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Source Parameters and Scaling Relation for Local Earthquakes in the Garhwal and Kumaun Himalaya, India

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Abstract Earthquake source parameters provide great deal of information about the characteristics of earthquake source. Parameters such as stress drop, corner frequency, and f_{max} have applications in the estimation of strong ground motion. In the present study source parameters of 107 local events ($0.1 \leq M_L \leq 3.5$), have been estimated using software EQK_SRC_PARA. Epicenters of majority of events are distributed along the trace of MCT between Barkot and Chamoli. Few events occurred in the Higher Himalaya to the northwest of Barkot and also in the Sub Himalaya. Seismic moments, Source radii, and Stress drops span the range from 3.03 x 10^{17} dyne-cm to 2.75 x 10^{21} dyne-cm, 111.7 m to 314.4 m, and 0.01 bars to 40 bars respectively. Maximum observed stress drops are associated with the events located at a distance of about 25 km in the west of epicenter of the Chamoli earthquake. Events with stress drops between 5 bar and 40 bars occurs at a depth of about 15 km. Stress drop increases with seismic moment for events with seismic moments above 1 x 10^{19} dyne-cm, and follows the relation: $\Delta\sigma$ (bars) = 6×10^{-16} $M_0^{0.8}$. A scaling law $M_0\ f_c^{2.7}$ =5.0 x 10^{13} N-m/sec$^{2.7}$ between seismic moment and corner frequency ($1.0<M_w<3.3$) has been developed for the region. Almost similar trend between f_c and f_{max} with seismic moment has been observed and f_c and f_{max} follow the empirical relation: f_{max} = 3 f_c -2.6 for the region. Consistency in the f_c and f_{max} which decreases with seismic moment has confirmed the stochastic nature of high frequency ground motion in the Garhwal and Kumaun Himalaya.
Keywords *Source Parameters, Stress Drop, Chamoli, Garhwal and Kumaun Himalaya,* f_{max}

1. Introduction

Earthquake source parameters provide detailed knowledge regarding the characteristics of earthquake source. Parameters such as stress drop, corner frequency, and f_{max} have applications in the estimation of strong ground motion. Spatial and temporal variations of stress drops of earthquakes can be useful in the earthquake prediction research. Several methods in the time domain and frequency domain have been developed for the estimation of source parameters.

In India, studies of source parameters using local earthquake data started in 1990s after the deployment of a digital telemetered array in the Garhwal Himalaya to study the local seismicity of the region. Various researchers estimated earthquake source parameters in the Himalayan regions, some of the studies carried in this region are Sharma and Wason [2], Kumar et al. [3], Sriram et al. [4], Wason and Sharma [5], Kumar et al. [6], Paul and Kumar [7], Kumar et al. [8], Kumar et al. [9], Kumar et al. [10], Mittal et al. [11], Kumar et al. [12, 13].

In the present study software EQK_SRC_PARA [1] based on Brune source model [14, 15] and high-cut filter presented by Boore [16] to estimate f_{max} has been used for analysis. The source parameters and f_{max} of 107 local earthquakes ($0.1 \le M_L \le 3.5$) occurred in the Garhwal and Kumaun Himalaya from January 2008 to March 2008 has been estimated. Attempt has been made to develop scaling law and interrelationship between various estimated source parameters.

2. Study Area and Data

The study area is bound between latitude 29.50º N to 31.50º N and longitude 77.00º E to 81.50º E and falls in the Garhwal and Kumaun Lesser Himalaya (Figure 1). The area lies between the rupture zones of two great earthquakes viz., Kangra earthquake of 1905 and Bihar Nepal earthquake of 1934. The area has been selected for the study because of the occurrence of two gap-filling moderate earthquakes, namely the Uttarkashi earthquake of 1991 (m_b 6.6) and the Chamoli earthquake of 1999 (m_b 6.3) and because several river valley projects are either in operation or under investigation and planning stage in the region, and the availability of digital data of local earthquakes to allow estimation of source parameters.

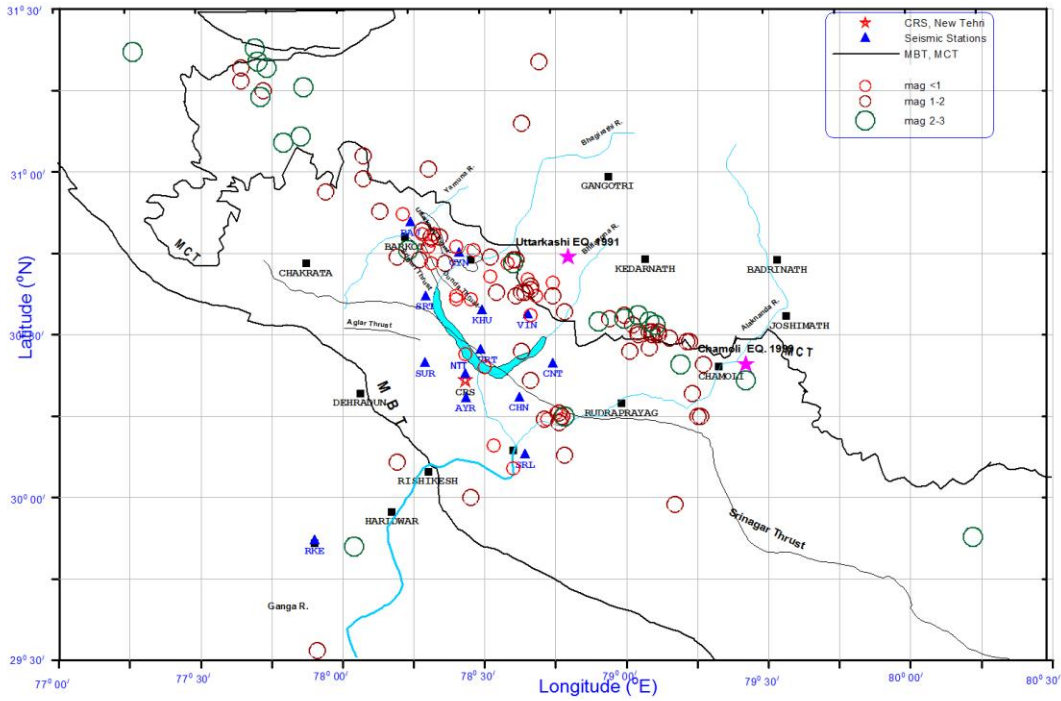

Figure 1: Map Shows the Study Area, Location of Recording Stations and Epicenters of Local Earthquakes (Tectonics after GSI [17]*).*

The data set consists of 107 local earthquakes recorded by a seismological network deployed in the Garhwal Himalaya to monitor the local seismicity around Tehri dam region. The network comprises of 12 remote stations. Nine remote stations are radio linked to the central receiving and recording station located at New Tehri Town (NEWT), whereas the remaining three remote stations operate in an independent mode. The layout of network is shown in Figure 1. Each remote station of the network houses a tri-axial short-period seismometer (Guralp: CMG 40T-1) to sense the ground motion. The data is acquired at a sampling rate of 100 samples per second.

3. Methodology

Software EQK_SRC_PARA [1] has been used that first correct recorded time histories for instrument response, rotate them to get SH component and a frequency dependent attenuation, $Q_c=110f^{1.02}$ [18] developed for the Garhwal Himalayan region from coda-waves of local earthquakes, has been applied. A Brune source model [14,15] and high-cut filter presented by Boore [16] has been fitted to observed spectra to get spectral parameters namely; low frequency displacement spectral level (Ω_0), corner frequency (f_c) above which spectrum decays with a rate of two, the high-cut frequency (f_{max}) above which the spectrum again decays.

A typical example of the time series of local earthquakes along with the estimated source spectra is depicted in Figure 2.

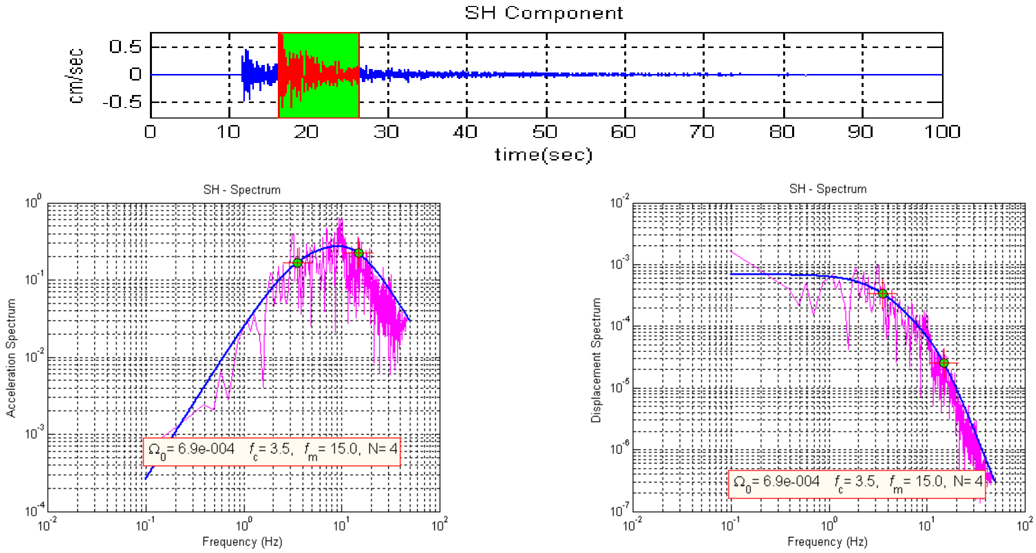

Figure 2: *A Typical Example of the SH-Component of Velocity Time History of an Earthquake Recorded at Srikot Station of Tehri Network. The Acceleration and Displacement Spectra Along with Fitted Source Model*

The seismic moment [19] is estimated from the value of Ω0 as

$$M_o = \frac{4\pi\rho\beta^3 R\Omega_0}{R_{\theta\varphi} \cdot S_a}$$

where ρ is the average density (=2.67 g/cm3), β is shear wave velocity in the source zone (=3.2 km/s), R is the hypocentral distance that accounts geometrical spreading, $R_{\theta\varphi}$ is the average radition pattern (=0.63), S_a is free surface amplification (=2).

The moment magnitude [20],

$$M_\omega = \frac{2}{3}\log(M_o) - 10.7$$

The source radius and stress drop [14, 15] are

$$r = \frac{2.34\beta}{2\pi f_c} \quad \text{and} \quad \Delta\sigma = \frac{7M_o}{16r^3}$$

Source parameters of 107 local earthquakes ($0.21<M_L<3.3$) that occurred in the Garhwal Himalaya have been estimated. These parameters have been computed adopting the procedure described in this section. The Hypocenter parameters of these events are listed in Table 1 and the epicenters are plotted on the tectonic map (Figure 1). The spectral parameters and source parameters, viz., seismic moments, stress drops, and source radii of these events are listed in Table 2.

Table 1: *Hypocenters Parameters and Magnitudes of Local Earthquakes Occurred in the Garhwal and Kumaun Himalaya*

Sr. No	Origin Time (GMT)	Latitude ° N	Longitude ° E	Depth km	Mw	RMS (km)	ERH (km)	ERZ (km)	No. of Stations
1	20080101 08:15:18.6	30.36	78.66	11.48	1.2	0.23	2.60	3.70	10
2	20080101 20:34:29.5	30.32	79.23	12.15	1.38	0.30	2.40	1.40	9
3	20080102 09:27:36.4	30.24	78.71	8.11	1.51	0.26	1.60	2.50	10
4	20080102 15:09:48.0	31.86	78.64	9.27	2.38	0.28	3.30	3.20	8
5	20080102 19:24:01.9	30.00	78.45	32.26	1.13	0.35	4.80	3.60	10
6	20080103 01:24:58.4	30.79	78.31	9.38	0.81	0.45	1.90	2.80	11
7	20080104 06:59:06.4	30.57	78.78	15.71	1.24	0.35	1.60	0.60	11
8	20080104 18:34:11.5	30.73	78.61	14.38	1.25	0.46	1.80	1.50	10
9	20080105 16:51:48.8	30.61	78.45	7.82	0.81	0.29	0.90	1.60	6
10	20080106 13:44:35.1	31.15	78.63	9.90	1.91	0.45	2.50	1.60	11
11	20080106 15:43:55.0	30.11	78.19	11.63	1.57	0.25	1.70	1.30	6
12	20080107 04:08:33.3	31.37	77.26	15.00	2.49	0.29	4.80	3.00	3
13	20080111 15:48:48.7	30.48	79.21	11.98	1.51	0.09	1.50	0.70	1
14	20080111 16:33:07.4	30.51	79.11	13.41	1.66	0.43	3.40	1.70	5
15	20080112 16:31:24.2	30.55	78.99	12.96	2.44	0.39	1.80	1.00	5
16	20080114 05:38:46.3	30.72	78.60	15.32	2.55	0.45	1.80	1.00	9
17	20080114 05:41:32.4	30.73	78.60	15.07	1.67	0.44	1.70	1.10	9
18	20080115 04:49:42.3	30.56	78.99	11.35	1.65	0.51	2.70	2.50	9
19	20080115 22:51:31.0	30.13	78.78	11.90	1.92	0.44	2.40	1.40	8
20	20080116 05:20:30.1	30.56	79.04	11.96	2.17	0.40	2.00	1.20	9
21	20080116 21:31:07.2	30.65	78.66	6.63	1.53	0.45	1.60	3.30	10
22	20080117 20:15:47.5	30.25	79.26	7.65	1.64	0.38	3.40	2.60	11
23	20080119 18:34:41.7	30.16	78.53	9.33	0.62	0.15	0.90	1.50	8
24	20080119 23:28:19.0	30.45	78.63	0.81	1.26	0.47	2.70	3.20	11
25	20080120 20:41:48.8	30.62	78.61	16.57	1.62	0.49	1.60	2.40	10
26	20080120 20:49:33.2	30.41	79.19	13.39	2.01	0.41	2.30	1.40	10
30	20080124 17:34:03.5	30.77	78.30	1.63	0.23	0.25	1.90	1.60	9
31	20080124 23:14:10.1	30.62	78.74	16.90	1.02	0.50	2.20	2.50	6
32	20080125 15:24:25.3	30.51	79.08	15.56	1.81	0.41	2.20	1.30	10
33	20080125 17:17:38.2	30.50	79.11	15.27	1.75	0.52	3.30	1.90	11

34	20080125 19:25:23.5	30.50	79.09	13.56	1.58	0.36	2.80	1.30	11
35	20080125 20:49:24.8	30.63	78.63	8.70	1.15	0.50	2.10	3.00	9
36	20080125 21:29:36.9	30.53	79.10	14.40	2.36	0.45	2.30	1.20	10
37	20080125 21:33:04.7	30.51	79.04	14.68	1.62	0.33	1.70	0.80	10
38	20080125 23:59:03.9	30.54	79.08	14.65	2.24	0.45	2.30	1.10	9
39	20080126 10:51:07.7	30.65	78.66	13.18	1.74	0.44	1.60	2.00	9
40	20080126 15:43:01.0	30.80	78.34	6.86	1.57	0.49	2.80	4.30	10
41	20080127 13:11:36.2	30.64	78.66	12.19	1.33	0.47	1.90	2.00	2
42	20080127 16:55:49.1	30.51	79.09	15.00	1.82	0.46	2.20	1.10	11
43	20080128 03:14:02.9	29.98	79.17	9.91	1.67	0.33	4.90	3.00	6
44	20080129 04:36:11.3	31.05	78.07	42.89	1.79	0.23	2.90	0.60	6
45	20080130 14:16:50.7	30.54	78.90	14.72	2.07	0.45	2.10	0.90	11
46	20080130 20:50:38.1	30.63	78.64	41.35	1.90	0.41	1.90	1.70	11
47	20080130 21:14:23.2	30.62	78.61	41.71	1.52	0.41	2.30	2.20	11
48	20080201 02:20:14.8	29.16	77.74	15.16	1.71	0.34	3.90	2.60	11
49	20080201 19:54:12.4	31.09	77.79	8.54	2.02	0.48	4.00	1.70	11
50	20080203 09:40:40.5	30.62	78.40	9.05	0.21	0.46	1.10	2.10	11
51	20080204 15:04:27.6	30.77	78.40	5.79	0.84	0.44	2.00	2.30	7
52	20080206 05:17:37.0	30.68	78.52	2.05	0.43	0.45	2.00	1.90	9
53	20080208 16:38:35.3	30.74	78.52	9.17	1.09	0.33	1.80	2.00	9
54	20080209 08:42:49.4	30.26	78.75	14.09	0.88	0.29	1.70	1.50	5
55	20080209 19:29:59.4	30.72	78.58	12.47	0.57	0.38	1.50	1.50	7
56	20080210 09:21:26.1	30.23	78.76	14.90	1.34	0.20	2.20	1.50	7
57	20080210 13:28:16.4	30.25	79.25	10.47	1.75	0.50	2.70	1.40	7
58	20080211 16:07:18.7	30.61	78.40	11.05	0.33	0.44	1.00	1.80	9
59	20080211 22:46:25.1	30.44	78.43	7.13	0.16	0.30	0.80	1.90	10
60	20080213 08:52:14.9	30.26	78.76	11.97	1.38	0.32	1.10	1.10	11
61	20080214 20:12:03.7	29.85	78.04	40.16	2.59	0.29	1.90	0.90	7
62	20080215 16:57:29.1	30.66	78.74	15.15	0.25	0.11	1.60	0.50	5
63	20080215 17:05:57.3	30.62	78.68	12.82	0.27	0.48	2.10	2.40	10
64	20080216 01:25:57.1	30.88	78.13	5.65	1.95	0.48	2.90	2.90	10
65	20080218 21:12:44.2	30.46	79.08	13.81	1.41	0.28	1.60	0.70	10
66	20080219 23:23:53.7	30.76	78.23	12.81	2.15	0.50	2.60	1.20	10
67	20080219 23:36:47.1	30.82	78.28	15.15	1.62	0.50	3.20	1.30	10
68	20080220 07:12:45.0	30.72	78.36	15.23	1.61	0.31	1.50	0.60	9
69	20080221 06:06:04.2	30.73	78.27	13.50	1.18	0.20	1.30	0.80	11
70	20080221 15:05:09.7	30.72	78.31	15.88	0.24	0.11	2.10	0.70	11
71	20080221 18:54:17.2	30.74	78.19	18.03	1.43	0.43	3.30	3.20	2
72	20080222 15:17:28.7	30.56	78.66	13.38	0.69	0.32	1.60	2.50	10
73	20080225 03:28:29.0	30.63	78.54	24.61	1.72	0.42	2.50	2.10	10
74	20080225 08:24:00.6	30.24	78.72	9.37	0.94	0.28	1.30	2.30	10
75	20080225 17:30:37.7	30.45	79.01	14.12	1.75	0.48	3.00	1.50	6
76	20080228 08:57:31.6	30.25	78.77	11.32	1.05	0.30	1.20	2.10	9
77	20080229 13:02:39.1	30.09	78.60	11.04	0.76	0.16	1.10	1.00	10

78	20080302 06:13:27.2	30.98	78.07	14.85	1.72	0.34	3.60	1.30	10
79	20080304 08:01:13.9	30.67	78.65	17.32	0.82	0.25	1.80	1.60	10
80	20080305 03:28:32.8	30.41	79.27	11.95	1.81	0.50	3.10	1.90	9
81	20080305 16:14:40.4	29.53	77.91	37.35	1.75	0.20	2.60	1.00	9
82	20080306 14:54:28.2	30.80	78.31	2.21	1.22	0.23	1.20	0.70	8
83	20080306 18:19:07.2	30.40	78.50	10.17	0.30	0.44	1.00	1.90	10
84	20080307 09:34:46.9	30.49	79.15	10.41	1.48	0.50	4.40	2.60	10
85	20080308 08:02:43.8	30.76	78.46	1.84	0.46	0.43	2.00	1.10	4
86	20080308 18:29:14.6	31.11	77.85	43.46	2.06	0.22	2.50	0.50	11
87	20080310 20:52:57.9	29.88	80.22	19.20	2.62	0.37	5.00	1.20	10
88	20080311 19:31:26.8	30.50	79.04	13.57	1.80	0.42	2.80	1.20	10
89	20080312 12:08:37.4	30.81	78.32	13.79	0.99	0.20	1.40	0.60	10
90	20080312 18:57:45.7	30.81	78.28	15.00	0.90	0.50	4.30	2.40	9
91	20080313 05:03:56.5	30.94	77.94	34.20	1.52	0.39	4.60	3.20	10
92	20080314 00:30:25.7	30.55	78.94	12.99	1.32	0.49	3.20	1.90	10
93	20080315 06:46:14.3	30.48	79.22	14.34	1.86	0.17	1.50	0.70	9
94	20080315 08:25:30.3	30.24	78.77	10.78	0.59	0.13	1.20	1.50	10
95	20080315 23:53:25.9	30.36	79.42	43.11	2.21	0.29	2.40	0.70	7
96	20080317 19:30:33.4	31.54	77.13	5.00	2.74	0.40	5.80	2.30	10
97	20080318 20:59:44.2	31.60	78.52	2.42	2.70	0.51	4.60	1.10	11
98	20080319 05:06:49.1	31.34	78.69	4.87	1.80	0.42	3.30	2.10	6
99	20080321 20:15:19.4	31.32	77.64	3.18	1.95	0.35	4.30	1.50	7
100	20080321 20:43:30.7	31.34	77.70	7.30	2.30	0.42	5.80	2.00	9
101	20080321 20:52:27.3	31.28	77.64	5.00	1.15	0.33	4.60	1.70	8
102	20080321 21:49:41.7	31.32	77.73	1.51	2.08	0.43	6.30	1.10	10
103	20080321 22:31:07.7	31.23	77.71	3.42	2.86	0.36	4.20	2.20	8
104	20080321 22:38:04.3	31.25	77.72	1.44	1.75	0.41	5.30	0.70	8
105	20080322 02:37:05.1	31.38	77.69	1.85	2.56	0.34	4.30	0.80	10
106	20080325 08:37:04.0	30.25	78.78	6.22	2.43	0.16	0.80	2.80	10
107	20080330 16:06:31.3	31.26	77.86	12.56	2.23	0.42	4.60	1.70	10

Table 2: *Source Parameters of Local Earthquakes Occurred in the Garhwal and Kumaun Himalaya*

Sr. No.	Date	Depth (km)	M_L	f_c	f_{max}	Mo (dyne - cm)	M_ω	R (m)	Δσ (bars)
1	200801010815	11.48	1.2	5.5	19.3	1.59E+18	1.4	244.1	0.10
2	200801012034	12.15	1.38	7.3	16.5	9.04E+17	1.28	166.5	0.11
3	200801020927	8.11	1.51	4.7	15.4	2.48E+18	1.50	264.6	0.05
4	200801021509	9.27	2.38	4.4	11.6	3.82E+19	2.34	275.2	0.96
5	200801021924	32.26	1.13	9.5	14.9	3.77E+17	0.97	148.3	0.16
6	200801030124	9.38	0.81	5.8	16.3	3.72E+18	1.5	227.1	0.14
7	200801040659	15.71	1.24	6.2	16.3	4.32E+18	1.66	223.2	0.29
8	200801041834	14.38	1.25	4.2	14.7	1.98E+18	1.40	277.5	0.04
9	200801051651	7.82	0.81	4.2	16.1	4.99E+17	1.11	289.1	0.01

10	200801061344	9.9	1.91	4.9	11.1	1.46E+19	1.96	249.9	0.36
11	200801061543	11.63	1.57	4.0	17.9	9.30E+17	1.3	302.3	0.02
12	200801070408	15	2.49	4.7	9.5	2.15E+20	2.87	240.5	6.53
13	200801111548	11.98	1.51	8.5	19.2	3.03E+17	0.99	131.4	0.06
14	200801111633	13.41	1.66	5.3	13.9	8.10E+17	1.19	230.6	0.03
15	200801121631	12.96	2.44	5.4	14.9	1.19E+19	1.98	225.7	0.44
16	200801140538	15.32	2.55	4.7	13.1	6.19E+19	2.4	253.0	2.34
17	200801140541	15.07	1.67	6.3	16.5	1.28E+19	1.81	215.3	0.37
18	200801150449	11.35	1.65	7.0	15.1	2.69E+18	1.53	184.5	0.22
19	200801152251	11.9	1.92	6.1	15.1	5.83E+18	1.79	204.9	0.34
20	200801160520	11.96	2.17	5.6	14.2	9.85E+19	2.61	217.7	5.61
21	200801162131	6.63	1.53	6.3	15.0	9.49E+18	1.9	192.8	0.58
22	200801172015	7.65	1.64	6.2	16.3	1.30E+18	1.34	211.2	0.09
23	200801191834	9.33	0.62	6.4	19.5	4.58E+17	1.05	210.8	0.05
24	200801192328	0.81	1.26	6.2	17.3	5.68E+17	1.10	201.1	0.05
25	200801202041	16.57	1.62	6.6	16.3	1.25E+19	1.94	194.0	0.76
26	200801202049	13.39	2.01	6.1	15.8	3.98E+18	1.7	199.4	0.34
27	200801210451	12.7	1.29	4.7	15.2	1.79E+18	1.49	260.7	0.06
28	200801211130	12.51	0.59	6.3	12.7	1.30E+18	1.37	192.8	0.09
29	200801211754	14.5	1.6	5.9	14.6	6.66E+17	1.22	190.6	0.04
30	200801241734	1.63	0.23	5.4	15.5	6.38E+17	1.11	226.0	0.03
31	200801242314	16.9	1.02	5.4	14.6	1.02E+18	1.3	229.8	0.05
32	200801251524	15.56	1.81	4.0	10.5	6.54E+20	3.17	302.5	13.68
33	200801251717	15.27	1.75	5.6	15.8	1.05E+18	1.27	214.3	0.05
34	200801251925	13.56	1.58	5.2	14.7	4.19E+18	1.53	252.4	0.11
35	200801252049	8.7	1.15	6.8	15.6	5.34E+17	1.13	191.9	0.12
36	200801252129	14.4	2.36	3.9	13.5	7.62E+19	2.5	314.4	1.19
37	200801252133	14.68	1.62	5.2	15.0	2.32E+18	1.56	220.0	0.10
38	200801252359	14.65	2.24	6.4	14.3	1.29E+19	2.04	188.8	1.22
39	200801261051	13.18	1.74	6.5	14.1	2.81E+19	2.24	186.3	2.24
40	200801261543	6.86	1.57	5.5	14.7	9.05E+19	1.51	232.5	2.96
41	200801271311	12.19	1.33	10.0	18.9	1.33E+18	1.4	111.7	0.42
42	200801271655	15	1.82	4.5	11.5	2.75E+21	3.26	278.5	39.67
43	200801280314	9.91	1.67	7.1	15.6	2.05E+18	1.43	177.7	0.15
44	200801290436	42.89	1.79	5.3	17.8	5.08E+18	1.73	235.1	0.22
45	200801301416	14.72	2.07	7.1	13.4	3.25E+18	1.63	174.9	0.35
46	200801302050	41.35	1.9	6.3	14.8	2.24E+19	2.1	198.6	1.16
47	200801302114	41.71	1.52	5.7	16.1	1.66E+18	1.40	240.4	0.08
48	200802010220	15.16	1.71	7.3	19.5	4.11E+18	1.6	189.2	0.31
49	200802011954	8.54	2.02	5.9	17.3	5.49E+18	1.80	200.1	0.36
50	200802030940	9.05	0.21	6.0	14.1	3.51E+18	1.64	214.6	0.21
51	200802041504	5.79	0.84	6.3	13.7	3.09E+18	1.48	189.8	0.19
52	200802060517	2.05	0.43	7.3	17.4	2.89E+18	1.57	162.5	0.28
53	200802081638	9.17	1.09	5.6	16.3	1.72E+18	1.3	231.6	0.06

54	200802090842	14.09	0.88	4.4	19.0	2.55E+18	1.55	275.7	0.08
55	200802091929	12.47	0.57	6.0	15.8	7.56E+17	1.15	202.2	0.05
56	200802100921	14.9	1.34	6.9	21.1	2.37E+18	1.41	212.6	0.30
57	200802101328	10.47	1.75	5.3	16.6	4.80E+18	1.74	223.8	0.24
58	200802111607	11.05	0.33	6.2	13.8	8.79E+17	1.3	190.3	0.06
59	200802112246	7.13	0.16	5.2	16.7	4.21E+17	1.04	239.3	0.02
60	200802130852	11.97	1.38	4.1	12.1	7.05E+18	1.82	296.8	0.15
61	200802142012	40.16	2.59	6.2	14.8	8.22E+18	1.89	212.4	0.55
62	200802151657	15.15	0.25	5.8	14.0	5.26E+17	1.07	202.5	0.02
63	200802151705	12.82	0.27	7.2	16.6	4.12E+17	1.0	184.2	0.08
64	200802160125	5.65	1.95	9.9	25.1	6.57E+17	1.00	182.2	0.33
65	200802182112	13.81	1.41	7.5	15.9	1.02E+18	1.30	155.9	0.14
66	200802192323	12.81	2.15	6.3	12.7	2.78E+19	2.03	193.2	1.64
67	200802192336	15.15	1.62	7.0	25.7	5.62E+18	1.61	197.2	0.43
68	200802200712	15.23	1.61	6.1	9.8	1.26E+20	2.5	194.7	7.57
69	200802210606	13.5	1.18	5.9	15.6	5.32E+18	1.67	206.0	0.50
70	200802211505	15.88	0.24	7.3	15.4	8.66E+17	1.08	188.9	0.05
71	200802211854	18.03	1.43	6.9	10.0	9.74E+18	1.79	162.4	0.86
72	200802221517	13.38	0.69	5.8	16.2	1.10E+18	1.27	229.4	0.05
73	200802250328	24.61	1.72	6.3	16.3	1.53E+19	2.0	206.9	0.85
74	200802250824	9.37	0.94	3.8	21.3	2.84E+18	1.6	301.1	0.05
75	200802251730	14.12	1.75	8.5	16.4	1.45E+18	1.28	164.9	0.14
76	200802280857	11.32	1.05	5.5	15.0	1.97E+18	1.41	219.3	0.09
77	200802291302	11.04	0.76	8.5	18.8	1.11E+18	1.27	173.0	0.22
78	200803020613	14.85	1.72	6.3	14.5	3.84E+18	1.65	192.7	0.29
79	200803040801	17.32	0.82	5.5	17.1	5.26E+18	1.7	232.3	0.24
80	200803050328	11.95	1.81	6.3	16.0	6.41E+18	1.82	206.4	0.47
81	200803051614	37.35	1.75	8.2	19.7	1.12E+18	1.20	216.5	0.12
82	200803061454	2.21	1.22	6.3	14.5	4.97E+18	1.72	190.2	0.36
83	200803061819	10.17	0.3	7.6	16.3	1.30E+18	1.18	193.8	0.08
84	200803070934	10.41	1.48	8.2	20.3	2.16E+18	1.5	173.7	0.33
85	200803080802	1.84	0.46	6.8	16.9	1.47E+18	1.29	197.6	0.06
86	200803081829	43.46	2.06	5.5	13.4	1.71E+19	2.07	225.4	0.87
87	200803102052	19.2	2.62	5.5	13.4	3.61E+19	2.26	225.4	1.74
88	200803111931	13.57	1.8	8.0	16.6	1.89E+18	1.46	150.9	0.31
89	200803121208	13.79	0.99	5.7	14.9	1.82E+19	2.0	249.1	0.68
90	200803121857	15	0.9	5.6	17.0	1.87E+18	1.47	233.1	0.12
91	200803130503	34.2	1.52	5.9	13.7	1.22E+19	1.89	215.2	0.63
92	200803140030	12.99	1.32	6.5	17.9	4.61E+17	1.06	201.8	0.05
93	200803150646	14.34	1.86	7.3	16.8	6.42E+18	1.63	177.8	0.64
94	200803150825	10.78	0.59	4.4	17.5	2.22E+18	1.5	272.1	0.07
95	200803152353	43.11	2.21	8.0	17.2	8.28E+17	1.23	176.0	0.13
96	200803171930	5	2.74	6.7	12.9	8.27E+18	1.80	180.8	0.60
97	200803182059	2.42	2.7	5.6	12.7	3.06E+18	1.60	211.4	0.21

98	200803190506	4.87	1.8	5.7	19.8	2.34E+18	1.49	219.6	0.13
99	200803212015	3.18	1.95	6.7	12.2	1.38E+19	2.0	174.8	1.12
100	200803212043	7.3	2.3	5.9	14.7	1.22E+18	1.4	210.3	0.09
101	200803212052	5	1.15	7.2	12.5	5.43E+18	1.76	164.5	0.57
102	200803212149	1.51	2.08	7.2	19.5	4.89E+17	1.07	156.5	0.06
103	200803212231	3.42	2.86	7.0	12.7	3.04E+18	1.58	173.2	0.31
104	200803212238	1.44	1.75	7.1	19.2	5.03E+17	1.05	174.7	0.05
105	200803220237	1.85	2.56	7.1	13.9	5.92E+18	1.8	176.1	0.70
106	200803250837	6.22	2.43	3.7	14.3	3.39E+18	1.54	312.5	0.04
107	200803301606	12.56	2.23	7.5	15.6	1.76E+18	1.29	179.2	0.12

4. Results and Discussion

Epicenters of local events for which source parameters are estimated are distributed in the vicinity of MCT (Figure 1). Events occur both in the Lesser Himalaya as well as in the Higher Himalaya. Three events occurred to the south of the MBT in the Ganga fore-deep.

The values of these source parameters range from 3.03×10^{17} dyne-cm to 2.75×10^{21} dyne-cm for seismic moments, 0.01 bars to 39.67 bars for stress drops, and 111.7 m to 314.1 m for source radii. The average values of f_{max} for these events vary from 9.5 Hz to 25.7 Hz. Various plots have been drawn in order to infer the characteristics of estimated spectral and source parameters.

The variation of source radii with seismic moments (Figure 3) showed a large scatter for events falling in the seismic moment range from 3.03×10^{17} to 2.75×10^{21}. However, weak linear trend that indicates increase of source radii with seismic moments seems to exist for events having moment magnitude (M_W >2.0). The stress drops of events range between 0.01 bar and 39.7 bars (Figure 3). From regression analysis, following scaling relation between corner frequency and seismic moment has been estimated (Figure 4).

$$M_0 \text{ (dyne-cm)} = 5.0 \times 10^{20} f_c^{-2.7}$$
$$M_0 f_c^{2.7} = 5.0 \times 10^{20} \text{dyne-cm*Hz}^{2.7}$$
$$= 5.0 \times 10^{13} \text{ N-m/sec}^{2.7}$$

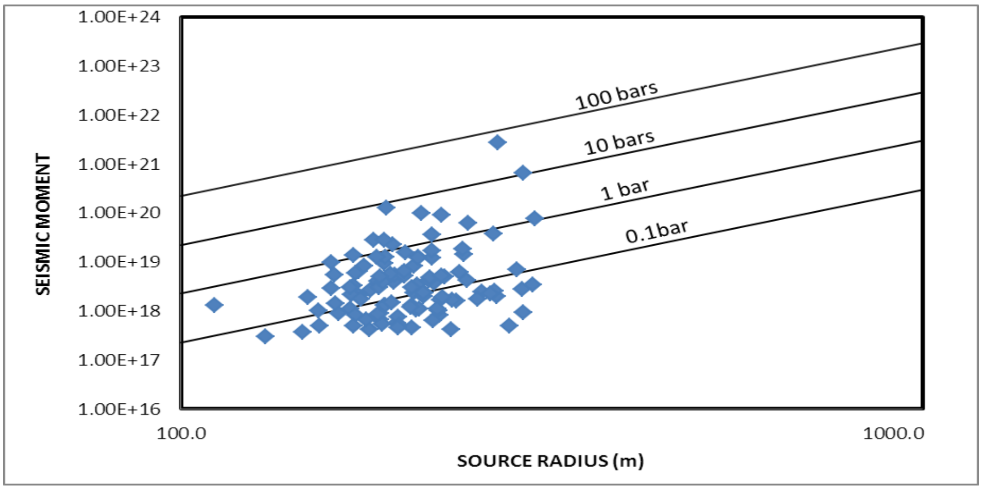

Figure 3: *Plot between the Source Radius and Seismic Moment*

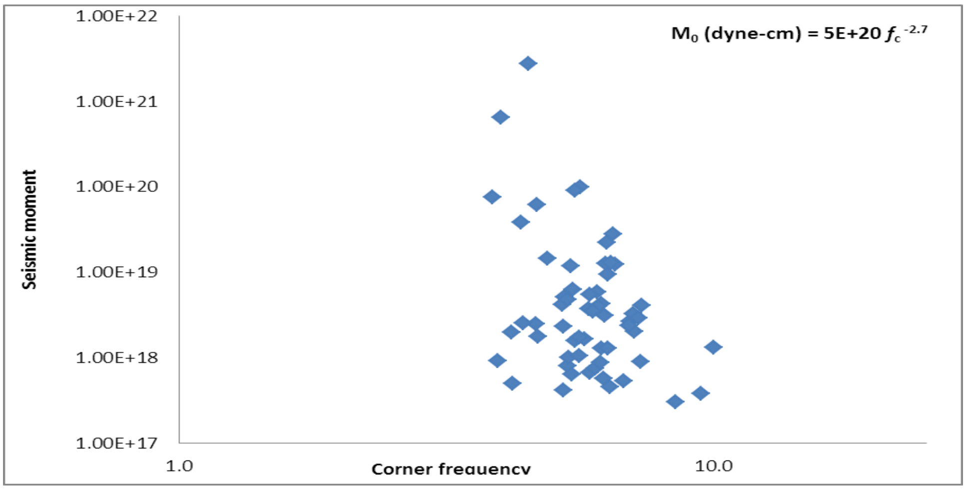

Figure 4: *Plot between Corner Frequency and Seismic Moment*

Similar scaling relations have been obtained for some of the seismically active regions in the world. Some of the typical relations are given below:

Himalayan Region (India) [21]	$M_0 f_c^3 = 1.7 \times 10^{16}$ N-m/sec^3
Kanto Basin (Japan) [22]	$M_0 f_c^3 = (2.5\text{-}3.0) \times 10^{16}$ N-m/sec^3
South-central Alaska [23]	$M_0 f_c^3 = 2.09 \times 10^{16}$ N-m/sec^3
Garhwal Himalaya (India) [24]	$M_0 f_c^3 = 3.0 \times 10^{16}$ N-m/sec^3

Majority of events exhibited low stress drops less than one bar and only fourteen events ($1.57<M_w<2.62$) have stress drops between about one bar to forty bars. Five events, out of these fourteen events, forming a cluster occurred in the vicinity of the MCT at distance of about 25 km in the northwest of Chamoli (Figure 5). Estimated stress drops of these events ($2.04<M_w<3.26$) are 1.2, 1.2,

5.6, 13.7 and 40 bars and events belonging to the cluster have maximum stress drops. Three events with stress drops of 1.6, 2.2 and 3.0 bars have occurred at distance of about 20 km from the reported epicenter of the Uttarkashi earthquake of 1991. Locations of these events follow the trace of MCT. Three events occurred in Lesser Himalaya in the vicinity of Barkot with stress drops of 1.2, 2.3 and7.6 bars. Remaining three events have stress drops of 1.1, 1.7 and 6.5 bars.

Variation between seismic moment and stress drop shows a linear trend (Figure 6) and follow the relationship: $\Delta\sigma$ (bars) = $1\text{x}10^{-16}$ $M_0^{0.82}$**.** However, the events with seismic moments less than 1 x 10^{19} dyne-cm show a large scatter. In view of this a second relationship $\Delta\sigma$ (bars) = $6E^{-16}$ $M_0^{0.8}$ is also estimated for the data set of events with seismic moments above $1\text{x}10^{19}$ dyne-cm. Majority of events with stress drops less than 1 bar have focal depths from 1km to 15 km, whereas most of the events with stress drops from 5 bars to 40 bars occurred at a depth of about 15 km (Figure 7). Few events occurred at a depth around 30 km have low stress drops between 0.1bar to 1bar.

One of the important parameters that control the level of high frequency strong ground motion is f_{max}. Observations have shown that the far-field shear wave acceleration spectra are flat from the corner frequency to f_{max}. The occurrence of f_{max} is either related to the effect of source [25, 26] or to the attenuation beneath the recording site [27]. However, Aki and Irikura [28] based on several research findings arrived at the conclusion that f_{max} is attributed to both site and source. While

Purvance and Anderson [29] and Kumar et al [12, 13] found source is the major contributing factor.

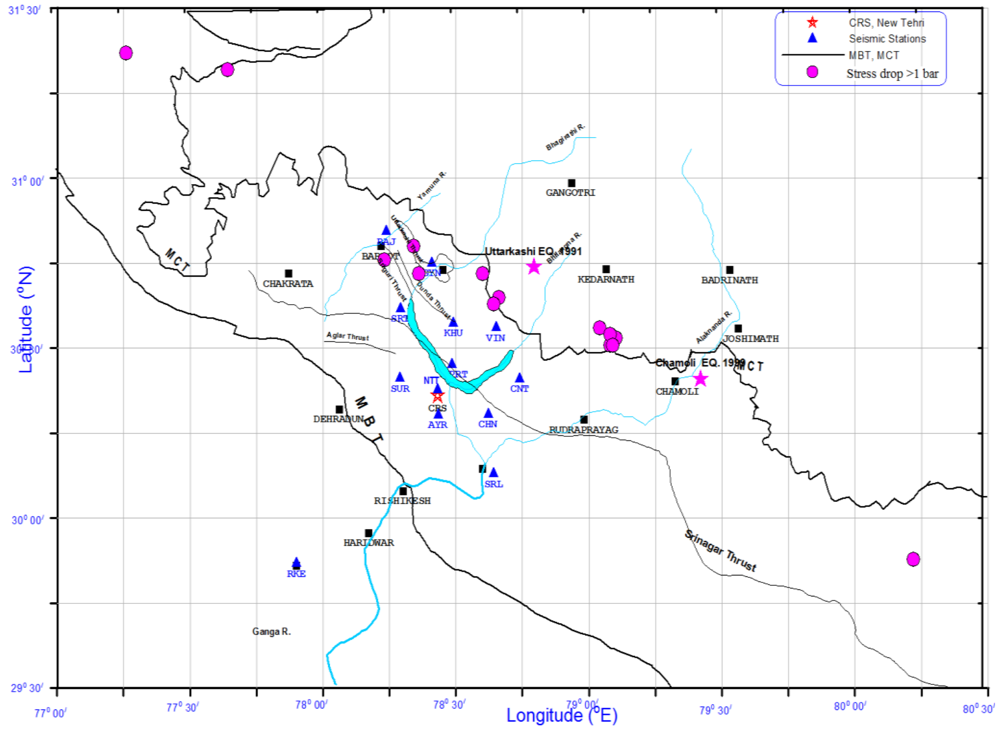

Figure 5: *Map Shows Location of Earthquakes Having Stress Drop More Than one bar (Tectonics after GSI*[17]*)*

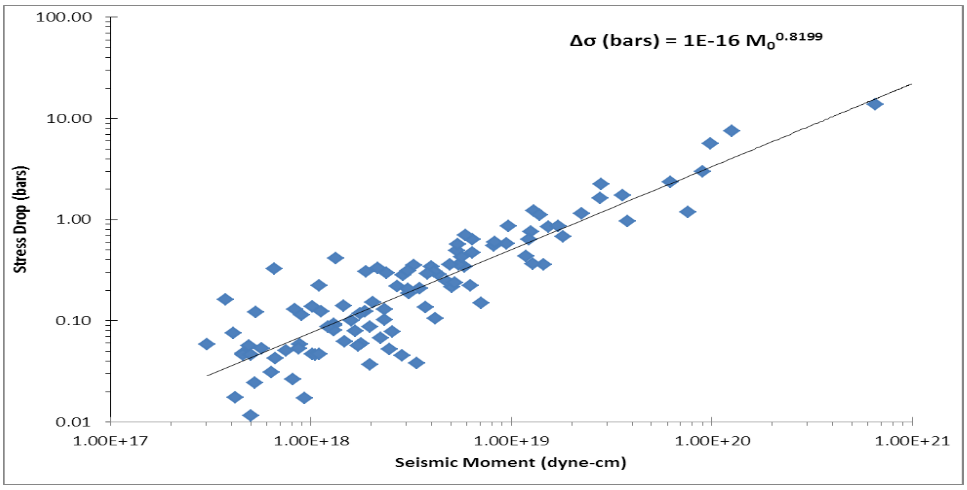

Figure 6: *A Plot between Seismic Moment and Stress Drop*

We have attempted to examine this aspect, and weak dependence of f_{max} on source size is evident from the plot between f_{max} and seismic moment (Figure 8) because as the source size increases the f_{max} decreases. This is particularly seen for events with seismic moments above $4.0x10^{18}$ dyne-cm, however, for events with seismic moments less than $4.0x10^{18}$ dyne-cm, data shows a large scatter. It can be safely concluded the f_{max} decreases with increasing seismic moment.

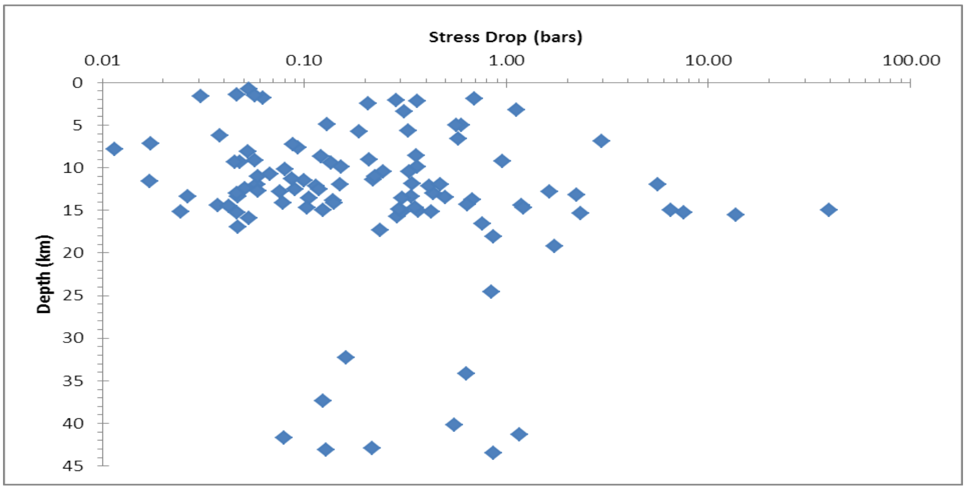

Figure 7: *A Plot between Stress Drop and Depth*

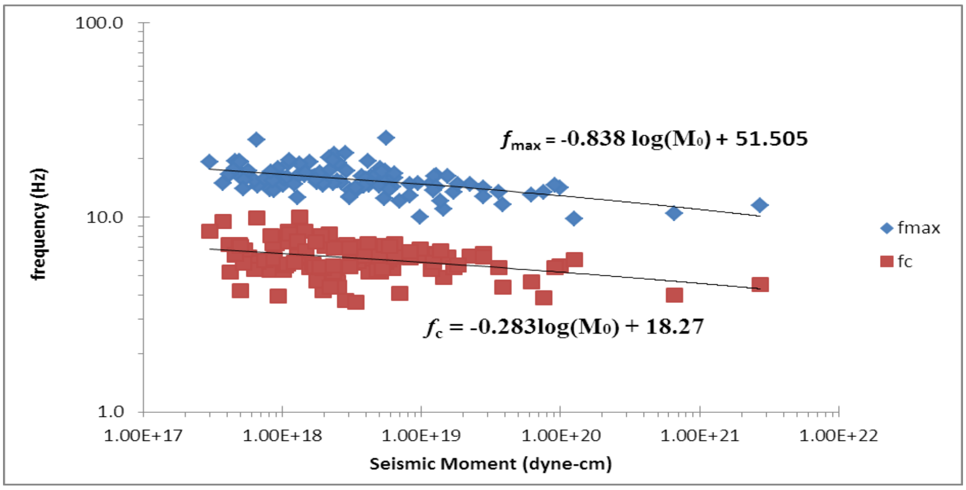

Figure 8: *Plot between Seismic Moment and f_{max} and Corner Frequency*

A relationship of seismic moment both with f_c and f_{max} shows that both f_c and f_{max} follow almost similar trend which further support the view that f_{max} is source dependent. Following two relationships have been developed between seismic moment and f_c and f_{max}:

$$f_c = -0.283\log(M_0) + 18.27$$
$$f_{max} = -0.838 \log(M_0) + 51.505$$

From these equations, we obtain a relationship between f_c and f_{max} in the high frequency range from about 4 Hz to 10Hz for the Garhwal Lesser Himalaya as:

$$f_{max} = 3f_c - 2.6$$

This relationship suggests that f_{max} depends on source size as f_c is inversely proportional to radius of earthquake fault according to Brune source model [13, 14].

5. Conclusion

Source parameters of 107 local earthquakes ($0.21<M_L<3.3$) that occurred in the Garhwal and Kumaon Himalaya have been estimated and following conclusions have been obtained:

- Seismic moments, Source radii, and Stress drops span the range from 3.03×10^{17} dyne-cm to 2.75×10^{21} dyne-cm, 111.7 m to 314.4 m, and 0.01 bars to 40 bars respectively.
- Maximum observed stress drops are associated with the events located at a distance of about 25 km in the west of epicenter of the Chamoli earthquake. Events with stress drops between 5 bar and 40 bars occurs at a depth of about 15 km.
- Stress drop increases with seismic moment for events with seismic moments above 1×10^{19} dyne-cm, and follows the relation: $\Delta\sigma$ (bars) = $6\times10^{-16} M_0^{0.8}$.
- A scaling law $M_0 f_c^{2.7} = 5.0 \times 10^{13}$ N-m/sec$^{2.7}$ between seismic moment and corner frequency ($1.0<M_w<3.3$) has been developed for the region.
- Almost similar trend between f_c and f_{max} with seismic moment has been observed and f_c and f_{max} follow the empirical relation: $f_{max} = 3 f_c - 2.6$ for the region.
- Consistency in the f_c and f_{max} which decreases with seismic moment has confirmed its dependency on source size and the stochastic nature of high frequency ground motion in the Garhwal and Kumaun Himalaya.

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