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A statistical study of Koyna aftershocks for the period January 1968-October 1973

H. S. S. SHARMA and G. S. MURTY

Bhabha Atomic Research Centre, Trombay, Bombay

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ABSTRACT. A statistical study of the aftershocks originating from Koyna region recorded at Gauribidanur seismic array is made to find the time dependence of energy release. A total number of 210 aftershocks, most of whose magnitudes on Richter scale vary from 3·8 to 5·8, which occurred during the period January 1968 to October 1973 were analysed. It is found that the cumulative energy release in this period shows, in general, a tendency to vary as the square root of time that elapsed after January 1968 apart from some fluctuations.

1. Introduction

The major earthquake that occurred at Koyna on 10 December 1967 was followed by a number of aftershocks. These were studied by Guha *et al.* (1971) and by Avadh Ram and Singh (1971) with a view to understand among other things the manner in which the energy is released as a function of time after the major earthquake. The data for both these studies is obtained from observations close to the region of seismic activity. It covers a period starting from 1964 to 1969. In the present study we have excluded the earthquakes which are immediately coming after the 10 December 1967 event, but have chosen only those events coming from Koyna from January 1968. This choice of time is no doubt arbitrary, but is preferred because we feel that the relaxation of the strained system is studied better by excluding the period immediately following the rupture than by including the period of rupture also in the energy estimates.

The details of all the events included in this study are given in Table 1. Most of the events listed in Table 1 are identified in the visual seismograms reproduced in 8-channel play-outs from the original magnetic tapes recorded at Gauribidanur array as coming from Koyna from an estimate of azimuth, Z, of the direction of arrival (mean value 320.4°, s.d.$=$2.8°) of signal at the Gauribidanur array centre and the difference (D) in the arrival times of P-phase (longitudinal wave) and S-phase (transverse wave) from the source which lies in the range 56.3 sec; s.d.$=$0.8 sec. In some of the events a second phase is also seen which is interpreted as most probably the surface reflected P-phase (Murty 1969, 1970). Where it is possible, the direction of first motion of the P-signal is identified from these playouts. The data is used to derive (*a*) the frequency-magnitude relation, (*b*) the energy release-time relation and (*c*) the focal depth of the events.

All the events are treated as belonging to one population and no notice is taken of the variations in the epicentral distance and the azimuth of the source with respect to Gauribidanur.

2. Frequency-Magnitude relation of aftershocks

One of the oft-used empirical relations in the statistical study of foreshocks and aftershocks of earthquakes is the Gutenberg-Richter formula) :

$$\log N(M) = a - bM \qquad (1)$$

where $N(M)$ is the cumulative number of earthquakes defined as the total number of shocks whose magnitude is M or larger than M , and a and b are numerical constants (Richter 1968). There exists extensive literature regarding the use and interpretation of this formula (Ohtake 1970, Drakopoulos 1971). The value b is of great significance because it reflects the pattern of energy distribution in a given number of events. The parameter b is determined in the laboratory study of fracturing of rocks and is found to vary between 0.3 and 2.5 depending on the ambient stress and the nature of the material subjected to deformation until cracking (Scholz 1968). The general conclusion is that the values of b are larger for heterogeneous medium than for homogeneous medium.

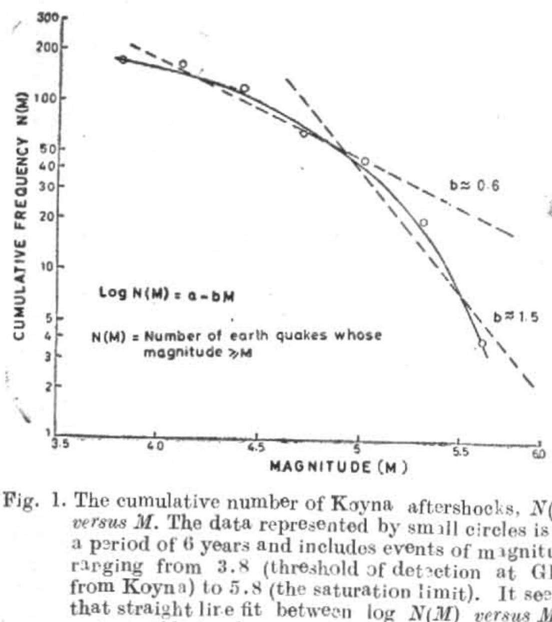

Fig. 1. The cumulative number of Koyna aftershocks, $N(M)$ *versus* M. The data represented by small circles is for a period of 6 years and includes events of magnitude ranging from 3.8 (threshold of detection at GBA from Koyna) to 5.8 (the saturation limit). It seems that straight line fit between log $N(M)$ *versus* M is not possible for these events.

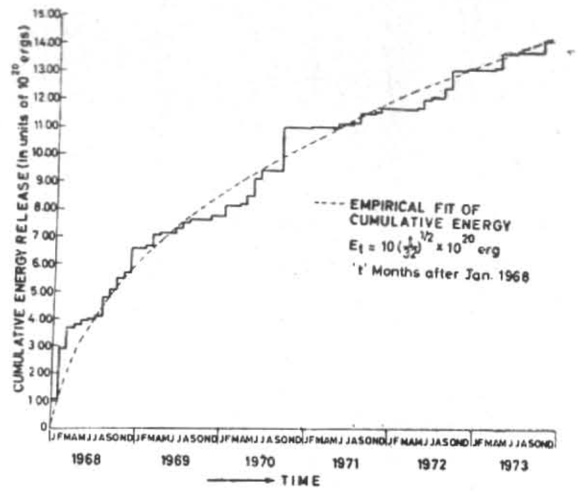

Fig. 2. Cumulative energy of Koyna aftershocks as observed at GBA during 1968-1973, as a function of time. The cumulative energy release appears to be following $t^{1/2}$ law with some fluctuations about the general trend. (The energy values are to be taken as only representative of the order of magnitude of strain release due to the aftershocks, since the magnitude estimate is uncertain within $\pm$ 0.2 which corresponds to variation within a factor of 2 in the energy estimates. This error which is random is not expected to alter the general trend of the variation of cumulative energy with time).

Owing to these various factors if log $N(M)$, *versus* M curve does not fit a single straight line, one may conclude that the population of the events is a mixture of several types of populations with different characteristic values of b. The data under study is shown in Fig. 1 where we see that log $N(M)$ *versus* M curve is not a straight line. This probably reflects also the fact that the low magnitude events are underestimated due to ambient noise, and that the magnitudes are estimated from single point observations without regard to azimuthal variation of radiation pattern.

3. Release of energy *versus* time

A knowledge of the rate of energy release from a seismically active region is of great interest in the study of earthquakes. Such studies have been made both for global and for local seismicity by several people (Benioff 1951, Kisslinger 1968). The aftershock energy release from Koyna region was studied by Avadh Ram and Singh (1971) and Guha *et al.* (1971). Both these authors conclude that the cumulative energy release varies at t^{α} where α is a constant of the order of unity. For all the events listed in Table 1, the cumulative energy is calculated by estimating the energy of each event by the formula (Richter 1958, Scholz 1968)

$$\log E = 11.4 + 1.5\,M \qquad (2)$$

where the magnitude is calculated on the basis of the observed amplitude of the P-wave seismic signal at the central sensor (short period 1 c/s seismometer) of the Gauribidanur Seismic Array (Singh *et al.* 1969), and E is expressed in ergs.

In estimating the magnitude, the small correction due to frequency-response of the seismometer which has a maximum response at about 1 cps is ignored through the Koyna aftershocks recorded at Gauribidanur have a spectral peak at 4 cps (Murty 1969). Since the frequency response is nearly flat between 1 cps to 5 cps, this approximation does not affect the magnitude estimates drastically. Further, we are primarily interested in the overall variation of earthquake energy release with time, and not in the absolute values of the energy released in the aftershocks.

The cumulative energy is calculated for all events listed in Table 1 by means of the Eq. (2) for the periods from January 1968 to October 1973, and the results are shown in Fig. 2. We see from this figure that the average variation of cumulative energy E_t, defined as the sum of energy of all the aftershocks upto time t from January 1968 can be approximated by the formula

$$E_t = 10 \times (t/32)^{1/2} \times 10^{20} \text{ ergs} \qquad (3)$$

where t is the time measured in months from January 1968.

In the Eq. (3) the numerical values should not be taken as an estimate of actual energy release, but only as an indication of the order of magnitude

TABLE 1

S. No.	Date	Onset time (GMT) at Gauribidanur	Body wave magnitude (Richter scale)	First Motion of P signal	Probable depth phase arrival w.r.t. 1st arrival (sec)	S. No.	Date	Onset time (GMT) at Gauribidanur	Body wave magnitude (Richter scale)	First motion of P signal	Probable depth phase arrival w.r.t. 1st arrival (sec)
1	3 Jan 68	04:36:21·5	4·4	Down		48	9 Mar 68	10:35:52·0	4·5	Down	
2	3 Jan 68	11:58:32·5	4·8	Up		49	10 Mar 68	08:21:33·2	5·1	Up	
3	4 Jan 68	06:20:11·2	4·8	Down	2	50	11 Mar 68	04:54:31·8	3·8		
4	4 Jan 68	07:25:15·7	4·7	Down	2	51	11 Mar 68	13:23:23·1	4·1		
5	5 Jan 68	09:42:11·5	4·5	Up	2	52	11 Mar 68	20:07:37·7	Weak signal		
6	5 Jan 68	09:53:18·1	4·4			53	16 Mar 68	00:52:14	4·6	Up	
7	7 Jan 68	02:25:06·9	5·5	Down		54	18 Mar 68	15:49:47	4·1		
8	9 Jan 68	20:11:42·4	4·3			55	19 Mar 68	17:22:59·6	4·1	Down	
9	16 Jan 68	03:34:37·5	4·4	Down		56	20 Mar 68	04:05:04·5	4·5	Up	1·5
10	16 Jan 68	06:18:18·8	5·3	Down		57	20 Mar 68	17:16:22·5	4·1		
11	17 Jan 68	21:10:14.8	4·4	Up	2	58	22 Mar 68	06:34:26·1	Very weak signal		
12	25 Jan 68	20:16:32·2	5·2	Up	3	59	23 Mar 68	16:18:25·5	4·4	Down	2·2
13	25 Jan 68	22:21:16·4	Very weak signal			60	25 Mar 68	16:50:03·4	4·5	Up	3
14	27 Jan 68	16:53:24·9	4·7	Up	1·2	61	26 Mar 68	02:45:28·6	4·4		
15	27 Jan 68	23:45:04·7	4·4	Up		62	26 Mar 68	11:21:39·8	4·3		
16	30 Jan 68	12:09:25·4	Very weak signal			63	28 Mar 68	09:59:25·5	5·1	Up	2
17	7 Feb 68	23:50:42	3·8			64	29 Mar 68	07:54:39·8	4·1		
18	8 Feb 68	19:38:54·2	4·1	Down	1·5	65	30 Mar 68	17:23:26·9	4·8	Down	
19	9 Feb 68	22:53:19·6	5·4	Up	2	66	31 Mar 68	07:02:21·4	4.4		
20	10 Feb 68	12:11:40	Very weak signal			67	31 Mar 68	22:56:30	Very weak signal		
21	11 Feb 38	07:48:40	4·1		1·6	68	4 Apr 68	09:19:07·6	3·8		
22	11 Feb 68	17:30:36·7	Very weak signal			69	6 Apr 68	04:10:10·5	4·4		
23	12 Feb 68	09:14:41·4	5·7	Down	2	70	6 Apr 68	07:05:10·0	4·9	Down	1
24	13 Feb 68	21:43:22·4	4·4			71	7 Apr 68	04:23:43·8	4·3	Down	1
25	14 Feb 68	03:11:40·8	4·6	Up	1·4	72	8 Apr 68	05:42:53·5	4·3		
26	14 Feb 68	09:17:54·4	4·1			73	9 Apr 68	23:25:05·0	4·7	Up	
27	14 Feb 68	20:34:36·2	5·5	Up	2·5	74	25 Apr 68	04:16:33			
28	15 Feb 68	18:23:20	Very weak signal			75	28 Apr 68	12:53:54·6	4·5	Up	
29	20 Feb 68	17:50:24·4	5·1	Up	2·5	76	30 Apr 68	03:23:26·0	4·3	Down	
30	20 Feb 68	20:39:56	4·1		1·5	77	1 May 68	07:47:34·8	4·7	Down	1
31	21 Feb 68	10:45:40	Very weak signal			78	1 May 68	15:46:04·3	4·3	Up	
32	21 Feb 68	16:28:11·8	4·4			79	3 May 68	02:38:18·3	4·4		
33	22 Feb 68	08:18:43·1	4·4	Down		80	6 May 68	10:42:02·9	4·1		
34	22 Feb 68	19:28:34	Very weak signal			81	9 May 68	13:04:32·5	4·3	Down	
35	25 Feb 68	01:00:16·5	4·1			82	10 May 68	04:58:24·4	4·1	Down	
36	25 Feb 68	21:44:32·6	3·8			83	11 May 68	11:29:07·9	4·1		
37	26 Feb 68	04:10:34·8	3·8			84	22 May 68	15:23:57·2	4·9	Up	
38	26 Feb 68	06:49:15·0				85	24 May 68	20:46:10·5	4·4		
39	26 Feb 68	07:55:40·0				86	24 May 68	20:56:16·5	4·1		
40	26 Feb 68	14:01:25·0				87	28 May 68	16:11:20·8	Very weak signal		
41	26 Feb 68	21:26:15·0				88	10 Jun 68	14:32:13·4	4·1		
42	29 Feb 68	18:22:49·0	4·6	Up		89	21 Jun 68	04:18:32	4·6	Up	1·5
43	3 Mar 68	21:47:27·5	5·1	Up	1·5	90	21 Jun 68	06:52:27·7	4·5	Up	
44	4 Mar 68	21:37:51·0	5·3	Down		91	17 Jul 68	09:24:30·0	5·1	Down	1
45	4 Mar 68	23:32:49·2	4·1			92	26 Jul 68	08:06:54	3·8		1
46	7 Mar 68	22:10:59·5	4·1			93	28 Jul 68	04:12:28·4	4·6	Down	
47	9 Mar 68	07:48:54·5	5·0	Up	2·4	94	26 Aug 68	20:12:46·5	4·3	Up	1

TABLE 1 *(contd)*

S. No.	Date	Onset time (GMT) at Gauribidanur	Body wave magnitude (Richter scale)	First motion of *P* signal	Probable depth phase arrival w.r.t. 1st arrival (sec)	S. No.	Date	Onset time (GMT) at Gauribidanur	Body wave magnitude (Richter scale)	First motion of *P* signal	Probable depth phase arrival w.r.t. 1st arrival (sec)
95	30 Aug 68	08:16:00	Very weak signal			143*	29 Sep 70	15: 03:14	4·1		
96	31 Aug 68	02:54:54·4	5·6	Down		144*	1 Jan 71	04:56:02	4·4		
97	2 Sep 68	02:56:43·5	4·7	Up	2	145	16 Feb 71	13:40:51·4	4·3	Up	
98	20 Sep 68	10:12:47·5	5·3	Up	2·5	146	16 Feb 71	14:10:07·5	4·3	Down	
99*	7 Oct 68	00:03:55	Very weak signal			147	28 Feb 71	20:44:59·0	4·6	Up	
100	29 Oct 68	10:01:19·8	5·5	Up	1	148	20 Mar 71	04:59:06	Very weak signal		
101*	30 Oct 68	11:31:10	3·8			149	24 Apr 71	22:57:27·5	4·3		
102	23 Nov 68	11:12:56·0	5·2	Up		150	9 May 71	02:30:02·6	3·8		
103	25 Nov 68	23:55:49·7	4·6	Up		151	14 May 71	01:14:18·4	4·4	Up	
104	5 Dec 68	22:53:45·2	5·7	Down	2	152	29 May 71	00:28:35·2	5·0	Down	2·2
105	22 Dec 68	22:18:27·9	4·5	Down	2·5	153	6 Jun 71	04:18:14·4	4.7	Down	
106	21 Jan 69	22:33:28·0	4·4	Down	1·5	154	15 Jun 71	16:38:15·9	4·4	Down	
107	13 Feb 69	18:27:17·0	5·1	Down	1·8	155	15 Jun 71	20:11:53	Very weak signal		
108	7 Mar 69	14:29 46·7	5·4	Down	2·5	156	15 Jun 71	20:48:51·7	4·3		
109	18 Mar 69	04:05:28·5	4·9	Up	2·8	157	16 Jun 71	13:47:02	4·1		
110	26 Mar 69	09:48:40·2	4·3		1·5	158	22 Jun 71	15:15:41·5	4·3		
111	1 Apr 69	21:34:39·3	4·4			159	24 Jul 71	05:43:46·4	4·8	Up	
112	3 Apr 69	16:19:37·5	4·3		2·5	160	30 Jul 71	00:05:56·8	3·8		
113	3 Apr 69	17:17:58	Very weak signal			161	10 Aug 71	06:16:37·5	5·4	Down	1·6
114	27 Jun 69	20:06:25·6	5·3	Down	2	162	11 Aug 71	18:01:06·4	4·3		1
115	18 Jul 69	01:31:23·2	4·7	Up	1·5	163	25 Aug 71	01:35:16·5	3·8		
116	22 Jul 69	21:50:42·1	5·2	Up	1·8	164	18 Oct 71	06:02:18·0	3·8		
117	13 Aug 69	01:05:27·8	4·4			165	22 Oct 71	23:42:07·7	4·7	Up	1
118	19 Aug 69	00:36:44·3	4·6			166	23 Oct 71	00:32:31·0	4·5	Up	1
119*	16 Sep 69	18:20:59	4·1			167	11 Nov 71	11:09:00	Very weak event		
120*	16 Sep 69	21:44:45	4·5			168	22 Nov 71	10:40:21·0	5·2	Up	3·1
121*	23 Sep 69	21:14:16	4·1			169	25 Nov 71	13:00:58	Very weak signal		
122	3 Nov 69	23:23:28·0	5·2	Up		170	1 Jan 72	17:46:04·5	4·1		
123	4 Nov 69	05:13:05·8	4·4	Up	1·4	171	21 Jan 72	00:14:50	4·1		
124	29 Dec 69	04:48:37	Very weak signal			172	10 Feb 72	17:33:50·2	4·4		
125	1 Jan 70	22:32:07·3	5·4	Up	2·2	173	27 Feb 72	21:37:11	4·4		
126	9 Jan 70	22:35:57·4	4·9	Up	1·5	174*	8 Mar 72	02:01:44	4·1		
127	12 Jan 70	07:37:42·3	4·1			175	30 Apr 72	23:28:17·7	4·8		
128	12 Jan 70	09:06:32	4·5			176	1 May 72	21:12:58·3	4·7		
129	12 Jan 70	15:44:42·7	4·3			177	11 May 72	11:50:47·7	5·2		
130	12 Jan 70	16:38:56·4	4·5	Down		178	30 May 72	03:43:08	5·1		
131	24 Jan 70	09:47:32·1	4·4	Up		179	4 Jun 72	07:54:35·5	5·1		
132	5 Mar 70	01:48:43·8	4·6		2·2	180	14 Aug 72	01:57:00·3	4·9		
133	16 Apr 70	14:48:10·9	5·4	Up	2·2	181	15 Aug 72	15:15:18·5	4·1	Up	
134	27 May 70	12:46:55·5	5·6	Up	2	182	16 Aug 72	07:45:21·8	5·0	Down	
135	29 May 70	05:42:09	4·3			183	25 Aug 72	19:52:25·6	5·0		
136	8 Jun 70	05:31:30·8	5·3	Up		184	26 Aug 72	19:10:32·7	4·1		
137	17 Jun 70	06:50:11·3	5·0	Up		185	28 Aug 72	14:17:13·5	5·0	Up	
138	19 Aug 70	00:36:44·3	4·7	Down	1·8	186	16 Sep 72	11:56:09·4	5·5	Up	
139	21 Sep 70	03:03:35·3	4·8	Up	1·8	187	17 Sep 72	21:22:49·6	5·0	Down	
140	21 Sep 70	08:52:08·6	4·7	Up	1	188	19 Sep 72	02:49:07·5	4·4		
141	25 Sep 70	04:14:15·4	5·3	Down		189	24 Sep 72	08:59:22·6	5·1	Down	2
142	26 Sep 70	16:37:57	5·8			190	27 Sep 72	17:33:00	Noisy record		

TABLE 1 (*contd*)

S. No.	Date	Onset time (GMT) at Gauribidanur	Body wave magnitude (Richter scale)	First motion of P signal	Probable depth phase arrival w.r.t. 1st arrival (sec)	S. No.	Date	Onset time (GMT) at Gauribidanur	Body wave magnitude (Richter scale)	First motion of P signal	Probable depth phase arrival w.r.t. 1st arrival (sec)
191	4 Oct 72	14:26:46	4·3			201*	5 Jun 73	10:28:39	4·9		
192	11 Nov 72	04:03:07·4	4·8	Up		202†	3 Oct 73	14:38:47	4·7		
193	20 Jan 73	17:14:36	4·5			203†	6 Oct 73	09:22:23	4·0		
194	28 Jan 73	18:54:49	4·3			204†	13 Oct 73	07:46:38	4·0		
195	6 Mar 73	07:14:38·6	4·8			205†	13 Oct 73	07:58:40	Very feeble		
196*	31 Mar 73	02:10:10	Very weak event			206†	17 Oct 73	08:04:28	4·4		
197	1 Apr 73	13:32:24	4·5	Up		207†	17 Oct 73	14:41:33	5·0		
198	2 Apr 73	20:22:41	5·1	Up		208†	17 Oct 73	15:26:05	5·3	Main shock (felt in Bombay)	
199	2 Apr 73	20:46:07	4·7			209†	24 Oct 73	05:02:55	4·1		
200	19 Apr 73	19:01:46				210†	24 Oct 73	18:07:00	5·0		

The table gives list of Koyna aftershocks recorded at Gauribidanur seismic array. Most of the events are read on the 8-channel visual seismograms obtained from the magnetic tapes. Some events marked '*' are read on the three channel helicorders, and confirmed by a comparison with the data from Poona. The events marked '†' are read on helicorder only. For 161 events, both the azimuth, Z and the time difference, D, of arrival of P-Phase and S-Phase could be determined. It is found that the mean value of Z is 320 .4° (s.d.=2.8°) and the mean value of D is 56.3 sec (s.d.=0.8 sec). The magnitude of the events is determined from the amplitude of P-wave as seen in the 8-channel play-out or the helicorder as the case may be.

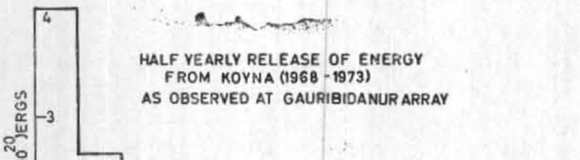

Fig. 3. Histogram of half yearly release of seismic energy from Koyna as observed at GBA during 1968-73. The figure reveals that the seismic activity is decreasing slowly with some fluctuation whose period is about 2 years.

of energy release. The most important feature of the Eq. (3) is that it shows that the average rate of energy release is decreasing slowly and it can be represented in the form:

$$dE_t/dt \propto t^{-1/2} \tag{4}$$

during the period under study. The fact that the data of 6 years fits into one single curve apart from some fluctuations (depending on seasonal effects) shows that *the nature of average energy release from Koyna as observed at GBA has not drastically changed during the past six years though the seismic activity has not come to a halt.*

To show the effect of 'seasonal' variations, we have plotted the histogram of half-yearly release of energy during the period under study in Fig. 3, where we see a general decrease in the energy release with time with a tendency to fluctuate with a period of about two years. Since the energy release in an earthquake is a non-linear phenomenon, it is difficult to establish a direct correlation with external factors like water level in Koyna dam, etc. However one fact emerges from the present study that whatever be the factors that caused the Koyna earthquake, the strain release pattern has not changed drastically till now since January 1968 and the average rate of energy release seems to be varying inversely as the square root of time that elapsed since January 1968.

4. Focal depths of the aftershocks

In Table 1, some of the aftershocks are observed to contain a phase following the first arrival with a lag of 1 to 3 sec. In a previous study of Koyna aftershocks, it was suggested that the second signal in Koyna aftershocks is most probably a surface reflected P-phase (Murty 1969, 1970). Following this suggestion, the 'depth' of source of these events showing a 'second phase' is estimated to vary between 4 to 12 km with a mean value of 6·8 km and a standard deviation of 2.3 km.

The cross-correlation coefficient between the estimated magnitude and estimated depth is 0.3, which indicates that there is a very weak correlation between these variables.

5. Conclusions

The aftershocks observed at Gauribidanur from Koyna region during January 1968-October 1973 show that the seismic activity is decreasing and the rate of energy release is varying inversely as the square root of time that elapsed after January 1968. There seems to be a tendency for the energy release to fluctuate around the general trend with a period of about 2 years. There is a little correlation between the estimated depths and the estimated magnitudes of the events under study.

We wish to emphasise that our conclusions are based exclusively on the data obtained along only one azimuthal direction with respect to the source. It would be worthwhile to compare our results with those obtained from data along other azimuthal directions.

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