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Empirical scaling relationships between earthquake magnitudes, epicentral distances and amplitudes of radon anomalies in N-W Himalaya

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Radon data accumulated during the time-window (1992-1999) in the grid (30-34°N, 74-78°E) in N-W Himalaya has been analysed vis-a-vis seismic data recorded in the same area, supplied by Indian Meteorological Department (IMD) network. In general, there is a positive correlation between total radon emission and the micro-seismicity in the area under investigation. The earthquake magnitude has moderate positive correlation with epicentral distance and low positive correlation with amplitude of radon precursory signal, whereas, both show low negative correlation between them. Empirical scaling relations are proposed using the best-fit straight line from the log-linear graphs between magnitude of the events (M) and log of the product of amplitude of radon anomaly (A) and epicentral distance (D). The error between recorded and the calculated magnitude is also taken into account. The number of points lying within ± 25 % limit is 74 out of the total 142 cases, on which the test is applied. The error range is higher at lower epicentral distances and magnitudes, which shows that, the local geology and tectonics have predominant influence on radon signals.

1 Introduction

The research on seismo-geochemical algorithms is aimed at defining quantitative relations between seismic parameters such as, earthquake magnitude and epicentral distance, and geochemical anomalies occurring in sub-surface gas and groundwater. Such relations can be classified both theoretically and empirically[1].

The primary problem is that, the lithosphere is an unstable and non-linear system; consequently, it is very difficult to establish a definite model of interaction between rock fracturing/dislocation motion and geochemical behaviour of crustal fluids. There is no consensus on the type or number of geochemical parameters that may be sensitive to earthquake preparation mechanism or any universal opinion on the mechanisms responsible for geochemical anomalies.

Empirical algorithms are based on the statistical comparison of geochemical data with seismic ones, from an existing database. Attempts have been made to find mathematical relations between geochemical time-series regarding, gas and groundwater parameters and the occurrence of seismic events. Till date, there has been no model univocally linking earthquakes and geochemical anomalies, meaning that, the validity of the proposed models is not yet proved. The seismo-geochemical algorithm involves geochemical (i.e. anomaly amplitude and precursor time) and seismic (magnitude of earthquake and epicentral distance from observed site) parameters.

Table 1 — Seismic events recorded by IMD network and average radon concentration in the grid (30-34°N, 74-78°E) during the time window 1992-1999

Year	No. of seismic events	Average radon concentration (Bq/L)
1992	27	9.0
1993	19	13.3
1994	20	12.9
1995	40	15.3
1996	83	20.9
1997	70	22.0
1998	80	23.4
1999	79	25.1

As seismo-geochemical studies have been fragmentary and unsystematic, and the results obtained were often ambiguous and controversial, very few opportunities allowed definite mathematical relations between geochemical and

Table 2 — Amplitude of radon anomaly, epicentral distance along with recorded and calculated magnitude of earthquakes with their percentage error

Sl No	A	D	M Rec	M Calc	Percentage error
1	112.6	15.5	2.4	0.81	66.34
2	103.4	15.5	2.4	0.68	71.45
3	91.1	17.0	3.0	0.63	78.80
4	89.2	22.0	3.1	0.98	68.50
5	57.0	23.0	2.1	0.40	81.13
6	118.1	24.0	3.0	1.50	49.82
7	112.7	31.0	2.8	1.81	35.49
8	33.1	33.0	2.5	0.13	94.65
9	70.2	33.0	3.8	1.06	1.91
10	72.7	35.0	3.3	1.35	59.09
11	99.0	35.8	3.2	1.82	42.91
12	152.7	35.8	3.2	2.45	23.43
13	141.3	36.0	3.3	2.35	28.89
14	172.8	39.0	2.6	2.75	-5.82
15	81.0	42.0	3.0	1.77	41.07
16	209.4	42.0	3.0	3.13	-4.47
17	55.4	42.0	3.0	1.22	59.28
18	61.7	43.0	3.2	1.41	55.94
19	199.6	44.0	2.8	3.13	-11.86
20	23.4	46.0	3.2	2.44	23.71
21	118.1	46.0	3.2	0.11	96.48
22	111.9	47.0	3.3	2.39	27.44
23	37.5	49.0	2.3	0.88	61.66
24	88.3	49.0	2.5	2.11	15.45
25	80.6	49.3	3.5	1.99	43.10
26	102.7	52.9	3.0	2.44	18.62
27	51.4	53	3.0	1.45	51.72
28	51.4	53	4.1	1.39	66.16
29	389.4	53.1	4.5	5.39	-19.75
30	282.0	53.1	4.5	4.75	-5.51
31	102.7	54.2	2.7	2.48	8.28
32	102.7	55.5	2.5	2.51	-0.41
33	33.1	56	2.2	2.40	-9.32
34	88.3	60	2.2	0.89	59.34
35	125.0	60.1	3.3	2.91	11.93
36	93.4	60.8	2.5	2.50	-0.20
37	198.2	60.8	2.8	3.59	-28.12
38	182.1	60.8	2.8	3.46	-23.76
39	47.3	61.0	2.5	1.53	38.76
40	92.4	61.0	3.6	2.82	21.59
41	71.8	63.0	2.6	1.96	24.72
42	61.6	63.0	2.6	2.18	16.24
43	62.7	64.8	2.4	2.02	15.69
44	59.9	67.0	2.5	2.00	19.77
45	120.5	67.0	3.0	3.01	-0.37
46	17.5	67.0	3.5	0.23	93.27
47	81.0	68.0	3.2	2.46	23.09
48	55.4	68.0	3.2	1.91	40.17
49	55.1	69.0	3.5	1.93	44.92
50	66.7	71	3.2	2.24	29.88

(Contd).....

Table 2 ....(Contd)

Sl No	A	D	M Rec	M Calc	Percentage error
51	66.0	71	3.2	2.22	30.35
52	62.0	74	3.8	2.42	36.41
53	90.6	74.8	2.1	2.76	-31.39
54	68.2	74.8	2.1	2.35	-11.94
55	118.0	74.9	2.5	3.14	-25.65
56	173.8	74.9	2.5	3.70	-47.93
57	59.9	75.0	4.8	2.37	50.52
58	85.3	75.6	3.2	2.69	16.00
59	249.7	75.9	4.0	5.22	-30.41
60	131.0	75.9	4.0	3.94	1.42
61	224.7	75.9	4.0	5.00	-25.21
62	79.7	76.0	2.8	2.60	7.22
63	39.8	78.0	2.3	1.64	28.86
64	80.9	80.0	2.3	2.69	-17.09
65	18.8	81.0	2.4	0.61	74.51
66	28.4	81.0	2.6	1.20	53.65
67	21.8	81.0	2.6	0.82	68.28
68	64.9	81.0	3.4	2.39	29.59
69	29.4	84.0	2.1	1.31	37.75
70	64.5	84.0	4.2	2.74	34.65
71	60.1	85.0	2.3	2.35	-2.29
72	94.03	85.2	3.3	3.24	1.76
73	111.3	85.2	3.3	3.00	9.11
74	123.8	86.1	3.1	3.41	-10.03
75	78.3	86.9	2.9	2.76	4.65
76	59.9	87.0	2.5	2.38	4.74
77	105.7	87.0	3.2	3.20	10.05
78	57.9	88.0	4.5	2.62	41.71
79	46.2	88.0	2.4	2.02	15.65
80	185.6	88.0	2.5	4.02	-60.99
81	161.8	88.0	2.5	3.83	-53.09
82	61.3	88.0	2.9	2.43	16.17
83	124.5	90.0	3.0	3.48	-16.09
84	31.3	93.0	2.3	1.54	32.88
85	67.0	93.0	3.0	2.65	11.69
86	67.5	93.0	3.0	2.64	12.05
87	169.9	95.4	2.7	4.01	-48.66
88	204.4	95.4	2.7	4.28	-58.50
89	92.4	98.0	2.6	3.18	-22.16
90	74.4	100.0	2.7	2.89	-7.17
91	123.8	103.9	4.7	4.45	5.29
92	89.1	104.4	3.2	3.21	-0.46
93	113.0	106.4	3.5	3.58	-2.40
94	78.3	107.7	3.5	3.07	12.18
95	160.2	108.9	2.7	4.12	-52.57
96	110.6	108.9	2.7	3.59	-32.83
97	53.8	110.0	2.6	2.56	1.37
98	79.0	110.0	2.6	3.12	-19.88
99	71.4	111.0	3.4	2.98	12.22
100	51.9	111.0	3.4	2.52	25.72
101	101.6	113.0	2.8	3.52	-25.63

Contd......

Table 2 ...(Contd)

Sl No	A	D	M Rec	M Calc	Percentage error
102	59.9	113.0	2.8	2.76	1.52
103	63.9	113.7	2.6	2.86	-9.98
104	58.7	114.0	2.7	2.74	-1.52
105	125.6	115.0	3.3	3.85	-16.60
106	160.2	118.2	3.1	4.24	-36.69
107	110.6	118.2	3.1	3.70	-19.50
108	120.9	125.6	2.9	3.82	-31.68
109	112.6	125.7	2.9	3.92	-35.17
110	58.8	126.3	3.1	2.89	6.73
111	67.5	127.0	3.0	3.10	-3.25
112	67.0	127.0	3.0	3.09	-2.89
113	107.7	130.2	3.8	4.62	-21.65
114	120.2	133.0	3.0	3.99	-33.13
115	10.3	133.0	3.0	0.46	84.69
116	120.2	133.0	4.1	4.88	-19.04
117	73.8	135.0	3.7	3.43	7.29
118	56.8	135.0	3.7	3.95	-6.68
119	95.0	137.0	3.6	4.47	-24.30
120	111.3	141.7	4.0	4.85	-21.35
121	111.3	141.7	4.0	4.85	-21.35
122	58.8	141.7	4.0	3.59	10.13
123	94.0	141.7	4.0	4.52	-13.03
124	51.3	146.0	3.2	2.90	9.27
125	120.2	150.0	3.5	4.17	-19.05
126	10.3	150.0	3.5	0.63	81.93
127	71.0	150.0	3.5	3.41	12.58
128	85.0	153.0	4.2	4.47	-6.50
129	164.6	159.3	3.1	4.70	-51.79
130	107.7	159.3	3.0	4.09	-36.52
131	212.2	159.4	3.1	5.07	-63.61
132	111.5	165.0	3.0	4.19	-39.86
133	38.3	165.0	3.6	3.05	5.32
134	80.6	165.7	3.0	3.73	-24.51
135	42.2	169.0	3.6	3.29	8.69
136	81.6	171.1	3.6	4.61	-28.15
137	78.3	171.6	3.5	3.74	-6.98
138	113.0	173.6	3.1	4.29	-38.33
139	92.7	175.5	3.2	4.09	-27.96
140	126.8	191.0	3.4	4.59	-35.04
141	105.7	393.0	6.8	6.77	0.50
142	22.9	393.0	6.8	3.75	44.90

A – Amplitude of radon anomaly; D – Distance; M- Magnitude; Rec – Recorded; Calc – Calculated

seismic parameters to be formulated. Empirical algorithms are often based on limited data and need validation for different geological environments. Nevertheless, empirical aigorithms represent a unique tool to predict earthquakes without a full understanding of rock-mechanics and fluid geochemistry interactions, and local and regional stress-field recognition.

To understand the mechanism of radon anomalies and establish its earthquake prediction capability and reliability, empirical scaling relationships between radon data and earthquake data are needed. In this paper, an attempt has been made to interpret the available radon data[2-3] of the Kangra and Chamba valleys of Himachal Pradesh recorded during the period 1992-1999 and to establish an empirical relationship with the seismic data monitored using IMD network in the area represented by the grid (30-34 °N, 74-78 °E). It is evident from Table 1 that, both radon emanation and seismicity show a rising trend during the time window 1992-99.

Table 3 — Average values of radon anomaly amplitudes and epicentral distances for different magnitude events taken for analysis

Sl No	M	A	D
1	2.1	61.3	64.2
2	2.2	60.7	58.0
3	2.3	49.9	77.0
4	2.4	68.7	53.0
5	2.5	98.4	62.8
6	2.6	71.7	84.3
7	2.7	125.8	96.7
8	2.8	133.4	71.2
9	2.9	93.3	106.5
10	3.0	88.2	86.5
11	3.1	129.1	120.4
12	3.2	82.4	76.7
13	3.3	111.7	66.2
14	3.4	78.7	123.5
15	3.5	69.5	113.4
16	3.6	69.9	140.6
17	3.7	65.3	135.0
18	3.8	78.0	79.1
19	4.0	140.1	113.5
20	4.1	60.6	106.3
21	4.2	74.8	118.5
22	4.5	243.1	64.7
23	4.7	123.8	103.9
24	4.8	59.9	75.0
25	6.8	64.3	393.0

M – Magnitude; A – Amplitude of radon anomaly; D – Epicentral distance

2 Empirical Relationships for Earthquake Prediction

A critique of some empirical relations have been proposed in the past, relating precursor time of radon anomalies to earthquake magnitude and epicentral distance. On the basis of precursor data published up to 1977, Rikitake[4] had given a relationship between precursor time (T) and earthquake magnitude (M), which was obtained on the basis of the best-fitting straight line using least square method as follows:

$$\log T = 0.6\,M - 1.01 \qquad \ldots(1)$$

This formula is based on a general linear equation:

$$\log T = a + bM \qquad \ldots(2)$$

which holds well for all the precursor disciplines.

On the basis of strain field models, Dobrovolsky *et al.*[5] and Fleischer[6] had given relations between earthquake magnitude and the radius of the effective precursory manifestation zone, where radon anomaly occurs, as follows:

$$D = 10 \exp 0.43\,M \qquad \ldots(3a)$$

$$D = (10 \exp 0.813\,M)/1.66 \text{ for } M < 3 \qquad \ldots(3b)$$

and

$$D = (10 \exp 0.480\,M)/1.66 \text{ for } M > 3 \qquad \ldots(3c)$$

where D is the epicentral distance in km and M is the magnitude of the earthquake on the Richter scale. According to Dobrovolsky *et al.*[5] formulation, an earthquake of magnitude 5 can be detected by means of radon precursory anomalies up to a distance of 142 km only, whereas, experimental observations prove that, earthquakes are correlatable with radon anomalies which occur at distances much greater than those calculated by the given empirical relationship.

Hauksson and Goddard[7] proposed a modified relationship based on experimental field data for radon:

$$M = 2.4 \log D - 0.43 \qquad \ldots(4)$$

This was used to fit worldwide radon data in groundwater for earthquakes of magnitude ≥ 5. Taking into account, the characteristics of the crustal structure in Italy and Austria, on both sides of the Alps, Friedmann[8] further modified the above relationship as:

$$M = 2.4 \log D - 0.43 - 0.4 \qquad \ldots(5)$$

Sultankhodzhayev *et al.*[9], on the basis of radon data in a seismically active zone of Central Asia, established an empirical formula relating, precursor time T (in days) to magnitude M and epicentral distance D (in km) as follows:

$$\log DT = 0.63\,M - 0.15 \qquad \ldots(6)$$

Taking recourse to the strain field models, Virk[10] proposed the following four relations for fitting world-wide radon data:

Epicentral distance (in kms), $10 < D < 50$

$$D = 10 \exp 0.32\,M \qquad \ldots(7a)$$

Epicentral distance (in km), $50 < D < 100$

$$D = 10 \exp 0.43\,M \qquad \ldots(7b)$$

Epicentral distance (in km), $100 < D < 500$

$$D = 10 \exp 0.56\,M \qquad \ldots(7c)$$

Epicentral distance (in km), $500 < D < 1250$

$$D = 10 \exp 0.63\,M \qquad \ldots(7d)$$

From the analysis of all the above models, one can clearly infer that, there is no universal empirical relationship, which is valid for interpretation of radon data for all earthquake magnitudes. There is a large scatter in the data set, for low magnitudes (2-4 M) and short distances (< 500 km) because, local geology has a significant effect on radon emanation and it differs from area-to-area. At best, one can use the scaling developed on the basis of fitting parameters that depend upon local geology, meteorological variables and other geophysical effects encountered at the monitoring site.

3 Analysis of Radon Data and the Proposed Empirical Relationship

Keeping in mind all the above formulations and local geological, meteorological and geophysical variables, a new empirical relationship is proposed between earthquake magnitude, epicentral distance and amplitude of radon anomaly for interpretation of radon data[2] recorded at Palampur and Dalhousie stations for the period June 1992-August 1995 and June 1996-September 1999, using emanometry technique in both the media and both the data sets. Radon data set pertains to 142 cases of radon anomalies in soil-gas and groundwater correlated with earthquakes of magnitude range between 2.1 and 4.8 and having epicentral distances less than 200 km (Table 2) except the Chamoli earthquake of magnitude 6.8 having epicentral distance of 393 km.

Relationships between the amplitude of radon anomaly (A), epicentral distance (D) and earthquake magnitude (M) from the given data set are evaluated. The correlation coefficients (R) between these variables are as follows:

Seismo-geochemical parameters	Correlation coefficient (R)
M-D	0.54
M-A	0.13
D-A	-0.10
M-log(AD)	0.33

From the above analysis, it can be concluded that, magnitude of earthquake and epicentral distance have moderate correlation, whereas, these parameters show low correlation with amplitude of radon anomaly. Amplitude of radon anomaly is positively correlated with magnitude and negatively correlated with epicentral distance, as it is influenced by both these seismic parameters, which mutually perturb each other's effect. Amplitude of anomaly is also controlled by other parameters like meteorological, geophysical and geological variables. In general, both amplitude of anomaly and epicentral distance increase with the increase in magnitude of earthquake, whereas, amplitude decreases with increase in epicentral distance and the same trend was also observed for other geochemical precursors[11].

All the earthquakes for which the value of magnitude is to be calculated using the given empirical relationship, is summarized in Table 2. To find an empirical relation for the given grid, the average values of radon anomaly amplitudes and epicentral distances are calculated for all recorded magnitudes of earthquakes (Table 3). On the basis of magnitude of earthquakes, the data are divided into two regimes, one with earthquakes of magnitude 2.0-3.5 (Fig. 1) and the other with magnitude > 3.5 (Fig. 2).

From Figs 1 and 2, the following scaling relations are proposed using the best-fit straight line from the log-linear graphs between magnitude of the events (M) and log of the product of amplitude of anomaly (A) and epicentral distance (D):

$$\log(AD) = 0.30\,M + 3.00 \text{ (For } M = 2.0\text{-}3.5) \quad \ldots(8a)$$

$$\log(AD) = 0.22\,M + 3.13 \text{ (For } M > 3.5) \quad \ldots(8b)$$

In the generalised form, the above relationship can be written as:

$$\log(AD) = a\,M + b \quad \ldots(9)$$

where a and b are constants. The value of both the constants varies from area-to-area and depends on local geology and other geophysical factors.

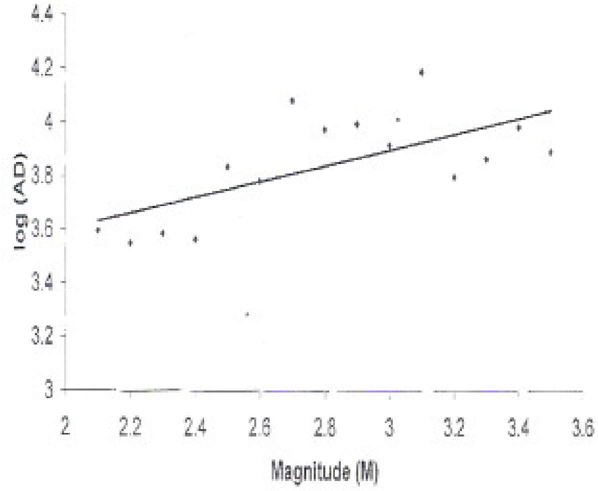

Fig. 1 — Best-fit plot of magnitude (M) versus log of product of radon anomaly amplitude (A) and epicentral distance (D) for the earthquakes of magnitude (M) in the range 2.0-3.5

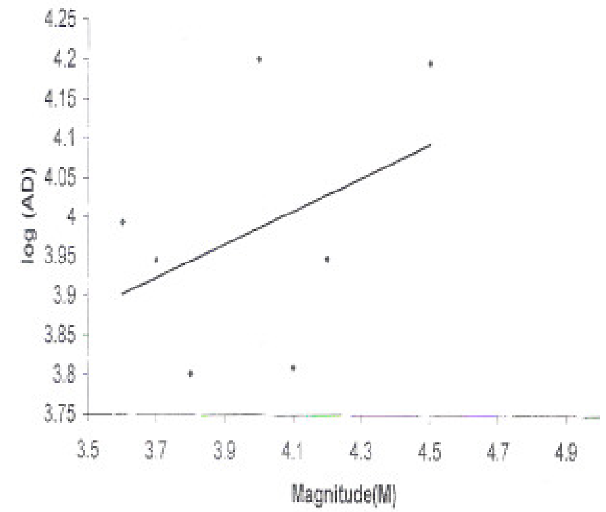

Fig. 2 — Best-fit plot of magnitude (M) versus log of product of radon anomaly amplitude (A) and epicentral distance (D) for the earthquakes of magnitude $M > 3.5$

4 Discussion

To find out the efficacy of the proposed empirical relationships in the area under study, the values of earthquake magnitudes are calculated. Table 2 gives the calculated magnitude alongwith the recorded magnitude and epicentral distance. The error between recorded and the calculated magnitude is also given in Table 2. A comparison of recorded and calculated magnitudes of earthquakes shows some interesting features. The error is assigned a positive value, if calculated magnitude is more than the recorded one and, vice versa. The maximum value of percentage error is 96.48, which is recorded for an earthquake of magnitude 3.2, having epicentral distance of 46 km. There are three cases which show percentage error more than 90 and all these are having magnitude ≤ 3.5 and epicentral distance less than 100 km. The number of points lying within ± 25 % limit is 74 out of the total 142 cases, i.e. more than half, lying within this error limit, on which the test is applied. The various percentage error ranges are given below:

Range of % error (±)	Number of cases
0-10	36
11-20	27
21-50	52
> 50	27

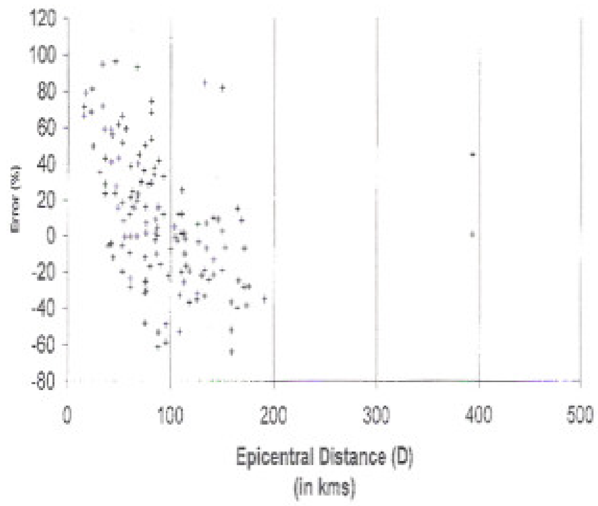

Fig. 3 — Plot of percentage error between recorded and calculated magnitudes versus epicentral distance

Fig. 3 gives a plot of percentage error and epicentral distance. From the plot, it can be inferred that, for distances less than 100 km the error is more, i.e the average value of error is ± 33.10 % as compared to ± 29.15 % for the whole data set, whereas, the error is ± 22.31 %, when the distance is more than 100 km. The plot between magnitude and percentage error (Fig. 4) shows that, with increase in magnitude, the error range decreases. From the two plots it can be concluded that, error range is higher at lower epicentral distance and magnitude, which shows that, the local geology has significant influence on radon signals.

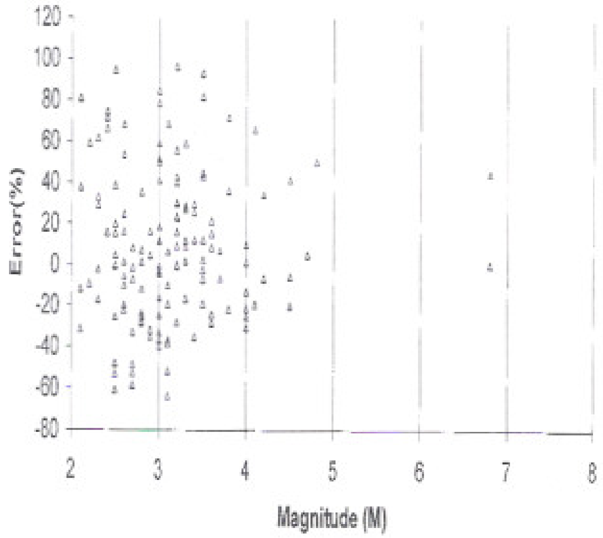

Fig. 4 — Plot of percentage error between recorded and calculated magnitudes versus recorded magnitude of earthquakes

High range in the percentage error may be because radon data were taken from two different stations having different geological and geophysical environments, and also the different nature of media. This shows that, radon anomalies are not only influenced by the magnitude and epicentral distance of earthquakes, but also by the mechanism of radon migration. The large scattering in the data set for low magnitudes (2-4 M) and short distances (< 500 km) is reported by various authors[10,12].

5 Conclusions

1. In general, the micro-seismicity and radon emanation has been showing a rising trend during the time-window (1992-1999), in Kangra and Chamba valleys of Himachal Pradesh, India.

2. The epicentral distance and magnitude of earthquake has moderate correlation, whereas, these parameters show low correlation with amplitude of radon anomaly. In general, it can be stated that, the greater the magnitude of a seismic event, the greater is the distance where precursors can be recorded and the larger the signal appears to be.

3. Due to inhomogeneity of the geophysical medium and non-linearity of the precursor, the percentage error between observed and calculated earthquake magnitudes is found to be very high, with maximum value of error 96.48%.

4. It is established from the analysis that, there is no universal empirical relationship, which holds good for interpretation of radon data for all earthquake magnitudes and epicentral distances. Hence, the earthquake prediction using this method will remain an enigma in future.

References

1 Etiope G, Calcara M & Quattrocchi F, *Ann Geofis (Italy)*, 40 (1997) 1483.

2 Sharma A K, PhD thesis (unpublished), (1999).

3 Virk H S & Walia V, *Bull Indian Geol Assoc*, 34 (2001) 243.

4 Rikitake T, *Tectonophys*, 54 (1979) 689.

5 Dobrovolsky I P, Zubkov S I & Miachkin V I, *Pure Appl Geophys*, 117 (1979) 1025.

6 Fleischer R L, *Geophys Res Lett*, 8 (1981) 477.

7 Hauksson E & Goddard J G, *J Geophys Res*, 86 (1981) 7037.

8 Friedmann H, *International Conference on Earthquake Prediction: State-of-the-art*, Strassbourg, France, (1991).

9 Sultankhodzhayev A N, *Proc International Symposium on Earthquake Prediction*, UNESCO, Paris 1979, (Terra Sci Publ Co, Tokyo), 1984, p.181.

10 Virk H S, *J Earthquake Prediction Res*, 5 (1996) 574.

11 Kissin I G, *J Earthquake Prediction Res*, 1 (1992) 235.

12 Hauksson E, *J Geophys Res*, 86 (1981) 9397.