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Intensity and Source Parameters Study of August 20, 1988 Udaipur Nepal Earthquake of Magnitude 6.8

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ABSTRACT

The paper gives a glimpse of the manual determination of hypocenter, magnitude and focal mechanism etc. in the pre-internet and digital era. Hypocenter of the Udaipur eastern Nepal earthquake of magnitude, Mw 6.8 on August 21 (local time), 1988 is inferred along a NE–trending strike-slip fault beneath the Main Boundary fault at 57 km depth. On surface there is no major tectonic feature following this transverse fault. The parameters of the earthquake as determined by USGS are: origin time 23h 09m 09.56s, Aug. 20, 1988 (UT), 26.775º N 86.616º E, Focal depth = 57.4 km. The epicentral determination using data of near stations in Nepal and northeast India matches with the estimates of the epicenter and depth by the USGS. The depth phases indicate 70km focal depth. However, the focal depth of 57 km estimated using broadband displacement analysis by USGS may be preferred. The deeper depth of this earthquake is significant regarding seismotectonics of Himalaya. Results of intensity survey and seismotectonic study of the earthquake are presented. Geology of the epicentral area is also described. The earthquake caused over 1000 deaths. Severely damaged area was in Nepal extending 60 km north and 100 km east of the epicenter. Maximum damaged towns were Dharan and Dhankuta located 60km east of the epicenter (east of Koshi river). Some damage due to soil amplification occurred in Kathmandu-Bhaktapur area located 175 km northwest and in Bihar at 100 to 150 km south. In Nepal 721 persons died, 6908 persons injured and 64,470 buildings collapsed or damaged. The earthquake had a maximum intensity of VIII in an area of 250 km x 125 km with an estimated acceleration of 0.2 g. There was extensive damage in north Bihar, particularly in Darbhanga, Madhubani-Saharsa area where at least 283 persons were killed, 3147 were injured and 36,144 houses collapsed or damaged. There was damage in Sikkim, Bhutan and Darjeeling. The earthquake was felt in large parts of northern India from Delhi to the Burma border and in much of Bangladesh. The earthquake caused widespread liquefaction and ground cracks in an area of about 125 km x 125 km in Bihar and southern Nepal. The intensity due to the 1934 Mw 8.4 earthquake was two grades higher as compared to 1988 earthquake.

Keywords: Nepal Seismicity, Earthquakes, Nepal 1988 earthquake

1. Introduction

At 4.39 a.m. on Sunday, August 21, 1988 (UT Aug. 20), the Bihar-Nepal border region was struck by a devastating earthquake of magnitude, Mw 6.8. Parameters of the earthquake are given in Table 1. The epicenter (26.775ºN 86.616ºE) was in eastern Nepal along the Main Boundary Thrust of Himalaya (Fig. 1), but associated with a deep transverse fault. The earthquake caused more than 1000 deaths (721 in Nepal and 283 in India) and collapse / severe damage of over 100,000 buildings (64,470 in Nepal and 36,144 in India). More than 54 years ago on the Sankranti Day on Monday, January 15, 1934, the same region had experienced a catastrophic earthquake of M 8.4. The 1988 earthquake was the most damaging earthquake in India, after the 1950 Assam-China border earthquake of M 8.7.

Just 2 days after the earthquake, I started field investigations of the earthquake-affected areas in India and Nepal to assess the damage. The past seismicity data and geology of the area has been studied. Worldwide seismic data was collected and studies on source mechanism were done.

The paper gives a glimpse of the way manual analysis of seismic data was done some three decades ago when USGS data was not available immediately due to absence of internet and digital data.

Table 1: Parameters for Bihar-Nepal 1988 Main Earthquake and aftershocks (USGS data)

SN	DATE	ORIGIN TIME H:M:S	LAT N	LONG E	DEPTH	Mb	Ms
1	88 08 20	23:09:09.56	26.775 (47′)	86.616 (37′)	57.4	6.4	6.6
2	88 08 22	11:34: 33.34	26.662 (40′)	86.916 (55′)	33	4.3	
3	88 08 24	09:55:33.80	26.829 (50′)	86.627 (38′)	33	4.8	4.1
4	88 09 01	22:04:11.20	26.766 (46′)	86.564 (34′)	33	4.8	
5	88 09 02	06:35:33.00	26.616 (37′)	86.518 (31′)	33	4.4	

2. Geological Setup of the Epicentral Area

The epicenter of 1988 Udaipur earthquake is in eastern Nepal Himalaya, about 175 km east of Kathmandu and about 50 km north of India-Nepal border. It is south of the Main Boundary Thrust (Fig.2) in the Siwalik rocks. The focus is 57 km deep at the base of the crust. As will be discussed later the fault-plane solution indicates strike-slip with reverse component along a NE trending moderately dipping fault.

Due to 57km focal depth, the causative fault is not having any matching tectonic feature on surface. Patna fault, if extended north would be about 50km west of the epicenter, Munger-Saharsa Ridge if extended northward would be 40km east. Koshi river (or Sapta Koshi River as it is having confluence of seven tributaries in upper reaches) is also about 40 km east of the epicenter. Local geology map shows a small right-lateral NNE trending Gaighat fault just west of the epicenter in the Siwaliks. However, sense of motion on this fault is right-lateral, while the focal mechanism indicates left-lateral movement along the NE trending plane. Hence, deeper tectonics is slightly different than that indicated at surface. About 30-40 km northeast also two small strike slip transverse faults are extending from Siwaliks to Main Central Thrust zone (Fig. 3). The small faults may not extend to base of the crust. Dharan and Dhankuta situated about 60km east of the epicenter are the two most damaged towns. Siwaliks lie south of the Main Boundary Thrust (MBT) and older rocks north of it. The MBT is the most important tectonic feature of the area and runs nearly E-W.

This Munger-Saharsa ridge and also the Delhi-Haridwar Ridge and Faizabad Ridge are basement highs. Locales of the abutment of these ridges may be favorable sites for higher stress / strain accumulation.

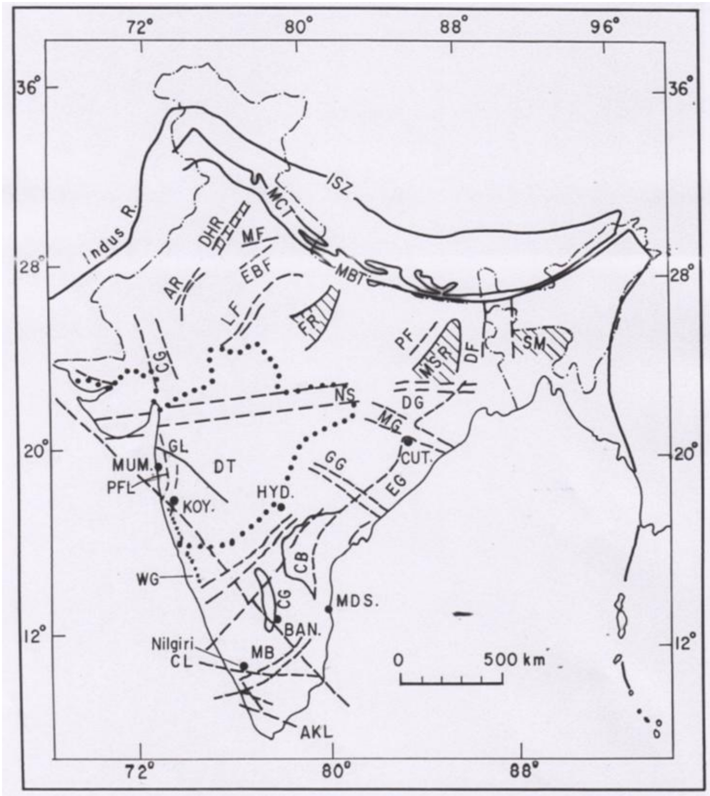

Fig.1: Simplified Tectonic Map of India (after Oil and Natural Gas Commission)

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Himalaya: ISZ-Indus Suture Zone, MCT-Main Central Thrust; MBT-Main Boundary Thrust

Indo-Gangetic Plains:

DHR-Delhi Haridwar Ridge, FR- Faizabad Ridge, MSR- Munger-Saharsa Ridge, AR-Aravali Ridge, SM-Shillong Masif

MF- Moradabad F., EBF-Etawa - Badaun F. LF- Lucknow F., PF-Patna F., DF-Dauki F.

Peninsular India:

KR-Kutch Rift, CG-Cambay Graben, NS-Narmada-Son L., DG-Damodar Graben, MG-Mahanadi Graben, GG-Godavari Graben, EG-Eastern Ghats, WG-Western Ghats, DT-Deccan Traps, PFL-Panvel Flexure, GL - Ghod L., CG-Cuddapah Basin, CG-Closepet Granite, MB-Moyar-Bhavani L., CL - Cauvery L., AKL- Achan-Kovil L.

Locations: CUT - Cuttak, Mum -Mumbai, Koy - Koyna, HYD - Hyderabad, MDS - Madras, BAN - Bangalore

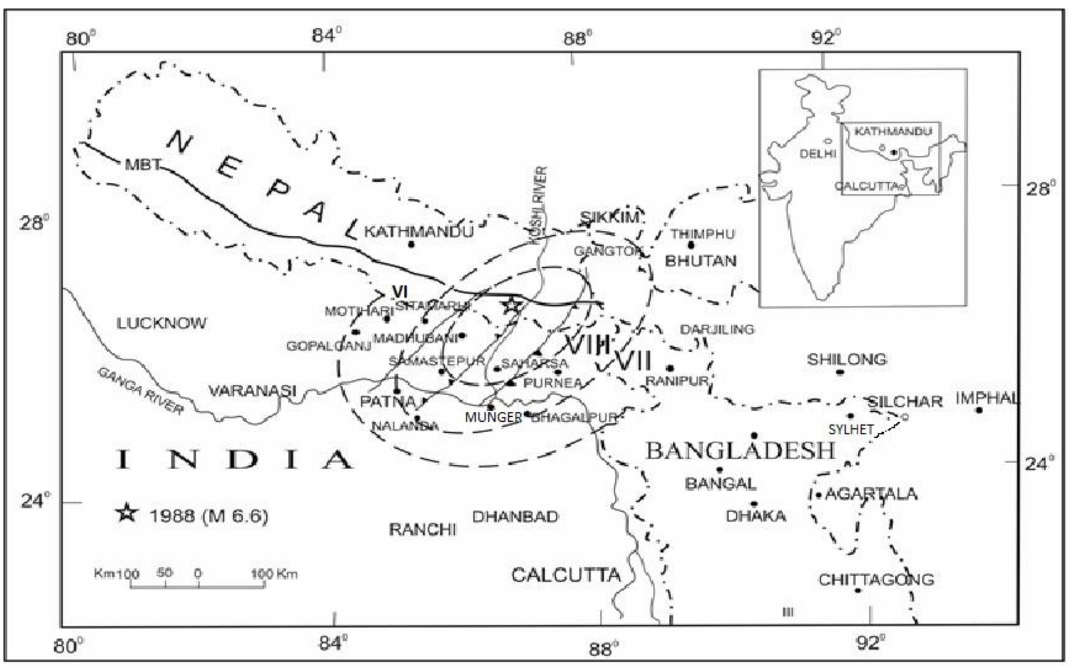


Fig.2: Epicenter is marked by a star. Patna Fault is plotted 40 km west of Patna. Munger-Saharsa ridge, east of Patna, lies in between two faults marked with triangles. Saharsa is located in the middle. The three isoseismals of intensity VIII, VII and VI are also shown.

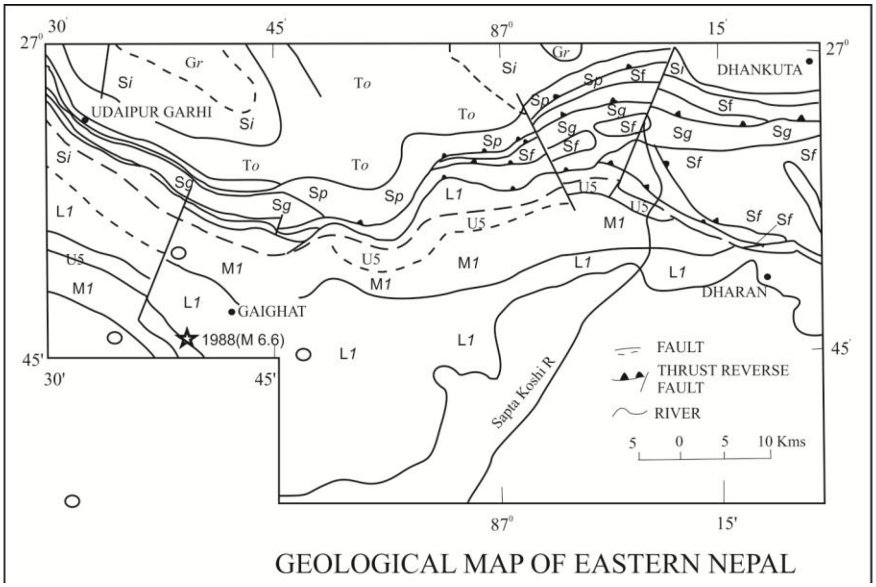


Fig.3: Geology of the epicentral area (E Nepal). Dharan and Dhankuta are the two most damaged towns. Epicenter of the main shock (star) and aftershocks (circle) are marked. U_5, M_1 and L_1 are upper, middle and lower Siwaliks of Mid-Miocene to Pleistocene age south of Main Boundary Thrust. North of the MBT are older rocks of Precambrian, Late Paleozoic and Permo-Carboniferous age marked by S,T and G with different subscripts (After Dept Mining and Geology, Nepal)

3. Past Seismicity

The region is in the Himalayan belt which is one of the most active earthquake belts of the world. Damaging earthquakes have occurred frequently in this region. The NOAA catalogue lists some 300 earthquakes of magnitude about 4.5 or greater from 1908 onwards between the latitudes of 26º to 32º N and longitudes of 80º to 90º E. Epicenters of these earthquakes are mostly within the southern half of Nepal in Lesser Himalaya with concentration in western Nepal within longitudes 80-82˚ and some concentration around Kathmandu. Periodically large earthquakes occur around MCT and Nepal - Tibet border area. The area north of MCT is locked zone.

The fault plane solutions determined for earthquakes in Nepal by various workers (Rastogi, 1974; Chandra, 1978; Molnar et al. 1973; Molnar and Tapponier, 1978) indicate mostly thrust faulting along shallow plane trending along the thrust belt. The February 25, 1970 earthquake near Kathmandu shows combination of normal and strike-slip faulting similar to that for the 1988 earthquake as described in the next section. Sikkim area, east of Nepal, has prominent strike-slip fault. For an earthquake in Sikkim on Feb 26, 1970, Ni and Barazangi (1984) report fault plane solution similar to that for 1988 earthquake. Sikkim 2011 earthquake also shows similar mechanism (USGS).

4. Fault Plane Solution

The fault plane solution for the present earthquake as given in EDR of USGS (Fig. 4(a)) shows a combination of thrusting and strike-slip either along the NE trending, shallow dipping plane or along the NW trending, steeper dipping plane. The NE trending plane is preferred as fault plane as the region has NE trending structures, the transverse faults in Himalaya usually trend NE and isoseismals also trend NE. The fault plane solution from P-waves is as follows:-

NP1: Strike 125, Dip 75, NP2 : Strike 225, Dip 50
Principal axes: T - Plunge 36, Azimuth = 70, P - Plunge 20, Azimuth = 180

The P-wave first motion directions as reported in Earthquake Data Report (EDR) and used for the FPS are also shown. The focal mechanism is moderately well controlled. There are about 25 inconsistent observations including inconsistent dilatations in NW sector of compression of European stations and some inconsistent observations in SE direction near the nodal plane. Self reading of seismograms may reduce inconsistent observations.

The first motion directions read from long-period seismograms are more consistent. For example station Mundaring (MUN) in Australia reports compression while it is read by us as dilatation which is consistent with the fault plane solution. The c and d are the compressions and dilatations observed on long-period seismograms, while the plus and minus are the compressions and dilatations from short-period seismograms. These observations are plotted on lower hemisphere of the equal area projection. The station location is plotted at a given azimuth and angle of incidence. The value of azimuth is given in EDR. The angle of incidence is read from the tables of Nuttli (1969) for a given distance. For distances less than 15º, the angle of incidence is calculated as co-tangent inverse of the extended distances given in the tables by Hodgson and Storey (1953).

As there were inconsistent observations reported in EDR data, I supplemented additional P-wave 1st motion data personally collected by me and also S-wave polarization directions. However, I did not find any appreciable change. Fault plane solution was also determined using first motions from long-period seismograms only. It indicated steeper dipping fault plane in NE-SW direction as indicated by black curves in Figure 4(b). However, the FPS by USGS (shown by broken curves in Fig. 4 (b)) is preferred as the steeper fault will make several more 1st motion observations inconsistent.

(a) (b)

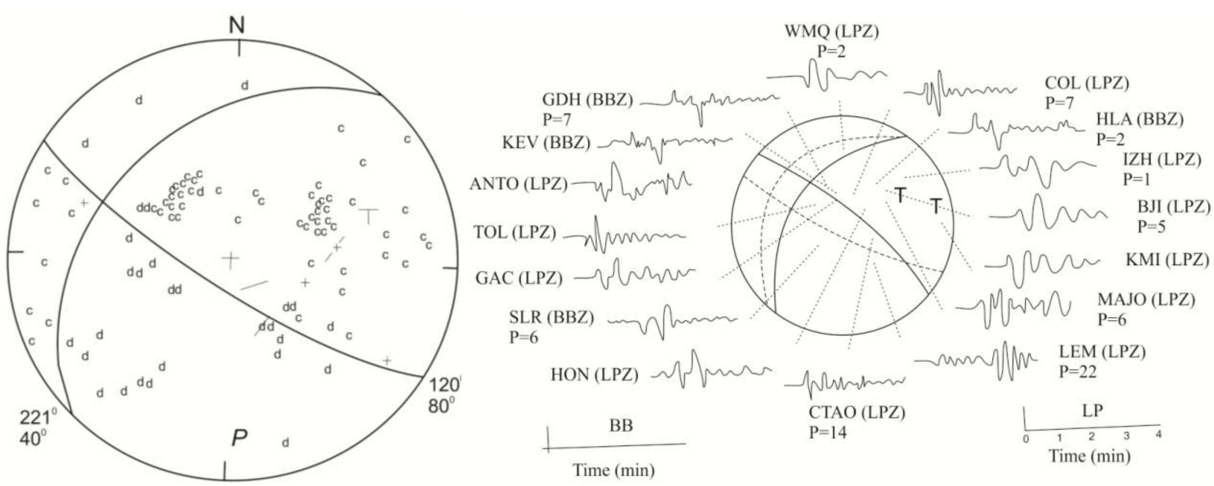


Fig.4(a): Fault plane solution of Bihar-Nepal earthquake of 1988 by USGS. The P 1st motion directions as reported in EDR are plotted in lower hemisphere of equal area projection. The c and d are compressions and dilatations on long-period seismograms, while + and – are compressions and dilatations on short-period seismograms. The S-wave polarization directions are marked by four short segments. The pressure (P) and tension (T) axes are also marked. (b): FPS using 1st motions from long-period seismograms only.

S-wave polarization angles were determined at some of the stations by drawing particle motion from the N-S and E-W long period seismograms. The polarization angles are usually determined in the distance range 44º to 82º. For lesser distances correction for free surface effect is to be applied. The correction is unreliable for distances less than 22º. The Polarization angles are shown in **Fig.** 4a and the particle motions are plotted in **Fig**. 5. The S-wave polarization directions should appear merging towards P and T

axes. The S-wave polarization directions support the fault plane solution from P-waves. The NE plane can be preferred to be the fault plane from the trend of isoseismals in the same direction.

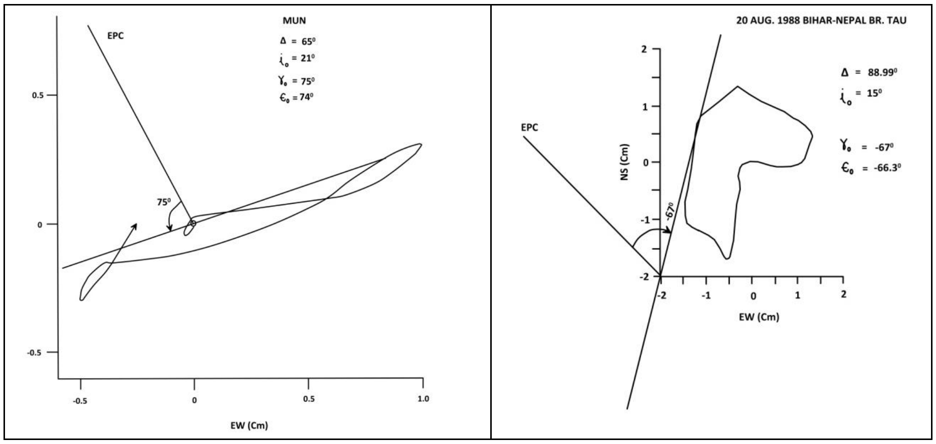


Fig.5: Horizontal component of S-wave particle motion by combining NS and EW long-period seismograms at some of the stations. Angle T_o is measured off from the azimuth to the epicenter to the direction of polarization. The angle of polarization along the ray is obtained by the equation $\tan \varepsilon = \cos i_0 \times \tan \gamma_0$, where i_0 is the angle of incidence of S wave at the surface. Tables are available for i_0 vs distance. If the polarization angle is measured off clockwise, it is plotted at the source anticlockwise or vice versa. It is done to account for the reversal of polarization along the ray due to curvature of the ray as it travels from the source to the receiving station.

5. Location and Depth Phases

I tried to see the manual estimation of epicenter and depth by plotting distance arcs of the nearest stations in Nepal around 200 km west and then in Northeast India at 400-500 km distance. Most of the arcs are about 50km short (Fig. 7) indicating depth of about 60km. Centroid of the area within the intersection of the arcs gives nearly the same epicenter as given by USGS.

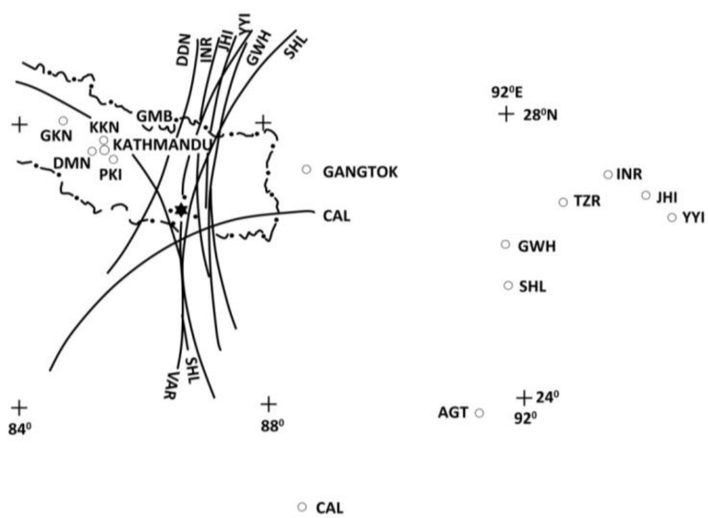


Fig. 6: Locations of near seismic stations, epicenter of the main shock and epicenters of aftershocks. As most of the distance arcs are 50-70 km short, the hypocenter was estimated to be within the elliptical area at a depth of 50-70 km.

Depth of the main shock is obtained to be 70 km from depth phases at a number of stations as given by USGS in Preliminary Determination of Epicenters (PDE). Some of the seismogram portions and depth phases are shown in Figure 8. However, more acceptable depth is 57 km as obtained from broadband displacement analysis by USGS.

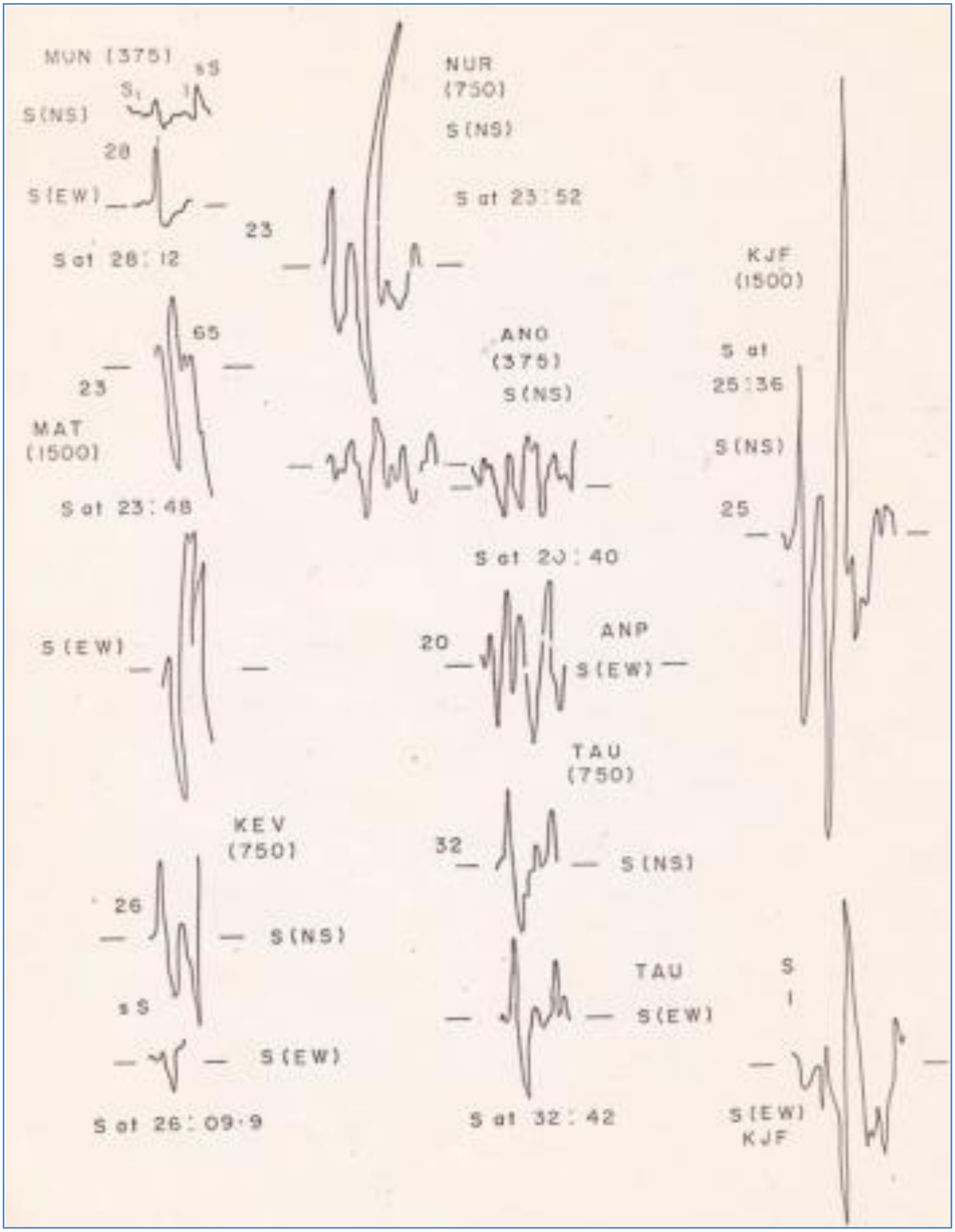


Fig.7: Seismogram portions showing depth phases

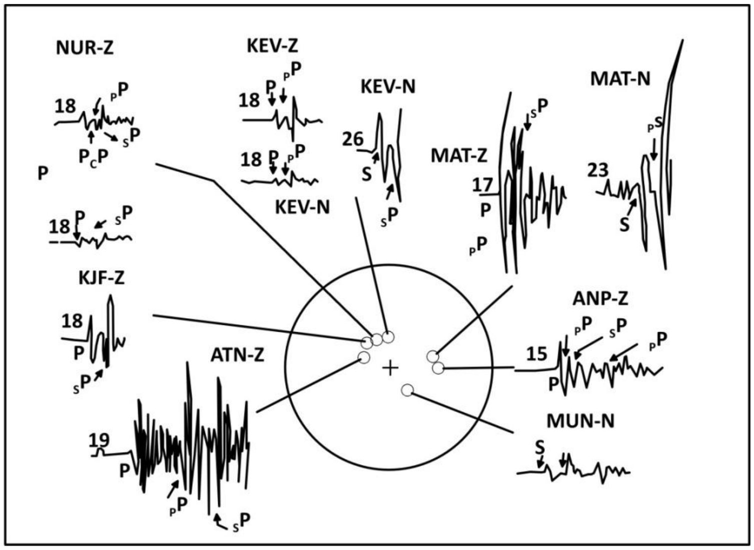


Fig. 7 (Contd.)

6. Source Parameters

D.D. Singh (personal communication) determined source parameters like seismic moment, fault length and stress drop from spectral analysis of P and S portions of seismograms for some distant stations. The value of seismic moment obtained is 3 x 10^{26} dyne-cm (Table 2). The value of fault length is obtained to be 45 km. The value of stress drop is about 10 bars. These values are reasonable. Gupta and Singh (1980) have determined source parameters for some past earthquakes in Nepal which are comparable to these values.

Table 2: Source Parameters

Station	Comp.	Spect. Level	Corner freq.	Seismic moment (dyne-cm)	Radius (Km)	Stress Drop (bars)	Rad. Pat.
ANP	P(Z)	0.03	0.075	10.9X10^26	32	14.9	0.1
NUR	P(Z)	0.016	0.09	8.3X10^27	26	19.5	0.1
MAT	P(Z)	0.0037	0.085	1.3X10^28	28	2.6	0.13
NUR	S(NS)	0.2	0.08	2.6X10^29	17	22.7	0.85
NUR	S(EW)	0.06	0.06	1.0X10^26	23	2.8	0.85
TAU	S(NS)	0.027	0.078	0.84X10^26	18	6.8	0.61
TAU	S(EW)	0.032	0.09	0.86X10^26	15	10.7	0.61
HEL	S(NS)	0.046	0.067	0.71X10^26	20	3.6	0.85
HEL	S(EW)	0.036	0.057	0.65X10^26	24	2.1	0.85
			Average:	3.018X10^26	22.6	9.6	

Displacement spectral level= velocity spectral level/2 Π fo
Fault length= 2 r = 45 km, Fault Area = Πr^2 = 6359 km^2
Dislocation = Mo/A = 3.0x10^26/3.1x10^11x6359x10^10 = 300000/19713 =15 cm

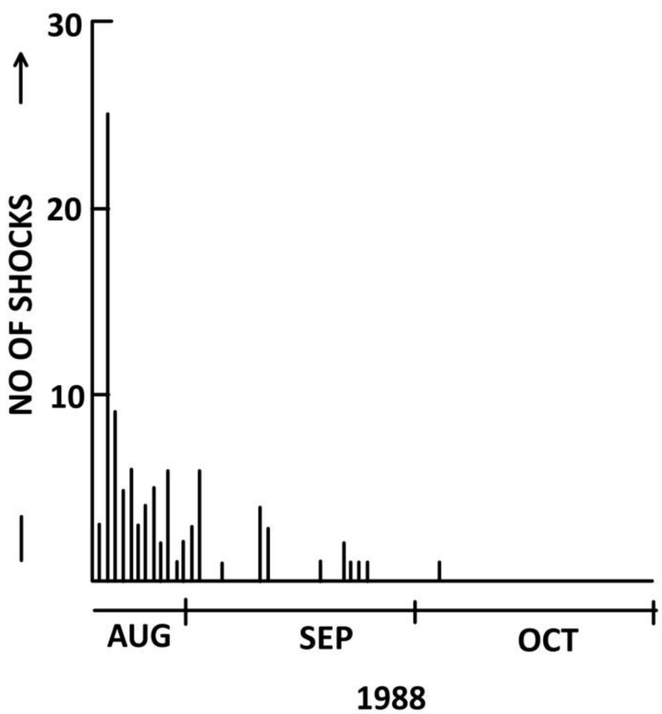
USGS has given body wave magnitude, M_b 6.4, surface wave magnitude, M_s 6.6 and Moment magnitude, Mw 6.8. The radiated energy is obtained to be 2.3 ± 0.6 x 10^{14} Nm. As given in the EDR, moment tensor analysis gives seismic moment of 2.1 x 10^{19} NM (2.1 x 10^{26} dyne-cm) by USGS and 2.3 x 10^{19} NM (2.3 x 10^{26} dyne-cm) by Harvard. According to the formulae given below Mw is obtained to be 6.8.

Mw = (2/3) log Mo – 10.73, if Mo is in Dyn.cm or Mw = (2/3) log Mo – 6.06, if Mo is in N-m

In the Harvard solution a half-duration of 10.2 seconds is assumed.

7. Aftershocks and b-Value

The epicenters determined by USGS for the main shock and aftershocks are shown in Figure 3. Overall, the main shock and after-shocks define a NE trend, barring one aftershock which is east of this trend. There were a total of 108 aftershocks recorded in the months of August to October 1988 (Appendix, Fig.8) and only a few aftershocks after this. More than seventy of these are micro earthquakes of magnitude less than 3 (Fig. 9). Overall there is less no. of smaller shocks compared to larger shocks giving low (0.54) b-value as depicted in Figure 10.



The nearest stations during 1988 were in Nepal at a distance of about 200 km and thereafter in Northeast India at 400-500 km. We operated two stations; one near Darjeeling and the other near Gangtok from November 1988 to March 1989. Roorkee University in collaboration with us started three seismic stations along Bihar-Nepal border sometime in the beginning of 1989. However, most of the aftershock activity had ceased by that time.

Fig.8: Daily frequency of aftershocks as recorded at seismic stations in Nepal.

8. Acceleration

A report from Roorkee University (now IITr) gives the results of strong motion study (Kumar et al., 1989). The earthquake has been recorded at 41 structural response recorder (SRR) stations in the affected area. Spectral acceleration response on SRR instruments indicates amplification around Darbhanga (100 km SW of epicenter) and Jogbani (75 km SE of epicenter or 15 km NE of Forbesganj). This may be attributed to local soil conditions. The acceleration recorded on strong motion accelerographs at four places (19 to 33 cm/s^2) is given in Table 3.

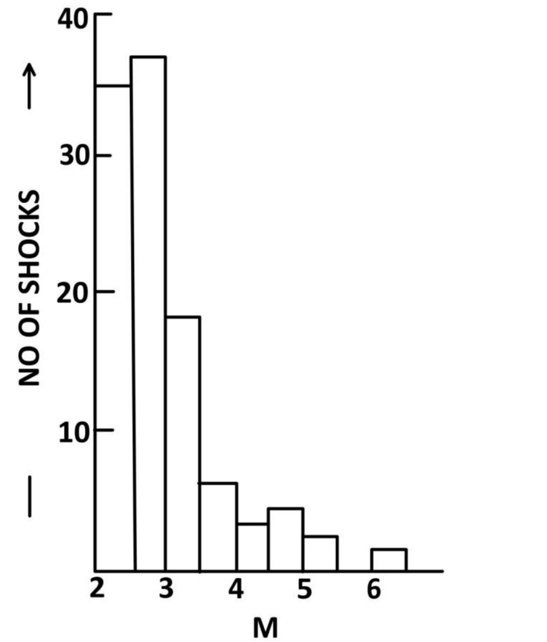


Fig. 9: Number of aftershocks at different magnitude intervals.

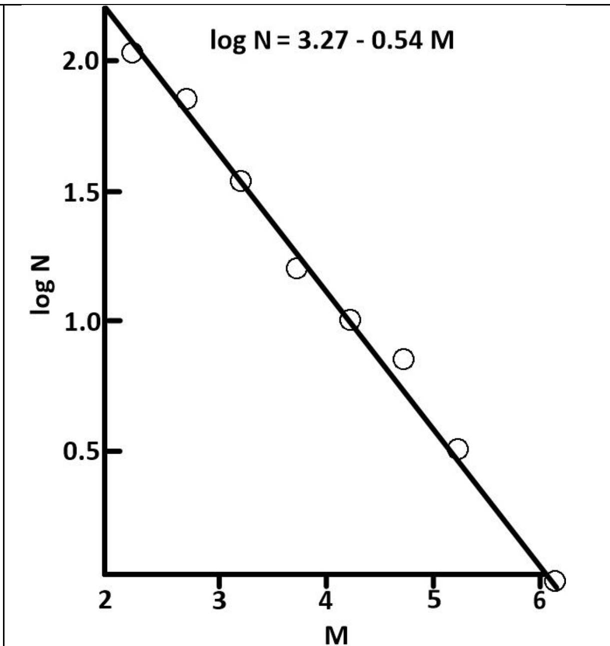


Fig. 10: Frequency-magnitude relation and slope ‘b’ of the line.

Table 3: Recorded acceleration in India

Place	Distance from epicenter	Direction	Max. Acceleration (cm/sec^2)
Sitamarhi	124 km	WSW	33.83
Munger	200 km	S	20.50
Raxaul	225 km	W	18.56
Gorakhpur	330 km	W	25.38

9. Intensity Survey

Figure 2 shows the isoseismal map. District wise damage in Nepal and Bihar is given in Tables 4a and 4b, respectively. The detailed description of damages is available in another report. The damage survey was done by me in parts of Bihar, Darjeeling, Assam, Kathmandu and Bhaktapur. Intensity at other places was assessed from newspapers and personal reports. Isoseismals trend in NE direction.

Maximum intensity was assessed to be VIII on Modified Mercalli (MM) scale in an area of about 250 km x 125 km. Within the limits of this area, liquefaction occurred in an area of about 125 km x 125 km extending from Saharsa and Samastipur in south up to the alluvial areas of Nepal. Isoseismals extend southward due to amplification in the Bihar Gangetic plain. Collapse and damage to buildings and the resulting deaths and injuries occurred in intensity VIII as well as VII areas. Cracks in buildings and stray incidences of collapse of walls is reported beyond these areas. The most damaged towns are Dharan, Dhankuta, Tehrathum, Panchattar and Ilam in Nepal while Darbhanga, Madhubani, Samastipur, Saharsa and Munger in Bihar. In Nepal the most damaged towns are in the area extending 60 km north and 100 km east of the epicenter.

The main earthquake was felt for duration of about 50 seconds with a tremendous sound and violent shaking. People in Bihar described that the shaking and sound for 1988 earthquake was stronger than that for 1934 earthquake. The duration of strong shaking was much more in 1934 i.e. about 1.5 to 2 minutes.

Table 4a: Preliminary district wise damage in Nepal (final figures: 721 deaths, 6908 injured and 64,470 buildings damaged)

SN	District	Deaths	SN	District	Deaths
1	Dharan	130	13	Diktel	11
2	Panchathar	89	14	Bhaktapur	7
3	Dhankuta	79	15	Okhaldunga	6
4	Ilam	69	16	Siraha	5
5	Tehrathum	65	17	Taplejung	3
6	Udaipur	45	18	Sindhupalchowk	2
7	Morang	25	19	Charikot	2
8	Khotang	15	20	Ramachhap	1
9	Sindhuli	14	21	Dhanusha	1
10	Bhojpur	13	22	Mahottari	1
11	Sankhuarsabha	11	23	Kavre	1
12	Saptari	11	Total deaths (606)		

Table 4b: Preliminary district wise damage in Bihar (final figures: 283 dead, 3147 injured and 36,144 houses collapsed or damaged)

SN	District	Dead	Wounded	Houses Damaged	SN	District	Dead	Wounded	Houses Damaged
1	Madhubani	104	477	20,200	10	Muzaffarpur	6	20	
2	Darbhanga	84	1270	8,148	11	Bhagalpur	3	24	
3	Samastipur	22	141	2,711	12	Purnia	2	17	
4	Saharsa	21	108	704	13	Nalanda	1	20	
5	Munger	16	587	1,870	14	Girdih	1	1	
6	Khagaria	9	178	999	15	Jahanabad	1	-	
7	Madhupara	8	30	400	16	Sahibganj	-	5	
8	Begusarai	6	96	557	17	Gopalganj	-	3	
9	Sitamarhi	6	48	485	18	Saran	-	3	
						Total	290	3028	36,074

10. Discussions

Maximum intensity of Mw 6.8 Udaipur1988 earthquake is two grades lower i.e. VIII as compared to X for Mw 8.4 Bihar-Nepal 1934 earthquake. The maximum damaged area spreads wide in 250km x 125 km for a magnitude 6.8 of 1988 earthquake due to deeper depth of 57 km. The affected area in Nepal is much larger extending from Kathmandu - Bhaktapur valley in the west to Udaipur-Gaighat-Dharan-Dhankuta-Ilam-Panchattar area in the east i.e. around Koshi river and close to Nepal - Darjeeling border.

The epicentral area is comprised of Siwalik rocks. On surface there is no major tectonic feature following this NE-SW trending transverse fault. A moderately-dipping and NE trending fault is inferred to be the causative fault at the base of the crust at 57 km depth. Such deep transverse fault could exist in Himalaya (Hirn, 1988). The Koshi river, which follows western margin of Munger–Saharsa Ridge, is 40 km east of the epicenter. The Patna fault, which is an inferred NE trending major basement fault beneath the Gangetic alluvium if extended northward would be about 50 km west of the epicenter. Hence, these features 40-50 km east and west of the epicenter of 1988 earthquake are not the causative fault. Just west of the epicenter is NE trending Gaighat strike-slip fault in the Siwaliks which is transverse to the Main Boundary Thrust (Fig. 3). The right lateral sense of motion along this fault doesn't match with the sense of left-lateral motion inferred for the 1988 Udaipur earthquake. Moreover, a small fault may not extend to 60 km depth. Hence, the nearby existing fault could not be the causative fault.

Nevertheless, some of the features may indicate presence of asperity like the NW-SE trend of the Himalaya west of the 1988 epicenter becomes E-W in the epicentral area and the width of Himalaya becomes narrow. This can give rise to a zone of asperity. The Munger-Saharsa ridge abutting against Himalaya could also cause accumulation of stress / strain.

11. Conclusions

1. Manual determination of earthquake parameters of Bihar-Nepal earthquake of 1988 are matching with those determined by USGS. The earthquake has occurred along the Main Boundary Thrust (MBT), but at base of the crust at 57 km depth along a transverse NE trending strike-slip fault. The role of such faults is visualized as segmentation faults of different thrusting blocks.

2. The estimated source parameters are: seismic moment 3 x 10^{19} Nm or 3 x 10^{26} dyne-cm, Stress drop 10 bars, Fault length 45 km, dislocation 15 cm and rupture duration 20 seconds.

2. Maximum intensity is VIII on M.M. Scale with an inferred acceleration of about 0.2 g in an area of 250 km x 125 km extending in NE direction. The felt duration was about a minute accompanied by loud sound. Within the limits of this area, liquefaction and ground water changes occurred in the alluvial tract of about 125 km x 125 km. Large damage has occurred in the hilly areas of Nepal due to nearness of the source and in the Ganga alluvial area as well as isolated intramontane Kathmandu Valley due to amplification of seismic waves.

3. Special tectonic features of the area include abutting of Munger-Saharsa ridge against Himalaya which may cause accumulation of stress and strain while sharp bend and narrowing of Himalaya may cause asperity in the area.

Acknowledgements

The work was carried out while the author was at NGRI, Hyderabad. Geological Survey of India helped in all possible ways during the field visit in Bihar while the Nepal Department of Geology and Mining readily provided the phase data of the main shock and aftershocks as well as a set of new geological maps of

Nepal. D.D. Singh ex-scientist NGRI determined the source parameters. Author is thankful to J.R. Kayal and Arun Bapat for reviewing the manuscript.

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APPENDIX

List of shocks recorded in Nepal. Duration is measured at Phulchoki (PKI) station in Laltpur with 500 K Magnification and MD, magnitude from that data is given. Mb, body wave and Ms, surface wave magnitudes by USGS are also given. Epicenters are mostly close to Udaipur in Nepal. Shocks of M≥4 are recorded by most Indian stations and strongly felt at Darbhanga, Munger and Forbesganj etc. in Bihar.

Date	Time at PKI h m s	Duration m s	MD
20 Aug. 1988	23:09:35.3	40:00	Mb6.4 Ms6.6
	23:37:18.0	04:00	3.8
	23:39:26.6	12:00	5
21 Aug. 1988	00:12: 54.5	01:30	2.7
	00:14:36.0	04:30	3.9
	00:36:41.3	02:00	3
	00:54		
	01:01:04.9	01:30	2.7
	01:06:		
	01:10:13.0	02:00	3
	01:25:35.9	02:00	3
	01:26:35.7	02:00	3
	02:00:32.8	02:30	3.2
	02:00:54.4		
	02:34:32.8	04:30	3.9
	03:36:10.0		
	04:03:45.1	02:30	3.2
	05:43:02.3	02:30	3.2
	06:11:23.1	01:30	2.7
	06:20:10.8	03:00	3.4
	07:02:29.5	01:30	2.7
	07:29:55.5	02:00	3
	09:26:23.0	01:00	2.2
	09:30:35.1	01:00	2.2
	10:21:09.8	02:00	3
	12:07:08.0	01:30	2.7
	12:15:52.4	01:00	2.2
	13:18:10.9		
	14:07:20.8	01:00	2.2
	14:24:27.2	01:00	2.2
	15:09:25.4	01:30	2.7
	16:32:59.01		

	18:59:08.0	01:30	2.7
	21:44:16.8	02:00	3
	23:09:08.06		
22 Aug. 1988	01:04:46.2	03:00	3.4
	05:09:24.3	01:30	2.7
	06:14:15.4	01:00	2.2
	10:13:09.5		
	11:35:00.5	11:00	4.9 Mb5.1
	13:37:15.3	02:00	3
	17:02:17.7		
	07:02:40.8	01:30	2.7
	19:01:44.8	01:30	2.7
	20:58:08.0	01:00	2.2
	23:53:51.0	03:00	3.4
	03:03:45.5		
23 Aug. 1988	03:35:00.8	02:30	3.2
	03:46:18.2	01:00	2.2
	05:52:07.8	04:00	3.8
	15:54:05.9	01:00	2.2
	22:59:48.5	01:00	2.2
24 Aug. 1988	02:59:07.4	01:00	2.2
	03:11:31.4	01:00	2.2
	09:56:02.8	15:00	5.3
	13:07:24.8	03:30	3.6
	13:43:09.3	01:00	2.2
	22:12:46.1	01:00	2.2
25 Aug. 1988	00:54:58.6	03:00	3.4
	11:21:12.3	02:30	3.2
	20:45:41.1	02:20	3.2
26 Aug. 1988	09:13:00.3	01:00	2.2
	12:16:43.6	01:00	2.2
	14:09:22.4	01:30	2.7
	17:42:57.0	03:00	3.4
27 Aug. 1988	04:37:31.6	01:30	2.7
	12:10:14.3	06:00	4.2 Mb4.5
	16:04:58.9	01:50	2.9
	19:11:26.2	01:30	2.7
	23:35:03.0	01:00	2.2
28 Aug. 1988	13:15:23.6	01:30	2.7
	14:02:48.6	01:00	2.2

29 Aug. 1988	06:25:24.0	01:40	2.8
	12:12:52.0	01:00	4.8 Mb4.7
	17:05:40.7	01:30	2.7
	20:07:09.2	01:00	2.2
	22:15:26.6	01:30	2.7
	23:54:57.6	01:20	2.5
30 Aug. 1988	14:39:54.3	01:20	2.5
	02:36:07.7	01:30	2.7
	05:29:15.0	03:20	3.6
	00:25:15.1	02:00	3
	12:29:15.8	01:00	2.2
	22:05		4
	23:25:59.2	01:30	2.7
02 Sept. 1988	06:35:58.3	16:00	5.3 Mb4.8
	07:26:26.2	02:30	3.4
	09:55:09.3	01:30	2.7
	09:56:45.4	02:30	3.4
	10:25:42.0	01:30	2.7
	22:04:41.3	10:00	4.8
	22:20:20.8	01:00	2.2
05 Sept. 1988	06:11:45.4	02:30	3.4
10 Sept. 1988	06:44:08.6	01:00	2.2
	09:26:28.5	01:00	2.2
	17:46:02.1	01:30	2.7
	19:06:45.4	01:00	2.2
11 Sep 1988	02:58:41.4	01:00	2.2
	03:41:56.5	02:10	3.1
	04:43:06.1	03:00	3.4
18 Sep 1988	11:57:10.3	01:10	2.4
21 Sep 1988	08:33:49.8	01:30	2.7
22 Sep 1988	13:26:07.8	02:30	3.2
22 Sep 1988	04:45:02.8	01:30	2.7
23 Sep 1988	15:18:13.5	02:30	3.2
24 Sep 1988	11:08:18.8	07:00	4.4
03 Oct 1988	18:15:38.3	02:00	3