FLUCTUATIONS IN CIRCUM-PACIFIC VOLCANIC ACTIVITY AND IN THE SEISMICITY OF SOUTH AMERICA

A DISSERTATION SUBMITTED TO THE
GRADUATE DIVISION OF THE UNIVERSITY OF HAWAII
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN GEOLOGY AND GEOPHYSICS

MAY 1973

By

Marion O. Michael

Dissertation Committee:

Augustine S. Furumoto, Chairman
Agatin T. Abbott
Joseph T. Keeler
Gordon A. Macdonald
Kost A. Pankiwskyj
George H. Sutton

We certify that we have read this dissertation and that in our opinion it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Geology and Geophysics.

DISSERTATION COMMITTEE

Chairman

ABSTRACT

Graphs of the number of volcanoes in eruption per annum from 1900 through 1968 for volcanic areas of the circum-Pacific belt show fluctuations which, in 16 out of 21 areas studied, are statistically significant. The significance of the amplitude of these fluctuations was tested using a chi-square test, the null hypothesis being that the number of volcanoes in eruption per annum in each area is equal to their arithmetic mean. Calculation of serial correlation coefficients at various lags tested the series for serial correlation and periodicity.

It was found that the time series for the number of volcanoes in eruption per annum in the areas of the western Pacific margin have periods approximately half those found for areas of the eastern Pacific margin, the periods being around 17 years and 34 years respectively.

A similar statistical analysis was done for shallow, intermediate and deep seismic activity in South America, the data being divided into three categories: number of $M \geq 6$ earthquakes per annum, number of $M \geq 7$ earthquakes per annum and annual $M \geq 7$ earthquake energy release.

In most cases, the amplitudes of the fluctuations of these series are statistically significant, but they show very little

serial correlation. However, $M \geq 6$ earthquakes possibly have a 30-year periodicity.

On both the eastern and western Pacific margins, large pulses of volcanic activity tend to migrate south with time, this tendency being more pronounced in the east than in the west where there is more simultaneity in volcanic activity.

No such well-marked pattern of migrating pulses was found for seismic activity in South America, although large pulses in the number of shallow and of intermediate $M \geq 6$ earthquakes per annum may have a tendency to migrate from south to north and then north to south, and large pulses in $M \geq 7$ shallow earthquake energy release tend to be simultaneous or to migrate south with time.

Cross correlation was performed between shallow, intermediate and deep earthquake activity, and it was found that intermediate seismic pulses tend to occur before deep seismic pulses, and often also before shallow pulses. This does not fit early theories of crustal material being pushed or sucked as a single, coherent plate under the Andes, because this would be expected to generate the respective sequences shallow, then intermediate, then deep, or deep, followed by intermediate, followed by shallow earthquakes, or else approximately simultaneous pulses if transmission of energy is rapid. However, recent work indicates that the descending slab may not remain coherent.

The series for the number of volcanoes in eruption per annum in South America was cross correlated with the South American large magnitude seismic data and the correlation was found to be low, the maximum cross correlation coefficient, 0.54, occurring at zero lag by cross correlating the number of volcanoes in eruption per annum (1904 to 1968) with the annual $M \geq 7$ shallow earthquake energy release for the same period. This correlation arises mainly from the fact that 1906 and 1960 were years both of maximum volcanic activity and seismic energy release. The tectonic activity of 1906 was widespread throughout South America, whereas that of 1960 tended to be localized in Chile.

TABLE OF CONTENTS

Table of Contents (Continued)

Table of Contents (Continued)

LIST OF TABLES

List of Tables (Continued)

LIST OF ILLUSTRATIONS

List of Illustrations (Continued)

List of Illustrations (Continued)

List of Illustrations (Continued)

I. INTRODUCTION

The circum-Pacific volcanic belt, including the Indonesian arc, contains 88 percent of the world's active volcanoes.

The first aim of the present study is to determine the statistical significance of fluctuations in the number of volcanoes in eruption per annum in individual volcanic areas of the Pacific margin and, if they be significant, to investigate the space-time relationship between pulses of volcanic activity. This may give some clue as to whether causes of volcanism are global or local and as to their nature.

The second aim is to carry out a similar study of large magnitude seismic activity in South America.

The final aim is to investigate the relationship between volcanic activity and large magnitude seismic activity in South America.

The analyses of data by calculation of serial correlation and cross correlation coefficients are described later in the text. Alternate techniques would have been to perform spectral and cross spectral analyses using computer programs available at the University of Hawaii Computing Center. However, the author prefers the serial and cross correlation methods because she understands them better, was able to write the programs and finds them easier to interpret than spectral estimates. Also, to be ideal for spectral analysis, the series should be longer.

Data on volcanoes from 1900 to, in most cases, the early 1960's were obtained from the Catalogue of Active Volcanoes of the World, except for the Aleutians where data came from Coats (1950), and for New Zealand. The New Guinea-Solomons data were augmented by later information from the Rabaul Observatory. The data were brought up to date to the end of 1968 from a computer printout lent to me by Dr. John H. Latter of the Department of Scientific and Industrial Research Geophysics Division, Wellington, New Zealand. He also supplied data and references on New Zealand volcanic activity. Data are very reliable for some areas, such as Japan, but rather vague for others, such as the Aleutians and Colombia-Ecuador.

Earthquake data from 1904 through 1952 were obtained from Gutenberg and Richter (1954). From 1953 to 1959 the computer printout from the Hypocenter Data File of the Environmental Data Service, U. S. Department of Commerce, was my only data source. From 1960 to 1962, I obtained earthquake data from Seismological Notes in the Bulletin of the Seismological Society of America. Finally, from 1963 to 1971, I again used the computer printout from the Hypocenter Data File, but supplemented the data with magnitudes (determined by the Seismological Laboratory at Pasadena) from Seismological Notes, up to the end of October 1971. A great difficulty in obtaining meaningful earthquake data for time series analysis lies in the lack of uniformity of magnitude data. This is discussed further in Chapter IV, section 1.

Very little work has been done on volcanic periodicity on a global scale. Eggers and Decker (1969) found that "the apparent frequency of eruptions increases with time to the present" probably due to "better observation and recording of more recent events." Machado (1967) noted that there has been a "remarkable sequence of volcanic eruptions ... in the Atlantic during the last twenty years" and concluded that "the long period components of the earth tide seem to influence the eruptive epochs, acting as trigger forces." Rinehart (1972) found "that the 18.6-year tidal component strongly regulates the frequencies of eruption of Grand and Steamboat geysers" in Yellowstone National Park, Wyoming.

Jaggar (1931a, 1931b, 1932, 1947), referring to the Hawaiian volcanoes, remarked that Green (1887) and Wood (1917) had commented on possible 7-year, 9-year, 18.6-year, 65-year and 130-year periodicities, and he himself suggested 11-year, 33-year 66-year and 132-year cycles. He noted "a general similarity between the curves of frequency of sunspots and of frequency of volcanic eruptions."

Latter (1971) plotted a cumulative graph of worldwide seismo -volcanic energy release which showed that "energy release is significantly clustered, tending to occur in bursts rather than evenly spread along the time axis." These bursts of energy for time series analysis lies in the lack of uniformity of magnitude data. This is discussed further in Chapter IV, section 1.

Very little work has been done on volcanic periodicity on a global scale. Eggers and Decker (1969) found that "the apparent frequency of eruptions increases with time to the present" probably due to "better observation and recording of more recent events." Machado (1967) noted that there has been a "remarkable sequence of volcanic eruptions ... in the Atlantic during the last twenty years" and concluded that "the long period components of the earth tide seem to influence the eruptive epochs, acting as trigger forces." Rinehart (1972) found "that the 18.6-year tidal component strongly regulates the frequencies of eruption of Grand and Steamboat geysers" in Yellowstone National Park, Wyoming.

Jaggar (1931a, 1931b, 1932, 1947), referring to the Hawaiian volcanoes, remarked that Green (1887) and Wood (1917) had commented on possible 7-year, 9-year, 18.6-year, 65-year and 130-year periodicities, and he himself suggested 11-year, 33-year 66-year and 132-year cycles. He noted "a general similarity between the curves of frequency of sunspots and of frequency of volcanic eruptions."

Latter (1971) plotted a cumulative graph of worldwide seismo -volcanic energy release which showed that "energy release is significantly clustered, tending to occur in bursts rather than evenly spread along the time axis." These bursts of energy release "include events over a wide geographic range, suggesting that their immediate cause lay in variation of a first order parameter on a global scale...." He noted that "the Americas as a whole suffer periods of increased activity" such as "the marked instability in the Caribbean area in 1902....Other periods of widespread activity in the Americas were 1898 to 1899, 1906, 1916 to 1917, 1924 to 1927, and 1943 to 1951...."

Some work has been done on the distribution of earthquakes in space. For example, Tsuboi (1958) divided Japan into 44 compartments and, by cross correlating yearly numbers of earthquakes in these compartments, was able to establish six earthquake provinces, these being groups of compartments having sympathetic seismic activity. Lomnitz (1966) states that "similar results were obtained in Chile by Gajardo and Lomnitz (1960). The earthquake provinces obtained by this method are influenced by the selection of the time interval and grid size and by the presence of aftershock sequences." Kelleher (1970) investigated the space-time distribution of large magnitude earthquakes in the Alaska-Aleutian seismic zone and stated that "the evidence suggests that major earthquakes of this zone tend to progress in time from east to west." According to Heck (1936) "Omori made one of the few correct earthquake predictions of history. Taking into account a series of great earthquakes around the Pacific up to and including the California earthquake in April 1906, he said that the next great earthquake should occur in the northern part of the trans-Pacific belt and in Peru or Chile. Earthquakes occurred in both these regions on the same day of August 1906."

Many workers have tried to establish periodicities in earthquakes usually related to astronomical frequencies, but, according to Lomnitz (1967) most of these have now been rejected on solid statistical considerations. One recent publication by Whitten (1971) suggests a strong "correlation between the total energy release and the daily movement of the pole during the last 20 years." This mean daily polar shift has an approximate period of seven years.

Walker, Sutton, Woollard and leTourneau (1972) compared seismic energies released (from 1964 through 1970) on the rising and on the sinking edges of the Nasca Plate and found a temporal relationship between them. They obtained similar results for the rising and the sinking or shearing edges of the Cocos Plate and part of the Main Pacific Plate and also found a possible relationship in time between world activity and the activity along various individual plate edges.

I am very grateful to Dr. John Latter for the assistance mentioned previously. His help has saved me months of data collection. I would also like to thank Mr. Carl A. von Hake of the National Geophysical Data Center of the Environmental Data Service, U. S. Department of Commerce, for supplying me with the computer printouts from the Hypocenter Data File, and Dr. D. I. J. Mallick, Senior Geologist in the Geological Survey Department of the New Hebrides for giving me data on Yasour volcano. My thanks go also to Professor R. H. Clark, Professor of Geology, Victoria University of Wellington, Wellington, New Zealand, for information on White Island.

II. STATISTICAL SIGNIFICANCE OF FLUCTUATIONS IN VOLCANIC ACTIVITY IN THE INDIVIDUAL AREAS OF THE CIRCUM-PACIFIC REGION

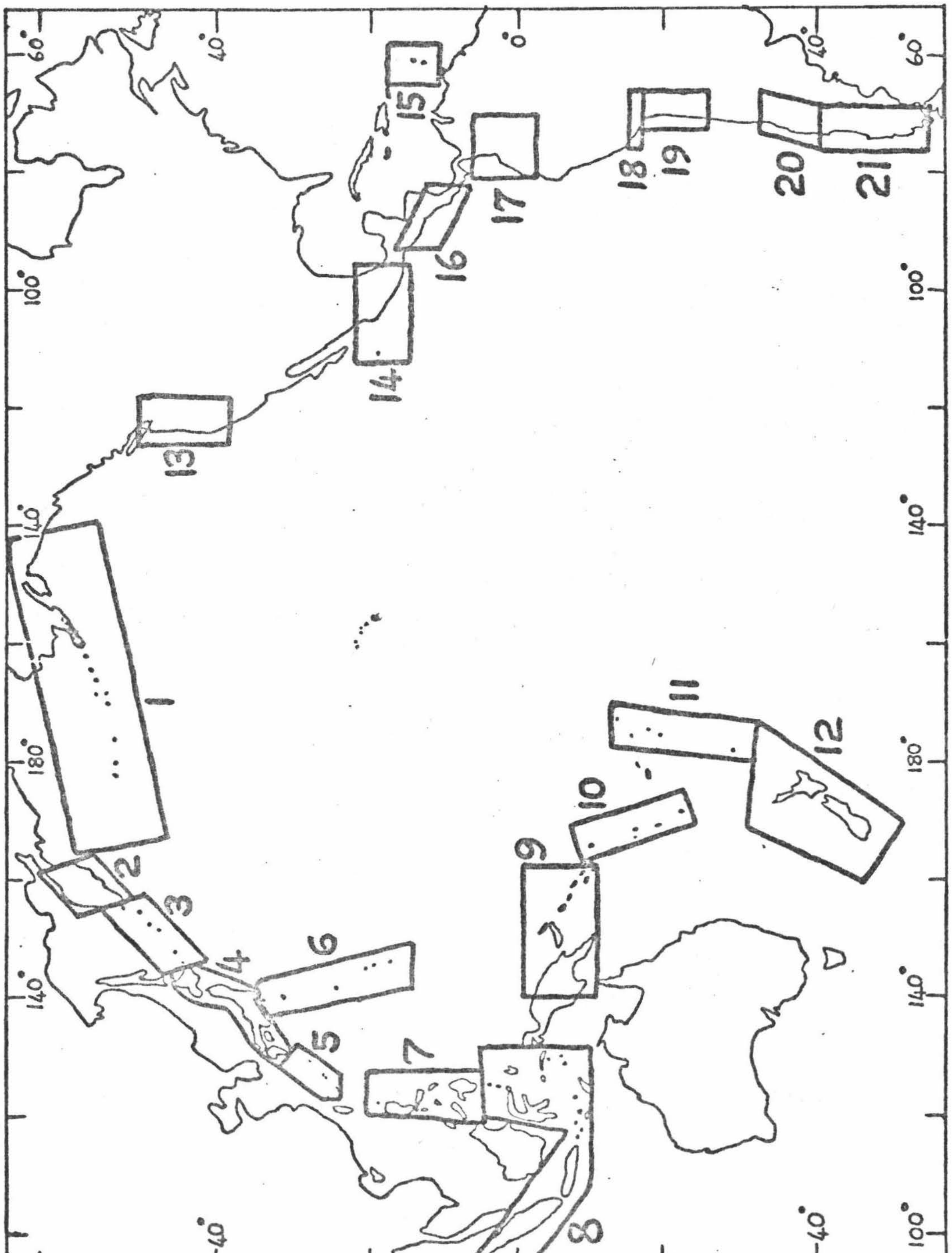
1. Method of Analysis of Data

Two complementary statistical procedures, the chi-square test, and the calculation of serial correlation coefficients, were applied to determine whether fluctuations in the number of volcanoes in eruption each year versus years from 1900 through 1968, for an individual area (Figs. 1 through 4), were significantly different from simply random departures from the mean number of volcanoes in eruption each year for that area. For U. S. A. and New Zealand, data are available from 1900 through 1971. The mean, variance, standard deviation and the years for which the number of volcanoes in eruption is more than two and more than three standard deviations away from the mean are given in Table I.

The chi-square test (Dixon, W. J. and Massey, F. J., Jr., 1969, p. 238) is used for testing hypotheses concerning situations where the number, O_i, of observations in n different categories are noted. It is assumed that each observation can fall into one and only one category. Under the null hypothesis, a certain number, E_i, of observations is expected in each category. The sample size should be such that not more than 20 percent of the

Fig. 1. Locations of the circum-Pacific volcanic areas discussed in the text:

1. Aleutians
2. Kamchatka
3. Kuriles
4. Kyusyu-Honsyu-Hokkaido
5. Ryukyu Islands
6. Izu-Mariana Islands
7. Philippines
8. Indonesia
9. New Guinea-Solomons
10. Santa Cruz-New Hebrides-Matthew Island
11. Kermadec-Tonga-Samoa
12. New Zealand
13. U. S. A.
14. Mexico
15. West Indies
16. Central America
17. Colombia-Ecuador
18. Peru
19. Northern Chile
20. Central Chile
21. Southern Chile



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
60°
40°
0°
100°
140°
180°

Fig. 2. Number of volcanoes in eruption per annum in some areas of the western Pacific margin:

1. Aleutians
2. Kamchatka
3. Kuriles
4. Kyusyu-Honsyu-Hokkaido
5. Ryukyu Islands
6. Izu-Mariana Islands
7. Philippines
8. Indonesia

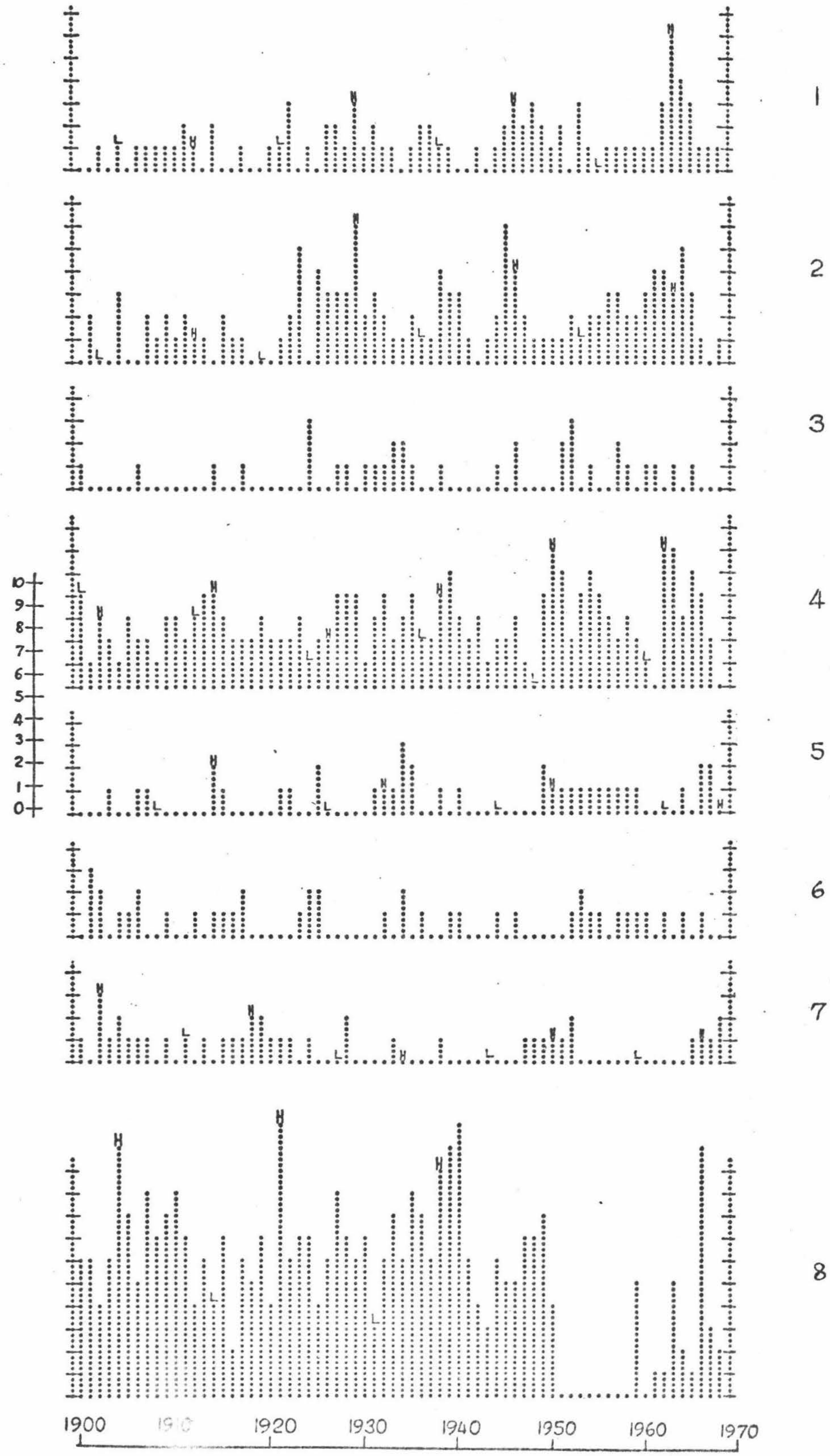

1
2
3
4
5
6
7
8
10 9 8 7 6 5 4 3 2 1 0
1900 1910 1920 1930 1940 1950 1960 1970

Fig. 3. Number of volcanoes in eruption per annum in some areas of the south-west Pacific:

1. New Guinea-Solomons
2. Santa Cruz-New Hebrides-Matthew Island
3. Kermadec-Tonga-Samoa
4. New Zealand

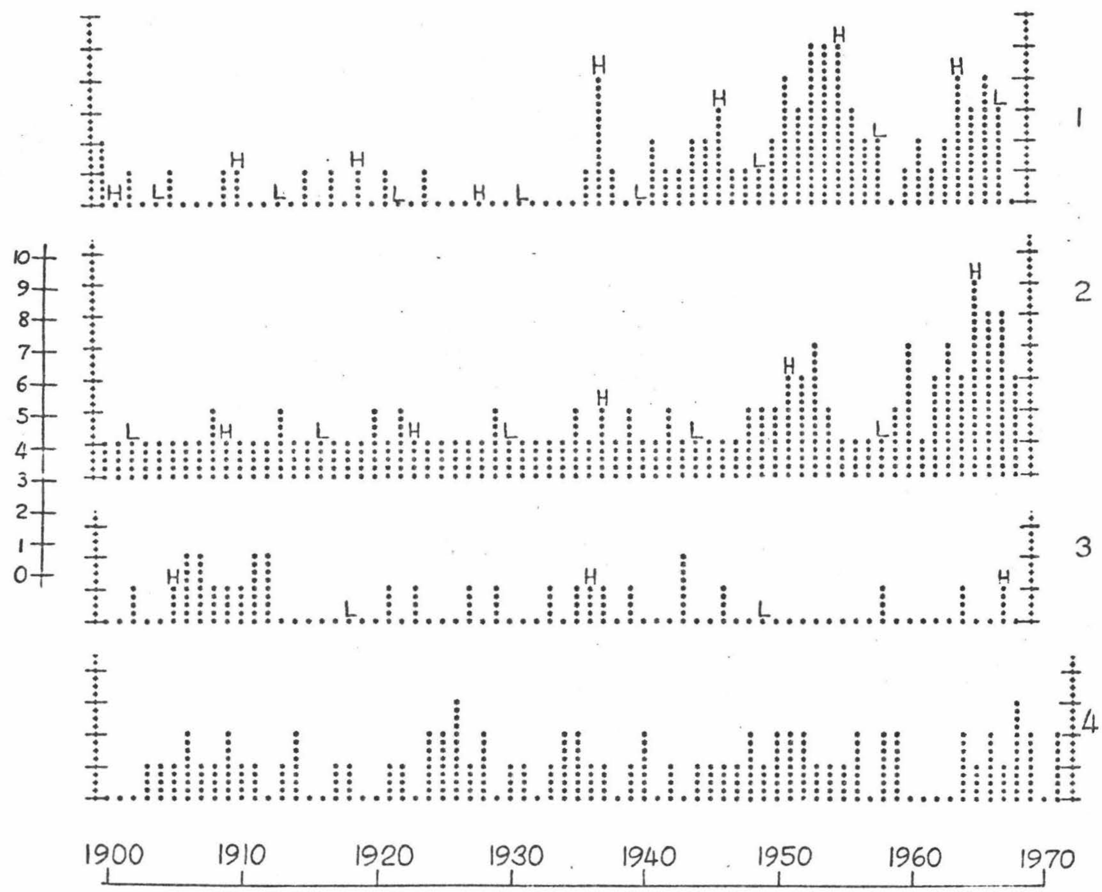

1
2
3
4
10
9
8
7
6
5
4
3
2
1
0
1900
1910
1920
1930
1940
1950
1960
1970

Fig. 4. Number of volcanoes in eruption per annum in some areas of the eastern Pacific margin and Caribbean:

1. U. S. A.
2. Mexico
3. West Indies
4. Central America
5. Colombia-Ecuador
6. Peru
7. Northern Chile
8. Central Chile
9. Southern Chile

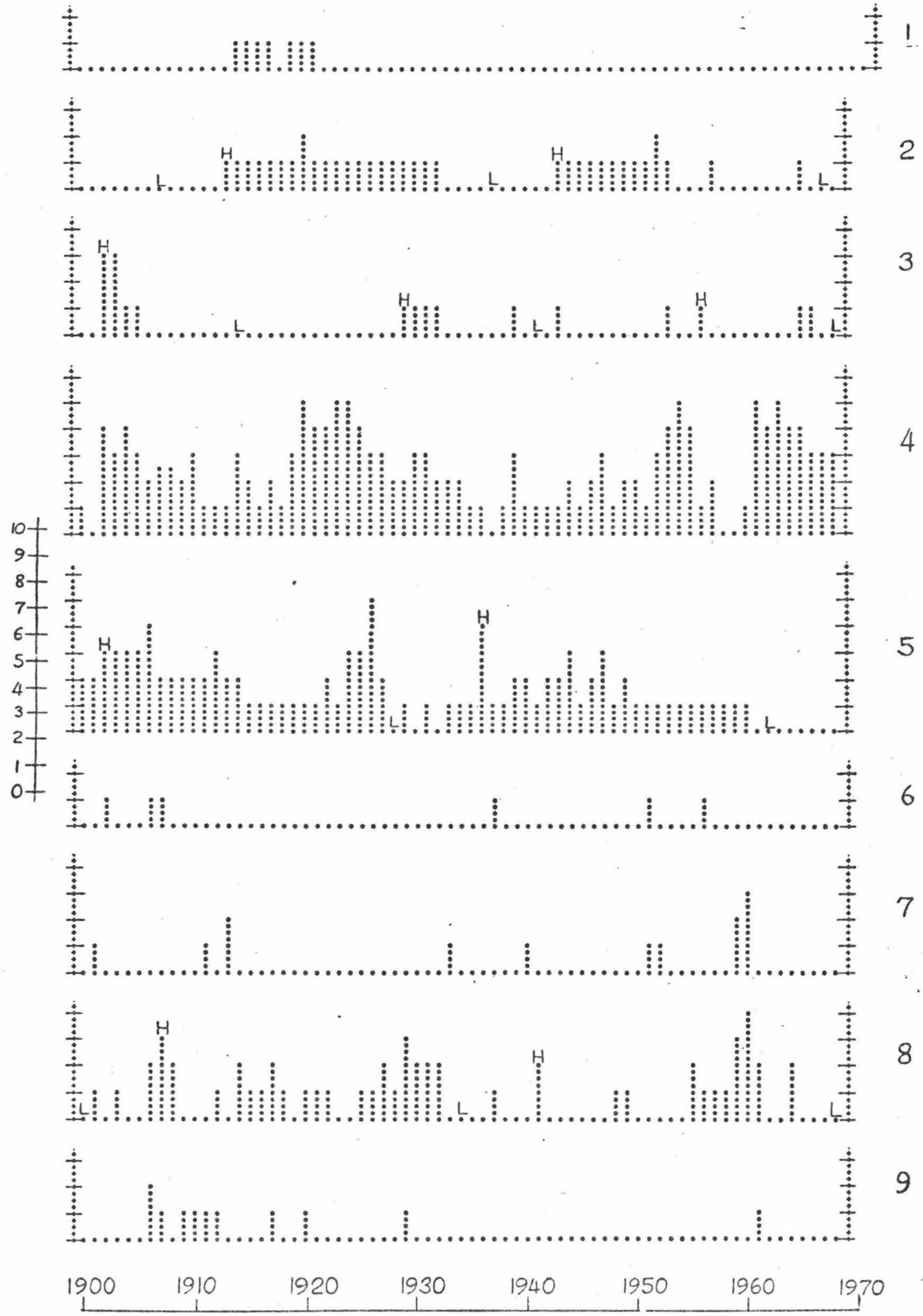

1
2
3
4
5
6
7
8
9
10
9
8
7
6
5
4
3
2
1
0
1900
1910
1920
1930
1940
1950
1960
1970

Table I

Number of Volcanoes in Eruption Per Annum in Individual Areas of the Circum-Pacific Belt--Arithmetic Mean, Variance, Standard Deviation, and Years for Which the Number of Volcanoes in Eruption is More Than Two and More Than Three Standard Deviations Above the Mean

Area	Arithmetic Mean, $\overline{X}$	Variance, S^2	Standard Deviation, S	$\overline{X} + 2S$	$\overline{X} + 3S$	Years for Which No. of Volcanoes in Eruption is Greater Than $\overline{X} + 2S$	Years for Which No. of Volcanoes in Eruption is Greater Than $\overline{X} + 3S$
Aleutians	1.23	1.27	1.13	3.48	4.61	1963, 1964	1963
Kamchatka	1.88	2.19	1.48	4.85	6.33	1923, 1929, 1945, 1964	--
Kuriles	0.49	0.58	0.76	2.01	2.77	1924, 1952	1924, 1952
Kyusyu-Honsyu-Hokkaido	2.75	1.95	1.40	5.55	6.95	1950, 1962, 1963	--
Ryukyu Islands	0.54	0.52	0.72	1.97	2.69	1914, 1925, 1934, 1935, 1949, 1966, 1967	1934
Izu-Mariana Islands	0.59	0.54	0.73	2.06	2.80	1901	1901
Philippines	0.58	0.51	0.72	2.01	2.73	1902	1902
Indonesia	5.32	10.37	3.22	11.76	14.98	1921, 1940	--
New Guinea-Solomons	1.19	2.07	1.44	4.06	5.50	1953, 1954, 1955	--
Santa Cruz-New Hebrides-Matthew Island	1.67	1.28	1.13	3.93	5.07	1953, 1960, 1963, 1965, 1966, 1967	1965
Kermadec-Tonga-Samoa	0.41	0.39	0.63	1.66	2.28	1906, 1907, 1911, 1912, 1943	--
New Zealand	1.06	0.67	0.82	2.70	3.52	1926, 1968	--
U. S. A.	0.10	0.09	0.30	0.69	0.99	1914, 1915, 1916, 1917, 1919, 1920, 1921	1914, 1915, 1916, 1917, 1919, 1920, 1921
Mexico	0.51	0.31	0.56	1.63	2.18	1920, 1952	--
West Indies	0.26	0.37	0.61	1.48	2.09	1902, 1903	1902, 1903
Central America	2.41	1.94	1.39	5.19	6.59	--	--
Colombia-Ecuador	1.49	1.19	1.09	3.68	4.77	1906, 1926, 1936	1926
Peru	0.09	0.08	0.28	0.65	0.94	1902, 1906, 1907, 1937, 1951, 1956	1902, 1906, 1907 1937, 1951, 1956
Northern Chile	0.19	0.30	0.55	1.29	1.84	1913, 1959, 1960	1913, 1959, 1960
Central Chile	0.80	0.96	0.98	2.75	3.73	1907, 1929, 1959, 1960	1960
Southern Chile	0.16	0.17	0.41	0.97	1.38	1906, 1907, 1909, 1910, 1911, 1912, 1917, 1920, 1929, 1961	1906

E_i's are less than five and none is less than one. The chi-square statistic is defined as

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$$

Its value can be compared with tables of percentiles of the chi-square distributions, the number of degrees of freedom being (n - 1 - number of parameters estimated from the data).

For the data on volcanoes, the chi-square test is used to determine whether the amplitude of the fluctuations is significant, the null hypothesis being that the number of volcanoes in eruption per annum is equal to the arithmetic mean, $\overline{X}$. Because $\overline{X}$ is estimated from the data, the number of degrees of freedom is (n - 2). For most of the series, there are 69 years of observation, so the number of degrees of freedom is 67 in this case and the formula for chi-square then becomes

$$\chi^2 = \sum_{i=1}^{67} \frac{(O_i - \overline{X})^2}{\overline{X}} ,$$

the O_i's being the number of volcanoes in eruption in each of the years of observation. Because of the low value of $\overline{X}$ in most cases, the restriction on the values of the E_i's is not adhered to, and the test may not be as powerful as it may otherwise have been, possibly causing acceptance of the null hypothesis more often than necessary.

The chi-square test takes no account of whether the volcanic activity in one year affects that in another.

An alternate to the chi-square test with the null hypothesis as described above would have been to test whether the series for the number of volcanoes in eruption per annum have a Poisson distribution because, if this is so, the series are random with respect to fluctuations in amplitude. The Poisson distribution is used for rare events and is a discrete distribution whose mean is equal to its variance. If the series under discussion are Poisson distributed, the probability that x volcanoes are in eruption is given by

$$P(x) = \frac{\mu^{x} e^{-\mu}}{x!}$$

where μ is the mean and variance of the number of volcanoes in eruption per annum. A comparison of the means and variance in Table I indicates that some are very nearly equal (in which case the series maybe has a Poisson distribution) whereas others are not. To test whether a series has a Poisson distribution, the expected frequencies under this hypothesis are calculated and compared with the actual frequencies, using a chi-square test for goodness of fit. This method would be much more laborious than the chi-square test with the null hypothesis that the number of volcanoes in eruption per annum is equal to the arithmetic mean, and it is not very powerful because the series could still be random but have a probability distribution other than a Poisson distribution.

The serial correlation coefficient, R(L), at lag + L years, measures the degree of relatedness between the number of volcanoes in eruption per annum for a given year, i, and that for year (i + L), using the formula:

$$R(L) = \frac{(N-L)\sum_{i=1}^{N-L} X_i X_{i+L} - \sum_{i=1}^{N-L} X_i \sum_{i=1}^{N-L} X_{i+L}}{\sqrt{\left[(N-L)\sum_{i=1}^{N-L} X_i^2 - \left(\sum_{i=1}^{N-L} X_i\right)^2\right]\left[(N-L)\sum_{i=1}^{N-L} X_{i+L}^2 - \left(\sum_{i=1}^{N-L} X_{i+L}\right)^2\right]}}$$

where R(L) is the serial correlation coefficient at lag L years, X_i is the number of volcanoes in eruption in year i, and N is the number of years for which data are available (Ralston, A. and Wilf, H. S., 1966, p. 214). Note the similarity of the formula for R(L) to that for the ordinary simple correlation coefficient, r, used in simple linear regression of series Y on series X to measure the goodness of fit of the data to a straight line, the slope and y-intercept of which are determined by the method of least squares:

$$r = \frac{N\ \Sigma xy - (\Sigma x)\ (\Sigma y)}{\sqrt{\left[N\ \Sigma x^2 - (\Sigma x)^2\right]\left[N\ \Sigma y^2 - (\Sigma y)^2\right]}}\ .$$

(Ralston, A. and Wilf, H. S., 1966, p. 214.)

We are simply comparing a single series with itself by correlating series x_i (i = 1 to N-L) with the same series x_i (i = L + 1 to N). R(L) ranges from -1 (perfect negative serial correlation, through 0 (no serial correlation), through +1 (perfect positive serial correlation). The fluctuations in the time series are assumed to be normally distributed about the trend line.

For a test series with a well-defined period, T, R(T) will be a maximum having a very high positive value, whereas R(T/2) will have a very high negative value and R(L) will, itself, be a periodic function of L, with period T. Thus, calculation of the serial correlation coefficient for various lags can indicate periods in a time series.

Also, if the series has high serial correlation coefficients for very small lags, e.g., 1 or 2 years, this indicates that the volcanic activity in one year affects the volcanic activity for the one or two years following it.

Hence, high serial correlation coefficients indicate non-randomness in a time series.

It was not possible to calculate and study volcanic energy release because data on volcanic eruptions are, in general, not detailed enough and, for many volcanoes, very vague.

2. Results

Chi-square and serial correlation results are given for the following 21 circum-Pacific areas: Aleutians, Kamchatka, Kuriles, Kyusyu-Honsyu-Hokkaido (including volcano O-sima), Ryukyu Islands, Izu-Mariana Islands (excluding O-sima), Philippines, Indonesia, New Guinea-Solomons, Santa Cruz-New Hebrides-Matthew Island, Kermadec-Tonga-Samoa, New Zealand, U. S. A., Mexico, West Indies, Central America, Colombia-Ecuador, Peru, Northern Chile, Central Chile and Southern Chile.

The geographic areas (Fig. 1) are the ones used in the Catalogue of Active Volcanoes, the boundaries between the three regions of Chile being those chosed by Casertano (1963). The volcanoes of Northern and those of Central Chile are separated by a gap in active centers between 26° and 33°S. There is no obvious natural boundary between those of Central and Southern Chile, so it was taken to be the northern border of the depression containing Lakes Llaniquihue, Todos los Santos and Nahuel Huapi.

The data tested are shown graphically in Figs. 2 to 4.

2.1. Chi-Square Results

For Indonesia, New Guinea-Solomons, West Indies and Northern Chile, the null hypothesis was rejected at the 10 percent, or better, level of significance.

For Kuriles, Kamchatka and Central Chile, the null hypothesis was rejected at the 25 percent level, but not at the 10 percent level, of significance.

Hence, for the seven areas mentioned above, the amplitudes of the fluctuations about the mean number of volcanoes in eruption per annum are significant at the 25 percent level or better, and for the 14 other areas they are not.

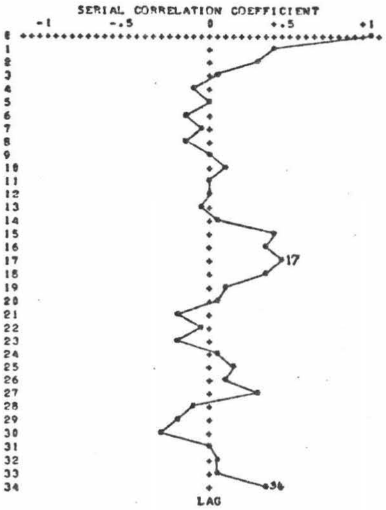
2.2. Serial Correlation Results

Figures 5 through 8 show the serial correlation coefficients for lags 0 through 34, and a graph of the serial correlation coefficient, R(L), versus lag, L, in years, rounding off the values of R(L) to the nearest 0.05. Only graphs which show some salient feature have been included. Kurile Islands, Izu-Mariana Islands, New Zealand, Peru, Northern Chile and Southern Chile have no serial correlation results worthy of note. It was not possible to plot a graph for the U. S. A. because of the large number of zeroes in the original data.

(a) Serial Correlation at Small Lags

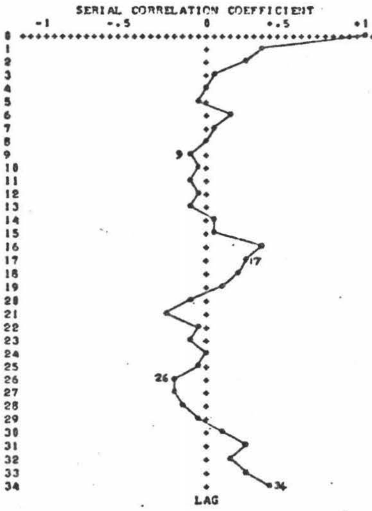
The following areas have serial correlation coefficients which plot greater than or equal to 0.5, for lags of one, and sometimes also two, years: Indonesia, New Guinea-Solomons, Santa Cruz-New Hebrides-Matthew Island, Mexico, West Indies, Central America and Colombia-Ecuador.

Coefficient	Lag
1	0
.3968129	1
.2799681	2
4.298707E-02	3
-9.543308E-02	4
-1.619031E-02	5
-.1391317	6
-3.716473E-02	7
-.1349655	8
1.083352E-02	9
7.552505E-02	10
-2.244901E-02	11
1.089098E-02	12
-5.483578E-02	13
6.977675E-02	14
.3899850	15
.3695442	16
.4252806	17
.3452697	18
8.735139E-02	19
5.866531E-02	20
-.1519296	21
-5.157563E-02	22
-.2145396	23
4.516348E-02	24
.1395571	25
.1101503	26
.2773353	27
-9.696746E-02	28
-.1859426	29
-.3170500	30
1.269598E-02	31
5.124503E-02	32
6.656021E-02	33
.3614345	34



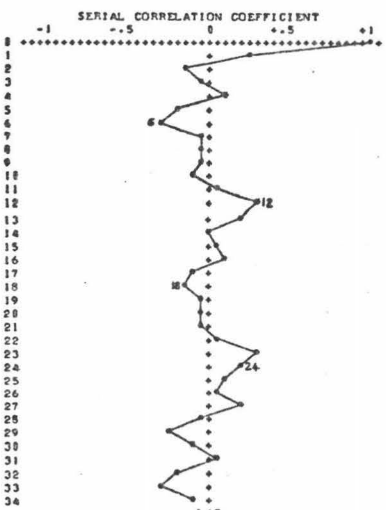
ALEUTIANS

Coefficient	Lag
1	0
.3566644	1
.2382203	2
6.134767E-02	3
-1.535638E-02	4
-5.466396E-02	5
.1727059	6
5.606848E-02	7
1.762583E-02	8
-8.475453E-02	9
-6.056585E-02	10
-.1154131	11
-4.240160E-02	12
-.1058195	13
4.511951E-02	14
6.803977E-02	15
.3376703	16
.2404740	17
.2181028	18
.1127182	19
-.1152109	20
-.2361980	21
-6.763911E-02	22
-9.999685E-02	23
-9.672220E-04	24
-3.594571E-02	25
-.2075220	26
-.1978102	27
-.1347219	28
-5.338328E-02	29
.1095650	30
.2282231	31
.1675904	32
.2635645	33
.3989823	34



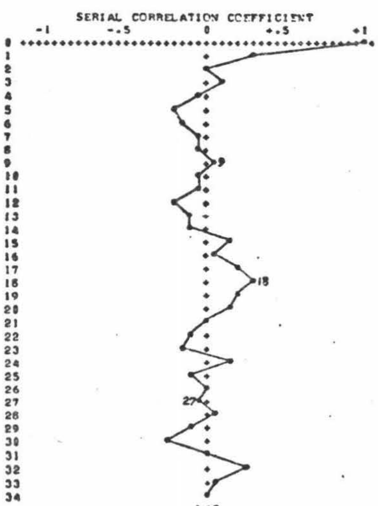
KAMCHATKA

Coefficient	Lag
1	0
.2676320	1
-.1591625	2
-2.703270E-02	3
8.430142E-02	4
-.1719334	5
-.3197162	6
-3.993564E-02	7
-5.183487E-02	8
-6.450212E-02	9
-.1130177	10
7.429957E-02	11
.2973045	12
.1776797	13
1.396177E-02	14
3.552292E-02	15
.1107336	16
-9.746450E-02	17
-.1352760	18
-6.395900E-02	19
-3.032906E-02	20
-6.157775E-02	21
2.712392E-02	22
.2834349	23
.1992155	24
8.797562E-02	25
6.797373E-02	26
.2205371	27
-6.445432E-02	28
-.2645036	29
-.1165759	30
2.623246E-02	31
-.2109896	32
-.2856196	33
-9.693140E-02	34



KYUSYU, HONSYU & HOKKAIDO

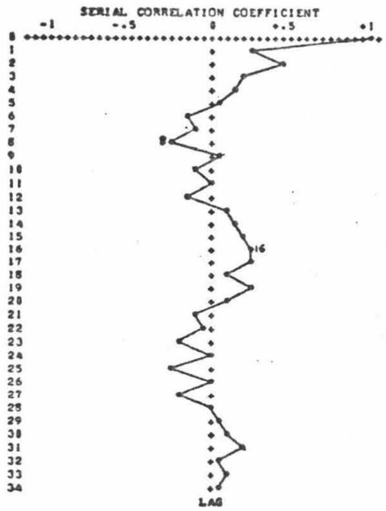
Coefficient	Lag
1	0
.2830028	1
-9.764120E-03	2
7.734132E-02	3
-7.093835E-02	4
-.2199888	5
-.1359094	6
-3.400298E-02	7
-2.690736E-02	8
2.816162E-02	9
-6.112122E-02	10
-5.248392E-02	11
-.1770087	12
-.1012450	13
-9.178030E-02	14
.1625779	15
4.914672E-02	16
.2054269	17
.2928844	18
.1982238	19
.1701304	20
3.297859E-03	21
-.1101359	22
-.1446221	23
.1261640	24
-8.959401E-02	25
-2.389054E-02	26
-3.718279E-02	27
3.648908E-02	28
-8.157724E-02	29
-.2340122	30
9.726744E-03	31
.2490726	32
7.036620E-02	33
1.424051E-03	34



RYUKYU ISLANDS

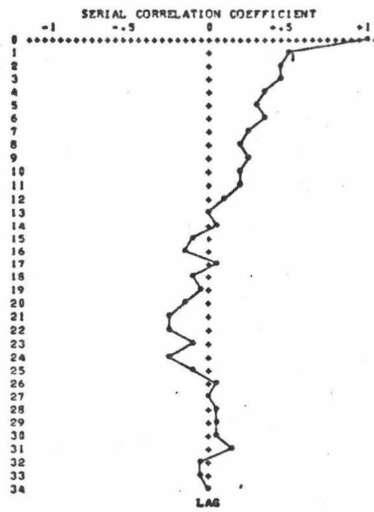
Fig. 5. NUMBER OF VOLCANOES IN ERUPTION PER ANNUM
SERIAL CORRELATION COEFFICIENT, LAGS 0-34

Serial correlation coefficient	Lag
1	0
.2732884	1
.4327344	2
.1770310	3
.1358591	4
6.755206E-02	5
-.1325389	6
-8.857256E-02	7
-.2581792	8
5.424740E-02	9
-.1171093	10
-1.647995E-02	11
-.1567553	12
9.455560E-02	13
.1451904	14
.2132171	15
.2259897	16
.2506900	17
8.801337E-02	18
.2341863	19
8.205197E-02	20
-.1174770	21
-3.475979E-02	22
-.2128605	23
2.091734E-02	24
-.2619534	25
-2.143494E-02	26
-.1903352	27
3.853925E-03	28
7.805209E-02	29
.1156135	30
.1823773	31
4.765252E-02	32
9.293175E-02	33
6.199712E-02	34



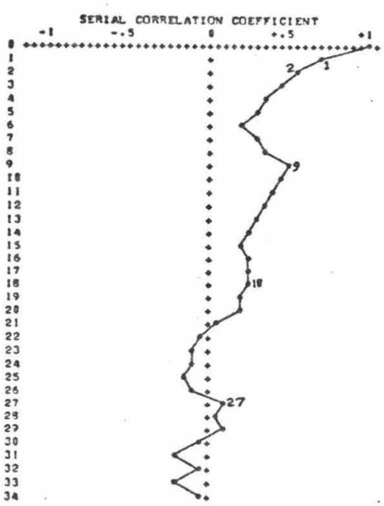
PHILIPPINES

Serial correlation coefficient	Lag
1	0
.5124589	1
.4438613	2
.4497076	3
.3727466	4
.2888408	5
.3407260	6
.2549937	7
.2194333	8
.2341601	9
.2156235	10
.1969437	11
.1219855	12
9.521198E-03	13
6.450665E-02	14
-.1072088	15
-.1269547	16
5.696957E-02	17
-.1114066	18
-4.200694E-02	19
-.1419688	20
-.2281208	21
-.2328786	22
-.1122692	23
-.2459914	24
-9.342140E-02	25
7.134151E-02	26
-1.088328E-02	27
4.870583E-02	28
5.203184E-02	29
4.188967E-02	30
.1516821	31
-5.977551E-02	32
-4.736531E-02	33
-5.393673E-03	34



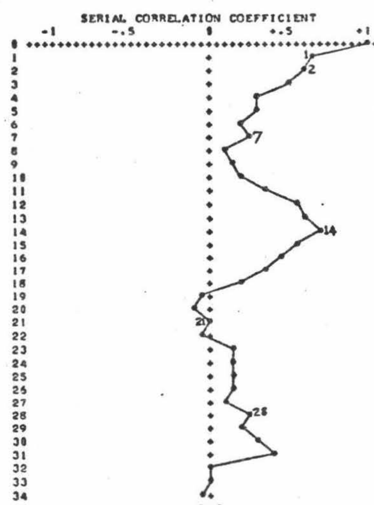
INDONESIA

Serial correlation coefficient	Lag
1	0
.6776372	1
.5444217	2
.4375033	3
.3257132	4
.2879741	5
.2157771	6
.2760152	7
.3376012	8
.4569590	9
.4621455	10
.3921512	11
.3654190	12
.3206725	13
.2717562	14
.1962933	15
.2463034	16
.2253700	17
.2330641	18
.1961022	19
.1544795	20
5.909015E-02	21
-5.925402E-02	22
-.1195192	23
-.1018912	24
-.1444576	25
-9.364733E-02	26
9.275811E-02	27
7.202792E-02	28
.1200805	29
-4.100455E-02	30
-.2134962	31
-6.767429E-02	32
-.1959754	33
-4.725075E-02	34



NEW GUINEA-SOLOMONS

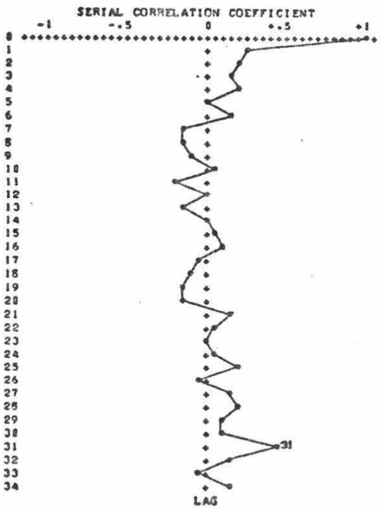
Serial correlation coefficient	Lag
1	0
.6523566	1
.6189638	2
.4905059	3
.3007277	4
.2948545	5
.2076689	6
.2599673	7
7.732821E-02	8
.1633918	9
.1767807	10
.3325659	11
.5363866	12
.5799296	13
.7000709	14
.5324714	15
.4526609	16
.3593515	17
.2110221	18
-2.640777E-02	19
-8.023053E-02	20
-2.642968E-03	21
-5.259376E-02	22
.1616357	23
.1551263	24
.1482043	25
.1408289	26
9.261978E-02	27
.2715368	28
.2174849	29
.2815372	30
.3755259	31
1.906412E-02	32
9.153534E-03	33
-5.136655E-02	34



SANTA CRUZ-NEW HEBRIDES-MATTHEW I.

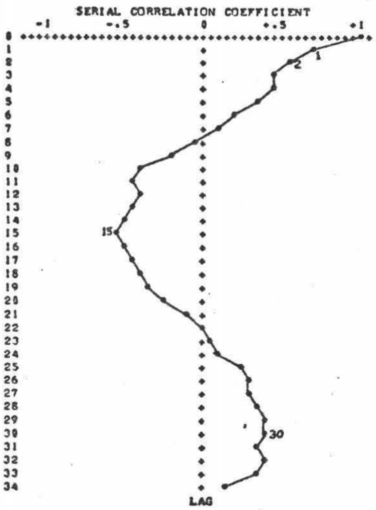
Fig. 6. NUMBER OF VOLCANOES IN ERUPTION PER ANNUM
SERIAL CORRELATION COEFFICIENT, LAGS 0-34

Coefficient	Lag
1	0
.2444443	1
.1797555	2
.1523642	3
.2243436	4
1.224372E-03	5
.1659698	6
-.1283652	7
-.1510270	8
-9.525692E-02	9
5.462698E-02	10
-.1964509	11
-2.331148E-02	12
-.1532741	13
1.840577E-02	14
6.057539E-02	15
.1115599	16
-7.099271E-02	17
-7.995629E-02	18
-.1490711	19
-.1596902	20
.1329747	21
3.452516E-02	22
-1.916693E-02	23
6.905625E-02	24
.1904474	25
-4.520506E-02	26
.1539178	27
.1853898	28
.1026085	29
8.138251E-02	30
.4531347	31
.1588335	32
-6.298143E-02	33
.1501830	34



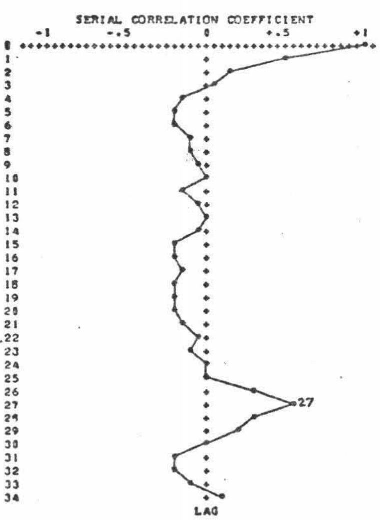
KERMADEC-TONGA-SAMOA

Coefficient	Lag
1	0
.7140856	1
.5655617	2
.4618235	3
.4306407	4
.3722031	5
.2097173	6
9.360677E-02	7
-2.677046E-02	8
-.2054504	9
-.3913085	10
-.4738677	11
-.4103316	12
-.4397864	13
-.4914994	14
-.5445543	15
-.4988688	16
-.4419160	17
-.3933323	18
-.3442472	19
-.2280858	20
-7.784426E-02	21
-2.173912E-02	22
3.548386E-02	23
9.395969E-02	24
.2307692	25
.2937956	26
.3203050	27
.3493021	28
.3811538	29
.4163036	30
.3670211	31
.4078734	32
.3598586	33
.1538461	34



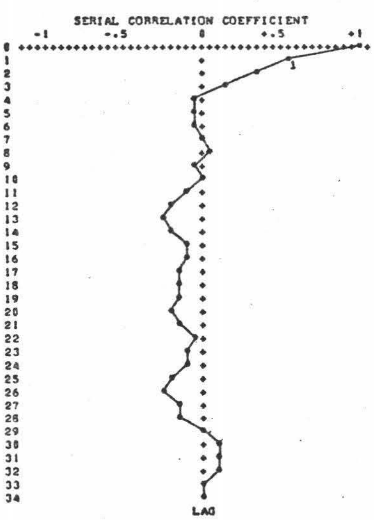
MEXICO

Coefficient	Lag
1	0
.4845487	1
.1257413	2
5.460325E-02	3
-.1273376	4
-.1859871	5
-.1759704	6
-.1117103	7
-.1150447	8
-4.740454E-02	9
2.855456E-02	10
-.1258740	11
-5.796377E-02	12
2.339399E-02	13
-5.312124E-02	14
-.2036494	15
-.1963745	16
-.1262929	17
-.2056323	18
-.2106752	19
-.2159165	20
-.1455053	21
-7.465917E-02	22
-7.999998E-02	23
-8.563604E-03	24
-1.409115E-02	25
.3127340	26
.5461790	27
.3047769	28
.2203096	29
1.946247E-02	30
-.2236067	31
-.2125119	32
-.1000000	33
9.452753E-02	34



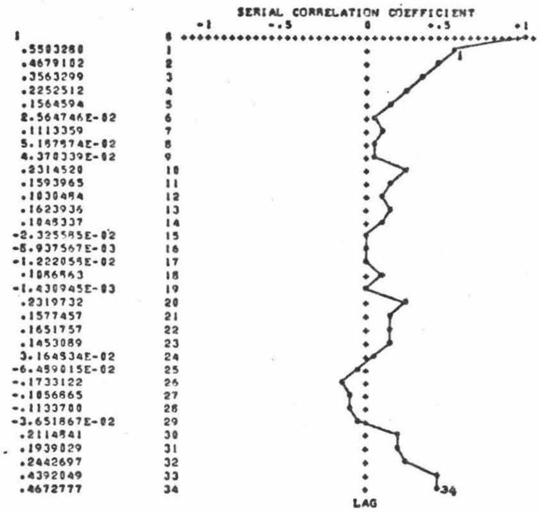
WEST INDIES

Coefficient	Lag
1	0
.5707039	1
.3285799	2
.1307526	3
-5.132261E-02	4
-7.388579E-02	5
-5.185245E-02	6
-1.241921E-02	7
6.001846E-02	8
-5.439081E-02	9
-9.221081E-03	10
-7.653409E-02	11
-.2142674	12
-.2317696	13
-.1984589	14
-.1032523	15
-9.137130E-02	16
-.1497625	17
-.1550341	18
-.1583036	19
-.1846597	20
-.1393985	21
-5.628301E-02	22
-.1167990	23
-.1245888	24
-.1778105	25
-.2328106	26
-.1489858	27
-.1302388	28
2.327625E-02	29
.1058090	30
9.124184E-02	31
.1110687	32
1.701329E-03	33
-1.879862E-02	34

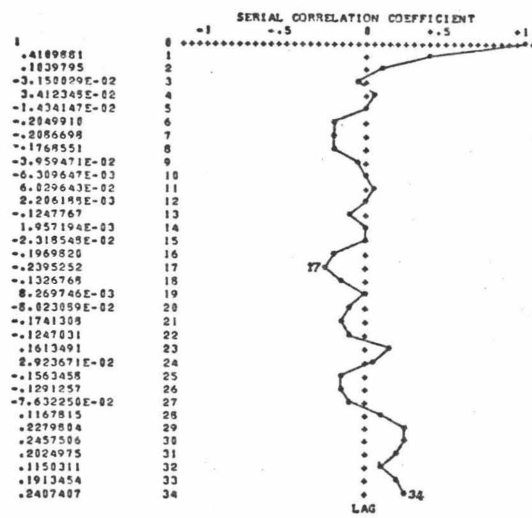


CENTRAL AMERICA

Fig. 7. NUMBER OF VOLCANOES IN ERUPTION PER ANNUM
SERIAL CORRELATION COEFFICIENT, LAGS 0-34



COLOMBIA-ECUADOR



CENTRAL CHILE

Fig. 8. NUMBER OF VOLCANOES IN ERUPTION PER ANNUM
SERIAL CORRELATION COEFFICIENT, LAGS 0-34

Hence, in these seven areas, the number of volcanoes in eruption in one year affects the number of volcanoes in eruption in the following one, and sometimes two, years.

Note that these are areas of the southwestern Pacific, and eastern Pacific, margins.

(b) Periodicity

The following areas show a poorly-defined periodicity, the periods being tabulated in Table II: Aleutians, Kamchatka, Kyusyu-Honsyu-Hokkaido, Ryukyu Islands, Philippines, New Guinea-Solomons, Santa Cruz-New Hebrides-Matthew Island, Kermadec-Tonga-Samoa, Mexico, West Indies, Colombia-Ecuador and Central Chile.

In Table II, the serial correlation coefficients are shown at the lags which correspond to the periods. Most of these are very small but the periods may be recognized on the graphs of the number of volcanoes in eruption each year versus years (Figs. 2, 3, 4). On these figures, years which should have a comparatively high value for the number of volcanoes in eruption, according to the computer-determined periodicity, are marked "H," and years which should have a low value, "L." The placement of the "H"'s and "L"'s was decided subjectively, but their spacing is determined by the tabulated periodicity. For Aleutians, Kyusyu-Honsyu-Hokkaido, New

Table II

Periodicity in Number of Volcanoes in Eruption Per Annum in Areas of the Circum-Pacific Belt

Area	Period (Years)	Serial Correlation Coefficient
Aleutians	17	0.43
Kamchatka	17	0.24
Kuriles	--	
Kyusyu-Honsyu-Hokkaido	12	0.30
Ryukyu Islands	18	0.29
Izu-Mariana Islands	--	
Philippines	16	0.23
Indonesia	--	
New Guinea-Solomons	9	0.49
Santa Cruz-New Hebrides-Matthew Island	14	0.70
Kermadec-Tonga-Samoa	31	0.45
New Zealand	--	
U. S. A.	--	
Mexico	30	0.42
Central America	--	
Colombia-Ecuador	34	0.47
Peru	--	
Northern Chile	--	
Central Chile	34	0.24
Southern Chile	--	
West Indies	27	0.55

Guinea-Solomons, and Santa Cruz-New Hebrides-Matthew Island, the periodicity is relatively convincing only in the later years of the graph. For Indonesia (Fig. 2), three highs and two lows, 17 years apart, have been marked on the graph. Apparently this 17-year pattern is not pervasive enough to constitute a periodicity.

It is interesting to note that, with very few exceptions, the periods for the western Pacific areas are approximately half those for the eastern Pacific areas.

3. Conclusions

3.1. Causes of Periodicity

It is usual, in a study of this kind, to attempt to relate periodicities to astronomical phenomena and their effects on the earth.

Fluctuations in gravity due to tidal forces are affected by the 18.6-year lunar nutation. The Ryukyu Islands graph has a period of 18 years so that maybe the number of volcanoes in eruption each year in the Ryukyu Islands is influenced by this 18.6-year component. This would agree with the findings of Rinehart (1972) in his study of the eruption frequency of geysers (refer to Chapter 1).

The earth tidal force also has an 8.8-year component (Rinehart, 1972). This is close to New Guinea-Solomons'

9-year periodicity and so perhaps there is a causal relationship here.

It must be emphasized that the above are merely suggestions; just because two phenomena have approximately the same period, they need not necessarily be related. For example, the sunspot cycle has a period of approximately 11 years. Japan has a volcanic period of 12 years, but its highest peaks do not correspond consistently to sunspot maxima or minima.

Munk and Macdonald (1960) mention "large irregular variations in the l.o.d. (length of day)" "with a decade time-scale" which "may be due to electromagnetic coupling of the mantle to a turbulent, fluid core." These variations have a continuous spectrum, the periods ranging from about six years to about 90 years. This would include all the volcanic periodicities in Table II, but their "decade variations" have a longer period after about 1906, the length of day increasing from a sharp maximum in about 1906 to a broad minimum at around 1930 and then increasing up to about 1948, where the data ends. Hence, this variation in the length of day does not explain the short term fluctuations in the volcano graphs.

A possible relationship between periodicity and global tectonics is discussed in section 3.2.

3.2. Summary of Chi-Square and Serial Correlation Results

Three areas, Indonesia, New Guinea-Solomons and West Indies, have significant amplitudes of fluctuations in the number of volcanoes in eruption per annum and also serial correlation coefficients of 0.5 or greater, rounding to the nearest 0.05. Hence, the number of volcanoes in eruption per annum in each of these three areas certainly does not appear to be random. It is interesting to note that their tectonic setting is rather different from that of the other circum-Pacific areas, in that Indonesia is an island arc extending east-west into the Indian Ocean, New Guinea-Solomons lies along the east-west, offsetting part of the andesite line, and West Indies is on an extension of the andesite line into the Caribbean, and all three lie in the tropics. Maybe their non-random volcanic behavior is due in some way to their near-equatorial location. Carey (1958), for example, has proposed a sinistral equatorial shear system between the northern and southern hemispheres and has stated that New Guinea lies right in the shear zone.

Note also that the New-Guinea Solomons and West Indies graphs are somewhat periodic, with periods of nine and 27 years respectively, so that the West Indies' period is three times that of New Guinea-Solomons.

Five areas, Izu-Mariana Islands, New Zealand, U. S. A., Peru and Southern Chile, do not seem to have statistically significant series for the number of volcanoes in eruption per annum. The amplitudes of the fluctuations do not seem to be significant, and there does not appear to be significant serial correlation or periodicity.

Hence, 16 out of the 21 areas analyzed seem to show some indication of non-randomness in their series although, in five of these (Aleutians, Kyusyu-Honsyu-Hokkaido, Ryukyu Islands, Philippines, Kermadec-Tonga-Samoa) this is merely a very poorly-defined periodicity.

The periodicities in the volcano graphs do not seem to be attributable to astronomical phenomena, except in the case of Ryukyu Islands, where the number of volcanoes in eruption per annum seems to be related to the variation in gravity, particularly to the 18.6-year lunar nutation, and possibly for New Guinea-Solomons, where the fluctuations may be related to the 8.8-year tidal component.

Because, in general, the periods vary from area to area and not all areas have periodic series, it is difficult to relate these periodicities to an overall periodicity in some very large scale phenomenon such as sea floor spreading. However, the fact that, with very few exceptions, the periods for the western Pacific areas are approximately half those for the eastern Pacific areas <u>does</u> suggest a global cause.

Maybe the pattern of currents within the earth's mantle is such that the currents descending under the western Pacific margin are irregular and not coherent as one goes from north to south, so that one portion has a periodicity of 17 years, another of 12 years and so on. Those going under the eastern Pacific margin are likewise irregul ar but have longer periods, maybe due in some way to the fact that the East Pacific Rise, where the upwelling takes place, is closer to the eastern Pacific margin than to the western. Because of the position of the East Pacific Rise, the mantle flow regime to the east of it woul d be expected to be different from that to the west of it.

III. SPACE-TIME RELATIONSHIP BETWEEN PULSES OF VOLCANIC ACTIVITY IN THE INDIVIDUAL AREAS OF THE CIRCUM-PACIFIC MARGIN

1. Method of Analysis of Data

Having established the non-randomness of most of the series for the number of volcanoes in eruption each year, it seemed reasonable to compare the graphs for different areas, to see whether the pulses of volcanic activity are local or regional.

Two different methods of investigation were used: (1) determination of cross correlation coefficients between two areas for various lags, and (2) comparing the years for which the maximum or one less than the maximum number of volcanoes is in eruption in each area.

The first method is strictly statistical and non-intuitive. The second method is subjective, rather than statistical.

The cross correlation coefficient, $r(L)$, at lag + L years, measures the degree of relatedness between the number, X_i, of volcanoes in eruption per annum in an area X for a given year, i, and the number, Y_{i+L}, in another area Y for year (i+L), using the formula,

$$r(L) = \frac{(N-L)\sum_{i=1}^{N-L} X_i Y_{i+L} - \sum_{i=1}^{N-L} X_i \sum_{i=1}^{N-L} Y_{i+L}}{\sqrt{\left[(N-L)\sum_{i=1}^{N-L} X_i^2 - \left(\sum_{i=1}^{N-L} X_i\right)^2\right]\left[(N-L)\sum_{i=1}^{N-L} Y_{i+L}^2 - \left(\sum_{i=1}^{N-L} Y_{i+L}\right)^2\right]}}$$

(Hoel, P. G. and Jessen, R. J., 1971, p. 221). R(L) ranges from -1 (perfect negative correlation), through 0 (no correlation), through +1 (perfect positive correlation), and the Y's are said to be lagged positively relative to the X's. N is the number of years for which data are available.

The basic computer program, "Volcross," written by me, calculates and tabulates r(L) for values of L ranging from -10, through 0, to +10. By inspection of this table, the lag for which r(L) has a maximum positive value may be determined.

If r(L) is a maximum for, say, L = 5, then volcanic maxima in area Y will tend to occur five years later than the corresponding maxima in area X. If, however, r(L) is a maximum for L = -1, then volcanic maxima in area Y will tend to occur one year earlier than the corresponding maxima in area X.

Note that when L is put equal to zero, r(L) becomes the simple correlation coefficient, r, used in simple linear regression. (For more details, refer to Chapter II, section 1.)

2. Results

2.1. Cross Correlation Results

The cross correlation results are given in Tables III, IV and V.

In Table III, the areas listed have been crossed with, and lagged positively to, Central America, in Table IV with

Table III

Cross Correlation Results for Areas Cross Correlated with Central America and Lagged Positively Relative to Central America

Western Pacific Margin	Lag (1)	Lag (2)
Aleutians	0 (r = 0.24)	+ 2 (r = 0.22)
Kamchatka	+ 7 (r = 0.23)	+ 8 (r = 0.22)
Kuriles	+10 (r = 0.23)	
Kyusyu-Honsyu-Hokkaido	+ 8 (r = 0.22)	+ 9 (r = 0.20)
Ryukyu Islands	+10 (r = 0.22)	+ 4 (r = 0.20)
Izu-Mariana Islands	- 8 (r = 0.29)	
Philippines	- 3 (r = 0.31)	- 2 (r = 0.31)
Indonesia	+ 9 (r = 0.14)	
New Guinea-Solomons	-10 (r = 0.42)	
New Hebrides	- 1 (r = 0.35)	- 2 (r = 0.33)
Kermadec-Tonga-Samoa	+ 4 (r = 0.20)	+ 3 (r = 0.18)
New Zealand	+ 4 (r = 0.40)	
Eastern Pacific Margin	**Lag (1)**	**Lag (2)**
U. S. A.	- 6 (r = 0.41)	- 5 (r = 0.41)
Mexico	- 4 (r = 0.27)	- 3 (r = 0.25)
Central America	0 (r = 1.00)	
Colombia-Ecuador	- 8 (r = 0.03)	+ 2 (r = 0.03)
Peru	+ 4 (r = 0.13)	
Northern Chile	+ 6 (r = 0.24)	-10 (r = 0.24)
Central Chile	+ 7 (r = 0.31)	+ 6 (r = 0.30)
Southern Chile	+ 7 (r = 0.26)	
Caribbean	**Lag (1)**	**Lag (2)**
West Indies	+ 9 (r = 0.29)	

Table IV

Cross Correlation Results for Areas Cross Correlated with Kyusyu, Honsyu and Hokkaido and Lagged Positively Relative to Kyusyu, Honsyu and Hokkaido

Western Pacific Margin	Lag (1)	Lag (2)
Aleutians	+ 9 (r = 0.31)	
Kamchatka	- 6 (r = 0.27)	
Kuriles	- 5 (r = 0.30)	
Kyusyu, Honsyu and Hokkaido	0 (r = 1.00)	
Ryukyu Islands	0 (r = 0.22)	
Izu-Mariana Islands	+ 4 (r = 0.17)	-10 (r = 0.16)
Philippines	-10 (r = 0.06)	+ 2 (r = 0.05)
Indonesia	+ 8 (r = 0.12)	
New Guinea-Solomons	+ 2 (r = 0.38)	
New Hebrides	0 (r = 0.29)	+ 2 (r = 0.29)
Kermadec-Tonga-Samoa	- 7 (r = 0.16)	+ 8 (r = 0.16)
New Zealand	- 4 (r = 0.22)	

Table V

Cross Correlation Results for Areas Cross Correlated with Indonesia and Lagged Positively Relative to Indonesia

Western Pacific Margin	Lag (1)	Lag (2)
Aleutians	- 1 (r = 0.02)	
Kamchatka	-10 (r = 0.13)	
Kuriles	+ 6 (r = 0.03)	+ 7 (r = 0.02)
Kyusyu, Honsyu and Hokkaido	- 8 (r = 0.12)	
Ryukyu Islands	+10 (r = 0.11)	
Izu-Mariana Islands	- 4 (r = 0.16)	- 6 (r = 0.14)
Philippines	- 2 (r = 0.20)	
Indonesia	0 (r = 1.00)	
New Guinea-Solomons	+ 6 (r = -.14)	+ 7 (r = -.16)
New Hebrides	-10 (r = -.15)	
Kermadec-Tonga-Samoa	+ 1 (r = 0.29)	+ 2 (r = 0.28)
New Zealand	+ 7 (r = 0.10)	

Kyusyu-Honsyu-Hokkaido, and in Table V with Indonesia.

Lag (1) and lag (2) are the lags for which the highest and the second highest cross correlation coefficients (given in parentheses) were obtained, provided that these cross correlation coefficients differ by no more than 0.02 because, with these two cross correlation coefficients being so nearly equal, the lags were both used as data in the linear regressions discussed below. It must be noted that the cross correlation coefficients are all low (less than 0.5) and some are very low (less than 0.1).

The areas are listed geographically, and then in order of increasing angular distance from the North Pole.

A cursory examination of Tables III, IV and V does not show a well-defined pattern, except in the case of the eastern Pacific margin areas crossed with Central America, where the lag tends to become increasingly more positive the greater the angular distance of the area from the North Pole. This indicates that a given pulse of volcanic activity would tend to occur later, the more southerly the area.

To test the observations in the preceding paragraph, multiple linear regressions were performed, using a Basic statistics program, "Mulreg" (a Hewlett-Packard library program to compute one or more multiple linear regressions on data), with angular distance from the North Pole (X_1) and angular distance from the Greenwich meridian (X_2) as independent variables, and lag as the dependent variable (X_3).

For all the Circum-Pacific areas listed in Table III crossed with Central America, for the western Pacific areas crossed with Kyusyu-Honsyu-Hokkaido (Table IV) and for the western Pacific areas crossed with Indonesia (Table V), the zero-order correlation coefficients r_{31} and r_{32}, for X_3 regressed on X_2, respectively, were so low (less than 0.2) that the program would not run to completion.

For the eastern Pacific areas crossed with Central America (see Table III), however, the relationship between lag and angular distance from the North Pole was confirmed. The following results were obtained, with X_2 taken to be the angular distance west of Greenwich:

(a) <u>X_3 Regressed on X_1</u>

The least squares regression line

$$X_3 = -13.06 + 0.136\ X_1$$

was obtained, both regression coefficients being significantly different from zero at the one percent level. The zero order (simple) correlation coefficient is

$$r_{31} = 0.657$$

The multiple correlation coefficient (X_2 constant) is

$$r_{31.2} = 0.616$$

A Durbin-Watson Statistic of 2.75 was obtained so that, using a two tailed test at the two percent level, the degree of serial correlation is not significant (Durbin, J. and Watson, G. S., 1951, pp. 162 and 175).

The Durbin-Watson statistic is defined as

$$d = \frac{\Sigma(\Delta z)^2}{\Sigma z^2}$$

where z is the residual from regression and Δz is the difference between successive residuals. This statistic is used to test for serial correlation in the error terms of a regression model. In order to use d, the independent variables in the regression model must be regarded as "fixed variables" and hence d cannot be used in schemes where independent variables are lagged values of the dependent variable. Upper and lower bounds (d_u and d_2 respectively) to critical values for d are tabulated for various levels of significance such that, if d is less than d_2, there is significant positive serial correlation, if d is greater than d_u, the degree of positive serial correlation is not significant and, if d has a value between d_2 and d_u, the test is not conclusive. Similar tests may be applied for negative serial correlation.

(b) X_3 Regressed on X_2

The least squares regression line

$$X_3 = 12.76 - 0.153\ X_2$$

was obtained, both regression coefficients being significantly different from zero at the five percent level. The zero order correlation coefficient is

$$r_{32} = -0.506$$

The multiple correlation coefficient (X_1 constant) is

$$r_{32.1} = 0.434$$

The Durbin-Watson Statistic is 2.35 and therefore there is no significant serial correlation at the two percent level.

(c) X_3 Regressed on X_1 and X_2

The equation for the least squares regression plane is

$$X_3 = -32.21 + 0.219\ X_1 + 0.133\ X_2$$

Only the coefficient of X_1 (angular distance from the North Pole) is significantly different from zero at the five percent level. The constant is significant at the 10 percent level, but the coefficient of X_2 is not significant, even at the 20 percent level.

The multiple correlation coefficient is

$$R_{3.21} = 0.603$$

The Durbin-Watson Statistic is 2.740, and therefore there is no significant serial correlation at the two percent level.

The conclusion from the results given above is that the best results (and highest correlation coefficients) are obtained if X_2, the angular distance west of Greenwich, is not included as an independent variable. Hence, lag is not significantly dependent on longitude even at the 20 percent level, but may be related to angular distance from the North Pole using the least squares regression line

$$X_3 = (-13.06 \pm 9.96) + (0.136 \pm 0.102) X_1$$

when 95 percent confidence limits on the regression coefficients are included. This means possible variations of about 75 percent in both the constant term and the coefficient of X_1.

The zero order correlation coefficient between lag and angular distance from the North Pole is

$$r_{31} = 0.657$$

Hence, on the eastern Pacific margin, volcanic pulses tend to travel south at the rate of 0.136 years per degree, or approximately seven degrees per year.

2.2. Comparison of Years for Which the Maximum or One Less than the Maximum Number of Volcanoes are in Eruption in Various Areas

Figure 9(A) is a plot of the years for which the maximum or one less than the maximum number of volcanoes is in eruption in the eastern Pacific and Caribbean areas listed on the facing page, in order of increasing angular distance from the North Pole.

Figure 10(A) is a similar plot for the western Pacific areas.

These figures both indicate (by diagonal series of pulses, sloping downwards from left to right) that volcanic pulses occur earlier in the northern areas than in the more southern ones, a fact confirmed for the eastern Pacific areas by the serial correlation results.

In Figs. 9(B) and 10(B), Figs. 9(A) and 10(A) have been replotted with an eye-estimated lag correction (the value of which, in years, is tabulated on the right-hand sides of the figures), applied. The simultaneity of the pulses has been improved, as can be seen by the now almost vertical alighment of corresponding pulses, as compared with the diagonal alignment of Figs. 9(A) and 10(A).

Figures 11(A) and 12(A) are histograms of the number of areas having the maximum or one less than the

Fig. 9

(A) Years in which the maximum (solid squares) or one less than the maximum (open squares) number of volcanoes are in eruption during the period 1900 to 1968 in some areas of the eastern Pacific margin and Caribbean: 1. U. S. A., 2. Mexico, 3. West Indies, 4. Central America, 5. Colombia-Ecuador, 6, Peru, 7. Northern Chile, 8. Central Chile, 9. Southern Chile. X is the angular distance (in degrees) of the area from the North Pole.

(B) Similar to (A) but corrected for lag. The lag corrections applied relative to U. S. A. are tabulated in years.

(C) Lag plotted as a function of angular distance, X, from the North Pole.

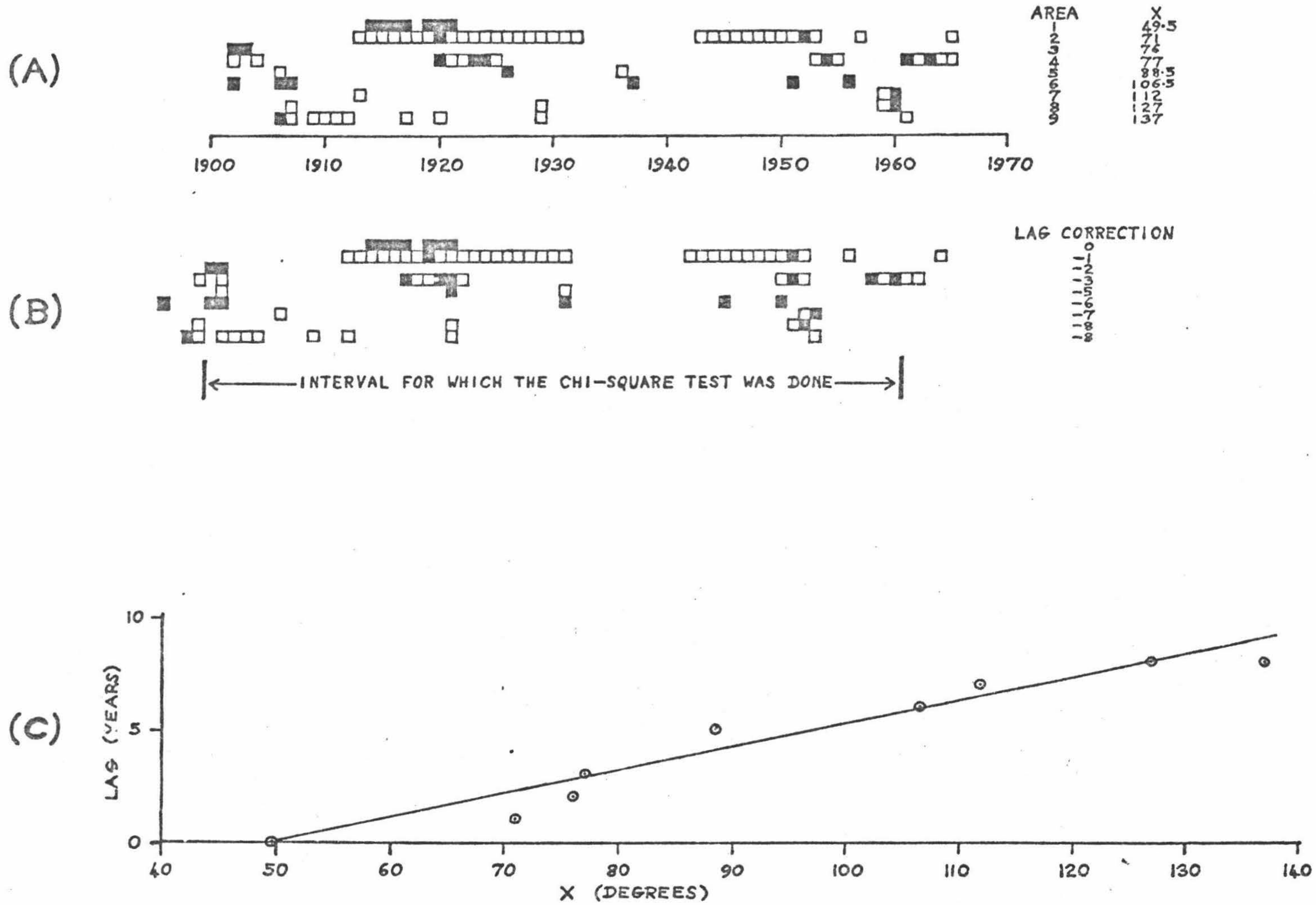
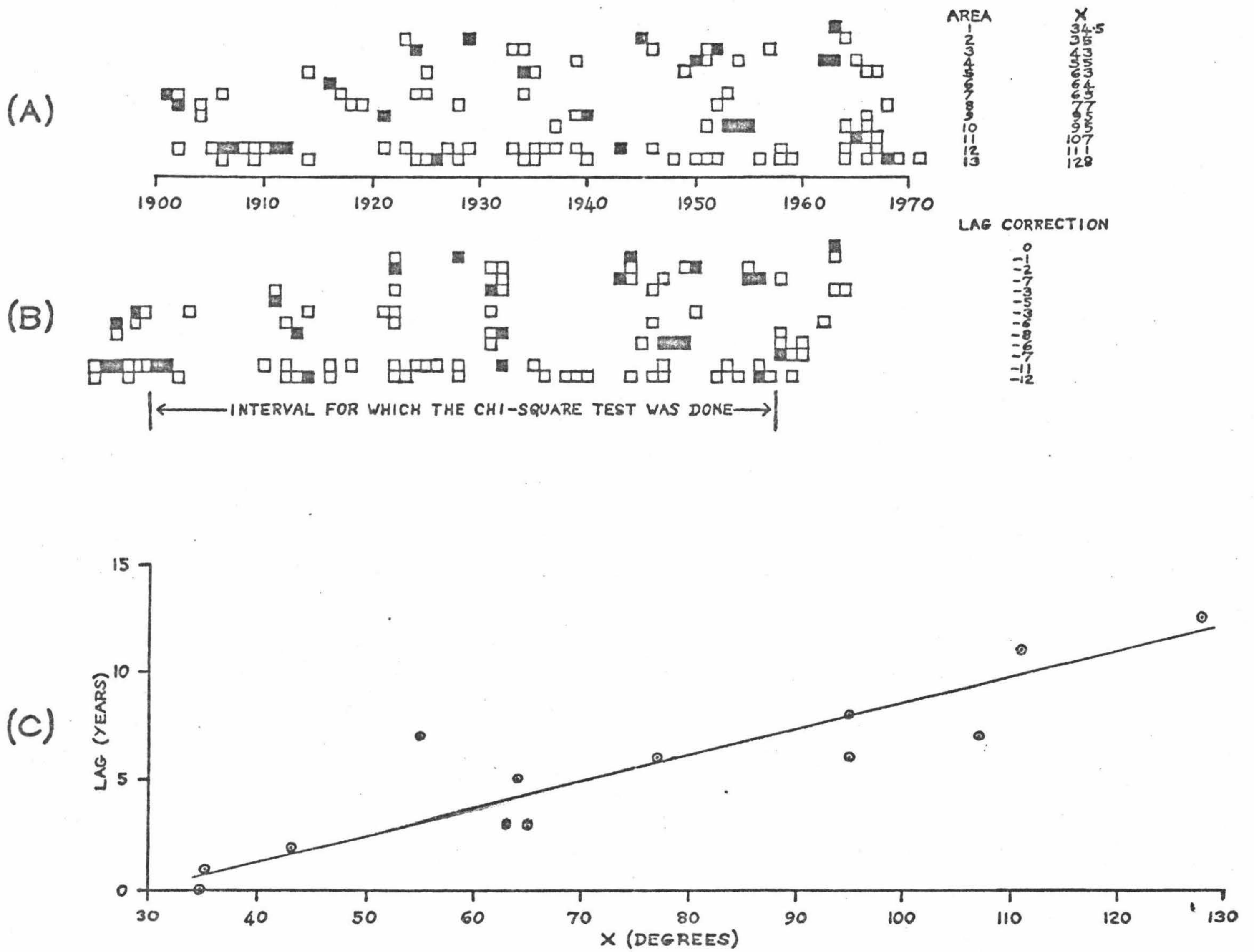

(A)
AREA
X
1 2 3 4 5 6 7 8 9
49.5 71 76 77 88.5 106.5 112 127 137
1900 1910 1920 1930 1940 1950 1960 1970
(B)
LAG CORRECTION
0 -1 -2 -3 -5 -6 -7 -8 -8
INTERVAL FOR WHICH THE CHI-SQUARE TEST WAS DONE
(C)
LAG (YEARS)
0 5 10
X (DEGREES)
40 50 60 70 80 90 100 110 120 130 140

Fig. 10

(A) Years in which the maximum (solid squares) or one less than the maximum (open squares) number of volcanoes are in eruption during the period 1900 to 1968 in some areas of the western Pacific margin: 1. Aleutians, 2. Kamchatka, 3. Kuriles, 4. Kyusyu-Honsyu-Hokkaido, 5. Ryukyu Islands, 6. submarine volcano north of Taiwan, 7. Izu-Mariana Islands, 8. Philippines, 9. Indonesia, 10. New Guinea-Solomons, 11. Santa Cruz-New Hebrides-Matthew Island, 12. Kermadec-Tonga-Samoa, 13. New Zealand.

(B) Similar to (A) but corrected for lag relative to the Aleutians. The lag corrections applied are tabulated in years.

(C) Lag plotted as a function of angular distance, X, from the North Pole.



(A)
AREA
1 2 3 4 5 6 7 8 9 10 11 12 13
X
34.5 35 43 55 63 64 65 77 95 95 107 111 128
1900 1910 1920 1930 1940 1950 1960 1970
LAG CORRECTION
0 -1 -2 -7 -3 -5 -3 -6 -8 -6 -7 -11 -12
(B)
INTERVAL FOR WHICH THE CHI-SQUARE TEST WAS DONE
(C)
LAG (YEARS)
0 5 10 15
30 40 50 60 70 80 90 100 110 120 130
X (DEGREES)

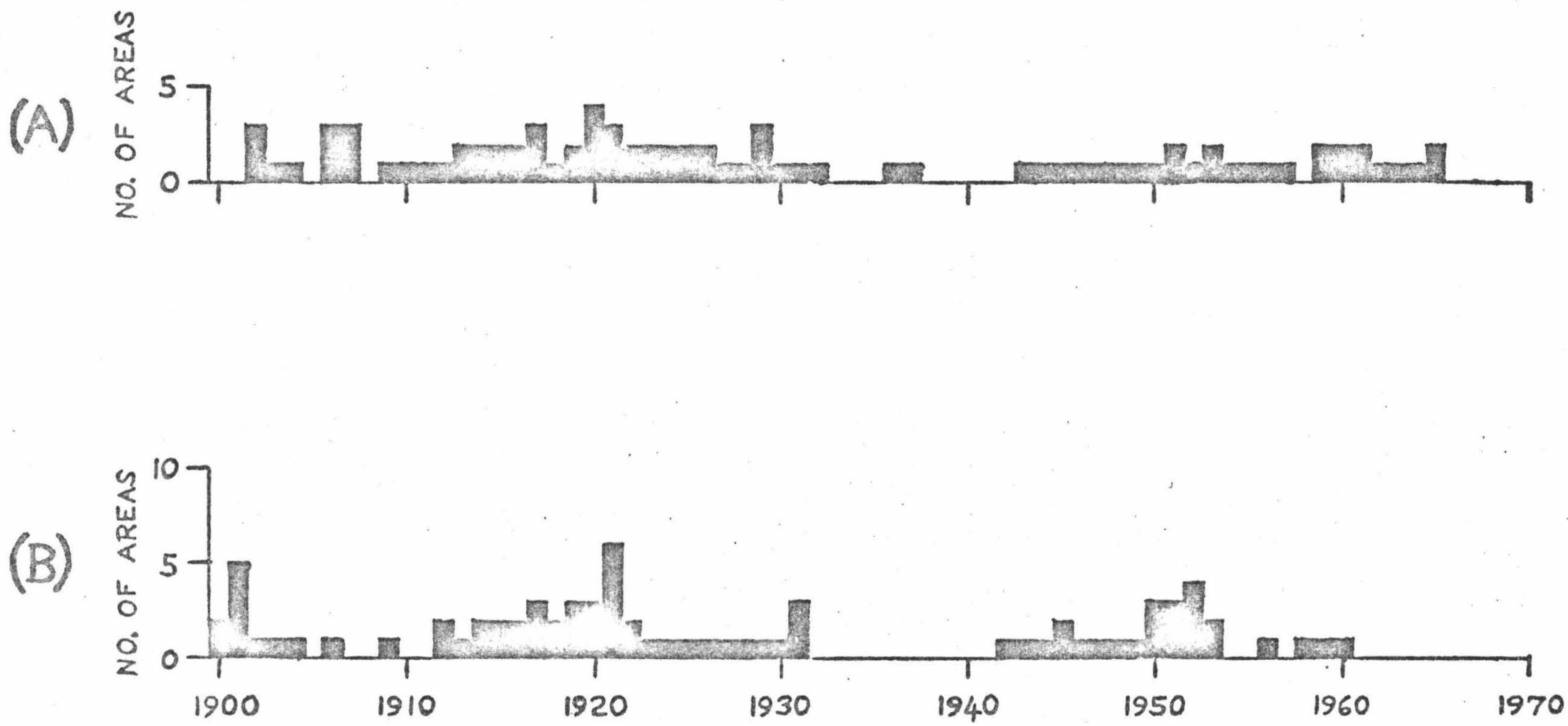


Fig. 11. (A) Number of areas having the maximum or one less than the maximum number of volcanoes in eruption per annum in the eastern Pacific and Caribbean.
(B) Similar to (A) but with the lag corrections applied.

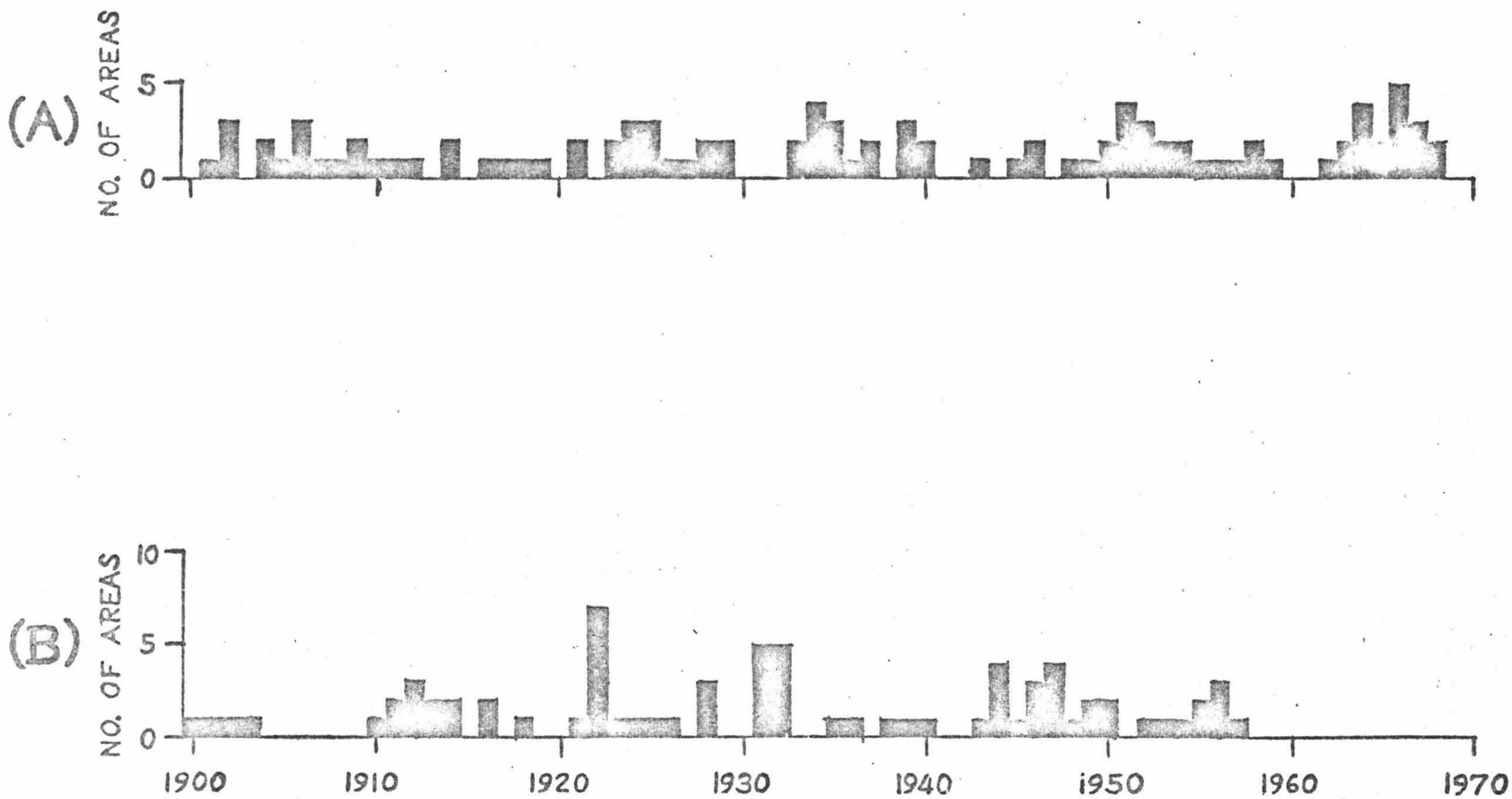


Fig. 12. (A) Number of areas having the maximum or one less than the maximum number of volcanoes in eruption per annum on the western Pacific margin. (B) Similar to (A) but with the lag corrections applied.

maximum number of volcanoes in eruption per annum in the eastern Pacific-Caribbean and the western Pacific respectively. They are obtained from Figs. 9(A) and 10(A) by vertical addition of the solid squares.

Figures 11(B) and 12(B) are similar histograms, with the lag corrections applied before addition.

Chi-square tests were applied to the data plotted in Figs. 11(A), 11(B), 12(A) and 12(B), the null hypothesis in each case being that the number of areas each year having the maximum or one less than the maximum number of volcanoes in eruption per annum is equal to the arithmetic mean.

For the non lag-corrected data of Figs. 11(A) and 12(A), the fluctuations about the mean were found not to be significant even at the 25 percent level, indicating that the pulses tend not to be simultaneous on a large regional scale.

However, for Figs. 11(B) and 12(B), the fluctuations about the mean for the lag-corrected data are significant at the five percent and 0.5 percent levels respectively.

Hence, the lagged effects predominate over the simultaneous effects.

It is interesting to note that the eastern Pacific margin lag-corrected data of Fig. 11(B) has a 30-year periodicity with a serial correlation coefficient of 0.72, as may be deduced from Fig. 13. This is probably the result of two pulses seen in

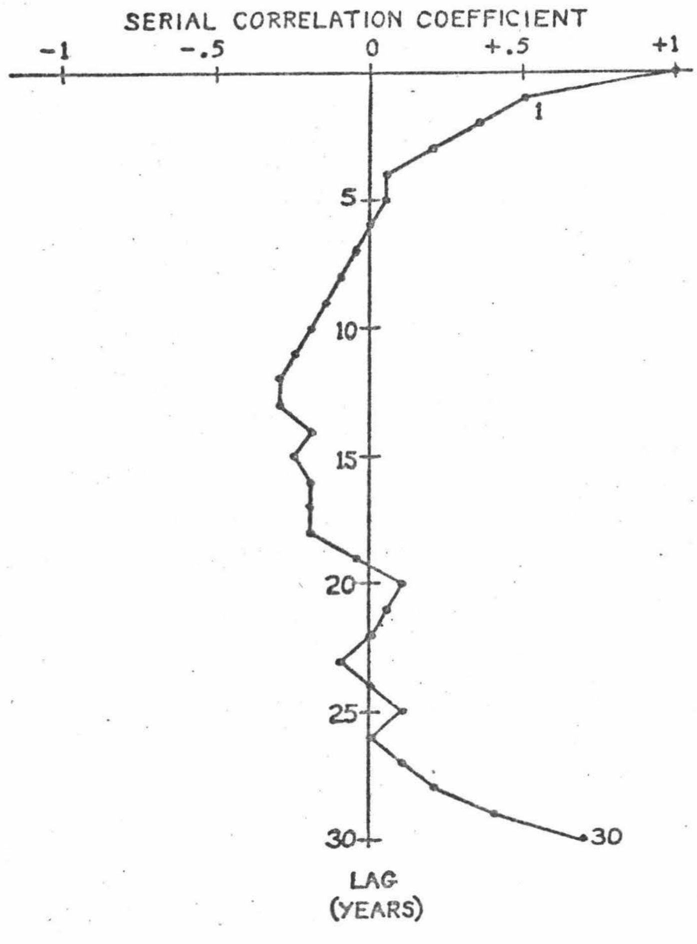


Fig. 13. Eastern Pacific margin and Caribbean. Number of areas having the maximum or one less than the maximum number of volcanoes in eruption per annum --serial correlation coefficient, lags 0-30. The original data have been corrected for lag.

Fig. 9, having the approximate ranges 1915 to 1930, and 1945 to 1960 respectively. These pulses are both quite general in the areas of the eastern Pacific margin, occurring in six out of the nine areas.

The lag corrections applied are the negative values of the lags referred to in the section on cross correlation.

The lags are plotted as a function of angular distance from the North Pole in Figs. 9(C) (eastern Pacific and Caribbean) and 10(C) (western Pacific). Because these lags are subjective estimations only, no rigorous statistical analyses of these plots have been made but the pulses seem to have a travel time of approximately five degrees per year in the eastern Pacific -Caribbean and four degrees per year in the western Pacific, both of which are of the same order of magnitude as the seven degrees per year, for the eastern Pacific, derived by cross correlation and linear regression analysis.

The question arises as to why this pattern did not show up in the cross correlation analysis of the western Pacific areas. It must be remembered that the data analyzed here is filtered data--only the largest pulses, those in which the maximum and one less than the maximum number of volcanoes are in eruption in each area, are considered, whereas cross correlation utilizes the small values, as well as the large. Maybe many of the large pulses are caused by some large regional effect which moves south with time, whereas the smaller pulses may often be caused by some local effect, peculiar to one particular area.

It is interesting to note that the non-lag corrected eastern Pacific-Caribbean data of Fig. 11(A) have a slight 30-year periodicity, and possibly also a 42-year periodicity (refer Fig. 14). The non-lag corrected western Pacific data of Fig. 12(A) have a slight 15-year periodicity (see Fig. 15), which is half the period of the eastern Pacific data. This is consistent with the findings, of Table II, for the number of volcanoes in eruption per annum in the individual areas of the western and eastern Pacific.

There thus seems to be an east-west asymmetry, around the Pacific, in periodicity in volcanic activity.

3. Conclusions

On both the eastern and western Pacific margins, pulses in volcanic activity in the individual areas tend to travel south with time at rates of the order of five degrees per year.

Even if this phenomenon is connected with migrating pulses of activity on spreading ridges, the latter would still require explanation. Maybe it is caused by circulation in the outer core, as is the Earth's dipole magnetic field whose lines of force have a north-south trend. Indeed, Gorshkov (1972) suggests that the

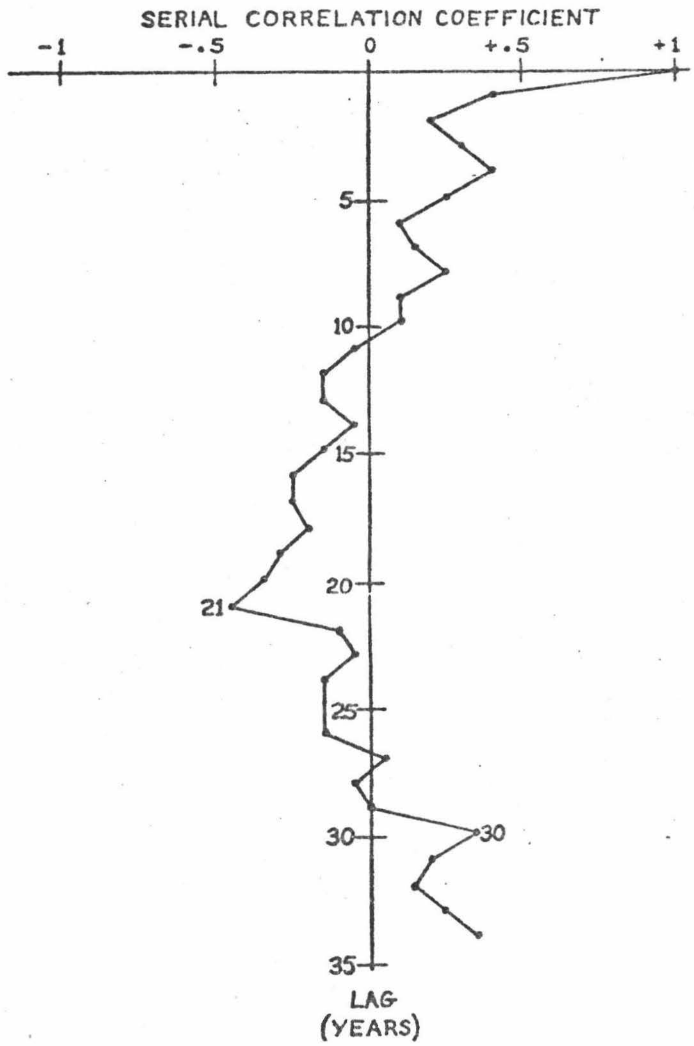


Fig. 14. Eastern Pacific margin and Caribbean. Number of areas having the maximum or one less than the maximum number of volcanoes in eruption per annum --serial correlation coefficient lags 0-34.

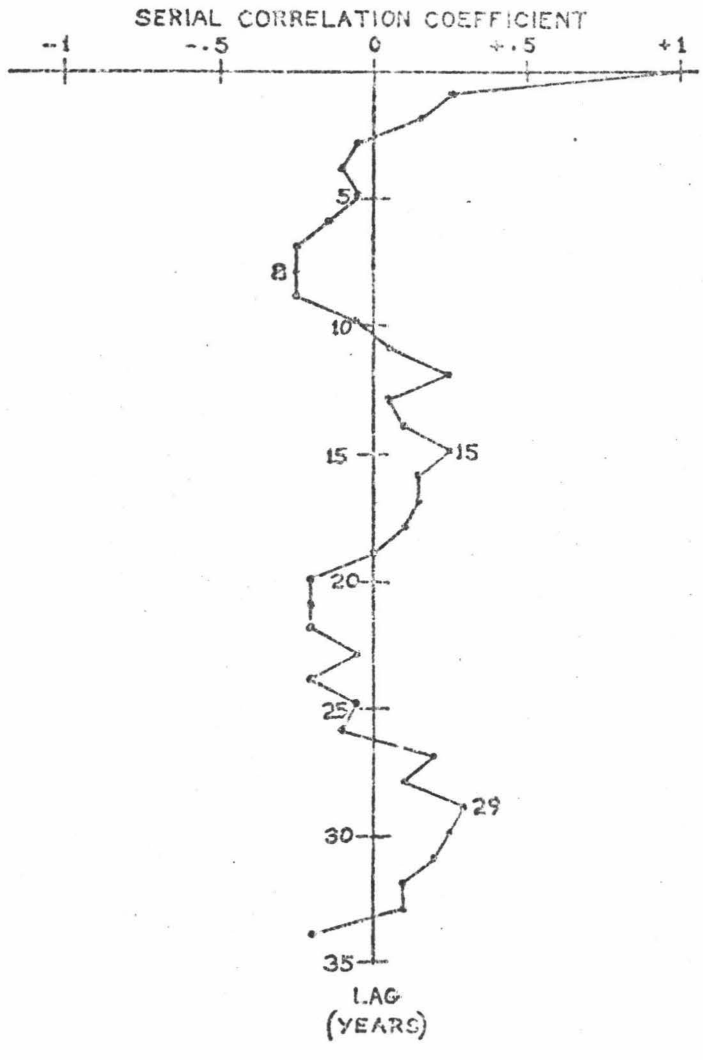


Fig. 15. Western Pacific margin. Number of areas having the maximum or one less than the maximum number of volcanoes in eruption per annum--serial correlation coefficient, lags 0-34.

"primary heat sources" for volcanism "may be very deep and may be, in particular, connected with gravitational differentiation at the core-mantle boundary (Artyushkov, 1970)."

It is interesting to note that there are variations with latitude in the spreading rate of the East Pacific Rise. Herron (1972) found that the yearly half-spreading rate of the eastern part of the East Pacific Rise increases monotonically from 4.5 cm at about 13°N to 10 cm at about 28°S, while that of the western part increases monotonically from 4.5 cm at about 13°N to nine cm at about 18°S but decreases to eight cm at about 28°S. However, it is difficult to see how this has any bearing on the southward migration of volcanic pulses.

IV. ANALYSIS OF VOLCANIC ACTIVITY IN LARGE REGIONS OF THE CIRCUM-PACIFIC BELT

1. Method of Analysis of Data

Having analyzed the series for the number of volcanoes in eruption per annum for the individual areas of the circum-Pacific belt, and finding that most of these series are statistically significant, it seemed logical to investigate the fluctuations in the number of volcanoes in eruption per annum in larger portions of the circum-Pacific belt. These data were obtained by adding together the data for various individual areas in the circum-Pacific region. The 1916 activity of the submarine volcano north of Taiwan was also included.

The large regions to be considered are: (1) the entire circum-Pacific belt (excluding Antartica and the Scotia Arc), (2) the eastern Pacific margin (including the West Indies), (3) the South American continent, (4) the western Pacific margin, (5) Indonesia and the south-west Pacific (New Guinea-Solomons -Santa Cruz-New Hebrides-Matthew Island-Kermadec-Tonga-Samoa-New Zealand), and (6) the south-west Pacific.

The arithmetic means, variances, standard deviations and years for which the numbers of volcanoes in eruption are more than two and more than three standard deviations away from the mean are given in Table VI.

Table VI

Number of Volcanoes in Eruption Per Annum in Large Regions of the Circum-Pacific Belt--Arithmetic Mean, Variance, Standard Deviation, and Years for Which the Number of Volcanoes in Eruption is More Than Two and More Than Three Standard Deviations Above the Mean

Area	Arithmetic Mean, $\overline{X}$	Variance, S^2	Standard Deviation, S	$\overline{X} + 2S$	$\overline{X} + 3S$	Years for Which No. of Volcanoes in Eruption $> \overline{X} + 2S$	Years for Which No. of Volcanoes in Eruption $> \overline{X} + 3S$
Circum-Pacific	23.7	22.9	4.8	33.3	38.1	1966	--
Western Pacific Margin	17.7	20.7	4.5	26.8	31.4	1963, 1966	1966
Eastern Pacific Margin	6.0	5.3	2.3	10.6	12.9	1902, 1906, 1920	--
South America	2.7	3.2	1.8	6.3	8.1	1906, 1907, 1960	1906
South-West Pacific & Indonesia	9.6	10.4	3.2	16.1	19.3	1966	1966
South-West Pacific	4.3	5.6	2.4	9.05	11.4	1953, 1964, 1965, 1966, 1967	--

The same two methods of analysis of the fluctuations were used as in the case of the individual areas, namely: the chi-square test with the null hypothesis that the number of volcanoes in eruption each year is equal to the arithmetic mean, and the calculation of serial correlation coefficients.

The histograms of the number of volcanoes in eruption per annum in these six regions are shown in Figs. 16 and 17.

2. Results

2.1. Chi-Square Results

For the South American continent and for the western Pacific margin, the null hypothesis was rejected at the 25 percent level of significance, and for the south-west Pacific it was rejected at the five percent level.

Hence, for South America, the western Pacific margin, and the south-western Pacific, the fluctuations in the number of volcanoes in eruption per annum appear to be statistically significant.

However, for the circum-Pacific belt, the eastern Pacific margin, and the south-west Pacific including Indonesia, the null hypothesis was accepted at the 25 percent level, and hence the fluctuations in volcanic activity are not significant, and the pulses in volcanic activity in the individual regions which make up these larger regions tend not to be notably simultaneous.

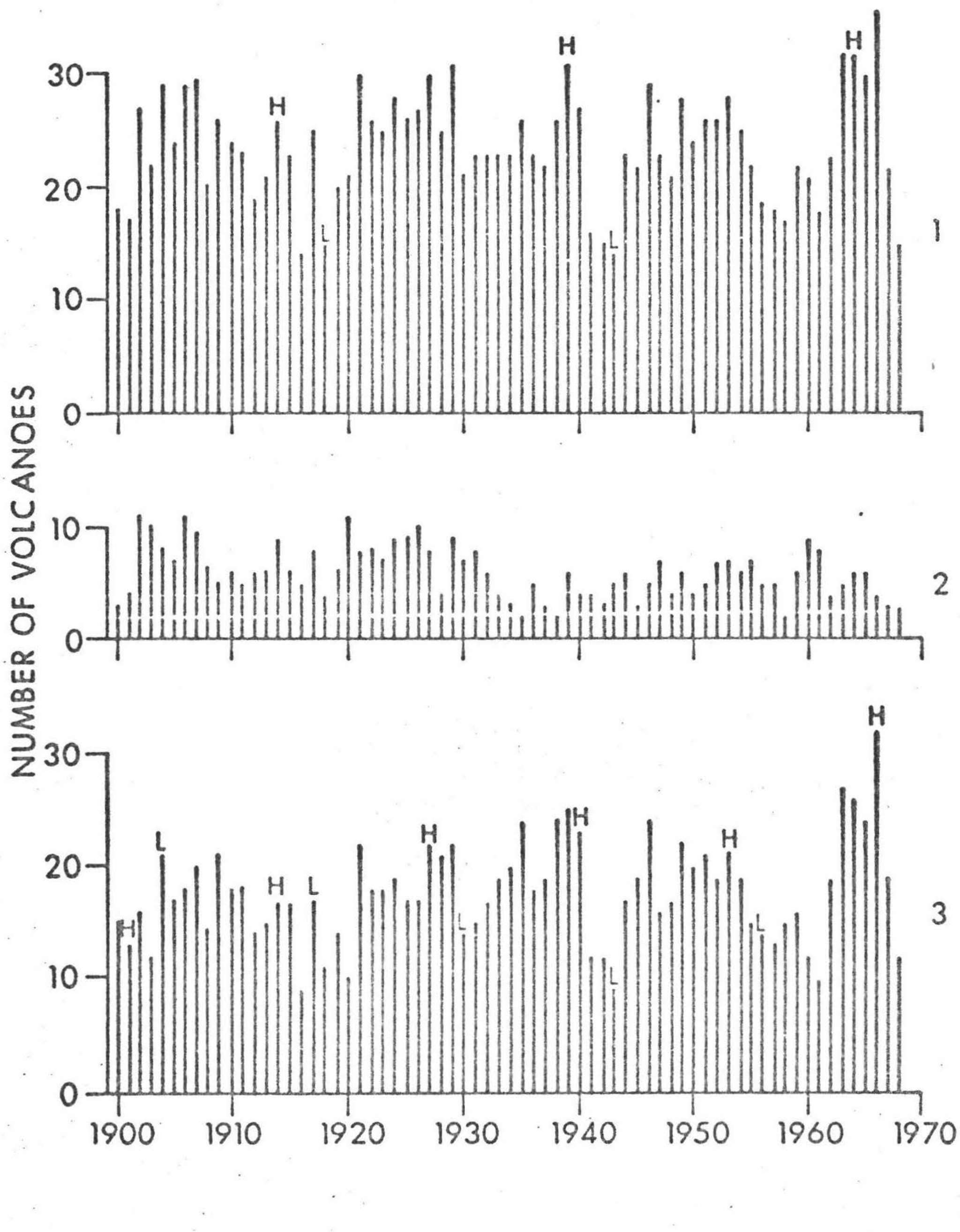


Fig. 16. Number of volcanoes in eruption per annum during the period 1900 to 1968 in 1. the circum-Pacific, 2. the eastern Pacific margin and Caribbean and 3. the western Pacific margin.

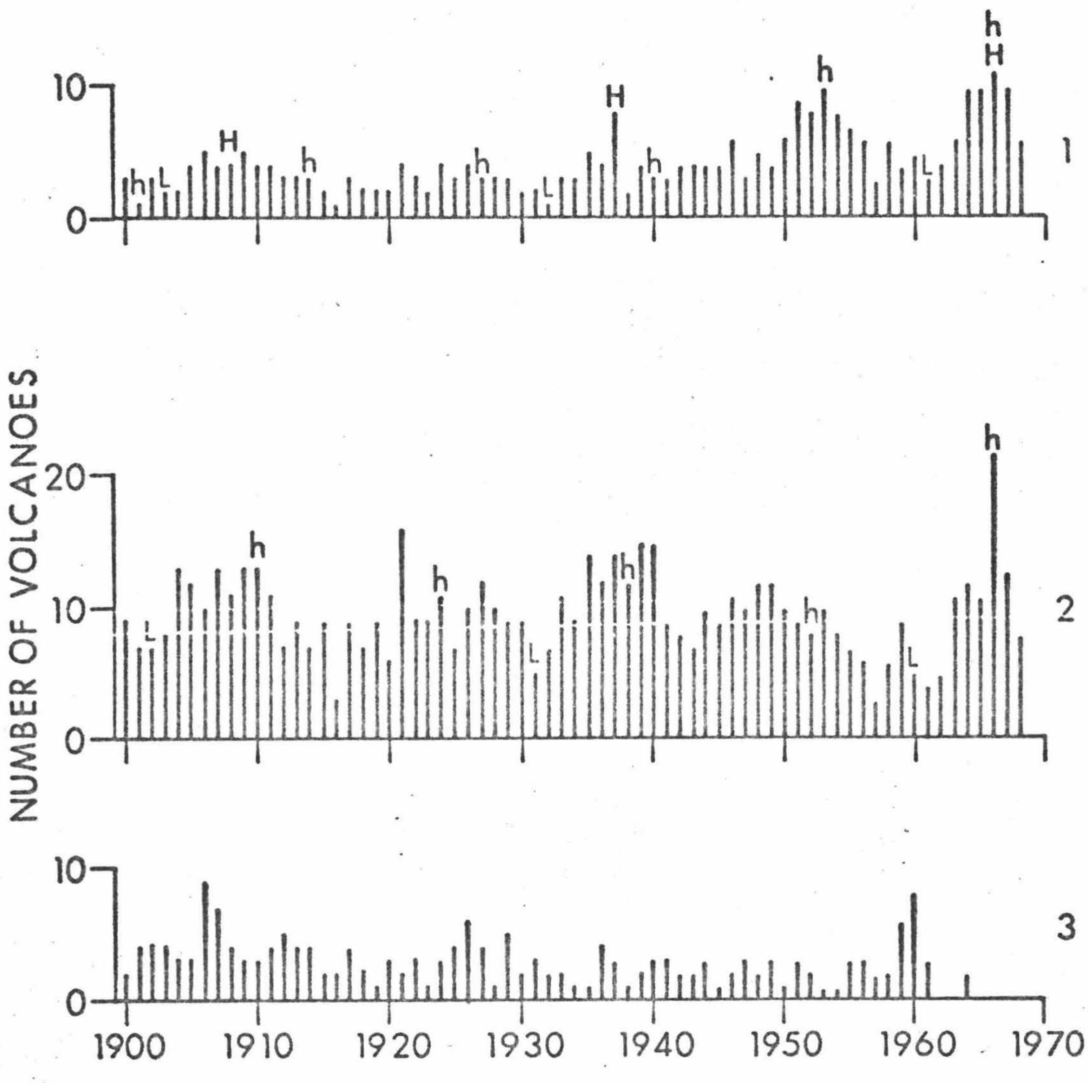


Fig. 17. Number of volcanoes in eruption per annum during the period 1900 to 1968 in 1. the south-west Pacific, 2. the south-west Pacific and Indonesia and 3. South America.

2.2. Serial Correlation Results

Figure 18 tabulates and graphs the serial correlation coefficients for lags 0 through 34 years. The graphs for the eastern Pacific margin and for South America are not included, as they show no salient features.

(a) Serial Correlation at Small Lags

The south-west Pacific is the only region with serial correlation coefficients (for any of the calculated lags) plotting greater than or equal to 0.5. The serial correlation coefficients at lags of one and two years are 0.72 and 0.66 respectively so the number of volcanoes in eruption in one year affects the number of volcanoes in eruption in the next two years.

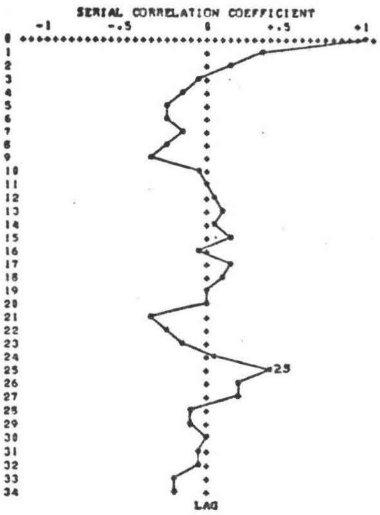
(b) Periodicity

The series for the number of volcanoes in eruption on the eastern Pacific margin and in South America do not seem to be periodic.

The circum-Pacific region has a poorly-defined 25-year periodicity, indicated by Fig. 18 and marked on Fig. 16 by "H" (for corresponding high points) and "L" for corresponding low points.

The western Pacific margin has an indistinct 13-year periodicity (Figs. 18 and 16).

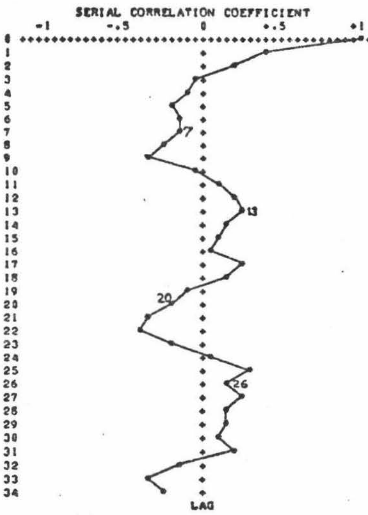
CIRCUM-PACIFIC



Coefficient	Lag
1	0
.3655818	1
.1498477	2
-2.804426E-02	3
-.1621724	4
-.2363005	5
-.2384209	6
-.1309855	7
-.2563202	8
-.3539249	9
-6.240550E-02	10
-2.211679E-02	11
4.715644E-02	12
7.639229E-02	13
5.651893E-02	14
.1613111	15
-4.175059E-02	16
.1380934	17
.1083211	18
-1.598034E-02	19
-1.596912E-02	20
-.3454536	21
-.2412873	22
-.1297650	23
5.226497E-02	24
.3995623	25
.1999170	26
.1818410	27
-.1105797	28
-6.707911E-02	29
-2.033924E-02	30
-2.586439E-02	31
-5.144120E-02	32
-.2021121	33
-.2144789	34

CIRCUM-PACIFIC

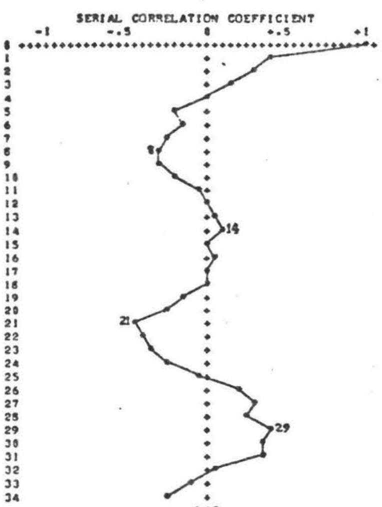
WESTERN PACIFIC MARGIN



Coefficient	Lag
1	0
.4224787	1
.1814852	2
-4.773574E-02	3
-6.085579E-02	4
-.1894166	5
-.1393943	6
-.1460273	7
-.2473787	8
-.3265120	9
-3.424572E-02	10
.1179268	11
.2096137	12
.2410178	13
.1697189	14
7.632297E-02	15
4.196165E-02	16
.2275298	17
.1359395	18
-7.876641E-02	19
-.1752788	20
-.3740396	21
-.4112379	22
-.2116311	23
3.498825E-02	24
.2773769	25
.1324361	26
.2252780	27
.1521437	28
.1682866	29
.1023508	30
.1872928	31
-.1743466	32
-.3347139	33
-.2691581	34

WESTERN PACIFIC MARGIN

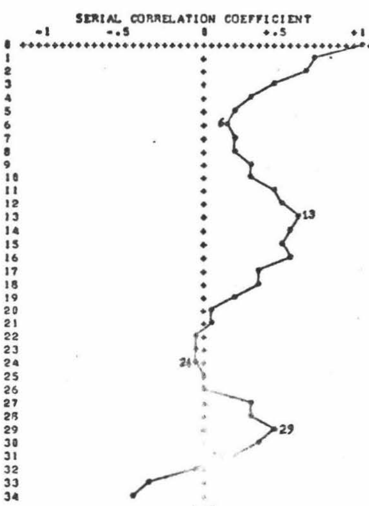
SOUTH-WEST PACIFIC & INDONESIA



Coefficient	Lag
1	0
.4181188	1
.2799596	2
.1611357	3
-7.641253E-04	4
-.1799495	5
-.1589912	6
-.2265245	7
-.3052679	8
-.3001751	9
-.1995334	10
-4.767565E-02	11
-1.740887E-02	12
5.766077E-02	13
9.493555E-02	14
-1.823743E-02	15
4.852952E-02	16
-7.355993E-03	17
-4.373055E-03	18
-.1360794	19
-.2509870	20
-.4702258	21
-.4380464	22
-.3414045	23
-.2680590	24
-4.998874E-02	25
.2207718	26
.3028356	27
.2591840	28
.4222255	29
.3643614	30
.3319276	31
6.304079E-02	32
-7.981700E-02	33
-.2465532	34

SOUTH-WEST PACIFIC & INDONESIA

SOUTH-WEST PACIFIC



Coefficient	Lag
1	0
.7174944	1
.6626389	2
.4358582	3
.2346849	4
.1821039	5
.1378011	6
.1980073	7
.1933802	8
.2923298	9
.2886323	10
.4580522	11
.5189917	12
.5752053	13
.5690271	14
.5224557	15
.5426256	16
.3388293	17
.3281622	18
.2122396	19
5.536423E-02	20
2.758488E-02	21
-2.586979E-02	22
-5.240462E-02	23
-5.746184E-02	24
1.897233E-02	25
2.466154E-02	26
.2773011	27
.2995946	28
.4325323	29
.3496348	30
.1857933	31
-6.926322E-02	32
-.3707273	33
-.4382127	34

SOUTH-WEST PACIFIC

Fig. 18. NUMBER OF VOLCANOES IN ERUPTION PER ANNUM
SERIAL CORRELATION COEFFICIENT, LAGS 0-34

The south-west Pacific including Indonesia has a 14-year periodicity and a 29-year periodicity, as indicated by Fig. 18. The highs corresponding to the 14-year periodicity are marked on Fig. 17 as "h" and the lows of the 29-year periodicity as L.

The south-west Pacific has a 29 and 13-year periodicity (see Fig. 18). The highs corresponding to the 13-year periodicity are marked as "h," and the highs and lows corresponding to the 29-year periodicity as "H" and "L" respectively on Fig. 17.

Note that here again there is a bimodal distribution of periods; they are either 13 or 14 years, or else 25 or 29 years.

It is interesting to note (Fig. 18) that the correlation coefficient versus lag graph for the circum-Pacific has a relative minimum at a lag of 21 years, and that the graphs for the western Pacific margin and the south-west Pacific including Indonesia have absolute minima at lags of 22 and 21 years respectively. This may indicate periodicities of about 42 years in these areas, but the data do not extend over a long enough time scale to confirm this.

3. Comparison of Volcanism on the Eastern Pacific Margin with that on the Western Pacific Margin

Figure 16 shows the number of volcanoes in eruption per annum on the eastern Pacific margin (including the West Indies) and the western Pacific margin respectively.

The first thing to note is that there is a higher level of activity on the western Pacific margin (the number of volcanoes in eruption per annum ranging between 9 and 32) than on the eastern Pacific (2 to 11 volcanoes in eruption per annum).

On the western Pacific margin, the year when the maximum number of volcanoes was in eruption was 1966, a year of relatively low activity on the eastern Pacific margin.

Conversely, the years 1902, 1906 and 1920, when the maximum number of volcanoes was in eruption on the eastern Pacific margin, were not years during which volcanoes were particularly active on the western Pacific margin.

This suggests a negative correlation between volcanic activity on the eastern and western Pacific margins and, to test this, cross correlation coefficients were calculated, using the program "Volcross," mentioned previously. The cross correlation coefficient at zero lag is -0.15, confirming the suggestion, but its magnitude is very small. The highest cross correlation coefficient (the western Pacific being lagged positively relative to the eastern Pacific) is 0.09 at lag +3. The highest magnitude negative cross correlation coefficient is -0.34 at lag -4.

Thus, it appears that there is little correlation between the number of volcanoes in eruption on the western and eastern Pacific margins.

4. Conclusions

Both chi-square and serial correlation results show the fluctuations in the number of volcanoes in eruption per annum, for the south-west Pacific, to be statistically significant.

Similarly, the series for the western Pacific margin has significant fluctuations according to the chi-square test, and has a slight periodicity.

The circum-Pacific belt and also the southwestern Pacific including Indonesia have only a slight periodicity.

The series for the South American continent has significant fluctuations at the 25 percent level according to the chi-square test, but shows little serial correlation.

Hence, only the series for the eastern Pacific margin appears not to be statistically significant, probably due to the pronounced lagging in volcanic pulses from one individual area to another (see Chapter III).

There is a higher level of activity on the western Pacific margin (9 to 32 volcanoes in eruption per annum) than on the eastern (2 to 11 volcanoes in eruption per annum), and there is little correlation between the number of volcanoes in eruption per year on the two sides of the Pacific, possibly because the mantle currents descending under the western Pacific margin and those going down under the eastern belong to two different flow regimes as discussed in Chapter II.

There is a bimodal distribution of periods in the large regions of the circum-Pacific; they are either 13 or 14 years, or else 25 or 29 years, and there is also a possible 42-year period in some areas.

V. PERIODS OF VOLCANIC SERIES

Figure 19 contains histograms of the distributions of the periods found in Chapters II, III and IV.

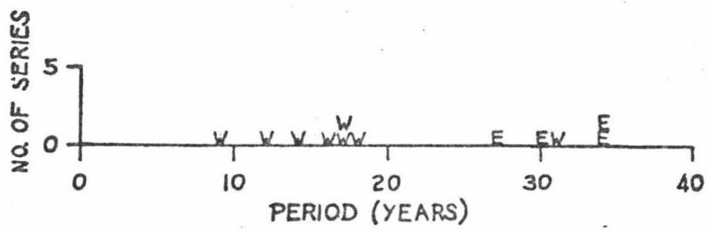
The top histogram shows the periods for the number of volcanoes in eruption per annum for the individual areas of the circum-Pacific region (see Table II). The distribution is bimodal, with a mode at 17 years for the western Pacific areas, and a mode at 34 years for the eastern Pacific areas.

The middle histogram is a plot of the periods of the number of volcanoes in eruption per annum for the larger regions of the circum-Pacific belt. Again, the distribution is bimodal, with modes at 13 and 29 years, in this case both for western Pacific areas.

The bottom histogram shows the periods for the number of areas having the maximum or one less the maximum number of volcanoes in eruption per annum. The western Pacific has a period of 15 years, and the eastern Pacific has a period of 30 years.

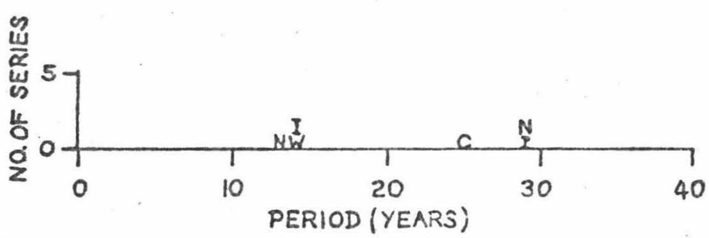
Note that in each of these three histograms a bimodal distribution is indicated, with one mode double or nearly double the other mode, the larger period usually being for the eastern Pacific, and the smaller period for the western Pacific. A possible reason for this has been suggested in Chapters II and IV.

Fig. 19. Periods of volcanic time series in the circum-Pacific area: number of volcanoes in eruption per annum in the individual areas of the Pacific margin (top), number of volcanoes in eruption per annum in larger regions (middle), and number of areas having the maximum or one less than the maximum number of volcanoes in eruption per annum (bottom).



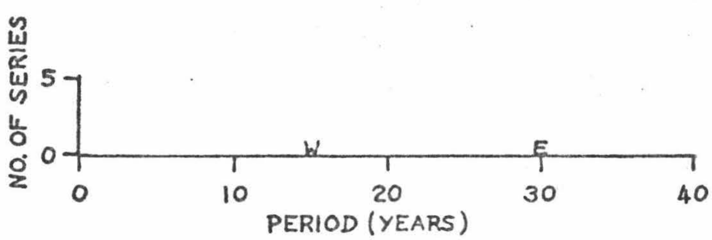
W WESTERN PACIFIC AREA
E EASTERN PACIFIC AREA

MODES: 17 + 34 YEARS



C CIRCUM-PACIFIC
W WESTERN PACIFIC MARGIN
I INDONESIA + S.W. PACIFIC
N S.W. PACIFIC

MODES: 14 + 29 YEARS



E EASTERN PACIFIC
W WESTERN PACIFIC

MODES: 15 + 30 YEARS

VI. ANALYSIS OF THE SIGNIFICANCE OF FLUCTUATIONS IN THE NUMBER OF EARTHQUAKES PER ANNUM IN SOUTH AMERICA

1. Method of Analysis of Data

The area under discussion is that portion of South America bounded by the parallels 6°N and 53°S and the meridians 55°W and 85°W, that is, the South American part of the circum-Pacific seismic zone.

The data to be analyzed were divided into two main groups: $M \geq 6$ earthquakes (1931 to 1971) and $M \geq 7$ earthquakes, M being the surface wave magnitude of the earthquake. Each of these groups was subdivided into shallow ($H \leq 60$ km), intermediate (60 km $< H \leq 300$ km) and deep ($H > 300$ km) earthquakes, where H is the depth of focus of the earthquake. Their means, variances, standard deviations and the years for which the number of earthquakes per annum is more than two and more than three standard deviations above the mean are shown in Table VII.

A great difficulty in obtaining meaningful earthquake data for time series analysis lies in the lack of uniformity of magnitude data. Up to the end of 1959, the magnitudes were mainly Richter surface wave magnitudes, M, determined by the Seismological Laboratory at Pasadena, and so I have given these

Table VII

Number of M$\geq$ 6 and M$\geq$ 7 Earthquakes Per Annum in South America (6°N-53°S, 55°W-85°W)--Arithmetic Mean, Variance, Standard Deviation, and Years for Which the Number of Earthquakes is More Than Two and More Than Three Standard Deviations Above the Mean

Category for Number of Earthquakes Per Annum	Arithmetic Mean, $\overline{X}$	Variance, S^2	Standard Deviation, S	$\overline{X}+2S$	$\overline{X}+3S$	Years for Which No. of Earthquakes $> \overline{X}+2S$	Years for Which No. of Earthquakes $> \overline{X}+3S$
M$\geq$ 6 Shallow Earthquakes	5.0	17.2	4.2	13.3	17.4	1960	1960
M$\geq$ 6 Intermediate Earthquakes	5.0	9.9	3.1	11.3	14.5	1960	--
M$\geq$ 6 Deep Earthquakes	1.0	1.2	1.1	3.3	4.4	1950	--
M$\geq$ 6 Total Earthquakes	11.0	35.5	6.0	22.97	28.9	1960	1960
M$\geq$ 7 Shallow Earthquakes	1.0	1.5	1.2	3.5	4.7	1922, 1928, 1960	1960
M$\geq$ 7 Intermediate Earthquakes	0.76	0.63	0.79	2.4	3.1	1943, 1960	--
M$\geq$ 7 Deep Earthquakes	0.24	0.36	0.60	1.4	2.04	1950, 1961	1950, 1961
M$\geq$ 7 Total Earthquakes	2.0	2.7	1.6	5.3	6.9	1922, 1960	1960

preference whenever they were available. When only surface wave magnitudes determined by the Lamont Geological Observatory at Palisades were given, I converted them into a magnitude equivalent to a Pasadena magnitude using a least squares regression equation, as Palisades magnitudes are usually lower than the corresponding Pasadena magnitude. Similarly, I converted body wave magnitudes determined by the Coast and Geodetic Survey (CGS) into Pasadena magnitudes and used these equivalent magnitudes to calculate energy release, when surface wave data were not available, but difficulty was experienced in trying to count numbers of earthquakes with $M \geq 6$ and $M \geq 7$ for various years, because the data obtained using body wave magnitudes equivalent to a Pasadena magnitude of 6 or 7 gave results for the 1960's which were inconsistent with the number of earthquakes obtained for previous years--many more $M \geq 6$ earthquakes and much fewer $M \geq 7$. This happened when taking CGS body wave magnitudes of 5.2 and 6.5 as equivalent to Pasadena magnitudes of 6.0 and 7.0 respectively.

To obtain more reliable equivalent magnitudes an averaging process was used. All the CGS body wave magnitudes for which a surface wave magnitude of 6 had also been determined were added and then averaged, and similarly for those equivalent to a magnitude of 7. A CGS body wave magnitude of 5.7 was found to be equivalent to a Pasadena magnitude of 6.0, and a

CGS body wave magnitude of 6.3 was found to be equivalent to a Pasadena magnitude of 7.0. These values gave consistent figures for the number of earthquakes with $M \geq 6$ and $M \geq 7$ in the years after 1962 when few surface wave magnitudes were given. Hence, earthquakes with body wave magnitudes greater than or equal to 5.7 and 6.3 were assumed to have $M \geq 6$ and $M \geq 7$ respectively and their energy release was then calculated from the energy-magnitude relationship for surface wave magnitudes, by finding the Pasadena equivalent magnitude using a least squares regression equation linking CGS body wave magnitudes and Pasadena surface wave magnitudes.

The methods of analysis of these data were the same as those discussed in detail in Chapter II, namely, the chi-square test with the null hypothesis that the number of earthquakes per annum is equal to the arithmetic mean and the determination of serial correlation coefficients.

2. Results

2.1. Chi-Square Results

For the total number of $M \geq 6$ earthquakes per annum, the null hypothesis was rejected at the 0.5 percent level of significance. Also in the $M \geq 6$ earthquake category, the null hypothesis was rejected at the 0.5 percent level for shallow and for intermediate earthquakes, and at the 25 percent level for deep earthquakes.

The null hypotheses were rejected at the five percent level for the total number of $M \geq 7$ earthquakes per annum; and at the 0.5 percent level for the shallow and for the deep sub-categories. However, it was accepted at the 25 percent level for $M \geq 7$ intermediate earthquakes.

The graphs for these time series are shown in Figs. 20 and 21.

2.2. Serial Correlation Results

(a) Serial Correlation at Small Lags

For the $M \geq 6$ earthquakes, only the shallow earthquake category had a serial correlation coefficient greater than or equal to 0.5 when rounded to the nearest 0.05. This occurs at a lag of two years. Thus the number of earthquakes in one year tends to affect the number of earthquakes two years later.

None of the categories of $M \geq 7$ earthquakes had a serial correlation coefficient greater than or equal to 0.5 when rounded to the nearest 0.05.

(b) Periodicity

The relevant serial correlation coefficient versus

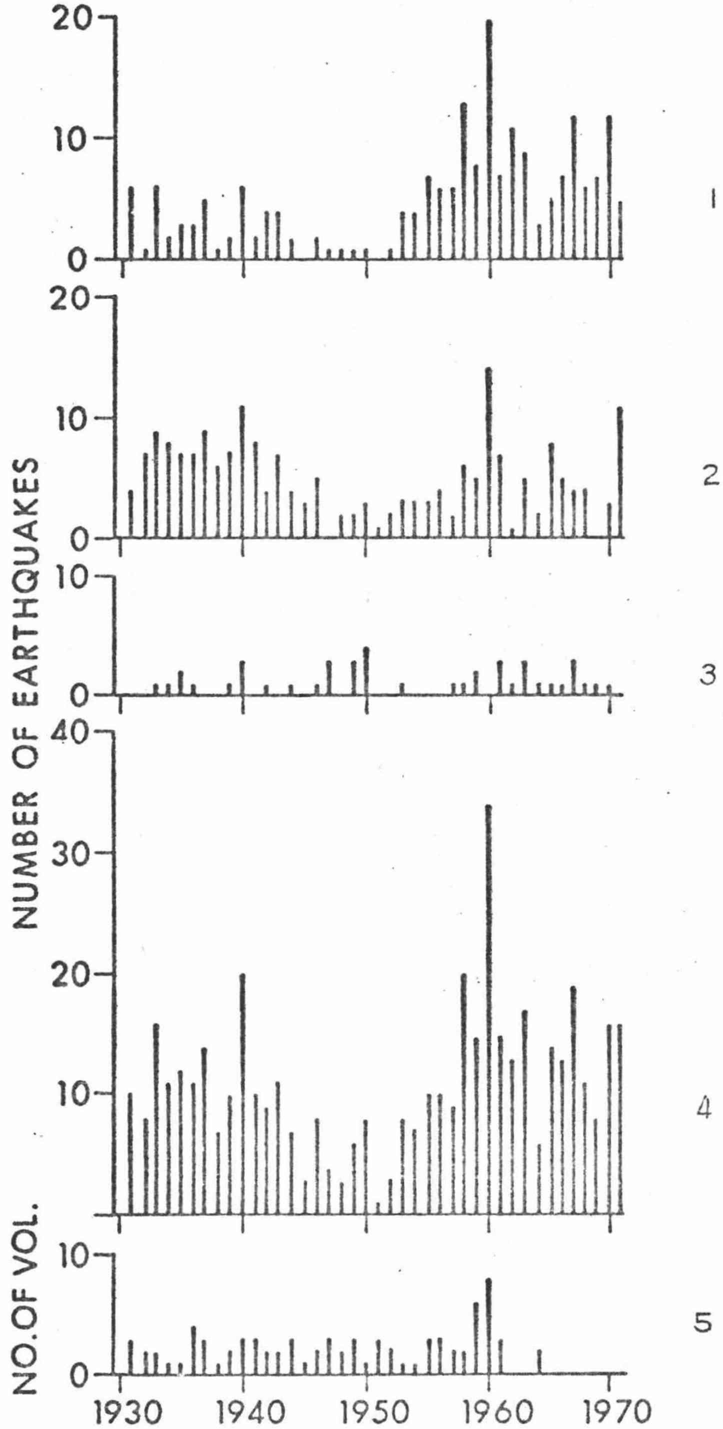


Fig. 20. Number per annum of $M \geq 6$ 1. shallow, 2. intermediate, 3. deep, and 4. total earthquakes (1931 to 1971) and of 5. volcanoes in eruption (1931 to 1968) in South America.

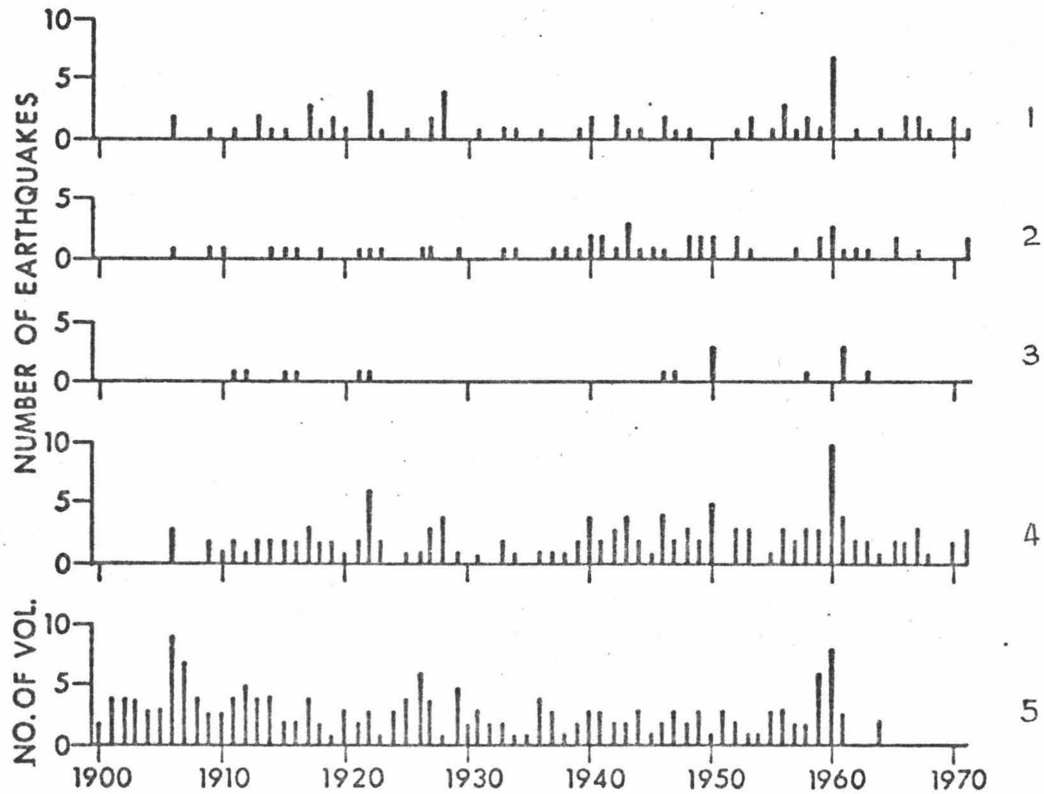


Fig. 21. Number per annum of M ≥ 7 1. shallow, 2. intermediate, 3. deep, and 4. total earthquakes (1904 to 1971) and of volcanoes in eruption (1900 to 1968) in South America.

lag graphs are shown in Fig. 22. Only the $M \geq 6$ total (shallow + intermediate + deep) earthquakes, shallow earthquakes and intermediate earthquakes have any indication of periodicity.

Unfortunately, the time period for which numbers of $M \geq 6$ earthquakes per annum has been recorded accurately has been too short to determine periodicities with any certainty but examination of the serial correlation coefficient graphs in Fig. 22 combined with a study of the number of earthquakes per annum graphs of Fig. 20 indicate a 30-year periodicity in total $M \geq 6$ earthquakes (a serial correlation coefficient of -0.49 being obtained at a lag of 15 years) and in $M \geq 6$ shallow earthquakes, and a 25-year periodicity in $M \geq 6$ intermediate earthquakes. The 30-year periodicity in total $M \geq 6$ earthquakes is due to the hump in intermediate earthquake activity in the early 1930's through middle 1940's and the hump in shallow earthquake activity in the late 1950's through early 1970's.

3. Conclusions

The chi-square test indicates that the amplitude of the fluctuations about the mean number of earthquakes per annum is significant for total $M \geq 6$ earthquakes and for $M \geq 6$ shallow earthquakes, intermediate earthquakes and deep earthquakes.

It is also significant for $M \geq 7$ total earthquakes, shallow earthquakes and deep earthquakes, but not for $M \geq 7$

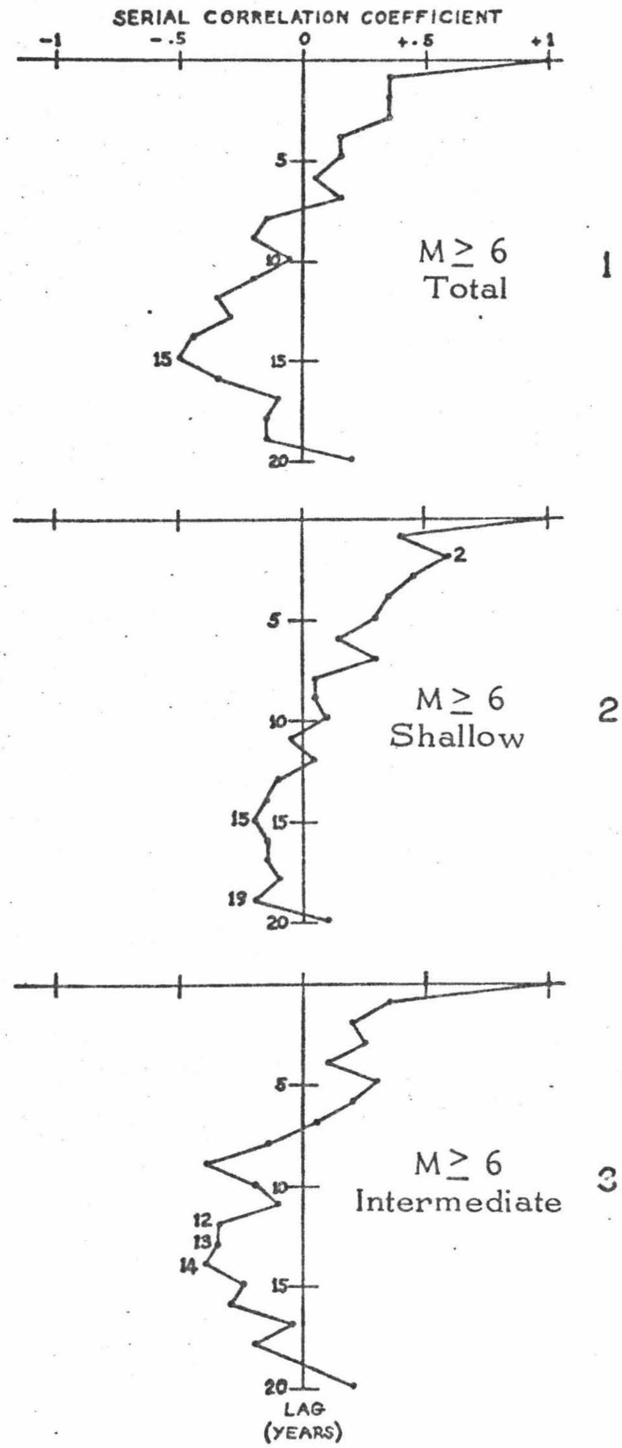


Fig. 22. Serial correlation coefficient, lags 0-20, for the number per annum (1931 to 1971) of $M \geq 6$ 1. total, 2. shallow, and 3. intermediate earthquakes in South America.

intermediate earthquakes.

The only group of earthquakes having serial correlation at small lags is the $M \geq 6$ shallow earthquakes, with a serial correlation coefficient greater than 0.5 at a lag of two years. Hence, the number of shallow $M \geq 6$ earthquakes in one year tends to affect the number two years hence.

None of the groups of $M \geq 7$ earthquakes appear to be periodic, and neither do the $M \geq 6$ deep earthquakes.

The total $M \geq 6$ earthquakes, and the $M \geq 6$ shallow earthquakes have possible 30-year periodicities, and the $M \geq 6$ intermediate earthquakes have a possible periodicity of 25 years. These periodicities are of the same order as those for the number of volcanoes in eruption for areas of the eastern Pacific margin and thus may have a similar cause (see Chapter II).

The only time series whose fluctuations do <u>not</u> appear to be statistically significant is that for the number of $M \geq 7$ intermediate earthquakes per annum.

VII. ANALYSIS OF THE SIGNIFICANCE OF FLUCTUATIONS IN EARTHQUAKE ENERGY RELEASE IN SOUTH AMERICA

1. Method of Analysis of Data

Because magnitude is a logarithmic function of energy, only the energy released by earthquakes with a surface wave magnitude of 7 or greater was considered as this constitutes the bulk of the energy. The energy release was calculated from the magnitude using the formula

$$\log_{10} E = 11.4 + 1.5M ,$$

where M is the surface wave magnitude and E is the energy in ergs.

The area of South America under consideration is the same as that for Chapter VI and the period of time is 1904 to 1971.

Because the chi-square statistic, as defined in Chapter II, has squared quantities in the numerators and non-squared quantities in the denominators of the fractions which are summed, the chi-square test can only be used for dimensionless numbers, it could not be applied to the energy release data, as these are all given in ergs. Hence, only the serial correlation coefficients (refer to Chapter II) were calculated.

The histograms of the energy release from shallow, intermediate and deep earthquakes are shown in Figs. 23, 24 and 25. The total $M \geq 7$ earthquake energy release is shown in Fig. 26. The arithmetic means, variances, standard deviations, and the years for which the energy release is more than two, and more than three standard deviations above the mean are given in Table VIII.

2. Results

2.1. Serial Correlation Results

None of the serial correlation coefficients were greater than, or equal to 0.5, when rounded to the nearest 0.05, and the series do not appear to be periodic.

3. Conclusions

The shallow, intermediate, deep and total earthquake energy release in South America do not appear to be periodic or serially correlated.

Although the data were not suitable for performing a chi-square test, it is obvious from inspection of Figures 23 to 26 that large fluctuations in annual energy release have occurred, particularly for shallow earthquakes.

The years of greatest energy release in South America were 1906 and 1960 when 3.0×10^{24} ergs and 2.3×10^{24} ergs respectively were liberated. These are about three times

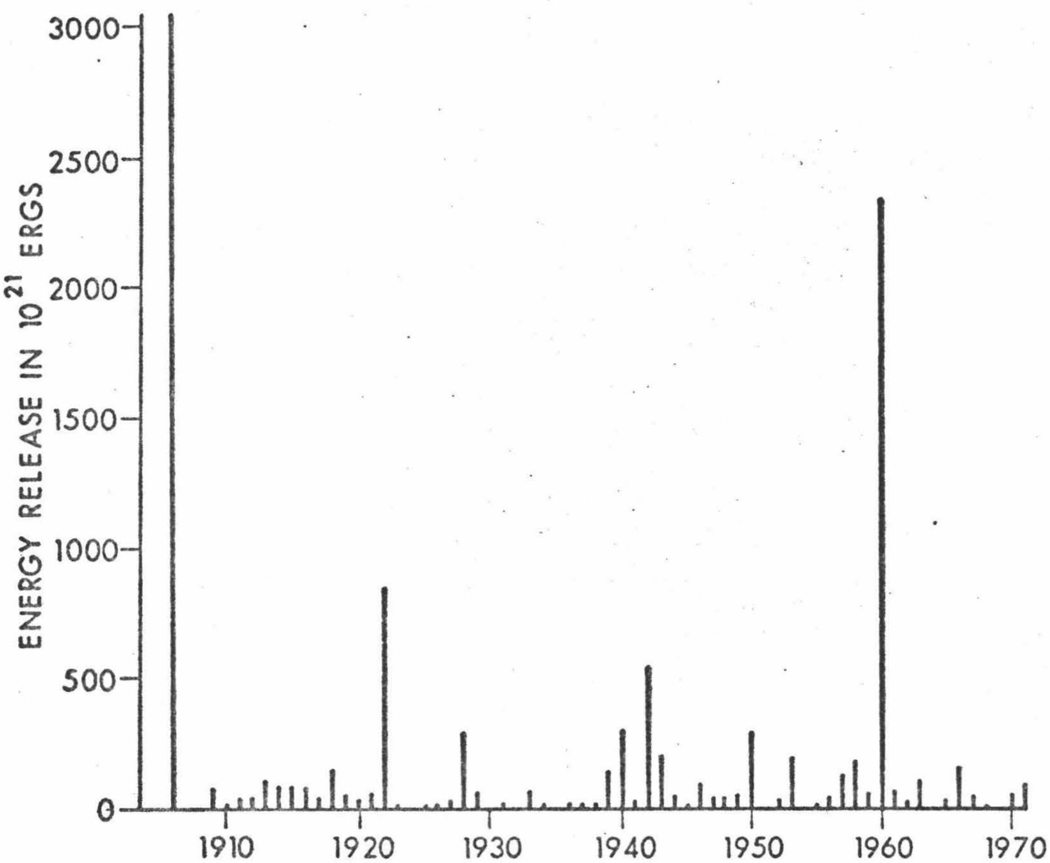


Fig. 23. M ≥ 7 shallow earthquake energy release per annum in South America during the period 1904 to 1971.

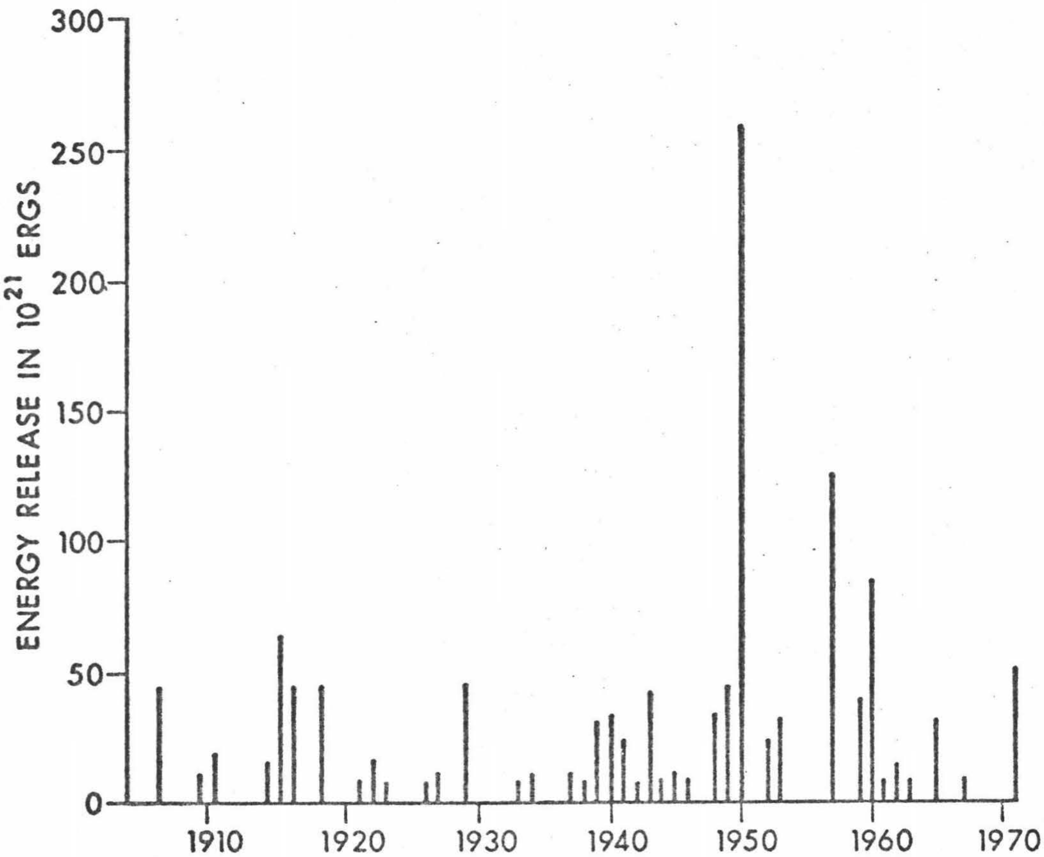


Fig. 24. M ≥ 7 intermediate earthquake energy release per annum in South America during the period 1904 to 1971.

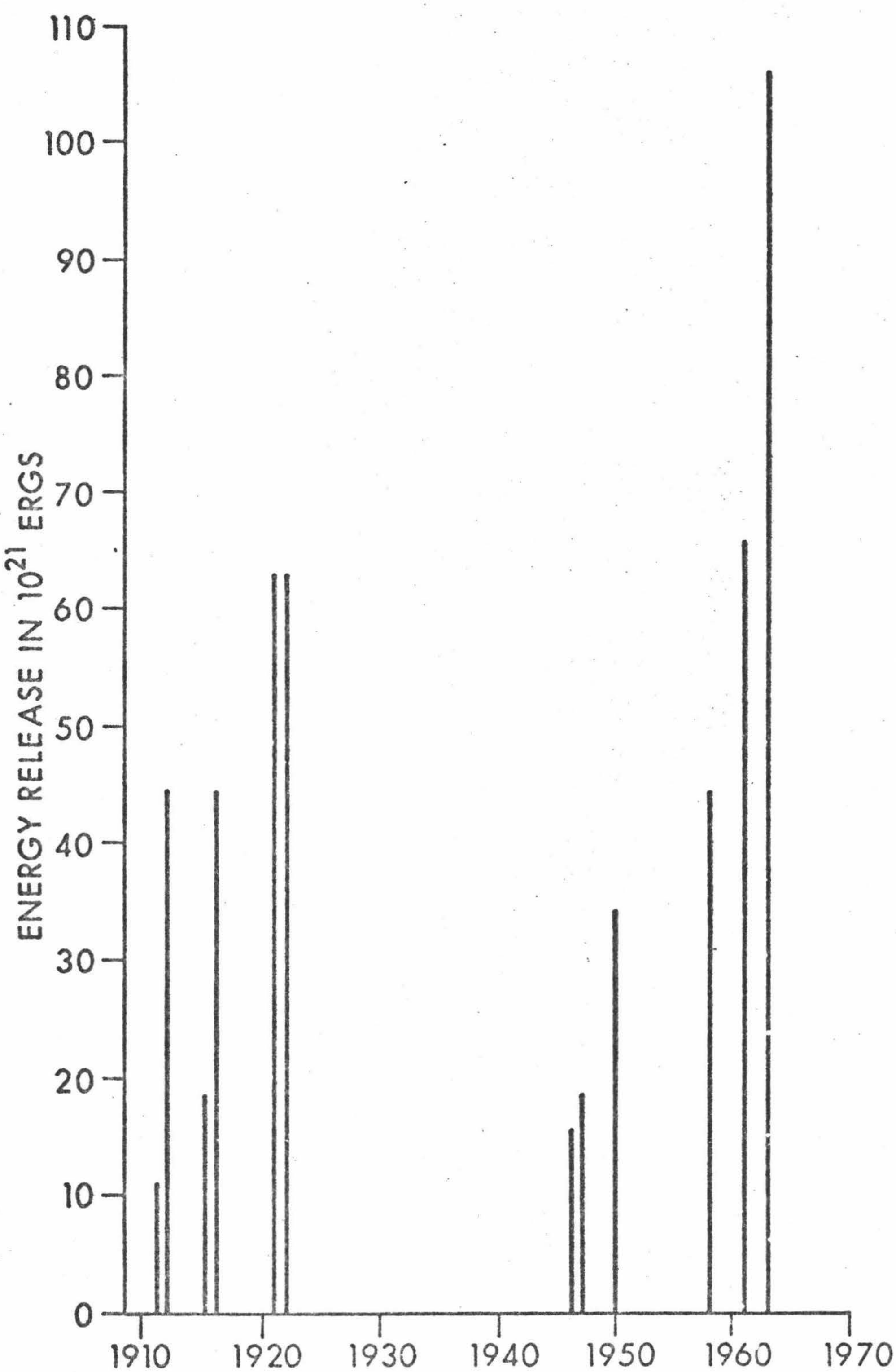


Fig. 25. M ≥ 7 deep earthquake energy release per annum in South America during the period 1904 to 1971.

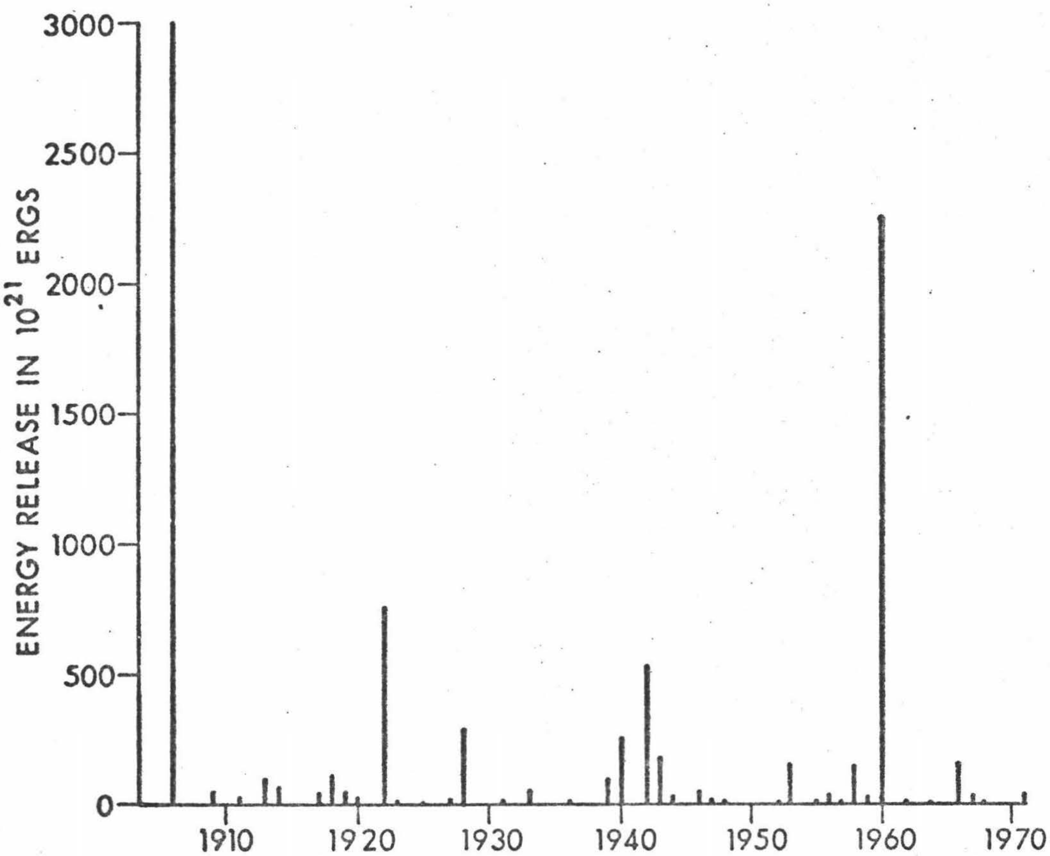


Fig. 26. Total M ≥ 7 earthquake energy release in South America during the period 1904 to 1971.

Table VIII

Annual M ≥ 7 Earthquake Energy Release in South America (6°N-53°S, 55°W-85°W)--Arithmetic Mean, Variance, Standard Deviation and Years for Which the Energy Release is More Than Two and More Than Three Standard Deviations Above the Mean

Earthquake Energy Release ($X10^{21}$ Ergs)	Arithmetic Mean, $\overline{X}$	Variance, S^2	Standard Deviation, S	$\overline{X}$ + 2S	$\overline{X}$ + 3S	Years for Which Energy Release > $\overline{X}$ + 2S	Years for Which Energy Release > $\overline{X}$ + 3S
M ≥ 7 Shallow Energy Release	131	211087	459	1050	1509	1906, 1960	1906, 1960
M ≥ 7 Intermediate Energy Release	19	1400	37	94	131	1950, 1957	1950
M ≥ 7 Deep Energy Release	8	413	20	48	69	1921, 1922, 1961, 1963	1963
M ≥ 7 Total Energy Release	158	218886	468	1093	1561	1906, 1960	1906, 1960

greater than the next largest energy release: 8.4×10^{23} ergs in 1922. Most of the energy released in these three years is due to shallow earthquake activity.

VIII. RELATIONSHIP BETWEEN SHALLOW, INTERMEDIATE AND DEEP SEISMIC ACTIVITY IN SOUTH AMERICA

1. Method of Analysis of Data

The data were divided into three main groups: number per annum of $M \geq 6$ earthquakes (1931 to 1971), number per annum of $M \geq 7$ earthquakes (1904 to 1971), and annual $M \geq 7$ earthquake energy release (1904 to 1971). Each of these three groups was subdivided into shallow, intermediate and deep, using the categories described in Chapter VI.

In each of the three main groups, shallow earthquake data were cross correlated with intermediate and with deep earthquake data, and intermediate earthquake data were cross correlated with deep earthquake data, as described in Chapter III. The lag for which the highest cross correlation coefficient, r, was obtained was noted in each case.

2. Results

2.1. Number of $M \geq 6$ Earthquakes per Annum

When intermediate earthquakes are lagged positively with respect to shallow earthquakes, the highest cross correlation coefficient ($r = 0.29$) is obtained for a lag of 0 years. Hence, shallow and intermediate earthquake pulses tend to be simultaneous.

When deep earthquakes are lagged positively with respect to shallow earthquakes, the maximum cross correlation coefficient (r = 0.38) is obtained at a lag of +7 years, so that shallow earthquake pulses tend to occur seven years before deep earthquake pulses.

When deep earthquakes are lagged positively with respect to intermediate earthquakes, the highest cross correlation coefficient (r = 0.36) occurs at a lag of +7 years. Therefore, intermediate earthquake pulses tend to occur seven years before deep earthquake pulses.

The results are shown pictorially in Fig. 27, from which it may be seen that the three results are internally consistent.

2.2. Number of $M \geq 7$ Earthquakes Per Annum

When intermediate earthquakes are lagged positively with respect to shallow earthquakes, the highest cross correlation coefficient (r = 0.20), is obtained at a lag of -7 years, so that intermediate earthquake pulses tend to occur seven years before shallow earthquake pulses.

When deep earthquakes are lagged positively with respect to shallow earthquakes, the maximum cross correlation coefficient (r = 0.41) occurs at a lag of -10 years. Hence, deep earthquake pulses tend to occur 10 years before shallow

Earlier Time→ Later

No. Per Annum of $M \geq 6$ Earthquakes (1931 to 1971)

S
|
I (r = 0.29)

S —7 years— D (r = 0.38)

I —7 years— D (r = 0.36)

No. Per Annum of $M \geq 7$ Earthquakes (1904 to 1971)

I —7 years— S (r = 0.20)

D —10 years— S (r = 0.41)

I —1 year— D (r = 0.35)

$M \geq 7$ Earthquake Energy Release (1904 to 1971)

I —10 years— S (r = 0.72)

S —3 years— D (r = 0.32)

I —6 years— D (r = 0.30)

Fig. 27. Summary of cross correlation results. Time relationships between shallow (S), intermediate (I) and deep (D) earthquakes based on the lag for which the cross correlation coefficient (r) is a maximum.

earthquake pulses.

When deep earthquakes are lagged positively with respect to intermediate earthquakes, the highest cross correlation coefficient (r = 0.35) is obtained at a lag of +1 year. Therefore, intermediate earthquakes tend to occur one year before deep earthquakes.

A study of the pictorial representation of these results in Fig. 27 shows the relationship between intermediate and deep earthquakes to be inconsistent, probably because the correlation coefficients are all so low.

2.3. Annual $M \geq 7$ Earthquake Energy Release

When intermediate earthquake energy release is lagged positively with respect to shallow energy release, the highest cross correlation coefficient (r = 0.72) is obtained at a lag of -10 years, so that intermediate earthquake energy pulses tend to occur 10 years before shallow pulses.

When deep earthquake energy release is lagged positively with respect to shallow energy release, the maximum cross correlation coefficient (r = 0.32) is obtained at a lag of +3 years. Hence, shallow energy pulses tend to occur three years before deep energy pulses.

When deep energy release is lagged positively with respect to intermediate energy release, the highest cross correlation coefficient (r = 0.30) occurs at a lag of +6 years. Therefore, pulses in intermediate earthquake energy release tend to occur six years before pulses in deep earthquake energy release.

An inspection of Fig. 27 shows there to be an inconsistency in the relationship between shallow and deep earthquake energy release. This is possibly because the correlation between deep and shallow, and deep and intermediate energy release is low and not very meaningful.

3. Conclusions

3.1. Internal Consistency of Results

The results for the number of $M \geq 6$ earthquakes per annum are internally consistent, whereas those for the number of $M \geq 7$ earthquakes per annum and for the annual $M \geq 7$ earthquake energy release are not.

3.2. Degree of Correlation between Shallow, Intermediate and Deep Earthquakes

In all cases, the correlation coefficients at lag 0 are very small (less than 0.3).

The maximum correlation coefficients are shown on Fig. 27 and they are all less than 0.5, except for a value of 0.72 obtained at a lag of 10 years when intermediate earthquake energy release is crossed with shallow earthquake energy release.

3.3. Time Relationships between Shallow, Intermediate and Deep Earthquakes

In all three cases, pulses in intermediate earthquake activity tend to occur before pulses in deep earthquake activity, although the length of the lag varies.

In two out of the three cases, pulses in intermediate earthquake activity tend to occur earlier than pulses in shallow earthquake activity; in the third case, there is zero lag between them.

Also, in two out of the three cases, shallow earthquake pulses tend to occur before deep earthquake pulses, but in the other case the reverse is indicated, and the correlation coefficient is higher than in the first two cases.

Hence, it appears that pulses in intermediate earthquake activity tend to occur earlier than pulses in both deep and shallow earthquake activity. If these results are meaningful, they seem to contradict earlier theories of crustal material descending under the Andes as a single, coherent plate because, if the seismic activity is caused by rapid spreading occurring at the oceanic ridge, this would be expected to generate shallow, then intermediate, then deep earthquakes. However, if convection suddenly sucks the lithospheric plate under the continent, one would expect deep earthquakes first, then intermediate, then shallow. If transmission of energy along the underthrusting plate is rapid compared with a time scale of a year, the pulses in shallow, intermediate and deep seismic activity will appear simultaneous. However recent work indicates that the descending slab may, at least in some parts of the Pacific margin, not remain coherent (Barazangi et al., 1973).

3.4. Correlation between M $\geq$ 6 Shallow and Intermediate Earthquakes

As was mentioned previously, the highest cross correlation coefficient for M $\geq$ 6 intermediate and shallow earthquakes during the period 1931 to 1971 was obtained at zero lag, but was only 0.29.

This is surprising, because a visual inspection of the graphs of numbers of earthquakes per annum (Fig. 20) shows there to be a noticeable correspondence between relative maxima and minima in numbers of shallow and intermediate earthquakes, during the period 1931 to 1961. However, there seems to be very little correlation between M $\geq$ 6 shallow and intermediate earthquake pulses during the last 10 years, and this is apparently why such a low correlation coefficient was obtained.

When the number per annum of M $\geq$ 6 shallow earthquakes is cross correlated with the number per annum of M $\geq$ 6 intermediate earthquakes, only for the period 1931 to 1961, a maximum cross correlation coefficient of 0.54 is obtained at zero lag. This is still lower than might have been anticipated from comparison of the graphs.

IX. SPACE-TIME RELATIONSHIP BETWEEN PULSES OF SEISMIC ACTIVITY IN SMALLER REGIONS OF SOUTH AMERICA

1. Discussion

In Chapter III it was suggested that pulses of volcanic activity in the areas of both the eastern and western Pacific margin seem to travel south with time.

Hence, it seemed logical to investigate whether a similar situation exists with earthquake activity in South America.

For the purpose, the area bounded by the parallels 6°N and 53°S, and the meridians 55°W and 85°W was divided from north to south into six regions: region A (6°N – 5°S), region B (5+°S – 15°S), region C (15+°S – 25°S), region D (25+°S – 32°S), region E (32+°S – 41°S), and region F (41+°S – 53°S), as shown in Fig. 28.

As in Chapter VIII, the shallow, intermediate and deep earthquake activity was considered under three categories: number of $M \geq 6$ earthquakes per annum (1931 to 1971), number of $M \geq 7$ earthquakes per annum (1904 to 1971) and annual $M \geq 7$ earthquake energy release (1904 to 1971). These are graphed in Figs. 29 to 37.

2. Method of Analysis of Data

The first and simplest method was by visual study of

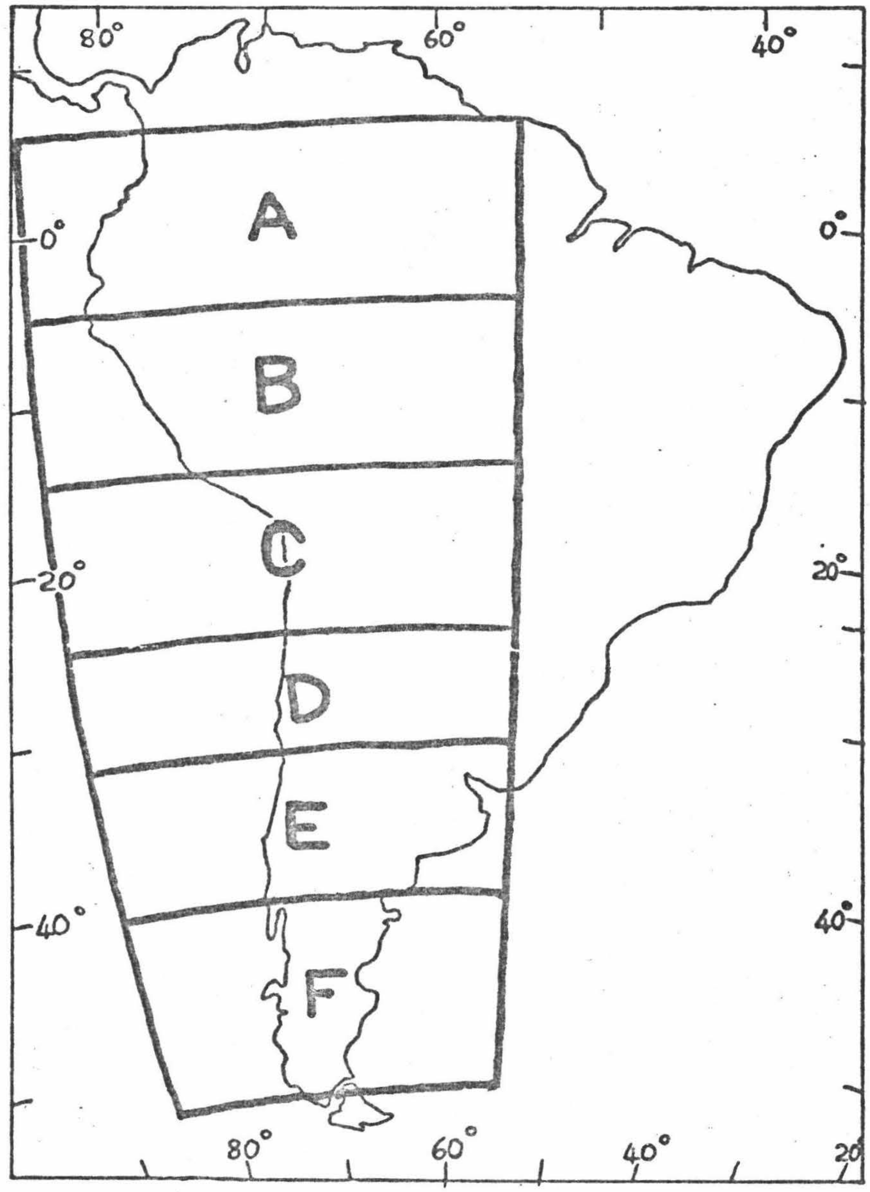


Fig. 28. Locations of regions A to F in South America.

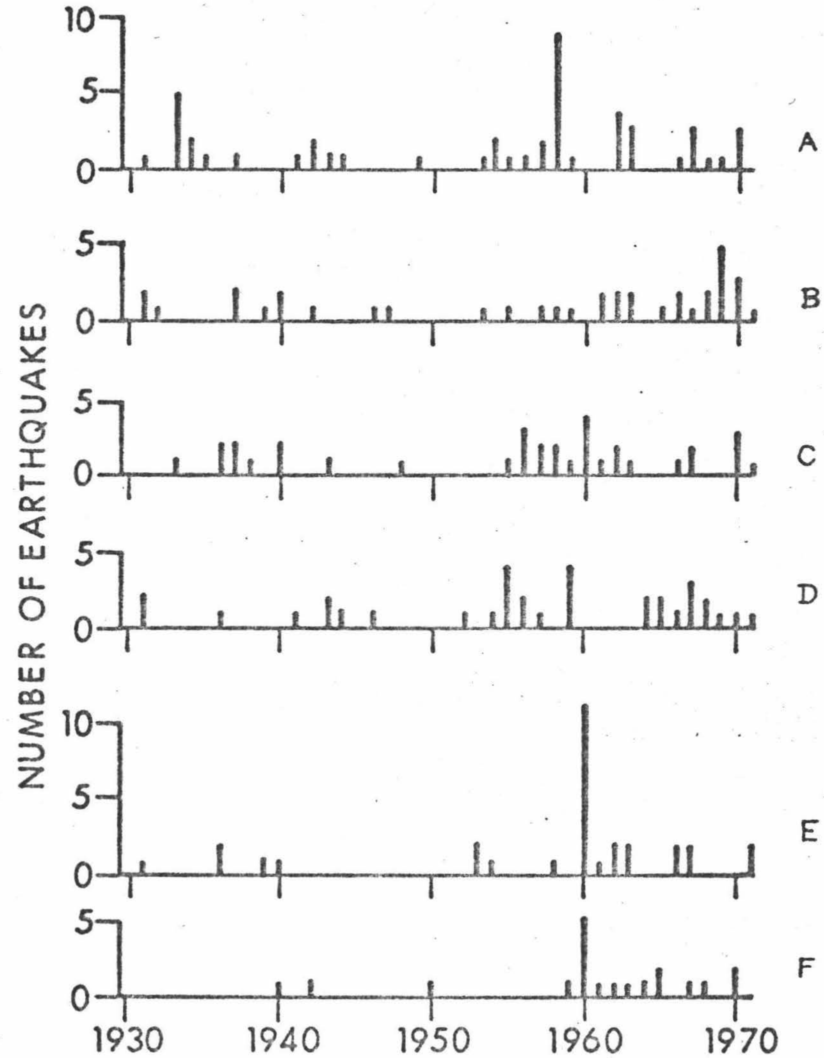


Fig. 29. Number per annum of $M \geq 6$ shallow earthquakes (1931 to 1971) in South America, regions A to F.

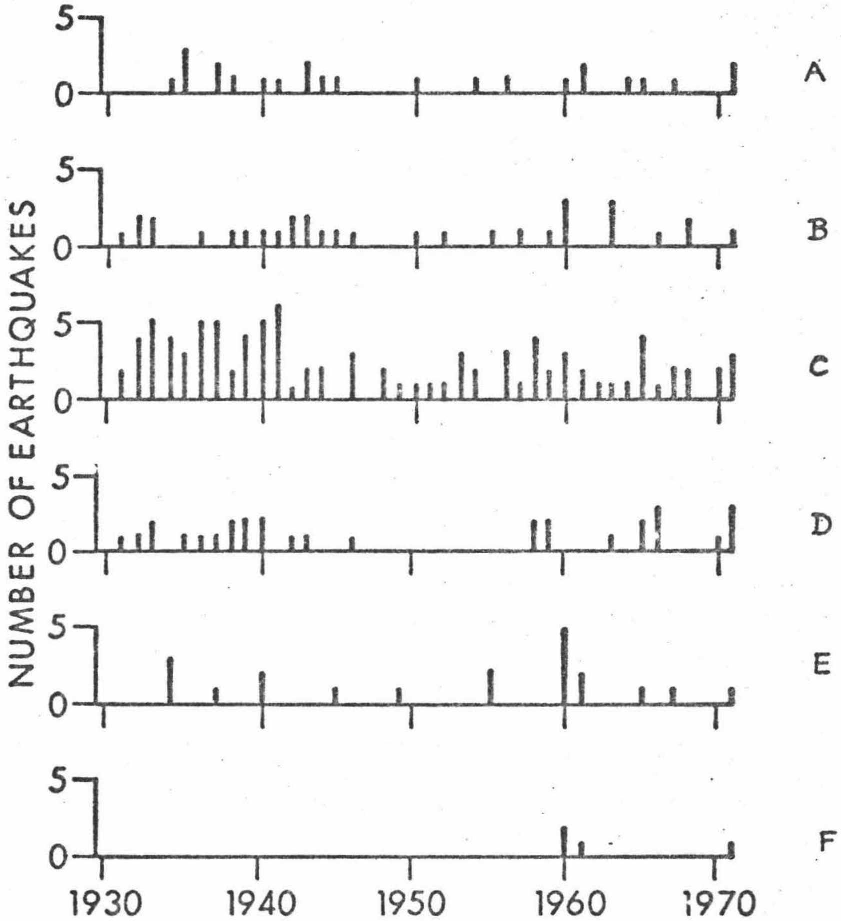


Fig. 30. Number per annum of $M \geq 6$ intermediate earthquakes (1931 to 1971) in South America, regions A to F.

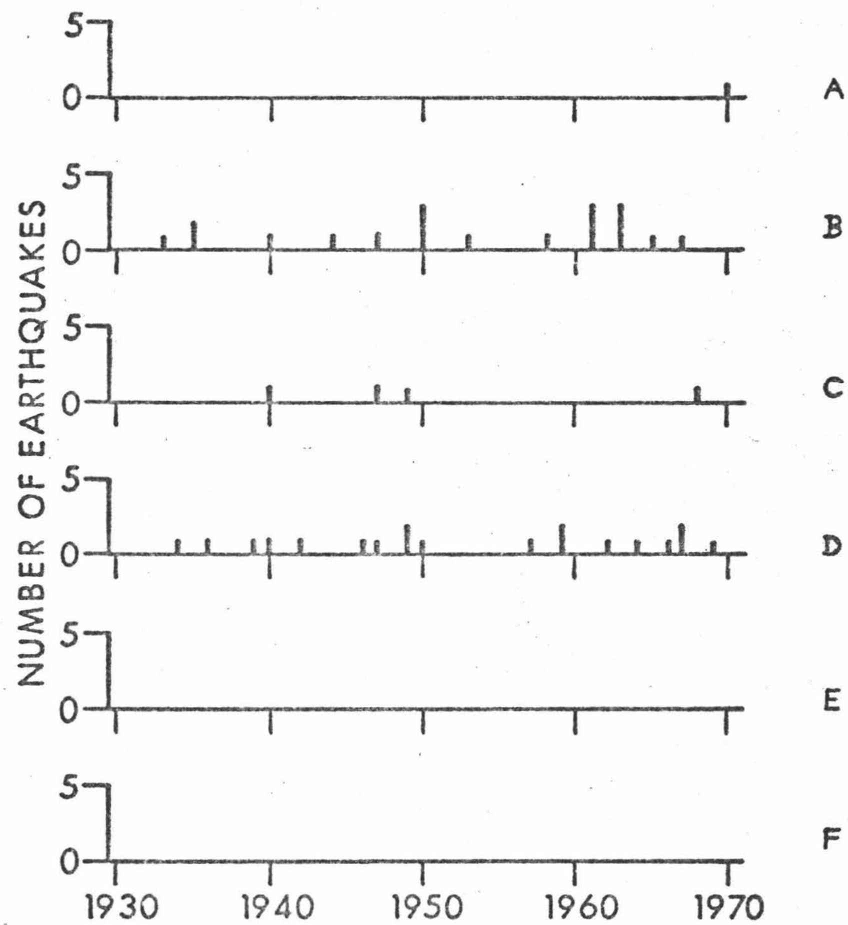


Fig. 31. Number per annum of $M \geq 6$ deep earthquakes (1931 to 1971) in South America, regions A to F.

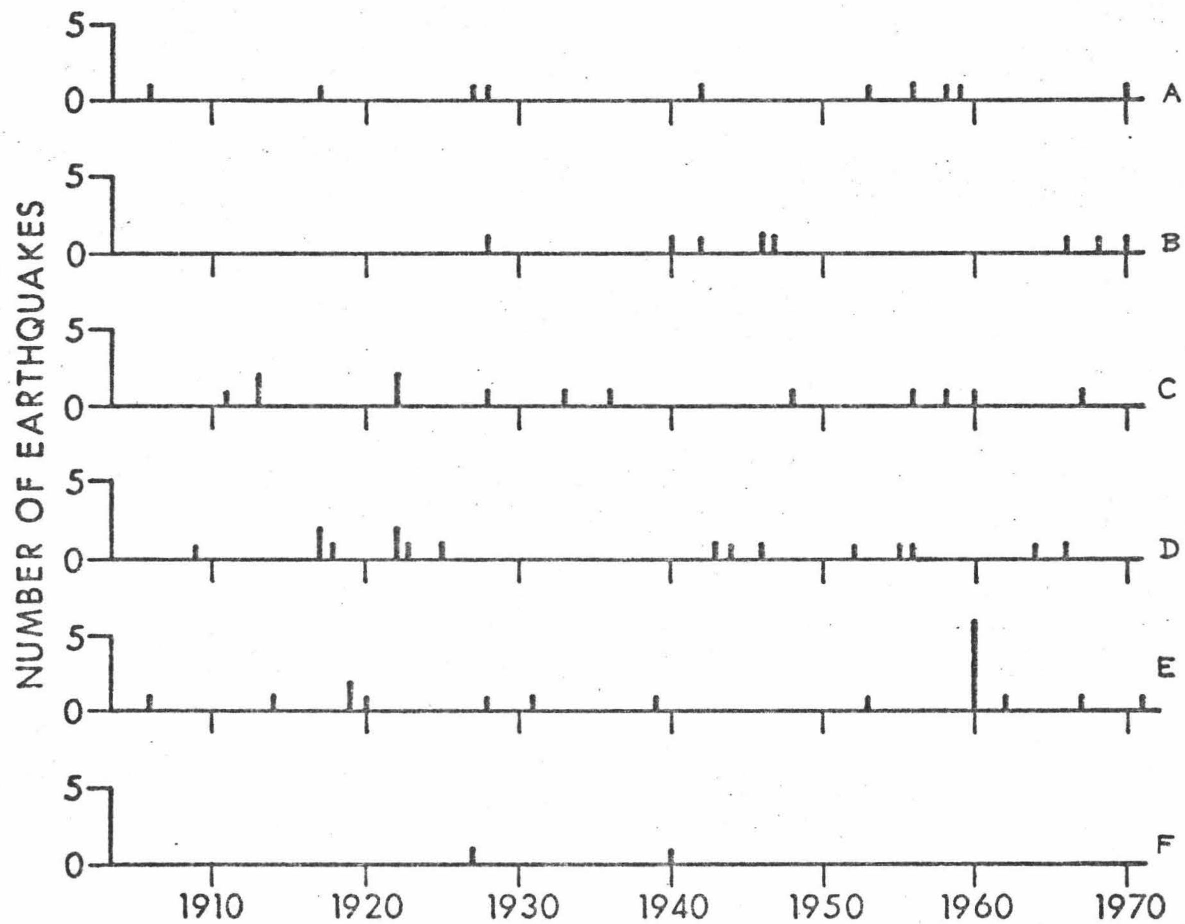


Fig. 32. Number per annum of M≥ 7 shallow earthquakes (1904 to 1971) in South America, regions A to F.

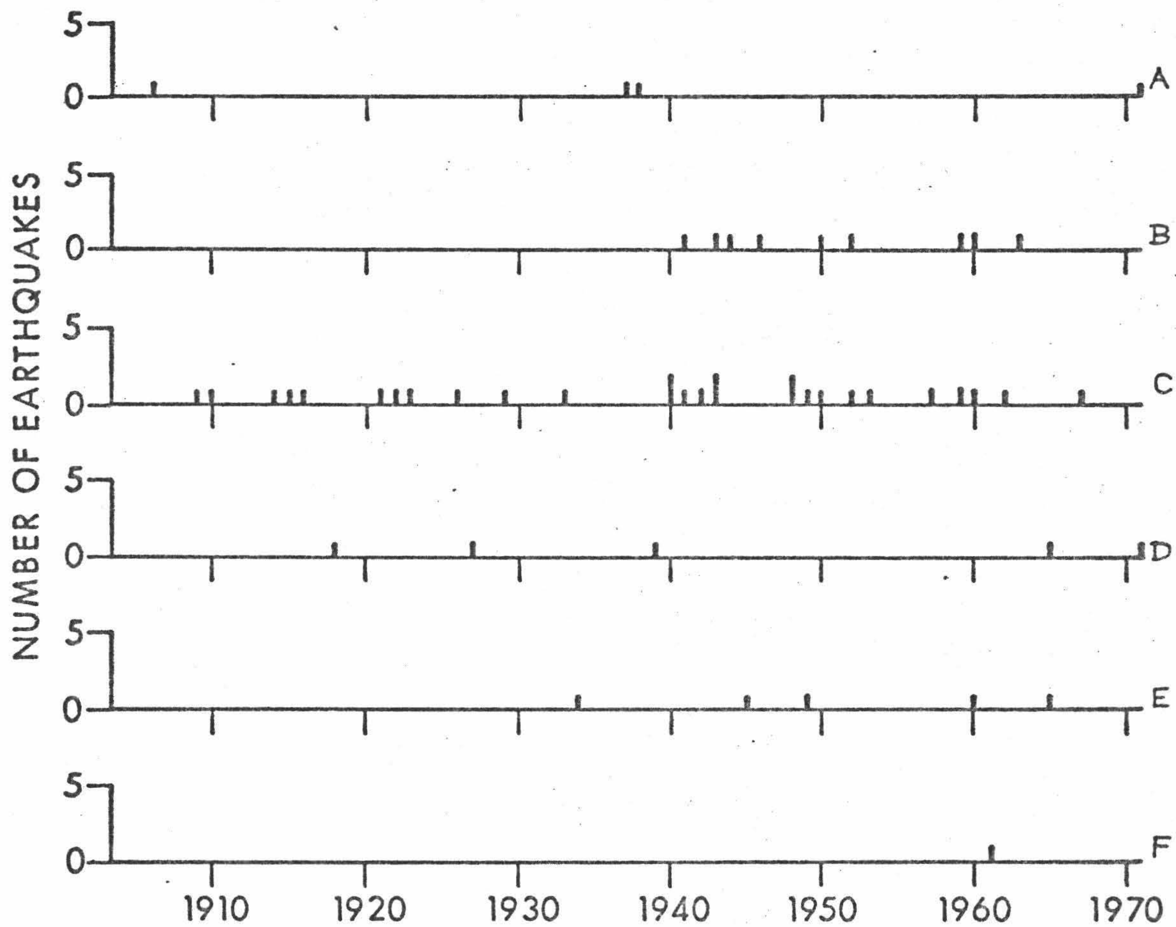


Fig. 33. Number per annum of M≥ 7 intermediate earthquakes (1904 to 1971) in South America, regions A to F.

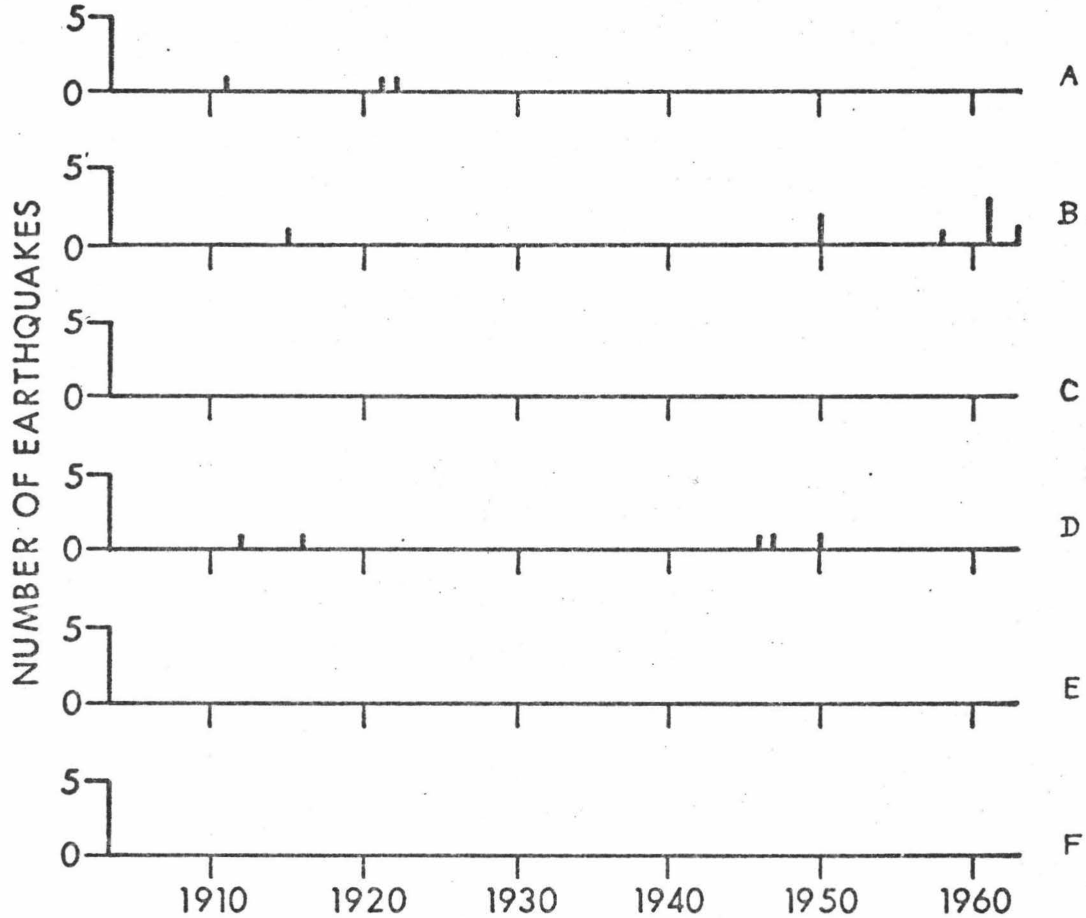


Fig. 34. Number per annum of $M \geq 7$ deep earthquakes (1904 to 1971) in South America, regions A to F.

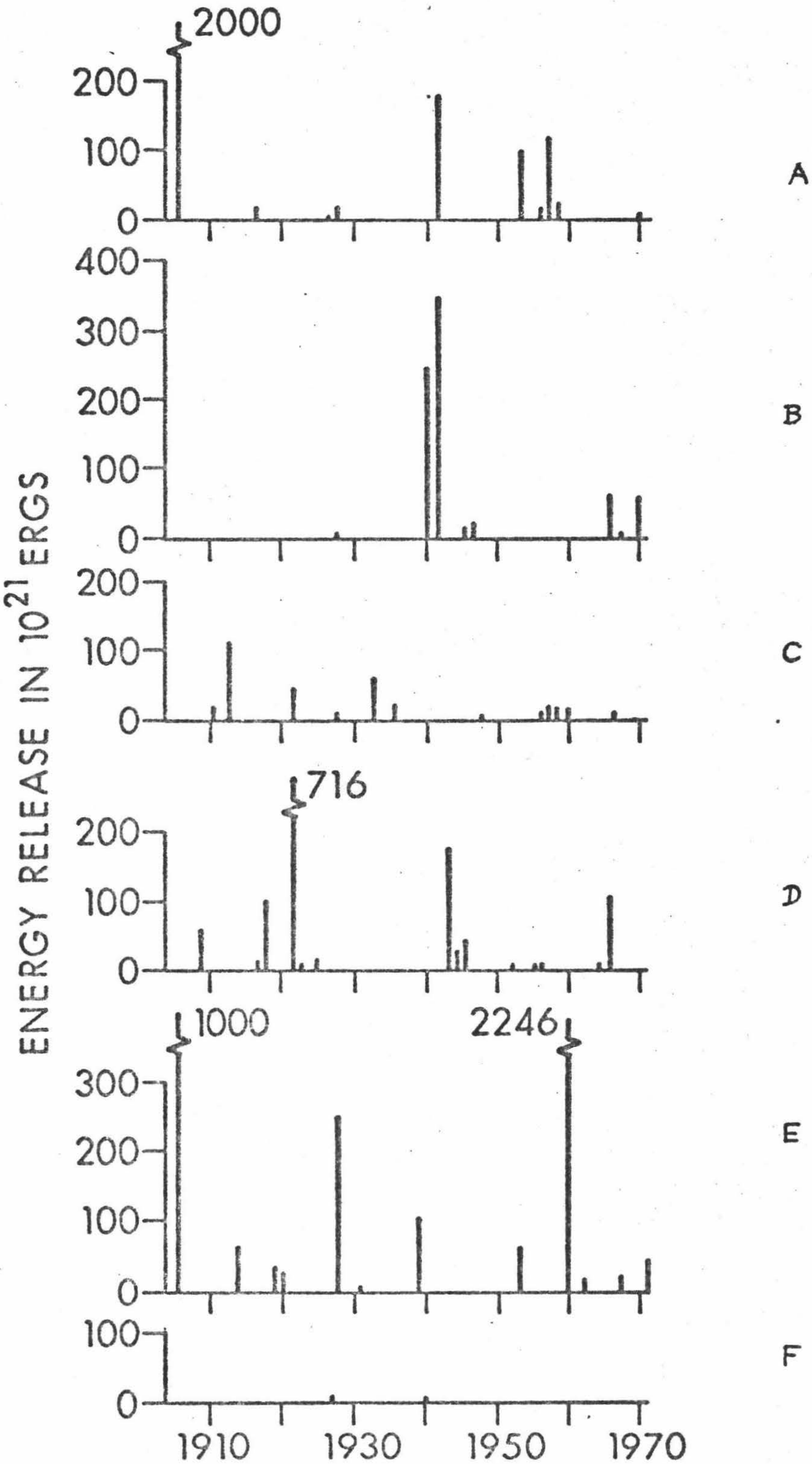


Fig. 35. M≥7 shallow earthquake energy release per annum (1904 to 1971) in South America, regions A to F.

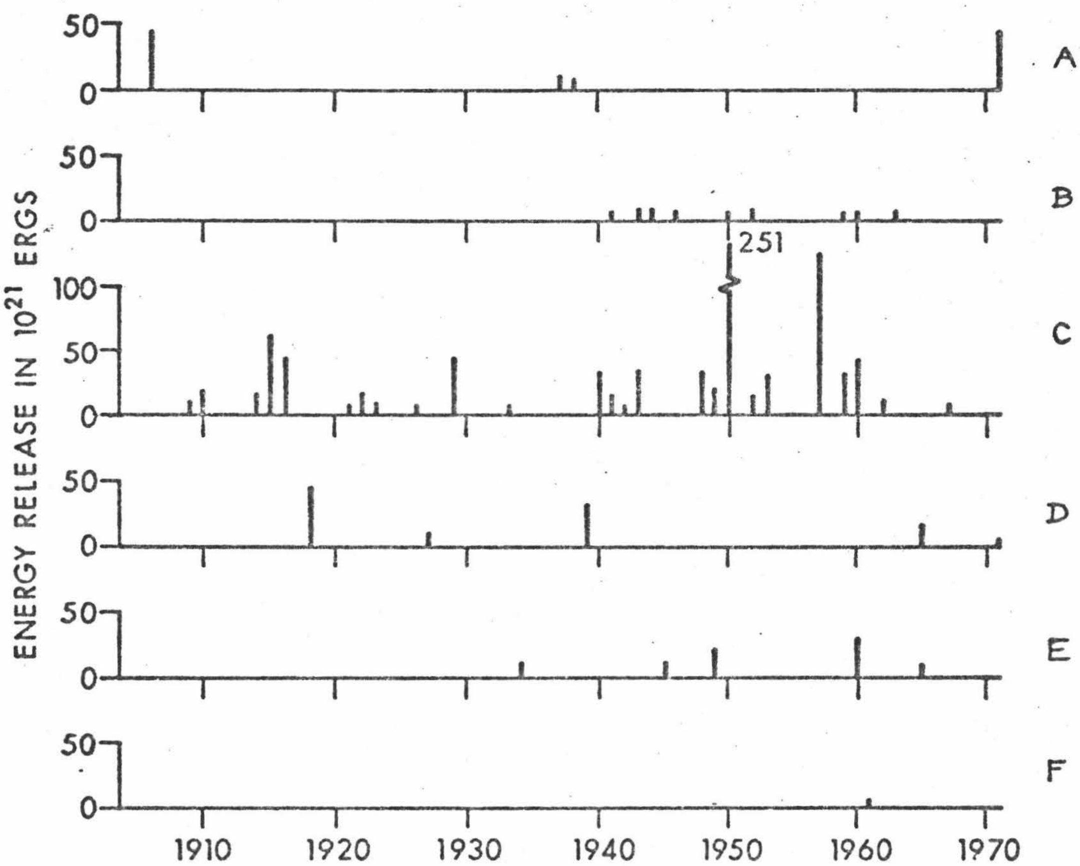


Fig. 36. M≥7 intermediate earthquake energy release per annum (1904 to 1971) in South America, regions A to F.

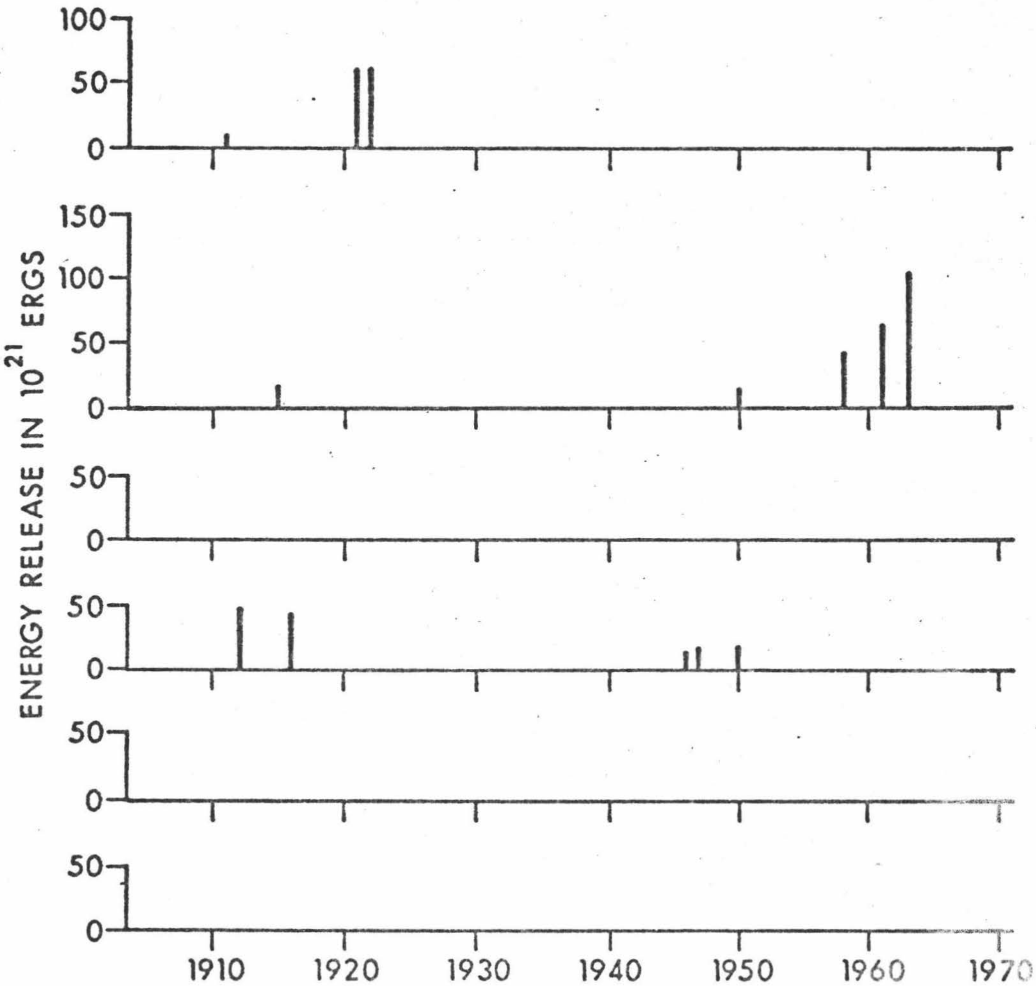


Fig. 37. $M \geq 7$ deep earthquake energy release per annum (1904 to 1971) in South America, regions A to F.

Figs. 29 to 37 to see if there was any obvious pattern of pulses.

In the cases of the number per annum of $M \geq 6$ and $M \geq 7$ earthquakes, graphs were also drawn showing the years for which the maximum or one less than the maximum number of earthquakes occurred in a particular category (Figs. 38 and 39). This emphasizes only the largest pulses and filters out smaller ones which may be due merely to local effects. It was not possible to do this for energy release because it does not have integer values.

Because of the large volume of data, the cross correlation technique was used only if there appeared to be a convincing pattern, with the presumed same pulse occurring in a large number of areas.

3. Results

3.1. Number of $M \geq 6$ Earthquakes Per Annum

The diagonal lines of markers in the three graphs in Fig. 38 indicate the possibility of a pattern of migration of pulses.

For deep earthquakes they appear to occur earlier in the south and travel north, but the pattern is not very well defined.

For shallow and for intermediate earthquakes of regions A, B, C and D, the inverted V_s, made up of diagonal lines of pulses, suggest that pulses may travel from south to

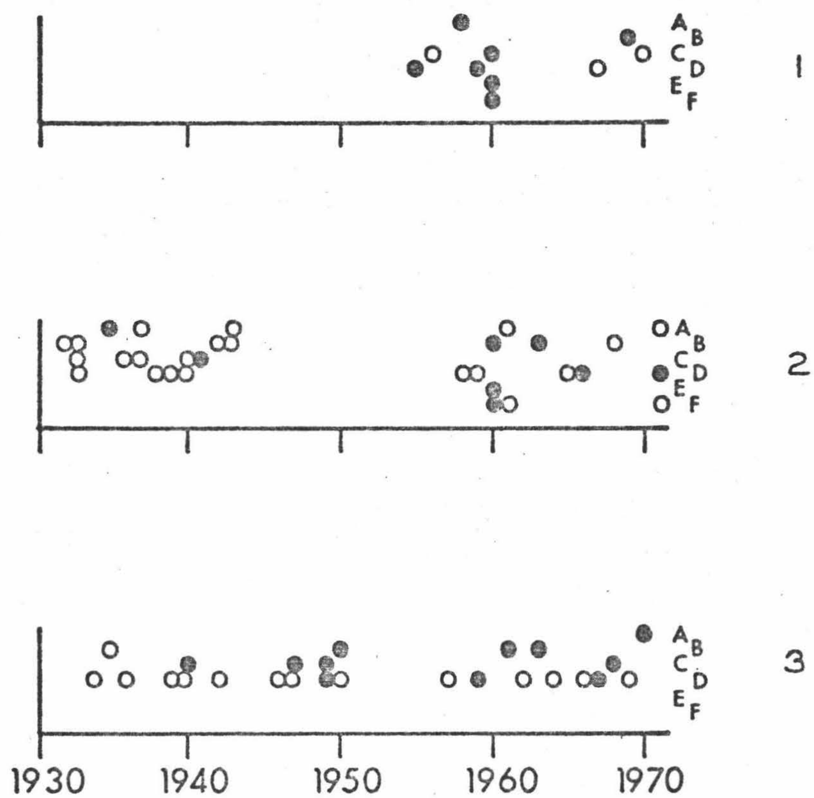


Fig. 38. South America, regions A to F: years with the maximum (solid black circles) or one less than the maximum (open circles) number of $M \geq 6$ earthquakes per annum (1931 to 1971)--1. shallow, 2. intermediate, 3. deep.

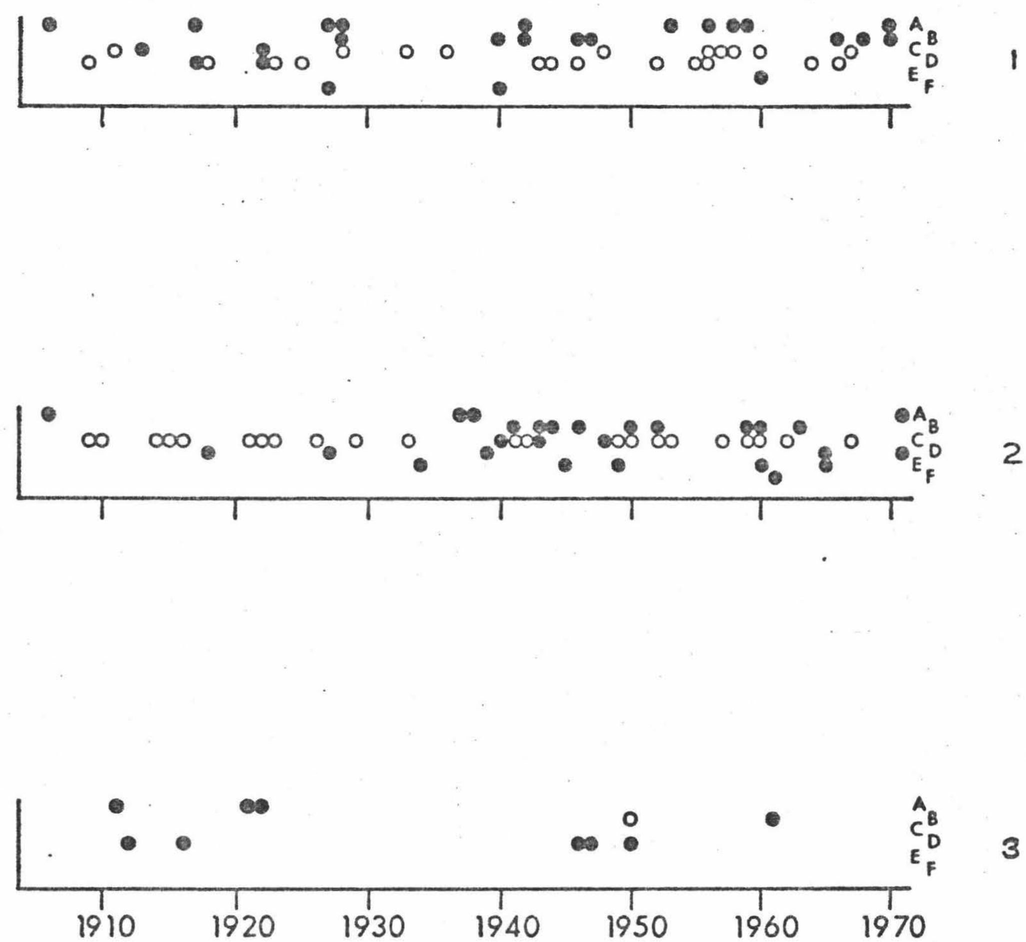


Fig. 39. South America, regions A to F: years with the maximum (solid black circles) or one less than the maximum (open circles) number of M≥ 7 earthquakes per annum (1904 to 1971)--1. shallow, 2. intermediate, 3. deep.

north and then from north to south. For shallow earthquakes in regions E and F, the pulses may be simultaneous.

Cross correlation was performed on the shallow, intermediate and deep earthquake data and the results are shown in Tables IX, X and XI--no such pattern of pulse migration is revealed, but the simultaneity of shallow earthquake pulses in regions E and F is confirmed. However, a south-north then north-south migration of pulses would not be expected to show up clearly with cross correlation. It is interesting to note that for the shallow earthquakes, the maximum cross correlation coefficients obtained for regions D, E and F (at lags of -3, +2 and +2 years respectively relative to region A) are quite high (greater than 0.6). For the intermediate earthquakes, for which the regions were cross correlated with region C, the maximum cross correlation coefficients become smaller with increasing distance north or south of region C. A similar result was obtained at zero lag by Tsuboi (1958) in Japan.

3.2. Number of $M \geq 7$ Earthquakes Per Annum

Figure 39 does not reveal a consistent pattern of pulse migration.

3.3. Annual $M \geq 7$ Earthquake Energy Release

Comparison of the higher maxima in the graphs for shallow earthquakes in Fig. 35 suggests that these pulses tend to

Table IX

South America--Number of Shallow
$M \geq 6$ Earthquakes Per Annum

Cross Correlation Results

Areas being cross correlated with, and lagged positively with respect to region (A). Lags (1) and (2) are the lags for which the highest and second highest cross correlation coefficients (r) occur, provided that these differ by no more than 0.02.

Area	Lag (1)		Lag (2)
Region (A)	0		
Region (B)	+7	(r = 0.32)	
Region (C)	+4, +2	(r = 0.31)	-2 (r = 0.31)
Region (D)	-3	(r = 0.67)	
Region (E)	+2	(r = 0.64)	
Region (F)	+2	(r = 0.62)	

Table X

South America--Number of Intermediate
$M \geq 6$ Earthquakes Per Annum

Cross Correlation Results

Areas being cross correlated with, and lagged positively with respect to, region (C). Lags (1) and (2) are the lags for which the highest and second highest cross correlation coefficients (r) occur, provided that these differ by no more than 0.02.

Area	Lag (1)	Lag (2)	
Region (A)	+4 (r = 0.30)	+2 (r = 0.29)	
Region (B)	-8 (r = 0.42)		
Region (C)	0		
Region (D)	-1 (r = 0.40)		
Region (E)	+1 (r = 0.15)	+2 (r = 0.15)	0 (r = 0.14)
Region (F)	-5 (r = 0.12)		

Table XI

South America--Number of Deep
$M \geq 6$ Earthquakes Per Annum

Cross Correlation Results

Areas being cross correlated with, and lagged positively with respect to, region (D). Lags (1) and (2) are the lags for which the highest and second highest cross correlation coefficients (r) occur, provided that these differ by no more than 0.02.

Area	Lag (1)	Lag (2)
Region (A)	Program would not run, but shows negative r at lag 0.	
Region (B)	+ 4 (r = 0.34)	+1 (r = 0.32)
Region (C)	-10 (r = 0.42)	
Region (D)	0	

be simultaneous or to migrate south with time.

The graphs for intermediate earthquakes (Fig. 36) do not seem to indicate a pattern, and neither do those for deep earthquakes (Fig. 37).

4. Conclusions

Omori (1923) suggested that, because they release excess strain in the earth's crust, great shallow earthquakes do not repeat at one and the same place in a seismic zone, and in this chapter it has been found that large pulses in the number of shallow and of intermediate $M \geq 6$ earthquakes per annum may indeed have a tendency to migrate from south to north and then from north to south with time. Pulses in $M \geq 6$ shallow earthquake activity tend to be simultaneous in regions E and F.

Large pulses in annual $M \geq 7$ shallow earthquake energy release tend to be simultaneous or to migrate south with time. For example, the 1906 pulse occurred in both regions A and E, whereas the 1942 pulse of regions A and B occurred in 1943 in region D.

However, the earthquake patterns are not nearly as well marked as the migration patterns of circum-Pacific volcanic pulses (see Chapter III).

X. RELATIONSHIP BETWEEN THE NUMBER OF VOLCANOES IN ERUPTION PER ANNUM AND LARGE MAGNITUDE SEISMIC ACTIVITY IN SOUTH AMERICA

1. Method of Analysis of Data

To compare volcanic and seismic activity, the cross correlation technique, described in Chapter III, was used.

Again, the shallow, intermediate and deep earthquake data were grouped into three categories: number of $M \geq 6$ earthquakes per annum (1931 to 1968), number of $M \geq 7$ earthquakes per annum (1904 to 1968), and annual $M \geq 7$ earthquake energy release (1904 to 1968). These were cross correlated with the data on the number of volcanoes in eruption per annum in South America for the same time periods. The reason for these series being truncated at 1968 is that the South American volcano data stop at 1968.

The relevant series are graphed in Figs. 20, 21, 23, 24 and 25.

2. Results

The cross correlation results are shown in Table XII.

For all three categories of shallow seismic activity, the highest cross correlation coefficient is obtained at lag 0. Hence, pulses in volcanic activity tend to coincide with pulses in shallow earthquake activity.

Table XII

South America

Number of Volcanoes in Eruption Per Annum and Seismic Activity--Cross Correlation Results with Earthquake Data Being Lagged Positively Related to Volcano Data

	L	r
$M \geq 6$ shallow earthquakes	0	0.26
$M \geq 6$ intermediate earthquakes	0	0.36
$M \geq 6$ deep earthquakes	-10	0.46
$M \geq 7$ shallow earthquakes	0	0.22
$M \geq 7$ intermediate earthquakes	-10	0.15
$M \geq 7$ deep earthquakes	-10	0.45
$M \geq 7$ shallow earthquake energy release	0	0.54
$M \geq 7$ intermediate earthquake energy release	-10	0.39
$M \geq 7$ deep earthquake energy release	+ 8	0.39

For $M \geq 6$ intermediate earthquakes, the highest cross correlation coefficient is obtained at lag 0. Hence, pulses in the number of $M \geq 6$ intermediate earthquakes per annum tend to coincide with pulses in the number of volcanoes in eruption per annum.

For the number of $M \geq 7$ intermediate earthquakes per annum, and for the annual $M \geq 7$ intermediate earthquake energy release, the highest cross correlation coefficient is at lag -10, so pulses in earthquake activity tend to occur 10 years before pulses in volcanic activity. It was found in Chapter VIII that pulses in intermediate earthquake energy release also occur 10 years before pulses in shallow earthquake energy release, suggesting that the latter should coincide with pulses in volcanic activity--a fact confirmed above.

For the number of $M \geq 6$ and $M \geq 7$ deep earthquakes per annum, the highest cross correlation coefficients were obtained at a lag of -10 years. Hence, the peaks in deep earthquake activity tend to occur 10 years before peaks in volcanic activity.

For $M \geq 7$ deep earthquake energy release, the highest cross correlation coefficient is obtained for a lag of +8 years, so that pulses in deep earthquake energy release tend to occur approximately 8 years after pulses in volcanic activity.

The cross correlation coefficients for the $M \geq 6$ shallow, intermediate and deep earthquakes are greater than the corresponding $M \geq 7$ earthquake cross correlation coefficients. Hence the number of volcanoes in eruption per annum correlates better with the numbers of $M \geq 6$ shallow, intermediate and deep earthquakes per annum (1931 to 1968) than it does with the corresponding $M \geq 7$ earthquakes per annum (1904 to 1968).

However, the cross correlation coefficients for $M \geq 7$ shallow and for $M \geq 7$ intermediate earthquake energy release are higher than the corresponding cross correlation coefficients for $M \geq 7$ and $M \geq 6$ numbers of earthquakes per annum, so that it seems that the correlation between the number of volcanoes in eruption per annum and shallow or intermediate earthquake energy release is higher than that between the number of volcanoes in eruption per annum and the corresponding numbers of shallow or intermediate earthquakes per annum.

3. Conclusions

The maximum cross correlation coefficients are all low, so that there is not a very strong correlation between the number of volcanoes in eruption per annum and large magnitude seismic activity in South America.

The only maximum cross correlation coefficient exceeding 0.5 was a value of 0.54 at zero lag obtained by cross correlating the number of volcanoes in eruption per annum (1904 to 1968) with annual $M \geq 7$ shallow earthquake energy release for the same period. Hence, the best correlation between volcanic activity and large magnitude seismic activity is that for $M \geq 7$ shallow earthquake energy release.

When the volcano graph (Fig. 17) is compared with the above-mentioned energy release graph (Fig. 23) it may be seen that the correlation arises mainly from the fact that 1906 and 1960 were years both of maximum volcanic activity in terms of the number of volcanoes in eruption and maximum seismic energy release (both for $M \geq 7$ shallow earthquakes and for total $M \geq 7$ earthquakes). Hence, perhaps high volcanic activity is connected with the occurrence of $M > 8$ earthquakes, and shocks of lower magnitude may be considered as noise.

These two years must have been times of extraordinary tectonic instability in the South American continent.

1906 was a year of comparatively high volcanic activity in Colombia-Ecuador, Peru and Southern Chile, and two great earthquakes occurred, one with magnitude 8.6 in region A (off the coast of Colombia-Ecuador) and one with magnitude 8.4 in region E (Central Chile). Hence, the tectonic activity was widespread rather than localized.

1960 was a year of comparatively high volcanic activity in Northern Chile and Central Chile and a magnitude of 8.25 to 8.5 earthquake, accompanied by many smaller ones, occurred in region E (Central Chile). Thus, the 1960 tectonic activity was more localized than that of 1906.

It is interesting to note that after 1961, the volcanic activity in South America dropped to the lowest level this century; there were no volcanoes in eruption during the period 1962 to 1968, except for 1964 when two were in eruption. The same is not true of earthquake energy release, nor did this happen after the 1906 tectonic activity.

XI. CONCLUSIONS

In 16 out of 21 circum-Pacific areas studied, fluctuations in the number of volcanoes in eruption per annum (1900 to 1968) appear to be statistically significant.

In 12 of these areas, the time series for the number of volcanoes in eruption per annum display a poorly-defined periodicity. The periods have a bimodal distribution, those of the western Pacific areas, with few exceptions, being approximately half those of the eastern Pacific areas. The periods range from nine through 34 years.

If these short-term periodicities are due to pulsations in sea floor spreading, they may be related to two major mantle flow regimes, one to the west of the East Pacific Rise, the other to the east of it. The East Pacific Rise is closer to the eastern Pacific margin and hence the pattern of mantle currents to the east of the Rise would be expected to be different from that to the west of it. This may account for the bimodal distribution of periods. Also, because of the probable complexity of mantle flow under the Pacific (for example, to the east of the Rise there is more than one plate) the periods may be expected to differ from area to area.

On both the eastern and western Pacific margins, the large pulses in volcanic activity tend to travel south with time, at rates of the order of five degrees per year. This tendency is more pronounced on the eastern Pacific margin than on the western, possibly because the amplitude of the fluctuations in the number of volcanoes in eruption per annum is statistically significant on the western Pacific margin, considered as a single unit, and not on the eastern Pacific margin, so that there is presumably more simultaneity in volcanic activity on the western Pacific margin whereas on the eastern Pacific margin lagged effects predominate.

There is little correlation between the number of volcanoes in eruption per annum on the western and eastern Pacific margin; at zero lag, the correlation is slightly negative.

Earthquake activity in South America was considered in three main categories: number of $M \geq 6$ earthquakes per annum (1931 to 1971), number of $M \geq 7$ earthquakes per annum (1904 to 1971) and annual $M \geq 7$ earthquake energy release (1904 to 1971), and each of these was subdivided into shallow, intermediate and deep seismic activity. The fluctuations in most of these series have a significant amplitude, but little serial correlation or periodicity, except that the total (shallow + intermediate + deep) $M \geq 6$ earthquakes, and the $M \geq 6$ shallow earthquakes have a possible 30-year periodicity, and the $M \geq 6$ intermediate earthquakes have a possible 25-year periodicity. These periodicities are of the same order as periodicities in volcanic activity on the eastern Pacific margin.

In all three of the main categories, pulses in intermediate earthquake activity tend to occur earlier than pulses in deep earthquake activity, and in two out of the three categories, pulses in intermediate earthquake activity tend to occur earlier than pulses in shallow earthquake activity. This does not seem to fit in with theories of crustal material descending under the Andes as a single coherent lithospheric plate.

Large pulses in the number of shallow and of intermediate $M \geq 6$ earthquakes per annum, in South America, may have a tendency to migrate from south to north and then from north to south with time, and large pulses in annual $M \geq 7$ shallow earthquake energy release tend to be simultaneous or to migrate south with time. However, the earthquake pulse migration patterns are not nearly as well-marked as those of the circum-Pacific volcanic pulses.

There is not a very strong correlation between pulses of volcanic and large magnitude seismic activity in South America. However, the highest cross correlation coefficient is 0.54, obtained at lag 0 when annual $M \geq 7$ shallow earthquake energy release was cross correlated with the number of volcanoes in eruption per annum. This correlation arises mainly from the fact that 1906 and 1960 were years both of maximum volcanic activity (in terms of the number of volcanoes in eruption per annum) and very high seismic energy release, mainly from shallow $M > 8$ earthquakes.

The 1906 tectonic activity in South America was widespread, whereas that of 1960 tended to be localized in Chile.

XII. REFERENCES

Artyushkov, E. A. 1970. Density differentiation on the core-mantle interface and gravity convection. Phys. Earth Planet. Inter., V. 2, pp. 318-325.

Barazangi, M., Isacks, B. L., Oliver, J., Dubois, J., and Pascal, G. 1973. Descent of lithosphere beneath New Hebrides, Tonga-Fiji and New Zealand: evidence for detached slabs. Nature, V. 242, No. 5393, pp. 98-101.

Carey, S. W. 1958. The tectonic approach to continental drift. In Continental Drift. A Symposium. Univ. Tasmania, Hobart.

Casertano, L. 1963. Catalogue of the active volcanoes of the world including solfatara fields. Part XV. Chilean continent. Int. Volc. Assoc., Rome.

Clark, R. H. 1970. Volcanic activity on White Island, Bay of Plenty, 1966-69. Part 1. Chronology and crater floor level changes. New Zealand J. Geol. Geophys., V. 13, No. 3, pp. 565-574.

Coats, R. R. 1950. Volcanic activity in the Aleutian arc. U. S. Geol. Survey Bull. 974-B.

Coombs, H. A., and Howard, A. D. 1960. Catalogue of the active volcanoes of the world including solfatara fields. Part IX. United States of America. Int. Volc. Assoc., Naples.

Dixon, W. J., and Massey, F. J., Jr. 1969. Introduction to statistical analysis. McGraw-Hill, Inc., New York.

Durbin, J., and Watson, G. S. 1951. Testing for serial correlation in least squares regression II. Biometrika, V. 38, pp. 159-178.

Eggers, A. A., and Decker, R. W. 1969. Frequency of historic volcanic eruptions. Trans. Amer. Geophys. Union, V. 50, No. 4, p. 343 (abstract only).

Fisher, N. H. 1957. Catalogue of the active volcanoes of the world including solfatara fields. Part V. Melanesia. Int. Volc. Assoc., Naples.

Gajardo, E., and Lomnitz, C. 1960. Seismic provinces of Chile. Proc. Second World Conf. Earthquake Eng., V. 3, pp. 1529-1540.

Gorshkov, G. S. 1958. Catalogue of the active volcanoes of the world including solfatara fields. Part VII. Kurile Islands. Int. Volc. Assoc., Naples.

Gorshkov, G. S. 1972. Progress and problems in volcanology. Tectonophysics, V. 13, pp. 123-140.

Green, W. L. 1887. Vestiges of the molten globe Honolulu.

Gregg, D. R. 1960. The geology of Tongariro subdivision. New Zealand Geol. Survey Bull., No. 40, 152 pp.

Gutenberg, B., and Richter, C. F. 1954. Seismicity of the earth and associated phenomena. Princeton University Press, Princeton, New Jersey.

Hamilton, W. M., and Baumgart, I. L. 1959. White Island. Bull. New Zealand Dept. Scient. Ind. Res., No. 127.

Hantke, G., and Parodi, I. A. 1966. Catalogue of the active volcanoes of the world including solfatara fields. Part XIX. Colombia, Ecuador and Peru. Int. Volc. Assoc., Rome.

Heck, N. H. 1936. Earthquakes. Princeton University Press, Princeton, New Jersey, p. 217.

Hoel, P. G., and Jessen, R. J. 1971. Basic statistics for business and economics. John Wiley, New York.

Jaggar, T. A. 1931a. The Hawaiian volcanic cycle. The Volcano Letter, No. 325. Hawaiian Volcano Observatory, National Park, Hawaii.

Jaggar, T. A. 1931b. Volcanic cycles and sunspots. The Volcano Letter, No. 326. Hawaiian Volcano Observatory, National Park, Hawaii.

Jaggar, T. A. 1932. Eruption cycles in Hawaii. Hawaiian Annual for 1932, pp. 83-93.

Jaggar, T. A. 1947. Origin and development of craters. Geol. Soc. Amer., Memoir 21, 508 pp.

Kelleher, J. A. 1970. Space-time seismicity of the Alaska-Aleutian seismic zone. J. Geophys. Res., V. 75, No. 29, pp. 5745-5756.

Kuno, H. 1962. Catalogue of the active volcanoes of the world including solfatara fields. Part XI. Japan, Taiwan and Marianas. Int. Volc. Assoc., Rome.

Latter, J. H., 1968. Active volcanoes and fumarole fields of the world on punched cards (with their eruptions since January 1963). Bull. Volc., Tome XXXIII, Fasc. 1, pp. 299-300.

Latter, J. H. 1971. The interdependence of seismic and volcanic phenomena: some space-time relationships in seismicity and volcanism. Bull. Volc., Tome XXXV, Fasc. 1, pp. 127-142.

Lomnitz, C. 1966. Statistical prediction of earthquakes. Rev. Geophys., V. 4, No. 3, pp. 377-393.

Lomnitz, C. 1967. Time series and earthquake prediction. Proc. IBM Scient. Comp. Symp. Envir. Sci., Thomas J. Watson Research Center, Yorktown Heights, N. Y.

Machado, F. 1967. Activity of the Atlantic volcanoes, 1947-1967. Bull. Volc., Tome XXX, pp. 29-34.

Mooser, F., Meyer-Abich, H., and McBirney, A. R. 1958. Catalogue of the active volcanoes of the world including solfatara fields. Part VI. Central America. Int. Volc. Assoc., Naples.

Munk, W. H., and MacDonald, G. J. F. 1960. The rotation of the earth. Cambridge, New York.

Neumann van Padang, M. 1951. Catalogue of the active volcanoes of the world including solfatara fields. Part I. Indonesia. Int. Volc. Assoc., Naples.

Neumann van Padang, M. 1953. Catalogue of the active volcanoes of the world including solfatara fields. Part II. Philippine Islands and Cochin China. Int. Volc. Assoc., Naples.

Omori, F. 1923. Earthquake zones in and around the Pacific. Bull. Imper. Earthquake Investig. Committee, V. XI, No. 1, pp. 28-32.

Ralston, A., and Wilf, H. S. 1966. Mathematical methods for digital computers. John Wiley & Sons, Inc., New York.

Richard, J. J. 1962. Catalogue of the active volcanoes of the world including solfatara fields. Part XIII. Kermadec, Tonga and Samoa. Int. Volc. Assoc., Rome.

Rinehart, J. S. 1972. 18.6 year earth tide regulates geyser activity. Science, V. 177, pp. 346-347.

Robson, G. R., and Tomblin, J. F. 1966. Catalogue of the active volcanoes of the world including solfatara fields. Part XX. West Indies. Int. Volc. Assoc., Rome.

Tsuboi, C. 1958. Earthquake province--domain of sympathetic seismic activities. J. Phys. Earth, V. 6, pp. 35-49.

Vlodavetz, V. I., and Piip, B. I. 1959. Catalogue of the active volcanoes of the world including solfatara fields. Part VIII. Kamchatka and continental areas of Asia. Int. Volc. Assoc., Naples.

Whitten, C. A. 1971. Preliminary investigation of the correlation of polar motion and major earthquakes. Technical Rep., "Earthquake research in ESSA 1969-70," Catalogue No. C52.15: ERL 182 - ESL 11, U. S. Govt. Printing Office, Washington, D. C.

Wood, H.O. 1917. On cyclical variations in eruption at Kilauea. Second Rep. Hawaiian Volcano Observatory, Cambridge, Mass.