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Seismic Risk in Chile

Francisco Silva Silva

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16. Abstract (Limit: 200 words)

In treatment earthquake occurrences as probabilistic phenomena, this approach compares different probabilistic models in a study on the development of seismic risk levels in Chile. Acceleration is used to assess the seismic risk in a particular region of the country since damages are related to peak ground acceleration. The report summarizes the historical, geographical backgrounds and tectonics of Chile, and utilizes data containing time, epicentral location, depth, and Richter magnitudes of 3351 earthquakes between 1906 and 1972. Two models for the occurrence of earthquakes are described and their results compared. The Markov process is based on a one-step memory and the Poisson process is based on the assumption that earthquakes occur independently of time and space. In incorporating risk in a planning program, it is suggested that a risk map could be developed, similarly to an iso-acceleration map, in which levels of risk could be defined in terms of additional expense required to prevent structural damage due to the calculated probable ground acceleration. The report includes acceleration maps, probability distribution for acceleration, and chronological listings of Richter magnitudes and epicenter locations of Chilean earthquakes between 1934 and 1972.

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SEISMIC RISK IN CHILE

A THESIS

SUBMITTED TO THE DEPARTMENT OF CIVIL ENGINEERING

AND THE COMMITTEE ON GRADUATE STUDIES

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

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Francisco Silva Silva

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CHAPTER 1
INTRODUCTION

1.1 Objectives

Historical accounts of seismic activity in Chile go back as far as the sixteenth century; that is, nearly three hundred years before the first known California earthquakes.[6*] Investigations and historic evidence show that these events have been more intense and potentially more dangerous than those occurring in California.

The structural engineer in an active seismic zone such as Chile faces the problem of deciding how much safety must his design include. In the extreme case, the structure could be designed to resist the strongest possible earthquake. On the other hand, no earthquake resistance could be provided. It is evident that additional safety can be purchased at a cost. A trade-off exists between safety and cost, and an intermediate point must be selected between the two extremes. Inherent to this decision is the acceptance of some damage level in the event of an earthquake. The idea of seismic risk can be expressed as the probability of having a certain damage. The purpose of this thesis is to develop risk levels for Chile, which is known to be a highly seismic country. Damages can be related to peak ground acceleration, among many other factors; thus, acceleration will be used to assess the seismic risk in a particular region of the country.

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*Superscript numbers refer to the list of references at the end of this thesis.

Earthquake occurrences and their destructiveness are problems which cannot be met with certainty, but when treated as probabilistic phenomena, they can be analyzed in a realistic way. It follows, then, that any risk study must be developed in a probabilistic way. This approach will be used here, and different probabilistic models will be compared.

1.2 Historical and Geographical Backgrounds

Montandon[6] describes about 44 destructive earthquakes in Chile between 1530 and 1899. This figure accounts for 12% of the total number of earthquakes which have been felt in all America between these same years. It is interesting to point out that Chile's area is only 5% of the South American continent. The same author indicates the number of times that the following Chilean cities were seriously damaged before 1899:

Arica	10 times
Copiapó	7 "
Coquimbo-La Serena	5 "
Valparaíso	6 "
Santiago	5 "
Concepción	6 "
Valdivia	5 "

A more detailed investigation shows that Concepción has been completely destroyed 3 times (1570, 1751, 1831) and severely damaged at least 6 more times, 2 of them in the last 30 years. Santiago also suffered a devastating earthquake in 1647 and experienced considerable damage 6 other times.

From a geographic standpoint, we should say that continental Chile extends roughly from 18° latitude south to 55° latitude south and has an average width of 160 kilometers. Because the country spans approximately 3000 miles, its physical characteristics are quite varied. These variations, in weather especially, are responsible for population concentration in the central valleys. Its population of 9,600,000 (as of 1960 census) is heavily concentrated in the central portion of the country, thus increasing the seismic risk in such regions.

Table 1.1 shows the distribution of Chile's area and population. Zones I, II, and III are the same seismic zones which will be defined in section 1.5. A brief analysis of these figures shows that Zones II and III should be considered more carefully in a risk analysis as compared to zone I. Although the latter accounts for as much as 35% of the territory, only 6% of the population lives there. In the foreseeable future, these distributions are likely to remain unchanged due to the arid characteristics of the northern zone.

Table 1.1

CHILEAN AREA AND POPULATION DISTRIBUTION

Zone	Lat. South	Area	% of Total	Population	% of Total
I	18°-29°	267,312 km^2	35.3	606,364	6.3
II	29°-34°	73,074 km^2	9.7	4,697,024	48.5
III	34°-55°	416,559 km^2	55.0	4,369,106	45.2
Totals		756,945 km^2	100.0	9,672,494	100.0

1.3 Tectonics of Chile

As previously stated, there is historic evidence that between 1534 and 1899 at least 44 destructive earthquakes with an estimated Richter magnitude (RM) of from 7.0 to 8.5 occurred in Chile. Furthermore, in the period from 1934 to 1972 where records are more reliable, at least 35 events in the RM range 7-8.5 have been recorded.

However, despite such a high seismic activity, it is difficult to establish relationships between earthquakes and surface tectonics. No active surface faulting has ever been reported. Only some evidence was found in the form of cracks in the ground following the great Chilean earthquake of May 22, 1960. These cracks appeared 300 miles from the estimated epicenter and their cause may be attributed to surface faulting or landsliding.[8]

Possible mechanisms are attributed to the uptilt of the Coast Range. Field evidence was reported after the 1939 Chilean earthquake.[6]

1.4 Data Compilation

A set of data containing date, time, epicentral location, depth, and Richter magnitude of 3351 earthquakes between 1906 and 1972 was the basic information of this study. These records were provided by the Environmental Data Service of the National Oceanic and Atmospheric Administration in Boulder, Colorado.

The above-mentioned data were scanned and reduced to a homogenous set of 580 events of RM 5.0 or higher for the 38-year period 1934-1972. A complete sequence of the 580 earthquakes, sorted according to chronological occurrence, is given in appendix A.

1.5 Seismic Zoning and Correlation

All of the data have been sorted by decreasing latitude and are presented in table 1.2. The total energy released in each degree of latitude has been computed with the empirical formula[18]

$$\log_{10} E = 11.8 + 1.5 M \qquad (1.1)$$

where:

E: total energy released by an earthquake, in ergs

M: Richter magnitude of the said earthquake.

Table 1.2

NUMBER OF EVENTS PER DEGREE OF LATITUDE, CHILE 1934-1972

Degrees Latitude South	Number of Events	Energy [HP-Hrx10^9]*	Average Energy [HPx10^6]
18-19	25	0.25	10.04
19-20	25	4.63	185.40
20-21	33	6.28	190.32
21-22	48	14.38	299.58
22-23	46	9.201	200.02
23-24	43	69.689	1620.67
24-25	45	4.57	101.55
25-26	28	2.63	93.93
26-27	8	17.26	2157.50
27-28	18	3.08	171.10
28-29	25	0.29	11.60
29-30	17	0.56	32.90
30-31	30	68.97	2299.00
31-32	20	3.94	197.00
32-33	28	1.44	51.43
33-34	17	3.20	188.23
34-35	9	0.06	6.67
35-36	8	0.46	57.50
36-37	8	72.43	9053.75
37-38	13	5.10	392.30
38-39	25	9.48	379.20
39-40	9	133.36	14817.78
40-41	6	1.74	290.00
41-42	9	1.69	187.78
42-43	7	0.08	11.42
43-44	6	0.06	10.00
44-45	6	0.28	46.67
45-46	6	1.10	183.33
46-47	3	0.47	157.67
51-52	3	0.03	10.00
52-53	2	0.09	4.50
53-54	1	0.37	370.00
54-55	1	-	-

Figure 1.1 shows a histogram of the events between 1934 and 1972, and figure 1.2 indicates the released energy in that same period, organized by decreasing latitude.

Figure 1.1 shows the spatial distribution of earthquakes. Although the number of events is shown to diminish toward the southern latitudes,

*1HP-Hr = 3.725×10^{-14} ergs.

FIGURE 1.1

HISTOGRAM OF EARTHQUAKE OCCURRENCES

CHILE, 1934-1972

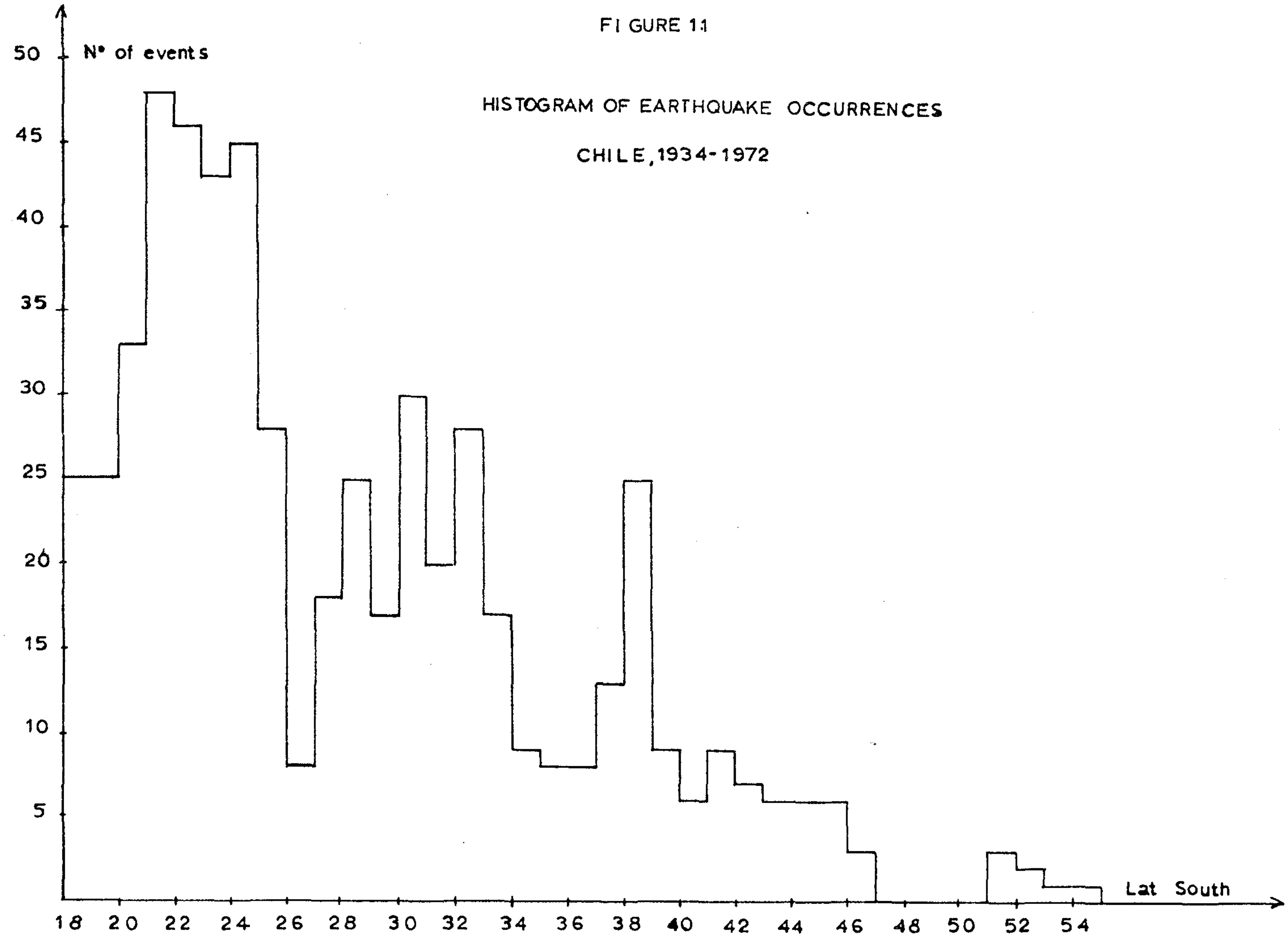
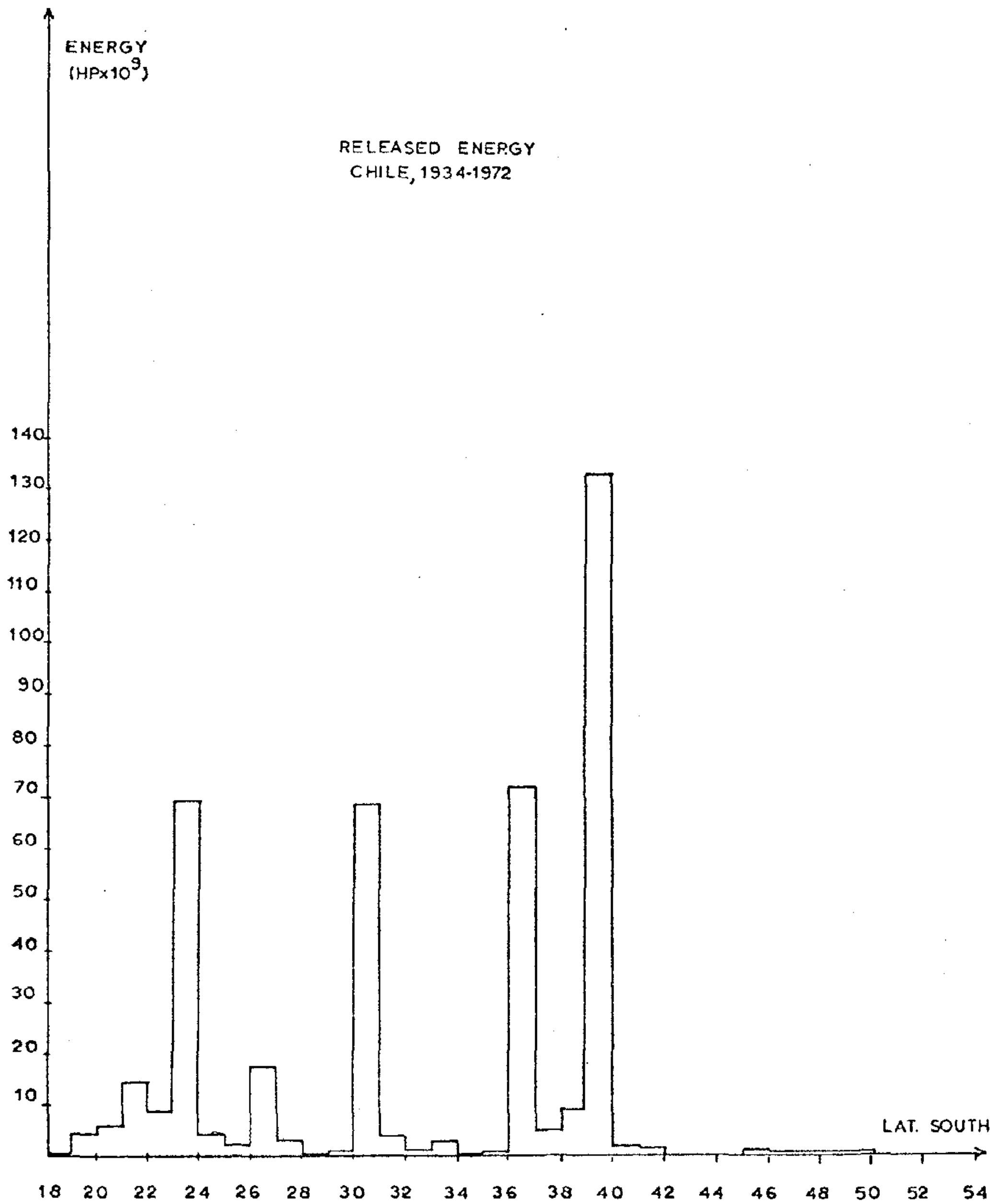


FIGURE 1.2


ENERGY
(HPx10⁹)
RELEASED ENERGY
CHILE, 1934-1972
140
130
120
110
100
90
80
70
60
50
40
30
20
10
LAT. SOUTH
18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54

no clear conclusion can be drawn as to a clear seismic zoning for the country as a whole. Figure 1.2, however, clearly depicts three separate zones with unique seismic characteristics. They are described below as zones I, II, and III, respectively:

Zone I: 18° to 29° Latitude South

Large number of events with relatively moderate Richter magnitude and fairly uniform release of energy.

Zone II: 29° to 34° Latitude South

Moderate number of events with fairly large magnitudes. This area shows a decline in both the number of earthquakes and their relative magnitude, as compared with zone I above.

Zone III: 34° to 47° Latitude South

Small number of occurrences, but high energy release.

From latitude 47° south down to the most southern part of the country, a very small number of events were reported (7 in 38 years). For this reason, this complete area has been discarded as a possible location for destructive earthquakes. This assumption is strengthened by the fact that the area is sparsely populated. It is likely that these conditions will remain unchanged in the future due to its extremely bad weather and its isolation from continental Chile.

Seismic zoning as the one just described also can be justified from a geologic point of view. To this effect, Gajardo and Lomnitz[16] have shown that Chile can be divided into seismic provinces. Such division is justified with the use of statistical methods and calculating a correlation coefficient between adjacent compartments of one degree of latitude, which is also affected by time. Based on Gajardo and Lomnitz' calculations and data, which are not available for this study, they have described the existence of 4 distinct seismic regions. Their first 2 regions coincide with region I, and the other 2 regions refer to what has been identified as zones II and III. In the following table, the seismic activity of Chile is briefly summarized for the period 1934-1972.

Table 1.3

SEISMIC ACTIVITY IN CHILE, 1934-1972

Latitude	Zone	Number of Events	Energy [HP-Hr$\times 10^{12}$]	Energy/event [HP-Hr$\times 10^{9}$]	Average Magnitude
18-29	I	344	0.132	0.384	7.2
29-34	II	112	0.077	0.685	7.4
34-55	III	122	0.238	1.955	7.7
		578	0.447	0.774	7.4

The mean magnitude has been calculated by the inverse of formula 1.1, using the average energy for the whole country. Also, it is noteworthy that the number of events tend to decrease from north to south whereas the magnitude increases in the opposite direction.

Seismicity maps appearing in appendix B show the location, magnitude, and depth of epicenters of the events under consideration. It is apparent that no real clustering of foci in fault lines can be detected. Considering the origin of such events, it has been hypothesized that deep north-south faults exist. However, transverse deep faults seem to exist also and cannot be discarded as potential sources of major earthquakes. This should be more carefully considered between 27° and 32° S, where transverse valleys exist.

A brief review of the seismicity maps in appendix B reveals that a great number of epicenters fall directly on the lines of even latitudes and longitudes. This is an indication that epicenter locations are not too reliable. According to NOAA, the data for events between 1934 and 1962 have been extracted from reference 17. The data from 1962 on have been gathered from various seismological stations across the United

States. Clearly then, the epicenter determination from:

$$d = \frac{t_s - t_c}{\frac{1}{v_s} - \frac{1}{v_c}} \tag{1.2}$$

where,

t_s: arrival time of shear waves

t_c: arrival time of compression waves

v_s: propagation velocity of shear waves

v_c: propagation velocity of compression waves

will introduce significant errors because t_s and t_c are graphically determined from telerecorded accelerograms.

A cross-examination with other sources of data reveals that some parameters as depth or epicenter location vary as much as 20%. However, these discrepancies will probably not affect the conclusions in a measurable way due to the probabilistic nature of the models which will be used.

CHAPTER 2

PROBABILISTIC MODELS FOR THE OCCURRENCE OF EARTHQUAKES

2.1 General Description of Probabilistic Models

In this chapter, two different models of earthquake occurrence will be presented. The first approach is suggested by the Elastic Rebound Theory. This theory explains earthquake occurrences by considering the strain energy accumulated by the earth along some external or internal fault. If strain energy exists, an earthquake may be expected in the near future. However, if an earthquake has recently occurred, strain energy has been released and a new earthquake is not likely to occur. This process can be described as a memory process whose current state depends on its last state. A memory process can be described by a first order Markov chain.

The second approach considers each event as an independent occurrence not related to previous or future earthquakes. Each earthquake can be identified as an arrival with an epicentral distribution for its interarrival time. This latter model is well described as a Poisson process, by considering each earthquake as a Poisson arrival.

2.2 Markov Model

2.2.1 Generalities of a Markov Model

This model is based on the classic Markov property of a chain of events of probabilistic nature; e.g., the current status of the system depends only on where the system was at the previous observation period. In terms of earthquake occurrences, we say that the probability of having an earthquake in any given time period depends on whether or not we have observed an occurrence in the previous period. Since we have assumed that three different tectonic units exist, we will focus our attention on each unit as an independent seismic zone.

For each independent tectonic unit, there is a build-up of energy which is randomly released, producing an earthquake. We can assume that the next event will depend only on the last occurrence. Should such an assumption be valid, we have a Markov chain which can either be a continuous or discrete time chain.

Such a Markovian assumption can be stated as "...only the last state occupied by the process is relevant in determining its future behavior..."[12] Thus, if we have N states, the probability of entering a given state j in the next transition depends on the last state. This can be written as:

$$P\left(s(n+1)=j/s(n)=i,\ s(n-1)=b,\ \ldots..s(o)=m\right) = P\left(s(n+1)=j/s(n)=i\right) \quad (2.1)$$

In other words, the probability of being in state j at time (n+1), given all previous states which the system has occupied, depends only on the state i where it was at time <u>n</u>. This probability is described as transition probability p_{ij}. Hence,

$$p_{ij} = P\left(s(n+1)=j/s(n)=i\right) \quad (2.2)$$

If we have N possible states, we can build a matrix [P] with the elements p_{ij}, thus

$$[P] = \begin{bmatrix} p_{11}\text{-----}p_{1N} \\ p_{N1}\text{-----}p_{NN} \end{bmatrix} \quad (2.3)$$

Since at any time the process must be in one of N states, each row must add equal to 1. P is called a one-step transition probability matrix.

Assuming we know the probability matrix, P, we will calculate the probability that the process will occupy state j at time n given that it occupied state i at time 0. Let $\phi_{ij}(n)$ be this probability, then

$$\phi_{ij}(n) = P\left(s(n)=j/s(o)=i\right) \tag{2.4}$$

The quantity $\phi_{ij}(n)$ is called the n-step transition probability of the Markov process, from state i to state j. This probability may be related to the transition probabilities, as follows

$$\phi_{ij}(n+1) = \sum_{k=1}^{N} \phi_{ik}(n) p_{kj} \tag{2.5}$$

and $\phi_{ij}(n+1)$ can be evaluated in a recursive form, considering that:

$$\phi_{ij}(o) = \begin{cases} o & \text{if } i \neq j \\ 1 & \text{if } i=j \end{cases} \tag{2.6}$$

The multistep transition probabilities satisfy the same requirements as the transition probabilities do, hence

$$o \leqslant \phi_{ij}(n) \leqslant 1 \qquad 1 \leqslant i \quad j \leqslant N \quad n=0, 1, \ldots\ldots \tag{2.7}$$

and

$$\sum_{j=1}^{N} \phi_{ij}(n) = 1 \qquad i=1, 2, \ldots\ldots N \quad n=0, 1, 2, \ldots \tag{2.7.a}$$

The n-step probabilities can also be arranged in a N by N matrix, the n-step probability matrix, $\Phi(n)$.

$$\Phi(n) = \begin{bmatrix} \phi_{11}(n) \ldots\ldots \phi_{1N}(n) \\ \\ \phi_{N1}(n) \ldots\ldots \phi_{NN}(n) \end{bmatrix} \tag{2.8}$$

From the recurrent relationship of equation 2.5 we can write $\Phi(n+1)$ in matrix form, thus

$$\Phi(n+1) = \Phi(n)P \tag{2.9}$$

We know that

$$\Phi(o) = I \text{ (identity matrix)} \tag{2.10}$$

hence we can compute $\Phi(n)$ for successive values of n, namely n=1,2,....

We find that

$$\Phi(o)= I$$
$$\Phi(1)= P$$
$$\Phi(2)= P^2 \qquad (2.11)$$
$$\vdots$$
$$\Phi(n)= P^n$$

In general, $\Phi(n)$ can be evaluated in a closed form by using its Z-transform. If $\Phi^g(Z)$ is the Z-transform of $\Phi(n)$ it can be shown that:

$$\Phi^g(Z)=[I-ZP]^{-1} \qquad (2.12)$$

We can speak of the probability that a given state is occupied after n transitions regardless of the initial state. This is called the state probability. The probability that state i is occupied at time n will be designated as $\pi_i(n)$, and it is defined as:

$$\pi_i(n)=P\left(s(n)=i\right) \qquad \begin{matrix} i=1,\ 2,\ldots\ldots N \\ n=0,\ 1,\ldots\ldots \end{matrix} \qquad (2.13)$$

The state probabilities must add up to 1, considering all states of the process:

$$\sum_{i=1}^{N} \pi_i(n)=1 \qquad n=0,\ 1,\ldots\ldots \qquad (2.14)$$

The state probabilities at time n can be calculated as:

$$\pi=\pi(o)\Phi \qquad (2.14.a)$$

where,

π: vector of state probabilities at time n
$\pi(o)$: vector of state probabilities at time o
Φ: n-step transition probability matrix.

Another interesting concept concerning a Markov process is that of first passage time. The first passage time of the system from i to j will be θ_{ij}. The probability that θ_{ij}=n is called $f_{ij}(n)$. In other words,

$$f_{ij}(n)=P(\theta_{ij}=n) \qquad n=1,\ 2,\ldots\ldots \qquad (2.15)$$

by definition, for n=o

$$f_{ij}(o)= o \qquad (2.16)$$

Again, we can think of an F(n) matrix whose element (i,j) is $f_{ij}(n)$. If $F^g(Z)$ is the Z-transform of the matrix F(n), it can be shown that,

$$F^g(Z)=\left(\Phi^g(Z)-I\right)\ \left(\Phi^g(Z)xI\right) \qquad (2.17)$$

where,

$\Phi^g(Z)$ is the Z-transform of $\Phi(n)$.

In general, the element (i,j) of the matrix A x B is $a_{ij}b_{ij}$.

2.2.2 Discrete Time, Two-State Markov Process

Throughout this section, the results derived in section 2.2 will be applied to a two-state Markov process. The states in this process are defined as:

State 1: No earthquake occurs.
State 2: An earthquake occurs.

The transition probability matrix can be written as:

$$P=\begin{bmatrix} 1-a & a \\ b & 1-b \end{bmatrix} \qquad (2.18)$$

where,

1-a: probability of having an earthquake this current period, given that one earthquake occurred during the last period.

b: probability of having an earthquake this current period, given that no earthquakes occurred during the last period.

In selecting a time period, one must not include more than one event. If this occurs, information is lost, since two or more earthquakes are considered as only one.

The n-step probability matrix can be shown to be:[12]

$$\Phi(n)=\begin{bmatrix} \frac{b}{a+b} & \frac{a}{a+b} \\ \frac{b}{a+b} & \frac{a}{a+b} \end{bmatrix}+(1-a-b)^n\begin{bmatrix} \frac{a}{a+b} & \frac{-a}{a+b} \\ \frac{-b}{a+b} & \frac{b}{a+b} \end{bmatrix} \qquad (2.19)$$

The limiting state probability vector of the process can be expressed as:

$$\pi=\left[\frac{b}{a+b}, \frac{a}{a+b}\right] \tag{2.19.a}$$

It can be shown that probability distribution of the first passage time is:[12]

$$F(n)=\begin{bmatrix} (1-a)+ab(1-b)^{n-2} & a(1-a)^{n-1} \\ b(1-b)^{n-1} & (1-b)+ab(1-a)^{n-2} \end{bmatrix} \tag{2.20}$$

Thus, knowing the probability distribution of each θ_{ij}, it is possible to calculate their expected values and variances.

These parameters are used to determine the mean waiting time before an earthquake occurs.

The matrix of first passage times is:

$$\bar{\theta}=\begin{bmatrix} \frac{a+b}{a} & \frac{1}{a} \\ \frac{1}{b} & \frac{a+b}{b} \end{bmatrix} \tag{2.21}$$

The matrix of variances is:

$$\breve{\theta}=\begin{bmatrix} \frac{a(2-a-b)}{b^2} & \frac{(1-a)}{a^2} \\ \frac{(1-b)}{b^2} & \frac{b(2-a-b)}{a^2} \end{bmatrix} \tag{2.22}$$

Figures 2.1 and 2.2 illustrate the sensitivity of θ_{11} and θ_{22} to the variations of the probabilities a and b. The values of a and b are determined from past data which may not be totally reliable. It is important, then, to realize the errors which the mean and variance may include due to variations of a and b.

It is important to realize that $\bar{\theta}_{11}$ does not have a clear physical meaning and it is presented in figure 2.1 solely for illustrative

Fig. 2.1

Mean First Passage Time from State 1 to State 1

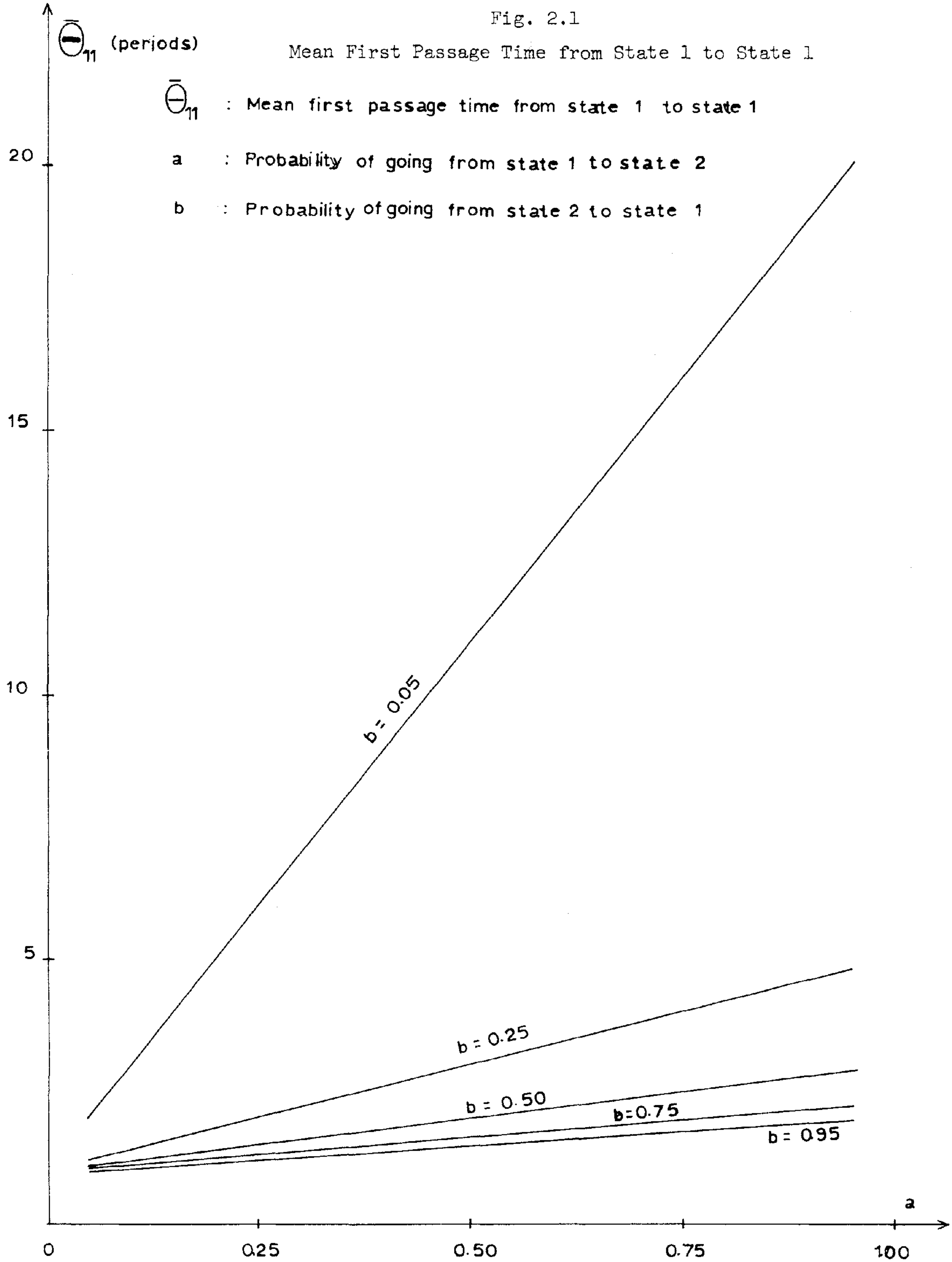
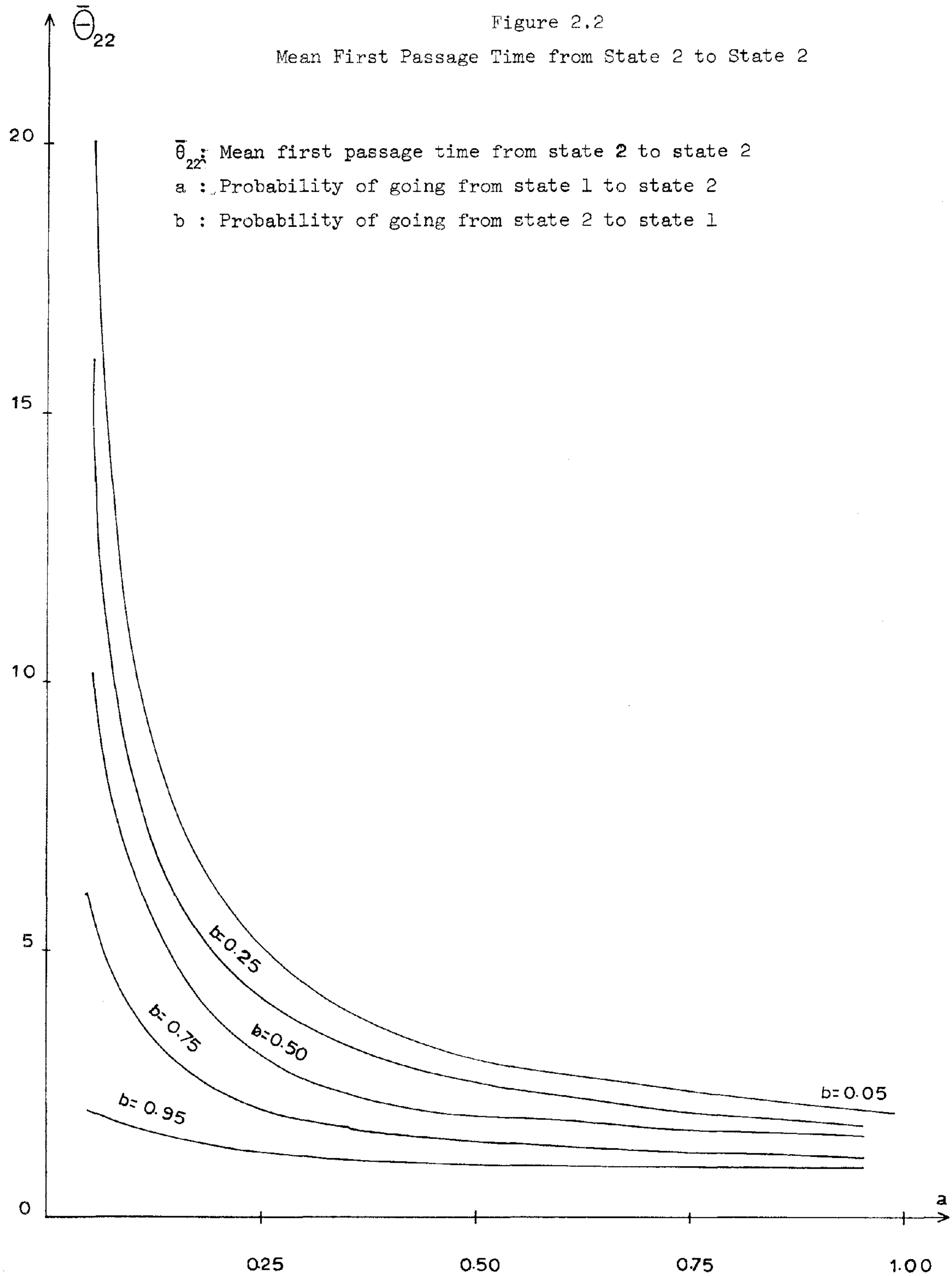


Figure 2.2

Mean First Passage Time from State 2 to State 2



purposes. However, $\bar{\theta}_{11}$ is an important quantity and it is interpreted as the mean waiting time between 2 successive earthquakes.

Earthquakes will be arranged in 4 categories according to their increasing magnitudes, as follows:

Earthquake Type 1: $5.0 \leq$ Richter Magnitude ≤ 5.9

Earthquake Type 2: $6.0 \leq$ Richter Magnitude ≤ 6.9

Earthquake Type 3: $7.0 \leq$ Richter Magnitude ≤ 7.9

Earthquake Type 4: $8.0 \leq$ Richter Magnitude

For each zone of the country, and each earthquake category, we need to determine:

a: probability of an earthquake next year given that this year no event occurred.

b: probability of no earthquake next year given that this year an event occurred.

$\bar{\theta}_{22}$: mean waiting period between two consecutive earthquakes.

$\check{\theta}_{22}$: variance of the mean waiting period $\bar{\theta}_{22}$.

From historic data presented in table 2.1, it is possible to determine the transitions from one state to another. Furthermore, if a and b are known, one may determine $\bar{\theta}_{22}$ and its variance $\check{\theta}_{22}$.

In the following pages, transition, probability, mean first passage time and variance matrices are presented.

Table 2.1

EARTHQUAKE OCCURRENCES

Year	Area I				Area II				Area III			
	Type				Type				Type			
	1	2	3	4	1	2	3	4	1	2	3	4
1934	x	x			x						x	
1935	x	x			x					x		
1936	x	x	x			x						
1937	x	x			x	x			x	x		
1938		x			x	x						
1939	x	x	x		x	x						x
1940	x	x	x			x				x	x	
1941	x	x	x		x	x						
1942			x			x						
1943			x			x						
1944		x					x					
1945							x					
1946	x	x	x			x			x			
1947	x		x									
1948												
1949		x	x								x	
1950				x						x		
1951		x	x									
1952		x					x					
1953		x	x			x					x	
1954	x	x				x				x		
1955		x				x	x			x		
1956	x	x	x			x						
1957			x			x						
1958		x				x						
1959		x	x			x			x			
1960	x	x							x	x	x	x
1961	x	x								x	x	
1962	x	x	x							x	x	
1963	x	x			x				x	x		
1964	x	x			x				x	x		
1965	x	x			x	x			x	x		
1966	x	x			x	x			x			
1967	x	x			x				x			
1968	x				x				x			
1969	x				x				x			
1970	x	x			x	x			x	x		
1971	x	x			x	x			x			
1972	x				x	x			x			

TRANSITIONS AND PROBABILITY MATRICES FOR AREA I
(18°-29° Latitude South)

Earthquake Type 1 ($5.0 \leq RM \leq 5.9$):

Transitions $\begin{bmatrix} 10 & 5 \\ 5 & 18 \end{bmatrix}$ Probability Matrix $P = \begin{bmatrix} 0.667 & 0.333 \\ 0.217 & 0.783 \end{bmatrix}$

Earthquake Type 2 ($6.0 \leq RM \leq 6.9$):

Transitions $\begin{bmatrix} 4 & 6 \\ 7 & 21 \end{bmatrix}$ Probability Matrix $P = \begin{bmatrix} 0.400 & 0.600 \\ 0.250 & 0.750 \end{bmatrix}$

Earthquake Type 3 ($7.0 \leq RM \leq 7.9$):

Transitions $\begin{bmatrix} 14 & 9 \\ 9 & 6 \end{bmatrix}$ Probability Matrix $\begin{bmatrix} 0.609 & 0.391 \\ 0.600 & 0.400 \end{bmatrix}$

Earthquake Type 4 ($8.0 \leq RM$):

Transitions $\begin{bmatrix} 36 & 1 \\ 1 & 0 \end{bmatrix}$ Probability Matrix $\begin{bmatrix} 0.973 & 0.027 \\ 1.000 & 0.000 \end{bmatrix}$

TRANSITIONS AND PROBABILITY MATRICES FOR AREA II
(29°-34° Latitude South)

Earthquake Type 1 ($5.0 \leq RM \leq 5.9$):

Transitions $\begin{bmatrix} 20 & 3 \\ 3 & 12 \end{bmatrix}$ Probability Matrix $\begin{bmatrix} 0.870 & 0.130 \\ 0.200 & 0.800 \end{bmatrix}$

Earthquake Type 2 ($6.0 \leq RM \leq 6.9$):

Transitions $\begin{bmatrix} 13 & 5 \\ 4 & 16 \end{bmatrix}$ Probability Matrix $\begin{bmatrix} 0.122 & 0.278 \\ 0.200 & 0.800 \end{bmatrix}$

Earthquake Type 3 (7.0 ≤ RM ≤ 7.9):

Transitions

$$\begin{bmatrix} 31 & 3 \\ 3 & 1 \end{bmatrix}$$

Probability Matrix

$$P= \begin{bmatrix} 0.912 & 0.088 \\ 0.750 & 0.250 \end{bmatrix}$$

Earthquake Type 4 (8.0 ≤ RM):

Transitions

$$\begin{bmatrix} 36 & 1 \\ 1 & 0 \end{bmatrix}$$

Probability Matrix

$$P= \begin{bmatrix} 0.973 & 0.027 \\ 1.000 & 0.000 \end{bmatrix}$$

TRANSITIONS AND PROBABILITY MATRICES FOR AREA III (34°-44° Latitude South)

Earthquake Type 1 (5.0 ≤ RM ≤ 5.9):

Transitions

$$\begin{bmatrix} 21 & 4 \\ 3 & 10 \end{bmatrix}$$

Probability Matrix

$$P= \begin{bmatrix} 0.840 & 0.160 \\ 0.231 & 0.769 \end{bmatrix}$$

Earthquake Type 2 (6.0 ≤ RM ≤ 6.9):

Transitons

$$\begin{bmatrix} 18 & 7 \\ 7 & 6 \end{bmatrix}$$

Probability Matrix

$$P= \begin{bmatrix} 0.720 & 0.280 \\ 0.538 & 0.462 \end{bmatrix}$$

Earthquake Type 3 (7.0 ≤ RM ≤ 7.9):

Transitions

$$\begin{bmatrix} 27 & 4 \\ 5 & 2 \end{bmatrix}$$

Probability Matrix

$$P= \begin{bmatrix} 0.871 & 0.129 \\ 0.714 & 0.286 \end{bmatrix}$$

Earthquake Type 4 (8.0 ≤ RM):

Transitions

$$\begin{bmatrix} 34 & 2 \\ 2 & 0 \end{bmatrix}$$

Probability Matrix

$$\begin{bmatrix} 2.944 & 0.056 \\ 1.000 & 0.000 \end{bmatrix}$$

MEANS AND VARIANCES OF FIRST PASSAGE TIMES
ZONE I (18°-29° Latitude South)

Type 1

$$\bar{\theta}= \begin{bmatrix} 2.53 & 3.00 \\ 3.60 & 1.65 \end{bmatrix} \qquad \breve{\theta}= \begin{bmatrix} 10.25 & 6.02 \\ 16.62 & 2.83 \end{bmatrix} \qquad \pi=(0.395,\ 0.605)$$

Type 2

$$\bar{\theta}= \begin{bmatrix} 3.40 & 1.67 \\ 4.00 & 1.42 \end{bmatrix} \qquad \breve{\theta}= \begin{bmatrix} 11.04 & 1.11 \\ 12.00 & 0.80 \end{bmatrix} \qquad \pi=(0.294,\ 0.706)$$

Type 3

$$\bar{\theta}= \begin{bmatrix} 1.65 & 2.56 \\ 1.67 & 2.53 \end{bmatrix} \qquad \breve{\theta}= \begin{bmatrix} 1.10 & 3.98 \\ 3.75 & 3.96 \end{bmatrix} \qquad \pi=(0.606,\ 0.394)$$

Type 4

$$\bar{\theta}= \begin{bmatrix} 1.03 & 37.00 \\ 1.00 & 38.00 \end{bmatrix} \qquad \breve{\theta}= \begin{bmatrix} 0.03 & 13.32 \\ 0 & 13.32 \end{bmatrix} \qquad \pi=(0.974,\ 0.026)$$

MEANS AND VARIANCES OF FIRST PASSAGE TIMES
ZONE II (29°-34° Latitude South)

Type 1

$$\bar{\Theta}= \begin{bmatrix} 1.65 & 7.67 \\ 5.00 & 2.54 \end{bmatrix} \qquad \breve{\Theta}= \begin{bmatrix} 5.43 & 51.47 \\ 20.00 & 19.76 \end{bmatrix} \qquad \pi=(0.606,\ 0.394)$$

Type 2

$$\bar{\Theta}= \begin{bmatrix} 2.39 & 3.60 \\ 5.00 & 1.72 \end{bmatrix} \qquad \breve{\Theta}= \begin{bmatrix} 10.58 & 9.34 \\ 20.00 & 3.94 \end{bmatrix} \qquad \pi=(0.418,\ 0.582)$$

Type 3

$$\bar{\Theta}= \begin{bmatrix} 1.12 & 11.33 \\ 1.33 & 9.50 \end{bmatrix} \qquad \breve{\Theta}= \begin{bmatrix} 0.24 & 117.76 \\ 0.44 & 112.54 \end{bmatrix} \qquad \pi=(0.895,\ 0.105)$$

Type 4

$$\bar{\Theta}= \begin{bmatrix} 1.03 & 37.00 \\ 1.00 & 38.00 \end{bmatrix} \quad \breve{\Theta}= \begin{bmatrix} 0.03 & 13.32 \\ 0 & 13.32 \end{bmatrix} \quad \pi=(0.974,\ 0.026)$$

MEANS AND VARIANCES OF FIRST PASSAGE TIMES
ZONE III (34°-44° Latitude South)

Type 1

$$\bar{\Theta}= \begin{bmatrix} 1.69 & 6.25 \\ 4.33 & 2.44 \end{bmatrix} \quad \breve{\Theta}= \begin{bmatrix} 4.82 & 32.81 \\ 14.41 & 14.52 \end{bmatrix} \quad \pi=(0.591,\ 0.409)$$

Type 2

$$\bar{\Theta}= \begin{bmatrix} 1.52 & 3.57 \\ 1.86 & 2.92 \end{bmatrix} \quad \breve{\Theta}= \begin{bmatrix} 1.14 & 9.18 \\ 1.60 & 8.11 \end{bmatrix} \quad \pi=(0.658,\ 0.342)$$

Type 3

$$\bar{\Theta}= \begin{bmatrix} 1.18 & 7.75 \\ 1.40 & 6.53 \end{bmatrix} \quad \breve{\Theta}= \begin{bmatrix} 0.29 & 52.34 \\ 0.56 & 49.64 \end{bmatrix} \quad \pi=(0.847,\ 0.153)$$

Type 4

$$\bar{\Theta}= \begin{bmatrix} 1.06 & 18.00 \\ 1 & 19.00 \end{bmatrix} \quad \breve{\Theta}= \begin{bmatrix} 0.05 & 3.06 \\ 0 & 3.06 \end{bmatrix} \quad \pi=(0.947,\ 0.043)$$

The values of a and b were used for calculating the matrices of mean waiting periods and their variances, as described by formulas 2.21 and 2.22. However, the only values which will be presented here are those of $\bar{\Theta}_{22}$ and $\breve{\Theta}_{22}$, since the other elements of the matrices do not have a physical meaning.

Table 2.2

MEAN WAITING TIMES AND STANDARD DEVIATIONS
(in Years)

	Type 1 (5.0≤RM≤5.9)		Type 2 (6.0≤RM≤6.9)		Type 3 (7.0≤RM≤7.9)		Type 4 (8.0≤RM)	
Zone	Mean Waiting Time	Standard Deviation	Mean Waiting Time	Standard Deviation	Mean Waiting Time	Standard Deviation	Mean Waiting Time	Standard Deviation
I 18°-29°	1.65	1.68	1.42	0.89	2.53	1.99	38.0	36.5
II 29°-34°	2.54	4.46	1.72	1.98	9.50	10.58	38.0	36.5
III 34°-44°	2.44	3.79	2.92	2.85	6.53	7.04	19.0	17.5

2.2.3 Continuous Time, Multi-State Markov Model

As has been mentioned previously, information is lost by using one year as a time unit for the discrete time model. This could be avoided by considering smaller time periods, or by considering each occurrence as a transition from one state to another and model this situation as semi-Markov process. A semi-Markov process is such that its future transitions are defined by the transition probabilities of a Markov process. However, its permanence in any state is described by an integer random variable. The value of this random variable depends on the state currently occupied and that which will be entered in the next transition. We define p_{ij} as the probability that a semi-Markov process, that entered state i in its last transition, will enter state j in its next transition. Clearly, the transition probabilities must satisfy:

$$p_{ij} \geq 0 \qquad i=1, 2, \ldots N \quad j=1, 2, \ldots N \tag{2.23}$$

$$\sum_{j=1}^{N} p_{ij} = 1 \qquad i=1, 2, \ldots N \tag{2.24}$$

If the process enters state i, the next state, j, is determined according to the probabilities $p_{i1}, p_{i2}, \ldots\ldots p_{ij}, \ldots\ldots p_{iN}$. The process stays in state i for a length of time T_{ij}. These holding times are positive, integer random variables defined by probabilities $h_{ij}(T_{ij})$. Hence:

$$P(T_{ij}=m)=h_{ij}(m) \qquad \begin{array}{l} m=1,2,\ldots\ldots \\ i=1,2,\ldots\ldots N \\ j=1,2,\ldots\ldots N \end{array} \tag{2.25}$$

We assume that the mean value of T_{ij} is finite and at least one unit time in length. In order to completely specify a semi-Markov discrete time process, we need N by N holding time functions.

If the process enters state i and chooses state j as its next state, the probability density function assigned to the time T_i spent in i will be w_i, where

$$w_i(m)=\sum_{j=1}^{N} p_{ij}h_{ij}(m)=P(T_i=m) \tag{2.26}$$

T_i is called the waiting time in state i and w_i is the waiting time probability density function. The waiting time is related to the mean holding time by the following expression:

$$\bar{T}_i=\sum_{j=1}^{N} p_{ij}\bar{T}_{ij} \tag{2.27}$$

$\phi_{ij}(n)$ will be defined as the probability that a semi-Markov process will be in state j at time n, given that it entered state i at time 0. This probability can be shown to be:[12]

$$\phi_{ij}(n)=\delta_{ij}W_i(n)+\sum_{k=1}^{N} p_{ik}\Sigma h_{ik}(n)\phi_{kj}(n-m) \tag{2.28.a}$$

where,

$$\delta ij=\begin{cases} 1 & \text{if } i=j \\ 0 & \text{if } i\neq j \end{cases}$$

$W_i(n)$: complementary cumulative probability distribution for the waiting time T_i

Using the cross-notation for matrices, defined as:

$$A \times B = \left[a_{ij}\ b_{ij}\right] \tag{2.28.b}$$

equation (2.28.a) can be written as:

$$\Phi(n)=W(n)+\sum_{m=o}^{n} P{\times}H(m)\Phi(n-m) \tag{2.28.c}$$

A limiting interval transition probability matrix can be defined by:

$$\Phi=\lim_{n\to\infty}\Phi(n)$$

These probabilities do not depend on the initial state i so they can be referred to only as ϕ_j instead of ϕ_{ij}. Also, we define the limiting state probabilities π_j such that:

$$\pi=\pi P \tag{2.29}$$

where,

$$\pi=\left[\pi_1,\pi_2,\ldots\ldots\pi_N\right] \tag{2.29.a}$$

P=transition matrix (2.29.b)

The difference between vectors ϕ and π is that ϕ takes into consideration the time spent in each state, whereas π describes only successive transitions.

Other interesting statistics of the semi-Markov process are the first passage times θ_{ij} and their mean values $\bar{\theta}_{ij}$. The mean first passage time $\bar{\theta}_{ij}$ can be calcuated as:

$$\bar{\theta}_{ij}=\bar{T}_i+\sum_{\substack{r=1\\ r\neq j}}^{N} p_{ir}\bar{\theta}_{rj} \qquad \begin{array}{l} i=1,\ 2,\ldots\ldots N \\ j=1,\ 2,\ldots\ldots N \end{array} \tag{2.30}$$

In the following pages, the model developed in section 2.4 will be applied to each of the zones in which the country has been divided.

The following states are defined:

state 1: occurrence of an earthquake type 1

state 2: occurrence of an earthquake type 2

state 3: occurrence of an earthquake type 3

state 4: occurrence of an earthquake type 4

The ordering and labeling of all the events which occurred between January 1, 1934, and June 30, 1972, makes possible the construction of the following transition matrix:

Transition Matrix - Zone I

	1	2	3	4	Total
1	208	31	2	0	241
2	29	42	11	0	82
3	4	9	5	1	19
4	0	0	1	0	1
					343 transitions

Dividing each row by the number of transitions, the transition probability matrix can be determined. Thus,

$$P = \begin{bmatrix} 0.863 & 0.129 & 0.008 & 0 \\ 0.354 & 0.512 & 0.134 & 0 \\ 0.210 & 0.474 & 0.263 & 0.053 \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad (2.31)$$

A geometrical probability distribution will be assumed, since it is an appropriate distribution when time is considered as a discrete parameter. The mean of this distribution can be calculated as the total time of observation divided by the number of transitions which have taken place.

The matrix of mean holding times can be shown to be:[12]

$$T = \begin{bmatrix} 68 & 454 & 7031 & * \\ 485 & 335 & 1278 & * \\ 3516 & 1562 & 2812 & 14062 \\ * & * & 14062 & * \end{bmatrix} \qquad (2.32)$$

(*=corresponding values not defined)

The expression for mean waiting time was:

$$\bar{T}_i = \sum_{j=1}^{N} p_{ij} T_{ij} \tag{2.33}$$

If we evaluate this expression for i=1,2,3,4, we have

$$\begin{aligned} T_1 &= 175 \text{ days} \\ T_2 &= 514 \text{ days} \\ T_3 &= 2220 \text{ days} \\ T_4 &= 14062 \text{ days} \end{aligned} \tag{2.34}$$

Solving

$\pi = \pi P$ we find the limiting state probabilities to be

$\pi = (0.703,\ 0.239,\ 0.055,\ 0.003)$

and the limit interval transitions probabilities

$$\phi_j = \frac{\pi_j T_j}{\sum_{j=1}^{4} \pi_j T_j} \qquad j=1,2,3,4 \tag{2.35}$$

$$\begin{aligned} \phi_1 &= 0.298 \\ \phi_2 &= 0.300 \\ \phi_3 &= 0.299 \\ \phi_4 &= 0.103 \end{aligned} \tag{2.36}$$

The quantity ϕ_j is the probability of observing the process in state j after it has operated for a long time; that is, it is equally likely to observe an earthquake whose RM lies in the intervals 5-5.9, 6-6.9, 7-7.9. However, it is one-third less likely to observe one in the 8-8.9 interval. It should be kept in mind that these are average values which would be obtained in a long period of observation.

Based on exactly the same considerations, for zones II and III, the following characteristics can be deduced:

Zone II

$$P=\begin{bmatrix} 0.859 & 0.141 & 0 & 0 \\ 0.393 & 0.464 & 0.107 & 0.036 \\ 0 & 0.750 & 0.250 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$T=\begin{bmatrix} 210 & 1279 & * & * \\ 1279 & 1082 & 4687 & 14062 \\ * & 4687 & 14062 & * \\ * & 14062 & * & * \end{bmatrix}$$

$$\bar{T}=[\ 361,\ 2008,\ 7031,\ 14062\ ]$$

$$\pi=[\ 0.703,\ 0.252,\ 0.036,\ 0.009\ ]$$

$$\Phi=[\ 0.221,\ 0.448,\ 0.221,\ 0.110\ ]$$

Zone III

$$P=\begin{bmatrix} 0.805 & 0.143 & 0.039 & 0.013 \\ 0.438 & 0.375 & 0.187 & 0 \\ 0.167 & 0.583 & 0.167 & 0.083 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$T=\begin{bmatrix} 227 & 1279 & 4687 & 14062 \\ 1004 & 1172 & 2343 & * \\ 7031 & 2009 & 7031 & 14062 \\ * & 7031 & * & * \end{bmatrix}$$

$$\bar{T}=[\ 730,\ 1318,\ 4687,\ 7031\ ]$$

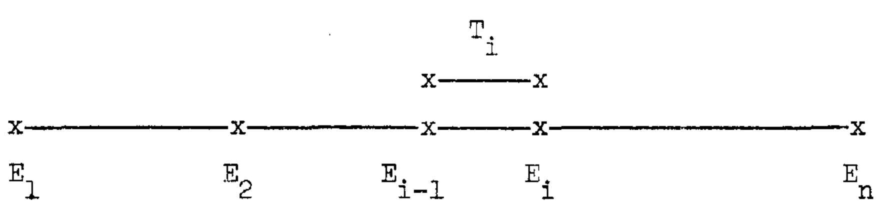
$$\pi=[\ 0.644,\ 0.253,\ 0.087,\ 0.016\ ]$$

$$\Phi=[\ 0.355,\ 0.252,\ 0.308,\ 0.085\ ]$$

2.3 Poisson Model

An alternative model for earthquake occurrences is suggested by a Poisson process which is based on the assumption that earthquakes occur independently of time and space; that is, an earthquake occurring at a given location does not affect the occurrence of future quakes nor is it influenced by past events. A process with these characteristics is called a memory-less process, as opposed to a Markov process, which does have a one-step memory.

Let E_i be the i^{th} event from a series of events, distant in time T_i from event E_{i-1}, as shown in the figure below:



In this case, the Poisson assumption states that the probability of occurrence of event E_n, $P(E_n)$ is independent of the past. This can be expressed as:

$$P(E_n/E_{n-1},\ldots, E_1) = P(E_n) \tag{2.37}$$

Define:

λ: mean number of occurrences during time t

n: number of occurrences

$P_t(n)$: probability of having n occurrences in time t

The Poisson probability distribution is given by:

$$P_t(n)=\frac{e^{-\lambda}\lambda^n}{n!} \tag{2.38}$$

Let $\lambda=\mu t$, where μ is the mean number of occurrences per unit time, $P_t(n)$ can be written as:

$$P_t(n)=\frac{e^{-\mu t}(\mu t)^n}{n!} \tag{2 .39}$$

The application of such model requires some means of calculating values for λ and μ, and a justification of the memory-less property. This latter assumption is justified by assuming that the crustal action will continue in the future as it has been in the past. In order to calculate a mean value λ and a rate of occurrence μ, a recursion relationship needs to be developed. Let N(M) be the number of earthquakes of RM M or greater in an area a and time t. The recursion relationship is developed by plotting the values of N(M) versus M. It is observed that a linear statistical relationship between lnN(M) and M exists. Using a least-square technique, a best-fit line can be derived. Its equation will have the general expression

$$Ln(N(M))=A+BM \tag{2.40}$$

The least-square line for areas I, II, and III is presented in figures 2.9, 2.10, and 2.11. A and B are seismic parameters of the zone under consideration. The value of A describes the seismicity of the area and is related to the total number of earthquakes. The parameter B represents the seismic severity, since it represents the relative frequency of the large earthquakes to the small ones.

Other recursion relationships are log-normal and gaussian. However, these will not be used in this study.

The recursion relationship is derived for a given area <u>a</u> and time <u>t</u>. Assuming that earthquakes are uniformly distributed over the area and time under consideration, a unit number of occurrences N'(M) can be defined. Thus,

$$N'(M)=\frac{N(M)}{at} \tag{2.41}$$

Introducing N'(M) in equation 2.40,

$$\mathrm{Ln}\; N'(M) = A'+BM \tag{2.42}$$

where,

$$A'=A-\mathrm{Ln}(at) \tag{2.43}$$

For some time-interval t and area a, the probability of having n(M) events is:

$$P_t\; n(M) = \frac{\mathrm{Exp}\left(-N'(M)at\right)\; N'(M)at^{\;n}}{n!} \tag{2.44}$$

Thus,

$$\begin{aligned}\mu&=N'(M)a\\ \lambda&=N'(M)at\end{aligned} \tag{2.45}$$

The probability of having no event of magnitude greater than M is found by making n(M)=o in equation 2.43. Hence,

$$P_t\left(n(M)=o\right)=\mathrm{Exp}\left(-N'(M)at\right) \tag{2.46}$$

The probability of having at least one occurrence is:

$$q(M)=1-P_t\left(n(M)=o\right) \tag{2.47}$$

which can be written as:

$$q(M)=1-\mathrm{Exp}\left(-N'(M)at\right) \qquad (2.47.a)$$

The log-linear recursion relationships for the three seismic sub-areas have been calculated based on the frequency histograms presented in Table 2.3.1.

Table 2.3.1

INTERVAL AND CUMULATIVE FREQUENCIES, CHILE, 1934-1972

RM Interval	Zone I Interval Frequency	Zone I Cumulative Frequency	Zone II Interval Frequency	Zone II Cumulative Frequency	Zone III Interval Frequency	Zone III Cumulative Frequency
5.0-5.1	44	344	12	112	13	124
5.1-5.2	38	300	10	100	13	111
5.2-5.3	33	262	13	90	4	98
5.3-5.4	25	229	9	77	12	94
5.4-5.5	34	204	3	68	6	82
5.5-5.6	26	170	9	65	11	76
5.6-5.7	11	144	11	56	3	65
5.7-5.8	11	133	3	45	6	62
5.8-5.9	17	122	6	42	5	56
5.9-6.0	3	105	3	36	5	51
6.0-6.1	23	102	8	33	8	46
6.1-6.2	4	79	0	25	2	38
6.2-6.3	5	75	1	25	0	36
6.3-6.4	11	70	3	24	2	36
6.4-6.5	4	59	2	21	1	34
6.5-6.6	12	55	5	19	8	33
6.6-6.7	3	43	1	14	2	25
6.7-6.8	2	40	1	13	0	23
6.8-6.9	16	38	5	12	5	23
6.9-7.0	2	22	2	7	4	18
7.0-7.1	8	20	2	5	2	14
7.1-7.2	1	12	1	3	1	12
7.2-7.3	2	11	0	2	1	11
7.3-7.4	3	9	0	2	3	10
7.4-7.5	3	6	1	2	2	7
7.5-7.6	0	3	0	1	0	5
7.6-7.7	0	3	0	1	1	5
7.7-7.8	0	3	0	1	0	4
7.8-7.9	1	3	0	1	2	4
7.9-8.0	1	2	0	1	0	2
8.0-8.1	0	1	0	1	0	2
8.1-8.2	0	1	0	1	0	2
8.2-8.3	0	1	0	1	0	2
8.3-8.4	1	1	0	1	1	2
8.4-8.5	0	-	1	1	0	1
8.5- -	0	-	-	-	1	1

These histograms and their cumulative frequencies are shown in figures 2.3 through 2.8. The log-linear relationships for each seismic area have been calculated by a least-square fit. They are presented in figures 2.9, 2.10, and 2.11. The coefficients of such relationships appear in table 2.3.2.

Table 2.3.2

COEFFICIENTS OF THE LOG-LINEAR RELATIONSHIPS

	A	B	A'
Zone I	15.705	-1.879	-0.76
Zone II	13.430	-1.689	-1.7211
Zone III	11.823	-1.377	-4.283

The values of A, B, and A' are used for calculating the probability q_m. The value of q_m is given in table 2.3.3, below, for various magnitudes and time periods.

Table 2.3.3

PROBABILITIES OF AT LEAST ONE EVENT

Richter Magnitude	Zone I Probability of at Least One Event		Zone II Probability of at Least One Event		Zone III Probability of at Least One Event	
	25 Years	50 Years	25 Years	50 Years	25 Years	50 Years
5.0	0.9834	0.9997	0.9624	0.9989	0.9612	0.9985
6.0	0.9442	0.9965	0.8858	0.9870	0.9041	0.9908
7.0	0.8115	0.9645	0.6532	0.8797	0.7629	0.9437
7.5	0.6537	0.8801	0.3956	0.6347	0.6270	0.8609
8.0	0.3753	0.5954	0.0575	0.1117	0.4135	0.6656
8.3	0.0837	0.1605	*	*	0.2305	0.4076
8.5	*	*	*	*	0.0775	0.1490

*The corresponding values are not defined.

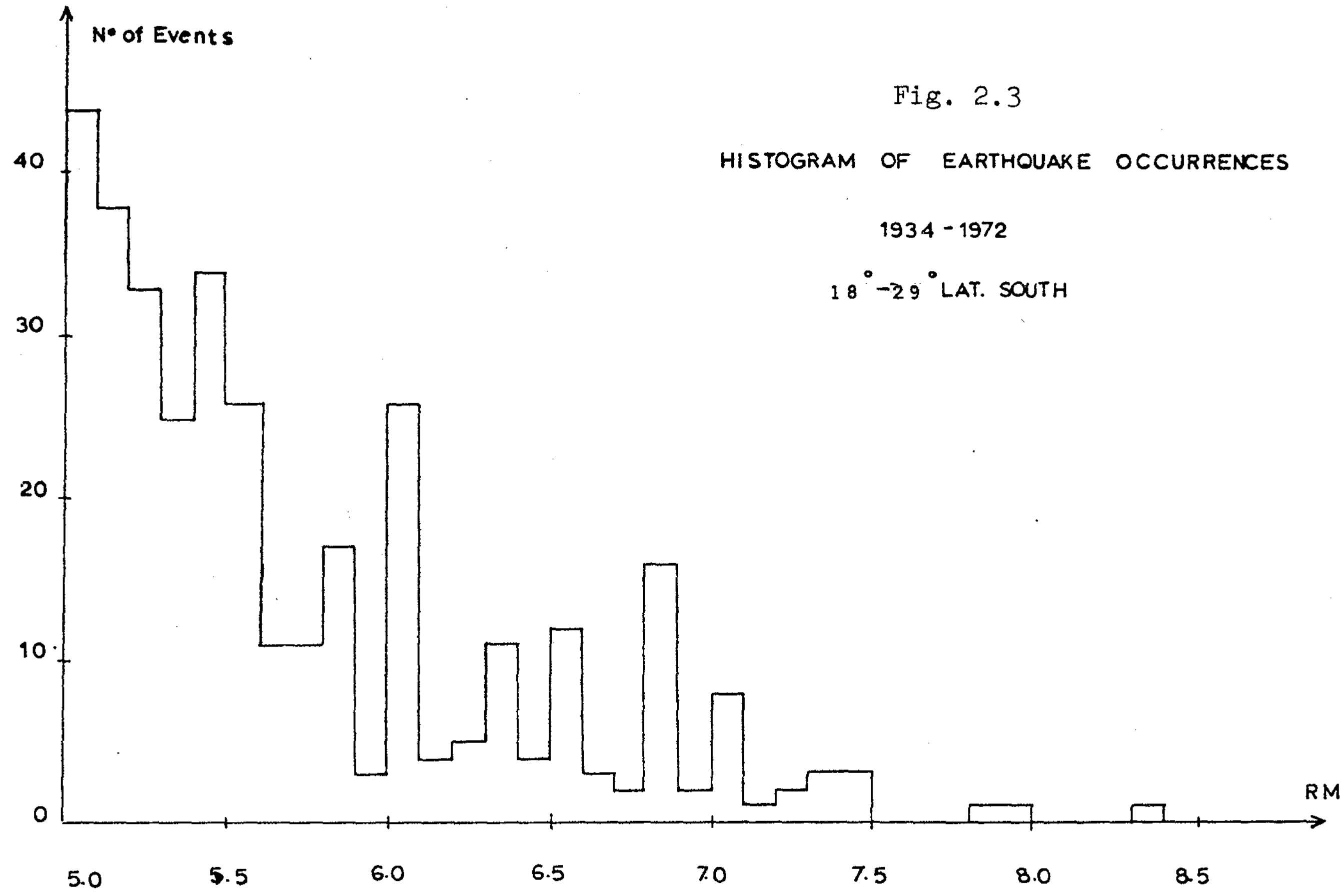


Fig. 2.3

HISTOGRAM OF EARTHQUAKE OCCURRENCES

1934 - 1972

18°-29° LAT. SOUTH

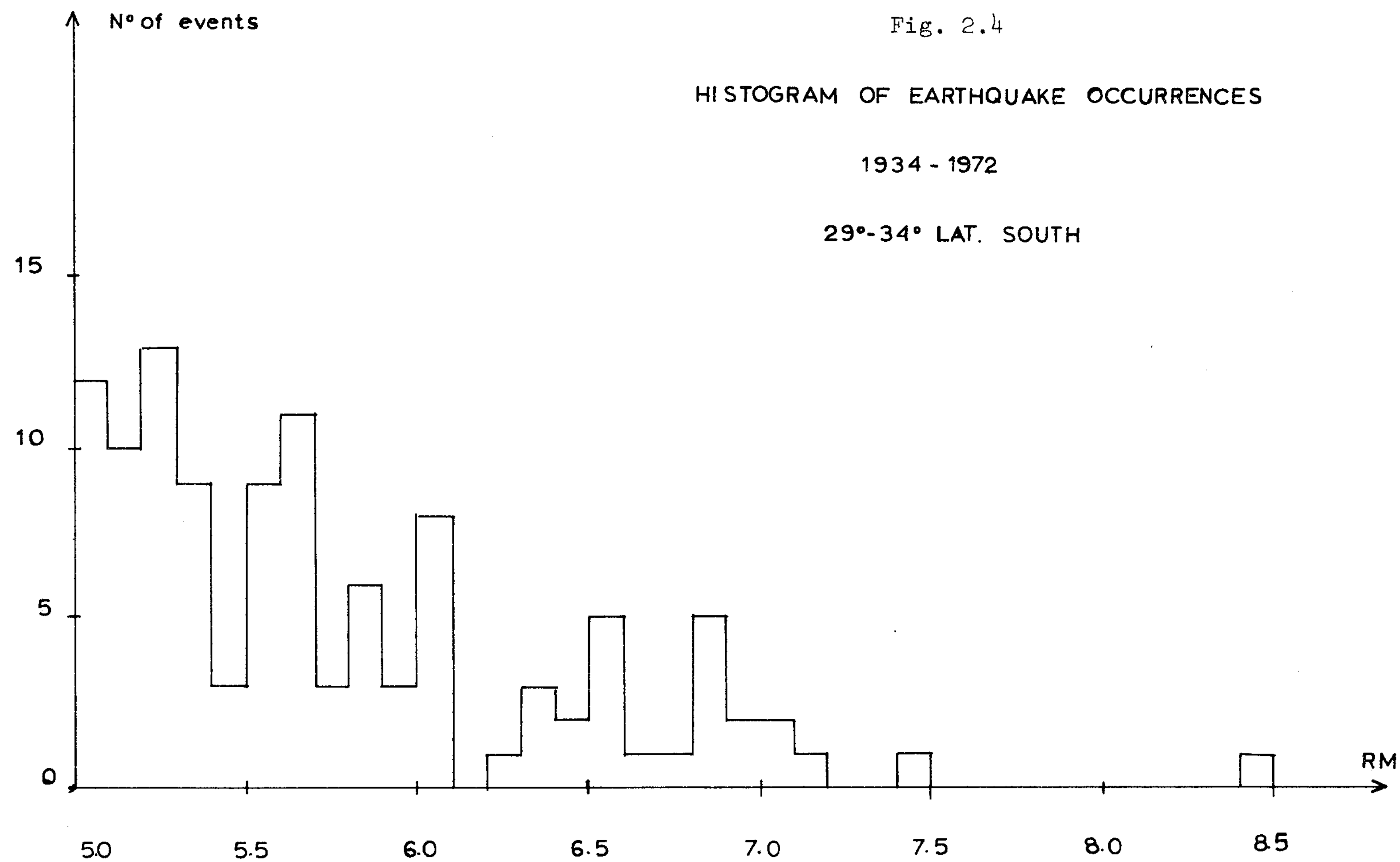


Fig. 2.4

HISTOGRAM OF EARTHQUAKE OCCURRENCES

1934 - 1972

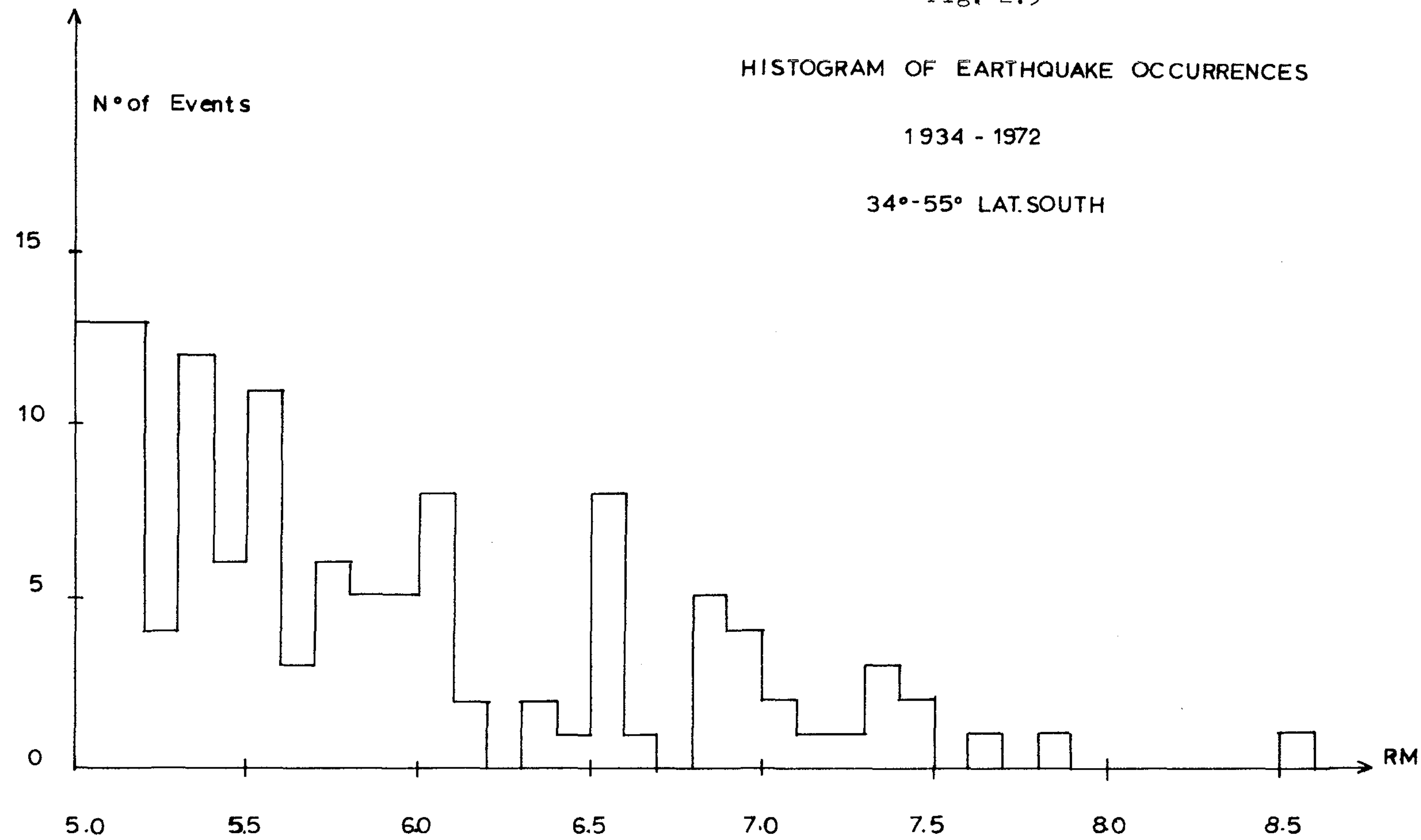
29°-34° LAT. SOUTH

Fig. 2.5

HISTOGRAM OF EARTHQUAKE OCCURRENCES

1934 - 1972

34°-55° LAT. SOUTH



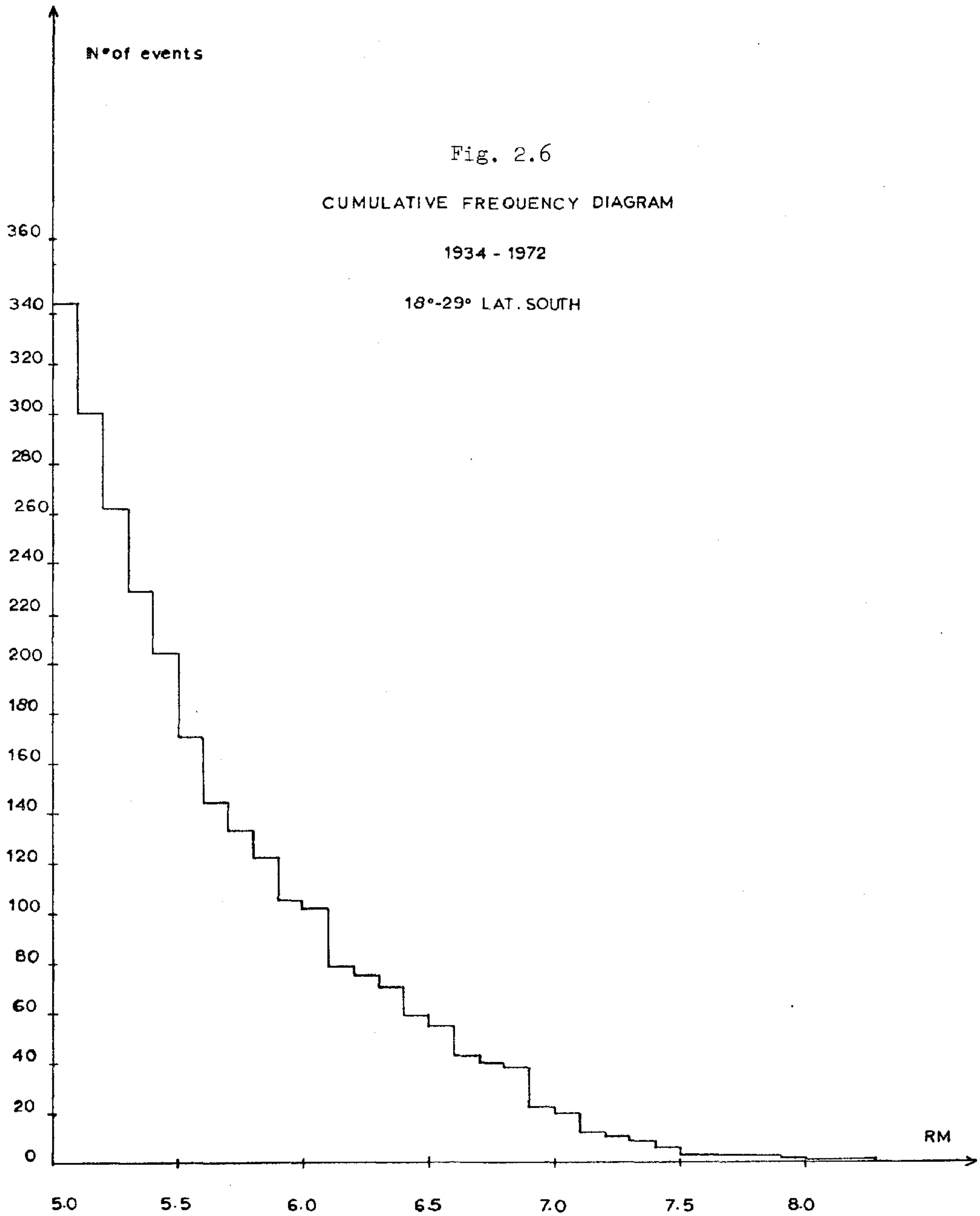


Fig. 2.6

CUMULATIVE FREQUENCY DIAGRAM

1934 - 1972

18°-29° LAT. SOUTH

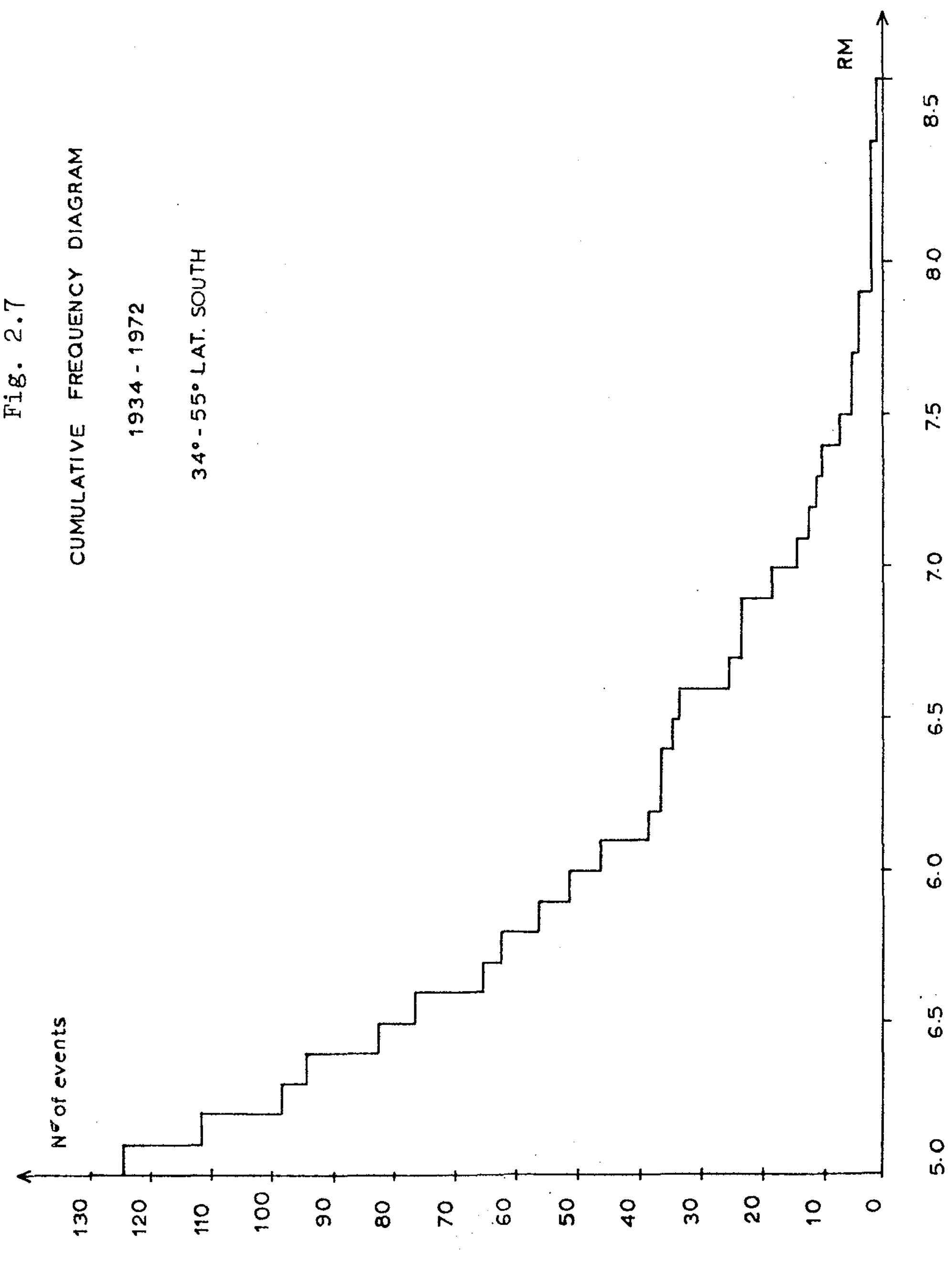


Fig. 2.7

CUMULATIVE FREQUENCY DIAGRAM

1934 - 1972

34° - 55° LAT. SOUTH

Fig. 2.8

CUMULATIVE FREQUENCY DIAGRAM

1934 - 1972

34° - 55° LAT. SOUTH

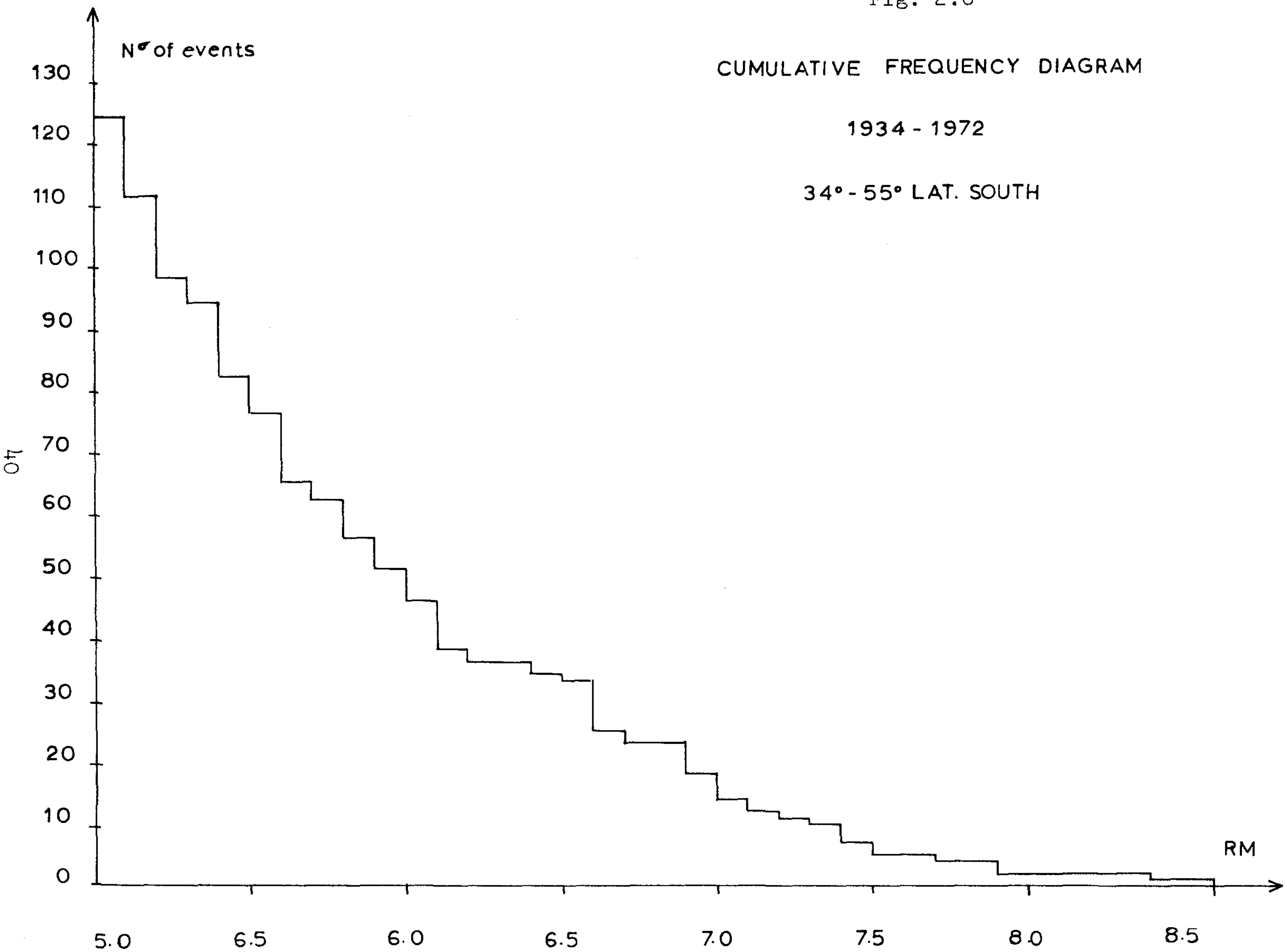
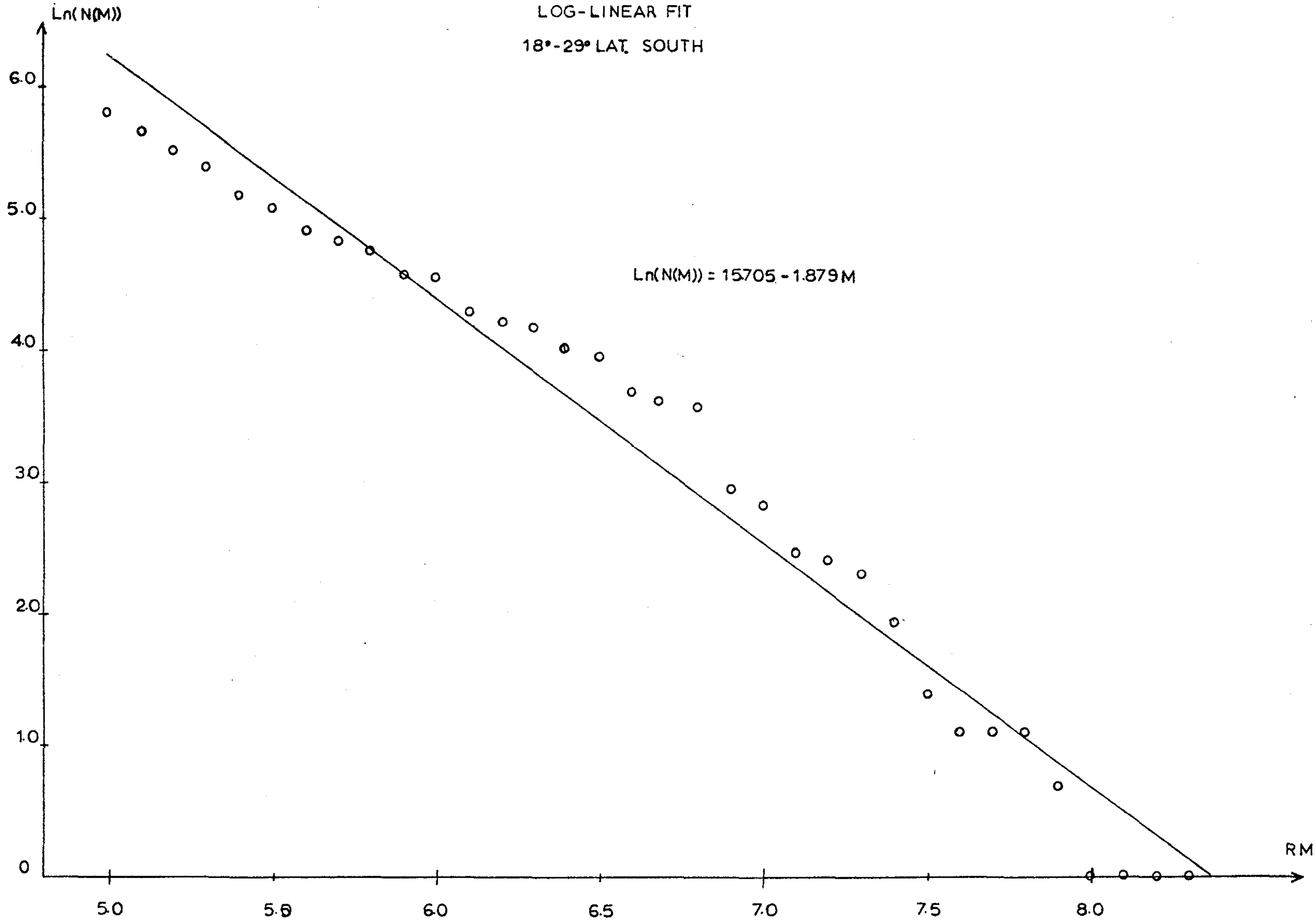


Fig. 2.9
LOG-LINEAR FIT
18°-29° LAT. SOUTH



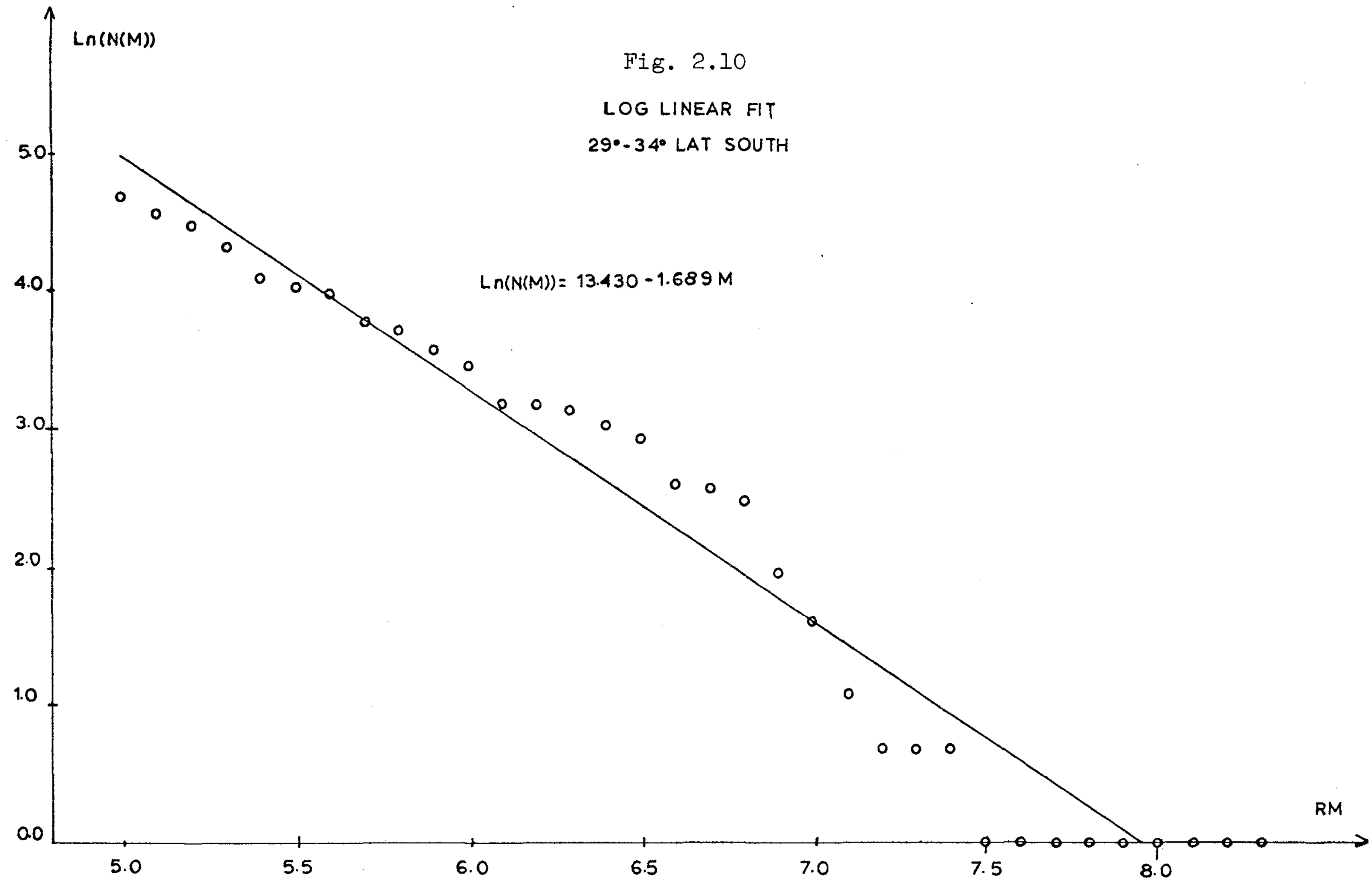


Fig. 2.10

LOG LINEAR FIT

29°-34° LAT SOUTH

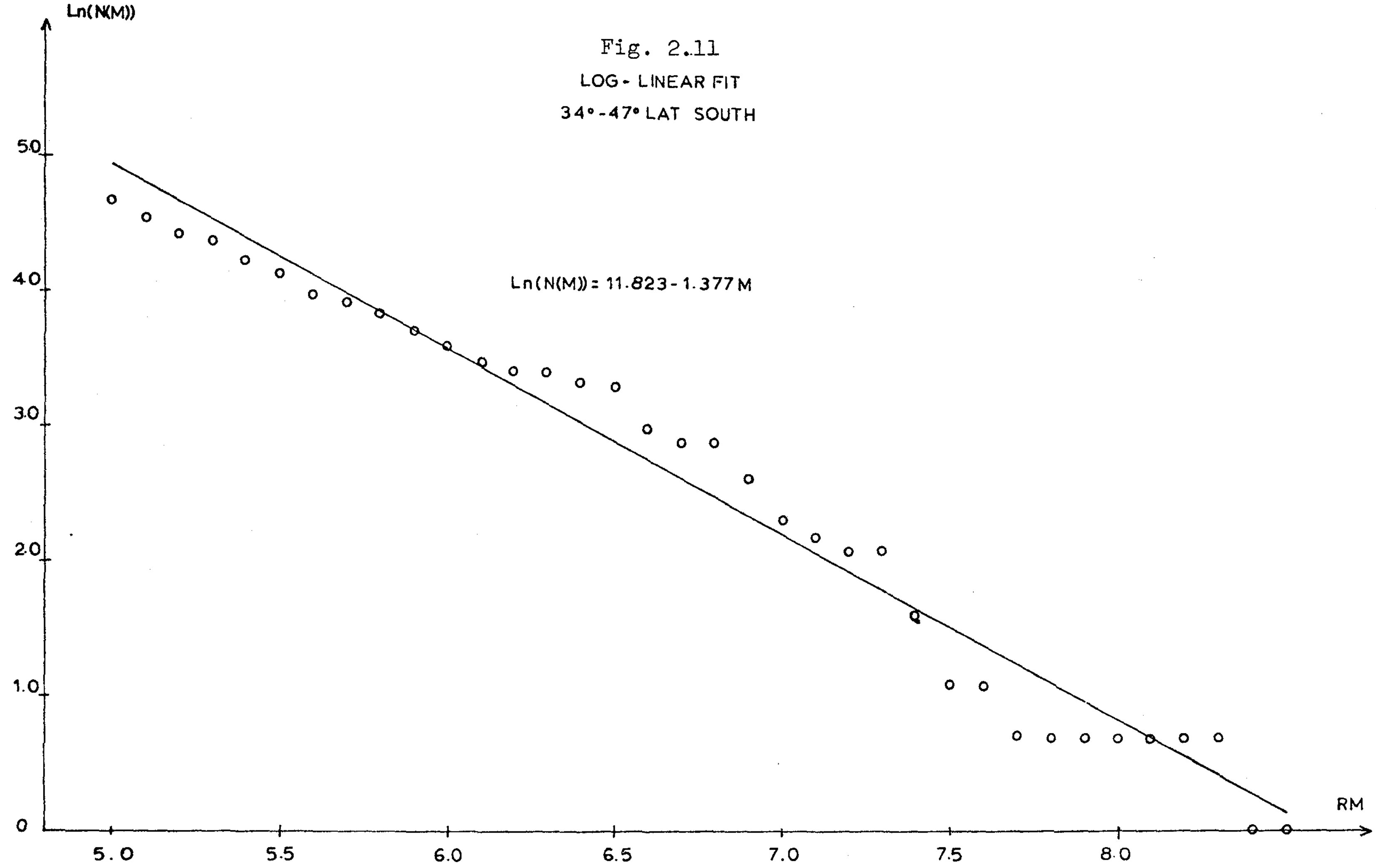


Fig. 2.11
LOG - LINEAR FIT
34°-47° LAT SOUTH

2.4 Comparison of Results Obtained by Markov and Poisson Models

As an illustrative example, both models will be used to calculate the probability of having an earthquake of RM $\geqslant$ 8.0 in the next T years (T=1, 2,.....,50).

Markov Model

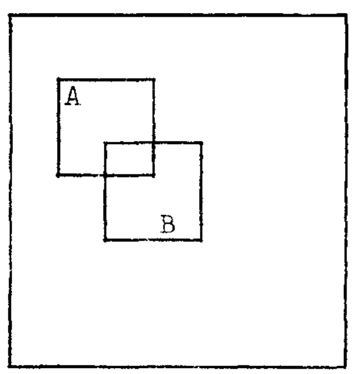
The probability of at least one occurrence in the next T years, given that no event occurred this year, can be expressed as:

$$P\text{ (at least 1 occurrence/no event this year)} = 1-P\text{ (no occurrence/no event this year)} \quad (2.48)$$

but the probability of no occurrence in T years, given nothing occurred this year, can be calculated as follows:

Let: A be the event that nothing occurs in T years from now;
B be the event that an earthquake occurs this year.

Since A and B are events with a finite probability of occurrence, they can be expressed in a Venn diagram as follows:



From the Venn diagram, we can write:

$$P(A/B)=\frac{P(AB)}{P(B)} = a \quad (2.49)$$

$$P(A/\bar{B})=\frac{P(A)-P(AB)}{1-P(B)}= b \quad (2.50)$$

equating P(AB) from 2.49 and 2.50,

$$a\ P(B)=P(A)-b+bP(B) \tag{2.51}$$

$$P(A)=b+(a-b)P(B) \tag{2.51.a}$$

However, in this case:

$$P(A/B)=\ a = \phi_{21}(T) \tag{2.52}$$

$$P(A/\bar{B})=\ b = \phi_{11}(T) \tag{2.52.a}$$

where the ϕ's refer to the n-step transition probabilities as defined in equation 2.19. In an ergodic process, as the 2-state Markov process we have defined, both quantities $\phi_{21}(T)$ and $\phi_{11}(T)$ rapidly converge to the limiting state probability π_1. This implies that a-b can be equated to zero. Therefore, the probability of having an earthquake in T years from now, given that nothing occurred this year, can be expressed as:

$$P(A/B)=P(A) \tag{2.53}$$

Thus, after a few steps, the memory Markov process turns into a memory-less process.

Formula 2.48 can be written as:

$$P(\text{at least 1 occurrence})=1-P(\text{no occurrence}) \tag{2.54}$$

In order to evaluate P(no occurrence in T years), let us illustrate the case when T=1, 2, and 3. Thus,

$$P(\text{No occurrence in 1 year}) = \phi_{11}(1)$$
$$P(\text{No occurrence in 2 years})= \phi_{11}(1)\times \phi_{11}(2)$$
$$P(\text{No occurrence in 3 years})= \phi_{11}(1)\times \phi_{11}(2)\times \phi_{11}(3)$$

Hence, for any number of years,

$$P(\text{No occurrence in T years})= \prod_{k=1}^{T} \phi_{11}(k) \tag{2.55}$$

Formula 2.55 was evaluated for T=1,2,.....50 years and the results are shown in table 2.4.1.

Table 2.4.1

MARKOV PROBABILITIES OF AT LEAST ONE EVENT

Time (Years)	Probability of at Least One Event
1	0.027
5	0.125
10	0.234
15	0.330
20	0.413
25	0.487
30	0.551
35	0.607
40	0.665
45	0.699
50	0.721

Poisson Model

The probability of having at least one event in a period of T years has been found to be (see formula 2.47):

$$P(\text{at least 1 occurrence}) = 1 - \exp\left(-N'(M)AT\right) \qquad (2.56)$$

for T=1, 2,.....50, the following results were obtained:

Table 2.4.2

POISSON PROBABILITIES OF AT LEAST ONE EVENT

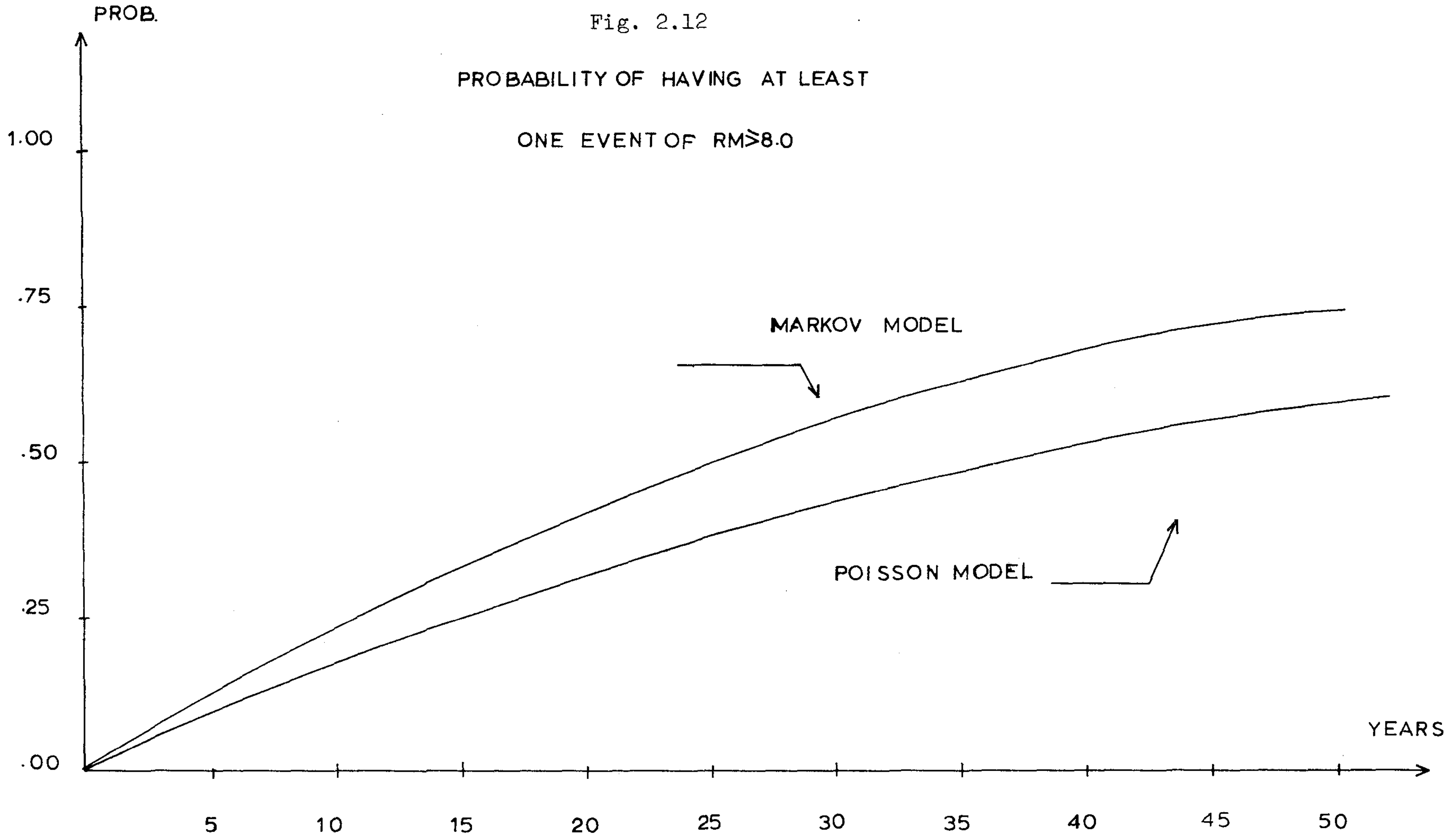
Time (Years)	Probability of at Least One Event
1	0.018
5	0.086
10	0.166
15	0.238
20	0.304
25	0.364
30	0.419
35	0.469
40	0.515
45	0.557
50	0.595

The values appearing in tables 2.4 and 2.5 have been plotted in figure 2.12. Both curves tend to agree; however, the Markov assumption yields higher values.

Fig. 2.12

PROBABILITY OF HAVING AT LEAST

ONE EVENT OF RM≥8.0



CHAPTER 3

ACCELERATION MAPS

The NOAA definition[18] will be used to develop a map showing zones of equal probable ground acceleration. Such a definition considers a design earthquake with a 50-year return period and a Richter magnitude determined by:

$$P(RM \geq M) = 0.1 \qquad (3.1)$$

The probability of exceeding a given magnitude during a 50-year and 25-year period were computed for each zone. Graphs of these results are presented in figures 3.1, 3.2, and 3.3.

If we enter with a 10% probability in the vertical axis and move horizontally until the 50-year curve is hit, we can determine the design earthquake for each zone. This procedure is indicated by arrows in figures 3.1, 3.2, and 3.3. The following values are obtained:

Zone	RM of Design Earthquake
I	8.3
II	7.9
III	8.5

Though the destructiveness of an earthquake is highly related to parameters such as soil conditions, duration, energy dissipation, frequency content, and peak ground acceleration, only the latter will be used to evaluate the seismic risk.

A first approximation that relates magnitude M and peak ground acceleration <u>a</u> is the empirical formula of Esteva and Rosenblueth:

$$a = \frac{0.778\ \mathrm{Exp}(0.8M)}{R^2+h^2} \qquad (3.2)$$

Fig. 3.1

Excedance Probabilities
50 and 25 Years
18°-29° Lat. S.

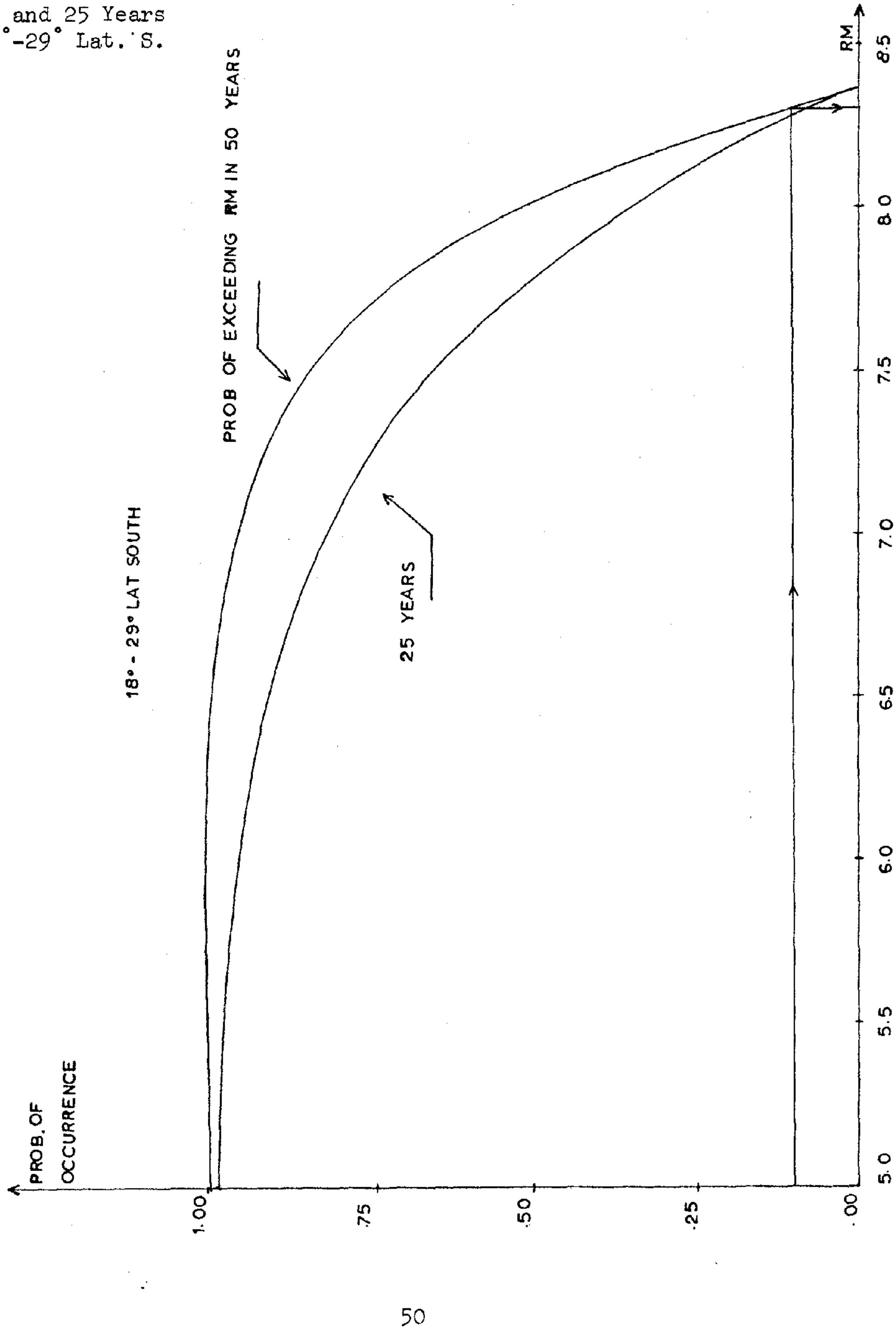


Fig. 3.2

Excedance Probabilities

50 and 25 Years

29°- 34° LAT SOUTH

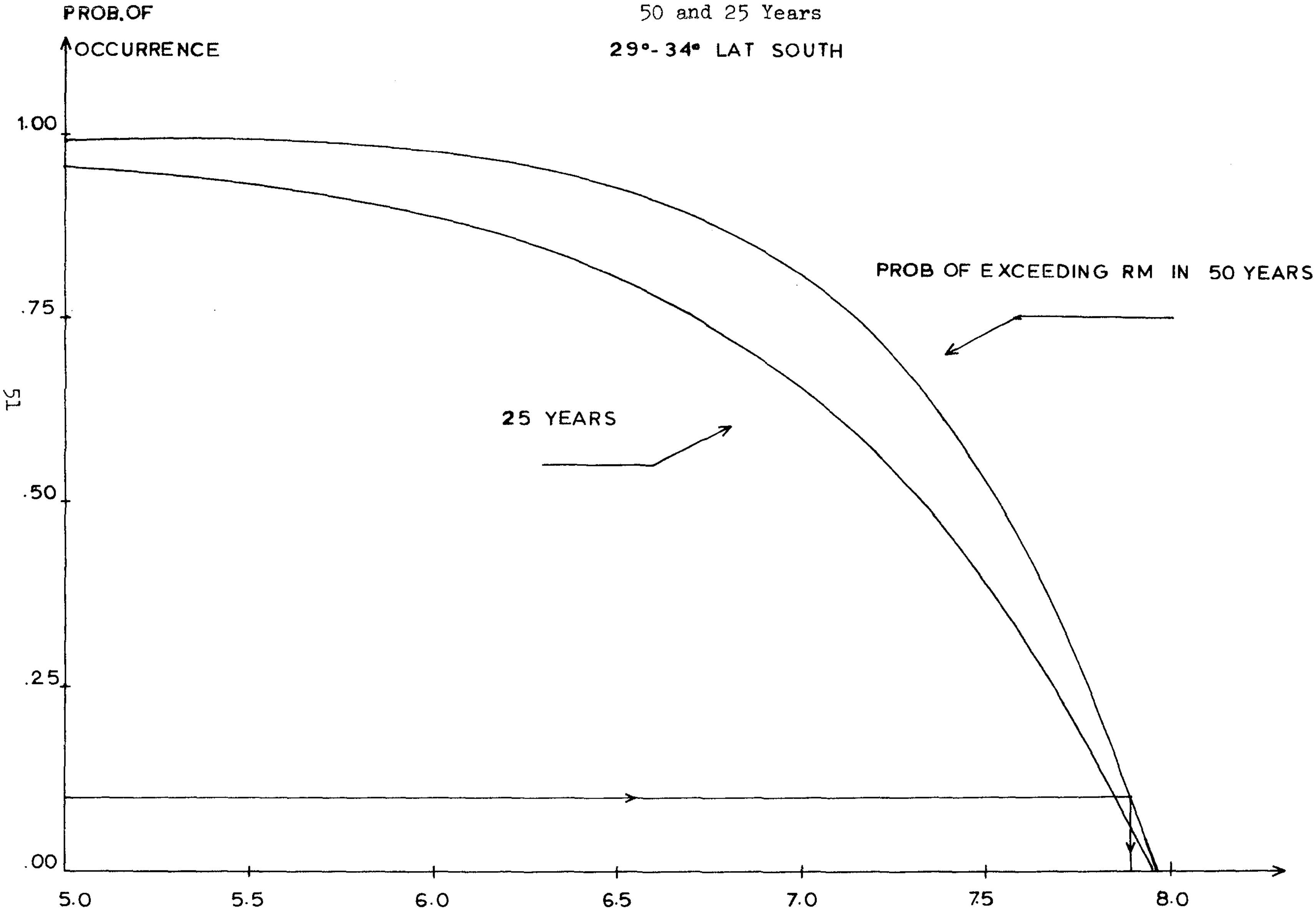
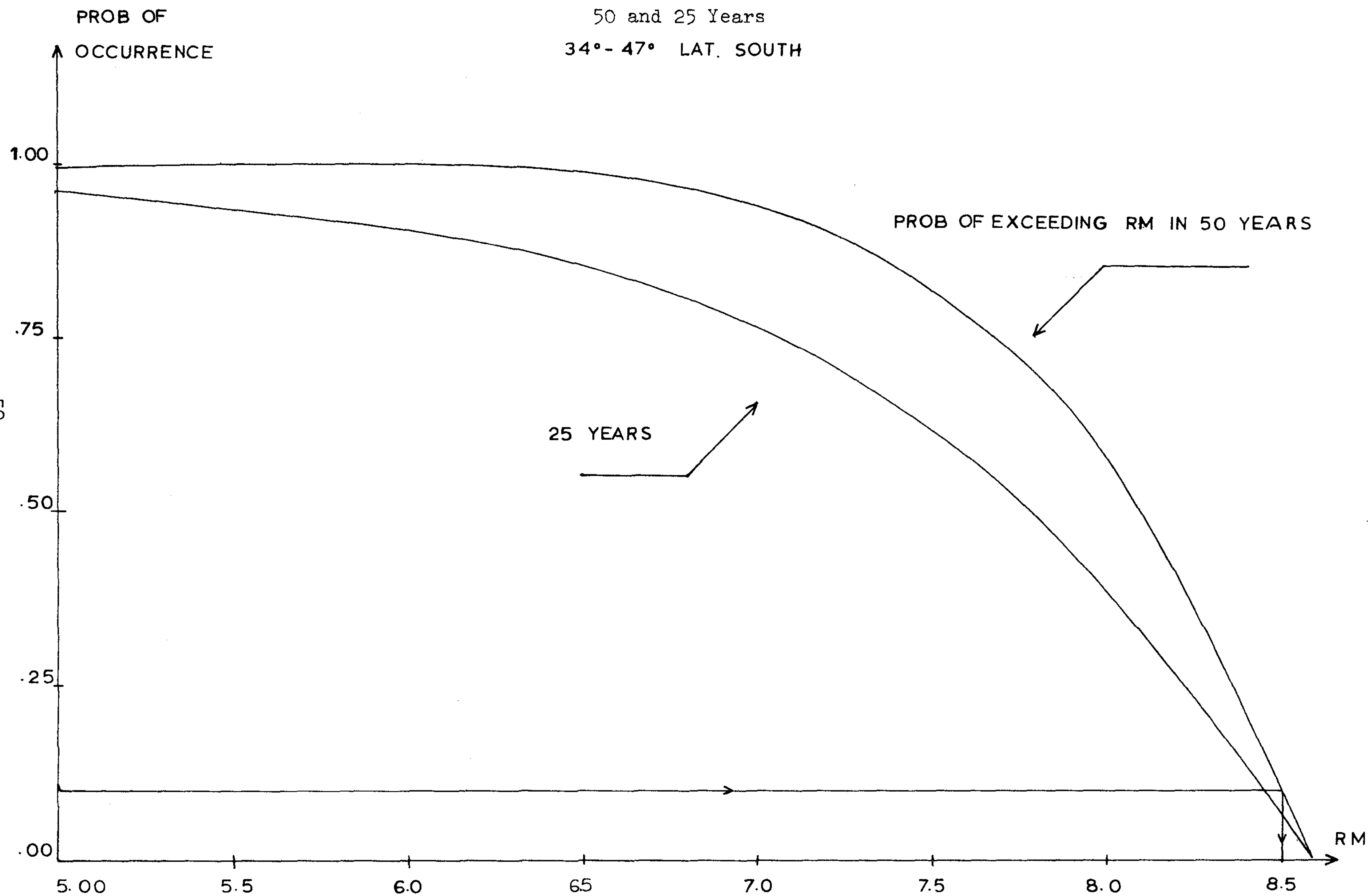


Fig. 3.3

Excedance Probabilities

50 and 25 Years

34°- 47° LAT. SOUTH



where,

M: Richter magnitude

R: epicentral distance in miles

h: focal depth in miles

a: acceleration in g units

This formula is used to determine the maximum ground acceleration of an earthquake, provided the other parameters are known.

The available data was analyzed and no relationship between focal depth and magnitude was detected. Spatial distributions did not seem to affect focal depth. However, the northeastern portion of zone I seems to be an exception. Focal depths there are mainly between 100 and 200 kilometers, while over other regions focal depths tend to fall below 100 kilometers. With this in mind, accelerations were calculated with h=100 km in the northeastern part of zone I and h=50 km for the rest of the country.

The question of selecting values for epicentral distances is more complicated. If epicenters were to fall on a clear fault line, epicentral distances could be measured with respect to this line. In Chile, however, no visible faults have been detected and epicenters seem to be randomly distributed (see appendix B). Though probability distributions for epicenters could be used, no attempt is made to do so in this study. Another alternative could be to use one design earthquake for each zone. However, this could result in errors if a unique peak ground acceleration were to be used for a large region. This problem was attacked by taking the normalized seismicity relationships and calculating design earthquakes meeting the NOAA definition for typical subregions in each of the three large regions. These subregions are circular areas with radii and surface indicated below:

Table 3.1

RADII AND CIRCULAR AREAS

Radius	Area
km	km^2
17.7	984
35.4	3937
53.0	8825
70.7	15692
80.0	20106
100.0	31416
125.0	49087
150.0	70686

Based on the uniformity of epicenter distributions, the average earthquake was assumed to have its epicenter in a point such that only half of the subregion would be affected by the event.

It was assumed that the average earthquake occurring within the subregion would be located at a distance $1/\sqrt{2}$ times the radius from its center. Half of the subregion area lies inside this distance and half outside.

For each radius circle, design magnitude, and assumed local depth the acceleration was determined using Esteva-Rosenblueth's formula. The results are plotted in figure 3.4. For each region the curve has a maximum acceleration. These values were used in the iso-acceleration maps shown in figures 3.5, 3.6, 3.7, and 3.8.

The accelerations decline in the eastern portion of region I due to the fact that greater depths were assumed. In regions II and III the accelerations decrease easterly because fewer earthquakes occur there. The rate of attenuation away from the zones of maximum acceleration was assumed to be one-half of that predicted by formula 3.2. This was justified by the fact that there is a nonzero probability of having an

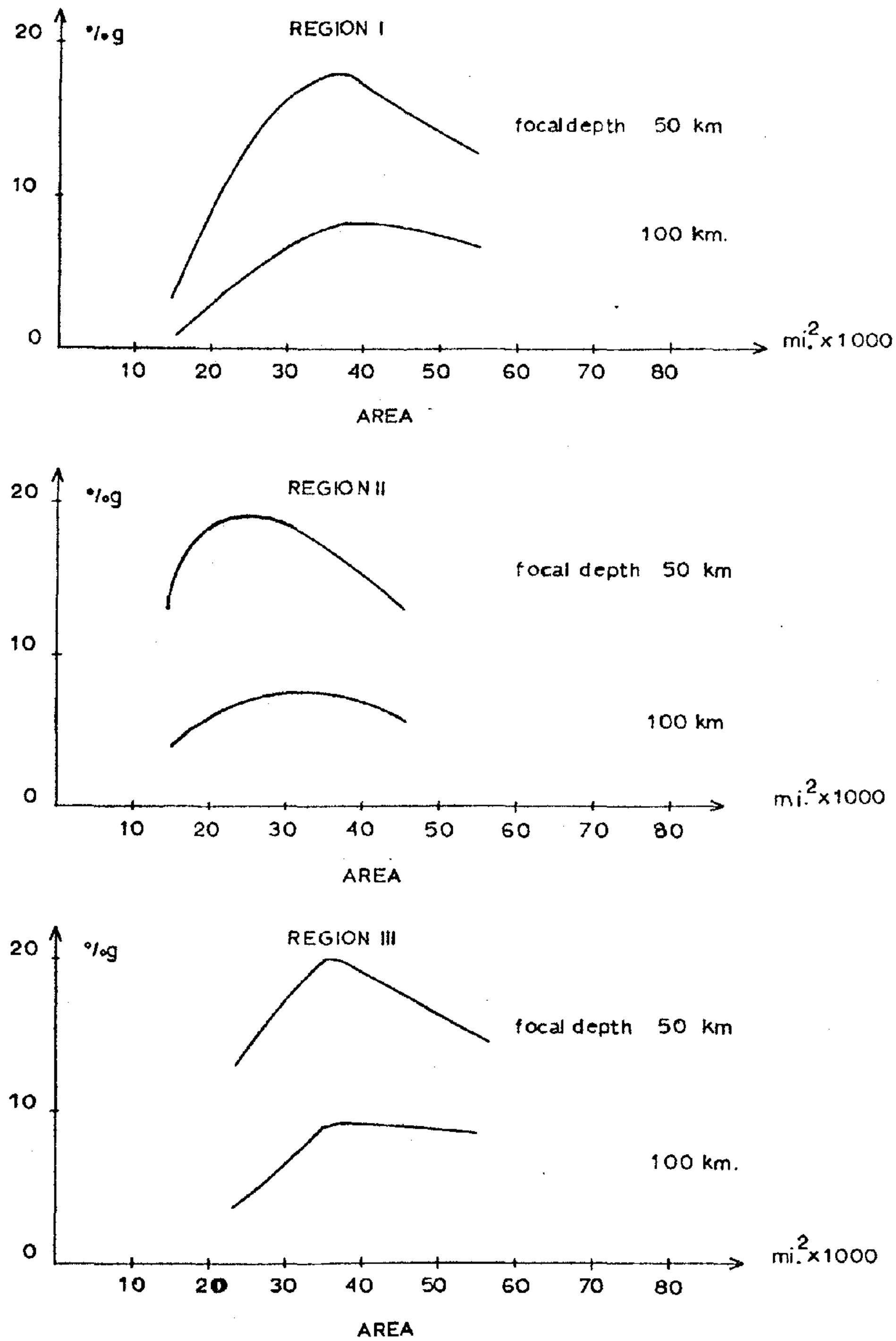


Fig. 3.4—MAXIMUM ACCELERATIONS IN CHILE

50 YR. RETURN PERIOD

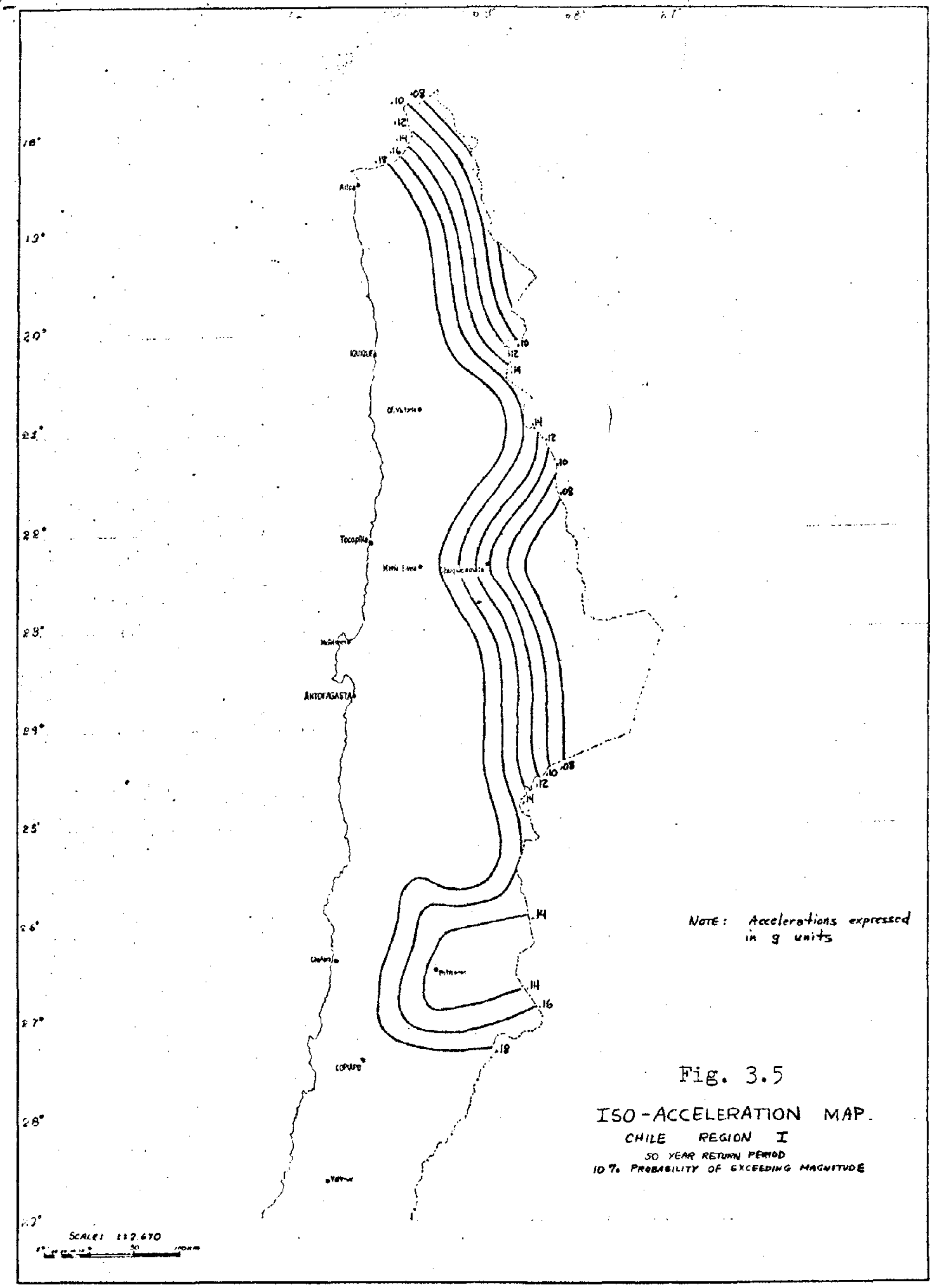


Fig. 3.5

ISO-ACCELERATION MAP.

CHILE REGION I

50 YEAR RETURN PERIOD
10 % PROBABILITY OF EXCEEDING MAGNITUDE

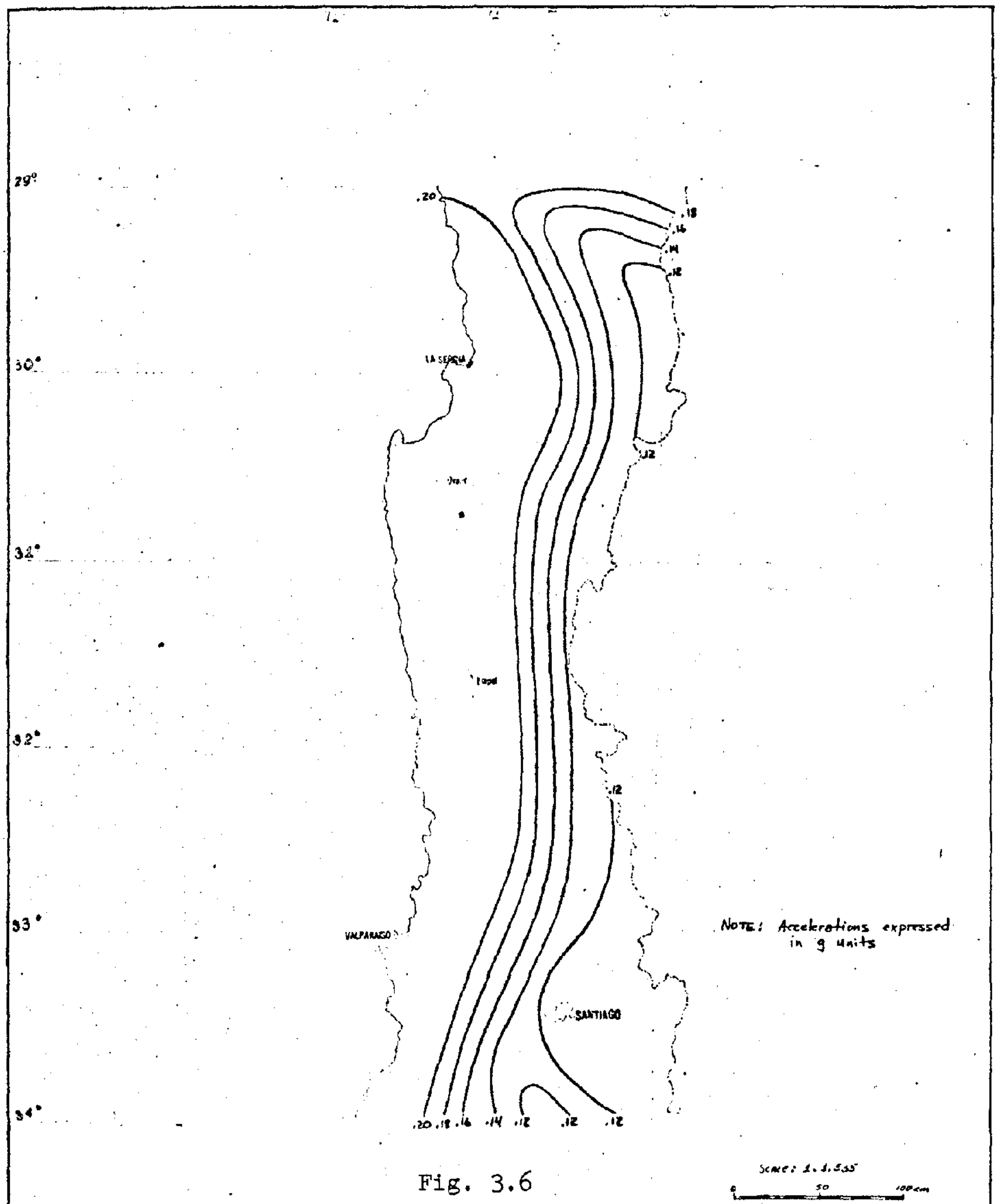


Fig. 3.6

ISO-ACCELERATION MAP

CHILE REGION II

50 YEAR RETURN PERIOD
10% PROBABILITY OF EXCEEDING MAGNITUDE

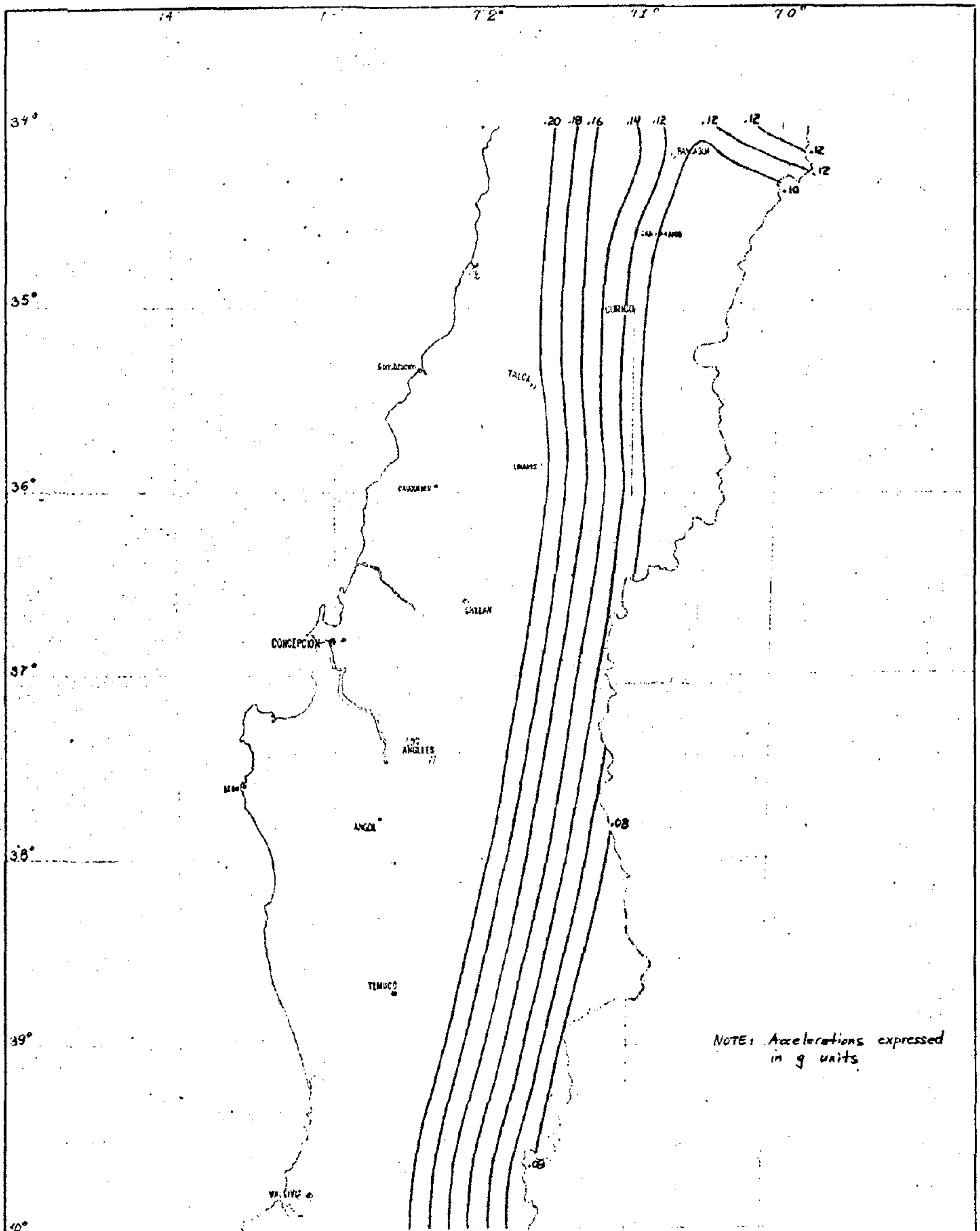


Fig. 3.7

ISO - ACCELERATION MAP

CHILE REGION III

50 YEAR RETURN PERIOD
10% PROBABILITY OF EXCEEDING MAGNITUDE

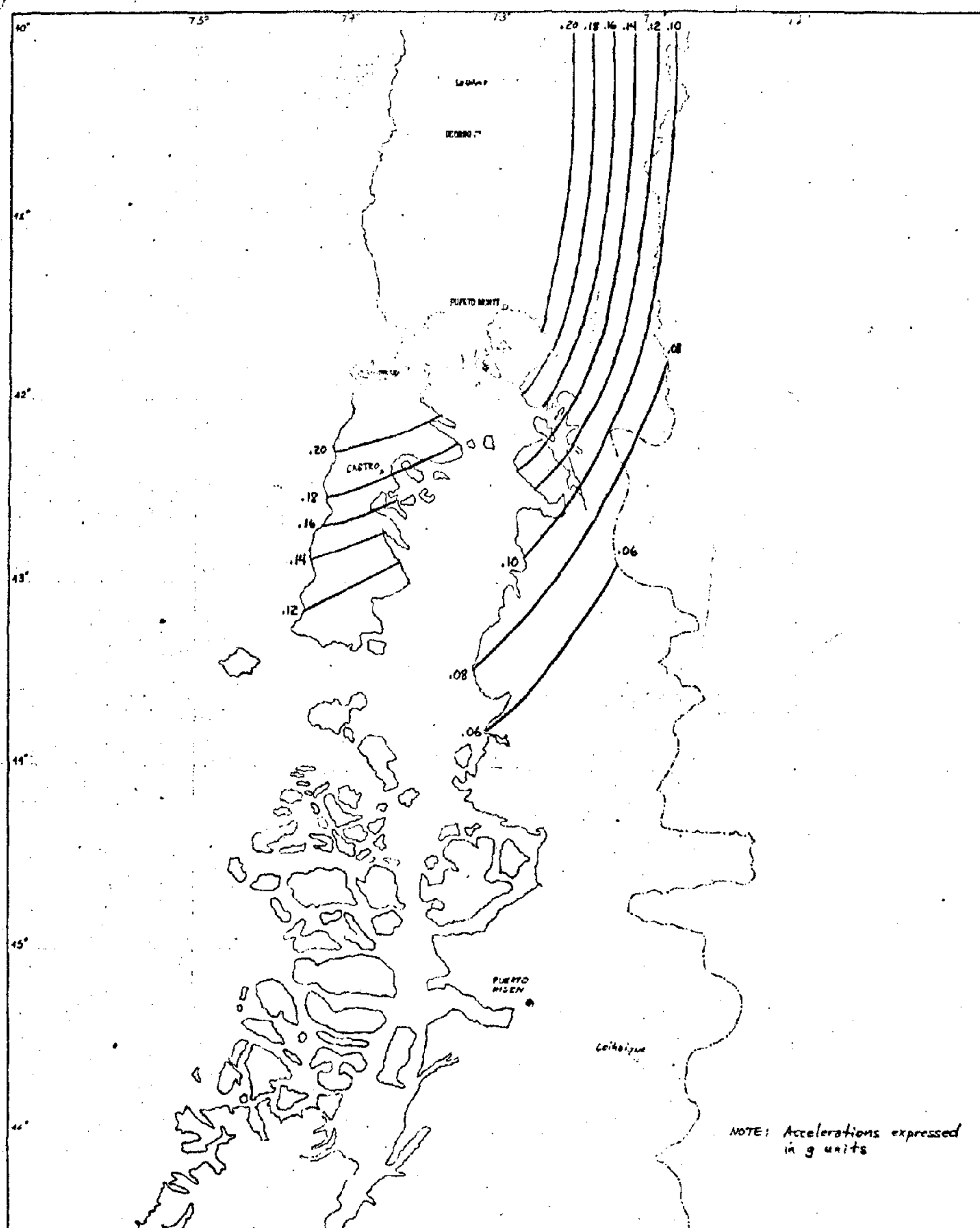


Fig. 3:8

ISO-ACCELERATION MAP

CHILE REGION III

50 YEAR RETURN PERIOD
10% PROBABILITY OF EXCEEDING MAGNITUDE

earthquake elsewhere. In other words, the probable acceleration is a function of both the distance from the design earthquake and the distance from local smaller events. Clearly, this is a guess, but it seems reasonable when compared to the maps showing epicenter locations. To develop a more accurate iso-acceleration map, detailed seismicity analyses for a very large number of micro regions would be required. However, the reliability of the results would be reduced because the areas under consideration are also reduced. For a limiting situation, if the area is reduced to a single point the reliability is zero.

CHAPTER 4

PROBABILITY DISTRIBUTION OF ACCELERATION

A probability distribution for peak ground acceleration can be developed from a probability distribution of magnitudes. This can be done if a monotonic increasing relationship exists between acceleration and magnitude. Such a relationship is provided by Esteva-Rosenblueth's formula expressed by relation 3.2.

J. Dalal has shown[4] that the PDF for the peak ground acceleration is:

$$PDF(a)=\lambda\delta Ta^{\delta-1}\exp(-\lambda Ta^{\delta}) \qquad (4.1)$$

where,

$$\lambda= -\frac{\pi\gamma}{(0.778)\delta}\,\frac{h^{2\delta+2}}{(\delta+1)} \qquad (4.2)$$

$$\gamma= \exp(A) \qquad (4.3)$$

$$\delta= 1.25\ B \qquad (4.4)$$

T= time in years

The cumulative distribution is given by:

$$CDF(a)=\exp(-\lambda Ta^{\delta}) \qquad (4.5)$$

The CDF and PDF were computed for 25, 50, and 100 years and for each area. They are plotted in figures 4.1, 4.2, and 4.3. Some representative values are given in table 4.1.

Fig. 4.1

CUMULATIVE DISTRIBUTION FUNCTION

PEAK GROUND ACCELERATION

ZONE I

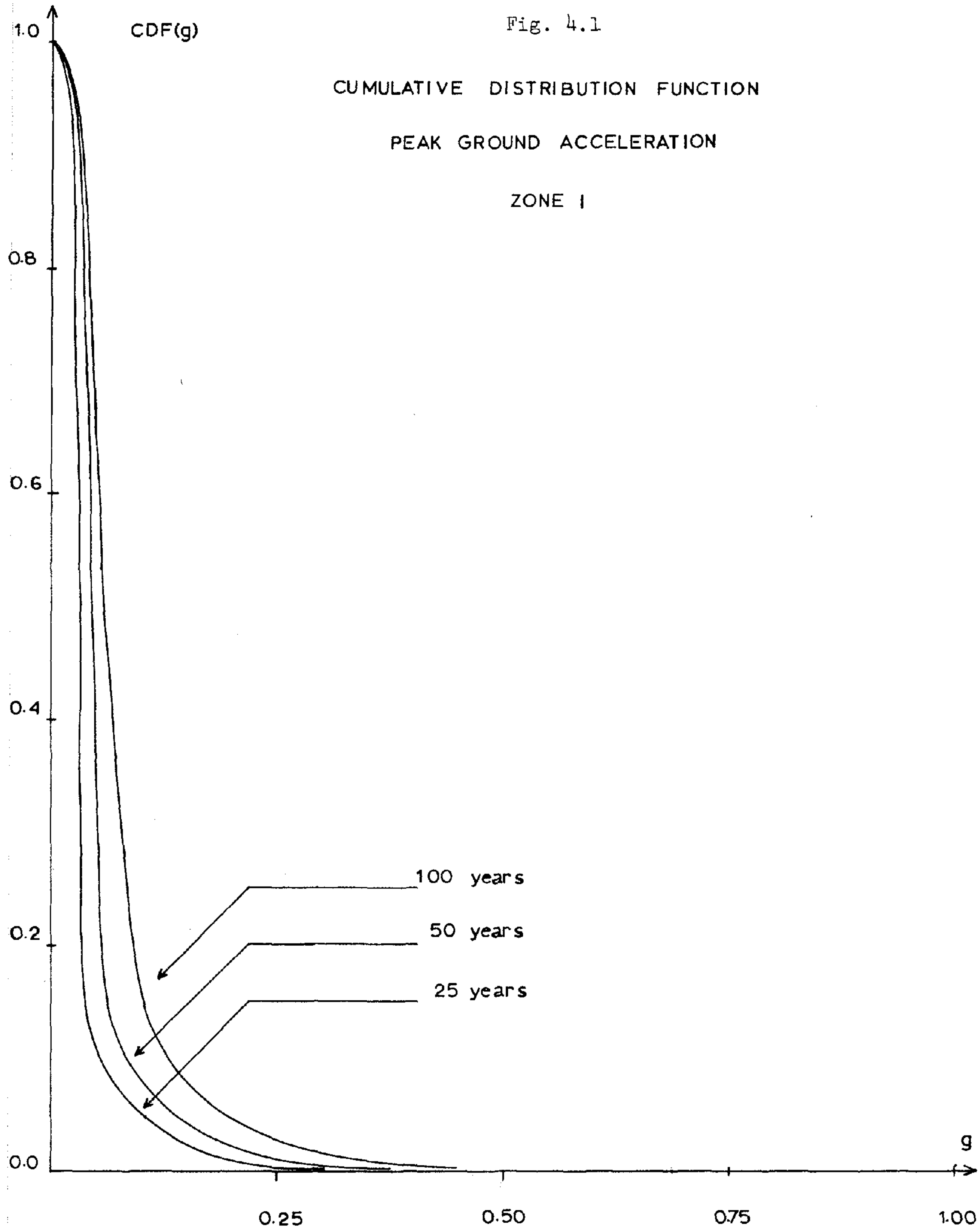
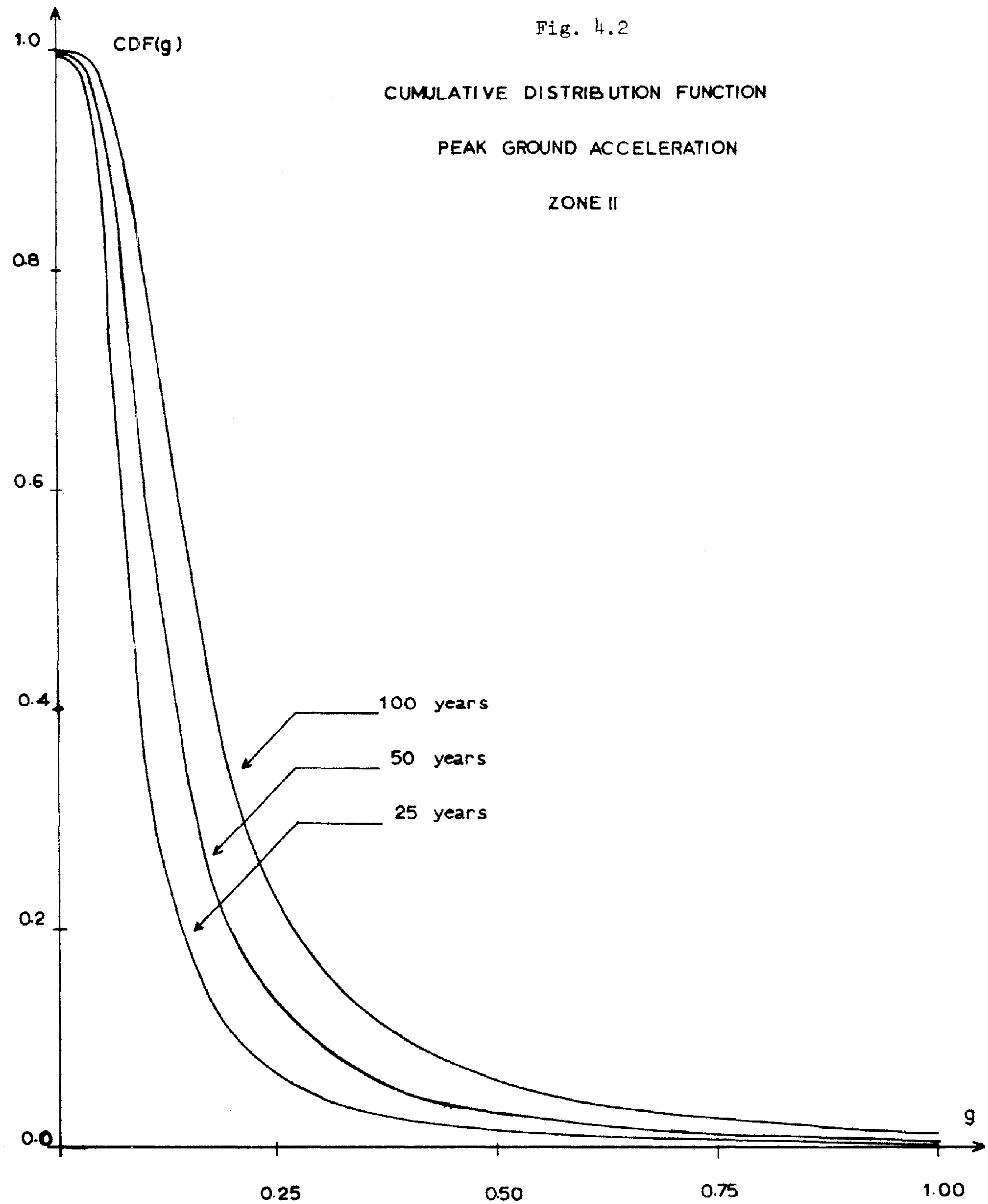


Fig. 4.2

CUMULATIVE DISTRIBUTION FUNCTION

PEAK GROUND ACCELERATION

ZONE II



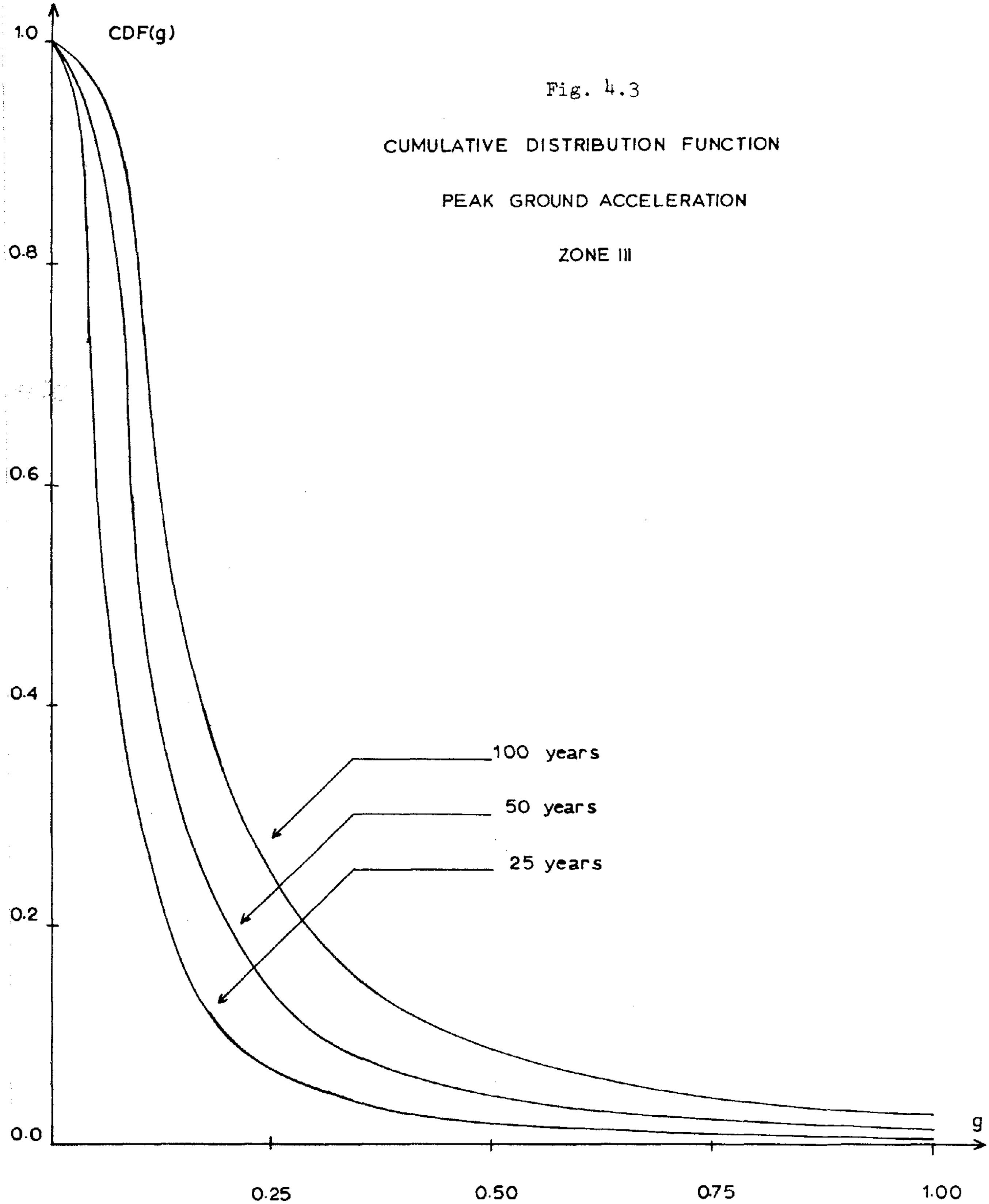

1.0
CDF(g)
Fig. 4.3
CUMULATIVE DISTRIBUTION FUNCTION
PEAK GROUND ACCELERATION
ZONE III
0.8
0.6
0.4
100 years
50 years
25 years
0.2
0.0
g
0.25
0.50
0.75
1.00

Table 4.1

PROBABILITIES OF EXCEDANCE

	Probability of Exceeding a in T Years T=25	T=50	T=100
Zone I—Depth 100 km (62 miles):			
a (g units)			
0.05	0.2221	0.3948	0.6337
0.25	0.0057	0.0114	0.0226
0.50	0.0011	0.0022	0.0045
0.75	0.0004	0.0009	0.0017
1.00	0.0002	0.0004	0.0009
Zone II—Depth 50 km (31 miles):			
a (g units)			
0.05	0.8664	0.9822	0.9997
0.25	0.0651	0.1260	0.2361
0.50	0.0154	0.0307	0.0604
0.75	0.0066	0.0131	0.0261
1.00	0.0036	0.0072	0.0143
Zone III—Depth 50 km (31 miles):			
a (g units)			
0.05	0.6973	0.9084	0.9916
0.25	0.0721	0.1390	0.2588
0.50	0.0224	0.0444	0.0868
0.75	0.0112	0.0223	0.0442
1.00	0.0069	0.0137	0.0272

CHAPTER 5
CONCLUSIONS

5.1 Seismic Zoning

Chile can be subdivided into seismic zones or regions. These regions are independent from one another and have unique seismic characteristics such as earthquake magnitude, frequency, and destructiveness. Three zones have been identified, although other studies point out the existence of four regions. This possible contradiction can be reconciled by realizing that zone I described in this study is composed of two of the zones described by Gajardo and Lomnitz.[16]

It is most likely that the geology of the country plays an important role in Chile's seismic activity. The existence of two geosynclines, separated by a wide ridge, has been postulated for north and central Chile.[6] In the south, the tectonic relationships are complex and imperfectly known.

No visible and active faults have been detected. However, some faults might exist along the coastline, as the trench deepens considerably.

The region below 45° south latitude represents an area of low seismicity. The northern part of zone II records destructive earthquakes located along the coast. Usually these events have generated large tsunamis.

5.2 Risk

It has been suggested[19] that a risk analysis should be based on an interaction between social needs, technical information, administrative policy, legal requirements, and economic considerations. This type of analysis, however, is not applicable to Chile. Chile is a country with low density of population and the public faces day-to-day problems which are more urgent than earthquake preparedness and awareness. This is illustrated by the fact that Chilean earthquakes, rated with respect to an intensity scale, are generally underestimated. For example, internal damage is considered to be an accidental loss and not a direct consequence of an earthquake. Thus, it appears that, unlike most insurance-conscious countries, only structural damage is mentioned in Chile. However, it must be pointed out that the planning authorities have incorporated the idea of risk in their planning concepts. This is true despite the fact that for the average citizen earthquake risk does not have a very high priority.

Regarding structural damage, strict design regulations are enforced for public buildings and medium- to high-cost housing. It should be pointed out that currently the building code is under revision to incorporate dynamic loading as a design parameter. However, because of the priority of investment programs and insufficient funding, an earthquake hazard prevention program has not been fully developed. Furthermore, earthquake insurance is not available in Chile. Thus, in considering the country as a whole, a definition of risk must be based only on technical information and economic considerations. A risk map could be developed similarly to an iso-acceleration map. The levels of risk could be defined in terms of the additional expense required to prevent structural damage due to the calculated probable ground acceleration.

It is worth repeating that the whole concept of risk as considered in the United States is not directly applicable to Chile.

5.3 First Passage Time and Maximum Acceleration

Through the introduction of the Markov characteristic, a two-state, discrete time model has been developed. The validity of a Markov assumption is acceptable under the elastic rebound theory; i.e., the energy builds up to a certain level until it is released by means of an earthquake. Thus, the probability of occurrence will depend on the state of the process during the previous observation period. The main pitfall of such a model is that some information may be lost because more than one occurrence in a period is considered as one. This can be circumvented by using smaller observation periods. This suggests the use of a continuous time, semi-Markov model, as it has been developed in section 2.2.3. Return periods or mean first passage times have been calculated as well as their variances and probability distributions. This model can incorporate new information by modifying the probability transition matrix accordingly, as new events occur.

Iso-acceleration maps have been developed for the whole country. They can be used to calculate the probability of exceeding certain levels of peak ground acceleration in a given period of time. These probabilities have been calculated by using a log-linear relationship for earthquake magnitudes and Esteva-Rosenblueth's formula for peak ground accelerations.

In addition, by means of a closed form expression of the PDF of the peak ground acceleration, probabilities of exceeding given acceleration levels can be determined.

5.4 Suggestions and Recommendations

Any further study on Chile's seismicity and seismic risk requires more information regarding ground acceleration and geologic conditions. More detailed geologic observations are required in order to establish the real existence or lack of surface faulting and fault activity.

A strong motion instrument network is of great importance in order to evaluate relationships between peak ground acceleration, epicentral distance, depth, and magnitude.

Although Chile's seismicity is high, it would be advisable to incorporate different levels of acceleration for different places and purposes in the building code. This would then account for the existence of different seismic zones.

APPENDIX A

Chronological List of Chilean Earthquakes
of Richter Magnitude 5.0 or Higher, 1934-1972

	DATE	LAT	LONG	DEPTH	MAG	TYPE
1	340101	29.50	71.00	0.00	5.60	1
2	340301	40.00	72.50	120.00	7.10	3
3	340324	23.00	66.00	270.00	5.80	1
4	340331	28.50	72.00	60.00	5.50	1
5	340511	19.50	71.00	0.00	5.60	1
6	340624	22.00	68.60	100.00	6.90	2
7	340728	31.00	71.50	0.00	5.60	1
8	341128	22.50	69.00	80.00	5.80	1
9	341204	19.50	69.50	130.00	6.90	2
10	341216	24.00	68.00	150.00	6.00	2
11	341223	21.00	68.00	100.00	6.50	2
12	350213	25.50	69.00	100.00	6.50	2
13	350228	23.00	67.00	200.00	6.30	2
14	350528	33.50	68.00	200.00	5.80	1
15	350628	34.00	73.00	0.00	6.00	2
16	350805	35.00	72.00	0.00	6.00	2
17	350928	23.00	68.50	100.00	5.30	1
18	360131	22.00	67.00	160.00	5.50	1
19	360216	28.00	71.50	0.00	5.60	1
20	360522	32.00	66.00	0.00	6.00	2
21	360622	22.00	68.00	100.00	6.00	2
22	360704	18.00	70.00	140.00	6.00	2
23	360704	21.00	66.00	290.00	6.80	2
24	360713	24.50	70.00	60.00	7.30	3
25	360726	24.00	70.00	40.00	6.80	2
26	361107	23.00	67.00	200.00	6.00	2
27	361107	24.00	66.00	200.00	5.80	1
28	361129	22.50	67.00	230.00	6.00	2
29	361205	20.00	70.50	100.00	6.00	2
30	361219	28.50	68.50	160.00	5.80	1
31	370130	36.00	72.00	100.00	5.50	1
32	370212	32.00	66.50	200.00	5.50	1
33	370224	23.00	67.00	260.00	5.30	1
34	370314	24.50	69.50	60.00	6.50	2
35	370319	29.00	70.00	70.00	6.00	2
36	370924	22.50	70.00	130.00	6.00	2
37	371012	25.00	68.50	110.00	6.50	2
38	371027	34.50	71.00	110.00	6.00	2
39	371101	25.00	70.00	75.00	6.00	2
40	371212	25.00	70.00	60.00	6.00	2
41	371224	37.00	72.00	70.00	5.50	1
42	380109	30.50	69.00	120.00	5.80	1
43	380417	19.00	69.50	60.00	6.50	2
44	380424	23.50	66.00	180.00	6.00	2
45	380615	31.00	70.50	70.00	6.00	2
46	380623	30.50	70.00	70.00	6.50	2
47	380804	24.00	68.00	220.00	6.80	2
48	390118	29.50	71.00	70.00	6.30	2
49	390118	21.50	70.00	70.00	5.80	1
50	390125	36.25	72.25	0.00	8.30	4
51	390219	30.50	71.00	100.00	5.50	1
52	390418	27.00	70.50	100.00	7.40	3
53	390513	22.00	66.00	210.00	5.50	1
54	390519	18.00	69.00	100.00	6.30	2
55	390708	29.00	68.00	170.00	5.50	1
56	390812	24.00	68.50	70.00	5.80	1
57	390913	18.50	70.50	130.00	5.75	1
58	391001	31.50	66.50	200.00	5.80	1

59	391005	22.00	67.00	240.00	6.00	2
60	391007	18.50	70.00	110.00	6.00	2
61	391101	21.50	68.00	240.00	5.75	1
62	400324	23.00	66.00	280.00	5.80	1
63	400331	19.00	70.50	50.00	6.00	2
64	400408	33.50	71.50	0.00	6.00	2
65	400412	26.50	71.00	70.00	6.50	2
66	400807	22.00	68.50	110.00	6.30	2
67	400918	23.00	68.00	110.00	6.50	2
68	400929	35.00	70.00	110.00	6.30	2
69	401001	30.00	72.50	80.00	6.50	2
70	401003	21.00	70.00	110.00	6.30	2
71	401004	22.00	71.00	75.00	7.30	3
72	401006	22.00	71.00	60.00	6.80	2
73	401011	41.50	74.50	0.00	7.00	3
74	401024	35.00	72.50	80.00	6.80	2
75	410403	22.50	66.00	260.00	7.20	3
76	410403	22.50	66.00	260.00	6.50	2
77	410703	31.50	69.50	0.00	6.30	2
78	410710	18.50	70.00	120.00	6.00	2
79	410810	23.50	66.50	220.00	5.50	1
80	410810	31.50	70.50	80.00	5.80	1
81	410814	23.00	66.75	180.00	6.00	2
82	411110	22.00	67.00	200.00	6.30	2
83	420629	32.00	71.00	100.00	6.90	2
84	420708	24.00	70.00	140.00	7.00	3
85	430314	20.00	69.50	150.00	7.20	3
86	430406	30.75	72.00	0.00	8.30	4
87	430522	30.75	72.00	0.00	6.80	2
88	431129	29.50	68.50	100.00	6.80	2
89	431201	21.00	69.00	100.00	7.00	3
90	440115	31.25	68.75	50.00	7.40	3
91	440723	24.00	66.50	250.00	6.00	2
92	441222	25.00	70.00	120.00	6.50	2
93	450913	33.25	70.25	100.00	7.10	3
94	460227	23.00	66.50	270.00	6.00	2
95	460416	41.00	73.00	60.00	5.80	1
96	460510	24.50	69.00	100.00	5.80	1
97	460726	19.75	70.50	70.00	6.80	2
98	460802	26.50	70.50	50.00	7.90	3
99	461013	22.00	66.50	200.00	6.00	2
100	461110	31.00	70.00	120.00	6.30	2
101	470121	25.00	70.00	0.00	7.00	3
102	470801	27.50	67.50	160.00	5.80	1
103	490420	38.00	73.50	70.00	7.30	3
104	490508	21.50	69.00	100.00	6.80	2
105	490525	19.75	69.00	110.00	7.30	3
106	490530	22.00	69.00	100.00	7.00	3
107	491217	54.00	71.00	0.00	7.80	3
108	491217	54.00	71.00	0.00	7.80	3
109	500103	46.00	75.50	0.00	6.00	2
110	500130	53.50	71.50	0.00	6.80	2
111	501209	23.50	67.50	100.00	8.30	4
112	510414	23.30	66.40	223.00	7.00	3
113	510423	21.00	67.50	287.00	6.40	2
114	511109	21.75	68.00	120.00	6.80	2
115	520524	20.50	70.50	0.00	6.80	2
116	520611	31.50	67.50	0.00	7.00	3
117	530503	36.50	73.00	60.00	7.60	3
118	530809	22.10	68.70	128.00	6.30	2

119	530904	32.70	71.80	33.00	6.90	2
120	531027	19.50	66.50	287.00	6.80	2
121	531207	22.10	68.70	128.00	7.40	3
122	540414	23.90	69.20	96.00	5.50	1
123	540621	23.20	68.30	128.00	6.60	2
124	540626	41.00	73.00	0.00	6.50	2
125	540723	30.50	71.50	60.00	6.80	2
126	541219	23.10	66.60	223.00	6.60	2
127	550419	30.00	72.00	0.00	7.00	3
128	550420	30.50	72.50	0.00	6.50	2
129	550422	30.00	72.50	0.00	6.50	2
130	551006	36.00	70.00	150.00	6.50	2
131	551104	33.50	69.50	100.00	6.80	2
132	551117	26.50	69.00	60.00	6.80	2
133	551206	20.20	70.20	0.00	6.80	2
134	560108	19.00	70.00	0.00	7.10	3
135	560609	30.10	71.50	0.00	6.80	2
136	560611	27.50	69.00	0.00	5.90	1
137	560722	19.00	69.00	100.00	6.10	2
138	560915	20.00	69.00	100.00	6.80	2
139	561003	20.09	69.38	90.00	6.50	2
140	561218	25.50	68.50	0.00	7.00	3
141	570724	30.00	70.50	0.00	6.50	2
142	570729	23.50	71.50	0.00	7.00	3
143	571129	21.00	66.00	200.00	7.80	3
144	580430	21.00	67.50	150.00	6.00	2
145	580508	24.23	67.16	178.00	6.40	2
146	580711	21.00	69.00	0.00	6.50	2
147	580904	33.50	69.50	0.00	6.70	2
148	590220	30.64	71.10	63.00	6.40	2
149	590521	28.00	69.00	60.00	6.00	2
150	590602	42.79	73.89	87.00	5.90	1
151	590614	20.42	69.00	83.00	7.40	3
152	590709	20.50	68.00	100.00	6.80	2
153	591128	28.50	71.00	0.00	6.50	2
154	591225	25.44	68.71	111.00	6.60	2
155	600521	37.50	73.50	0.00	7.30	3
156	600522	38.00	73.50	0.00	6.50	2
157	600522	37.50	73.00	0.00	7.40	3
158	600522	39.50	74.50	0.00	8.50	4
159	600522	38.00	73.50	0.00	6.50	2
160	600523	38.50	75.00	0.00	6.80	2
161	600523	39.50	73.00	0.00	6.90	2
162	600525	45.00	76.00	0.00	6.80	2
163	600526	38.50	73.00	60.00	5.50	1
164	600526	38.00	73.00	0.00	5.30	1
165	600527	41.00	76.00	0.00	5.90	1
166	600527	38.00	75.00	60.00	5.00	1
167	600528	39.50	74.50	0.00	5.50	1
168	600529	38.00	72.50	0.00	6.50	2
169	600529	37.50	73.00	0.00	5.80	1
170	600530	38.50	74.00	60.00	5.30	1
171	600531	39.50	75.00	0.00	6.50	2
172	600602	46.50	74.00	0.00	6.80	2
173	600603	42.50	75.00	0.00	5.50	1
174	600603	41.00	73.50	0.00	5.50	1
175	600604	39.00	73.50	0.00	5.50	1
176	600606	45.50	73.50	60.00	6.90	2
177	600620	38.00	73.50	0.00	7.30	3
178	600620	39.50	73.00	0.00	6.90	2

179	600630	43.50	73.50	0.00	5.75	1
180	600702	39.50	75.00	0.00	5.30	1
181	600704	43.00	74.00	60.00	5.80	1
182	600711	37.00	73.00	0.00	5.40	1
183	600721	38.00	73.50	0.00	5.50	1
184	600724	40.00	74.00	0.00	5.90	1
185	600727	44.50	76.00	150.00	6.40	2
186	600806	42.60	75.70	78.00	5.70	1
187	600813	40.00	74.90	56.00	6.90	2
188	601014	33.90	73.50	19.00	5.40	1
189	601030	23.40	70.30	76.00	6.80	2
190	601030	22.90	68.00	60.00	6.80	2
191	601101	38.50	75.10	55.00	7.40	3
192	601101	38.70	75.00	64.00	5.10	1
193	601109	23.40	70.60	52.00	5.60	1
194	601122	40.30	73.90	49.00	6.50	2
195	601127	37.20	73.40	61.00	5.40	1
196	601129	44.10	76.00	63.00	5.30	1
197	601202	24.60	69.70	19.00	6.70	2
198	601202	24.40	69.50	46.00	6.70	2
199	601206	21.40	69.20	28.00	5.40	1
200	601229	45.00	75.00	17.00	6.60	2
201	601231	44.10	75.40	25.00	6.60	2
202	610328	27.00	68.00	125.00	6.00	2
203	610408	38.20	72.70	60.00	6.00	2
204	610508	24.30	69.70	48.50	5.50	1
205	610913	41.60	73.20	154.00	7.00	3
206	611018	36.70	72.60	67.00	6.50	2
207	611109	22.90	67.90	84.00	6.20	2
208	611209	43.70	75.20	34.00	6.00	2
209	620214	38.10	73.10	44.00	7.20	3
210	620227	37.40	73.20	40.00	6.00	2
211	620615	20.40	70.90	60.00	5.00	1
212	620803	23.20	67.50	71.00	7.00	3
213	621229	20.00	69.90	46.00	6.30	2
214	630206	28.30	70.90	12.00	5.00	1
215	630505	24.80	69.60	53.00	5.40	1
216	630507	22.10	68.70	112.00	5.70	1
217	630518	29.70	68.60	42.00	5.10	1
218	630519	46.30	74.80	48.00	6.30	2
219	630525	24.20	66.80	185.00	5.10	1
220	630621	23.80	66.60	203.00	5.20	1
221	630811	38.10	73.10	60.00	5.00	1
222	630814	22.30	68.70	120.00	5.10	1
223	630827	45.90	75.30	33.00	5.30	1
224	631006	33.90	70.00	101.00	5.10	1
225	631020	37.00	73.20	35.00	5.00	1
226	631029	24.80	68.60	67.00	5.00	1
227	631203	22.40	39.30	18.00	6.10	2
228	631210	18.10	68.50	79.00	5.30	1
229	631219	35.20	68.00	32.00	5.30	1
230	631229	18.50	69.70	113.00	5.50	1
231	640219	21.40	70.70	80.00	5.20	1
232	640306	19.70	70.50	50.00	5.30	1
233	640322	35.70	72.90	33.00	5.10	1
234	640409	18.50	71.50	39.00	5.20	1
235	640607	30.40	67.60	29.00	5.20	1
236	640618	39.30	74.70	26.00	5.30	1
237	640712	24.50	66.90	164.00	5.10	1
238	640723	27.80	66.40	130.00	5.20	1

239	640725	27.90	70.90	26.00	6.10	2
240	640805	39.00	74.50	26.00	5.10	1
241	640805	41.10	74.90	33.00	6.10	2
242	640818	26.40	71.50	8.00	6.40	2
243	640829	19.30	66.30	232.00	5.00	1
244	640903	30.90	68.40	113.00	5.10	1
245	640904	18.30	69.00	101.00	5.40	1
246	640910	33.00	69.40	80.00	5.40	1
247	640911	23.90	66.60	195.00	5.30	1
248	640927	21.40	68.70	132.00	5.40	1
249	641002	21.70	67.70	49.00	5.00	1
250	641104	19.70	69.20	102.00	5.20	1
251	641118	31.20	67.60	8.00	5.60	1
252	641209	20.40	68.00	83.00	5.00	1
253	641225	25.30	68.10	101.00	5.00	1
254	641225	18.80	69.60	117.00	5.10	1
255	650102	21.60	68.20	110.00	5.10	1
256	650118	37.70	72.90	52.00	5.30	1
257	650119	28.10	66.80	146.00	5.20	1
258	650131	21.20	67.80	71.00	5.60	1
259	650131	21.10	67.80	71.00	5.10	1
260	650204	45.50	73.80	33.00	5.10	1
261	650213	22.80	68.20	33.00	5.20	1
262	650220	18.40	72.40	33.00	5.20	1
263	650223	25.70	70.50	80.00	6.20	2
264	650308	24.60	67.10	168.00	5.40	1
265	650322	23.80	66.70	176.00	5.50	1
266	650322	31.90	71.50	46.00	6.00	2
267	650322	22.40	68.10	110.00	5.00	1
268	650328	32.40	71.20	61.00	6.40	2
269	650412	26.50	70.80	52.00	5.40	1
270	650416	21.70	68.10	127.00	5.00	1
271	650502	19.80	69.50	117.00	5.50	1
272	650503	62.50	70.60	77.00	5.60	1
273	650503	24.20	67.80	114.00	5.60	1
274	650506	25.00	68.40	90.00	5.10	1
275	650507	22.20	68.50	84.00	5.50	1
276	650508	28.00	70.80	35.00	5.40	1
277	650602	38.70	73.40	18.00	5.10	1
278	650604	44.30	75.80	33.00	5.40	1
279	650612	20.50	69.30	102.00	5.80	1
280	650622	18.40	69.30	122.00	5.00	1
281	650630	21.20	66.10	170.00	5.10	1
282	650665	18.20	69.70	72.00	5.00	1
283	650701	23.30	67.70	85.00	5.10	1
284	650712	28.40	68.30	118.00	5.70	1
285	650719	28.20	68.80	97.00	5.20	1
286	650730	24.40	67.70	140.00	5.30	1
287	650730	18.10	70.30	72.00	6.00	2
288	650808	19.60	68.70	53.00	5.40	1
289	650808	20.40	68.70	115.00	5.20	1
290	650809	28.70	71.20	32.00	5.40	1
291	650820	18.90	69.00	128.00	6.20	2
292	650824	33.70	72.00	48.00	5.00	1
293	651003	42.90	75.20	31.00	6.10	2
294	651005	36.00	72.50	17.00	5.30	1
295	651014	32.30	71.80	36.00	5.10	1
296	651022	25.00	71.20	15.00	5.10	1
297	651023	29.50	71.80	8.00	5.60	1
298	651023	32.50	71.50	61.00	5.20	1

299	651026	24.50	70.20	52.00	5.50	1
300	651031	24.80	68.90	108.00	5.40	1
301	651113	29.30	68.10	34.00	6.00	2
302	651128	45.70	72.60	33.00	5.80	1
303	651211	29.80	67.30	31.00	5.10	1
304	651214	18.30	70.80	88.00	5.20	1
305	651216	22.50	68.50	104.00	5.40	1
306	660109	21.50	69.70	57.00	5.40	1
307	660114	37.90	73.50	36.00	5.00	1
308	660115	30.80	71.60	54.00	5.10	1
309	660115	33.50	69.80	50.00	5.50	1
310	660115	33.60	70.20	33.00	5.00	1
311	660203	21.70	68.40	117.00	5.30	1
312	660205	19.00	69.20	167.00	5.10	1
313	660222	24.20	68.30	33.00	5.00	1
314	660228	26.00	70.40	63.00	5.70	1
315	660308	20.00	68.90	112.00	5.70	1
316	660311	23.60	69.40	76.00	5.40	1
317	660311	19.60	69.30	111.00	5.40	1
318	660312	34.40	72.40	38.00	5.10	1
319	660312	34.40	72.40	38.00	5.10	1
320	660312	31.60	67.20	127.00	5.00	1
321	660321	21.10	68.70	128.00	5.20	1
322	660323	38.10	73.60	25.00	5.30	1
323	660410	31.50	71.00	63.00	5.60	1
324	660413	38.10	73.10	39.00	5.80	1
325	660422	37.80	73.40	16.00	5.50	1
326	660517	44.00	75.60	33.00	5.00	1
327	660517	44.10	75.50	33.00	5.40	1
328	660523	20.50	68.70	78.00	5.00	1
329	660603	30.90	68.70	109.00	5.00	1
330	660616	21.90	67.20	190.00	5.50	1
331	660727	24.10	70.30	35.00	5.50	1
332	660808	27.70	69.00	90.00	5.40	1
333	661011	30.10	71.90	34.00	5.20	1
334	661016	19.80	71.00	27.00	5.00	1
335	661021	27.80	67.50	67.00	5.00	1
336	661110	31.90	68.40	113.00	6.00	2
337	661112	23.90	67.70	118.00	5.60	1
338	661114	18.40	69.40	132.00	5.50	1
339	661126	25.60	70.70	54.00	5.60	1
340	661210	24.20	68.00	124.00	5.30	1
341	661217	22.70	68.80	105.00	5.20	1
342	661228	25.50	70.70	32.00	6.80	2
343	661229	29.00	71.10	39.00	5.00	1
344	661229	25.50	70.60	22.00	5.40	1
345	661230	24.80	70.60	45.00	5.20	1
346	670102	25.03	70.93	37.00	5.10	1
347	670116	24.17	66.82	188.00	5.40	1
348	670203	21.44	67.26	190.00	5.10	1
349	670212	21.70	70.25	27.00	5.50	1
350	670221	25.49	71.50	33.00	5.10	1
351	670313	40.12	74.63	36.00	5.60	1
352	670319	25.81	70.53	33.00	5.00	1
353	670411	23.21	68.87	92.00	5.00	1
354	670412	35.49	73.40	11.00	5.30	1
355	670425	32.80	68.97	28.00	5.70	1
356	670430	23.97	70.48	35.00	5.20	1
357	670511	20.26	68.69	79.00	6.10	2
358	670514	20.51	68.83	108.00	5.20	1

359	670610	41.30	73.60	37.00	5.70	1
360	670621	25.20	70.50	23.00	5.70	1
361	670704	38.10	73.40	28.00	5.40	1
362	670720	28.10	66.90	157.00	5.30	1
363	670820	25.20	69.00	109.00	5.60	1
364	670908	23.40	70.70	33.00	5.50	1
365	670918	24.10	70.30	49.00	5.10	1
366	670926	33.60	70.50	84.00	5.80	1
367	671007	29.60	71.10	42.00	5.30	1
368	671021	27.70	71.80	13.00	5.40	1
369	671102	28.80	69.50	79.00	5.30	1
370	671115	28.70	71.20	15.00	6.20	2
371	671127	30.80	71.00	62.00	5.40	1
372	671214	24.00	69.30	53.00	5.10	1
373	671219	28.50	71.00	18.00	5.30	1
374	671221	21.80	70.00	33.00	6.30	2
375	671225	21.50	70.40	53.00	5.80	1
376	671227	21.20	68.30	135.00	6.40	2
377	671230	25.70	70.30	44.00	5.00	1
378	680102	22.60	66.60	237.00	5.30	1
379	680106	27.80	71.10	33.00	5.80	1
380	680106	27.20	69.40	60.00	5.00	1
381	680108	18.60	69.90	116.00	5.40	1
382	680113	24.20	66.90	192.00	5.70	1
383	680119	42.60	75.20	22.00	5.50	1
384	680130	22.00	68.50	118.00	5.30	1
385	680204	19.60	68.20	114.00	5.30	1
386	680206	28.50	71.00	23.00	5.70	1
387	680226	23.60	66.30	204.00	5.30	1
388	680317	21.20	68.10	122.00	5.10	1
389	680320	20.30	70.00	47.00	5.10	1
390	680322	20.90	68.50	138.00	5.00	1
391	680322	20.40	69.00	96.00	5.50	1
392	680328	34.90	69.40	171.00	5.30	1
393	680404	22.70	68.40	110.00	5.10	1
394	680411	21.20	66.60	225.00	5.20	1
395	680421	23.40	70.50	41.00	5.50	1
396	680430	38.40	71.10	40.00	5.90	1
397	680509	18.40	69.36	125.00	5.00	1
398	680516	22.77	68.65	104.00	5.00	1
399	680619	43.95	75.11	24.00	5.70	1
400	680728	22.67	69.43	70.00	5.10	1
401	680729	19.16	69.77	71.00	5.20	1
402	680911	43.01	75.21	31.00	5.70	1
403	680911	43.02	75.37	20.00	5.00	1
404	680922	24.13	66.91	194.00	5.50	1
405	681008	23.35	66.54	221.00	5.60	1
406	681024	30.30	68.24	35.00	5.00	1
407	681028	24.39	66.89	163.00	5.10	1
408	681211	25.22	70.37	50.00	5.00	1
409	681229	23.94	66.67	205.00	5.20	1
410	690318	25.79	70.78	48.00	5.20	1
411	690330	27.58	70.93	33.00	5.10	1
412	690417	28.26	68.79	82.00	5.00	1
413	690426	30.65	71.54	33.00	5.90	1
414	690426	30.58	71.37	23.00	5.60	1
415	690505	30.79	71.76	38.00	5.30	1
416	690606	22.51	68.42	125.00	5.00	1
417	690608	36.49	73.59	30.00	5.00	1
418	690710	23.64	69.67	48.00	5.40	1

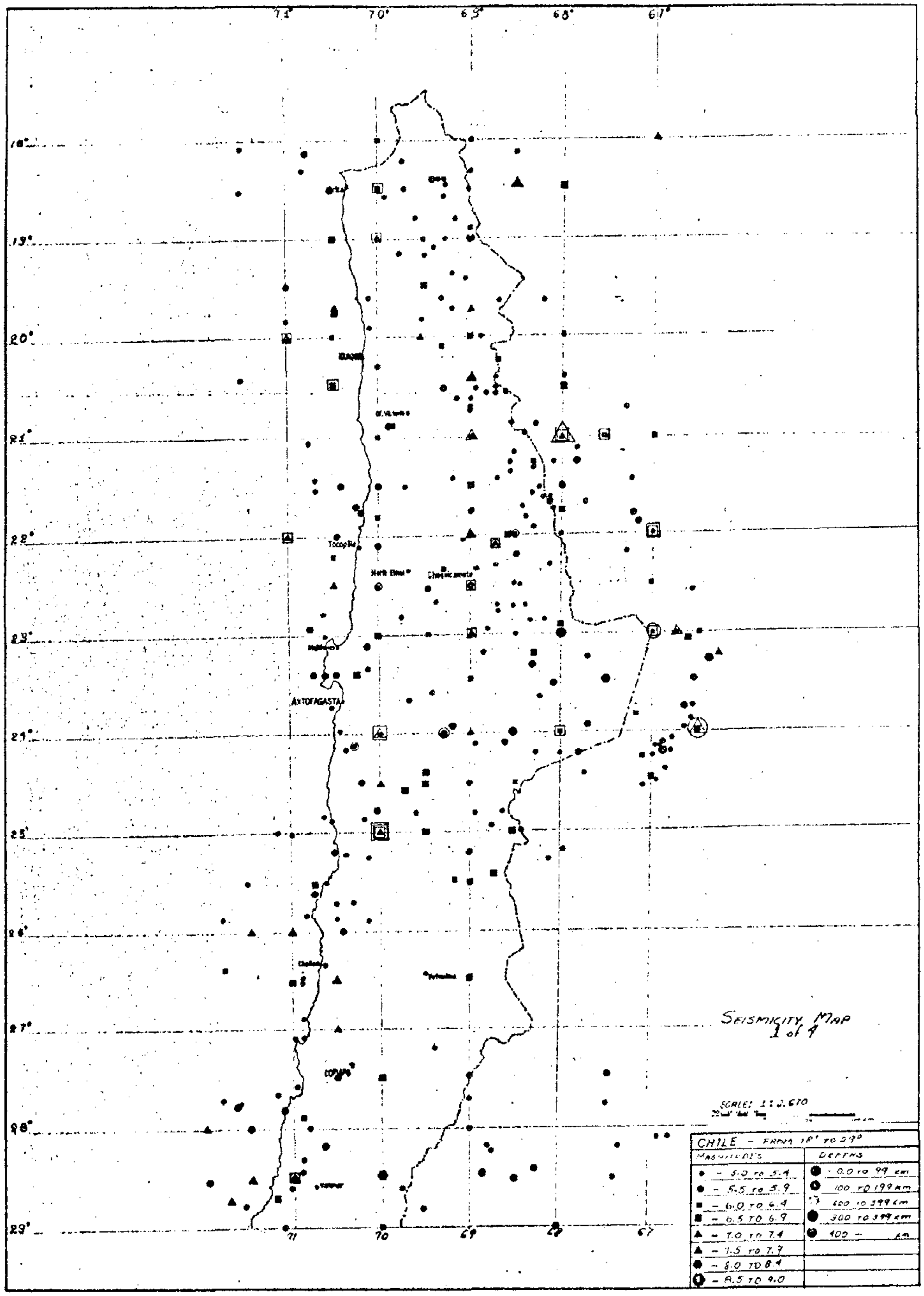
419	690804	26.89	70.89	33.00	5.30	1
420	690808	21.20	68.56	74.00	5.40	1
421	690816	22.72	68.54	102.00	5.00	1
422	690817	41.85	71.22	14.00	5.00	1
423	690902	27.75	66.49	174.00	5.50	1
424	690913	22.88	68.37	106.00	5.40	1
425	690915	18.55	69.02	177.00	5.20	1
426	690921	23.55	68.08	120.00	5.50	1
427	691026	18.09	71.54	23.00	5.40	1
428	691111	24.87	70.56	39.00	5.10	1
429	691113	27.79	71.65	33.00	5.80	1
430	691213	32.71	69.97	105.00	5.60	1
431	700118	28.46	70.91	41.00	5.10	1
432	700215	23.36	70.16	56.00	5.40	1
433	700224	34.67	72.34	25.00	5.10	1
434	700301	28.60	71.04	51.00	5.00	1
435	700305	18.82	69.23	127.00	5.20	1
436	700308	20.54	68.71	78.00	5.00	1
437	700315	29.65	69.50	119.00	6.00	2
438	700325	30.36	69.93	100.00	5.20	1
439	700330	21.16	68.76	121.00	5.20	1
440	700409	33.96	70.11	120.00	5.20	1
441	700502	21.57	68.34	130.00	5.10	1
442	700517	33.72	68.37	16.00	5.30	1
443	700605	31.76	67.28	127.00	5.00	1
444	700611	24.53	68.50	112.00	6.30	2
445	700614	51.96	74.22	33.00	5.20	1
446	700614	52.05	74.17	33.00	5.70	1
447	700614	51.95	73.85	33.00	6.00	2
448	700614	19.36	69.22	125.00	5.00	1
449	700619	22.19	70.52	52.00	6.20	2
450	700623	19.40	69.08	118.00	5.30	1
451	700712	23.39	68.39	101.00	5.50	1
452	700726	52.15	74.89	33.00	5.10	1
453	700726	25.87	71.81	18.00	5.10	1
454	700804	28.22	67.30	118.00	5.00	1
455	700807	24.26	66.99	169.00	5.10	1
456	700820	28.46	67.41	139.00	5.20	1
457	700909	19.60	70.11	49.00	5.00	1
458	700910	27.07	70.86	32.00	5.20	1
459	700911	27.08	70.98	22.00	5.00	1
460	700914	33.97	72.17	31.00	5.60	1
461	700914	33.89	72.01	33.00	5.10	1
462	700914	34.01	72.15	15.00	5.10	1
463	700917	31.81	69.95	118.00	5.30	1
464	700918	20.92	68.29	133.00	5.30	1
465	700918	33.78	72.11	25.00	5.20	1
466	700918	34.00	72.01	20.00	5.20	1
467	700919	33.50	71.85	21.00	5.50	1
468	700925	24.93	68.70	99.00	5.00	1
469	701003	25.23	71.12	31.00	5.00	1
470	701005	34.00	72.19	53.00	5.10	1
471	701013	23.74	70.54	25.00	5.10	1
472	701113	22.12	70.00	36.00	5.60	1
473	701115	21.93	68.31	134.00	5.20	1
474	701128	20.92	69.83	33.00	6.00	2
475	701128	20.92	69.87	34.00	5.90	1
476	701204	23.13	70.11	36.00	5.90	1
477	701206	19.10	69.39	111.00	5.30	1
478	701208	30.70	71.21	50.00	5.80	1

479	701222	20.53	68.61	115.00	5.50	1
480	701230	24.00	69.30	82.00	5.50	1
481	710102	32.16	68.38	136.00	5.00	1
482	710122	30.56	72.00	66.00	5.30	1
483	710124	22.05	67.09	149.00	5.30	1
484	710205	28.18	70.62	55.00	5.80	1
485	710218	36.77	73.21	31.00	5.60	1
486	710220	28.62	69.75	105.00	5.00	1
487	710221	23.85	67.16	169.00	6.30	2
488	710304	28.78	71.55	48.00	5.00	1
489	710306	21.29	68.27	71.00	5.40	1
490	710325	27.66	71.22	7.00	5.00	1
491	710406	42.88	75.71	33.00	5.20	1
492	710407	32.57	69.08	122.00	5.70	1
493	710409	31.54	67.54	45.00	5.20	1
494	710415	21.34	68.55	128.00	5.30	1
495	710420	21.76	68.96	93.00	5.70	1
496	710427	18.44	69.27	131.00	5.20	1
497	710508	42.22	71.69	151.00	5.90	1
498	710513	24.87	70.21	57.00	5.00	1
499	710517	19.17	69.50	107.00	5.10	1
500	710518	28.43	68.81	95.00	5.80	1
501	710520	35.25	72.29	42.00	5.00	1
502	710528	22.81	69.76	41.00	5.10	1
503	710530	20.59	69.13	104.00	5.40	1
504	710607	37.65	73.89	23.00	5.00	1
505	710609	29.80	71.86	29.00	5.00	1
506	710612	18.79	66.92	262.00	5.10	1
507	710616	24.15	70.37	47.00	5.40	1
508	710617	25.48	69.15	93.00	6.30	2
509	710618	23.64	68.22	115.00	5.20	1
510	710619	24.07	66.87	208.00	5.10	1
511	710628	19.86	70.09	47.00	5.20	1
512	710629	24.13	68.58	82.00	5.50	1
513	710703	24.13	68.93	103.00	5.40	1
514	710704	20.63	69.01	86.00	5.00	1
515	710709	32.24	71.67	53.00	5.20	1
516	710709	32.54	71.15	58.00	6.60	2
517	710709	32.39	71.47	47.00	5.20	1
518	710710	32.64	71.48	55.00	5.10	1
519	710711	32.98	71.90	49.00	5.10	1
520	710711	32.27	71.81	36.00	5.90	1
521	710717	21.53	68.24	123.00	5.40	1
522	710721	21.50	70.77	40.00	5.20	1
523	710725	32.41	71.65	43.00	5.20	1
524	710731	32.36	71.53	46.00	5.50	1
525	710802	32.84	72.02	9.00	5.30	1
526	710804	21.82	68.37	116.00	5.10	1
527	710805	30.31	71.13	80.00	5.20	1
528	710814	21.78	67.23	189.00	5.70	1
529	710815	20.72	68.95	80.00	5.30	1
530	710821	21.77	70.21	17.00	5.80	1
531	710831	30.77	71.42	43.00	5.20	1
532	710921	31.78	71.39	55.00	5.00	1
533	710921	20.47	68.96	94.00	5.30	1
534	710925	32.44	72.97	33.00	5.50	1
535	710928	32.03	69.97	110.00	5.60	1
536	711010	20.97	68.40	88.00	5.40	1
537	711013	21.67	68.18	92.00	5.80	1
538	711014	21.58	68.18	142.00	5.40	1

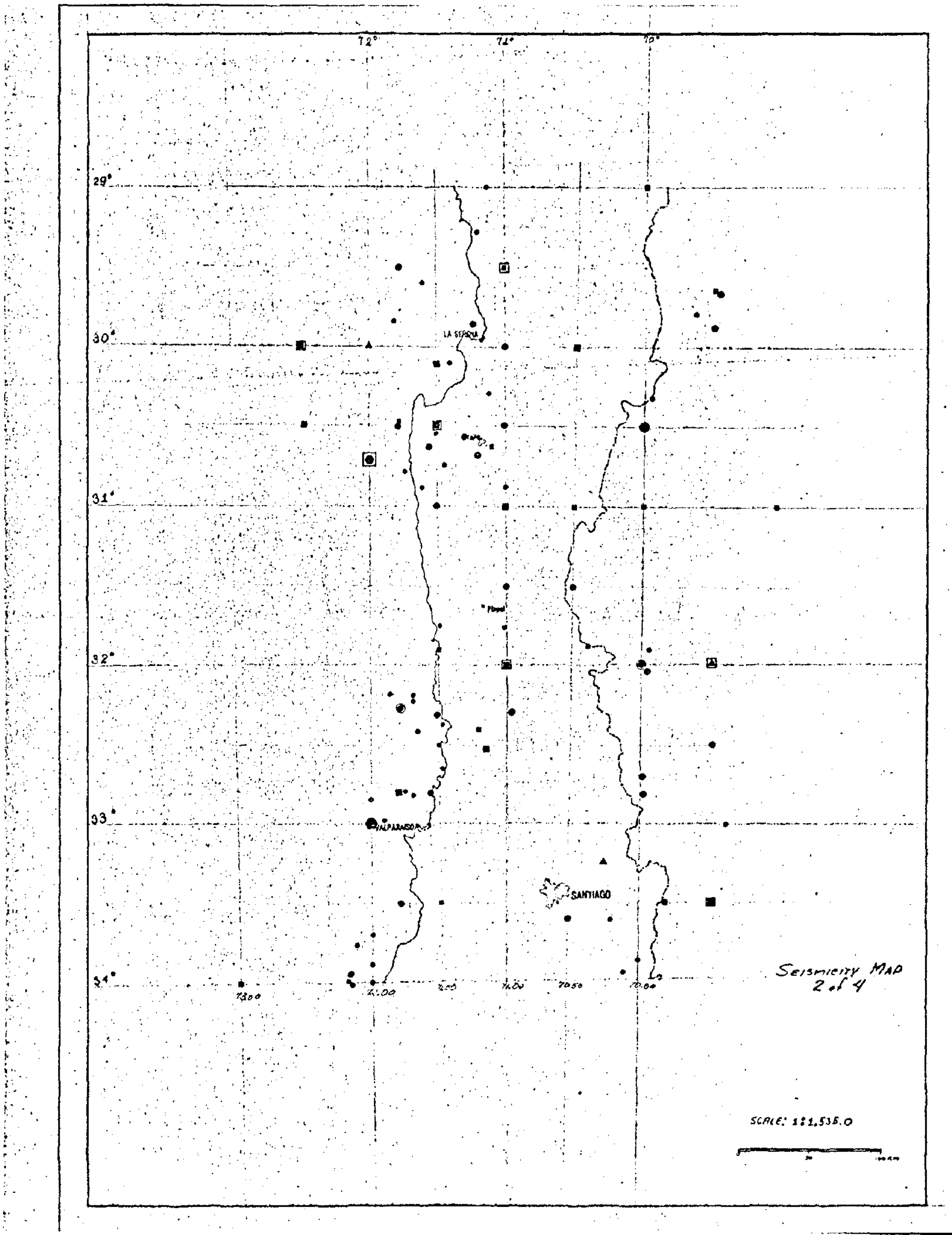
539	711020	32.70	71.76	51.00	5.20	1
540	711024	25.18	68.97	113.00	5.10	1
541	711026	32.22	71.67	44.00	5.10	1
542	711110	23.54	66.37	198.00	5.40	1
543	711127	31.75	71.49	64.00	5.30	1
544	711128	29.84	69.49	105.00	5.90	1
545	711203	22.79	70.61	37.00	5.10	1
546	711208	22.91	70.76	18.00	5.60	1
547	711210	38.45	73.62	16.00	5.10	1
548	711211	23.02	70.60	38.00	5.20	1
549	711211	22.91	73.51	33.00	5.00	1
550	711211	38.35	73.54	32.00	5.20	1
551	711214	25.88	70.16	59.00	5.00	1
552	711218	29.33	71.20	65.00	5.00	1
553	711220	40.20	75.08	33.00	5.00	1
554	720106	38.12	73.71	30.00	5.00	1
555	720113	32.32	70.93	80.00	5.50	1
556	720121	35.02	70.46	20.00	5.10	1
557	720201	20.66	96.03	99.00	5.30	1
558	720204	32.19	71.88	23.00	5.30	1
559	720204	22.93	68.79	94.00	5.40	1
560	720209	51.80	73.99	33.00	5.50	1
561	720213	21.15	68.49	133.00	5.10	1
562	720220	21.02	70.71	31.00	5.00	1
563	720301	24.79	70.04	61.00	5.50	1
564	720304	20.72	67.30	209.00	5.10	1
565	720320	37.92	74.85	33.00	5.00	1
566	720330	29.83	71.39	72.00	5.60	1
567	720418	20.44	71.55	33.00	5.10	1
568	720419	31.08	68.79	104.00	5.30	1
569	720430	31.68	71.02	68.00	5.00	1
570	720513	32.73	71.58	38.00	5.70	1
571	720513	32.69	71.77	40.00	5.40	1
572	720515	29.66	69.48	39.00	5.60	1
573	720521	18.61	69.28	132.00	5.20	1
574	720522	26.43	70.36	34.00	5.20	1
575	720527	27.75	71.63	4.00	5.00	1
576	720608	30.46	71.80	39.00	6.20	2
577	720608	22.58	66.17	259.00	5.40	1
578	720608	30.51	71.79	57.00	5.50	1
579	720618	24.17	66.99	146.00	5.30	1
580	720619	22.19	67.33	181.00	5.00	1

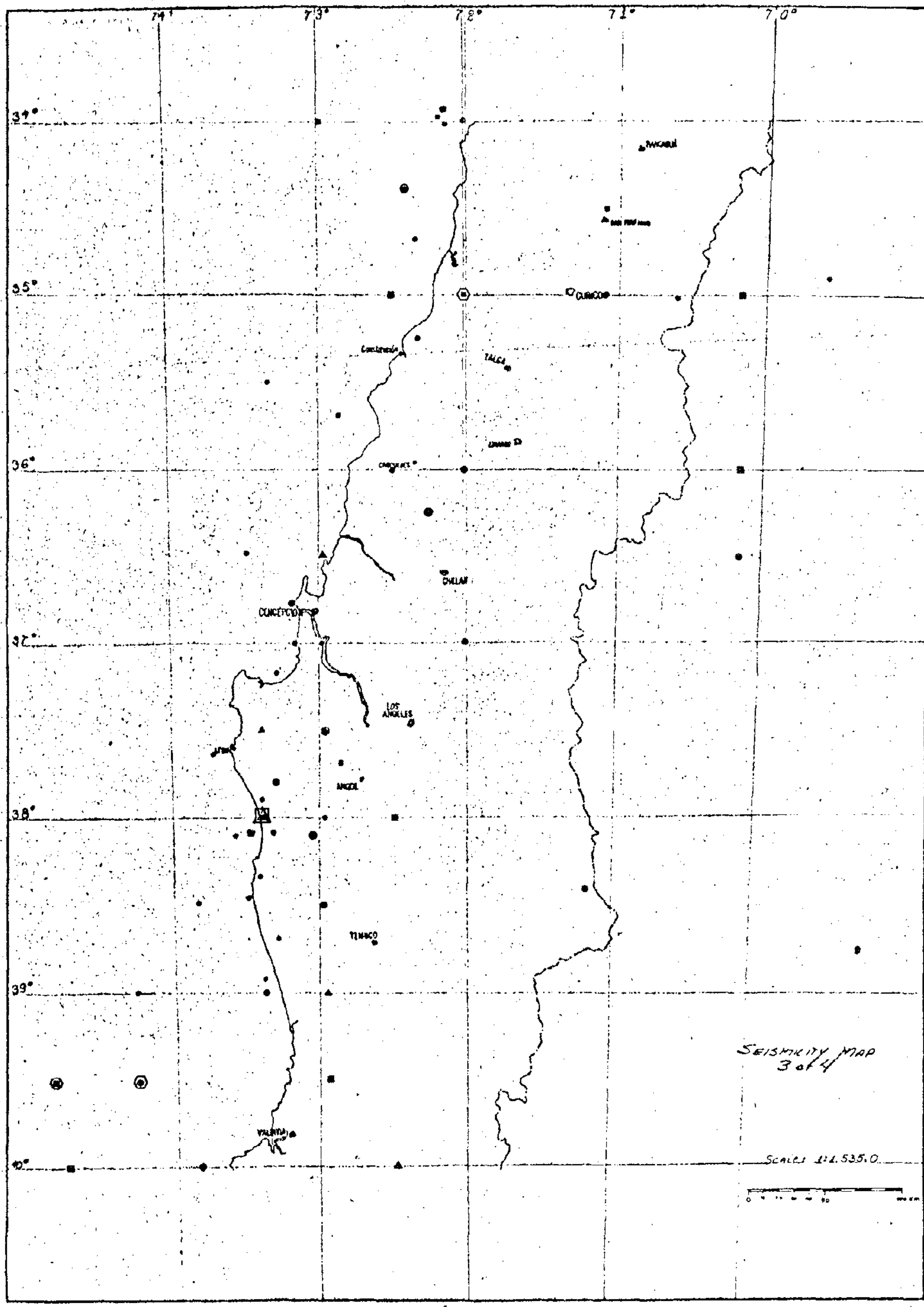
APPENDIX B

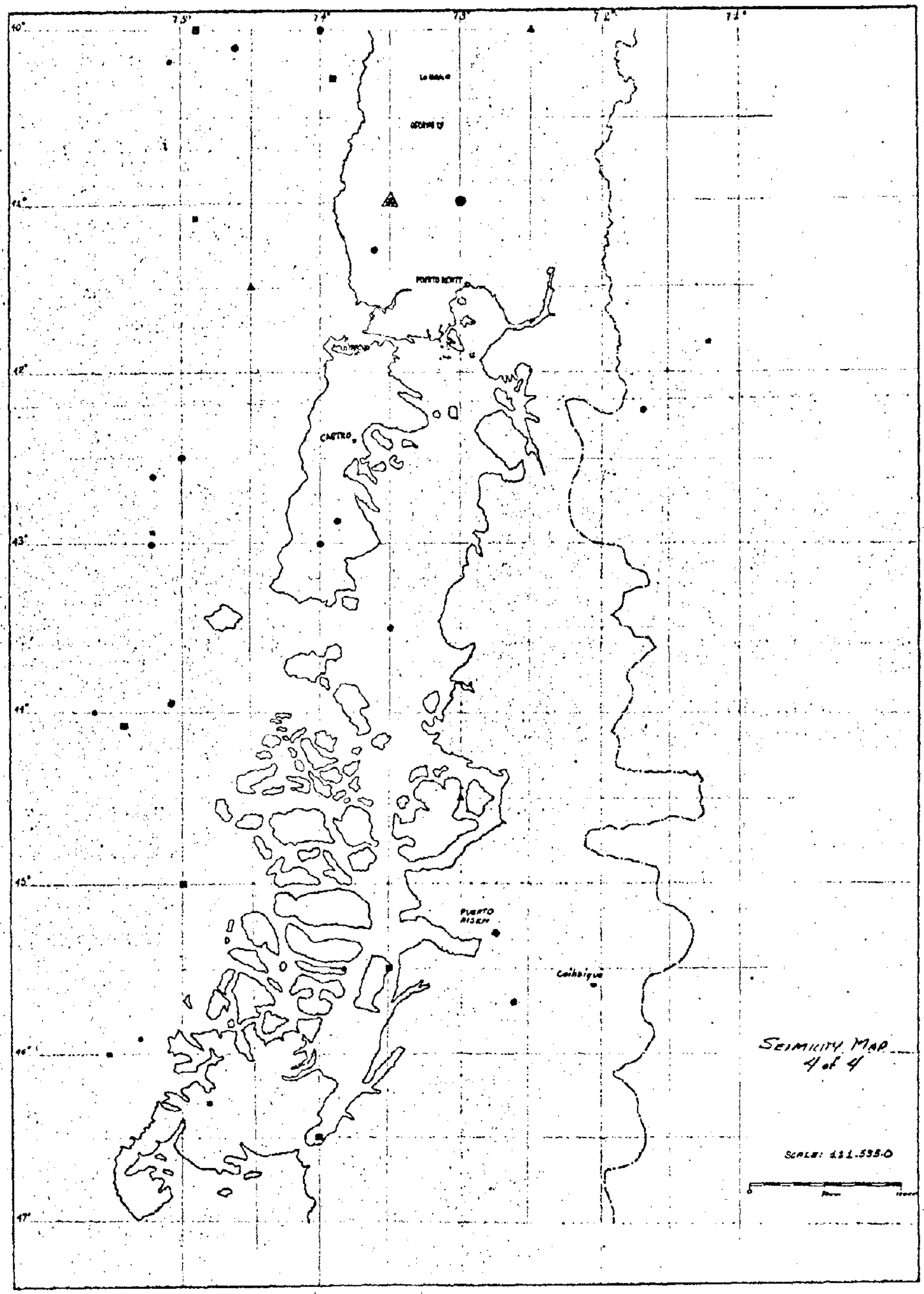
Epicenter Location of Earthquakes
Which Have Occurred in Chile, 1934-1972



SEISMICITY MAP
1 of 4
ANTOFAGASTA
CHILE - FROM 18° TO 29°
MAGNITUDES
DEPTHS
- 5.0 TO 5.4
- 5.5 TO 5.9
- 6.0 TO 6.4
- 6.5 TO 6.9
- 7.0 TO 7.4
- 7.5 TO 7.7
- 8.0 TO 8.4
- 8.5 TO 9.0
- 0.0 TO 99 km
100 TO 199 km
300 TO 399 km


72°
71°
70°
29°
30°
31°
32°
33°
34°
LA SERENA
VALPARAISO
SANTIAGO
Seismicity Map
2 of 4


74°
73°
72°
71°
70°
34°
35°
36°
37°
38°
39°
40°
CURICO
TALCA
CHILLAN
CONCEPCION
LOS ANGELES
ANGOL
TEMUCO
VALDIVIA
Seismicity Map
3 of 4


CASTRO
SEIMICITY MAP
4 of 4

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