

## Seven Years of Reservoir Seismic Monitoring at Berlín Geothermal Field, Usulután, El Salvador

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### ABSTRACT

Seismic monitoring of the reservoir at Berlín geothermal field started in 1996. The objectives were to identify major seismic areas in and around the geothermal system, to monitor the natural and possible induced seismicity due to exploitation, to identify active faults and fluid circulation paths in the reservoir and to obtain information on the heat source. The seismic network has detected about 2800 shallow and low-magnitude local events within the geothermal field, mainly in the southern part, along the volcanic chain, believed is responsible for the heat source.

Seismicity in the production and injection areas is related to pressure and pore pressure changes, respectively. It has been just a clear case of induced seismicity in a well stimulation operation at the TR10A well (Rivas and Torres, 2003) a reinjection well at Berlín geothermal field. This is a unique case of controlled experiment. Seismicity within the Berlín area is thought to be related to the heat source of the system and fluid bearing fractures. Numerous micro earthquakes within injection and production areas, are thought to be partly induced by increasing pore pressure and fluid motion. No clear correlation is apparent between the monthly seismicity and extracted and injected mass. However, two earthquakes ( $M_w=7.6$  and  $M_w=6.6$ ) occurred in January, 13<sup>th</sup> and February, 13<sup>th</sup>, 2001; two years after the start up of the two 28 Mw power stations, followed by a marked increase in seismic activity within the Berlin reservoir. The local seismic activity has been of low magnitude, indicating that the rocks have poor capacity to accumulate stress, releasing energy very often even with frequent low magnitude swarms. Therefore, it is believed that the seismic behavior in the field does not possess any threat to the environment, to the power station and surrounding communities.

### 1. INTRODUCTION

The tectonic setting and volcanism have provided El Salvador with abundant geothermal resources. Around ten geothermal areas have been identified including five high temperature geothermal fields (180-300°C), within Quaternary volcanoes (Monterrosa, 1998).

Two geothermal areas have had development, the Ahuachapán and Berlín geothermal fields. The Ahuachapán field is located in the western part of the country, about 100 km west of San Salvador, the capital of El Salvador, and has been exploited for energy production since 1975. This field has an installed capacity of 95 MWe. Late 2001 a GeoSIG portable digital seismic network was installed and is collecting some seismic data.

The Berlín geothermal field, located 100 km east of San Salvador, has been exploited since 1992. In 1992, two 5 MWe back pressure power units were installed. From 1997 to 1999, 18 wells were drilled and a new 56 MWe (2 x 28 MW) power plant was constructed (Rivas, 2000). In February 1996 a nine stations seismic telemetry network was installed in connection with this development inside and around the Berlín geothermal field. Enhanced knowledge of the seismic behavior of the field and more accurate hypocentral locations were needed in order to determine the cause of the microseismicity, i.e. whether it was of natural sources or induced by the reservoir exploitation.

The main geological features faults, caldera and Berlín-Tecapa volcanic complex and the seismic network array are shown in Figure 1. At present the network is divided into an outer and an inner array. Both arrays are telemetric and autonomous systems. The outer array is from Kinemetrics (USA) and has been working since 1996 (See Figure 1). The inner array, an ISS system from South Africa (not shown on Figure 1) was installed for monitoring a hydraulic stimulation experiment at well TR8A, an injector well located in the northern part of the geothermal field. The experiment was carried out during 2003 and early 2004 in partnership with Shell. The array for monitoring the stimulation experiment consisted of twelve geophones at six different sites. Two three component sensors were deployed in every site, inside boreholes, one shallow installed 10 m deep, and other one 90 m deep. The stimulation project included three digital accelerographs in addition to one SSA-2 installed since 1996. The accelerographs were installed very close to TR8A well.

The high density of seismic equipment installed at Berlin field has allowed a satisfactory coverage of the area, which includes geothermal system, wells, power station and Tecapa volcanic complex.

### 2. MONITORING RESULT

After the 2001 earthquakes several areas were activated by the released energy. See the Figure 2, this shows the seismic distribution since January 2001 to may 2001. The Figure 2 shows the seismic behavior mainly after the earthquakes and reveal how different areas reacted to the perturbation.

The spatial distribution of seismicity recorded since 1996 by LaGeo network, located in an area of 80 km, is shown in Figure 3. The recorded seismicity correlates well with the geothermal anomaly and lies mostly within the limits of the reservoir. The higher concentration of seismic events, central part of the area, shown on Figure 3, is where the wells (both production and injection wells) and power station are located. The high concentration of hypocentres with frequent and very low magnitude events within the well zone shows that this area has poor capacity to

accumulate stress and release energy continuously through seismic waves. Therefore, this reduces the risk in this area of having local events of considerable magnitude able to produce damages to people, housing and building. Obviously, there are more active zones, which could affect the Berlín area with major earthquakes. Some damages in Berlín area occurred during the 1951 Jucuapa-Chinameca earthquake sequence with intensities of IV-V MSK Scale (Ambraseys et. al., 2001). Similar damages were experimented during the earthquakes occurred early 2001.

Figure 4 shows a cross section at 553000 m Easting, in the central part of the geothermal area. The hypocentral distribution shows a close spatial correlation with depth and location of the wells and with reservoir. The hypocentres range between 0 and -3000 m.a.s.l, within the wells zone

(where the reservoir has been located) and from -5000 to -6000 m.a.s.l., beneath the volcanic chain. It is believed that the heat source of the system is underlying this seismic zone.

The hypocentres below volcanic chain are deeper and describe the up flow zone and the influence of the heat source of the system (See on Figure 3 cross section location). Since operation of the network, apart of big earthquakes occurred early 2001, at least 30 local events had magnitude larger than 2.5. Because the very shallow depth, lower than 5 Km, these events have been felt by local communities.

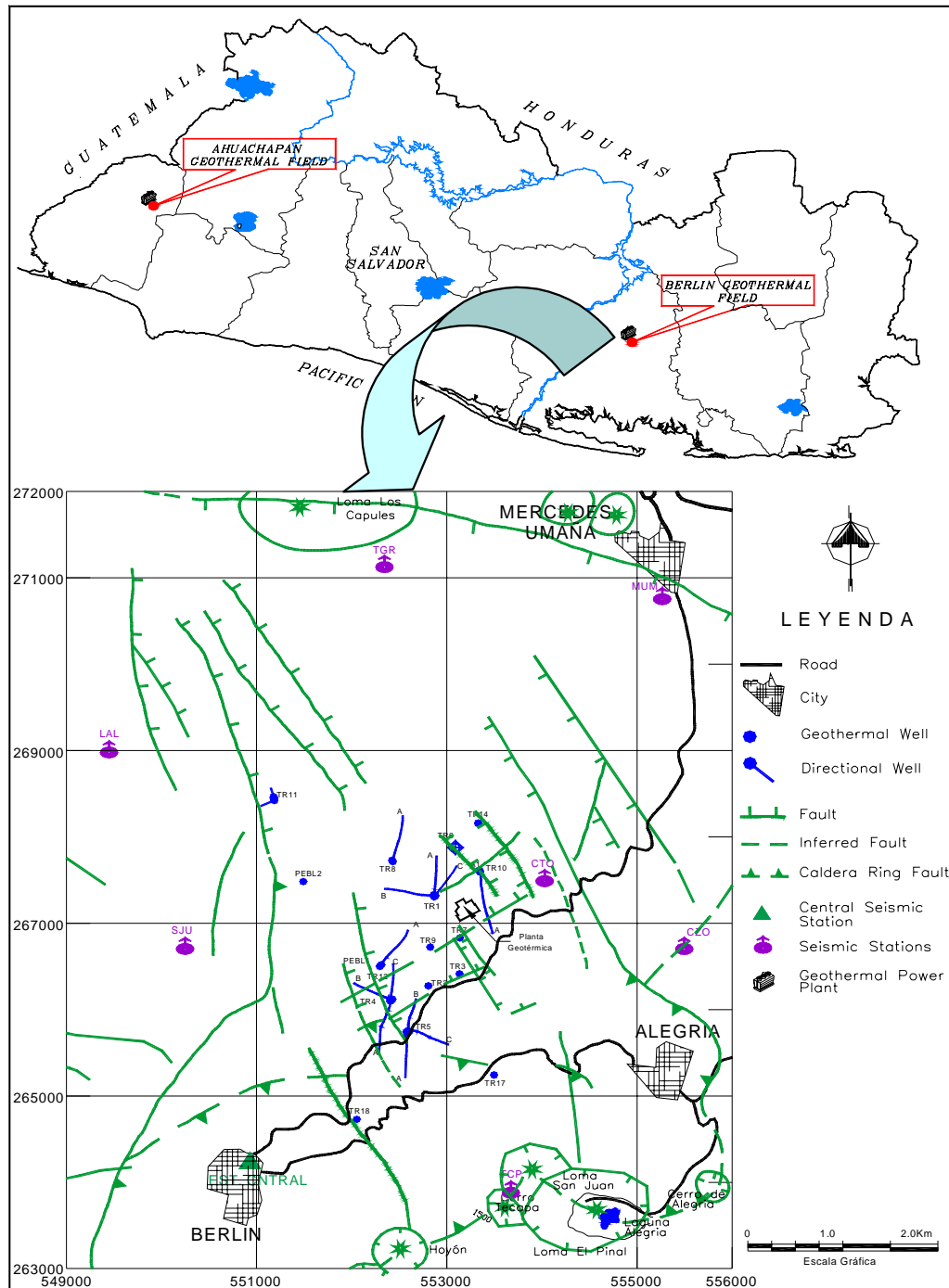
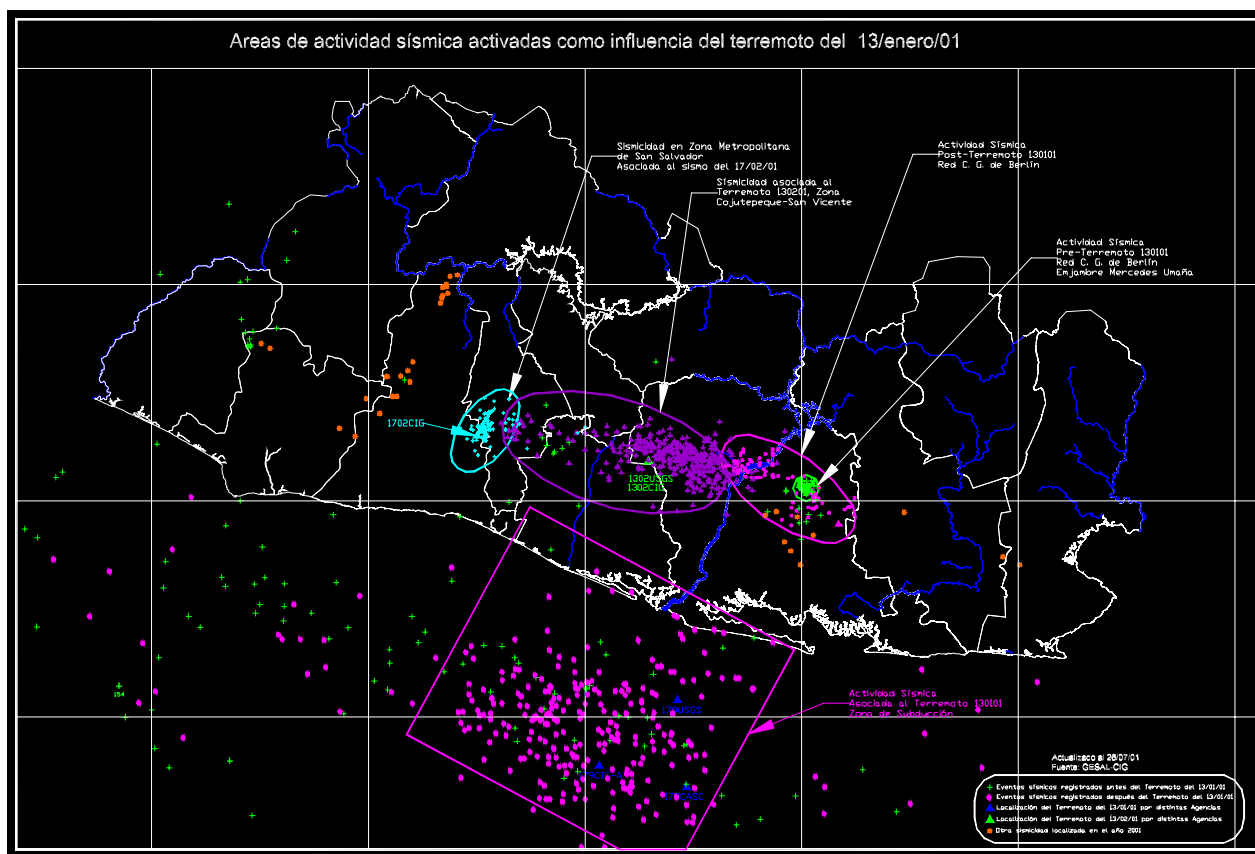


Figure 1: Structural map and surface seismic network at the Berlín geothermal field, El Salvador. (Rivas, 2001)



**Figure 2: Spatial distribution of seismicity before and after the 2001 earthquakes. Several areas were activated by the released energy. Pink dots: Mw = 7.6 January 13<sup>th</sup>, 2001 earthquake zone. Violet: Mw= 6.6 February, 13<sup>th</sup>, 2001 earthquake zone. Heavenly: M=5.4 February 17<sup>th</sup>, 2001 earthquake zone (San Salvador). Green dots epicenters before January, 13<sup>th</sup>, 2001 earthquake. (Rivas, 2001)**

### 2.1 Largest local event at geothermal field

The largest local event with magnitude  $M_c = 3.5$  occurred on September 16<sup>th</sup>, 2003 at 1:20 hour local time. It represented the main event of a seismic swarm located close to production zone, south of the geothermal field. The swarm was formed by 88 micro events and was able to locate 55 of them. At least three events were reported felt by local inhabitants. No damages at housing were reported but people were in panic for the shaking at 1:00 a.m.

Figure 5 and cross section on Figure 6 show the location of the swarm and main event. The depth range of this swarm was 0.2 – 4.2 Km and was located three kilometers Northeast from Berlín town. According to MM scale the intensity was up V. The magnitude ( $M_c$ ) of main event was 3.5, it was calculated with the limitation that records were overflowed and the events superimposed themselves. The magnitude calculated by SNET, using additional data and seismic moment scale, a value of 4 was determined.

The strong motion equipment (3 Etnas and one SSA2) triggered with main event. Apart of big earthquakes on January 2001, the acceleration record has been the largest during this swarm. Acceleration values obtained are shown in Table I. Stations HGZ and EXP recorded the maximum acceleration values in N-S component. SBO and MAS stations in E-W components. This is consistent according to station and epicenter location.

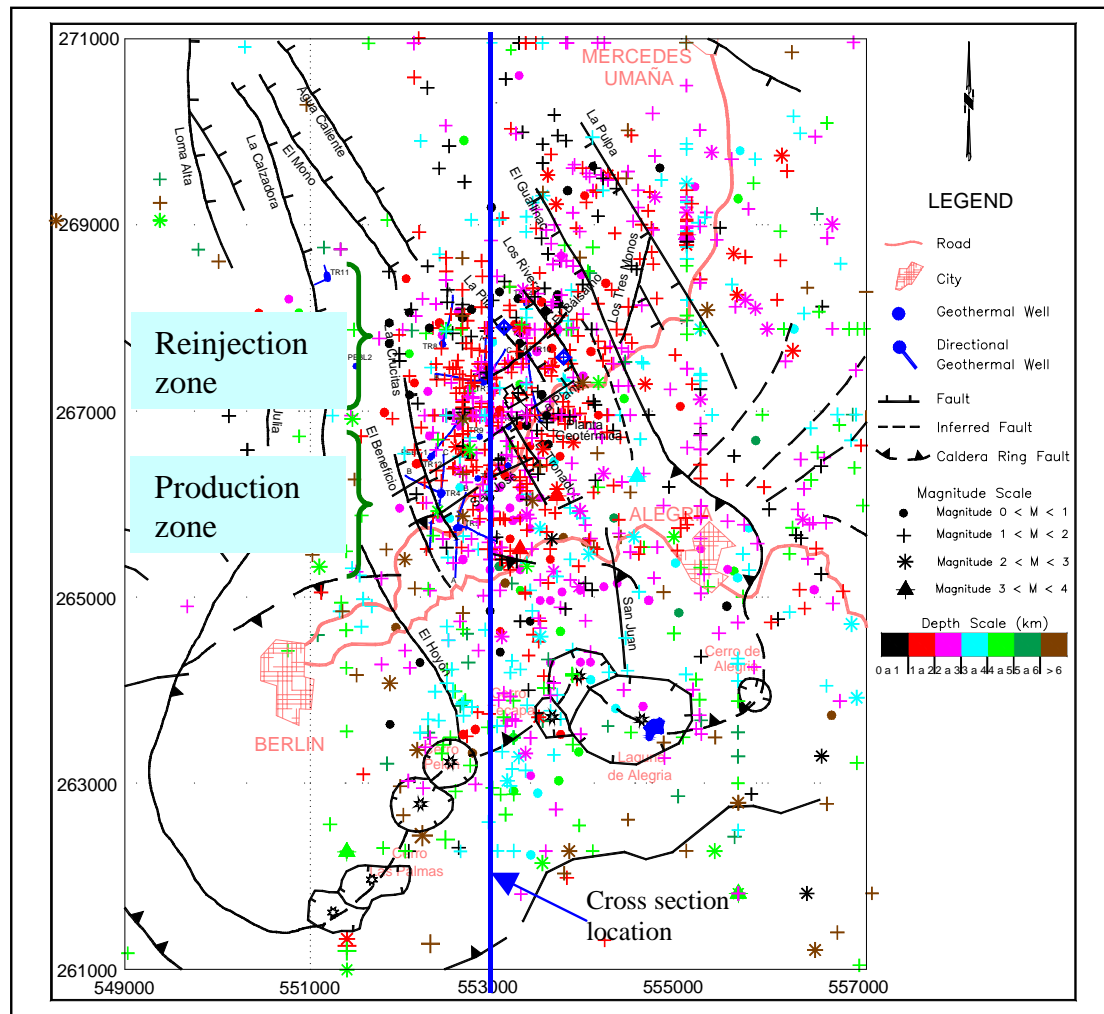
The SBO and EXP stations had comparable acceleration values, 220 and 263  $\text{cm/s}^2$ , respectively. They are located in

very stable rocks basement composite by lava flow. HGZ and MAS show very high values 498.8 and 939.9  $\text{cm/s}^2$ , respectively, which reflect the unstable soil conditions. The range of acceleration is 22.4 to 90 % of acceleration gravity. The maximum acceleration recorded by EXP during the magnitude 7.6 earthquake, January 13<sup>th</sup>, 2001, was 453  $\text{cm/s}^2$ . Figure 6 shows the corrected signal of the maximum acceleration at MAS y EXP stations.

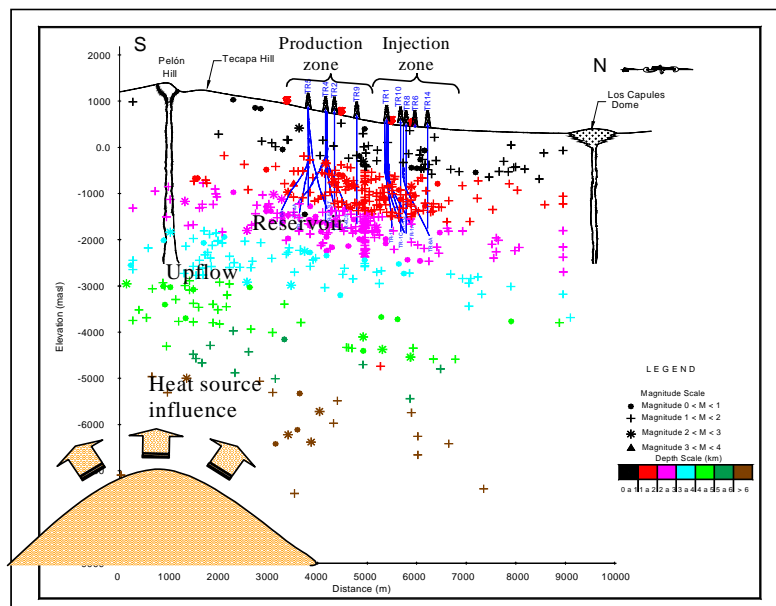
### 2.2 Recorded seismic swarms during seven years of network operation

At Tecapa-Berlín area, according seismic database, which started in 1996, have occurred several seismic swarm with main event felt by communities. It is well documented that in 1985 a seismic swarm (with main event  $M = 4.4$ ) located NW of Berlín town by the national network was recorded (Hernández, 19985). This cluster of events was able to produce surface fractures up to 20 cm wide. Table II shows a list of dates, location and magnitude of principal events located at Berlín field and surrounding areas since 1996 with LaGeo network.

The seismic swarm on September 16<sup>th</sup>, 2003 has been the more sensible to inhabitants because the distance, magnitude and shallow depth. This activity was slightly bigger than the swarm occurred close to Mercedes Umaña, one week before the 7.6 earthquake recorded on January 13<sup>th</sup>, 2001. The history on Table II shows how active is the Berlín geothermal area.



**Figure 3: Spatial distribution of seismicity at the Berlín geothermal field and surrounding areas. Period 1996 - 2003. Symbols are referred to a magnitude range and color to hypocentres depth. See magnitude and color scales on Figure. (Rivas, 2003).**



**Figure 4: South-North Cross section showing the hypocentres along 553000m Easting. Hypocentres located one km far from the profile have been projected.**

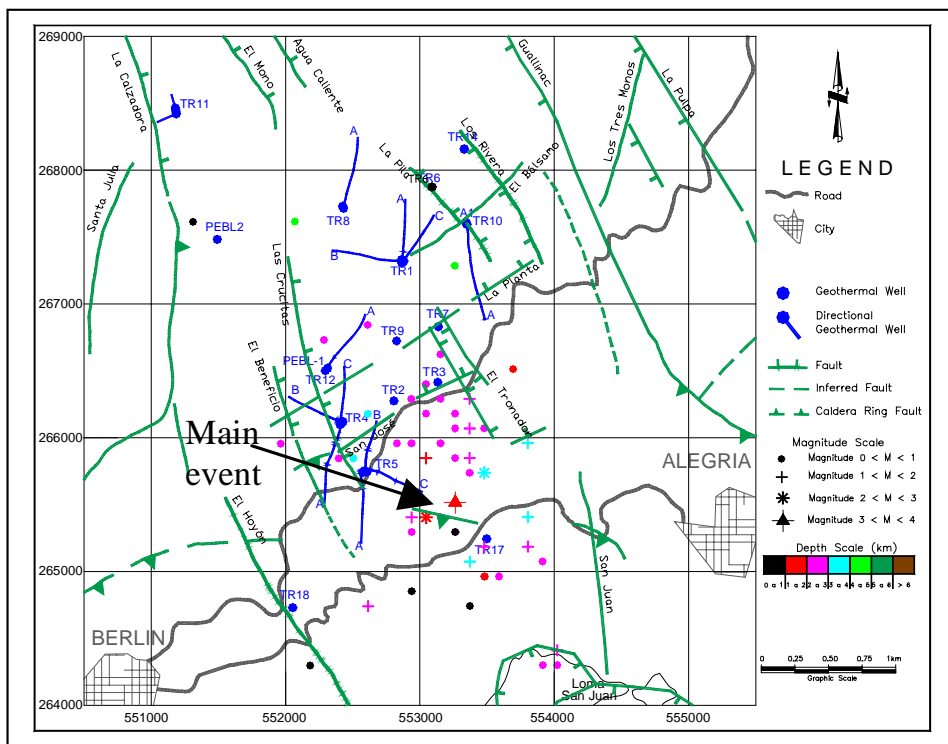


Figure 5: Location map of seismic swarm occurred on September 16th, 2003. Blue lines are production and injection wells.

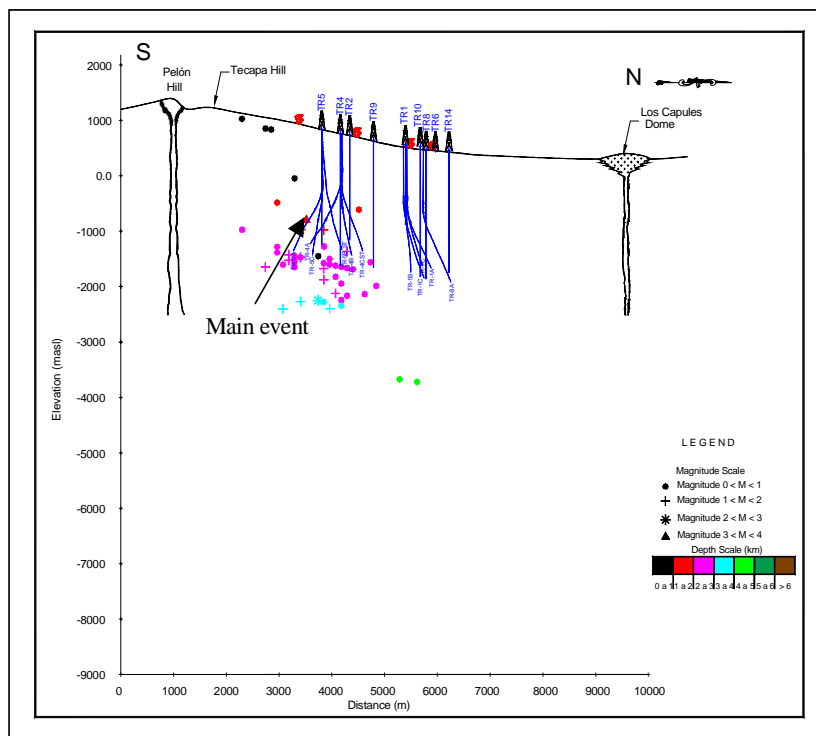
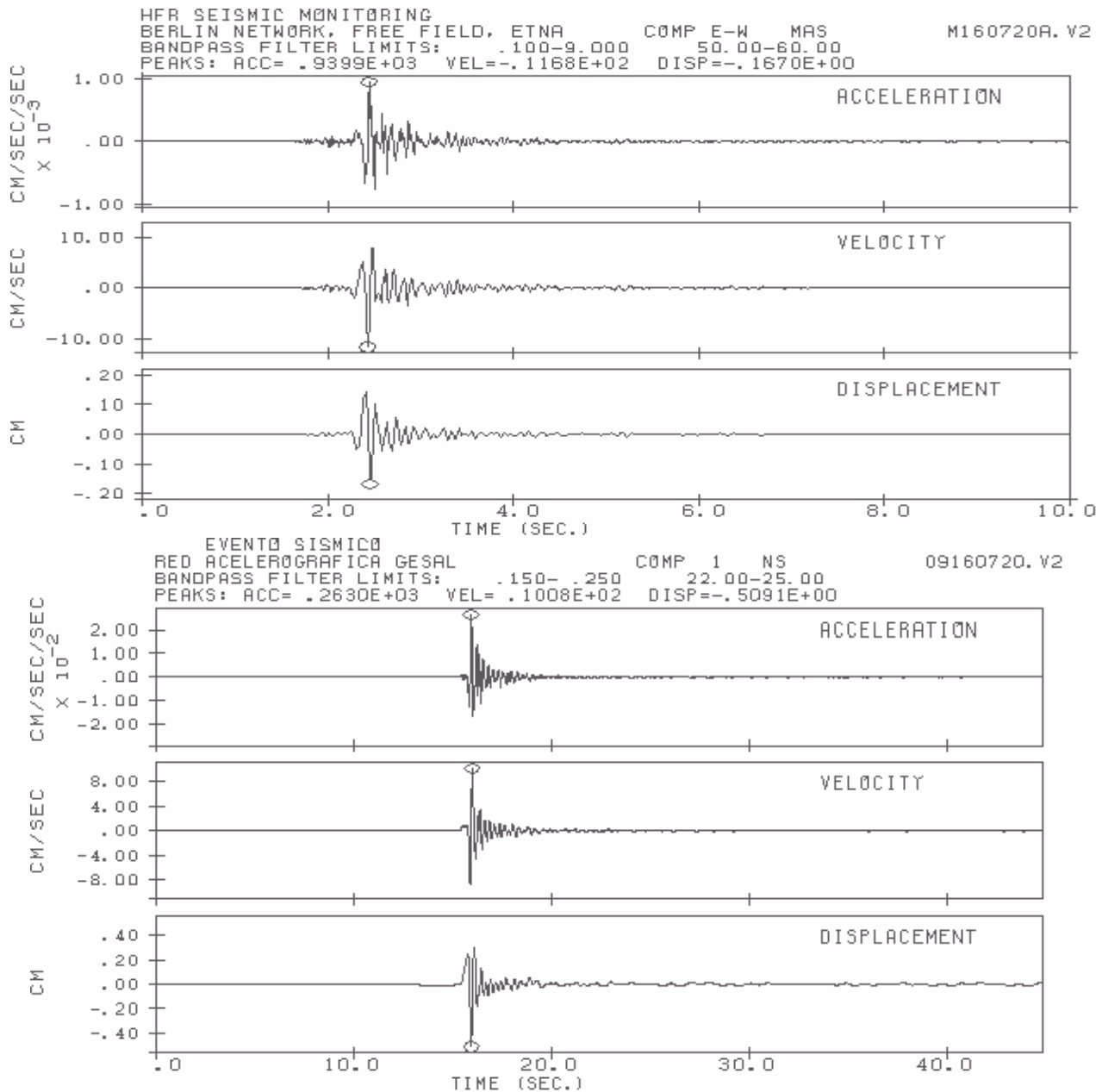


Figure 6: S-N Cross section of seismic swarm and main event. Berlín Geothermal field. September, 16th, 2003.



**Figure 7: Corrected signal of the maximum acceleration at MAS y EXP stations. (a) Left: MAS : E-W component 0.95g. (b) Right: EXP: N-S component 0.27g.**

### 3. SEISMICITY AND EXPLOITATION OF THE RESERVOIR

The history of reservoir exploitation, extract and inject mass, have been studied looking for any temporal correlation with seismicity.

The exploitation regime changed drastically at the end of 1999 and follows growing to 2003. The seismicity experimented some growing since 2001 (See Figures 8 and 9), after the big earthquakes occurred early 2001. Such growing was influenced for energy released during the earthquakes and aftershocks of January and February 2001. The first one occurred at subduction zone, 50 Km from the pacific coastline and second one in San Vicente area at the central part of the country.

Figures 8 and 9 show the injection and production history and seismicity in both areas. No close temporal correlation was observed and the growing is explained with the occurrence of earthquakes and energy released. Several areas were activated along the country because the occurrence of earthquakes. The pick of seismicity, June 2001 and September 2003, correspond to two seismic swarms, located at production zone of the geothermal field.

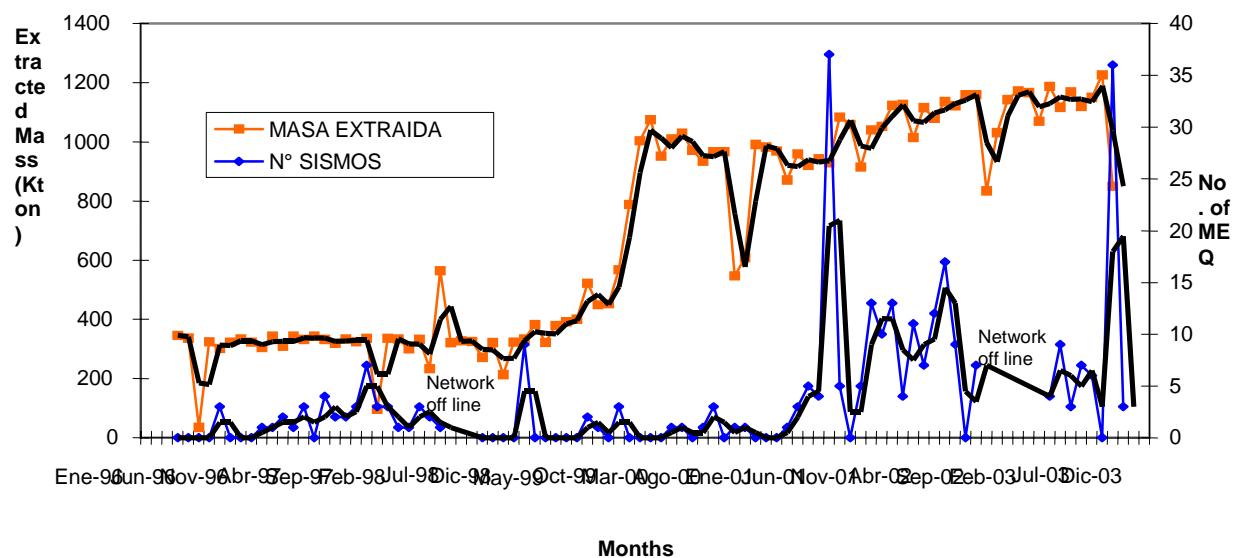
**Table I: Accelerations of main event of the swarm for each station**

MODEL	STAT. CODE	LOCATION	DIREC- TION	*(PGA, PGV) (CM/S <sup>2</sup> , CM/S)	
ETNA, KINEM.	HGZ	150 m SW TR8	N-S	<b>496.8</b>	<b>4.4</b>
			Vertical	167.0	1.8
			E-W	401.8	4.4
ETNA, KINEM.	SBO	400 m ENE from TR8	N-S	139.0	1.4
			Vertical	129.0	1.75
			E-W	<b>220.0</b>	<b>2.1</b>
ETNA, KINEM.	MAS	NNE from TR8	N-S	797.5	8.36
			Vertical	588.3	7.4
			E-W	<b>939.9</b>	<b>11.7</b>
SSA2, KINEM.	EXP	1000 m SSE TR8, Prox. TR9	N-S	<b>263</b>	<b>10.08</b>
			Vertical	93.0	2.3
			E-O	167.2	5.2

\*PGA: Peak Ground Acceleration; PGV: Peak Ground Velocity

**Table II: Recorded seismic swarms, since 1996, with Berlín seismic network.**

Date	Location	Main event magnitude
Nov, 1998*	Lempa river zone, NW of Berlín	3.8
Jan, 2001**	Between Berlín and Mercedes Umaña towns	3.4
May, 2001	Lempa river zone, NW of Berlín	3.4
Jun, 2001	Between Berlín and Alegría towns	3.3
Aug, 2001	Lempa river zone, NW of Berlín	3.4
Dec, 2001	North flank of Tecapa volcano	2.6
Aug, 2002	Tecapa volcano area	2.5
Jan, 2003	Alegría town	2.1
Mar, 2003	North Geothermal field	2.4
Apr, 2003	South Geothermal field	2.5
Sep, 2003	South Geothermal field	3.5

**Figure 8: Monthly extracted mass Vs seismicity. Period 1996 –2003**

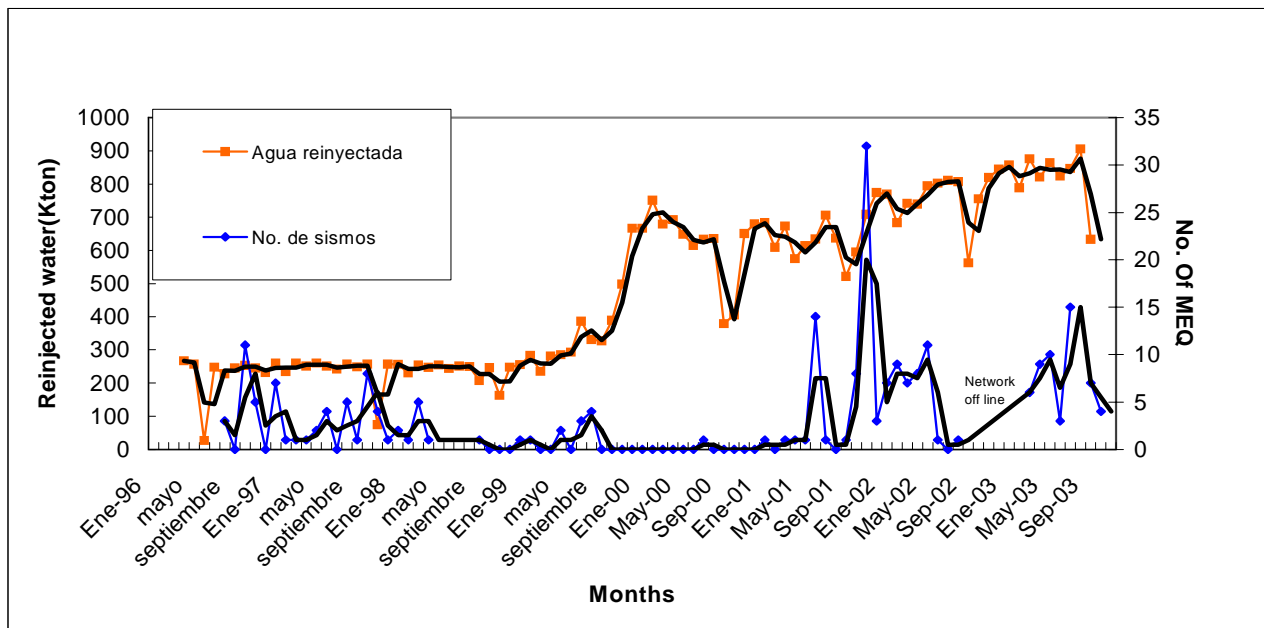


Figure 9: Monthly injected mass Vs seismicity. Period 1996 – 2003.

#### 4. FINAL REMARKS

The zone with major seismic activity, during the monitoring, has been the area where are located the geothermal anomaly and the geological structures responsible of fluids conduction. The limits of geothermal area, suggested by seismicity distribution, are very well constrained at E-W direction. There is no clear limit at the north, but suggest the extension of the fault system to the NW, specially the Guallinac fault.

The high concentration of hypocentres at well zone shows that this area has poor capacity to accumulate stress and release energy very often through seismic waves. This situation reduces the risk of having a quake of moderate or large magnitude able to cause damage at the geothermal field and surrounding. Seismicity at the Tecapa volcanic complex, deepest local seismicity, describes, the up flow zone and the influence of the heat source of the system.

There is no a clear temporal correlation between the seismicity and extraction-injection of mass, however there is a spatial correlation with geothermal anomaly and influence of wells operation. Seismicity increased in 2001 due influence of earthquakes occurred early that year and has kept the area very active.

The exploitation of the reservoir tends to increase with new project, so that it is important to continue the monitoring, because Berlín field has shown to be very active and sensible to exploitation and stimulation operation activities.

The Berlin geothermal field and surrounding towns could be affected by seismicity occurred in others areas as Jucuapa - Chinameca and San Vicente earthquakes, which produced similar effects for being in between these areas. It could also be affected for strong regional events occurred in Central American subduction zone.

According to database of seismicity at Berlín field, this area have been affected for several seismic swarm, which main events have been felt by local communities. Therefore this

area may classify as very active for its frequent seismic activity and for being located at very young volcanic environment.

#### 5. ACKNOWLEDGEMENT

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