR*2
      WRITE(8,131)ENL,BOY,YMOD,(YT(N),N=1,4)
  131 FORMAT(7(1X,F7.2))
      WRITE(9,131)ENL,BOY,YP,(YPD(N),N=1,4)
      PRINT 2
      PRINT 1
      GO TO 60
   13 CALL CURFIT(PRO,YML,SIGYML,LL,NTERMS,MODE,A1,DELTAA1,SIGMAA1,
     1FLAMDA,YFIT,CHISQR,SIGMAB,SIGMAG)
   14 Z=CHISQR
      CALL CURFIT(PRO,YML,SIGYML,LL,NTERMS,MODE,A1,DELTAA1,SIGMAA1,
     1FLAMDA,YFIT,CHISQR,SIGMAB,SIGMAG)
      U=Z-CHISQR
      IF(U.GT.0.01) GO TO 14
      WRITE(6,31)CHISQR
   31 FORMAT(1H ,'FINAL CHISQR=',F10.5)
C
C     PRINT  PARAMETERS AND ST.DEVIATIONS
C
```

```
      WRITE(6,16)A1(1),SIGMAA1(1)
   16 FORMAT(1H ,'W=',F7.4,3X,'SD.OF W=',F7.4)
      WRITE(6,17)A1(2),SIGMAA1(2)
   17 FORMAT(1H ,'U=',F7.4,3X,'SD.OF U=',F7.4)
C
C     PRINT COVARIANCE MATRIX
C
      WRITE(6,18)A1(3),SIGMAA1(3)
   18 FORMAT(1H ,'L=',F7.4,3X,'SD.OF L=',F7.4)
      DO 19 JJ=1,3
      WRITE(6,32)JJ,SIGMAB(JJ),JJ,SIGMAG(JJ)
   32 FORMAT(1H ,'COV2',I1,'=',F7.4,2X,'COV1',I1,'=',F7.4)
   19 CONTINUE
      C=0.05
C
C     ANNUAL  MODE
C
      ZM1=A1(1)-(A1(1)-A1(2))*(1.-A1(3))**A1(3)
C
C     N-YEAR MODE
C
      ZMN=A1(1)-(A1(1)-A1(2))*((1.-A1(3))/100.)**A1(3)
C
C     UPPER BOUND FOR MAXIMUM EXPECTED MAGNITUDE IN N YEARS
C
      ZUN=A1(1)-(A1(1)-A1(2))*((-1./100.)*ALOG(1.-C/2.))**A1(3)
C
C     MAGNITUDE WITH 70% PROBABILITY TO BE THE MAXIMUM ANNUAL MAGNITUDE
C
      ZM170=A1(1)-(A1(1)-A1(2))*((-ALOG(.70))**A1(3))
C
C   MAGNITUDE WITH 70%PROB.TO BE THE MAXIMUM IN THE NEXT N YEARS
C
      ZMN70=A1(1)-(A1(1)-ZM170)/(100.**A1(3))
      WRITE(6,527)ZM1,ZMN,ZUN
  527  FORMAT(1H ,'ANNUAL MODE=',F6.2,2X,'100 YEAR MODE=',
     1F6.2,2X,'UP.BOUND OF 100 YEAR MODE WITH 95 CON.LEV.=',F6.2)
      WRITE(7,528)ENL,BOY,ZM1,ZM170,ZMN,ZUN,ZMN70,YML1,L
  528 FORMAT(8F8.2,I6)
      A1(1)=AA1
      A1(2)=AA2
      A1(3)=AA3
   60 BOY=BOY+DEB
   50 ENL=ENL-DEB

    1 FORMAT(1H1)
    2 FORMAT(1H )
  101 FORMAT(6F6.2)
  102 FORMAT(7I5)
  200  FORMAT(1X,I4,4A4,F4.1,2F8.2,I5,9X,F3.1)
  250 FORMAT(5X,'SIZE OF EARTHQUAKE SOURCE REGION',
     1F8.2,' KMS.',/)
  300 FORMAT(5X,2I3,I5,3X,2I3,F6.1,F6.2,2(3X,F5.2,F6.2),
     1I5,F6.1)
```

```
 350 FORMAT(/19X,'NUMBER OF OBSERVED SHOCKS',I5,/,19X,
    1'BETWEEN',I7,'  -  ',I5,' YEARS')
    19X,'X      INTENSITY')
 550 FORMAT(6(2X,F8.1),' RETURN P.')
 600 FORMAT(6F10.2)
 650 FORMAT(6F10.7,' SHOCKS/Y.')
 800 FORMAT(13X,'K YEAR',5X,'AMP.',5X,'RANKED',6X,'G(Y)',
    15X,'PROB.',3X,'L')
 900 FORMAT(5X,'NUMBER OF PROCESSED EARTHQUAKE DATA',I5)
 950 FORMAT(10X,I4,I5,4F10.3,I4)
1300 FORMAT(/16X,2(2X,F9.2),I5,'  YEAR')
1400 FORMAT( 16X,2(2X,F9.2),I5,'  YEARS')
1500 FORMAT(5X,'RISK ANALYSIS BASED ON THE ACCELERATION VALUES
    1 IN CM./SEC.**2')
1600 FORMAT(5X,'RISK ANALYSIS BASED ON THE VELOCITY VALUES IN'
    1' CM./SEC.')
1700 FORMAT(5X,'RISK ANALYSIS BASED ON THE DISPLACEMENT VALUES',
    1' IN CM.')
1800 FORMAT(5X,'RISK ANALYSIS BASED ON THE MAGNITUDE VALUES')
2100 FORMAT(1X,I2,I4,4A4,F4.1,2F8.2,I5,F5.1,2F7.1,2F7.2)
5000 FORMAT(/9X,'RISK ANALYSIS IN A GIVEN REGION BASED ON THE'/,
    15X,'GUMBEL"S STATISTICAL THEORY OF EXTREME VALUES, '/)
     STOP
     END


     SUBROUTINE DIRCOS(RLA,RLO,A,B,C)
     PI=3.141592
     RAD=PI/180.
     EN=RLA*RAD
     BO=RLO*RAD
     EN=ATAN(0.99238*SIN(EN)/COS(EN))
     C= SIN(EN)
     X=-COS(EN)
     D= SIN(BO)
     E=-COS(BO)
     A= X*E
     B=-D*X
     RETURN
     END

     SUBROUTINE RANK(N,Y,X)
     DIMENSION X(85),Y(85)
     YMAX=1.E38
     X1=YMAX
     DO 10  J=1,N
     YMIN=1.E37
     DO 20  I=1,N
     IF(Y(I).GE.YMIN)   GO TO 20
     YMIN=Y(I)
     K=I
     IF(Y(I).GT.X1)   GO TO 20
```

```
      YMIN=Y(I)
   20 CONTINUE
      X(J)=YMIN
      X1=YMIN
   10 Y(K)=YMAX
      RETURN
      END

C       SUBROUTINE CURVFIT (X,Y,SIGMAY,NPTS,NTERMS,MODE,A,DELTAA,
C       SIGMAA,FLAMDA,YFIT ,CHISQR)
C     PURPOSE
C       MAKE A LEAST-SQUARES FIT TO A NON LINEAR FUNCTION
C         WITH A LINEARISATION OF THE FITTING  FUNCTION
      SUBROUTINE CURFIT (X,Y,SIGMAY,NPTS,NTERMS,MODE,A,DELTAA,
     1 SIGMAA,FLAMDA,YFIT,CHISQR,SIGMAB,SIGMAG)
      DOUBLE PRECISION ARRAY
      DIMENSION X(100),Y(100),SIGMAY(100),A(10),DELTAA(10),SIGMAA(10),
     1 YFIT(100),SIGMAB(10),SIGMAG(10)
      DIMENSION WEIGHT(100),ALPHA(10,10),BETA(10),DERIV(10),
     1 ARRAY(10,10),B(10)
   11 NFREE=NPTS-NTERMS
      IF(NFREE) 13,13,20
   13 CHISQR=0.
      GO TO 110
C
C         EVALUATE WEIGHTS
C
   20 DO 30 I=1,NPTS
   21 IF (MODE) 22,27,29
   22 IF (Y(I)) 25,27,23
   23 WEIGHT(I)=1./Y(I)
      GO TO 30
   25 WEIGHT(I)=1./(-Y(I))
      GO TO 30
   27 WEIGHT(I)=1.
      GO TO 30
   29 WEIGHT(I)=1./SIGMAY(I)**2
   30 CONTINUE
C
C    EVALUATE ALPHA AND BETA MATRICES
C
   31 DO 34 J=1,NTERMS
      BETA(J)=0.
      DO 34 K=1,J
   34 ALPHA(J,K)=0.
   41 DO 50 I=1,NPTS
      CALL FDERIV (X,I,A,DELTAA,NTERMS,DERIV)
      DO 46 J=1,NTERMS
      BETA(J)=BETA(J)+WEIGHT(I)*(Y(I)-FUNCTN(X,I,A))*DERIV(J)
      DO 46 K=1,J
   46 ALPHA(J,K)=ALPHA(J,K)+WEIGHT(I)*DERIV(J)*DERIV(K)
   50 CONTINUE
   51 DO 53 J=1,NTERMS
      DO 53 K=1,J
```

```
   53 ALPHA(K,J)=ALPHA(J,K)
C
C     EVALUATE CHI SQUARE AT STARTING POINT
C
   61 DO 62 I=1,NPTS
   62 YFIT(I)=FUNCTN(X,I,A)
   63 CHISQ1=FCHISQ(Y,SIGMAY,NPTS,NFREE,MODE,YFIT)

C        WRITE(6,66) CHISQ1
  66   FORMAT(1H ,'CHISQ1=',F10.5)
C
C   INVERT MODIFIED CURVATURE MATRIX TO FIND NEW PARAMETERS
C
   71 DO 74 J=1,NTERMS
      DO 73 K=1,NTERMS
   73 ARRAY(J,K)=ALPHA(J,K)/SQRT(ALPHA(J,J)*ALPHA(K,K))
   74 ARRAY(J,J)=1.+FLAMDA
   80 CALL MATINV (ARRAY,NTERMS,DET)
   81 DO 84 J=1,NTERMS
      B(J)=A(J)
      DO 84 K=1,NTERMS
   84 B(J)=B(J)+BETA(K)*ARRAY(J,K)/SQRT(ALPHA(J,J)*ALPHA(K,K));
C
C   IF CHI SQUARE,INCREASE FLAMDA AND TRY AGAIN
C
   91 DO 92 I=1,NPTS
   92 YFIT(I)=FUNCTN(X,I,B)
   93 CHISQR=FCHISQ(Y,SIGMAY,NPTS,NFREE,MODE,YFIT)
C        WRITE(6,999) CHISQR
 999  FORMAT(1H ,'CHISQR=',F10.5)
C        WRITE(6,998) A(1),A(2),A(3)
 998  FORMAT(1H ,'W=',F7.4,3X,'U=',F7.4,3X,'L=',F7.4)
      IF (CHISQ1-CHISQR) 95,101,101
   95 FLAMDA=10.*FLAMDA
      GO TO 71
C
C      EVALUATE PARAMETERS AND UNCERTAINTIES
C
  101 DO 103 J=1,NTERMS
      A(J)=B(J)
      SIGMAB(J)=ARRAY(J,2)/SQRT(ALPHA(J,J)*ALPHA(2,2))
      SIGMAG(J)=ARRAY(J,1)/SQRT(ALPHA(J,J)*ALPHA(1,1))
  103 SIGMAA(J)=DSQRT(ARRAY(J,J)/ALPHA(J,J))
      FLAMDA=FLAMDA/10.
  110 RETURN
      END
C
C    FUNCTION  FUNCTN (FOR THE THIRD ASYMPTOTIC DISTRIBUTION)

C    FUNCTN(X,I,A)=W-(W-U)*Z(I)**L
C
      FUNCTION FUNCTN(X,I,A)
      DIMENSION X(100),A(10)
      XI=X(I)
```

```
      Z1=-ALOG(XI)
      Z2=Z1**A(3)
      Z3=(A(1)-A(2))*Z2
      FUNCTN=A(1)-Z3
   20 RETURN
      END
C
C    FUNCTION  FCHISQ
C
C     PURPOSE
C   EVALUATE REDUCED CHI SQUARE FOR FIT TO DATA
C       FCHISQ=SUM((Y-YFIT)**2/SIGMA**2)/NFREE
C
      FUNCTION FCHISQ(Y,SIGMAY,NPTS,NFREE,MODE,YFIT)
      DOUBLE PRECISION CHISQ,WEIGHT
      DIMENSION Y(100),SIGMAY(100),YFIT(100)
   11 CHISQ=0.
   12 IF (NFREE) 13,13,20
   13 FCHISQ=0.
      GO TO 40
C
C     ACCUMULATE  CHI SQUARE
C
   20 DO 30 I=1,NPTS
   21 IF (MODE)  22,27,29
   22 IF(Y(I)) 25,27,23
   23 WEIGHT=1./Y(I)
      GO TO 30
   25 WEIGHT=1./(-Y(I))
      GO TO 30
   27 WEIGHT=1.
      GO TO 30
   29 WEIGHT=1./SIGMAY(I)**2
   30 CHISQ=CHISQ+WEIGHT*(Y(I)-YFIT(I))**2
C
C   DIVIDE BY NUMBER OF DEGREES OF FREEDOM
C
   31 FREE=NFREE
   32 FCHISQ=CHISQ/FREE
   40 RETURN
      END
C    SUBROUTINE FDERIV         ANALYTICAL
C
C      PURPOSE
C       EVALUATE DERIVATIVES OF FUNCTION FOR LEAST - SQUARES SEARCH
C        FOR ARBITRARY FUNCTION GIVEN BY FUNCTN
C
      SUBROUTINE FDERIV (X,I,A,DELTAA,NTERMS,DERIV)
      DIMENSION X(100),A(10),DELTAA(10),DERIV(10)
      XI=X(I)
      Z1=-ALOG(XI)
      Z2=Z1**A(3)
      DERIV(1)=1.-Z2
      DERIV(2)=Z2
```

```
      DERIV(3)=-(A(1)-A(2))*Z2*ALOG(Z1)
      RETURN
      END
C
C        SUBROUTINE  MATINV
C
C        PURPOSE
C
C   INVERT A SYMMETRIC MATRIX AND CALCULATE ITS DETERMINANT
      SUBROUTINE MATINV (ARRAY,NORDER,DET)
      DOUBLE PRECISION ARRAY,AMAX,SAVE
      DIMENSION ARRAY(10,10),IK(10),JK(10)
      DET=1.
      DO 100 K=1,NORDER
C
C   FIND LARGEST ELEMENT ARRAY(I,J) IN REST OF MATRIX
C
      AMAX=0.
   21 DO 30 I=K,NORDER
      DO 30 J=K,NORDER
   23 IF (DABS(AMAX)-DABS(ARRAY(I,J))) 24,24,30
   24 AMAX=ARRAY(I,J)
      IK(K)=I
      JK(K)=J
   30 CONTINUE
C
C  INTERCHANGE ROWS AND COLUMNS TO PUT AMAX IN ARRAY(K,K)
C
   31 IF (AMAX) 41,32,41
   32 DET=0.
      GO TO 140
   41 I=IK(K)
      IF (I-K) 21,51,43
   43 DO 50 J=1,NORDER
      SAVE=ARRAY(K,J)
      ARRAY(K,J)=ARRAY(I,J)
   50 ARRAY(I,J)=-SAVE
   51 J=JK(K)
      IF (J-K) 21,61,53
   53 DO 60 I=1,NORDER
      SAVE=ARRAY(I,K)
      ARRAY(I,K)=ARRAY(I,J)
   60 ARRAY(I,J)=-SAVE
C
C   ACCUMULATE ELEMENTS OF INVERSE MATRIX
C
   61 DO 70 I=1,NORDER
      IF (I-K) 63,70,63
   63 ARRAY(I,K)=-ARRAY(I,K)/AMAX
   70 CONTINUE
   71 DO 80 I=1,NORDER
      DO 80 J=1,NORDER
      IF (I-K) 74 ,80 ,74
   74 IF (J-K) 75,80,75
```

```
   75 ARRAY(I,J)=ARRAY(I,J)+ARRAY(I,K)*ARRAY(K,J)
   80 CONTINUE
   81 DO 90 J=1,NORDER
      IF (J-K) 83,90,83
   83 ARRAY(K,J)=ARRAY(K,J)/AMAX
   90 CONTINUE
      ARRAY(K,K)=1./AMAX
  100 DET=DET*AMAX
C
C   RESTORE ORDERING OF MATRIX
C
  101 DO 130 L=1,NORDER
      K=NORDER-L+1
      J=IK(K)
      IF (J-K) 111,111,105
  105 DO 110 I=1,NORDER
      SAVE=ARRAY(I,K)
      ARRAY(I,K)=-ARRAY(I ,J)
  110 ARRAY(I,J)=SAVE
  111 I=JK(K)
      IF (I-K) 130,130,113
  113 DO 120 J=1,NORDER
      SAVE=ARRAY(K ,J)
      ARRAY(K,J)=-ARRAY(I,J)
  120 ARRAY(I,J)=SAVE
  130 CONTINUE
  140 RETURN
      END
C
C
      SUBROUTINE LINFIT(X,Y,SIGMAY,NPTS,MODE,A,SIGMAA,B,SIGMAB,R)
      DOUBLE PRECISION SUM,SUMX,SUMY,SUMX2,SUMXY,SUMY2
      DOUBLE PRECISION XI,YI,WEIGHT,DELTA,VARNCE
      DIMENSION X(100),Y(100),SIGMAY(100)
C    ACCMULATE WEIGHTED SUMS
C
   11 SUM=0.
      SUMX=0.
      SUMY=0.
      SUMX2=0.
      SUMXY=0.
      SUMY2=0.
   21 DO 50 I=1,NPTS
      XI=X(I)
      YI=Y(I)
      IF(MODE) 31,36,38
   31 IF(YI) 34,36,32
   32 WEIGHT=1./YI
      GO TO 41
   34 WEIGHT=1./(-YI)
      GO TO 41
   36 WEIGHT=1.
      GO TO 41
   38 WEIGHT=1./SIGMAY(I)**2
```

```
   41 SUM=SUM+WEIGHT
      SUMX=SUMX+WEIGHT*XI
      SUMY=SUMY+WEIGHT*YI
      SUMX2=SUMX2+WEIGHT*XI*XI
      SUMXY=SUMXY+WEIGHT*XI*YI
      SUMY2=SUMY2+WEIGHT*YI*YI
   50 CONTINUE
C
C  CALCULATE COEFFICIENTS AND ST. DEVIATIONS
C
   51 DELTA=SUM*SUMX2-SUMX*SUMX
      A=(SUMX2*SUMY-SUMX*SUMXY)/DELTA
   53 B=(SUMXY*SUM-SUMX*SUMY)/DELTA
   61 IF(MODE) 62,64,62
   62 VARNCE=1.
      GO TO 67
   64 C=NPTS-2
      VARNCE=(SUMY2+A*A*SUM+B*B*SUMX2-2.*(A*SUMY+B*SUMXY-A*B*SUMX))/C
   67 SIGMAA=DSQRT(VARNCE*SUMX2/DELTA)
   68 SIGMAB=DSQRT(VARNCE*SUM/DELTA)
   71 R=(SUM*SUMXY-SUMX*SUMY)/DSQRT(DELTA*(SUM*SUMY2-SUMY*SUMY))

      WRITE(6,100)A,SIGMAA,B,SIGMAB,R
  100 FORMAT(1H ,'U='F7.4,2X,'S.D.OF U=',F6.4,'1/A=',F7.4,
     12X,'S.D.OF 1/A=',F6.4,30X,'R=',F10.5)
      RETURN
      END
C
C
C
C     EXAMPLE OF INPUT DATA
C
C     STREAM  5
C
C     -39.95-45.28-19.00-28.00-00.50--1.00
C     -----1----1-1900-1970----1----1----1
C     --4.20--0.30
C     -1920-APR 15---09-20-37.3---39.99---20.25--123---------5.7
C
C
C     STREAM  3
C
C     ---8.55---0.80
C     ---7.30---0.08
C     ---0.20---0.04
C
C
```

APPENDIX B

Earthquake catalogue for Greece since 1901

EARTHQUAKE CATALOGUE FOR GREECE SINCE 1901

The geographic region studied is 33.0°N to 42.5°N and 19.0°E to 29.0°E. The parameters listed for each earthquake are: i) Date, ii) Origin time, iii) Latitude, iv) Longitude, v) focal depth, vi) Number of reported stations, vii) Surface-wave magnitude, and viii) Shift of recalculated epicentres from the ISS locations in distance (km) and in azimuth (degrees). The catalogue presented here contains:

i) Earthquakes for which all parameters are recalculated (1917-1963). For these earthquakes, the focal depth error is estimated to be less than ± 10km for $h < 50$km and ± 15km for $h \geq 50$km.

ii) Earthquakes which do not permit relocations for the period 1901-1963. For these earthquakes, instead of the number of reported stations, the appropriate reference is given.

iii) Earthquakes for which relocations are not attempted (1964-1968). For these earthquakes all parameters, except magnitude, are those given by ISC.

Since 1907 the surface-wave magnitude for all earthquakes in the catalogue are determined using the Swedish network ground amplitude records and the conversion formulae (5-4), (5-7), and (5-9). The standard deviation of these magnitudes may, in general, be estimated as around ± 0.3 units.

The abbreviations used for references are:

UNS: Earthquake catalogue of Shebalin et al, 1974

ATB: Earthquake catalogue of Alsan et al, 1975, and

ROT: Earthquake catalogue of Rothé, 1969.

Complete details of the method by which this catalogue was produced are given in Chapter V.

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1901 DEC 24	23 18 00	37.2	22.2	15	UNS	5.8
1902 APR 11	18 35 00	38.5	23.5	24	UNS	5.8
1902 JUL 05	14 56 30	40.8	23.2	11	UNS	6.6
1902 NOV 05	23 50 00	38.2	20.5	13	UNS	5.5
1903 MAR 15	19 03 00	37.8	21.2	18	UNS	5.7
1903 MAY 29	09 34 54	39.8	18.7	30	UNS	6.0
1903 JUL 21	13 03 00	38.2	21.8	20	UNS	5.6
1903 AUG 11	04 32 54	36.3	23.0	120	UNS	8.0
1903 NOV 25	23 16 42	42.1	23.2	6	UNS	6.5
1904 APR 04	10 02 34	41.78	22.98	15	UNS	7.1
1904 04	10 25 55	41.80	23.10	18	UNS	7.8
1904 04	11 09 00	42.0	23.0	15	UNS	5.5
1904 13	09 55 00.0	42.41	22.8	45	UNS	5.5
1904 19	18 14 00	42.0	23.1	8	UNS	5.9
1904 25	20 02 00	42.0	23.0	15	UNS	5.5
1904 AUG 11	06 08 00	37.7	26.9	5	UNS	6.2
1904 18	20 07 00	38.0	27.0	30	UNS	6.0
1904 OCT 10	17 40 00	38.4	27.2	20	UNS	5.8
1905 JAN 20	02 32 30	39.7	22.9	5	UNS	5.6
1905 JUN 01	04 42 15	42.0	19.5	18	UNS	6.6
1905 01	21 46 48	42.3	19.2	20	UNS	5.5
1905 03	05 10 43	42.1	19.6	12	UNS	5.5
1905 JUL 16	12 21 04	42.0	19.6	12	UNS	5.4
1905 AUG 04	05 09 00	42.1	19.6	9	UNS	5.9
1905 06	23 45 55	42.0	19.5	20	UNS	5.5
1905 OCT 08	07 27 30	41.8	23.1	19	UNS	6.4
1905 23	02 38 36	41.4	24.0	65	UNS	5.6
1905 NOV 08	22 06 00	40.3	24.4	17	UNS	7.4
1905 18	00 19 00	41.0	23.0	16	UNS	5.6
1906 MAR 03	21 56 00	41.0	20.0	5	UNS	5.7
1906 SEP 28	02 30 00	40.9	20.7	20	UNS	5.7
1907 AUG 16	13 00 00	41.1	21.2	13	UNS	6.2
1908 MAY 17	12 30 42	35.5	24.0	120	UNS	6.4
1908 JUN 23	14 45 00	38.4	27.2	25	UNS	5.1
1909 FEB 15	09 34 00	42.5	26.5	6	UNS	6.1
1909 MAY 30	06 14 00	38.25	22.2	20	UNS	6.0
1909 JUN 15	23 30 00	39.2	22.2	14	UNS	5.6
1909 JUL 15	00 34 42	37.9	21.5	3	UNS	5.7
1909 OCT 29	16 04 42	38.0	27.0	20	UNS	5.5
1910 FEB 18	05 09 18	35.7	24.0	90	UNS	6.2
1910 23	07 52 00	41.7	23.4	12	UNS	5.2
1910 AUG 02	02 33 09	37.0	21.0	20	UNS	5.0
1910 21	16 11 30	34.4	27.0	173	UNS	6.0
1911 FEB 18	21 35 15	40.9	20.75	15	UNS	6.4
1911 MAR 11	20 40 18	42.0	23.0	50	UNS	5.4
1911 APR 04	15 43 53	36.5	26.5	140	UNS	6.5
1911 30	20 42 30	36.0	30.0	140	UNS	6.0
1911 OCT 22	22 32 00	39.5	23.0	15	UNS	5.6
1912 JAN 24	16 22 53	38.1	20.5	11	UNS	6.3
1912 25	19 52 48	38.2	20.6	30	UNS	5.5
1912 FEB 13	08 03 54	40.9	20.6	16	UNS	5.8
1912 APR 19	00 20 00	38.2	20.5	10	UNS	5.1
1912 21	02 53 48	37.5	19.5	15	UNS	5.0
1912 MAY 17	16 38 00	34.5	24.8	30	UNS	5.7
1912 AUG 09	01 29 00	40.6	27.2	16	UNS	7.3

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	AZIM DEG
1912 AUG 10	09 23 00	40.6	27.1	15	UNS	6.5		
1912 10	18 30 00	40.6	27.1	15	UNS	5.3		
1912 SEP 13	23 31 00	40.1	26.8	15	UNS	6.9		
1913 JUL 06	07 05 48	35.9	23.2	15	UNS	5.3		
1913 SEP 30	07 33 36	35.0	24.0	60	UNS	5.7		
1914 SEP 17	13 06 40	37.8	21.0	40	UNS	5.5		
1914 OCT 17	06 22 32	38.2	23.5	8	UNS	6.0		
1914 17	10 42 00	38.2	23.5	24	UNS	5.3		
1914 NOV 23	09 06 00	38.8	20.6	8	UNS	5.0		
1914 27	14 39 44	38.8	20.6	6	UNS	6.1		
1915 JAN 27	01 09 26	38.5	20.6	15	UNS	6.3		
1915 JUN 04	17 22 02	39.1	21.4	4	UNS	6.0		
1915 24	05 20 36	35.0	24.0	36	UNS	5.2		
1915 AUG 07	15 04 03	38.5	20.5	12	UNS	6.5		
1915 10	00 47 55	38.5	20.5	7	UNS	5.7		
1915 10	02 02 34	38.5	20.5	16	UNS	6.2		
1915 11	09 10 15	38.5	20.5	4	UNS	5.8		
1915 11	09 58 10	38.5	20.5	6	UNS	5.4		
1915 19	06 42 16	39.0	20.0	14	UNS	6.0		
1916 FEB 06	14 39 40	39.0	23.5	14	UNS	5.5		
1916 MAY 20	22 14 00	38.2	23.2	28	UNS	5.5		
1916 SEP 27	15 02 13	38.8	23.0	6	UNS	5.8		
1916 NOV 25	02 02 48	38.0	19.0	15	UNS	5.1		
1917 MAR 14	18 13 32.8	39.70	20.30	15	8	5.1	232.40	305.68
1917 APR 26	13 14 30.1	39.56	19.91	18	8	5.0	49.72	189.00
1917 MAY 23	05 46 29.0	38.78	19.80	20	14	5.7	118.98	241.32
1917 AUG 20	23 02 12.4	40.31	25.29	62	18	6.1	64.09	250.94
1917 NOV 28	10 21 12.6	37.07	20.18	10	12	5.5	64.09	138.12
1917 DEC 24	09 13 58.2	38.65	21.86	15	17	5.8	410.81	241.32
1917 27	07 42 10.1	35.76	21.07	18	8	5.0	680.79	220.95
1918 JAN 27	12 56 35	38.5	22.0	24	UNS	5.1		
1918 FEB 09	12 28 47.2	39.26	23.65	50	12	5.7	445.40	237.46
1918 MAR 17	13 44 53.8	34.13	29.39	35	14	5.6	243.17	148.17
1918 JUL 04	11 25 00	40.2	20.5	15	UNS	5.2		
1918 16	20 03 45.7	36.22	27.26	113	28	6.2	86.88	95.59
1918 NOV 13	10 13 27	37.8	27.3	35	UNS	5.5		
1919 JAN 05	15 25 30	40.0	20.0	16	UNS	5.2		
1919 FEB 24	01 55 58.8	36.70	21.00	5	21	6.1	13.38	51.63
1919 APR 05	04 17 55	37.0	26.0	15	UNS	5.0		
1919 JUL 18	07 01 20	36.0	28.0	15	UNS	5.0		
1919 AUG 22	22 35 49.8	37.75	19.32	12	11	5.3	580.62	233.28
1919 OCT 25	17 10 12.0	36.56	25.86	59	25	5.8	50.59	194.40
1919 25	17 54 00.5	38.28	23.72	44	9	5.0	246.39	305.91
1919 NOV 18	21 54 57.0	39.41	26.09	20	27	7.0	140.19	261.85
1919 DEC 22	23 41 01.8	39.75	20.62	10	22	5.9	59.88	326.94
1920 JAN 09	12 00 00	41.8	26.2	20	UNS	5.6		
1920 FEB 25	23 34 30.3	40.30	19.16	45	11	5.3	362.11	298.56
1920 APR 02	15 34 25.8	36.75	26.64	10	ATB	5.5		
1920 MAY 01	06 34 40	37.0	28.7	30	UNS	5.0		
1920 JUL 21	14 29 42.5	35.32	25.05	123	14	5.6	205.51	300.34
1920 SEP 14	02 08 45.3	40.88	21.60	15	11	5.3	16.31	147.68
1920 28	15 17 37.3	37.89	28.35	10	ATB	5.7		
1920 OCT 13	23 12 00	38.0	19.8	15	UNS	5.0		
1920 21	18 57 51.7	39.43	20.36	10	18	5.7	70.60	153.89
1920 NOV 15	09 20 51.4	35.11	25.89	87	10	5.1	106.00	50.02

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	SHIFT AZIM DEG
1920 NOV 26	08 51 08.5	40.26	19.44	08	23	6.0	56.04	301.35
1920 27	16 26 20	39.3	26.5	14	UNS	5.3		
1920 29	15 48 05.8	40.56	21.29	12	11	5.2	126.22	60.04
1920 DEC 18	02 01 32.3	41.18	20.58	10	11	5.2	140.05	20.35
1921 JAN 27	11 30 09	36.0	28.0	15	UNS	5.4		
1921 MAR 30	15 06 08.8	41.48	20.03	18	25	5.7	254.73	283.06
1921 MAY 10	04 56 08.7	38.93	20.55	12	17	5.1	415.47	237.72
1921 22	21 23 16	37.0	28.7	32	UNS	5.2		
1921 JUN 26	03 40 57.1	39.75	20.20	54	23	5.4	85.17	306.24
1921 AUG 10	14 10 40.4	42.39	21.86	71	31	6.0	157.37	10.87
1921 SEP 13	08 59 56.6	38.82	20.93	11	26	5.6	98.62	22.29
1921 14	03 27 36.8	37.51	20.45	28	15	5.1	54.82	184.65
1922 JAN 12	10 41 47.9	39.28	20.70	8	13	5.0	100.13	142.85
1922 MAR 08	17 34 02.9	34.21	23.46	50	18	5.5	145.35	257.64
1922 APR 11	04 35 20.6	40.04	19.25	15	21	5.5	51.54	175.22
1922 JUN 05	04 31 04.8	34.66	22.59	18	31	5.8	38.98	167.66
1922 09	15 36 34.4	41.71	20.77	45	13	5.0	144.68	187.61
1922 09	16 13 31.2	41.50	19.48	40	13	5.1	208.70	217.49
1922 JUL 22	16 26 56.8	34.58	22.44	46	26	5.4	47.18	186.74
1922 AUG 08	03 49 15.0	37.58	24.29	67	29	5.4	114.47	85.16
1922 11	08 19 46.2	34.85	27.07	53	40	6.5	153.07	213.77
1922 13	00 09 57.2	35.31	27.80	45	47	6.9	78.79	193.37
1922 13	12 46 11.2	35.61	27.70	34	26	5.8	51.31	212.16
1922 15	14 53 26.6	37.89	23.17	97	15	5.1	46.04	19.05
1922 NOV 04	04 20 18.6	36.64	20.32	35	31	6.0	43.32	201.96
1922 11	22 13 10.5	37.84	22.03	32	16	5.2	93.66	294.09
1922 DEC 07	16 22 28.7	42.08	21.06	15	21	5.8	247.71	20.75
1922 07	16 37 00.9	40.01	21.51	25	10	5.5	129.08	89.02
1923 JAN 21	04 13 32.5	36.55	20.14	10	20	5.2	59.56	212.87
1923 MAR 10	19 48 51.6	34.62	26.53	12	24	5.5	90.16	278.78
1923 MAY 20	20 51 40.8	38.28	20.14	20	16	5.2	135.79	213.69
1923 29	11 35 04.9	40.51	25.80	160	ATB	5.2		
1923 JUN 04	20 33 34.9	37.15	24.51	118	13	5.1	203.58	334.39
1923 AUG 01	08 16 34.7	34.67	25.36	91	34	5.5	129.79	106.01
1923 OCT 09	23 10 21.0	37.05	19.93	15	9	5.0	266.85	200.91
1923 DEC 05	20 56 51.4	39.84	23.60	20	50	6.6	38.92	242.68
1924 JAN 22	11 05 44.1	39.51	28.40	80	ATB	5.3		
1924 FEB 16	09 01 06	37.5	23.0	15	15	5.5		
1924 NOV 13	09 43 59.0	39.20	20.90	85	17	5.3	117.89	138.68
1924 DEC 23	17 04 50	42.1	24.7	22	13	5.1		
1925 FEB 07	12 14 45.4	35.37	20.67	5	25	5.5	152.98	144.80
1925 MAR 17	15 32 00	37.2	26.2	15	13	5.0		
1925 APR 05	03 04 43.3	35.06	29.34	150	27	5.7	58.03	147.54
1925 05	03 53 55.4	36.87	29.12	3	10	5.3	152.50	4.03
1925 12	19 27 00.9	38.64	23.52	24	14	5.0	598.99	307.19
1925 15	06 14 30	35.5	29.0	15	UNS	5.1		
1925 JUL 06	12 15 54.3	37.79	21.94	70	53	5.8	45.40	120.92
1925 AUG 16	20 59 14.6	37.44	28.77	10	ATB	5.0		
1925 SEP 01	08 16 30.4	37.56	29.17	130	23	5.4	226.34	225.62
1926 JAN 13	01 46 58.2	38.06	28.81	52	28	5.8	61.12	276.49
1926 13	08 08 40.7	38.43	28.68	12	24	5.7	86.38	303.86
1926 FEB 26	15 46 34.8	37.17	21.59	8	35	5.8	130.31	254.09
1926 26	16 08 26.7	37.85	21.47	6	29	5.6	140.53	286.52
1926 MAR 01	20 02 01.8	37.15	29.61	68	49	6.1	52.33	318.32
1926 18	14 06 14.0	35.99	30.13	42	81	7.0	123.92	27.31

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	AZIM DEG
1926 MAR 18	17 52 52.6	35.86	30.05	61	36	5.2	103.25	66.90
1926 19	00 28 30.0	36.23	29.93	25	30	5.0	116.78	45.77
1926 24	07 04 42.9	35.90	28.97	90	24	5.5	44.75	356.51
1926 31	15 06 45	36.0	29.0	15	UNS	5.0		
1926 APR 22	07 11 54.1	35.99	29.23	140	ATB	5.2		
1926 JUN 10	19 16 24.4	38.84	21.20	76	25	5.1	119.38	288.85
1926 26	19 46 42.1	36.75	26.98	109	96	7.3	123.79	312.58
1926 JUL 05	09 21 57.3	36.55	26.56	175	19	5.1	134.66	218.71
1926 AUG 18	17 05 02.3	38.08	20.93	56	42	5.5	39.10	76.63
1926 30	11 38 04.5	36.76	23.16	26	75	7.0	83.50	170.13
1926 SEP 19	01 04 01.9	36.09	22.08	71	49	5.9	66.07	6.28
1926 OCT 23	01 58 55.1	41.00	20.00	15	30	5.2	111.19	0.00
1926 DEC 17	06 31 11.1	41.26	20.01	20	39	5.7	51.87	55.84
1926 17	11 39 58.2	41.11	19.79	15	44	5.8	27.65	63.29
1927 MAR 24	14 46 47.5	35.45	26.39	2	35	5.7	61.47	35.31
1927 JUN 30	22 59 49.6	39.33	20.81	2	46	5.7	109.28	289.98
1927 JUL 01	08 19 01.0	36.72	22.85	45	68	6.5	87.71	188.80
1927 28	06 49 57.2	40.33	20.12	70	12	5.0	137.06	326.90
1927 AUG 07	06 33 50	42.4	19.5	6	UNS	5.0		
1928 JAN 22	00 18 26.0	38.83	22.60	12	13	5.1	37.97	13.33
1928 MAR 31	00 29 47.7	38.01	27.92	12	68	7.0	55.04	187.36
1928 31	05 12 37.7	39.49	27.74	10	ATB	5.2		
1928 APR 10	01 03 18	37.4	26.1	15	UNS	5.1		
1928 14	08 59 58.0	42.34	26.02	19	88	7.0	74.95	342.03
1928 14	10 23 47.1	42.29	26.05	21	18	5.5	68.89	342.54
1928 18	19 22 51.2	42.27	25.35	7	95	7.1	101.19	309.12
1928 18	19 40 56	42.2	25.1	45	UNS	5.6		
1928 18	20 05 45	42.0	26.0	36	UNS	5.5		
1928 18	23 14 53.1	42.27	25.52	12	39	5.7	90.65	314.66
1928 22	19 59 29.4	38.40	23.34	28	22	5.4	46.81	342.53
1928 22	20 13 55.9	38.08	23.12	8	56	6.5	34.85	285.02
1928 25	09 25 54.4	42.54	26.23	12	41	5.9	93.64	356.47
1928 28	17 59 05.5	42.00	25.27	10	27	5.6	91.94	291.63
1928 29	09 49 20.7	37.71	23.08	84	28	5.5	34.22	198.20
1928 MAY 26	05 55 30.2	39.84	19.80	42	18	5.0	25.08	223.97
1928 JUL 15	09 33 60.7	37.91	27.57	13	49	5.8	26.21	112.75
1928 DEC 10	07 03 07.5	36.32	24.59	110	39	5.5	180.33	228.78
1929 JAN 17	00 06 40	40.6	19.6	15	UNS	5.1		
1929 23	11 14 28.5	35.20	24.52	28	42	5.2	56.47	322.09
1929 MAR 27	07 41 46.5	36.63	26.68	106	25	5.1	25.37	139.50
1929 27	21 06 10	35.0	20.0	15	UNS	5.0		
1929 APR 17	11 48 18.5	36.55	24.43	11	14	5.1	147.76	200.22
1929 NOV 11	07 35 02.7	36.68	26.21	15	15	5.0	29.51	242.88
1929 DEC 20	20 19 34	40.2	23.8	6	UNS	5.1		
1930 JAN 15	23 58 22.9	36.93	28.25	45	11	5.0	224.64	17.31
1930 23	10 53 58.6	35.44	27.31	52	16	5.0	52.01	340.54
1930 FEB 14	18 38 18.6	35.96	24.71	91	81	6.2	26.94	260.45
1930 23	18 19 20.7	39.86	22.75	70	65	6.1	98.01	347.37
1930 MAR 06	08 21 47.0	34.78	26.31	101	29	5.5	32.55	345.15
1930 06	09 18 34.2	35.03	24.73	87	50	5.7	57.82	205.31
1930 31	12 33 51.4	39.70	23.34	10	66	6.1	65.84	239.68
1930 APR 17	20 06 49.2	37.80	23.17	66	70	6.1	77.89	358.05
1930 AUG 05	23 23 08.6	34.79	26.71	38	23	5.0	91.74	343.16
1930 SEP 13	20 06 03.2	37.85	22.77	183	14	5.3	91.66	335.57
1930 NOV 21	02 00 29.5	40.28	19.64	42	71	6.1	33.65	20.95

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	AZIM DEG
1930 NOV 21	19 26 00	40.2	19.6	16	UNS	5.4		
1931 JAN 04	00 00 52.5	38.22	23.27	8	52	5.7	25.55	14.09
1931 11	19 19 43	40.2	19.9	8	UNS	5.0		
1931 28	05 55 13.6	40.89	20.60	6	61	5.6	88.29	5.49
1931 MAR 07	00 16 50.3	41.50	22.48	38	69	6.2	55.82	358.28
1931 08	01 50 20.3	41.44	22.61	6	118	6.8	50.02	10.65
1931 APR 20	20 33 40	35.0	27.0	15	UNS	5.1		
1931 26	06 24 55	38.5	26.2	10	UNS	5.1		
1931 JUN 30	10 24 01.4	36.29	22.87	103	34	5.4	26.49	206.63
1931 JUL 12	22 24 38.9	39.72	24.83	38	36	5.2	103.53	284.03
1931 AUG 18	09 47 10	40.8	23.5	15	UNS	5.1		
1931 SEP 11	16 23 22.7	38.87	23.29	77	31	5.0	154.28	9.40
1931 23	13 28 16.2	39.99	19.94	6	29	5.0	226.28	347.79
1931 NOV 23	23 32 13.0	36.99	21.28	64	21	5.1	58.03	340.20
1932 MAR 09	10 16 52.3	38.23	20.62	11	53	5.4	28.08	22.36
1932 MAY 14	03 45 06.8	35.88	28.65	78	35	5.2	14.59	99.26
1932 JUN 12	23 24 24.3	36.43	25.19	122	14	5.0	240.71	333.19
1932 29	02 30 22.3	36.35	26.72	85	33	5.3	123.43	320.16
1932 29	18 33 45.2	35.53	26.70	155	24	5.6	81.86	272.60
1932 AUG 09	07 44 48.2	36.71	27.73	110	18	5.1	246.15	4.79
1932 15	04 34 40.1	39.10	22.17	51	41	5.7	19.05	52.91
1932 SEP 26	19 20 43.0	40.39	23.81	05	134	7.1	65.69	0.74
1932 26	21 27 02.1	40.75	23.80	35	58	5.8	105.63	0.00
1932 28	16 52 12.6	40.64	23.31	16	57	5.8	27.03	1.82
1932 29	03 57 24.4	40.83	23.46	25	87	6.4	49.87	15.78
1932 30	06 12 19.3	35.94	22.60	43	50	5.5	12.05	233.60
1932 OCT 09	06 24 56.8	40.00	23.45	81	18	5.2	37.52	306.69
1932 23	13 36 44.7	35.51	27.24	21	44	5.5	33.14	272.05
1932 NOV 01	16 19 33.5	40.55	23.37	57	53	5.5	18.14	19.59
1932 DEC 07	07 55 52.9	37.37	27.60	83	12	5.0	64.09	7.97
1933 FEB 25	23 19 53.8	34.04	22.15	68	22	5.2	29.51	232.49
1933 MAR 14	01 19 55.1	38.84	25.18	54	53	5.4	50.11	347.96
1933 22	18 14 41.0	38.06	20.45	59	25	5.1	7.98	326.73
1933 APR 23	05 57 41.8	36.76	27.17	44	117	6.7	30.24	261.53
1933 28	22 28 52.4	35.09	27.10	64	37	5.4	14.42	317.60
1933 MAY 08	01 13 50.7	40.65	23.17	74	13	5.0	53.02	301.89
1933 11	19 09 48.5	40.76	23.67	16	100	6.5	40.38	356.37
1933 15	20 01 37.9	36.35	26.80	10	ATB	5.2		
1933 31	19 55 50.1	40.48	23.47	98	18	5.0	17.60	58.31
1933 JUN 01	02 40 41.5	40.68	23.83	10	25	5.1	221.76	7.23
1933 JUL 02	12 19 49.8	40.43	22.87	156	16	5.2	325.56	358.06
1933 09	21 42 47.1	36.95	20.43	83	27	5.1	8.34	228.21
1933 AUG 17	06 24 42.9	37.32	28.90	60	16	5.0	39.96	26.51
1933 SEP 24	13 21 25.7	35.65	28.62	145	15	5.2	94.08	79.50
1934 FEB 04	09 35 25.6	41.54	19.42	10	54	5.6	19.17	32.77
1934 21	00 40 26.9	34.77	22.73	153	24	5.1	70.32	25.52
1934 21	11 37 28.3	34.60	22.29	74	55	5.7	45.83	347.19
1934 NOV 09	13 41 03.3	36.47	25.41	132	64	6.3	79.10	222.04
1934 21	22 26 30.0	33.67	25.89	120	25	5.3	41.33	358.71
1935 JAN 04	14 41 31.3	40.76	27.53	13	84	6.6	84.60	1.72
1935 04	15 18 54.6	40.12	27.65	12	12	5.5	57.57	158.19
1935 04	16 20 08.3	40.69	27.54	18	81	6.6	76.83	2.53
1935 FEB 18	06 40 09.8	40.33	23.64	8	28	5.2	30.24	104.95
1935 25	02 51 30.5	36.07	24.83	67	108	7.1	17.87	296.93
1935 MAR 18	08 40 47.2	36.08	27.30	83	60	6.1	70.01	22.76

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	AZIM DEG
1935 MAR 31	03 21 35.4	41.18	19.88	40	55	5.7	44.87	281.67
1935 AUG 20	08 53 49.0	34.81	26.92	47	22	5.0	23.89	4.49
1935 SEP 03	17 35 39.3	39.45	20.67	106	47	5.4	161.74	5.19
1935 OCT 22	07 29 43.3	40.13	27.18	34	26	5.0	15.55	353.26
1935 NOV 07	04 37 34.9	40.82	20.00	24	43	5.4	90.64	332.22
1936 JAN 14	15 11 25.8	36.10	22.30	74	27	5.2	90.86	232.55
1936 29	15 55 41.0	42.02	20.10	47	24	5.1	54.86	310.73
1936 FEB 12	10 57 20.8	33.94	23.53	14	29	5.2	79.43	157.36
1936 APR 08	04 17 09.0	40.66	23.09	15	30	5.2	93.74	175.34
1936 15	16 03 04.0	37.63	20.38	25	18	5.0	42.71	194.47
1936 28	23 15 29.3	36.15	26.35	115	25	5.1	23.58	256.22
1936 AUG 08	04 12 57.0	34.43	26.28	103	50	5.5	130.26	15.57
1936 OCT 24	14 06 15.0	36.04	22.54	61	37	5.2	15.71	287.16
1937 JAN 02	14 04 02.1	34.04	24.95	39	43	5.2	8.11	145.37
1937 MAY 23	10 57 28.8	38.74	27.54	8	40	5.6	82.40	2.42
1937 DEC 16	17 35 36.9	36.09	23.75	51	61	5.5	66.07	48.77
1938 JAN 02	10 54 44	35.4	26.0	14	UNS	5.2		
1938 16	13 36 35.0	35.34	27.92	131	21	5.2	31.65	328.44
1938 FEB 10	20 37 57.4	34.59	26.15	25	52	5.5	24.19	191.14
1938 MAR 11	14 51 06.1	39.23	20.52	55	54	5.3	48.49	351.77
1938 13	17 45 24.2	38.62	20.64	14	59	5.8	20.87	170.11
1938 MAY 12	22 09 43.9	35.15	26.24	23	58	5.8	39.29	5.36
1938 JUN 03	16 37 56.7	34.49	26.48	52	24	5.0	66.07	226.48
1938 JUL 02	12 26 45.3	40.48	27.79	6	12	5.0	165.43	353.81
1938 20	00 23 42.5	38.30	23.66	42	81	6.1	13.20	270.05
1938 27	01 29 18.7	38.32	23.79	44	19	5.0	2.39	338.60
1938 AUG 15	11 02 12.3	40.27	20.34	52	32	5.0	41.97	43.92
1938 SEP 18	03 50 40.9	38.27	22.47	53	72	5.9	116.52	268.77
1938 DEC 26	22 02 30.3	37.53	20.92	105	40	5.3	38.42	47.88
1939 JAN 02	04 36 17.9	39.74	27.86	100	UNS	5.7		
1939 MAY 20	09 35 30.4	40.95	19.69	60	38	5.1	37.13	116.79
1939 31	00 24 05	38.0	22.0	14	UNS	5.0		
1939 JUN 02	14 11 43.0	38.65	22.09	148	18	5.2	94.51	359.47
1939 JUL 28	10 12 53.0	35.47	25.21	54	22	5.0	131.29	8.35
1939 28	16 06 10.6	35.06	25.23	10	14	5.0	87.02	13.97
1939 AUG 09	03 30 34.1	40.52	19.38	8	20	5.1	66.39	29.12
1939 SEP 20	00 19 33.6	38.02	20.86	50	61	5.6	13.38	280.28
1939 22	00 36 34.2	38.78	26.73	05	81	7.0	28.93	211.18
1940 JAN 06	19 04 39.7	35.34	25.53	55	43	5.5	52.38	220.15
1940 FEB 01	06 20 06.0	41.31	24.43	15	14	5.2	164.30	56.25
1940 23	00 40 04.3	40.59	19.43	52	33	5.4	81.63	323.69
1940 29	16 07 47.5	34.84	25.48	43	77	6.1	102.89	201.95
1941 JAN 09	18 13 35.4	38.15	27.29	54	26	5.5	25.27	312.16
1941 MAR 01	03 52 55.2	39.73	22.46	25	61	6.3	26.12	352.35
1941 MAY 14	08 36 29.4	39.74	22.64	35	44	5.3	53.29	22.83
1941 16	01 27 58.2	39.62	22.41	34	35	5.1	35.87	1.38
1941 23	19 51 59.5	37.15	28.14	37	58	6.2	15.86	248.72
1941 23	22 34 17.9	37.18	28.29	47	40	5.7	2.39	201.71
1941 23	23 00 47.8	37.22	28.35	48	12	5.0	4.95	63.34
1941 JUN 23	08 00 38.5	37.95	27.81	10	ATB	5.1		
1941 24	15 15 58	40.5	21.0	15	UNS	5.0		
1941 JUL 13	15 39 42.7	38.25	26.46	69	49	6.2	92.71	38.61
1941 SEP 01	14 18 50.5	42.17	24.72	25	14	5.1	66.07	16.01
1941 21	22 40 31.1	37.50	28.29	70	ATB	5.3		
1941 NOV 21	12 12 24	39.7	23.8	15	UNS	5.0		

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	SHIFT AZIM DEG
1941 DEC 13	06 16 07.0	37.23	27.99	28	34	6.1	28.08	276.99
1942 FEB 05	01 16 01.1	36.87	27.94	36	23	5.1	236.57	181.30
1942 MAY 09	04 37 17.3	36.11	26.30	137	20	5.0	58.28	38.32
1942 21	03 42 33.8	36.98	20.18	21	27	5.0	51.73	226.55
1942 JUN 01	09 01 18.0	38.99	22.11	65	24	5.3	42.82	216.16
1942 01	09 17 45.0	38.98	22.56	68	30	5.6	38.35	158.67
1942 16	04 47 41.8	34.40	26.29	41	37	5.5	69.46	343.82
1942 16	05 42 35.3	40.82	27.70	18	41	6.0	53.34	331.53
1942 21	04 38 44.2	36.05	26.96	88	41	5.3	55.69	225.66
1942 AUG 12	20 38 47.4	39.22	27.79	55	23	5.1	30.72	323.43
1942 27	06 14 16.7	41.59	20.45	12	45	6.0	4.30	255.04
1942 SEP 01	09 42 16.1	35.19	26.73	22	45	6.0	147.38	204.48
1942 OCT 28	00 31 53.6	39.48	28.11	12	13	5.4	75.08	44.47
1942 28	02 22 52.7	39.27	27.87	37	26	6.0	44.16	46.75
1942 28	02 41 58.0	39.48	27.75	43	15	5.5	57.74	21.97
1942 NOV 15	17 01 22.9	39.55	28.58	10	ATB	6.1		
1943 JAN 07	11 14 46.9	37.92	20.55	90	29	5.3	69.11	356.34
1943 07	22 36 07.6	37.52	21.32	81	26	5.0	68.44	68.82
1943 08	23 56 43.7	40.92	28.10	20	ATB	5.0		
1943 11	11 56 20.4	36.55	27.26	26	16	5.3	117.58	232.43
1943 FEB 14	07 28 29.3	38.22	20.01	16	35	5.7	114.68	333.20
1943 MAR 25	02 51 06.2	40.41	21.89	259	23	5.5	278.47	15.75
1943 APR 09	19 46 49.6	34.55	28.01	8	23	5.0	61.20	0.86
1943 MAY 22	22 05 52.7	38.36	20.43	76	27	5.2	64.09	308.85
1943 JUN 14	07 47 03.2	38.76	20.42	78	21	5.2	98.52	329.18
1943 27	10 05 42.4	35.14	24.26	32	31	5.1	85.11	345.09
1943 JUL 22	07 09 30.2	38.84	20.39	15	35	5.3	19.30	283.76
1943 OCT 16	13 08 57.5	36.31	27.89	95	63	5.8	10.99	185.14
1943 NOV 15	11 43 08.9	36.81	28.84	83	14	5.5	11.43	160.33
1943 20	10 01 59.4	36.55	28.36	35	33	5.5	55.47	225.47
1944 JAN 05	05 05 03	36.4	27.4	150	UNS	5.1		
1944 05	07 44 14.1	36.61	27.61	69	32	5.6	30.32	38.85
1944 MAY 27	23 52 35.7	36.22	27.19	91	38	5.7	147.27	222.70
1944 JUN 25	04 16 29.3	38.74	29.00	69	51	6.2	31.87	235.81
1944 25	06 57 53.2	38.97	29.55	57	26	5.5	22.54	261.34
1944 JUL 20	10 37 30.9	36.06	27.02	53	23	5.4	78.11	36.96
1944 30	04 00 45.6	37.14	22.27	85	35	5.6	53.20	337.30
1944 AUG 09	17 36 38.2	35.84	27.07	137	19	5.6	64.13	53.67
1944 17	13 28 15.1	35.67	26.80	98	17	5.4	33.43	55.16
1944 OCT 06	02 34 48.5	39.46	26.43	26	76	7.0	24.59	286.08
1944 06	07 28 26.2	39.37	26.06	40	ATB	5.1		
1944 07	21 34 28.6	39.40	26.49	16	27	5.5	18.53	270.07
1945 JAN 08	22 42 23.3	39.17	20.47	53	25	5.4	42.88	344.71
1945 AUG 27	16 26 56.7	36.13	26.61	162	21	5.0	60.88	64.93
1945 SEP 02	11 54 04.6	34.43	28.61	62	68	6.4	27.30	277.20
1945 12	16 29 34.4	40.10	19.81	133	20	5.1	20.28	304.46
1946 APR 05	20 54 07.0	35.29	23.65	40	52	5.6	31.42	47.13
1946 12	07 37 02.7	36.72	26.97	78	34	5.5	141.93	17.22
1946 16	11 43 56.5	41.22	19.86	39	48	5.4	4.12	303.59
1946 JUL 16	05 26 34.5	34.20	25.65	17	61	6.0	55.12	35.99
1946 AUG 20	17 26 42.1	40.77	19.82	48	32	5.1	48.44	188.05
1946 OCT 13	21 24 42.6	34.28	25.81	15	42	5.2	83.18	310.08
1946 NOV 21	01 43 38.9	38.96	20.37	51	40	5.5	27.21	311.74
1947 MAR 21	23 00 04.2	34.92	23.30	21	40	5.1	22.54	204.60
1947 APR 12	14 05 13.4	39.86	25.01	8	40	5.3	63.18	233.33

DATE	ORIG.TIME	LAT	LON	DEPTH	OBS	MAG	SHIFT	
	GMT	N	E	KM		MS	DIST KM	AZIM DEG
1947 APR 19	20 29 44.4	39.33	23.55	30	35	5.3	66.43	27.13
1947 JUN 01	11 18 45.3	36.74	21.78	62	52	5.6	29.84	58.09
1947 04	00 29 57.6	40.09	23.96	45	65	6.0	58.94	22.16
1947 JUL 07	22 35 44.1	37.37	21.05	18	49	5.2	29.51	49.52
1947 21	09 36 36.3	37.55	22.99	60	29	5.0	103.99	24.63
1947 AUG 17	15 04 20.9	37.55	19.98	13	31	5.1	17.60	353.94
1947 30	22 21 41.9	35.50	23.37	34	88	6.2	44.75	356.49
1947 SEP 13	15 11 21.9	37.54	20.05	15	36	5.3	16.75	15.87
1947 OCT 06	19 55 36.3	36.71	21.79	2	118	6.7	28.60	221.70
1947 NOV 29	10 14 04.8	39.23	23.67	15	30	5.1	104.02	353.80
1947 DEC 09	23 19 04.6	42.20	19.75	50	22	5.0	127.93	16.91
1948 JAN 17	02 26 30.6	38.25	20.94	68	14	5.0	49.53	276.63
1948 FEB 09	12 58 17.9	35.32	27.15	25	124	7.2	21.21	192.83
1948 10	15 59 00.2	35.38	27.40	57	28	5.2	23.07	126.19
1948 11	22 31 24	35.5	27.1	15	UNS	5.0		
1948 12	22 27 19.6	35.91	27.35	70	45	5.4	47.74	16.57
1948 15	17 55 02.0	35.37	27.34	58	46	5.4	19.92	138.57
1948 MAR 06	20 12 59.1	35.26	25.93	48	41	5.2	59.43	30.45
1948 26	03 02 09.5	40.60	21.47	39	34	5.0	87.38	152.87
1948 29	02 33 04.5	35.69	27.23	89	50	5.4	21.88	7.34
1948 29	10 22 48.3	35.28	23.32	47	63	5.3	21.88	339.98
1948 APR 22	10 42 49.7	38.73	20.38	12	100	6.7	21.21	247.96
1948 MAY 07	14 57 20.8	39.05	18.90	10	35	5.1	105.95	184.69
1948 22	05 07 56.8	34.65	24.31	38	31	5.5	167.46	26.33
1948 27	07 32 43.9	36.53	23.31	162	16	5.1	112.98	289.28
1948 JUN 17	06 52 35.9	37.66	21.81	53	34	5.1	30.24	238.80
1948 30	12 21 21.3	38.96	20.53	36	96	6.7	19.42	341.15
1948 JUL 24	06 03 10.9	34.49	24.49	20	135	6.4	10.99	354.74
1948 26	11 26 33.3	35.70	27.43	45	21	5.0	30.87	43.14
1948 AUG 10	13 27 10.2	38.47	28.88	79	33	5.1	174.48	2.29
1948 27	10 44 16.8	42.06	19.38	41	55	5.4	41.50	346.05
1948 27	11 24 27.0	41.89	19.54	20	UNS	5.0		
1948 SEP 11	08 52 44.0	37.38	23.28	88	75	6.2	21.89	19.53
1948 20	18 00 00.5	34.60	26.58	74	42	5.2	51.07	229.25
1948 21	17 54 01.1	36.45	21.60	59	37	5.6	19.42	151.69
1948 OCT 10	17 43 10.5	35.43	23.54	43	62	5.6	39.04	19.14
1948 18	09 00 02.0	35.73	27.21	43	58	5.6	26.12	2.03
1948 19	03 04 39.1	35.62	27.88	86	13	5.0	63.29	77.62
1948 NOV 13	04 44 58.1	41.08	28.19	28	48	5.6	185.89	320.37
1949 JAN 14	15 53 58.7	38.76	25.23	12	40	5.7	7.52	233.77
1949 FEB 05	00 28 22.5	39.98	29.47	35	42	5.0	23.38	330.95
1949 05	15 24 22.5	38.03	21.69	57	27	5.0	60.84	86.64
1949 JUN 17	04 21 06.1	34.42	28.32	77	65	5.8	17.46	277.70
1949 26	05 42 34.4	39.80	20.47	52	47	5.1	111.71	354.27
1949 JUL 07	12 21 15.8	35.95	27.14	67	51	5.2	50.54	353.81
1949 23	15 03 35.2	38.71	26.27	17	124	7.0	13.56	347.94
1949 30	17 47 14.3	38.72	26.37	48	33	5.2	15.39	24.56
1949 SEP 17	11 30 15.8	37.07	22.67	42	43	5.0	62.76	72.25
1949 OCT 04	17 33 33.9	38.63	22.08	111	31	5.0	28.76	59.32
1949 NOV 23	16 51 02.6	38.58	26.22	25	52	5.6	7.30	252.26
1949 DEC 07	16 13 39.8	34.72	24.18	19	51	5.2	7.64	73.09
1950 FEB 12	09 43 52.0	34.40	24.26	29	17	5.0	36.67	156.14
1950 MAY 03	07 13 50.8	38.96	27.35	60	25	5.0	50.50	37.16
1950 30	09 52 42.6	35.69	27.50	50	21	5.0	34.85	52.13
1950 SEP 23	06 23 48.5	34.90	25.81	49	87	5.3	22.65	59.93

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	SHIFT AZIM DEG
1950 OCT 22	05 52 11.0	34.94	26.28	47	27	4.9	17.87	25.20
1950 NOV 28	17 53 23.0	39.53	28.19	49	33	5.1	48.29	148.72
1950 DEC 28	22 31 37.6	35.63	27.47	97	16	5.2	28.85	59.41
1951 JAN 09	00 28 02.5	38.04	20.26	61	50	5.3	85.33	201.72
1951 APR 05	03 15 29.4	37.46	20.30	41	78	5.3	34.15	78.69
1951 AUG 20	22 51 54.7	35.06	24.07	62	74	5.1	40.32	356.08
1951 24	10 27 34.1	37.22	21.43	51	67	5.1	15.24	127.55
1951 31	12 29 45.4	35.89	22.45	30	100	5.6	53.84	323.90
1951 31	20 18 38.9	35.51	22.73	23	68	5.1	6.43	279.96
1951 SEP 15	22 52 12.3	40.23	27.69	7	40	5.6	32.77	234.48
1951 OCT 01	01 26 41.4	34.60	26.62	49	70	5.1	16.61	44.76
1951 NOV 05	13 43 55	36.0	29.0		ATB	5.2		
1951 DEC 13	20 46 20.5	40.38	26.82	215	24	5.1	105.79	78.70
1951 20	19 12 05.6	38.07	20.05	27	39	5.3	70.66	249.00
1952 FEB 03	20 45 01.1	40.47	25.85	77	25	5.0	37.13	35.24
1952 MAR 09	04 45 29.9	37.48	20.49	47	26	5.2	73.32	218.07
1952 13	06 30 01.8	41.02	28.14	11	27	5.4	4.02	56.49
1952 19	01 27 27.7	39.61	28.60	33	116	5.8	23.38	202.16
1952 25	03 35 21.4	34.87	23.32	38	37	4.9	26.94	196.00
1952 APR 03	03 20 11.6	38.21	20.49	54	18	4.9	50.64	297.68
1952 JUN 09	14 48 43.3	36.94	27.62	42	19	4.9	63.22	18.10
1952 12	11 00 15.6	34.67	26.56	56	36	5.6	36.34	113.52
1952 13	01 07 30.2	37.31	21.98	55	64	5.3	11.85	276.01
1952 27	13 09 23.8	40.68	23.32	16	41	4.8	16.01	261.75
1952 JUL 08	20 58 44.1	36.00	21.94	50	15	4.6	22.86	170.77
1952 AUG 21	04 18 29.0	35.32	25.45	62	28	4.6	44.59	162.07
1952 24	20 44 29.3	35.35	27.29	80	41	4.9	19.30	153.82
1952 SEP 23	20 30 52.0	36.90	29.90	35	30	5.0	35.13	50.25
1952 OCT 05	10 21 19.1	37.07	20.92	24	43	5.0	49.09	167.39
1952 05	10 54 57.9	37.41	20.61	9	106	5.7	20.04	239.34
1952 07	16 08 34.7	37.02	20.72	28	19	4.7	53.88	187.61
1952 10	11 51 58.6	37.23	20.61	9	46	5.2	34.64	209.38
1952 13	16 42 32.7	39.18	23.40	15	55	5.2	45.88	22.27
1952 22	04 15 12.1	36.86	27.09	107	35	5.2	74.59	284.04
1952 DEC 17	23 04 02.0	34.47	24.22	17	232	6.6	27.30	286.87
1952 22	23 51 47.5	35.28	25.16	74	24	5.2	48.44	195.29
1952 31	14 48 52.8	35.75	25.95	80	102	5.5	36.21	39.16
1952 31	17 18 52.9	35.66	25.97	54	100	5.7	30.72	53.97
1953 JAN 07	00 01 28	41.3	20.6	35	UNS	5.2		
1953 07	01 18 57	41.3	20.6	19	UNS	5.4		
1953 10	23 29 11.9	38.28	25.23	20	ATB	5.0		
1953 FEB 05	22 42 05	35.7	22.7	15	UNS	4.9		
1953 07	22 31 13.2	34.83	24.11	33	138	5.7	15.24	3.63
1953 14	08 43 21.8	36.07	27.04	96	129	5.3	80.07	37.51
1953 22	18 26 23	37.7	21.2	80	UNS	5.3		
1953 MAR 18	19 06 16.8	40.20	27.52	8	259	7.4	29.51	40.12
1953 18	21 18 11.1	40.04	27.52	28	57	5.7	20.04	76.62
1953 19	12 53 45.2	40.00	28.04	50	18	4.9	63.45	89.76
1953 19	21 13 59.5	40.05	27.28	4	50	5.0	5.81	342.98
1953 26	15 10 30.5	39.94	27.48	10	ATB	5.1		
1953 31	00 55 52.3	40.51	19.86	17	48	5.0	24.59	209.37
1953 APR 01	01 47 40.3	40.13	27.48	23	42	5.3	21.77	46.72
1953 02	08 21 46.1	38.88	25.32	10	ATB	5.0		
1953 05	03 21 56.1	40.61	19.96	8	25	4.5	11.43	198.72
1953 MAY 01	20 06 47.0	38.74	26.66	48	33	4.9	35.40	63.50

DATE		ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	AZIM DEG
1953	MAY 02	05 41 59.3	38.87	27.04	55	34	5.2	71.18	64.79
1953	02	10 06 51.1	38.61	27.16	100	ATB	4.8		
1953	02	18 37 45.5	38.80	26.72	57	47	5.4	43.05	58.58
1953	14	13 00 29.8	38.17	26.61	100	ATB	5.0		
1953	JUN 03	16 05 28.0	40.19	28.72	28	52	5.7	13.01	325.72
1953	07	13 52 57.8	35.95	27.11	80	ATB	4.8		
1953	09	16 28 27.8	39.43	28.14	22	37	4.9	15.24	122.78
1953	13	18 38 58	38.1	22.6	4	UNS	5.1		
1953	18	05 44 11.6	41.84	26.54	17	110	5.4	17.04	342.23
1953	21	08 11 25	37.6	20.6	24	27	4.9		
1953	23	01 53 20.8	36.06	24.69	100	70	5.8	68.23	306.13
1953	JUL 22	15 09 39.8	39.35	28.24	12	85	5.6	36.08	321.11
1953	AUG 09	07 41 12.6	38.24	20.80	21	171	6.1	6.67	180.00
1953	11	03 32 26.7	38.35	20.74	11	244	6.8	7.63	316.74
1953	11	04 32 25	38.1	20.8	10	UNS	5.0		
1953	11	12 43 32.1	38.50	20.53	36	53	5.4	32.85	313.35
1953	11	13 11 09.7	38.25	20.87	17	47	5.1	8.26	132.28
1953	12	06 08 11.5	38.39	20.59	43	61	4.8	21.44	298.62
1953	12	09 23 55.4	38.13	20.74	11	257	7.3	20.16	195.58
1953	12	10 07 38	38.1	20.8	10	UNS	5.5		
1953	12	11 33 52.3	38.06	20.81	40	69	5.4	27.03	178.11
1953	12	12 05 25.6	37.88	20.76	18	160	6.3	25.36	237.81
1953	12	13 39 28.1	38.09	20.81	28	72	5.8	20.04	300.98
1953	12	14 08 44.1	38.12	20.84	20	95	6.0	20.98	170.04
1953	12	16 08 38.2	38.06	20.84	36	68	5.5	16.31	295.42
1953	13	03 22 10.5	38.29	20.88	10	65	5.5	7.07	99.04
1953	13	10 16 50	38.1	20.8	10	UNS	5.3		
1953	17	02 12 28.8	38.12	20.99	37	41	5.0	14.25	356.23
1953	SEP 05	01 08 12.9	36.96	29.35	80	ATB	5.1		
1953	05	14 18 46.0	37.88	23.17	18	95	5.7	20.51	131.66
1953	14	14 56 17.8	38.38	20.78	07	73	5.2	10.08	348.87
1953	OCT 10	21 29 18.2	38.08	20.98	22	73	5.3	29.51	147.09
1953	16	21 44 49.6	38.14	20.70	41	38	5.0	20.39	206.28
1953	21	11 31 10.7	38.38	20.70	14	79	5.4	13.38	315.48
1953	21	18 39 57.2	38.30	20.59	9	172	6.4	19.05	270.07
1953	21	23 44 01	38.3	20.8	15	UNS	5.0		
1953	NOV 03	22 29 25	37.9	21.2	4	UNS	4.9		
1953	08	14 45 54.4	38.98	23.99	22	33	5.0	23.07	233.84
1953	20	19 13 57	38.4	20.8	12	UNS	5.0		
1953	28	20 17 36.1	37.49	20.70	37	60	5.3	62.64	205.13
1953	30	13 21 03.9	38.32	21.60	33	45	4.8	27.03	138.77
1953	DEC 20	17 56 20.1	35.99	27.77	40	ATB	4.9		
1953	28	02 38 49.6	38.30	20.56	17	75	5.3	21.66	270.08
1954	JAN 02	01 13 41.3	36.98	27.12	140	ATB	5.2		
1954	18	14 16 14.8	37.62	21.60	37	41	5.1	67.76	128.42
1954	24	13 32 54.2	37.38	20.46	13	25	4.6	33.29	246.23
1954	MAR 08	08 17 21.9	38.06	20.61	9	64	5.2	6.73	7.47
1954	23	12 58 53.3	40.58	27.12	10	ATB	4.9		
1954	APR 17	20 52 51.5	37.99	22.98	19	71	5.1	13.20	35.12
1954	30	13 02 39.5	39.23	22.28	16	211	6.7	11.43	138.35
1954	30	19 33 30	39.3	22.2	26	UNS	4.7		
1954	MAY 01	15 24 59.3	37.79	27.07	42	35	5.0	12.83	31.67
1954	01	20 53 34.6	37.81	26.95	54	60	5.5	13.91	340.17
1954	03	05 24 55	36.0	21.5	15	UNS	4.8		
1954	03	08 51 17	36.0	21.5	15	UNS	5.0		

DATE	ORIG. TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	SHIFT AZIM DEG
1954 MAY 03	13 29 45.0	35.28	27.23	12	52	4.9	25.08	264.92
1954 04	16 43 26.0	39.26	22.14	27	80	5.5	6.81	229.27
1954 04	16 45 32.7	39.24	22.35	28	71	5.4	15.24	117.18
1954 04	23 44 54	39.3	22.2	20	UNS	4.8		
1954 12	02 16 33	37.7	21.8	5	UNS	4.9		
1954 15	12 24 34	36.2	21.7	15	UNS	5.0		
1954 25	22 03 37.1	39.26	22.30	22	91	5.3	10.54	117.20
1954 JUL 18	14 42 37.2	37.68	21.18	30	54	5.1	10.55	348.76
1954 AUG 03	18 18 11.8	40.28	24.28	35	118	5.8	38.56	53.61
1954 05	04 12 51	40.2	25.0	26	UNS	5.0		
1954 05	20 39 17.2	35.89	27.42	42	50	4.7	13.38	324.14
1954 06	11 33 51	36.8	23.2	20	UNS	5.0		
1954 06	16 01 00	39.8	25.0	28	UNS	4.8		
1954 SEP 02	01 54 38.7	41.96	19.68	15	48	4.9	19.05	212.62
1954 04	04 19 23.4	36.63	27.10	160	ATB	4.7		
1954 OCT 24	23 37 19.1	40.46	27.53	10	ATB	5.0		
1954 26	10 34 28.6	40.56	27.52	10	ATB	4.6		
1954 NOV 23	23 22 54.3	35.89	27.60	40	ATB	5.0		
1954 DEC 23	16 27 25.1	37.87	21.19	38	69	5.4	8.57	112.89
1954 30	02 07 26.5	40.59	22.84	14	39	4.9	17.60	306.45
1954 30	11 05 59.8	36.15	21.79	9	63	5.2	10.99	55.57
1955 JAN 03	01 07 10.9	39.19	22.27	41	100	5.6	26.12	34.83
1955 08	07 53 09.0	39.27	22.17	52	56	5.0	17.32	62.05
1955 28	07 42 06.2	33.91	23.54	17	40	4.7	5.64	281.35
1955 FEB 21	19 46 44	39.4	23.1	4	UNS	4.7		
1955 22	09 43 00	39.4	23.1	7	UNS	4.8		
1955 MAR 28	14 45 52.5	37.60	21.24	9	78	5.1	12.44	162.35
1955 APR 13	20 45 51.3	37.29	22.50	19	99	5.2	10.31	262.91
1955 19	16 47 23.8	39.31	23.06	15	139	6.2	11.64	199.05
1955 21	07 18 18	39.3	23.0	5	UNS	5.8		
1955 22	10 02 33.0	34.75	23.77	46	46	4.7	22.54	284.82
1955 JUN 02	23 34 39.4	40.37	25.59	10	72	5.7	18 79	259.49
1955 JUL 09	23 53 48.5	40.82	22.42	32	72	5.0	23.38	54.27
1955 16	07 07 17.2	37.68	27.20	31	232	7.0	10.31	360.00
1955 18	03 06 11.1	37.75	27.72	40	ATB	4.9		
1955 AUG 28	13 39 28.8	37.36	27.02	48	41	5.3	29.59	238.00
1955 NOV 11	18 27 40.5	37.54	26.97	10	ATB	4.7		
1956 JAN 06	12 15 46.1	40.51	26.33	10	134	5.7	13.56	11.76
1956 27	01 13 32.1	36.40	23.75	56	40	4.6	23.07	270.08
1956 MAY 05	20 42 00.3	36.99	28.63	40	ATB	4.7		
1956 15	18 34 16.6	37.25	20.89	15	61	5.0	5.62	189.04
1956 15	22 56 57.3	37.28	20.95	20	63	5.2	10.25	185.41
1956 18	22 08 36.7	39.03	22.63	52	69	5.1	15.71	282.80
1956 JUN 11	01 11 31.5	34.26	26.02	36	49	4.8	18.40	291.92
1956 JUL 09	03 11 43.7	36.64	25.91	15	270	7.4	14.91	135.41
1956 09	03 24 16.5	36.45	25.51	95	57	7.2	26.76	220.48
1956 09	06 19 16.9	36.66	25.70	70	ATB	5.0		
1956 09	06 22 59.0	36.71	25.60	78	50	5.3	27.12	255.67
1956 09	07 36 30.0	36.27	25.89	30	ATB	4.8		
1956 09	09 45 10.0	36.60	25.93	10	ATB	4.8		
1956 09	11 30 55.7	36.54	26.32	40	ATB	4.9		
1956 09	20 13 58.9	36.62	25.84	14	61	5.3	16.75	231.45
1956 09	20 48 08.3	36.45	26.09	60	ATB	4.8		
1956 09	21 28 51.6	36.52	25.81	61	46	4.7	16.61	236.58
1956 10	03 01 35.2	36.82	26.15	55	78	5.5	16.01	323.85

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	AZIM DEG
1956 JUL 22	03 29 06.7	36.89	26.32	40	57	4.8	5.83	17.74
1956 28	15 19 06.0	35.06	25.87	60	ATB	4.7		
1956 30	05 41 06.9	35.83	26.06	20	57	5.5	15.71	342.61
1956 30	05 47 22.3	35.81	25.98	120	ATB	5.1		
1956 30	09 15 02.0	35.85	25.86	10	100	6.1	10.08	263.03
1956 30	09 21 18.4	35.81	25.91	10	ATB	5.3		
1956 30	10 40 05.0	35.89	25.91	41	64	5.3	14.42	11.50
1956 AUG 09	03 37 16.1	35.62	26.30	120	ATB	4.9		
1956 16	00 38 39.0	36.25	21.90	15	56	5.4	4.62	76.06
1956 SEP 06	11 46 43.4	35.72	25.90	37	76	5.7	10.99	10.27
1956 06	12 58 42.8	36.03	25.88	10	ATB	4.9		
1956 16	18 07 44.4	35.97	25.87	29	55	5.0	19.67	263.38
1956 OCT 29	06 59 00	35.5	26.0	15	UNS	5.0		
1956 29	07 35 01.8	35.80	26.59	30	ATB	5.0		
1956 NOV 02	16 04 36.1	39.35	23.11	5	83	5.2	3.75	27.26
1956 20	23 21 00.5	39.31	26.15	41	53	5.4	12.82	298.25
1956 DEC 02	19 41 22.3	36.58	25.92	60	ATB	4.9		
1956 27	10 08 10.7	35.55	28.03	10	ATB	4.9		
1957 JAN 03	07 36 27	38.2	21.3	17	UNS	5.2		
1957 23	17 26 58.7	36.89	21.58	34	58	5.0	22.43	345.76
1957 FEB 05	17 20 35.3	36.45	28.84	70	51	5.2	23.89	357.80
1957 09	01 39 38.3	36.75	26.44	40	ATB	5.0		
1957 19	07 44 00.1	36.27	21.74	28	113	6.0	16.46	68.86
1957 23	22 13 28	40.0	20.0	12	UNS	4.8		
1957 MAR 08	12 14 18.7	39.34	22.68	18	165	6.5	5.62	322.29
1957 08	12 21 18.7	39.34	22.66	30	155	6.8	2.81	66.67
1957 08	20 38 01.6	39.34	22.85	23	58	5.0	14.76	283.62
1957 08	23 35 17.3	39.41	22.76	41	119	6.0	19.42	357.39
1957 11	09 31 14	39.5	22.8	28	UNS	5.1		
1957 11	13 39 36.0	39.5	22.8	21	UNS	4.7		
1957 28	22 26 07.4	39.34	22.68	30	75	5.1	4.78	338.86
1957 APR 24	19 10 17.3	36.44	28.58	69	255	6.8	7.83	353.44
1957 25	02 25 45.6	36.48	28.58	66	274	7.1	2.10	58.09
1957 25	07 52 08.3	36.12	28.60	10	ATB	5.0		
1957 26	06 33 42.4	36.37	28.81	56	131	5.9	19.18	343.13
1957 26	16 09 07.7	36.41	28.80	10	ATB	4.7		
1957 MAY 21	13 24 25.2	39.42	22.81	37	83	5.4	2.05	302.95
1957 29	18 39 27.2	37.62	23.42	120	77	5.3	60.48	332.08
1957 AUG 14	02 45 00	35.50	28.0	15	UNS	4.7		
1957 SEP 20	02 19 10	38.5	23.0	20	UNS	4.8		
1957 OCT 05	11 36 55.0	34.57	26.47	61	84	5.2	21.77	312.78
1957 08	07 00 55.8	38.88	20.61	84	39	5.1	6.20	135.79
1957 11	07 33 04.6	39.32	28.19	10	ATB	4.9		
1957 18	01 50 53.3	38.34	21.98	24	55	4.7	4.83	133.71
1957 30	01 43 10.4	35.30	27.11	66	98	5.5	19.30	333.81
1957 30	07 30 27.2	35.43	27.68	47	108	5.5	20.40	357.40
1957 NOV 09	23 55 58.5	38.57	22.54	23	42	4.8	30.32	22.20
1957 26	08 15 33.3	39.44	22.71	57	62	5.0	15.40	349.85
1957 26	11 50 12.0	39.37	22.64	47	52	5.0	14.08	328.18
1957 27	03 08 12.1	39.37	22.65	42	111	5.3	16.75	12.51
1957 DEC 05	13 55 31.7	35.47	27.74	40	ATB	5.1		
1958 JAN 02	02 08 22.4	36.29	22.37	42	94	5.1	16.16	20.48
1958 16	04 18 18.7	39.48	25.50	15	100	5.5	5.43	127.86
1958 MAR 04	11 32 18.4	36.34	27.85	120	ATB	5.1		
1958 15	06 27 11.7	40.86	21.28	19	93	5.1	20.04	59.30

DATE			ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	AZIM DEG
1958	APR	03	02 23 48.4	41.19	19.76	29	116	5.4	10.54	306.34
1958		03	07 18 41.8	34.90	27.29	40	91	5.2	15.86	282.86
1958		04	09 18 56.5	41.24	19.74	37	36	4.4	27.65	80.49
1958		24	08 00 39.5	36.76	26.55	10	ATB	4.8		
1958	MAY	03	20 18 20.8	36.19	21.73	16	107	5.0	4.53	348.60
1958		09	02 40 56.8	36.61	27.60	67	133	5.5	21.09	336.89
1958		27	18 27 48.0	36.86	26.67	163	124	5.1	7.45	287.34
1958	JUN	05	13 29 48.6	37.20	20.73	29	72	4.8	24.59	14.93
1958		10	08 28 57.5	41.15	19.81	41	45	4.6	37.07	62.93
1958		30	08 42 47.1	36.44	27.28	112	148	5.3	10.77	338.01
1958	JUL	15	07 59 25.1	35.54	23.58	38	88	4.8	21.77	2.46
1958		17	05 37 11.4	40.72	23.39	19	134	5.5	13.38	11.73
1958	AUG	27	15 16 34.6	37.45	20.67	9	183	6.5	4.41	270.00
1958		30	07 35 44.9	37.35	20.60	11	56	4.6	15.71	41.27
1958	SEP	02	01 13 25.5	37.44	20.62	13	86	5.4	5.53	232.93
1958		04	00 03 00.5	36.54	26.70	35	86	5.0	6.67	180.02
1958		04	02 51 06.2	36.40	27.01	140	ATB	4.9		
1958	NOV	15	05 42 40.5	37.45	21.73	31	123	5.5	37.00	220.77
1959	JAN	03	07 59 23.9	35.26	29.04	80	ATB	4.8		
1959		06	14 28 40.9	36.66	29.11	30	ATB	4.7		
1959		07	22 22 03.2	36.79	29.14	26	48	4.7	8.39	301.98
1959		09	01 55 08.2	36.15	21.67	16	70	4.9	13.38	290.81
1959		11	04 27 35.1	36.77	29.07	61	52	4.7	14.25	356.17
1959		26	11 38 43.9	36.78	29.02	47	42	5.0	12.24	299.50
1959	FEB	07	20 08 25.7	37.56	20.90	50	59	4.6	26.48	340.11
1959	MAR	08	11 17 18.5	40.21	19.89	47	39	4.5	3.40	90.00
1959		13	19 08 11.2	34.43	26.48	29	59	4.5	15.71	14.30
1959		29	23 07 24.5	37.39	23.81	61	49	4.6	11.64	19.52
1959	APR	08	19 02 37.3	36.57	26.80	160	ATB	4.7		
1959		19	17 39 04.4	37.37	20.94	87	66	5.0	2.39	21.66
1959		25	00 26 46.5	37.03	28.57	35	149	5.9	10.31	43.06
1959		25	01 05 47.7	37.00	28.59	35	94	5.3	5.63	9.08
1959		30	22 44 39.4	36.22	26.68	100	ATB	4.8		
1959	MAY	14	00 55 58.0	39.95	22.89	9	40	4.6	35.06	290.72
1959		14	06 27 11.6	35.28	24.54	73	50	4.6	14.25	348.42
1959		14	06 36 59.3	35.11	24.65	23	200	6.1	7.19	117.66
1959		14	19 22 32.6	40.17	23.44	97	48	4.9	36.41	349.14
1959		20	16 37 01.6	36.81	26.53	62	42	4.8	12.05	292.55
1959	JUN	09	11 21 19.6	36.81	29.08	20	ATB	4.7		
1959		10	04 16 09.0	35.67	23.57	37	130	5.1	13.01	0.00
1959	JUL	12	16 52 31.5	36.03	26.28	80	ATB	5.1		
1959		26	17 07 06.5	40.94	27.60	9	77	5.4	10.08	50.49
1959	AUG	11	23 28 11.6	41.31	23.02	43	35	4.2	11.64	121.05
1959		16	18 42 09.5	37.23	22.38	63	72	5.1	18.14	17.73
1959		17	01 33 18.2	40.97	19.73	15	147	5.8	13.56	313.83
1959		17	04 29 08.4	40.92	19.69	46	74	4.8	38.66	10.12
1959		18	22 04 05.6	41.00	19.73	7	63	4.6	7.36	232.87
1959	SEP	01	11 37 46.3	40.95	19.63	26	175	6.1	12.44	286.97
1959		03	04 02 07.4	40.78	19.67	22	58	4.5	4.74	314.73
1959		16	05 13 58.0	35.03	25.76	55	85	5.5	29.51	237.83
1959	OCT	05	20 34 10.3	40.90	19.67	27	101	5.2	16.01	274.24
1959		07	08 30 46.7	40.97	19.77	28	161	5.7	10.77	297.84
1959	NOV	06	07 37 23.4	41.94	20.21	17	48	4.6	59.67	312.39
1959		15	17 08 47.6	37.78	20.46	20	269	6.9	5.62	188.98
1959		19	14 00 32.0	38.98	26.55	8	93	5.3	8.51	336.05

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	AZIM DEG
1959 NOV 27	00 22 26.9	37.74	20.14	15	92	5.4	3.77	332.21
1959 27	00 26 15.3	37.80	20.16	10	41	5.6	4.15	122.33
1959 29	23 49 48.3	36.05	23.54	16	35	4.5	27.03	282.07
1959 DEC 01	12 38 50.9	37.83	20.13	18	130	5.4	53.16	350.42
1959 08	09 35 18.7	36.95	29.00	53	31	5.0	5.55	233.10
1959 27	05 22 51.3	35.16	25.95	83	61	5.0	39.35	322.70
1960 JAN 09	03 58 55.2	37.07	28.90	49	80	4.9	21.21	345.05
1960 26	13 05 45.5	37.00	28.93	72	69	5.2	18.92	336.84
1960 FEB 01	11 59 47.2	35.27	22.90	35	97	5.4	8.24	262.24
1960 22	21 04 25.7	39.13	20.62	57	41	4.6	23.48	15.25
1960 23	00 31 08.3	39.13	20.57	51	47	4.7	11.84	355.55
1960 23	07 34 38.1	39.09	20.66	38	100	5.4	14.42	35.04
1960 23	07 47 58.1	38.94	20.86	42	68	5.0	23.98	67.65
1960 MAR 12	11 54 05.9	41.91	21.00	24	146	5.8	11.43	29.26
1960 APR 10	22 05 33.5	37.79	27.67	27	68	4.8	14.59	324.48
1960 12	04 22 44.9	37.80	27.60	13	50	4.6	18.66	303.75
1960 25	16 28 40.6	38.60	25.34	12	58	4.9	14.25	7.45
1960 28	16 33 28.2	34.51	26.45	46	52	5.4	29.26	354.54
1960 30	10 12 48.7	35.98	26.34	100	ATB	4.7		
1960 MAY 21	06 41 19.4	37.72	20.21	26	66	4.8	8.93	354.35
1960 26	05 10 16.6	40.56	20.63	20	194	6.4	8.11	46.76
1960 JUN 09	09 24 08.5	40.44	20.00	26	60	4.8	11.43	18.76
1960 18	02 04 18.7	34.42	26.21	52	40	4.6	18.27	28.04
1960 JUL 09	22 42 57.4	40.74	20.71	32	50	4.7	15.24	23.92
1960 13	13 01 07.1	40.61	23.45	24	128	5.4	8.74	50.54
1960 AUG 08	20 36 25.4	35.42	27.20	63	62	4.8	15.55	334.49
1960 27	10 17 23.2	34.58	26.19	50	84	5.1	16.46	290.73
1960 29	18 00 39.6	34.39	26.23	92	44	4.6	48.49	323.74
1960 SEP 10	00 19 14.7	34.58	26.23	17	88	5.2	16.31	328.20
1960 OCT 01	05 30 46.1	35.38	25.97	77	77	5.1	16.46	336.20
1960 NOV 05	20 20 53.8	39.12	20.63	22	156	5.8	4.22	37.81
1960 11	05 31 33.5	38.84	20.81	31	103	5.2	7.83	6.35
1960 18	06 03 57.8	35.17	27.83	199	53	4.7	27.91	263.14
1960 DEC 29	18 19 40.5	34.86	22.17	27	59	4.9	33.58	254.59
1961 JAN 07	10 30 57.6	35.53	26.09	84	88	5.5	12.44	320.75
1961 07	15 52 59.9	37.70	21.14	44	76	4.7	10.77	158.33
1961 28	07 18 17	39.4	22.0	33	UNS	4.9		
1961 FEB 16	03 44 46.9	40.22	19.87	37	57	4.5	20.75	187.28
1961 21	03 02 01.3	36.50	22.91	60	73	4.7	21.10	336.86
1961 23	21 45 55.4	36.75	27.02	42	59	5.1	6.23	270.00
1961 23	21 56 53.3	36.83	27.07	32	38	4.8	36.54	297.48
1961 27	21 40 08.2	36.68	26.95	64	55	5.0	32.55	358.41
1961 27	21 54 38.9	36.66	26.95	48	46	5.1	20.63	279.67
1961 MAR 13	15 32 01.8	36.21	26.43	10	ATB	4.7		
1961 13	19 17 19.3	34.57	26.58	25	97	5.0	15.55	325.91
1961 MAY 23	02 45 24.1	36.82	28.40	74	212	6.4	14.25	336.32
1961 25	13 11 47.9	36.72	26.66	60	ATB	4.8		
1961 JUN 21	16 04 52.5	37.93	28.82	64	60	5.3	29.02	300.44
1961 JUL 12	02 48 34.7	39.26	23.79	38	45	4.6	32.70	58.84
1961 19	23 00 58.9	37.71	20.18	22	96	5.2	5.28	90.01
1961 27	18 35 44.8	34.83	25.16	17	54	4.5	22.75	4.71
1961 AUG 27	22 08 51.9	35.67	23.41	60	99	5.0	10.08	360.00
1961 SEP 18	05 08 35.4	34.48	25.82	36	47	4.4	17.04	307.85
1961 OCT 02	07 21 45.1	36.66	21.86	19	138	5.4	4.79	338.14
1961 NOV 28	08 58 47.9	40.21	26.30	76	53	5.2	71.65	11.69

DATE			ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS	SHIFT DIST KM	AZIM DEG
1961	DEC	10	08 39 11.6	34.56	25.60	51	57	4.7	40.32	1.32
1961		11	16 53 13.7	36.42	23.44	75	80	4.9	6.65	70.45
1962	JAN	10	12 36 35.7	35.82	22.48	77	48	5.0	5.61	233.50
1962		19	19 38 02.7	38.35	22.25	35	90	5.3	22.51	210.50
1962		19	22 18 28.0	38.38	22.15	40	63	4.9	34.21	10.41
1962		26	08 17 39.8	35.32	22.78	11	198	5.8	11.21	27.12
1962	MAR	18	15 30 33.0	40.69	19.59	15	187	6.0	5.18	257.59
1962		26	09 22 12.6	38.44	20.86	67	93	5.1	49.62	22.87
1962	APR	04	20 51 05	34.6	25.5	20	UNS	4.7		
1962		04	20 59 41.5	34.41	25.16	47	87	4.9	17.73	15.44
1962		10	21 37 10.3	37.76	20.09	5	196	6.3	3.77	207.78
1962		10	22 10 50.0	37.79	20.13	11	60	5.1	12.24	218.45
1962		11	10 47 29.3	37.65	20.16	6	146	5.4	4.93	116.81
1962		16	00 15 16.9	37.70	20.12	46	81	4.8	46.56	256.29
1962		16	07 19 06.0	36.15	27.23	140	ATB	5.2		
1962		17	11 15 30	37.60	20.10	25	UNS	4.8		
1962		17	11 33 55.2	37.78	20.09	33	85	5.2	14.92	61.59
1962		19	02 05 57.2	37.74	20.26	42	65	4.5	16.16	30.77
1962		28	11 19 02.9	36.20	26.84	56	173	6.0	16.89	16.14
1962		28	12 43 52.0	36.13	26.87	51	151	5.5	2.11	58.26
1962	MAY	01	11 53 59	38.20	20.50	90	UNS	4.9		
1962		08	23 53 59.0	35.23	24.12	79	79	4.8	6.35	314.41
1962	JUN	28	06 51 07.7	40.76	20.69	40	95	5.0	7.13	200.74
1962	JUL	06	09 16 17.1	37.79	20.12	37	168	5.8	3.68	287.55
1962		06	15 54 25.9	37.79	20.31	6	56	4.4	6.25	79.76
1962		10	10 06 02.4	38.42	25.92	10	ATB	4.8		
1962	AUG	28	10 59 57.4	37.80	22.88	95	226	6.6	2.39	201.57
1962	SEP	10	09 36 28.7	34.74	26.62	45	156	5.4	13.01	337.57
1962	OCT	04	19 46 12.1	37.93	22.36	53	123	5.0	6.72	7.49
1962		26	11 26 11.8	33.52	27.55	11	102	5.5	7.29	242.80
1962	DEC	13	22 45 34.7	35.22	27.97	65	59	4.7	35.06	7.54
1963	JAN	31	15 07 06.3	35.94	22.02	52	64	4.8	13.01	79.25
1963	FEB	15	10 18 25.7	40.15	19.89	31	64	4.6	27.91	143.89
1963		22	14 12 54.8	40.34	20.11	30	104	5.1	12.24	125.46
1963	MAR	04	15 10 20.8	34.96	25.18	39	134	5.3	5.85	18.15
1963		11	07 27 24.3	37.96	29.14	40	74	5.5	3.76	152.27
1963		17	14 17 24.0	39.35	20.89	41	94	5.1	8.19	132.73
1963		29	03 09 14.6	40.54	26.46	2	69	5.1	31.41	41.05
1963	APR	28	00 41 52.2	39.32	27.82	30	ATB	4.6		
1963	MAY	06	19 30 32.6	39.32	20.34	53	60	4.5	48.04	263.50
1963		15	11 15 42.3	41.56	20.13	49	73	4.5	19.30	161.81
1963	JUN	04	22 11 35.0	38.92	20.54	46	90	5.0	2.82	113.18
1963	JUL	08	16 02 35.4	36.63	27.82	78	80	4.7	27.03	315.16
1963		10	07 19 41.3	39.80	23.90	127	ROT	4.6		
1963		26	04 17 16.1	42.04	21.43	14	192	6.1	4.12	90.00
1963		26	19 46 39.1	36.84	28.76	80	ATB	5.0		
1963	SEP	18	16 58 13.5	40.71	29.02	48	184	6.3	14.42	222.94
1963		24	02 10 45.8	40.91	28.90	11	71	4.8	6.88	14.14
1963		29	13 35 49.2	36.44	29.00	60	ATB	4.8		
1963	OCT	02	21 05 16.5	35.02	23.49	58	67	4.5	21.88	7.40
1963	NOV	12	07 06 35.8	35.48	29.61	83	97	5.1	12.44	346.21
1963	DEC	16	13 47 57.4	36.97	20.96	15	162	5.8	10.99	214.52
1964	JAN	10	03 34 24.0	38.70	21.00	40	19	4.6		
1964		30	17 45 57.0	37.41	29.89	59	123	5.5		
1964		31	09 23 15.5	37.68	22.51	13	17	4.0		

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1964 FEB 18	08 35 15.0	37.80	23.70	52	11	4.4
1964 23	22 41 03.9	39.21	23.73	10	131	5.4
1964 24	23 21 13.0	38.10	24.00	16	14	4.6
1964 24	23 30 28.0	39.09	23.80	41	59	4.7
1964 MAR 30	03 27 13.3	34.94	24.02	65	54	4.6
1964 31	09 33 12.3	36.43	28.78	57	34	4.5
1964 APR 08	14 12 28.5	35.04	24.29	64	119	5.1
1964 11	16 00 43.0	40.30	24.83	33	136	5.6
1964 15	20 54 27.4	39.04	23.71	44	52	4.4
1964 17	18 11 39.6	38.20	20.30	17	25	4.4
1964 20	18 37 32.6	35.09	24.46	68	30	4.4
1964 25	12 44 15.0	35.46	27.70	61	67	4.7
1964 29	04 21 05.1	39.25	23.72	20	137	5.5
1964 29	17 00 01.3	39.14	23.55	15	99	5.0
1964 MAY 13	17 06 14.8	36.28	28.21	82	27	4.4
1964 14	17 00 27.8	38.52	20.44	36	17	5.0
1964 18	20 03 14.2	36.95	24.29	109	13	4.3
1964 JUN 08	16 49 03.5	36.26	28.26	62	28	4.4
1964 12	07 46 21.0	37.34	29.93	5	27	4.6
1964 JUL 04	11 11 17.9	41.96	23.43	2	66	4.8
1964 17	02 34 26.7	38.05	23.63	155	241	6.0
1964 18	03 40 19.4	36.13	26.01	99	139	5.2
1964 AUG 17	00 17 48.5	35.28	25.90	64	95	4.6
1964 24	21 42 46.2	40.51	19.20	41	23	5.0
1964 25	11 11 52.0	35.75	28.84	51	125	5.3
1964 25	07 08 14.9	35.50	28.76	28	31	4.5
1964 25	08 05 01.8	35.28	28.67	55	38	4.4
1964 25	11 42 55.8	35.35	28.58	12	47	4.6
1964 25	14 37 33.6	35.55	28.82	35	70	5.6
1964 27	19 31 59.7	35.56	28.84	38	113	5.4
1964 28	12 06 18.4	37.80	19.95	61	55	4.6
1964 29	19 37 55.2	35.29	28.72	35	42	4.7
1964 31	19 35 39.0	36.10	20.20	21	21	4.9
1964 SEP 13	22 53 22.9	41.71	20.60	00	21	4.9
1964 18	00 08 47.6	35.69	29.07	40	95	5.3
1964 30	04 39 45.4	34.51	23.26	49	92	4.9
1964 OCT 06	14 29 57.9	40.24	28.16	23	151	5.1
1964 06	14 31 23.0	40.30	28.23	34	210	7.0
1964 07	23 07 53.9	40.19	28.36	31	45	4.4
1964 13	10 30 09.2	36.94	28.29	76	10	4.3
1964 17	09 50 28.0	35.02	25.43	18	117	5.0
1964 20	08 47 56.0	40.00	28.60	00	10	4.8
1964 NOV 05	20 55 45.8	35.11	24.13	27	40	4.7
1964 DEC 01	10 21 03.3	38.53	22.45	48	15	4.7
1964 09	18 28 46.0	41.57	20.92	78	66	4.4
1964 09	19 06 21.4	41.20	20.92	55	41	4.7
1964 15	21 03 15.7	40.02	28.79	26	43	4.5
1964 31	16 18 02.2	35.76	25.51	89	110	5.2
1965 JAN 02	13 47 43.4	36.46	26.10	59	12	4.9
1965 07	10 22 17.2	36.50	26.85	35	79	4.7
1965 09	04 11 51.0	36.00	27.40	63	17	4.3
1965 10	08 02 51.7	38.70	22.00	46	18	4.3
1965 17	03 39 32.5	34.58	27.83	29	33	4.6
1965 29	23 39 02.5	34.91	27.60	25	48	4.7
1965 FEB 06	03 47 57.8	35.41	27.04	71	59	4.7

DATE			ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1965	FEB	09	20 38 41.7	37.92	20.25	08	54	4.8
1965		09	23 32 56.4	37.79	20.85	23	28	4.9
1965		20	22 47 08.6	38.40	22.10	06	21	4.3
1965	MAR	02	22 00 07.2	38.47	28.33	42	115	5.6
1965		03	01 37 18.3	38.27	28.47	42	18	4.5
1965		08	23 02 55.9	37.85	21.00	55	24	4.6
1965		09	17 57 54.5	39.34	23.82	18	215	6.3
1965		09	19 46 58.7	39.12	23.86	19	66	5.0
1965		09	21 20 04.5	39.19	23.87	07	50	4.8
1965		09	18 37 54.6	39.28	23.93	33	85	5.0
1965		09	22 19 06.4	39.17	23.96	13	30	4.6
1965		09	22 35 15.3	39.26	23.84	18	60	4.9
1965		10	01 36 05.8	39.08	23.77	18	101	5.1
1965		10	21 50 19.8	39.35	23.94	37	34	4.4
1965		13	04 08 40.6	39.11	23.97	11	62	4.9
1965		13	04 09 37.9	39.03	23.68	33	78	5.3
1965		13	15 42 16.5	39.14	23.90	18	23	4.6
1965		14	06 04 49.3	39.90	20.20	05	9	4.5
1965		15	23 08 30.9	39.16	24.00	33	24	4.7
1965		19	04 35 45.4	41.50	23.10	12	23	4.4
1965		19	23 37 31.9	41.39	22.88	33	17	4.4
1965		22	03 22 22.2	39.13	23.84	01	38	4.6
1965		31	09 47 26.3	38.38	22.26	45	279	6.6
1965		31	12 01 11.7	38.47	22.23	78	27	4.9
1965		31	20 08 25.5	39.20	24.10	33	32	4.7
1965	APR	03	05 19 18.0	37.70	23.80	15	9	4.3
1965		03	14 30 48.2	38.24	20.50	25	66	4.6
1965		05	03 12 54.6	37.75	22.00	34	218	6.0
1965		07	04 16 39.6	37.10	22.30	36	25	4.3
1965		09	23 57 02.0	35.06	24.31	39	210	6.1
1965		10	00 19 59.7	34.90	24.37	55	47	4.7
1965		19	06 46 33.7	34.56	28.36	33	24	4.4
1965		27	14 09 05.6	35.63	23.53	37	182	5.5
1965		29	09 46 56.8	37.14	26.89	08	56	4.8
1965	MAY	01	01 59 43.9	37.18	26.91	15	48	4.7
1965		02	22 33 25.4	35.61	23.52	56	41	4.6
1965		07	14 42 21.7	36.74	26.86	162	30	4.4
1965		13	21 09 16.7	39.22	20.73	58	20	4.4
1965		16	01 35 56.0	35.26	27.85	41	80	4.6
1965		29	01 47 48.0	35.13	22.64	56	33	4.6
1965		29	04 14 56.1	35.19	22.57	43	69	4.7
1965	JUN	03	18 31 51.0	39.72	23.21	33	107	4.8
1965		10	15 24 17.1	36.44	26.64	142	50	4.5
1965		29	15 40 31.5	34.20	26.23	33	67	4.6
1965	JUL	06	03 18 42.1	38.37	22.40	18	244	6.4
1965		06	13 34 14.8	34.73	25.64	61	37	4.7
1965		10	08 09 46.1	34.73	23.30	07	30	4.3
1965		13	14 19 01.0	37.50	27.80	35	22	4.4
1965	AUG	04	19 15 04.6	35.30	26.50	52	35	4.6
1965		14	04 47 51.7	38.45	21.60	30	24	4.3
1965		23	14 08 58.6	40.51	26.17	33	170	6.1
1965		24	01 11 07.2	35.67	23.50	54	56	4.7
1965		24	23 57 35.4	40.39	26.20	18	48	4.7
1965		25	04 57 45.7	34.72	25.08	10	95	4.8
1965	SEP	11	04 49 12.8	39.07	22.09	42	31	4.3

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1965 OCT 11	06 37 03.0	42.00	21.50	05		4.6
1965 18	14 32 48.3	38.83	27.83	36	36	4.6
1965 28	04 27 12.9	38.41	22.37	29	31	4.3
1965 28	14 39 28.5	41.67	19.30	28	24	4.3
1965 NOV 02	03 27 07.4	39.48	25.32	05	94	5.0
1965 28	05 26 05.3	36.12	27.43	73	209	5.6
1965 DEC 04	16 39 57.5	34.26	26.25	12	68	4.5
1965 07	01 00 57.0	36.30	27.00		4	4.5
1965 07	08 25 03.2	35.60	27.50		4	4.8
1965 08	11 22 05.0	37.30	28.50		7	4.7
1965 13	17 44 08.4	40.25	19.82	07	45	4.6
1965 20	00 08 16.0	40.21	24.82	33	175	6.0
1965 20	00 30 57.6	40.01	24.80	42	31	4.7
1965 22	08 43 44.5	37.10	28.10		9	4.7
1965 25	12 15 33.1	39.84	25.00	41	31	4.7
1965 25	15 10 30.0	37.31	21.06	04	28	4.3
1966 JAN 02	23 12 18.0	37.67	23.18	12	92	4.7
1966 14	18 39 31.0	34.72	27.00	22	54	4.4
1966 15	18 07 46.5	36.72	23.09	37	60	4.7
1966 16	20 15 30.0	35.61	25.80	47	73	4.5
1966 17	08 39 42.6	40.09	20.57	46	29	4.7
1966 17	20 04 58.6	38.12	22.00	62	47	4.4
1966 18	21 20 02.6	35.12	23.49	60	47	4.4
1966 20	00 39 00.6	39.20	24.44	12	49	4.4
1966 26	13 30 28.0	38.94	21.47	46	36	4.6
1966 30	06 47 03.0	38.87	21.65	48	43	4.6
1966 31	04 30 57.0	39.05	21.90	51	24	4.4
1966 FEB 04	08 38 03.0	34.37	23.94	33	94	4.7
1966 05	02 01 45.3	39.10	21.74	16	261	6.2
1966 05	02 11 08.0	39.17	21.89	21	39	4.9
1966 05	02 58 01.2	39.11	21.91	50	130	5.0
1966 08	20 08 04.0	41.08	24.97	21	105	4.7
1966 08	13 16 22.2	36.23	28.11	79	62	4.4
1966 09	05 36 23.1	41.11	24.92	48	14	4.3
1966 10	13 21 45.9	38.95	21.70	39	31	4.3
1966 11	06 49 37.0	39.15	21.45	24	29	4.3
1966 12	13 36 22.2	38.83	21.43	46	55	4.9
1966 14	17 57 50.1	34.94	27.11	43	115	4.8
1966 14	20 16 58.0	38.82	21.42	39	52	4.3
1966 17	10 41 25.8	38.89	21.88	38	18	5.3
1966 19	10 22 27.0	39.04	21.65	08	16	4.4
1966 MAR 08	18 51 47.5	38.87	21.42	44	65	4.7
1966 11	20 01 45.0	34.40	24.23	30	126	5.0
1966 14	14 08 41.2	39.07	21.36	45	62	4.6
1966 29	00 08 42.8	37.00	26.80	33	15	4.5
1966 APR 01	13 15 05.2	38.72	21.49	45	91	4.7
1966 03	11 36 26.1	38.94	21.53	34	134	5.2
1966 07	03 25 45.0	37.83	21.14	25	106	4.8
1966 11	06 43 46.4	35.61	27.08	00	12	4.6
1966 13	20 44 08.7	36.80	28.50	00	3	4.8
1966 14	18 51 44.0	34.55	23.86	14	83	4.8
1966 21	06 45 26.9	34.49	25.69	51	99	5.1
1966 MAY 04	06 36 59.0	38.94	21.47	27	141	5.2
1966 04	21 49 01.8	37.74	27.71	37	126	5.2
1966 07	13 08 16.9	37.75	27.79	09	146	5.3

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1966 MAY 09	00 42 53.0	34.43	26.44	13	206	5.9
1966 09	06 08 29.6	34.31	26.44	43	88	4.7
1966 10	18 44 38.0	36.50	27.40	94	9	4.3
1966 11	10 21 41.8	34.30	26.40	06	22	4.7
1966 11	15 06 02.5	34.37	26.42	39	92	4.7
1966 12	20 31 02.5	38.56	25.82	33	54	4.5
1966 13	13 11 50.9	34.47	26.47	37	86	4.6
1966 14	23 00 44.7	37.00	22.02	40	71	4.5
1966 15	10 11 08.0	35.17	27.16	34	61	4.4
1966 16	17 30 56.1	34.48	26.46	41	91	4.6
1966 22	07 37 29.0	38.70	27.92	23	57	4.8
1966 24	09 39 26.5	37.33	21.89	34	128	4.9
1966 24	11 09 25.4	37.37	22.02	43	99	4.9
1966 24	17 43 32.3	34.87	24.62	43	63	4.7
1966 25	09 06 57.0	40.32	19.82	21	82	4.7
1966 JUN 02	22 51 28.0	38.50	27.23	30	43	4.5
1966 04	06 16 57.5	36.63	20.97	82	125	4.9
1966 05	20 52 02.5	37.24	21.94	35	47	4.3
1966 11	10 21 55.4	38.84	21.50	43	109	4.8
1966 11	12 05 02.7	37.37	21.08	47	91	4.7
1966 13	04 59 24.0	38.30	28.50	00	10	4.7
1966 19	17 55 30.0	38.55	27.35	09	82	4.8
1966 24	22 34 26.1	38.73	21.53	34	99	4.8
1966 25	06 20 46.9	38.54	26.90	00	8	4.4
1966 28	17 01 04.0	39.00	27.00	49	10	4.5
1966 29	00 49 35.0	41.29	20.47	16	43	4.2
1966 30	19 21 29.0	41.18	20.85	19	42	4.3
1966 JUL 12	02 56 22.0	35.50	22.49	07	144	5.4
1966 15	23 50 12.1	38.90	21.65	34	40	4.2
1966 19	02 52 33.0	38.30	27.10	00	9	4.5
1966 20	10 16 06.0	38.83	21.39	22	64	4.3
1966 24	01 27 39.0	38.98	21.94	15	17	4.3
1966 31	04 22 17.0	35.70	22.30	71	17	4.6
1966 31	11 03 21.0	41.20	21.20	31	10	4.6
1966 AUG 06	18 32 32.0	37.90	22.20	25	43	4.3
1966 07	14 30 46.0	36.34	22.31	49	50	4.6
1966 09	03 34 15.1	40.22	19.86	38	92	4.9
1966 10	15 22 40.2	36.40	22.22	39	80	4.6
1966 11	00 23 40.8	37.65	20.99	48	73	4.6
1966 11	04 34 13.0	38.74	21.76	06	84	4.6
1966 16	03 53 41.7	40.16	19.75	20	113	4.9
1966 21	01 30 43.5	40.33	27.40	12	154	5.5
1966 SEP 01	14 22 56.9	37.46	22.16	15	198	5.4
1966 01	12 35 34.0	38.03	22.81	39	47	4.6
1966 06	12 31 57.3	36.66	26.63	158	28	4.5
1966 10	10 55 16.7	36.53	26.90	146	33	4.5
1966 22	20 14 39.4	39.83	23.92	35	19	4.6
1966 23	23 47 58.1	38.60	21.73	47	31	4.5
1966 27	10 54 53.0	36.98	24.16	42	26	4.9
1966 OCT 21	16 17 04.0	39.53	22.11	57	64	4.6
1966 22	05 38 24.0	41.96	23.09	13	28	4.7
1966 29	02 39 24.8	38.90	21.10	01	266	5.8
1966 29	12 13 06.8	34.74	27.54	64	42	4.6
1966 30	02 10 14.0	38.75	21.58	26	72	4.7
1966 NOV 09	15 12 28.0	39.18	20.54	35	57	4.5

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1966 NOV 19	07 12 38.0	35.03	23.46	17	176	5.2
1966 DEC 18	07 42 20.0	35.10	26.92	33	88	4.7
1967 JAN 01	22 17 52.0	37.80	20.00	5	18	4.8
1967 04	05 58 52.5	38.37	22.04	1	172	5.5
1967 04	07 10 14.0	38.29	22.13	24	34	4.3
1967 FEB 09	14 08 18.2	39.92	20.26	1	207	5.6
1967 14	07 22 24.0	38.80	27.70	0	36	4.7
1967 20	09 11 38.0	34.68	24.74	48	24	4.4
1967 28	14 21 51.3	37.53	21.18	46	85	5.0
1967 MAR 04	17 58 09.0	39.25	24.60	60	329	6.8
1967 04	18 38 01.0	38.99	24.80	15	55	4.7
1967 28	00 04 28.0	38.44	25.42	29	76	4.6
1967 APR 04	16 59 06.2	35.59	23.56	73	93	4.7
1967 04	03 47 17.0	40.32	26.20	32	24	4.0
1967 MAY 01	07 09 03.0	39.60	21.29	34	301	6.2
1967 01	09 50 08.2	39.51	21.30	33	110	4.9
1967 01	08 15 46.9	39.75	21.42	38	46	4.7
1967 01	09 47 40.0	39.46	21.23	10	35	4.4
1967 01	14 38 02.0	39.36	21.31	21	49	4.4
1967 02	01 27 20.4	39.56	21.20	35	47	4.3
1967 02	08 11 55.9	39.45	21.29	39	40	4.4
1967 03	18 41 47.2	39.53	21.34	37	117	5.3
1967 04	13 31 07.8	39.63	21.26	39	72	4.7
1967 05	06 26 37.9	39.56	21.29	57	80	4.9
1967 09	08 00 47.3	39.72	21.39	53	55	4.7
1967 14	04 15 59.9	37.70	21.17	48	132	4.9
1967 15	08 12 57.9	34.53	26.64	35	178	5.2
1967 30	23 53 31.6	34.17	28.67	35	59	4.4
1967 JUN 01	10 39 23.5	36.81	29.26	43	148	5.0
1967 07	15 54 36.0	34.78	26.68	52	51	4.7
1967 11	05 35 05.0	38.14	22.91	40	71	4.4
1967 12	02 51 05.8	38.15	22.77	35	160	5.0
1967 12	01 29 09.5	38.08	22.90	47	78	4.4
1967 12	11 00 16.0	38.04	22.75	05	21	4.3
1967 12	18 12 46.6	39.06	21.27	46	72	4.6
1967 18	05 28 53.9	36.78	29.32	35	50	4.2
1967 20	16 37 23.4	38.23	20.77	39	32	4.4
1967 JUL 05	00 53 16.8	36.73	21.50	50	140	4.9
1967 06	08 21 51.3	36.67	21.43	43	64	4.6
1967 13	14 38 58.4	40.66	19.67	73	62	4.7
1967 19	09 06 22.2	38.10	28.87	41	105	4.9
1967 19	16 18 32.0	38.03	20.95	06	29	4.3
1967 20	19 03 30.4	40.72	19.88	58	58	4.4
1967 25	11 03 54.0	37.80	28.60	75	13	4.5
1967 25	12 39 28.0	37.90	28.70	101	12	4.5
1967 31	07 12 05.0	40.60	27.62	4	36	4.4
1967 AUG 09	00 33 15.0	36.98	28.40	64	19	4.2
1967 15	04 35 52.9	36.54	19.28	33	51	4.8
1967 28	17 36 41.0	36.73	26.74	169	67	4.7
1967 SEP 03	07 46 21.8	38.23	22.00	45	29	4.4
1967 05	08 31 02.2	36.72	29.33	24	22	4.6
1967 06	04 59 23.0	35.06	23.09	20	104	4.8
1967 07	00 32 22.0	40.75	19.58	13	35	4.3
1967 08	02 04 45.0	40.60	20.08	01	110	5.3
1967 08	09 51 42.8	39.08	21.40	40	65	4.4

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1967 SEP 12	14 46 42.0	39.23	21.46	25	56	4.7
1967 24	22 11 20.4	40.86	19.70	35	74	4.6
1967 26	05 05 37.4	41.53	20.94	39	49	4.3
1967 27	07 24 34.0	34.42	26.60	49	80	4.6
1967 OCT 05	12 00 53.7	37.74	20.80	37	145	5.1
1967 11	07 48 45.0	36.07	27.12	34	46	4.5
1967 22	05 38 04.7	36.90	21.10	05	24	4.9
1967 24	06 14 44.7	38.91	21.96	37	41	4.4
1967 26	04 55 39.3	37.22	29.05	46	150	5.1
1967 NOV 05	00 26 13.8	38.12	20.34	33	31	4.7
1967 06	10 32 58.0	39.05	20.61	01	44	4.6
1967 13	06 50 34.9	37.78	28.83	34	36	4.5
1967 18	02 31 36.0	35.25	23.05	34	97	4.7
1967 26	03 24 57.4	39.40	20.49	37	51	5.1
1967 30	07 23 50.4	41.41	20.44	21	312	6.5
1967 30	07 42 52.0	41.43	20.49	21	62	4.7
1967 30	08 13 17.5	41.40	20.50	30	18	4.4
1967 DEC 01	18 30 57.1	41.37	20.27	16	24	4.6
1967 01	20 07 51.0	41.28	20.28	28	39	4.7
1967 02	12 44 42.0	41.32	20.29	16	172	5.4
1967 02	00 24 13.0	41.31	20.34	08	54	5.5
1967 02	09 27 08.0	41.20	20.08	19	33	4.6
1967 02	14 18 04.0	41.29	20.29	42	28	4.4
1967 03	17 59 25.0	41.25	20.20	25	24	4.3
1967 04	00 48 51.0	41.17	20.66	10	19	4.4
1967 05	05 20 03.1	36.53	26.85	137	83	5.9
1967 06	00 01 56.0	41.30	20.40	42	30	4.4
1967 07	18 03 35.0	41.27	20.24	32	33	4.7
1967 14	02 54 54.0	34.49	26.27	57	85	4.5
1967 14	08 35 23.7	34.74	24.61	45	36	4.6
1967 19	08 32 32.3	41.49	20.43	29	110	4.9
1967 29	19 49 24.1	41.41	20.27	46	101	4.9
1967 30	21 27 20.3	40.66	21.47	34	32	4.6
1968 JAN 09	23 15 42.8	35.52	22.54	46	69	5.0
1968 FEB 07	22 22 19.0	36.65	26.74	153	146	5.8
1968 19	22 45 42.4	39.40	24.94	7	333	7.2
1968 19	23 09 46.4	39.36	24.70	15	25	4.6
1968 19	23 12 32.0	39.62	25.50	15	34	4.5
1968 19	23 53 51.0	39.55	25.30	33	36	4.6
1968 20	00 39 15.7	39.73	25.37	37	88	5.1
1968 20	01 28 29.0	39.40	25.60	46	18	4.2
1968 20	02 21 52.0	39.56	25.45	8	90	5.5
1968 20	02 29 28.0	39.30	24.90	33	8	4.6
1968 20	06 15 46.0	39.30	25.50	32	30	4.2
1968 20	09 35 51.6	39.41	24.88	33	98	4.8
1968 20	09 41 09.0	39.35	24.95	33	116	5.0
1968 20	16 50 44.8	36.15	27.39	64	121	5.0
1968 20	21 05 23.6	39.25	25.05	33	23	4.8
1968 21	00 17 28.0	39.56	24.97	2	22	4.6
1968 21	07 18 50.0	39.30	25.00	6	18	4.3
1968 21	12 35 55.3	39.61	25.30	5	27	4.6
1968 22	02 16 39.0	39.66	25.72	6	43	4.6
1968 22	04 57 47.0	39.39	25.02	19	78	4.5
1968 24	12 55 03.0	41.44	20.18	24	25	4.4
1968 26	05 43 30.4	39.39	24.79	5	12	4.3

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1968 FEB 27	13 20 15.7	39.59	25.51	36	19	4.3
1968 27	13 37 45.4	39.61	25.51	35	67	4.7
1968 29	11 46 42.0	39.50	26.00	5	19	4.0
1968 29	12 47 33.5	39.12	24.32	18	34	4.3
1968 MAR 06	05 14 49.0	39.34	25.04	10	29	4.4
1968 10	06 48 17.1	39.10	24.36	33	72	4.4
1968 10	07 10 59.0	39.13	24.23	9	167	5.4
1968 11	17 32 46.9	39.50	25.56	5	36	4.3
1968 16	18 11 05.8	39.38	24.94	43	86	4.5
1968 21	09 42 51.0	38.80	27.60	52	13	4.4
1968 21	16 09 23.8	39.76	25.49	19	53	4.8
1968 23	17 16 35.8	39.78	25.64	5	31	4.3
1968 23	17 25 55.0	39.76	25.48	33	127	5.3
1968 28	07 39 59.5	37.84	20.89	23	255	5.9
1968 28	16 37 47.3	39.49	20.38	18	129	5.3
1968 APR 05	15 54 32.7	39.76	25.55	18	50	4.1
1968 08	08 59 09.0	39.68	25.50	9	15	4.2
1968 18	03 08 03.4	41.25	20.22	36	54	4.3
1968 24	08 18 03.3	39.33	24.88	20	227	5.5
1968 MAY 28	21 31 41.3	38.78	23.57	10	33	4.2
1968 30	17 40 26.0	35.45	27.88	27	222	5.9
1968 JUN 12	09 05 04.0	35.30	27.89	16	77	4.6
1968 24	10 17 31.0	38.00	20.80	42	31	4.3
1968 JUL 04	21 47 53.6	37.76	23.23	20	226	5.5
1968 08	17 41 06.4	34.47	25.08	38	194	5.5
1968 08	18 18 11.4	34.29	25.20	57	44	4.4
1968 09	15 00 47.4	34.39	25.10	49	80	4.6
1968 13	19 34 07.0	35.56	28.05	0	7	4.5
1968 25	22 05 29.0	40.95	20.09	23	79	4.5
1968 27	02 45 51.0	35.43	27.92	29	213	5.2
1968 31	09 21 56.0	37.84	21.14	34	58	4.3
1968 31	19 29 29.7	35.54	28.00	49	126	4.7
1968 AUG 04	23 24 22.2	37.81	21.02	62	53	4.6
1968 15	02 29 43.1	35.18	26.70	48	159	5.1
1968 SEP 05	18 42 32.0	36.30	26.70	1	24	4.5
1968 15	04 55 58.4	34.70	25.05	17	144	4.9
1968 16	02 55 52.0	38.05	20.66	11	23	4.4
1968 18	04 01 59.0	34.74	25.01	30	96	4.6
1968 28	00 53 28.0	40.49	26.38	28	65	4.7
1968 OCT 03	18 18 34.8	40.13	19.85	58	22	4.7
1968 06	15 06 43.0	36.96	26.38	17	99	4.7
1968 10	05 16 26.0	36.50	29.20	0	15	4.7
1968 11	03 02 36.0	36.54	25.87	33	26	4.4
1968 17	23 56 04.0	38.21	20.17	17	81	4.5
1968 19	15 34 54.0	35.24	23.40	6	133	4.9
1968 21	18 16 41.0	35.25	23.35	1	106	4.9
1968 28	12 54 30.0	38.89	25.82	4	67	4.7
1968 31	03 22 14.0	36.62	27.01	2	159	5.4
1968 NOV 03	04 49 33.7	42.10	19.35	28	214	5.4
1968 03	18 44 08.0	38.60	28.70	56	15	4.3
1968 04	20 05 59.0	36.44	26.98	35	55	4.5
1968 10	12 50 37.0	34.44	23.77	1	39	5.1
1968 10	14 29 33.0	34.55	23.86	5	30	4.3
1968 11	23 34 21.5	36.61	27.15	23	22	5.0
1968 11	23 53 07.0	36.61	27.10	33	50	4.1

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1968 NOV 12	03 37 39.0	36.74	27.11	26	104	5.0
1968 12	06 08 55.6	36.64	27.16	24	92	5.0
1968 DEC 04	18 43 28.0	36.34	26.98	43	52	4.4
1968 04	19 37 22.0	36.50	27.02	32	87	4.7
1968 05	07 52 11.1	36.60	26.92	31	206	5.6
1968 21	00 36 40.0	36.60	27.07	30	88	4.9
1968 25	12 17 19.1	34.99	24.31	58	156	5.1
1969 JAN 10	04 32 03.4	39.23	19.97	37	44	4.4
1969 13	05 46 40.4	38.31	22.52	46	75	4.9
1969 13	07 57 07.6	34.57	24.93	60	56	4.4
1969 14	23 12 06.2	36.11	29.19	22	263	5.9
1969 31	14 40 04.0	34.29	26.14	31	78	4.9
1969 31	15 34 28.0	39.10	20.43	04	37	4.6
1969 FEB 13	15 09 32.0	34.70	22.30	25	28	4.6
1969 17	09 11 46.0	34.11	25.31	26	33	4.7
1969 21	18 39 57.0	39.14	21.87	33	51	4.6
1969 26	12 35 49.1	36.66	27.18	33	38	4.3
1969 MAR 03	00 59 10.5	40.09	27.50	6	225	5.9
1969 05	14 41 16.4	40.06	27.56	33	92	4.7
1969 22	18 00 55.0	39.10	28.67	28	37	4.7
1969 23	21 08 42.1	39.14	28.48	9	256	5.9
1969 24	01 59 34.0	39.11	28.51	30	156	5.1
1969 24	02 58 49.0	39.15	28.60	4	19	4.4
1969 24	08 13 05.4	39.02	28.41	43	55	4.7
1969 24	11 34 34.0	39.17	28.70	37	72	4.6
1969 24	12 13 17.0	39.08	28.65	20	34	4.7
1969 25	13 21 12.0	39.06	28.41	28	104	5.0
1969 25	13 21 34.2	39.25	28.44	37	197	5.8
1969 25	13 28 50.1	38.78	28.51	40	25	4.9
1969 25	14 18 52.1	39.17	28.49	34	120	4.9
1969 25	16 13 30.4	39.08	28.44	42	65	4.7
1969 26	03 31 26.5	39.03	28.27	37	56	4.6
1969 27	18 07 03.0	39.12	28.20	51	25	4.4
1969 28	01 48 29.5	38.55	28.46	4	296	6.4
1969 28	10 02 17.4	39.13	28.45	37	124	5.0
1969 APR 02	04 57 30.0	38.13	20.12	20	38	4.4
1969 03	22 12 21.9	40.66	19.98	21	197	5.6
1969 06	03 49 33.9	38.47	26.41	16	229	5.9
1969 08	15 48 50.4	40.67	19.77	17	128	4.9
1969 09	16 27 49.0	38.16	19.99	11	28	4.4
1969 14	05 11 45.5	38.90	21.79	36	82	4.5
1969 16	04 54 12.8	35.30	27.90	55	143	4.9
1969 16	22 55 40.5	35.32	27.77	52	173	5.3
1969 16	23 21 06.2	35.23	27.72	58	181	5.3
1969 17	00 54 38.2	35.19	27.83	55	132	4.9
1969 21	20 36 40.0	39.42	25.09	1	83	4.7
1969 24	14 45 48.8	36.35	28.73	53	79	4.7
1969 27	10 58 26.0	36.54	28.21	33	72	4.7
1969 30	20 20 32.0	39.12	28.52	8	141	5.1
1969 MAY 01	18 02 16.4	35.41	27.68	51	180	5.3
1969 01	20 06 45.4	35.39	27.73	67	145	4.7
1969 02	18 38 15.0	34.25	26.21	38	68	4.4
1969 03	03 25 36.3	35.21	28.03	81	48	4.6
1969 03	20 31 14.4	35.17	27.76	53	52	4.7
1969 13	17 48 02.1	39.03	28.57	35	42	4.6

DATE			ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1969	MAY	14	10 05 17.1	35.33	27.72	43	181	5.3
1969		14	23 57 35.5	39.15	28.49	36	28	4.6
1969		15	12 05 56.8	35.28	27.73	46	143	4.9
1969		16	05 09 34.4	35.00	24.51	51	70	4.6
1969		16	07 27 01.1	39.13	21.82	39	153	5.1
1969	JUN	07	15 31 09.0	37.85	20.19	9	104	4.6
1969		12	15 13 30.9	34.43	25.04	22	288	6.2
1969		12	18 00 30.8	34.23	25.22	63	53	4.9
1969		13	01 23 14.6	34.35	25.14	41	89	4.7
1969		14	13 47 26.4	34.34	25.05	21	154	5.1
1969		14	14 32 57.4	34.34	25.26	50	43	4.4
1969		15	05 58 43.2	34.30	25.13	35	67	4.6
1969		16	16 06 25.6	38.11	20.58	40	82	4.6
1969		17	05 18 43.0	38.23	20.21	11	57	4.4
1969		19	06 52 36.7	34.29	25.23	49	45	4.6
1969		25	06 11 51.8	35.98	27.60	48	54	4.7
1969	JUL	03	09 42 02.0	38.41	22.05	28	71	4.5
1969		04	10 13 52.0	35.32	27.89	30	33	4.7
1969		08	08 09 13.0	37.50	20.31	30	212	5.8
1969		11	01 45 26.0	35.32	28.10	40	20	4.4
1969		20	15 51 56.5	37.94	20.41	38	64	4.5
1969		24	23 21 19.3	34.93	26.00	60	81	4.5
1969	AUG	13	04 06 03.0	38.37	21.75	24	66	4.5
1969		14	21 51 05.3	39.52	27.87	21	56	4.7
1969		26	02 15 37.1	41.73	20.03	28	118	5.0
1969	SEP	04	19 25 26.6	35.11	27.17	43	83	4.9
1969		06	20 30 40.3	36.73	28.35	72	137	5.1
1969		22	08 17 43.4	36.57	28.01	86	42	4.7
1969		28	22 54 08.0	34.30	25.15	29	203	5.5
1969	OCT	02	23 13 40.6	38.47	22.29	45	50	4.7
1969		07	05 09 12.0	39.20	28.40	13	148	5.0
1969		07	18 49 02.6	39.16	28.54	49	32	4.5
1969		12	13 34 19.9	39.76	20.55	46	163	5.1
1969		13	01 02 30.8	39.78	20.59	27	236	5.7
1969	DEC	01	20 18 03.8	34.85	24.22	35	136	5.3
1969		19	23 54 40.5	38.92	22.00	65	65	4.3
1969		20	17 40 36.3	36.59	23.46	90	65	5.1
1969		21	22 01 06.8	36.66	28.42	69	47	4.6
1969		23	02 13 49.0	39.37	23.80	6	19	4.9
1969		27	07 31 54.5	39.22	23.82	42	44	4.6
1969		28	22 02 35.6	40.67	19.62	51	44	4.6
1969		31	05 08 10.1	34.26	26.37	51	22	4.5
1969		31	05 37 05.6	34.44	26.11	54	108	5.1
1970	JAN	24	15 43 54.0	37.21	23.45	105	42	4.7
1970	FEB	11	19 01 18.9	37.59	22.67	79	125	5.0
1970		17	00 16 28.3	39.34	20.62	53	89	4.6
1970		17	04 51 10.3	38.83	21.68	22	68	4.6
1970		20	20 19 32.0	36.55	27.26	20	39	4.9
1970		22	15 48 31.0	35.21	25.24	43	58	5.3
1970		22	15 52 17.1	35.38	25.27	34	75	4.9
1970	MAR	03	16 35 46.2	38.28	20.74	49	44	4.3
1970		04	01 51 30.7	34.47	26.48	44	60	4.7
1970		17	17 00 56.8	41.40	21.07	43	43	4.6
1970		23	20 56 01.0	39.04	20.49	7	119	5.0
1970		29	14 37 19.6	38.74	27.83	56	94	4.4

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1970 MAR 29	14 40 26.6	38.73	28.00	47	46	4.4
1970 30	06 46 24.9	39.09	29.03	23	57	4.4
1970 APR 05	04 55 39.5	34.68	25.07	35	68	4.5
1970 07	09 18 44.0	34.57	26.14	20	111	5.0
1970 08	13 50 28.3	38.34	22.56	23	281	6.2
1970 11	01 03 11.3	38.17	22.77	55	82	4.4
1970 16	22 39 31.3	40.67	23.45	20	159	5.0
1970 20	15 39 31.6	38.27	22.66	38	193	5.3
1970 23	04 29 48.2	37.51	22.73	74	133	4.9
1970 23	09 01 26.6	39.13	28.65	28	208	5.4
1970 24	14 37 20.0	36.75	28.66	34	61	4.6
1970 MAY 08	18 30 42.7	38.67	22.30	58	70	4.4
1970 12	22 49 03.2	38.21	22.55	39	146	4.9
1970 24	11 03 01.0	36.05	25.49	37	26	5.0
1970 JUN 08	06 51 03.0	41.44	20.40	29	31	4.4
1970 09	20 43 30.2	36.16	25.56	63	44	4.4
1970 19	22 27 01.3	39.48	20.56	58	77	4.5
1970 27	18 57 15.0	41.49	19.39	48	79	4.5
1970 30	18 21 22.0	38.80	20.57	22	89	4.6
1970 JUL 02	07 50 14.0	38.72	20.59	27	109	5.9
1970 02	14 12 55.9	38.65	20.21	17	20	4.7
1970 03	00 41 00.0	38.77	20.42	24	82	4.9
1970 11	23 29 19.6	38.86	20.57	36	76	4.5
1970 13	00 46 45.0	38.73	20.56	19	84	4.5
1970 AUG 08	12 13 19.8	37.79	21.80	77	51	4.4
1970 18	17 40 17.9	39.16	21.78	38	60	4.5
1970 19	02 01 51.6	41.08	19.77	21	207	5.3
1970 29	10 42 17.2	41.49	19.45	33	45	4.4
1970 SEP 01	01 06 40.0	38.94	20.21	7	132	4.8
1970 03	05 32 10.2	39.60	28.78	22	167	5.1
1970 18	16 53 38.0	34.33	26.26	12	62	4.7
1970 24	21 25 15.0	34.17	26.18	42	21	4.3
1970 27	15 56 35.5	39.18	20.40	53	53	4.8
1970 28	19 54 09.0	37.09	28.59	24	36	4.4
1970 OCT 01	22 21 56.9	38.04	22.85	35	115	4.9
1970 01	22 38 37.2	38.02	22.77	43	131	5.3
1970 08	22 14 22.4	38.10	20.29	46	86	4.6
1970 10	13 48 26.0	38.07	20.19	35	73	4.4
1970 11	02 35 29.0	38.04	20.25	15	71	4.4
1970 31	16 07 39.4	42.10	19.35	39	75	4.6
1970 26	01 57 39.7	34.50	24.05	47	87	4.7
1970 NOV 30	09 49 02.3	39.06	21.94	38	46	4.4
1970 DEC 28	03 42 15.0	37.06	29.02	7	27	4.4
1970 28	17 00 46.0	35.92	28.21	28	65	4.6
1970 29	00 49 04.0	35.05	23.32	36	52	4.5
1970 29	12 47 10.0	35.05	23.36	49	37	4.7
1970 29	21 03 38.0	36.03	28.34	26	39	4.6
1970 30	18 54 44.0	36.97	28.94	23	51	4.7
1971 JAN 02	00 46 15.9	35.12	23.17	42	95	4.6
1971 02	03 25 36.0	37.07	29.04	07	52	4.3
1971 03	23 18 43.1	34.63	26.32	47	220	5.4
1971 17	05 18 47.0	38.08	20.51	29	19	4.4
1971 18	10 35 50.0	37.51	20.40	40	43	4.4
1971 19	23 33 56.7	34.30	24.06	34	143	5.0
1971 FEB 03	18 28 12.8	38.53	21.67	39	37	4.3

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1971 FEB 09	21 20 35.3	38.13	22.77	40	67	4.4
1971 11	16 57 09.0	39.82	20.92	32	29	4.4
1971 23	19 41 23.0	39.62	27.32	10	214	5.3
1971 MAR 03	19 01 01.3	36.45	22.29	67	52	4.3
1971 09	04 58 41.3	38.74	20.44	36	108	4.7
1971 15	15 23 19.8	37.29	24.14	41	78	4.7
1971 18	16 08 02.1	36.32	26.98	141	81	4.3
1971 24	05 11 10.0	37.89	20.37	6	112	4.6
1971 25	15 26 34.1	34.43	24.14	44	70	4.6
1971 30	00 30 13.6	38.73	20.50	38	32	4.4
1971 30	19 40 13.3	38.98	20.79	46	72	4.7
1971 APR 09	22 09 21.5	34.76	24.23	42	81	4.6
1971 19	02 43 50.5	38.81	20.54	08	156	5.2
1971 22	09 28 27.8	41.89	20.38	40	97	4.7
1971 MAY 01	13 45 27.4	40.95	27.99	13	133	4.6
1971 05	01 15 35.0	41.87	20.28	11	68	4.4
1971 26	07 09 26.0	37.10	21.70	33	20	4.9
1971 JUN 05	19 55 52.0	38.40	21.86	02	29	4.3
1971 07	13 34 19.1	34.32	22.80	42	67	4.7
1971 JUL 03	04 05 55.4	35.15	27.89	40	116	4.5
1971 16	05 50 23.9	35.11	23.07	39	83	4.6
1971 AUG 08	19 39 28.7	38.44	21.69	36	50	4.3
1971 11	05 37 27.3	36.81	23.96	109	131	5.1
1971 SEP 03	13 17 00.7	36.81	28.79	0	22	4.6
1971 09	06 51 09.1	38.21	20.16	03	28	4.3
1971 11	02 03 11.5	38.87	22.31	5	58	4.4
1971 26	05 44 31.7	37.83	21.99	48	45	4.3
1971 29	21 02 34.3	37.02	23.28	60	44	4.4
1971 OCT 03	23 19 41.2	34.10	26.08	35	111	4.7
1971 04	16 35 09.5	34.16	26.18	17	103	5.0
1971 13	03 26 26.1	34.24	26.06	17	183	5.1
1971 16	09 45 35.8	36.63	28.54	61	55	4.9
1971 NOV 04	14 25 49.2	35.26	22.88	41	66	4.5
1971 12	12 30 50.9	36.61	27.09	23	55	5.3
1971 22	19 26 45.7	35.34	27.81	34	100	4.9
1971 27	03 54 28.4	39.75	25.66	24	61	4.6
1971 DEC 02	09 40 58.4	39.23	26.45	35	32	4.4
1971 17	02 06 04.6	34.94	23.96	25	104	4.9
1971 18	02 33 29.7	36.76	23.02	41	76	4.6
1972 JAN 12	13 51 20.0	35.01	23.61	46	149	5.1
1972 20	00 52 19.4	36.64	27.15	16	79	4.6
1972 20	02 15 06.9	36.64	27.23	34	83	4.9
1972 FEB 02	21 19 51.7	38.78	21.32	62	72	4.5
1972 13	11 27 39.8	36.07	23.98	77	42	4.3
1972 13	13 07 12.0	36.97	24.08	27	51	4.4
1972 16	00 42 24.9	37.03	24.17	24	49	4.3
1972 20	21 38 38.8	36.84	21.75	63	25	4.3
1972 28	10 52 47.5	37.06	24.09	31	19	4.7
1972 MAR 04	01 09 37.3	36.78	23.11	53	23	4.3
1972 16	03 35 35.9	37.89	23.43	142	63	4.3
1972 25	06 16 08.8	36.67	27.51	55	32	4.3
1972 31	02 58 08.0	36.43	21.26	19	132	4.7
1972 31	20 32 01.2	36.62	27.09	18	86	4.3
1972 APR 23	05 13 33.2	38.20	20.78	46	82	4.6
1972 26	06 30 23.2	39.43	26.36	18	144	5.1

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1972 APR 26	15 59 44.9	39.45	26.33	25	146	4.9
1972 29	18 29 38.3	34.80	24.66	48	178	5.3
1972 MAY 04	21 39 57.2	35.15	23.56	13	332	6.4
1972 08	09 20 55.5	41.69	23.64	12	168	5.1
1972 23	03 14 29.9	41.50	23.64	4	45	4.3
1972 JUN 05	10 44 59.6	37.83	21.38	57	2	4.3
1972 09	07 42 20.5	34.73	26.55	40	177	5.0
1972 15	00 33 24.9	38.34	22.20	33	5	5.1
1972 JUL 05	18 04 57.9	36.96	21.88	51	37	4.6
1972 08	05 46 15.3	41.56	23.68	38	39	4.7
1972 25	01 56 08.5	38.73	21.47	49	108	4.7
1972 AUG 12	23 47 57.9	41.09	22.69	12	108	4.6
1972 29	02 48 36.9	37.00	29.14	0	27	4.3
1972 SEP 03	08 38 46.3	39.16	27.98	30	118	4.6
1972 06	18 12 27.4	35.54	25.60	86	46	4.4
1972 13	04 13 19.7	37.96	22.38	75	344	6.2
1972 16	03 53 26.4	40.28	19.73	15	165	5.1
1972 16	14 06 26.7	41.35	20.68	6	86	4.4
1972 17	14 07 15.3	38.35	20.27	33	284	5.9
1972 17	14 44 10.4	38.39	20.36	39	62	4.6
1972 18	08 20 24.9	38.26	20.20	14	75	4.3
1972 23	01 53 16.5	42.25	25.31	24	89	4.6
1972 26	12 16 59.4	34.25	26.15	23	151	5.1
1972 OCT 10	04 31 40.3	35.24	25.42	33	92	4.6
1972 10	19 23 38.7	35.18	25.51	41	37	4.4
1972 15	22 02 54.3	37.99	21.03	66	103	4.4
1972 16	23 39 37.4	38.24	20.39	34	48	4.3
1972 23	09 56 27.5	37.78	26.32	28	35	4.3
1972 30	14 32 10.7	38.28	20.35	13	198	5.4
1972 NOV 05	19 25 42.6	35.03	24.77	31	198	5.3
1972 15	12 21 47.4	34.10	26.30	0	11	4.3
1972 17	02 42 35.8	37.39	20.33	41	90	4.3
1972 20	03 30 27.2	39.42	21.68	26	99	4.9
1972 24	03 48 34.2	39.39	20.43	09	209	5.4
1972 28	13 26 11.8	33.80	27.77	02	81	4.7
1972 DEC 02	13 28 22.8	35.28	27.06	36	168	5.3
1972 05	12 00 15.0	39.14	23.64	39	56	4.4
1972 14	17 50 21.7	37.99	20.39	10	66	4.3
1972 17	12 44 30.7	34.27	26.22	38	82	4.6
1972 19	19 34 30.0	35.29	27.74	40	120	4.7
1973 JAN 05	05 49 17.6	35.80	21.91	34	256	5.5
1973 10	03 24 12.0	37.69	21.42	45	148	4.9
1973 16	22 45 17.1	35.11	22.68	35	125	4.6
1973 23	11 46 43.0	34.28	24.98	37	101	4.7
1973 26	07 50 11.0	35.74	22.08	41	123	4.9
1973 FEB 20	05 55 15.0	34.38	23.88	19	101	4.5
1973 26	22 23 11.8	39.84	20.30	44	67	4.4
1973 MAR 12	20 30 43.9	35.86	21.81	45	114	4.7
1973 APR 06	14 13 57.3	34.41	25.18	37	199	5.3
1973 07	19 30 09.0	41.47	19.90	20	88	4.5
1973 16	00 05 42.2	34.64	25.01	44	131	4.5
1973 19	22 13 55.0	38.29	26.94	17	68	4.3
1973 22	13 39 44.4	35.07	23.45	46	118	4.5
1973 MAY 22	15 26 07.0	36.70	22.10	0	38	4.3
1973 JUN 12	11 01 52.3	34.18	26.15	47	63	4.3

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1973 JUN 26	19 05 23.4	34.36	26.13	50	158	4.9
1973 JUL 14	12 38 19.2	37.93	21.21	42	138	4.6
1973 21	12 51 55.0	34.94	24.72	33	73	4.4
1973 AUG 08	08 23 48.7	41.69	19.43	39	89	4.5
1973 SEP 12	09 36 50.5	40.72	21.01	91	75	4.4
1973 OCT 06	21 19 59.0	34.80	26.34	39	112	4.7
1973 10	11 05 34.8	34.34	28.45	63	78	4.6
1973 13	06 00 35.0	34.70	26.39	52	99	4.6
1973 14	18 07 06.4	34.68	26.31	51	152	4.8
1973 19	00 16 06.5	37.01	21.71	53	39	4.3
1973 NOV 04	15 52 12.6	38.87	20.54	13	277	5.9
1973 04	16 11 38.7	38.85	20.49	35	118	4.9
1973 12	00 07 11.3	35.35	27.74	47	160	4.7
1973 12	00 11 49.4	35.40	27.65	21	193	5.3
1973 14	09 33 57.4	35.29	27.74	42	102	4.5
1973 17	15 37 20.8	35.88	21.99	45	53	4.4
1973 19	07 28 59.9	35.34	27.71	60	118	4.7
1973 20	13 02 34.2	39.31	23.80	0	134	4.6
1973 29	10 57 44.3	35.18	23.81	37	309	5.9
1973 DEC 05	03 50 50.4	35.36	26.42	70	204	5.2
1973 24	13 53 54.8	35.08	27.69	53	68	4.3
1974 JAN 24	09 40 17.5	38.23	20.13	56	84	4.5
1974 27	21 06 17.4	35.04	25.38	35	119	4.7
1974 29	15 12 44.8	38.29	21.85	34	66	4.3
1974 FEB 01	00 01 02.2	38.55	27.22	24	176	5.4
1974 05	15 05 25.0	36.74	26.86	156	145	5.3
1974 23	01 28 47.0	38.02	22.00	40	82	4.4
1974 MAR 08	02 33 52.8	34.66	24.74	47	119	4.7
1974 09	04 12 07.5	34.59	24.80	42	96	4.4
1974 12	18 21 34.7	36.76	26.40	45	113	4.9
1974 13	17 20 45.2	34.60	24.75	46	144	4.6
1974 22	17 02 20.0	40.65	20.55	27	100	4.4
1974 APR 01	00 22 39.3	35.61	22.44	58	112	4.5
1974 07	14 22 48.7	34.75	24.70	38	204	4.7
1974 MAY 09	17 02 24.0	36.62	27.22	26	44	4.3
1974 19	22 01 09.7	35.47	26.31	84	238	4.9
1974 JUN 18	08 26 11.4	38.45	20.43	24	138	4.7
1974 22	23 30 12.1	41.25	23.05	08	159	5.1
1974 JUL 09	02 32 15.4	36.57	28.48	49	195	5.0
1974 AUG 14	16 05 20.1	35.44	23.04	64	53	4.3
1974 20	23 52 40.7	38.23	20.65	44	37	4.4
1974 SEP 05	11 34 37.4	35.71	24.75	53	118	4.4
1974 11	05 12 57.0	40.03	19.64	28	59	4.5
1974 13	18 24 57.4	40.48	23.39	8	91	4.4
1974 17	05 10 31.8	40.29	20.63	17	187	5.0
1974 18	09 07 02.0	40.21	20.78	3	56	4.3
1974 28	01 34 59.1	34.87	23.86	38	57	4.3
1974 OCT 20	11 25 50.3	39.57	18.83	33	163	5.0
1974 25	11 43 35.5	34.67	23.37	41	107	5.0
1974 NOV 09	06 00 45.0	38.92	20.32	24	83	4.9
1974 14	13 22 34.7	38.50	23.08	27	185	5.0
1974 14	14 26 46.6	38.48	23.01	6	182	5.1
1974 14	15 29 46.8	38.50	23.15	35	174	5.0
1974 23	07 52 28.2	39.77	18.81	38	36	4.3
1974 23	18 46 36.0	39.74	18.94	49	83	4.7

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1974 NOV 29	06 35 33.4	35.40	27.89	49	107	4.6
1974 DEC 01	12 09 29.5	39.48	26.35	36	95	4.5
1974 02	23 02 19.0	38.42	22.31	34	128	4.9
1974 14	02 36 37.7	38.19	20.75	32	243	5.4
1974 14	21 29 22.0	38.40	20.40	37	122	4.5
1974 18	21 30 54.8	39.95	23.86	33	46	4.4
1974 20	15 09 32.6	39.64	20.53	47	159	4.8
1974 20	16 02 06.2	39.71	20.74	47	46	4.3
1974 26	14 01 51.1	35.10	22.75	40	57	4.3
1975 JAN 03	01 59 44.4	35.62	27.34	42	156	4.9
1975 08	19 32 34.1	38.24	22.65	26	246	5.7
1975 08	19 58 16.0	38.10	22.75	33	110	4.5
1975 09	18 53 44.3	34.78	24.03	41	140	4.6
1975 11	18 06 55.0	34.76	23.98	42	41	4.3
1975 24	16 33 04.4	41.14	19.77	46	111	4.5
1975 25	14 14 05.0	37.84	20.01	1	62	4.6
1975 26	05 30 52.0	36.72	24.44	32	152	4.9
1975 26	06 24 42.7	38.75	20.13	0	22	4.3
1975 FEB 02	21 12 20.2	40.48	21.39	40	69	4.4
1975 09	12 36 05.0	38.71	26.16	27	79	4.5
1975 15	10 23 21.0	35.77	26.95	46	132	4.7
1975 20	13 55 35.9	38.54	20.39	4	59	4.4
1975 28	19 51 09.0	40.66	22.52	29	87	4.5
1975 MAR 17	02 06 39.1	40.48	26.03	2	114	4.6
1975 17	05 11 16.5	40.48	25.95	22	219	5.0
1975 17	05 17 47.1	40.40	26.24	5	138	4.9
1975 17	05 35 17.6	40.48	26.08	18	252	5.8
1975 25	02 52 52.6	34.66	23.69	0	44	4.4
1975 27	05 15 07.9	40.45	26.12	15	337	6.7
1975 27	06 15 46.0	40.41	26.23	22	100	4.7
1975 27	19 42 42.5	40.48	26.08	5	80	4.6
1975 30	13 03 17.6	40.57	26.36	0	64	4.4
1975 APR 01	08 20 02.0	38.53	23.25	8	44	4.4
1975 04	05 16 16.5	38.11	21.98	56	290	5.7
1975 05	03 30 24.0	36.27	21.68	58	38	4.3
1975 23	01 08 08.0	40.40	26.04	20	69	4.4
1975 24	22 58 16.6	37.48	22.60	68	164	4.9
1975 MAY 03	03 16 02.1	37.70	21.18	0	48	4.3
1975 11	23 11 47.9	37.36	23.84	43	81	4.7
1975 13	00 22 53.0	38.19	22.72	45	105	4.6
1975 19	03 26 20.4	38.34	22.34	26	153	4.7
1975 19	23 25 40.9	39.61	19.74	47	33	4.5
1975 JUN 02	03 19 08.0	36.47	26.52	31	92	4.7
1975 07	17 36 36.9	34.32	26.22	51	61	4.5
1975 08	17 22 28.3	34.60	23.45	47	67	4.5
1975 30	13 26 54.6	38.49	21.62	3	230	5.1
1975 30	18 40 32.0	38.45	21.61	41	84	4.6
1975 JUL 25	19 17 11.9	38.41	21.87	38	176	4.9
1975 29	15 07 12.8	34.84	24.95	47	169	4.8
1975 AUG 21	15 29 18.5	40.14	19.80	46	43	4.4
1975 SEP 12	13 10 19.6	36.27	21.90	43	212	5.0
1975 13	14 30 37.6	38.47	22.02	40	150	4.9
1975 16	05 06 19.1	41.54	19.33	25	217	5.1
1975 16	18 45 48.2	41.52	19.28	46	79	4.6
1975 17	23 04 07.2	36.37	23.06	35	201	5.1

DATE			ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1975	SEP	17	23 44 19.0	38.16	20.42	15	113	4.5
1975		20	05 22 18.2	34.60	26.41	60	89	4.9
1975		22	00 44 56.4	35.20	26.26	55	312	5.7
1975		23	21 34 14.1	36.60	26.76	158	86	4.6
1975	OCT	02	15 59 45.1	40.16	20.49	45	30	4.1
1975		06	21 27 54.0	34.13	25.22	24	80	4.3
1975		12	08 23 12.6	37.91	23.12	35	159	5.0
1975		16	17 45 49.3	38.28	21.95	40	40	4.0
1975		25	07 25 22.3	37.61	22.11	36	53	4.3
1975		28	02 43 23.8	35.34	23.19	67	31	4.0
1975	NOV	12	09 03 48.8	36.28	28.15	64	263	5.5
1975		13	03 07 20.5	33.42	22.84	0	203	5.3
1975		13	23 30 36.0	37.51	21.09	50	47	4.0
1975		17	14 36 41.0	34.29	23.34	2	64	4.1
1975		22	10 06 08.4	39.92	20.11	34	223	5.3
1975		30	04 20 46.8	37.02	21.25	52	47	4.3
1975	DEC	06	08 19 10.0	38.50	25.69	23	43	4.0
1975		08	23 03 38.0	36.43	27.90	5	18	4.1
1975		10	18 12 28.3	34.14	25.72	44	56	4.3
1975		16	08 08 29.4	39.44	20.45	50	26	4.4
1975		17	02 52 17.2	34.09	26.20	42	44	4.4
1975		21	15 37 16.6	35.62	26.78	98	62	4.4
1975		21	16 07 51.1	38.47	21.67	2	242	5.5
1975		21	21 05 15.0	38.38	21.85	0	41	4.2
1975		24	17 04 51.8	36.80	21.77	65	67	4.3
1975		31	06 34 04.0	38.42	21.70	28	53	4.1
1975		31	09 45 47.3	38.52	21.67	19	295	5.5
1975		31	14 53 42.0	38.45	21.70	26	80	4.5
1975		31	13 51 21.0	38.48	21.65	23	117	4.6
1975		31	15 14 36.2	38.38	21.76	0	54	4.2
1975		31	22 54 50.0	38.56	21.69	29	46	4.2
1976	JAN	01	00 04 06.0	38.42	21.72	18	122	4.7
1976		02	22 44 42.0	38.42	21.78	0	90	4.6
1976		03	05 54 35.1	38.37	21.54	27	33	4.2
1976		03	13 16 27.4	38.41	21.81	14	81	4.5
1976		03	13 50 08.0	38.36	21.77	2	35	4.0
1976		03	15 03 53.8	38.39	21.79	37	78	4.5
1976		10	07 11 20.0	36.80	27.92	31	70	4.5
1976		14	10 31 02.3	38.39	21.95	10	70	4.6
1976		18	15 10 28.4	38.81	20.51	5	254	5.7
1976		21	22 18 00.2	37.76	21.02	33	42	4.2
1976	FEB	01	14 46 07.0	36.12	22.28	60	50	4.3
1976		01	23 33 08.6	36.60	22.20	67	42	4.2
1976		02	12 13 01.0	39.78	20.60	36	43	4.4
1976		10	09 52 09.2	36.82	27.93	39	76	4.7
1976		18	11 41 37.9	38.70	20.44	48	87	4.5
1976		22	12 02 53.0	39.38	22.08	19	234	5.1
1976		22	22 01 48.8	39.39	22.13	34	143	4.8
1976		22	22 54 34.8	39.39	22.14	23	146	4.8
1976		22	22 56 34.2	39.33	21.91	69	31	4.3
1976		23	16 18 28.0	38.27	25.58	4	177	4.8
1976		23	17 12 18.8	34.90	26.90	70	33	4.1
1976		26	19 32 38.1	38.24	26.38	10	57	4.4
1976	MAR	02	19 41 34.1	40.66	19.59	11	191	4.7
1976	APR	04	22 26 27.4	34.83	26.42	36	44	4.2

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1976 APR 19	00 27 50.5	35.52	24.66	64	165	5.0
1976 30	16 09 30.2	35.97	24.66	98	98	4.8
1976 MAY 01	07 26 27.0	37.12	27.72	33	24	4.2
1976 06	17 59 02.6	34.69	23.86	46	42	4.7
1976 11	16 59 48.2	37.56	20.35	33	202	6.3
1976 11	17 10 10.6	37.33	20.46	20	81	5.4
1976 13	00 44 15.0	39.72	20.32	59	32	4.6
1976 13	20 44 52.5	36.84	21.39	51	41	4.7
1976 13	22 18 05.3	37.37	20.54	52	24	4.1
1976 15	02 47 31.6	35.46	27.06	45	11	4.0
1976 15	03 03 08.3	36.33	23.30	52	33	4.4
1976 18	08 30 21.4	35.03	25.39	73	102	4.9
1976 30	16 26 42.3	37.44	20.63	33	14	4.0
1976 JUN 05	20 30 11.5	38.58	22.21	51	16	4.0
1976 05	22 21 55.1	37.82	21.93	79	17	4.3
1976 10	05 55 22.4	35.50	23.74	92	18	4.3
1976 11	18 26 14.7	39.40	20.39	53	26	4.6
1976 12	00 59 16.9	37.54	20.55	8	160	5.3
1976 12	02 41 43.5	37.39	20.56	38	19	4.2
1976 12	04 54 48.2	37.39	20.44	43	32	4.6
1976 13	00 20 00.5	37.48	20.61	48	21	4.3
1976 15	00 07 54.4	34.22	24.77	33	21	4.0
1976 15	12 46 52.5	37.42	20.59	41	19	4.4
1976 20	04 51 17.0	38.53	22.12	51	17	4.7
1976 21	10 59 14.0	34.67	24.12	22	19	4.2
1976 25	07 01 08.0	35.09	23.31	33	94	5.4
1976 JUL 02	05 16 42.4	39.23	21.72	36	31	4.9
1976 08	15 20 39.7	37.61	20.71	49	22	4.4
1976 13	20 37 25.8	37.39	20.49	49	19	4.3
1976 18	02 17 11.9	36.71	23.35	66	20	4.1
1976 18	13 30 47.4	38.64	20.42	31	21	4.4
1976 23	20 51 02.9	37.99	21.53	33	14	4.3
1976 02	05 15 35.0	35.55	25.98	125	49	4.7
1976 17	17 37 56.6	36.88	27.05	167	96	5.2
1976 18	00 58 06.2	36.59	26.94	154	26	4.2
1976 18	17 06 35.5	36.78	27.42	163	35	4.7
1976 19	01 12 36.7	37.70	28.89	3	94	5.1
1976 19	22 36 26.6	39.23	22.27	58	26	4.2
1976 22	13 28 49.0	39.33	29.08	14	111	4.9
1976 22	17 18 46.9	37.41	20.56	63	35	4.3
1976 23	03 15 15.5	38.34	20.67	52	52	4.4
1976 SEP 12	00 42 19.3	36.67	26.98	168	22	4.2
1976 15	03 36 40.3	40.49	27.48	10	9	4.4
1976 30	00 33 02.0	37.53	20.37	43	122	5.0
1976 30	17 09 58.6	38.48	21.62	16	18	4.3
1976 OCT 02	12 45 29.4	37.12	21.22	68	36	4.3
1976 17	21 26 36.9	35.11	25.51	33	10	4.4
1976 21	12 48 11.8	35.91	26.98	99	68	4.9
1976 23	12 08 26.9	34.25	25.44	81	14	4.2
1976 27	00 38 45.9	38.42	22.57	33	21	4.2
1976 27	09 28 48.0	34.25	25.93	58	22	4.2
1976 28	01 04 46.7	34.85	26.27	42	21	4.3
1976 31	08 59 35.6	38.11	22.48	29	14	4.2
1976 NOV 09	16 02 19.6	35.67	24.00	69	29	4.5
1976 11	17 08 00.8	35.05	22.99	33	10	4.2

DATE			ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1976	NOV	12	09 51 10.8	38.62	26.73	24	34	4.3
1976		12	09 55 33.4	38.57	26.71	6	54	4.7
1976		13	06 09 46.5	34.97	23.32	29	88	5.3
1976		13	11 54 48.1	38.61	26.72	33	15	4.4
1976		18	12 09 22.8	36.86	24.56	65	22	4.2
1976		21	23 10 33.3	38.38	26.86	33	13	4.1
1976		22	03 31 15.7	38.80	22.01	33	20	4.4
1976		22	11 53 06.1	37.23	20.14	33	10	4.1
1976		24	20 57 05.5	37.21	20.33	33	25	4.2
1976		26	21 30 43.4	36.28	27.27	42	10	4.2
1976		27	15 36 41.4	37.50	20.08	33	10	4.4
1976		27	18 44 45.4	37.21	20.10	33	12	4.2
1976		28	19 25 17.3	37.30	20.34	24	106	4.9
1976		29	17 16 07.3	34.86	25.69	46	17	4.8
1976	DEC	15	16 06 24.7	35.48	23.33	49	50	4.4
1976		24	21 48 39.7	36.24	26.76	160	14	4.3
1976		26	08 41 27.3	38.93	20.17	33	9	4.4
1976		27	07 54 13.3	39.13	20.56	32	78	4.9
1976		30	15 12 37.9	37.91	22.82	34	52	4.7
1976		31	00 39 57.0	37.91	22.91	54	9	4.4
1977	JAN	03	00 44 07.8	38.21	23.11	23	8	4.4
1977		16	09 16 49.1	37.89	22.93	52	49	4.6
1977		18	20 46 51.9	35.78	29.41	57	39	4.3
1977		24	06 38 04.3	34.85	25.85	106	13	4.0
1977		25	23 54 18.1	39.36	28.13	23	25	4.6
1977	FEB	17	03 17 09.6	35.50	22.20	33	8	4.0
1977		21	17 44 15.3	37.48	20.51	53	25	4.9
1977		23	20 21 18.0	36.99	21.96	80	46	4.2
1977	MAR	08	03 01 36.7	36.54	28.43	63	34	4.0
1977		22	20 02 13.0	38.41	20.80	84	14	4.2
1977		23	11 55 53.4	39.66	28.55	23	43	4.6
1977		26	05 48 44.0	37.81	23.24	37	32	4.7
1977		28	10 50 18.0	36.80	27.51	24	66	4.9
1977	APR	05	17 15 08.1	39.28	23.29	37	18	4.7
1977		05	19 50 48.2	35.03	26.32	54	37	4.1
1977		13	09 30 55.2	37.49	19.88	33	5	4.1
1977		22	23 57 07.2	38.93	21.16	70	43	4.2
1977	MAY	05	23 13 07.3	34.63	24.79	16	54	4.1
1977		13	16 14 34.7	39.14	23.65	33	22	4.7
1977		16	08 16 00.6	35.38	26.52	47	46	4.2
1977		21	23 22 49.0	36.49	27.09	104	6	4.0
1977		27	22 31 49.1	35.23	26.50	68	100	4.8
1977	JUN	02	17 20 19.5	35.20	27.68	33	39	4.2
1977		10	23 02 32.3	35.12	22.76	33	52	4.1
1977		17	15 41 45.4	38.44	20.35	59	17	4.2
1977		21	19 13 26.1	35.57	29.60	46	39	4.7
1977		27	22 53 44.4	35.72	27.30	33	34	4.1
1977		28	21 03 41.4	37.74	21.18	33	13	4.7
1977	JUL	01	12 40 38.5	40.69	20.79	33	17	4.2
1977		09	10 24 26.5	35.22	23.54	73	43	4.2
1977		12	13 32 56.6	36.63	26.96	157	37	4.2
1977		14	00 39 01.9	36.21	27.71	33	25	4.0
1977		18	10 09 15.6	41.56	20.07	42	21	4.9
1977		25	22 28 54.9	35.09	23.78	46	48	4.2
1977		27	23 49 31.7	34.16	26.08	33	18	4.7

DATE	ORIG.TIME GMT	LAT N	LON E	DEPTH KM	OBS	MAG MS
1977 JUL 30	19 51 37.5	36.84	21.65	51	79	4.9
1977 AUG 05	13 19 54.8	34.27	25.80	24	56	4.2
1977 18	06 38 36.3	39.67	25.53	4	19	4.7
1977 18	09 27 40.0	35.22	23.39	42	125	5.3
1977 18	10 04 43.4	35.07	23.31	33	26	4.0
1977 25	03 03 09.3	35.00	28.28	10	14	4.1
1977 30	14 45 03.6	36.64	21.60	36	53	4.6
1977 30	20 51 50.2	36.38	21.56	33	13	4.6
1977 30	21 01 58.4	36.42	21.29	33	8	4.6
1977 31	08 22 15.3	37.74	21.24	73	43	4.7
1977 SEP 10	00 56 09.7	34.62	26.24	64	44	4.0
1977 10	06 31 41.8	34.93	23.01	33	74	5.1
1977 11	23 19 23.7	35.05	23.03	33	198	6.2
1977 12	02 57 55.0	34.99	23.17	36	106	4.5
1977 12	10 52 31.6	35.03	23.12	59	32	4.0
1977 12	23 10 32.3	35.65	24.17	165	14	4.1
1977 13	13 04 09.9	34.95	23.07	33	39	4.2
1977 14	18 49 07.6	34.99	23.06	33	80	4.5
1977 15	15 53 38.9	34.91	23.01	33	27	4.4
1977 18	05 57 19.3	34.92	23.31	33	17	4.2
1977 23	02 58 01.2	41.50	20.07	23	95	4.7
1977 24	20 43 08.9	35.06	23.21	64	54	4.2
1977 25	03 12 23.5	34.89	23.15	64	34	4.1
1977 OCT 07	12 42 51.3	38.76	20.63	33	17	4.3
1977 08	10 25 30.8	35.06	23.27	60	12	4.1
1977 10	08 49 42.5	35.40	23.38	81	17	4.3
1977 12	10 14 27.8	39.38	21.70	48	14	4.7
1977 12	20 37 34.3	34.98	23.99	33	8	4.1
1977 19	21 29 21.1	34.83	24.94	56	9	4.2
1977 22	10 02 09.1	34.95	23.16	33	107	5.1
1977 24	05 38 18.5	34.65	26.83	33	27	4.3
1977 27	22 43 32.5	37.96	27.88	24	90	4.7
1977 NOV 06	02 48 44.9	42.08	24.06	23	24	4.8
1977 17	06 28 09.1	42.02	24.08	12	22	4.7
1977 26	13 19 47.2	38.49	20.28	66	41	4.6
1977 28	02 59 10.8	36.05	27.76	85	229	5.9
1977 DEC 03	05 39 29.5	40.25	19.91	27	55	5.0
1977 09	15 53 36.7	38.35	27.19	19	94	4.6
1977 09	20 36 44.0	39.37	28.55	33	8	4.2
1977 08	00 40 43.6	35.21	23.38	62	42	4.4
1977 15	08 06 10.8	34.92	23.08	47	17	4.2
1977 16	07 37 30.1	38.43	27.22	34	72	4.8
1977 29	16 52 56.7	38.44	22.30	18	71	4.8
1978 JAN 29	10 23 44.3	35.18	25.94	33		5.7
1978 MAR 07	22 33 46.1	34.66	25.50	33		5.7
1978 APR 27	08 33 29.2	38.99	22.03	33		5.2
1978 MAY 23	23 34 15.3	40.78	23.41	33		5.3
1978 JUN 19	10 31 05.5	40.77	23.10	10		5.2
1978 19	10 48 10.7	40.68	23.06	10		4.8
1978 20	20 03 29.5	40.75	23.41	15		6.4
1978 20	21 51 03.4	40.64	23.02	10		4.1
1978 21	03 20 25.6	40.67	23.10	10		4.2
1978 21	06 00 05.7	40.67	23.19	10		4.2
1978 24	00 14 28.0	41.78	20.50	10		4.8
1978 26	00 03 48.8	42.37	20.40	10		4.6

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