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SOME SEISMOLOGICAL ASPECTS OF THE BERLIN GEOTHERMAL FIELD AND LEMPA RIVER AREA, EL SALVADOR.

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ABSTRACT

In this study some characteristics of the seismicity at Berlin geothermal field and Lempa river area are presented. In and around Berlin geothermal field, CEL (Comisión Ejecutiva Hidroeléctrica del Río Lempa) installed a digital seismic network with 9 stations short period on February 1996. From 06/1996 to 06/1997, 437 events were recorded, and 228 were reread and located. The results show three significant spatial clusters, two in the geothermal field and one in the neighbourhood of the Lempa river.

For the Lempa river area, data from CIG (Centro de Investigaciones Geotécnicas) network were used too. The statistics show an increase of the seismicity since 1995. Correlation between reinjection and seismicity was not found for the Berlin geothermal field and a-value shows that geothermal production has little influence on the level of local seismicity.

The stress drop in the Geothermal field is smaller than the Lempa river area. The average observed values are 0.4 and 2.5 bar respectively. Differences for b values and Vp/Vs ratio were also observed. The focal mechanism at the injection zone suggest thrust faulting. In the volcanic structures east and south-east of Berlin the mechanisms do not show any consistent type although fault planes are dominantly in the NE-SW or NW-SE direction in agreement with the local observed surface faulting.

INTRODUCTION

Monitoring earthquakes is important in geothermal exploration. Microearthquakes are frequently related to major hydrothermal convection systems and accurate location of these earthquakes can provide helpful

data in locating active faults that may channel hot water toward the surface (Wright et al., 1985).

The Berlin geothermal field is situated 100 km east of San Salvador in the north slope of the volcanic complex Berlin-Tecapa. The Lempa river is some kilometers west from the geothermal field. For monitoring the seismicity at the geothermal field, CEL (Comisión Ejecutiva Hidroeléctrica del Río Lempa) installed on February 1996 a digital seismic network with 9 short period stations of which two have three components.

At the Berlin geothermal field there are two fault systems, one near the wells with mainly in the NW-SE direction, the other in the volcanic axis of Berlin-Tecapa complex, oriented NE-SW (CEL, 1996). In the study area, the Lempa river direction is NE-SW and cut the fault systems W-E and NW-SE.

The purpose of the study is to make an evaluation of the seismicity in the area and quantify some important aspects using data from the new stations in the area.

DATA SELECTION AND ANALYSIS

The location of epicenters using CEL network suggests separating of the seismicity in two groups, one in Berlin geothermal field with coordinates between 13.45° N - 13.57° N and 88.54° W - 88.45° W and the other in the neighbourhood of Lempa river with coordinates between 13.50° N - 13.64° N and 88.78° W - 88.58° W (Figure 2). Events recorded in these areas were selected from CIG data base for the period 1984 to 08/1997 (Figure 1).

For this study 228 events were selected for the period from 07/96 to 06/97 (Figure 4). The criteria for the selection were; a good signal to noise ratio and recordings from at least 4 stations. For the purpose of finding the common events, a comparison with the seismicity reported by CIG network was done.

For the data processing the SEISAN system was used (Havskov, 1997). The magnitudes were calculated with the relations Lee et al., (1972) for

Mc and Kanamori (1977) for Mw. The velocity crustal model reported by Marroquin and Havskov (1998) was used for the locations.

SEISMICITY BEFORE CEL NETWORK

In order to compare the seismicity level recorded by CEL network with the level before the installation, we used the CIG (Centro de Investigaciones Geotecnicas) data base. Data since 1984 were selected for the coordinates between 13.25° N - 13.75° N and 88.85° W - 88.25° W and focal depth between 0 to 20 km (Figure 1). This area was selected because it is approximately the location area for the events reported by CEL network (Figure 2). Except 1985 (see later), CIG reported on average 30 events per year from 1984 to 1994 and a considerable increase is observed since 1995 (Figure 3), where 201 events were reported until august 1997. The minimum magnitude reported by CIG is 1.3 using the relation Lee et al., (1972). In total 645 events have been reported in the area by the CIG network from 1984 to august 1997. The majority of the events occurred in the neighbourhood of Lempa where 241 events were recorded between the coordinates 13.50° N - 13.64° N and 88.78° W - 88.58° W. 126 of them ocurred from 1995 to august 1997. Figure 3 shows the yearly event statistics.

In this century, two important seismic activities occurred in the area. On may 6, 1951 an earthquake of magnitude 6.25 (USGS) located at 13.50° N and 88.42° W killed more than 400 people. The maximum Mercalli modificaded intensity was VIII (Meyer-Abich, 1951). On April 23, 1985 a swarm started at the Berlin area. Two cracks of approximately 6.1 km of length were formed during the activity and have a vertical displacement of about 30 cm. (Morán, 1989). According to CIG reports (CIG, 1985) more than 5000 events were recorded. The location for the event with maximum intensity was 13.56 °N and 88.67 °W (Figure 1). The magnitude for the main event was Mb=4.8 (USGS). For this seismicity, only some events were located by CIG, because for this area the station coverage were poor with only one station in the area.

SEISMICITY RECORDED BY CEL NETWORK

In the area mentioned before, 437 events has been recorded by the CEL network from 06/96 to 06/97 (Figure 2). 350 of them are reported by Rivas (1997). In this study, a sample of 228 events were selected and reread (Figure 4). 62 of them were also recorded by the CIG Network. With the purpose to get good locations, the data from the two network were merged. The minimum magnitude (Mc) for the common events is 1.2 and 58 of them were located in the neighbourhood of Lempa river. The seismicity in the Berlin geothermal field is shallow with focal depth between 0 and 5 km and the magnitude very small and none were recorded by the CIG network. The focal depth for the seismicity in the neighbourhood of Lempa river are between 0 and 15 km with a concentration between 2 and 6 km.

b VALUE

The b value was calculated for the Berlin geothermal field and Lempa river area for different period and magnitude ranks using the relation by Richter and Gutenberg. This relation is represented by

$$\log N = a - bM$$

where N is the number of earthquakes with magnitudes larger than M, and a and b are constants. The constant b is called the b-value. In Figure 5 and Table 1 the results are shown.

FOCAL MECHANISMS

P-wave polarities were used to determine focal mechanism, using the FOCMEC program (Snoke et al., 1984) which is part of SEISAN software package (Havskov, 1997). FOCMEC use a grid search algorithm.

Focal mechanisms for eight events were made (Figure 4 and Table 2). The fault plane solutions were found using a search grid of 5° and insisting on no polarity errors.

SPECTRAL ANALYSIS

The spectral analysis was done for 80 events. 27 were located at the Berlin geothermal field with magnitudes (Mc) between 1.1- 1.7 and 53 located in the neighbourhood of Lempa river with magnitudes from 1.2 to 3.0. The spectrum were corrected for instruments response and anelastic attenuation ($Q= 52f^{0.78}$, Marroquín and Havskov (1998)).

The stress drop, $\Delta\sigma$ was calculated using the moment Mo and the radius r (Brune, 1970, 1971)

$\Delta\sigma= 7\ Mo/16r^3$

The source radius was computed using Brune's relation for a circular fault:

$r = 2.34\beta/2\pi fc$

where β is shear wave speed and fc is corner frequency of the spectrum.

$Mo = (4\pi*\rho*V^3*\Omega*\Delta)*K$

where V is the seismic wave velocity, ρ the density, Ω the spectral flat level on the displacement spectrum , Δ the hypocentral distance and K a factor of 1/(2.0*0.6) to correct for the free surface and radiation pattern.

The moment is calculated in Nm, the source radius in km and the stress drop in bars.

Vp/Vs RATIO

The Vp/Vs ratio for Berlin geothermal field was determined to 1.76 ± 0.10 by taking the averages Vp/Vs calculated with a Wadati diagram individually for 29 events. Only events with at least 4 pairs of P and S-

times, a maximum Wadati fit of 0.3 sec RMS and a correlation coefficient of at least 0.7 were used. For the neighbourhood of the Lempa river, the Vp/Vs is 1.71 ± 0.06 using 41 events recorded by both networks the condition were at least 6 pairs of P and S-times, a maximum Wadati fit of 0.4 sec RMS and a correlation coefficient of at least 0.9.

DISCUSSION

As also reported by Rivas (1997), most of the epicenters relocated can be grouped into three populations, in the geothermal field, in the reinjection zone and in the volcanic structures east and south-east of Berlin, and the neighbourhood of the Lempa river (Figure 4). We find only some variation with respect to the focal depth of the epicenters in the neighbourhood of the Lempa river. The depths are between 0- 15 km but the majority are from 2 to 6 km. Rivas (1997) reported depths from 9 to 22 km. The reason for this smaller variation is because we use additional data from CIG network, which gives better locations. At the geothermal field the depth are from 0 to 8 km with a concentration between 0 to 4 km in the reinjection zone.

In Figure 4 it is clear that there are two clusters in the geothermal field and three station symbols are not seen because they are covered by epicenter symbols. This seismicity is migth to be induced by the geothermal exploitation but is little difficult to confirm since no stations were intalled before the start of the exploitation. The geothermal plant started to work in the second semester of 1992 (Rivas, personal communication) and the network was installed in February 1996.

An increase of the seismicity is observed since 1995 according to the CIG data base (Figure 3) but comparing Figure 1 and 2, the increase can not be assigned to the geothermal field, because the events in this area are of very small magnitudes and difficult to be recorded by CIG stations. The increase migth be related to the hydroelectric dam "September 15" which is located some few km north-east from the seismicity cluster near Lempa river. This dam started to work in 1981 (Rivas, personal communication). The location is seen on Figure 4.

In order to check whether there was any increase in the seismicity due to the geothermal production the a and b-values were calculated for the

geothermal area (Figure 5 and Table 1). Prior to the geothermal production, only 21 events were recorded by CIG in the same area (Figure 1 and 3). Since this is too few for calculate the a and b-values, only the a-value was calculated assuming the b-value to be the same as for the later CEL seismicity. Table 1 gives the two normalized (by year) a-values. Since they are almost the same, it can be concluded that geothermal production has little influence on the level of local seismicity. The a and b-value also were calculated for the Lempa river area using CIG data for period before and after that the seismicity increase is observed (Table 1 and Figure 5).

The stress drop in the Geothermal field is smaller than in the neighbourhood of Lempa river. 27 events from the geothermal field show stress drops from 0.1 to 1.7 bars with a average of 0.4 bar and from 0.3 to 25.0 bars with a averages of 2.5 bars for Lempa river area using 53 events (Table 3).

Good location of the seismicity in the neighbourhood of the Lempa river is now possible with the combination of data from the CIG and CEL networks. But only events with magnitude 1.2 or more were recorded by both networks. The CIG station nearest to this epicentral area is approximately 37 km away and the CEL stations are within 10-20 km. Maybe smaller events similar to the events at the Berlin geothermal field occurred but with the present seismic networks ther are not possible to record.

Eight well-constrained focal mechanism solution are derived (Figure 4). Table 2 summarizes the focal mechanism results. The two mechanism for the reinjection zone suggest thrust faulting. The 5 mechanism for the volcanic structures east and south-east of Berlin show a diversity type of faulting but the fault planes are dominantly in the NE-SW or NW-SE direction. The mechanisms for Lempa river show strike-slip faulting.

The moment magnitude (Mw) calculated with the relation Kanamori (1977) show a little variation with the magnitude Mc calculated with Lee et al., (1972). For the magnitude range between 1.1- 3.0 Mc and 0.9- 3.1 Mw (Figure 6), the relation is:

$$Mw = 0.94MC + 0.07$$

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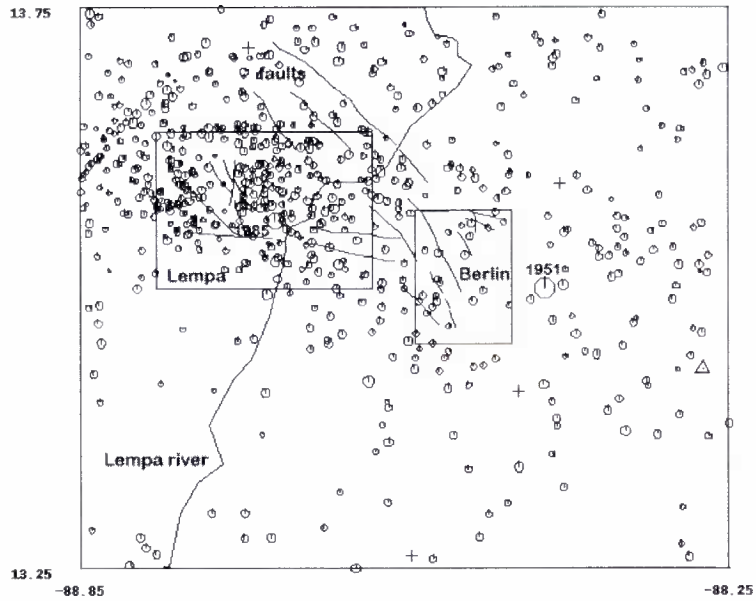

Figure 1: Seismicity recorded by CIG network from 1984 to 08/1997. 1951 and 1985 events.
Circles and crosses are event epicenters. Crosses indicate no magnitude is calculated while the circles have a size proportionally with the magnitude. Triangle is seismic station. Only one station is located within the area. The lines are some principal faults (Mapa Geologico de la Republica de El Salvador, 1978, scale 1:100000).

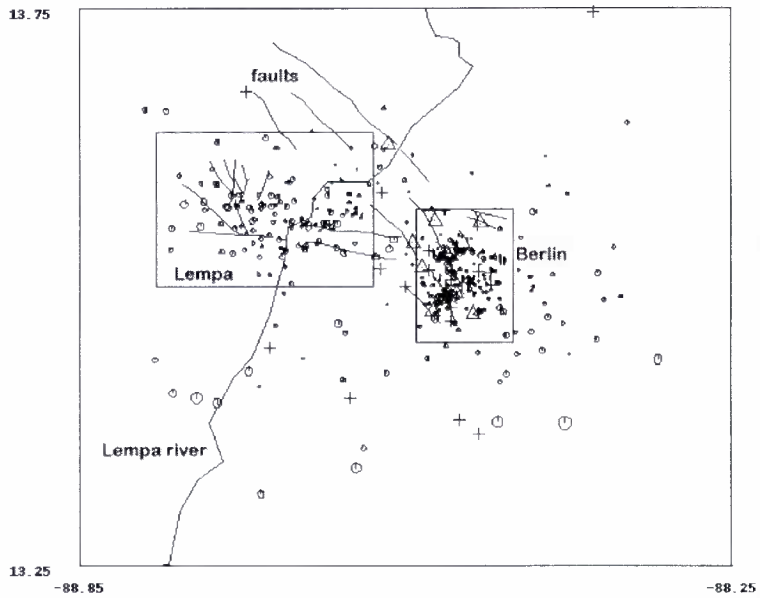

Figure 2: Seismicity recorded by CEL network and located by CEL from 06/1996 to 06/1997.
Circles and crosses are event epicenters. Crosses indicate no magnitude is calculated while the circles have a size proportionally with the magnitude and triangles are seismic stations.

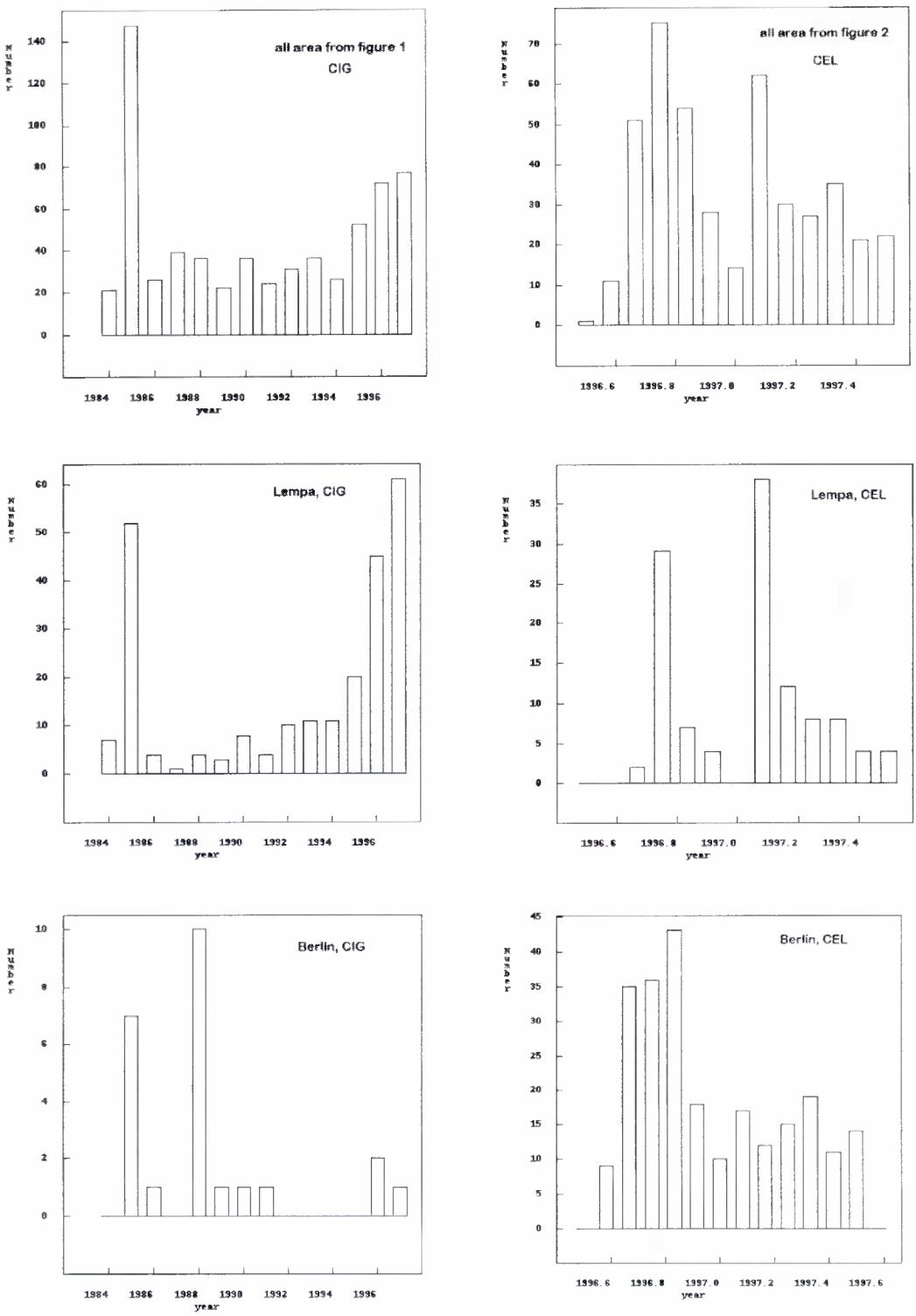

Figure 3: Number of events by year for CIG and number of events by month for CEL. Lempa and Berlin correspond to the areas shown in Figure 1 and 2.

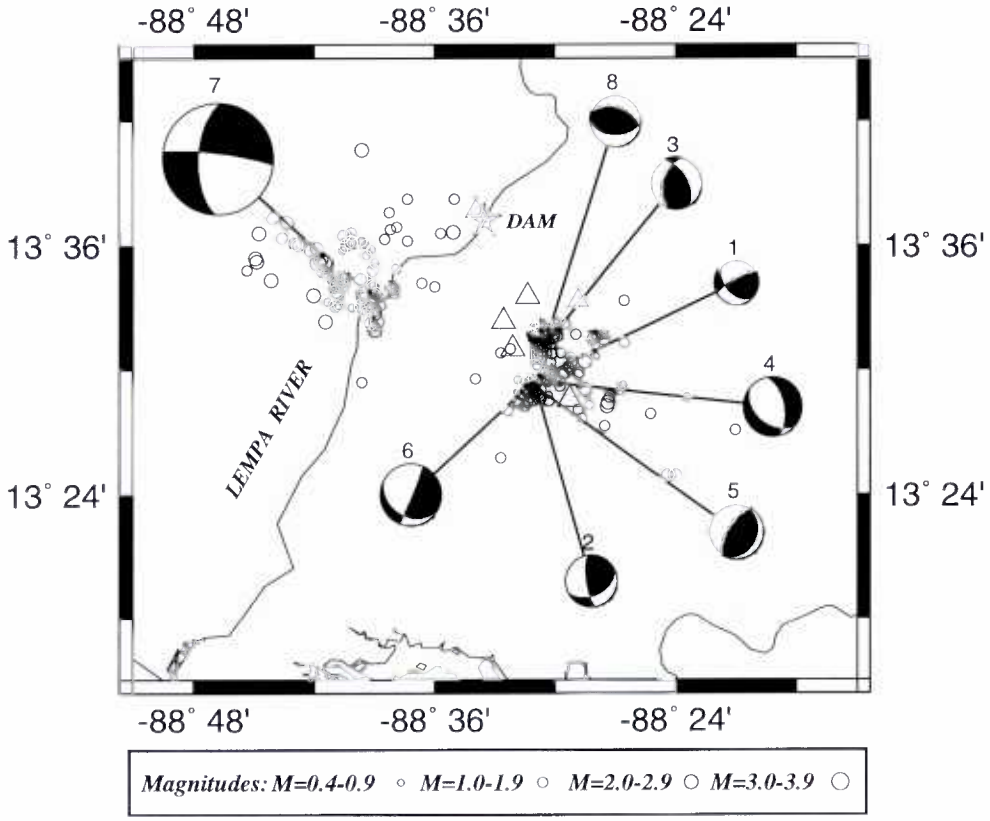

Figure 4: Events selected and reprocessing.
Epicenters (circle), stations (triangle) and wells (square). The size focal mechanisms sphere are proportional to the magnitude, compressional quadrants are shaded, the identification numbers refer to Table 1. It is seen that in the Lempa river area, earthquakes are aligned in the NW-SE direction which is also the predominant direction of faulting.

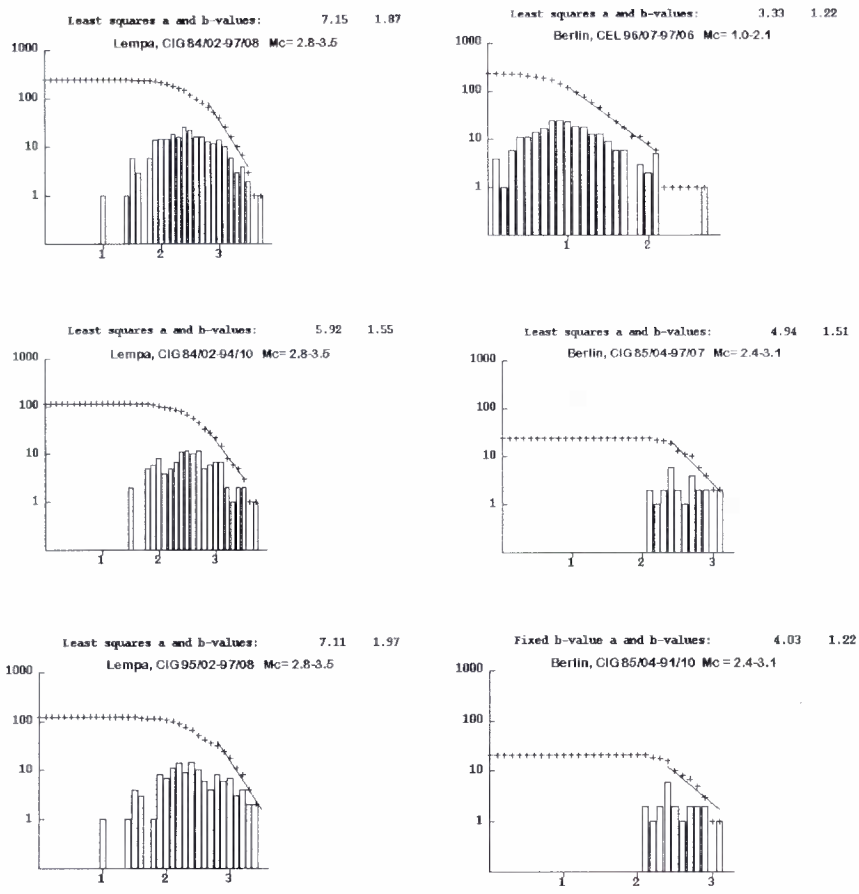

Figure 5: a and b-values for a different periods and magnitude rank.

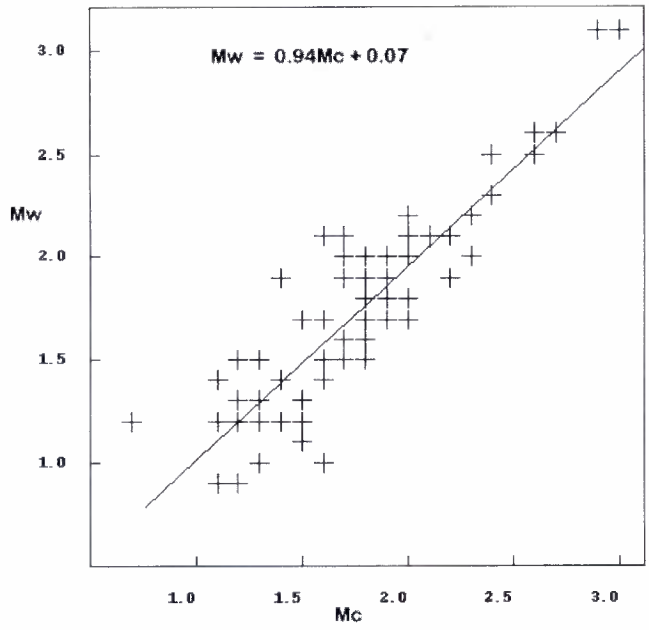

Figure 6: Magnitude relation. Mw is Kanamori (1977) and Mc is Lee et al., (1972).

Table 1: b value data.
a value normalized is for one year, number expected and observed are with respect to inferior magnitude rank.

area	data	date	duration (years)	magnitude range for b-value (Mc)	b	a (normalized)	number expected	number observed
Lempa	CIG	84/02 - 97/08	13.49	2.8 - 3.5	1.87	6.02	6.1	4.8
Lempa	CIG	84/02 - 94/10	10.68	2.8 - 3.5	1.55	4.89	3.6	3.1
Lempa	CIG	95/02 - 97/08	2.48	2.8 - 3.5	1.97	6.72	15.7	12.9
Berlin	CEL	96/07 - 97/06	0.89	1.0 - 2.1	1.22	3.38	143.4	132.6
Berlin	CIG	85/04 - 97/07	12.25	2.4 - 3.1	1.51	3.85	1.7	1.5
Berlin	CIG	85/04 - 91/10	6.48	2.4 - 3.1	1.22 (fixed)	3.22	1.9	2.5

Table 2: Focal mechanism solutions.

No	date	time	lat. °N	lon. °W	depth (km)	mag Mc	strike	dip	rake	strike	dip	rake
							nodal plane 1			nodal plane 2		
1	960806	11:31	13.495	88.512	3.2	1.3	241°	76°	43°	138°	48°	161°
2	960901	06:42	13.490	88.517	3.4	1.5	172°	75°	48°	65°	44°	158°
3	961014	16:00	13.533	88.497	0.7	1.5	330°	54°	59°	197°	46°	126°
4	961018	07:39	13.489	88.497	4.9	1.7	348°	57°	-66°	129°	40°	-122°
5	961019	21:24	13.489	88.520	2.2	1.8	19°	25°	78°	212°	65°	95°
6	961027	10:23	13.490	88.518	4.1	1.8	22°	86°	-60°	120°	30°	-171°
7	970227	14:32	13.593	88.695	1.9	3.2	11°	66°	7°	279°	84°	156°
8	970308	07:41	13.519	88.509	0.7	1.5	90°	46°	76°	290°	46°	104°

Table 3: Events selected for spectral analysis.

LEMPA RIVER AREA									
date	time	latitude ° N	longitude ° W	depth (km)	RMS	Mc	Mw	stress drop (bars)	corner frequency (Hz)
SEISMOS RECORDED BY CEL AND CIG NETWORK									
960907	09:19	13.551	88.654	4.1	0.2	1.8	1.8	1.5	9.5
960907	11:56	13.570	88.649	4.6	0.1	2.2	2.1	1.8	7.7
960907	11:57	13.567	88.651	4.3	0.2	2.6	2.6	4.5	4.6
960907	12:47	13.534	88.648	4.5	0.1	1.8	1.9	0.8	7.6
960907	14:39	13.567	88.649	5.0	0.1	1.2	1.5	0.3	8.7
960907	16:08	13.559	88.652	3.9	0.2	2.4	2.3	4.0	7.1
900907	16:11	13.563	88.634	14.7	0.2	1.8	2.0	1.5	8.1
960907	19:26	13.568	88.654	4.3	0.1	1.7	1.9	0.9	7.1
960907	20:20	13.582	88.634	12.1	0.3	1.7	2.0	0.9	6.9
960907	20:54	13.535	88.650	4.4	0.2	2.0	2.2	2.2	6.0
960908	05:57	13.544	88.648	8.9	0.1	1.7	1.9	0.6	5.9
960908	10:44	13.543	88.652	4.4	0.1	2.0	2.1	1.0	6.0
960911	06:48	13.569	88.686	3.5	0.2	1.8	1.6	0.3	7.3
960925	21:52	13.608	88.593	5.2	0.2	1.7	2.1	0.6	5.7
961022	01:26	13.616	88.625	9.3	0.2	1.6	2.1	2.9	7.5
961027	05:03	13.611	88.746	4.0	0.2	2.4	2.5	4.3	6.1
970121	01:19	13.533	88.693	5.0	0.2	2.0	2.1	2.2	7.4
970121	02:23	13.596	88.652	4.4	0.2	1.9	1.9	1.6	9.2
970121	03:54	13.572	88.660	4.5	0.3	2.0	1.7	1.3	9.1
970121	08:16	13.558	88.658	5.1	0.1	2.0	1.8	0.6	7.0
970122	03:49	13.564	88.671	2.2	0.2	2.2	2.1	1.9	7.7
970122	03:50	13.551	88.670	3.3	0.2	2.3	2.2	2.5	7.6
970227	13:33	13.594	88.690	3.2	0.2	3.0	3.1	25.0	5.4
970227	14:37	13.586	88.691	3.9	0.2	2.0	2.0	2.0	7.9
970227	14:54	13.585	88.694	3.8	0.2	1.8	1.8	1.4	8.6
970227	15:34	13.566	88.701	3.4	0.3	2.9	3.1	16.9	5.2
970227	23:39	13.586	88.695	2.8	0.2	2.0	2.0	1.4	7.5
970305	06:58	13.589	88.690	3.3	0.2	2.6	2.5	10.1	8.0
970316	04:29	13.618	88.722	1.5	0.2	2.0	1.8	2.0	9.9
970317	01:54	13.601	88.696	3.3	0.2	2.2	2.1	3.6	8.5
970420	09:49	13.594	88.747	2.4	0.2	2.2	1.9	1.3	8.1
970420	12:43	13.595	88.748	3.6	0.2	2.7	2.6	6.6	5.8
EVENTS RECORDED BY CEL NETWORK									
960827	17:32	13.563	88.603	10.3	0.1	---	1.7	0.8	8.8
960829	07:49	13.566	88.602	10.8	0.1	1.4	1.4	0.4	10.1
960907	11:56	13.559	88.636	8.1	0.1	---	2.1	0.9	6.2
960907	11:58	13.570	88.614	11.2	0.2	1.9	1.7	0.7	8.9
960907	12:08	13.561	88.661	4.2	0.1	1.4	1.9	0.9	7.8
960907	12:28	13.578	88.616	14.7	0.1	---	2.0	0.7	6.7
960907	16:16	13.546	88.662	4.2	0.1	1.8	1.9	1.9	9.7
960908	16:54	13.570	88.621	13.5	0.0	---	1.7	0.5	7.2
970119	08:04	13.561	88.668	0.1	0.1	1.9	1.8	0.9	8.1
970120	01:26	13.550	88.686	3.4	0.1	1.9	2.0	1.1	7.6
970120	06:29	13.551	88.661	2.1	0.1	1.9	1.8	1.0	8.2
970121	07:02	13.594	88.650	2.5	0.1	1.8	1.7	0.4	7.5
970121	08:04	13.561	88.661	3.9	0.1	2.3	2.0	1.7	7.6
970122	05:08	13.596	88.651	0.0	0.1	1.9	1.8	0.5	7.2
970227	12:42	13.614	88.683	5.0	0.2	2.0	2.0	3.9	9.8
970227	18:22	13.575	88.695	8.9	0.2	1.8	1.5	0.4	8.6
970316	04:11	13.616	88.730	1.7	0.1	2.0	1.7	1.2	9.6
970509	10:14	13.557	88.658	5.9	0.1	1.6	1.4	0.3	9.4
970614	16:36	13.560	88.655	9.9	0.1	1.8	2.0	1.7	7.1
970615	01:42	13.618	88.583	4.8	0.1	2.1	2.1	2.5	8.5
970615	02:14	13.627	88.658	18.2	0.1	---	1.9	2.2	9.5
average								2.5	

Continuation Table 3.

BERLIN GEOTHERMAL FIELD									
date	time	latitude ° N	longitude ° W	depth (km)	RMS	Mc	Mw	stress drop (bars)	corner frequency (Hz)
960725	16:04	13.496	88.503	1.8	0.0	1.6	1.5	0.2	6.9
960806	11:31	13.495	88.512	3.2	0.1	1.3	1.3	0.2	8.6
960808	02:04	13.524	88.506	0.3	0.1	1.3	1.2	0.1	7.6
960825	10:23	13.480	88.512	3.4	0.1	1.2	0.9	0.1	8.5
960901	06:42	13.490	88.517	3.4	0.1	1.5	1.3	0.2	8.9
960903	03:29	13.527	88.464	1.9	0.1	1.6	1.4	0.5	11.0
960903	21:24	13.521	88.467	0.0	0.1	1.6	1.4	0.2	7.8
960910	18:27	13.477	88.455	6.5	0.1	1.6	1.7	1.5	11.1
960912	03:10	13.526	88.470	0.4	0.0	1.1	0.9	0.2	14.0
960913	15:49	13.492	88.508	5.1	0.2	1.1	1.4	0.2	8.1
961004	04:37	13.534	88.515	2.8	0.1	1.2	1.2	0.3	10.9
961007	02:04	13.477	88.522	2.2	0.2	1.4	1.2	0.2	10.7
961020	08:47	13.522	88.503	0.7	0.2	1.6	1.0	0.1	10.1
961020	19:34	13.481	88.519	2.4	0.1	1.7	1.5	0.3	7.6
961028	06:00	13.487	88.523	4.3	0.1	1.5	1.2	0.1	7.9
961123	04:25	13.525	88.516	2.8	0.1	1.1	1.2	0.1	8.1
961123	04:26	13.515	88.537	10.5	0.1	1.5	1.7	1.7	11.8
970130	08:09	13.529	88.503	0.9	0.1	1.3	1.0	0.1	10.5
970221	03:23	13.493	88.529	2.5	0.1	1.6	1.4	0.3	9.7
970308	07:41	13.519	88.509	0.7	0.1	1.5	1.2	0.1	8.9
970328	16:19	13.475	88.484	3.8	0.1	1.7	1.5	0.7	10.2
970328	16:52	13.475	88.471	4.8	0.2	1.6	1.7	0.7	8.9
970413	09:08	13.476	88.523	3.3	0.1	1.7	1.6	0.4	7.6
970430	05:02	13.487	88.451	4.4	0.1	1.2	1.3	0.5	12.6
970512	05:47	13.462	88.481	5.0	0.1	1.3	1.5	0.2	7.5
970528	03:59	13.529	88.483	0.6	0.1	1.4	1.2	0.3	11.4
970619	07:23	13.528	88.516	2.5	0.2	1.4	1.4	0.3	9.5
average								0.36	

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