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EARTHQUAKE PREDICTABILITY IN HINDUKUSH REGION USING SEISMICITY PATTERN AND CHAOS

S.N. Bhattacharya
Meteorological Office, New Delhi-110 003

H.N. Srivastava
Meteorological Office, Pune-411 005

ABSTRACT

The predictability of earthquakes in Hindukush region has been examined based on spatio-temporal variations of seismicity patterns and the theory of Chaos Physics. Since the spatio temporal pattern of seismicity preceeding earthquakes do not always show a well defined quiescence in this region, recourse taken through the application of Chaos Physics gives the fractal dimension of the strange attractor as 6.9. This implies the possibility of modelling earthquake system in Hindukush region with atleast seven parameters.

INTRODUCTION

The Hindukush ranges are located in the northeast of Nanga Parbat at the western extremity of the Himalaya. The spatial distribution of earthquake foci in the region shows sharply defined E-W alignment about 120 km long and about 25-30 km wide and centered around 36.3°N, 70.5°E; these earthquakes normally have intermediate focal depths. (Chatterjee and Dube, 1979).

The largest earthquake of magnitude 8.0 in the region occurred on 21 October 1907 and 7 July 1909. The epicentres form more or less a V-shaped region (Drakopoulas and Srivastava, 1974) which are explained by considering the remnants of the lithosphere in the Tethys Oceans. Seismicity is attributed to Herat (north of Kabul) fault, the Chaman fault and mountain ranges in the Pamir knot. Focal mechanism of earthquakes in the region has shown thrust faulting. Tension axis was found to be nearly vertical for earthquakes of focal depth of 200 km, implying the sinking of the lithosphere into the mantle due to its greater density. (Tandon and Srivastava, 1975).

For Hindukush region we shall study whether spatio temporal variation of seismicity preceding earthquakes shows any well defined seismic gap and whether earthquake occurrence could be considered as an example of the deterministic Chaos that many non-linear dynamical systems can exhibit.

DATA

We have considered here earthquakes bounded between latitude 36°N and 37°N and longitude 69°E and 72°E and for the period from 1964 to 1988 after the establishment of WWSSN stations by the US Geological Survey. The hypocentres were obtained from the Bulletins of the International Seismological Centre, UK. The minimum magnitude of these earthquakes is determined from the spatial distribution of stations around this region and as this distribution did not change during the period under consideration, the minimum magnitude remained the same whose value was 3.5.

SPACE TIME VARIATION OF SEISMICITY

A major earthquake occurs after sufficient strain energy is accumulated across the faults in the region. It has generally been seen that before a major earthquake, small earthquakes surrounding this region decrease significantly so that sufficient energy is accumulated before it is released during the major earthquake. In space-time diagram of earthquake occurrence of this region, this period of quiescence is seen as a gap. Thus, during the last two decades attempts have been made to use space time variation of seismicity as a tool to predict a major earthquake (Srivastava et al. 1987, Srivastava and Gautam, 1987, Srivastava and Rao, 1991). In order to investigate such space-time variations, we have considered the main earthquakes of magnitude 6 and above. The lowest detection threshold from the ISC for this region is magnitude 4.0. The data is considered homogeneous as explained earlier. The distances of all the earthquakes preceding the major event were obtained and plotted against time. We have also plotted square of this distance against time as space time variation diagram. The plotting begins after the occurrence of an earthquake of magnitude 5.9 or above in the study region. We have studied two major earthquakes namely the earthquake of 30.7.74 near 36.42°N, 70.76°E of magnitude 6.3 preceded by an earthquake of 24.6.72 of magnitude 5.9 and the earthquake of 27.11.76 near 36.52°N, 71.05°E of magnitude 6.2 preceded by the major shock of 30.7.74. The figures 1-a and 1-b show the space time variation preceding the major earthquake of 30.7.74. Ignoring two small earthquakes, the gap is shown in these figures. The figures 2-a and 2-b show the space time variation preceding the major earthquake of 27.11.76. The gap is not discernible. In view of this, earthquake predictability in the Hindukush region has been examined based on Chaos Physics.

MODELLING EARTHQUAKE OCCURRENCE

Earthquake risk assessment is generally based on some statistical technique based on the past history of earthquakes. Srivastava and Dattatrayam (1986) have computed the return periods of earthquakes in the Hindukush region using Gumbel's statistics which compared well with those based on Gutenberg Richter's relationship. However, when the number of earthquakes for each 10 days block during 1964 to 1988 is plotted (Fig. 3), it is noted that the frequency of earthquakes shows irregularity of recurrence with could be attributed to the complexity in the underlying mechanism and to the geological heterogeneity of the earth. Over the last decade, scientists of many disciplines have developed physics of Chaos which offers information about a model, if any, directly from the observation. The realisation that highly irregular and quasi-random behaviour may be generated from simple deterministic dynamics led to search of deterministic chaos in many fields.

A dynamical system can be described by trajectories in the state space which consist of the variables for describing evolutation of the system. Normally all trajectories converge and remain on a submanifold of the total available space. The submanifold which attracts the trajectories is called the attractor. Knowing the evolution of such a system from an initial condition, we can predict the evolution of the system from some other initial condition. Such attractors which have integer dimensions are called non-chaotic attractors. However, there are other dynamical systems where trajectories remain on an attracting submanifold that is not topological. Such manifold is a strange attractor which is associated with a new geometrical object called a fractal set and has a non-integer, dimension (Mandelbrot, 1977; and Peitgen and Richter, 1986). Thus, following the equations that describe the system, the state of the system after some time can be anything even though the initial conditions were close to each other. This imposes limits on prediction and even if the system is described by equations, the system shows randomness. Such systems are chaotic dynamical systems and their attractors are called strange or chaotic attractors. The dimension D of an attractor (chaotic or non-chaotic) indicates the minimum number of independent variables present in the system (Moon, 1987). Thus, if $D = I + p$, where I is an integer and $0 \leq p < 1$, then minimum number of independent variables of the system is $I + 1$. Thus, determination of dimension of the attractor helps us in modelling the system.

DIMENSION OF THE ATTRACTOR FOR EARTHQUAKES IN STUDY AREA

We may consider the dynamics of a system, such as earthquakes, simulated by partial differential equations describing underlying physical processes. These equations can be transformed to a set of n time dependent ordinary differential equations :

$$v'_j = f_j(v_1, v_2, \ldots, v_n) \; ; \; j = 1, 2, \ldots, n \tag{1}$$

where prime denotes differentiation with respect to time t. The time evolution of the system from an initial condition can be described by trajectories in n-dimensional state space with coordinates $v_1, v_2, \ldots, v_n$ which are n different variables. The system (1) can be reduced to a single differential equation of one of the variables $v_j(t)$, say $v(t)$ if all others are eliminated by differentiation. This gives an n th order nonlinear differential equation as

$$v^{(n)} = f\,[v, v', \ldots, v^{(n-1)}]$$

so we replace the state space with $v, v', \ldots v^{(N-1)}$ without any loss of information about the dynamics of the system.

According to the theorem of Takens (1981) D-dimensional manifolds can be embedded into $m = 2D + 1$ dimensional space. Thus, for deriving the dimension of an attractor from a single state variable, it is sufficient to embed them into an m-dimensional space spanned by v and its (m-1) derivatives i.e. $v, v', v'', \ldots v^{(m-1)}$. Thus, it is not necessary to know the original state space and its dimension n as long as m is chosen large enough. Ruelle (1981) suggested that instead of continuous variable $v(t)$ and its derivatives, a discrete time series $v(t)$ and its shifts (m-1) time lags by a delay parameter τ can be considered.

We may begin computation with a time series of a dependent or independent variable v of the system. We choose here v as the number of earthquakes in 10 days block. The delay parameter is chosen either 10 days or 20 days and then the convergence is checked. Let the series be $v_1, v_2, \ldots v_N$, where N is total no. of data and in our case $N = 900$. These values are embedded to construct points X_i in an m - dimensional embedding space

$$X_i = (v_i, v_{i+1}, \ldots \ldots v_{i+m-1})$$

$i = 1, 2, \ldots N - m + 1$ (= k, say). For embedding dimension m, the correlation integral $(C_m(r))$ as a function of correlation length r is given by (Grassberger and Procaccia, 1983).

$$C_m(r) = 1/k_o \sum_{i=1}^{k} \sum_{j=i+1}^{k} H(r - |X_i - X_j|) \tag{2}$$

where H(x) is a Heaviside function

$$H(x) = 1 \quad \text{for } x > 0$$
$$= 0 \quad \text{for } x < 0$$

and $k_o = K(K-1)/2$ is the number of distinct pairs of points x_i and x_j. In equation above, $|X_i - X_j|$ is the distance between X_i and X_j and is obtained by conventional Euclidean measure of distance i.e. by square root of the sum of the squares of components. The correlation of fractal dimension is defined by :

$$D = \lim_{r \to 0} \lim_{m \to \infty} \frac{d[\ln C_m(r)]}{d(\ln r)} \qquad (3)$$

Thus, to obtain correlation dimension of attractors of earthquakes in Hindukush region, we have obtained $C_m(r)$ for different values of r using the relation (2). $C_m(r)$ is plotted against $\ln r$ in figures 4 and 5 for $\tau = 10$ and $\tau = 20$ respectively. To obtain D using equation (3) we require the slope ν of the straight line passing through the points corresponding to each embedding dimension m. However, $C_m(r)$ saturates at large values of r due to finite size of the attractor and at small values of r due to finite N.

Abraham et al. (1986) showed that it is possible to obtain D with small set such as N = 500 by proper choice of scaling region wherein the plot $\ln C_m(r)$ is linear to $\ln r$. Thus, the slope ν of the straight line through the points in scaling region is obtained. The value of ν is obtained for increasing sequence of embedding dimension and plotted in figure 6. It is seen that it increases until saturation value of ν is reached at m = 14 and the saturation value is 6.9 for both $\tau = 10$ days and 20 days. This gives fractal dimension D = 6.9 of the attractor and since the dimension is a non-linear, it is a strange attractor. Thus, minimum 7 independent variables are necessary to model the dynamics of earthquake system in Hindukush region.

DISCUSSION

Considering the seismicity pattern in Hindukush region, it was noted that the earthquakes were not necessarily preceded by well defined seismic gaps. In the Dharamshala - Dalhousie region, however, an increase of seismic activity followed by a period of relative quiescence was noted in the neighbourhood of epicentres of earthquakes 1968 and 1978. The aftershock and migration patterns of earthquakes differed for these earthquakes (Srivastava et al. 1987). But no well defined gap could be observed prior to the Dharamshala earthquake of 1986 in the same region. In the India Nepal region, while the earthquake of 1980 showed a quiescence before the occurrence of main earthquake, no such quiescene area could be found preceding the 1966 shock although the aftershock activity extended till 1967 (Srivastava and Gautam, 1987). The earthquake of 1988 near Nepal Bihar Border also did not show a seismic gap. However, the Manipur Burma border region showed a definite increase in seismicity for several years and a seismic gap prior to the main shock of the August 1988 (Srivastava and Rao, 1991).

Based on a catalogue of 15,196 small earthquakes from Parkfield for the period 1980 to mid 1986, Horowitz (1989) constructed a 15-dimensional parameter space and found that there is an underlying structure with only about six degree of freedom. Thus, a dynamical system based on six variables can describe the seismic behaviour of the region, implying that a chaotic process is involved.

In the Dharamshala - Dalhousie region in Western Himalaya which lies near the complex zone of Indian Eurasian plate boundary, Bhattacharya (1990) reported a fractal dimension of 9.8 implying atleast 10 independent variables. This is three order more as compared to Hindukush region which is characterised by V shaped lithosphere extending upto a depth of 250 km or so. Thus, fractal dimension or the low predictability of earthquakes in the Western Himalaya compared to Hindukush region is attributed to complex tectonic nature in Dharamshala-Dalhousie region.

It may, therefore, be summarised that although a few earthquakes in the Himalayan region have shown a specific pattern of seismicity preceding earthquakes, different patterns of seismicity for earthquakes of similar magnitude and source mechanism at the same location (tectonics) do suggest complexities in deriving a model for earthquake prediction. This is supported by the application of the theory of chaos in the Dalhousie-Dharamshala and Hindukush regions. However, earthquake predictability is relatively better with only six or seven variables in the Hindukush region which can be used to model earthquake system.

CONCLUSIONS

The above study has brought to light the following interesting conclusions :

1. Based on the theory of Chaos, the fractal dimension is 6.9 implying predictability in Hindukush region is almost similar to that for San Andreas region. We require atleast seven variables to model the earthquake system in Hindukush region.

2. The spatio temporal pattern of seismicity preceding earthquakes does not show a well defined gap in Hindukush region as was reported in the case of a few earthquakes in other regions of Himalayas. Thus, present study of the chaotic nature of earthquakes in the Hindukush region is useful to model earthquake system.

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REFERENCES

1. Abraham, N.B., Albano, A.M., Das, B., DeGuzman, G., Yang, S., Gioggia, R.S., Puccioni, G.P., and Tredicce, J.R. (1986), Calculating the dimension of attractors from small data sets. Phys. Lett. 114A, 217-221.

2. Bakun, W.H., and McEvilly, T.V. (1984), Recurrence models and parkfield, California earthquakes. J. Geophy. Res. 89, 3051-3058.

3. Bhattacharya, S.N. (1990). National symposium on recent advances in seismology and their applications, Bangalore.

4. Chatterjee, S.N., and Dube, R.K. (1979), Seismotectonics of the Hindukush and adjoining area, Mausam 30, 191-202.

5. Drakopaulos, J., and Srivastava, H.N. (1974), The dependence of earthquake frequency magnitude relationship and strain energy release upon the focal depth in Hindukush region. Annali di Geof. 27, 594-605.

6. Grassberger, P., and Procaccia, I. (1983), Characteristics of strange attractors. Phys. Rev. Lett. 50, 346-349.

7. Horowitz, F. (1989), Chaos physics and Californian earthquakes. EOS. 70, 70.

8. Mandelbrot, B.B. (1977), The fractal geometry in nature. W.H. Freeman, San Francisco.

9. Peitgen, H.O., and Richter, R.H. (1986), The beauty of fractals, Springer-Verlag, Berlin

10. Moon, F.C. (1987), Chaotic vibrations. John Wiley & Sons, NY.

11. Ruelle, D. (1981), Chemical kinemetical and differentiable dynamical systems. Ed. A. Pacoult and C. Vidal, Springer - Verlag, 30-37.

12. Srivastava, H.N., and Dattatrayam, R.S. (1986), Study of return periods of earthquakes in some selected Indian and adjoining regions, Mausam 37, 333-340.

13. Srivastava, H.N., Dube, R.K., and Raj, H. (1987), Space and time variation in the seismicity patterns preceding two earthquakes in the Himachal Pradesh, India. Tectonophysics, 138, 69-77.

14. Srivastava, H.N., and Gautam, U.P. (1987), Spatio temporal variations of seismicity precedings earthquakes of 1966 and 1980 near Indian Nepal border.

15. Srivastava, H.N., and Rao, P.C.S. (1991), Spatio temporal seismicity patterns preceding Bihar-Nepal and Manipur-Burma border earthquakes of 1988. Bull. Indian. Soc. Earthq. Techn. 28, 13-22.

16. Tandon, A.N., and Srivastava, H.N. (1975), Focal mechanisms of some recent Himalayan earthquakes and regional plate tectonics. Bull. Seism. Soc. America 65, 963-969.

17. Takens, F. (1981), Lecture notes in mathematics, 898, 366-381, Springer-Verlag, Berlin.

18. Thatcher, W. (1990), Order and diversity in the modes of circumpacific earthquake occurrence. J. Geophy. Res. 95, 2609-2623.

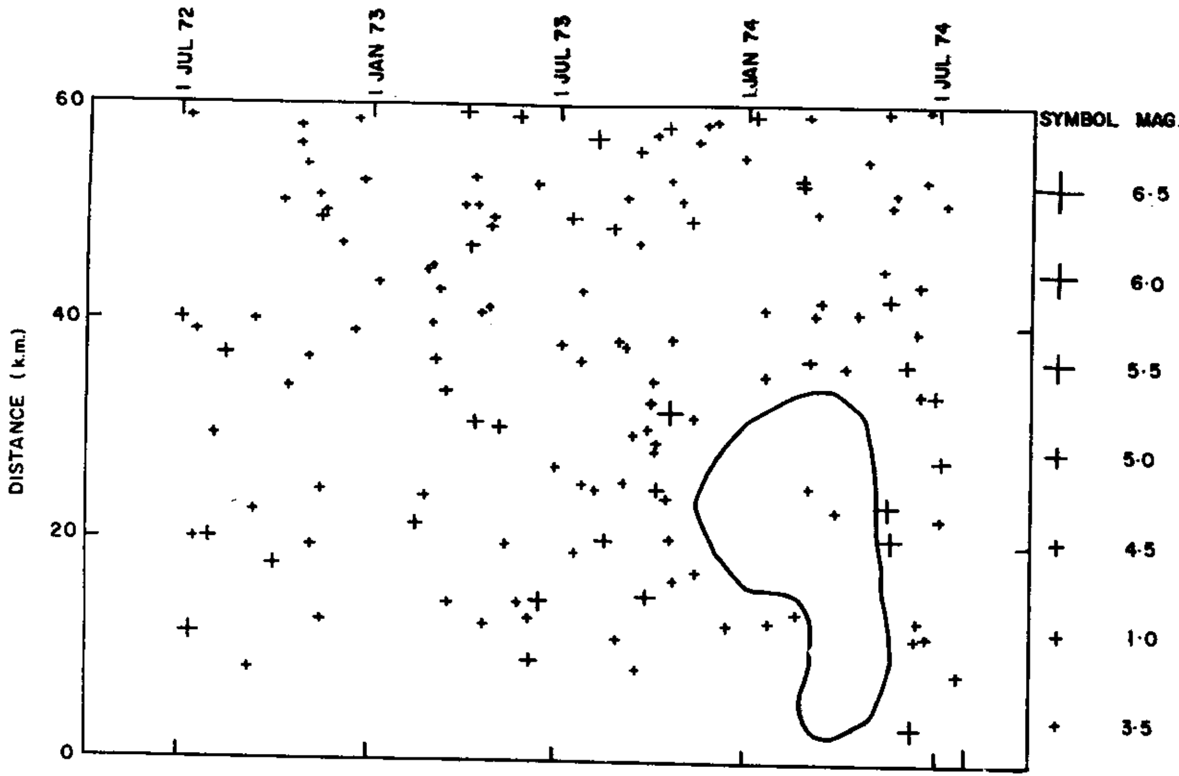

Fig. 1-a Space-time variation prior to major earthquake of 30.7.74. Distances are measured from hypocentre of this major earthquake. The area of quiescence is marked.

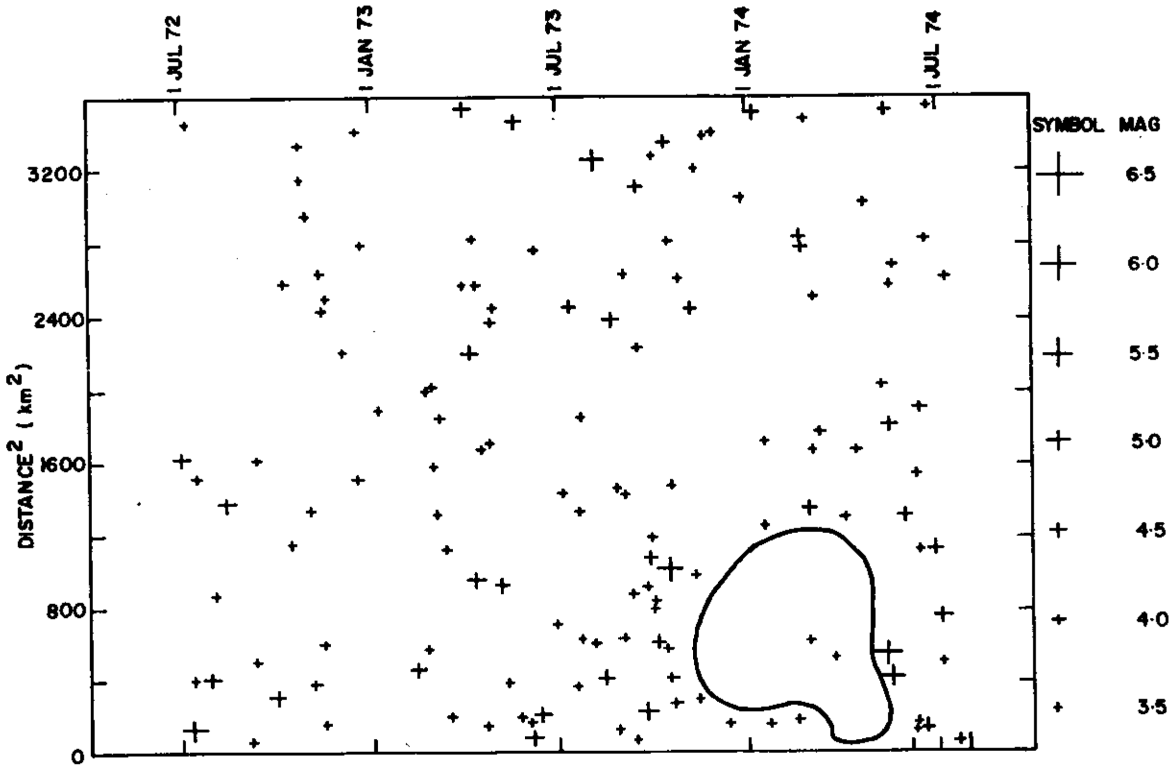

Fig. 1-b Space-time variation prior to major earthquake of 30.7.74. Distances are measured from hypocentre of this major earthquake. The area of quiescence is marked.

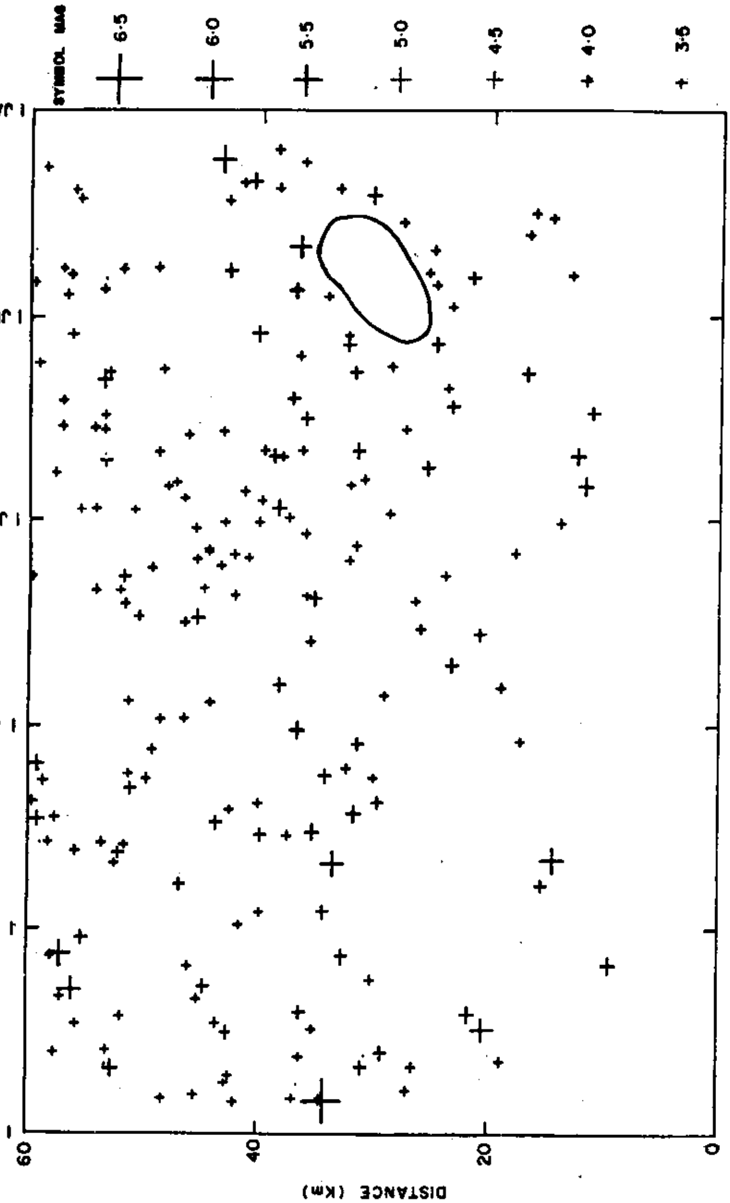

Fig. 2-a Space-time variation prior to major earthquake of 27.11.76. Distances are measured from hypocentre of this major earthquake. The area of quiescence cannot be demarcated.

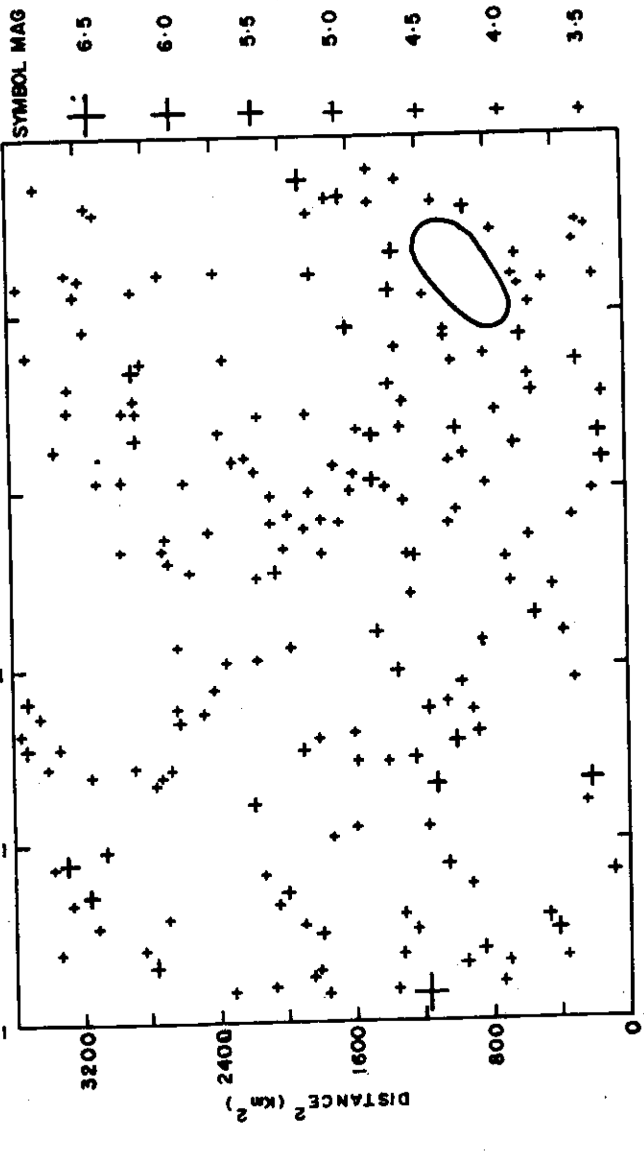

Fig. 2-b Space-time variation prior to major earthquake of 27.11.76. Distances are measured from hypocentre of this major earthquake. The area of quiescence cannot be demarcated.

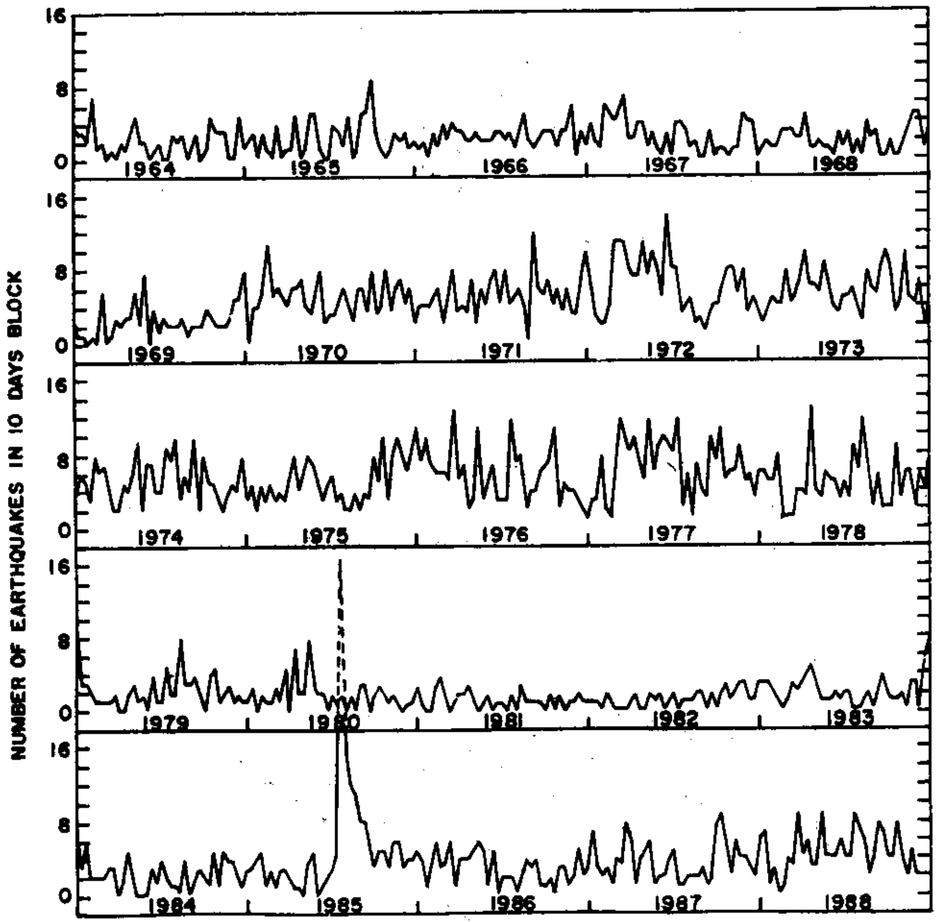

Fig. 3 Frequency of earthquakes for each 10 days block which occurred during the period January 1964 to December 1988.

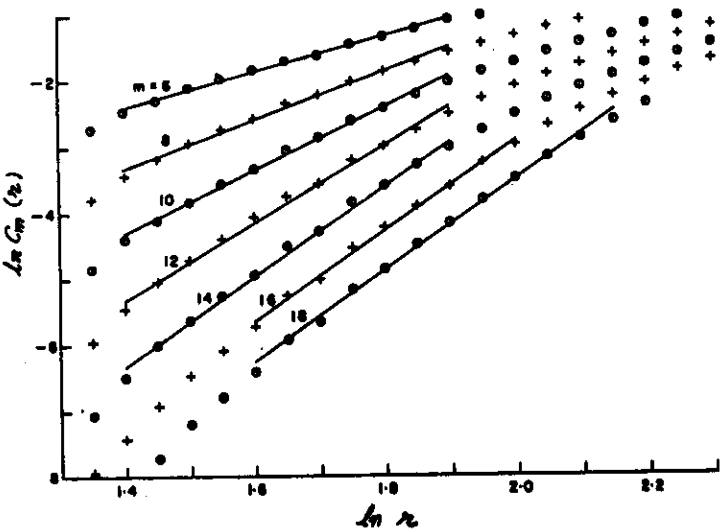

Fig. 4 Correlation integral $C_m(r)$ as a function of correlation length r for earthquake frequency for embedding dimensions m = 6 to 24 with τ = 10 days.

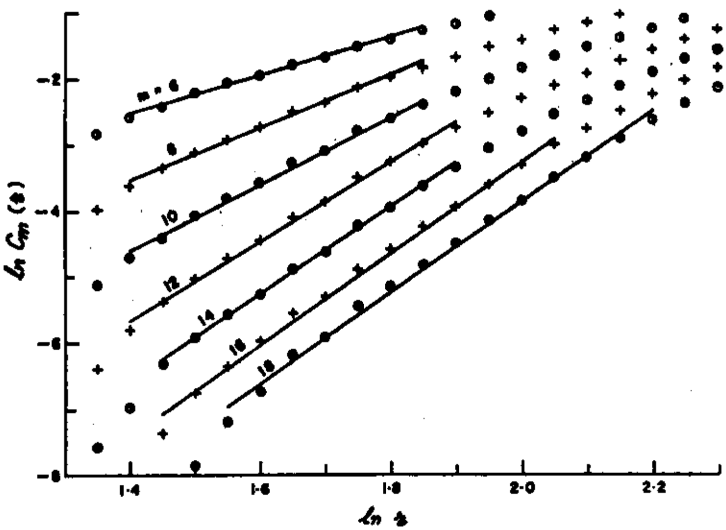

Fig. 5. Correlation integral $C_m(r)$ as a function of correlation length r for earthquake frequency for embedding dimensions m = 6 to 24 with τ = 20 days.

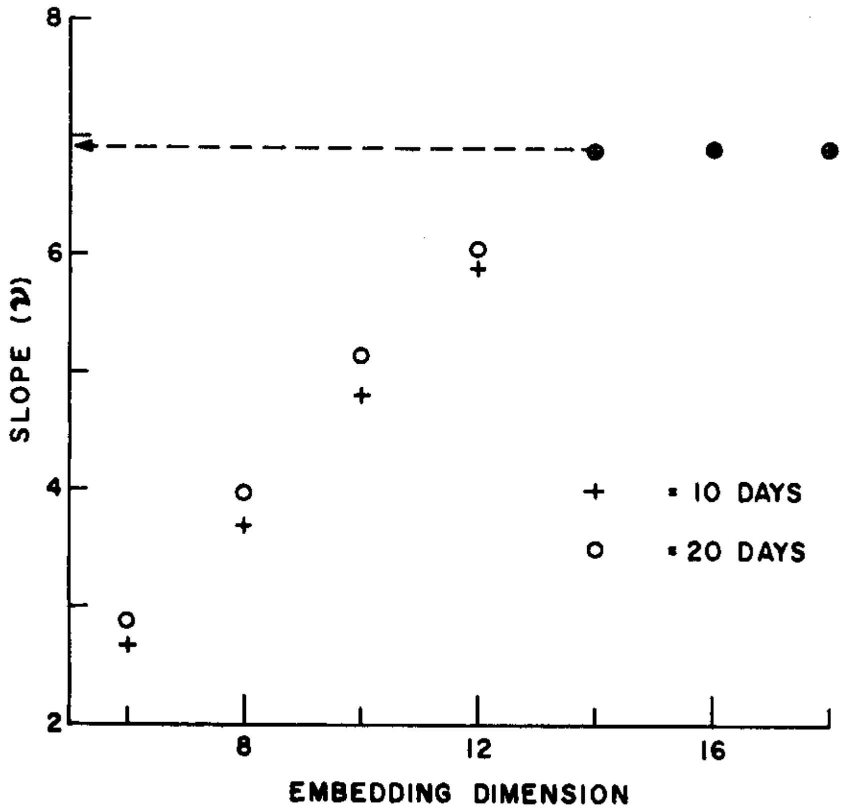

Fig. 6 Slope ν obtained from figures 2 and 3 for embedding dimension m = 6 to 24. This figure estimates fractal dimension of 6.9.