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SEISMIC MONITORING AND ITS APPLICATION AS AN EXPLORATION TOOL IN THE BERLÍN GEOTHERMAL FIELD, EL SALVADOR

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ABSTRACT

Seismic monitoring of the Berlín geothermal field has been carried out since 1996. The initial objectives were to identify major seismic areas in and around the geothermal system, to monitor natural and possible induced seismicity due to exploitation, to identify active faults and fluid circulation paths in the reservoir and to gain information on the heat source. The seismic network has detected important shallow and low-magnitude seismic activity in the geothermal area, mainly in the south and in the central part of the exploited area. This activity is related to the heat source and fluid-bearing fractures. A cluster of seismic events was detected close to the reinjection zone which is thought to have been induced by increasing pore pressure and fluid motion. There is no clear correlation between seismicity and the rate of mass extraction and injection, and pressure change. A large scale exploitation of the Berlin field started in February 1999 and since then, seismicity has reduced. The *b*-value calculated for the geothermal area is 1.51, which is common in a volcanic environment and reflects a low stress state of the source. The *Vp/Vs* and Poisson´s ratios indicate higher steam fraction in the volcanic zone south of the production area, but both areas are still liquid-dominated. The seismic activity is relatively low and with low magnitude and therefore, does not pose any threat to the environment and surrounding communities.

1. INTRODUCTION

El Salvador, the smallest country of Central America, is bordered by the Pacific Ocean to the south, Guatemala to the west and Honduras to the north and east. See Figure 1. The tectonics and volcanism of the region have provided El Salvador with abundant geothermal activity and ten geothermal areas have been identified, see Figure 2. Five of these areas have been identified as high- temperature geothermal fields (180-300˚C), lying on the northern flanks of young volcanoes (Monterrosa, 1998). Two geothermal areas have been developed, the Ahuachapán and Berlín geothermal fields. The Ahuachapán field is located in the western part of the country and has been exploited since 1975. The Ahuachapán power plant has an installed capacity of 95 MWe.

FIGURE 1: Map of Central America

The Berlín geothermal field, located 100 km east of San Salvador, the capital of El Salvador, has been exploited for electricity generation since 1992. In 1992, two 5 MWe back pressure power units were installed. In 1997 a new project started, named "*First condensing development of Berlín geothermal field*". From 1997 to 1999, 18 wells were drilled and a new 56 MWe (2 x 28 MW) power plant was constructed. The small back pressure power plant is still on-line and, hence, the total capacity is 66 MWe.

In connection with the *First condensing development project*, a seismic telemetry network (STNB) was installed in the Berlín geothermal field in February, 1996. The main objectives of the installation of this network were to identify major seismic areas in and surrounding the geothermal system, monitoring of natural and possible induced seismicity due exploitation processes, to identify active faults and fluid circulation paths in the reservoir and to estimate the location of the heat source (Rivas, 1996). The aim of seismic monitoring is to identify higher permeability and fractured zones of the geothermal system. Therefore, the spatial distribution of seismic events is of primary interest.

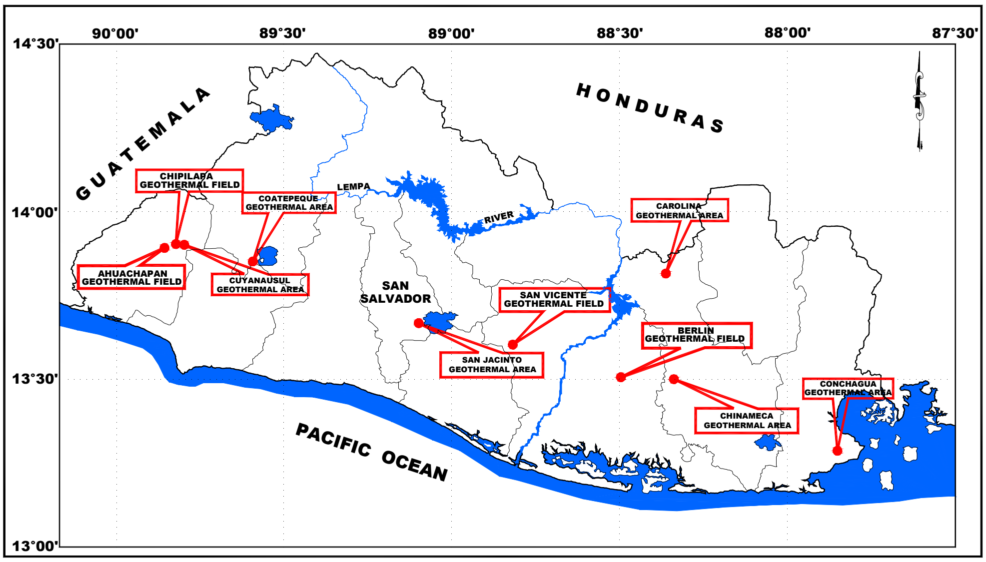


FIGURE 2: Geothermal areas in El Salvador

2. EXPLORATION AND EXPLOITATION HISTORY

Geothermal potential assessment in El Salvador began in 1953 when the Comisión Ejecutiva Hidroeléctrica del Río Lempa (CEL), the National Electricity Company, carried out reconnaissance geological, geochemical and geophysical surveys in several geothermal prospects, including Ahuachapán, Chipilapa, Berlín, San Vicente and Chinameca. Further exploration, headed by the United Nations Development Programme (UNDP) during 1968-1971, characterized the resources and established priorities for geothermal development. During the geoscientific investigations carried out by UNPD in the Berlín geothermal field, the first deep exploratory well (TR-1) was drilled to a depth of 1458 m, identifying a geothermal resource of at least 250°C. During 1976-1981, CEL conducted a resistivity survey and five wells (TR-2, 3, 4, 5 and 9) were drilled which proved to have production potential of 24 MWe (Monterrosa, 1998).

During 1990-1992, CEL installed two 5 MWe wellhead units. It was planned to use TR-2 and TR-9 as production wells and reinject the waste fluids into well TR-1. Because of the limited reinjection capacity of well TR-1, it was decided to put only one of the power units on line and use well TR-9 temporarily as an injection well. During 1993-1995 three deep wells were drilled for injection purposes (TR-8, TR-10, TR-14). Since February 1995 both 5 MWe units have been in operation using wells TR-2 and TR-9 as production wells (7.5 MWe) (Montalvo and Axelsson, 2000).

Electroconsult (ELC) assessed the feasibility of installing a condensing power plant in Berlín with a capacity of 50 MWe. The feasibility study gave positive results and encouraged geoscientific investigations and development of the resource (ELC, 1993). In 1994, Geothermal Energy New Zealand Ltd. (GENZL) conducted geological investigations and a magnetoteluric survey in Berlín. These studies confirmed the extension of a potential field south of the present production area (GENZL, 1995).

After the first stage of development at the Berlín geothermal field, using back pressure units (1992– 1998), a second stage began in 1999. From early 1997 to 1999, 18 additional wells were drilled (6 production and 12 reinjection wells) and a new power plant with two condensing units of 28 MWe each was built. The testing of the first unit started in February 1999 and the second in July 1999. Both of them started to operate in November 1999. A new stage of exploitation was started and the expected production of 56 MWe has almost been attained (50 MWe).

In a recent study, GENZL reassessed the potential of the Berlín field by reinterpretation of the MT survey and using additional data from new surveys and drilled wells. The result was that the field could sustain 152 ± 42 MWe (PB Power, GENZL Division, 2000). A conceptual model of the Berlín geothermal field was developed in the early nineties (Montalvo and Axelsson, 2000). This model was updated in 1997 by CEL and again in 2000 by Geotérmica Salvadoreña (GESAL) as more information was collected from drilled wells, reservoir studies and geoscientific surveys. The latest model is based on information available in March 2000 (GESAL, 2000). Recently, additional surveys were carried out (geology, DC-resistivity, gravity) in the southern part of the geothermal field in order to assess the possibility of installing a third 28 MWe power unit in the near future.

3. TECTONIC SETTING AND GEOLOGY

El Salvador is located on the western edge of the Caribbean Plate. The tectonics of the region are complex and, in some aspects, poorly defined. This is reflected in the differences in the delimitation of seismic sources in the hazard studies carried out for Central America and El Salvador by several organizations. The determination of the maximum magnitude for each seismogenic zone is another theme of discrepancy (Bommer et al., 1997).

3.1 Regional tectonic setting

The subduction of the Cocos Plate beneath the Caribbean Plate defines the Middle American Trench. This thrust interface is a major source of earthquake activity, with steep Benioff-Wadati zones descending to about 300 km (Bommer et al., 1997). The largest instrumentally recorded earthquakes on this interface had magnitudes of about 8 (Dewey and Suarez, 1991). The section of the trench in front of the coast of El Salvador has, however, been shown to have a relatively low seismic slip rate and the largest events in the last century had magnitudes between 7.1 and 7.3 (Ambraseys and Adams, 1996). However, the earthquakes which caused damage in El Salvador were of moderate magnitude and shallow focus (the

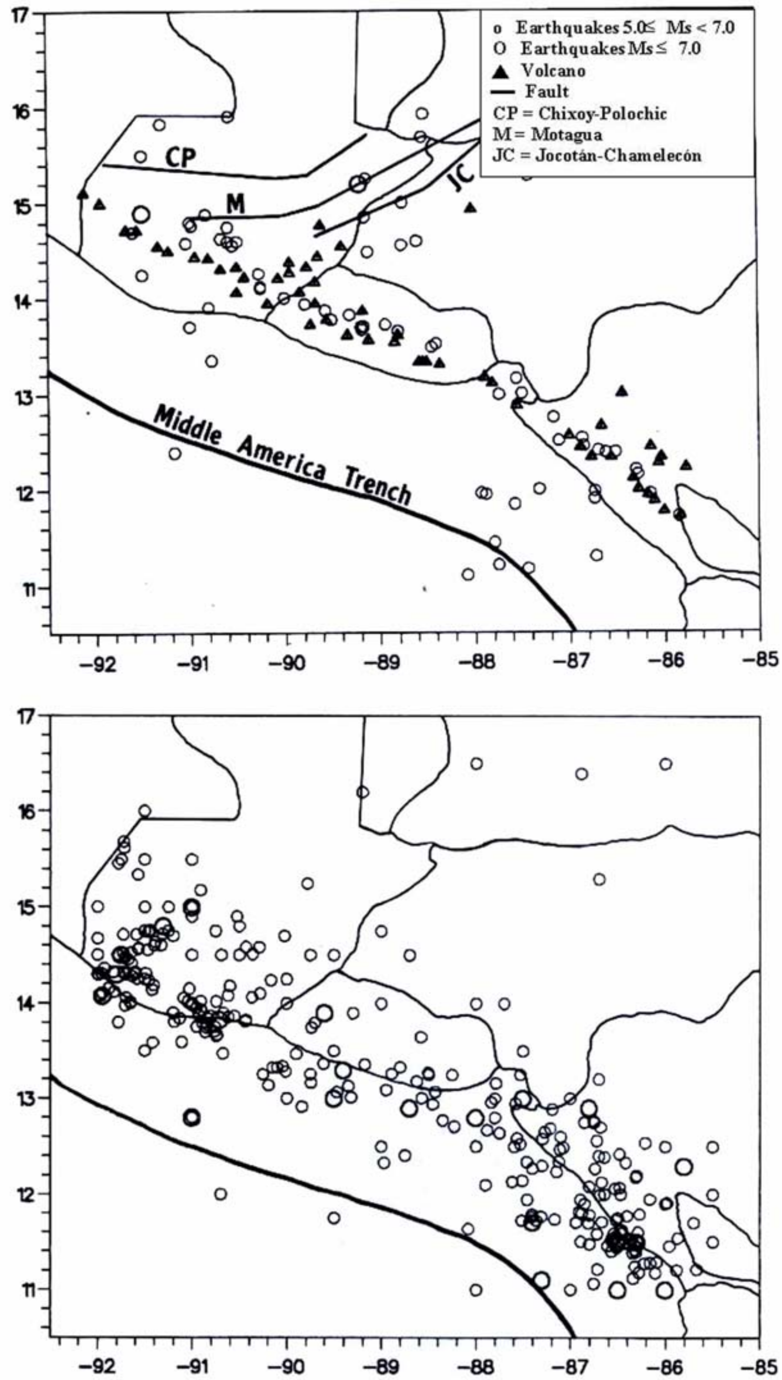


FIGURE 3: Main tectonic structures and seismicity in El Salvador and surrounding areas, circles show epicentres from 1898 to 1994. Top, upper-crustal seismicity with focal depth ≤ 25 km; Bottom, earthquakes with focal depth ≥ 25 km (Modified from Bommer et al., 1997)

Chinameca earthquakes in 1951 and the San Salvador earthquakes in 1965 and 1986, are three examples). These earthquakes were located within the Quaternary volcanic chain and the Central American graben formed by the subduction process, extending from Guatemala to northern Costa Rica. These events reach magnitudes of about 6.5, but they are often close to highly populated areas and, hence, often result in very severe destruction. The seismicity in the volcanic arc has been interpreted as resulting from a right-lateral shear zone driven by an oblique component of convergence between the Caribbean and Cocos Plates (White, 1991). The main tectonic structures and seismicity in Central America from 1898 to 1994 are shown in Figure 3.

3.2 Local tectonics and geology

Figures 2 and 3 show that all the hydrothermal manifestations in El Salvador are found within the Quaternary volcanic chain located at the southern margin of the Central American graben. The Berlín geothermal field is located on the northern flank of the Berlín-Tecapa volcanic complex. The field is controlled by a NW-SE trending fault system. Figure 4 shows the location of the power plant and geothermal wells.

The Berlín volcano seems to be centred where the regional northwest-trending fault system intersects the southern margin of the E-W trending fault system, forming the 5 km wide Berlín graben. The formation of the large basaltic andesite composite cone during the last 1-2 million years has twice been interrupted by explosive andesite eruptions forming black and grey ignimbrites. These eruptions were accompanied by a collapse of the upper part of the central cone. The collapse was partly controlled by the pre-existing northwest-trending fault, forming the outlines of the Berlín caldera (GENZL, 1995).

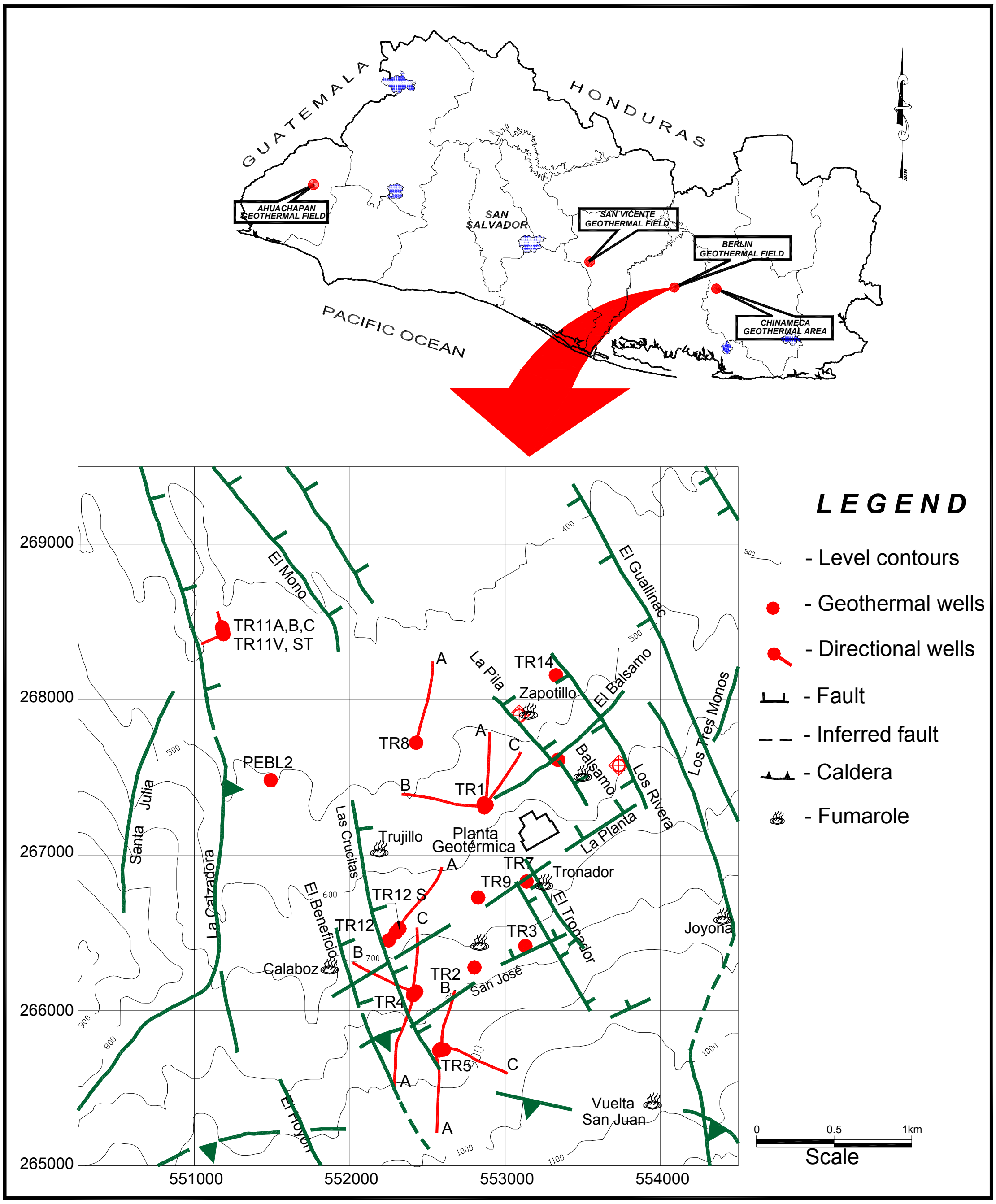


FIGURE 4: Simplified tectonic map of the Berlín geothermal field

4. SEISMIC DATA ACQUISITION AND PROCESSING

4.1 Acquisition system

The *Seismic telemetry network* at the Berlín geothermal field (STNB) was installed in February 1996. In the beginning, some calibration and configuration problems had to be solved so that a continuous database dates back to July 1996. The network was designed to cover the geothermal production/re-injection area with stations close enough to detect low magnitude events. The STNB has operated continuously except for the periods of December 15, 1996 - January 15, 1997 and May 15 - August 31, 1998. During these periods, equipment security was increased and it was necessary to stop the monitoring.

The data acquisition system consists of nine seismic stations. Two of them are equipped with three component sensors and seven with one vertical component. The seismometers are short period (1 Hz) SS-1 Ranger, manufactured by Kinemetrics Inc., USA. The signal from each site is received in real time, with a sample rate of 200 SPS, through a FM telemetry radio in a *Central recording station* (CRS) located in Berlín town. Two SSA-2 digital strong motion accelerographs with autonomous acquisition systems are also included. The recording system, named DATASEIS II, collects the data and creates a file for each trigger, which occurs every time a trigger threshold is exceeded. Timing in the DATASEIS II system is provided by a GPS clock. The *Seismic network acquisition program* (SNAP), provided by the manufacturer, manages the recording system. The analog signals are collected and converted to digital form and stored. In addition to digital recording, the CRS is equipped with three VR-2 drums for analogical recording.

Since the start of operations (54 months) some changes have been made to the original network array. Three stations were moved to more secure places and one was taken down, so at the moment there are eight stations in operation. Seven stations are located in, and around, the geothermal field and the volcanic complex (MUM, MTA, SDM, SJU, LAL, LPA, CZO). One station (LGU) is located to the northwest of the geothermal area, close to “15 September dam” in the Lempa river. The average distance between stations in the geothermal field is 4.4 km. The locations of the present network stations are listed in Table 1 and are shown in Figure 5.

TABLE 1: Names and location of the stations of the seismic network of Berlín geothermal field

Station name	Code	Latitude	Longitude	Elevation (m)
Mercedes Umaña	MUM	13°33.42’	-88°29.34’	424
Montañita	MTA	13°31.72’	-88°30.78’	699
Santiago de María	SDM	13°28.43’	-88°29.08’	900
Santa Julia	SJU	13°31.20’	-88°32.01’	1024
Loma Alta	LAL	13°32.36’	-88°32.53’	474
La Palma	LPA	13°28.68’	-88°32.12’	1528
Cuzco	CZO	13°31.18’	-88°29.24’	999
Las Guarumas	LGU	13°38.68’	-88°33.68’	220

4.2 Data processing

The digital files recorded by the system are downloaded to a PC. Here, the Seismic Work Station software (SWS) is used to process the data. The SWS contains several computer programs for editing time signals, picking phases, as well as an event location program HYPO71 (Lee and Lahr, 1975). The events are identified and classified into two categories based on arrival time differences and then the hypocentres of local events are determined. The categories are:

- Local events (Ts - Tp < 3 s)
- Regional events (Ts - Tp > 3 s)

Ts and Tp are the arrival times of the secondary (S) and primary (P) waves.

A five-layer velocity model (Table 2) is used to determine the hypocentres. This model was adapted from the model determined for Ahuachapán-Chipilapa geothermal area (Fabriol and Beauce, 1997), because the geological setting is similar to that of Berlín. This model was tested and calibrated using a dynamite explosion fired in the centre of the network. The distance between the calculated hypocenter and the location of the explosion was 280 m. This error is within the 68% confidence estimate of the horizontal error of 200 m given by HYPOELLIPSE software (Lahr, 1997) for this model. The average of the 68% confidence horizontal and vertical errors is 0.8 ± 0.4 km and 1.5 ± 1.0 km, respectively, for events inside or close to the network (Fabriol et al., 1997). The *Vp/Vs* ratio is taken to have a value of 1.74. This value was calculated using the database available until October 1997.

TABLE 2: Five-layer P-wave velocity model used for HYPO71

P – wave velocity (km/s)	**Top of layer (km)**
2.0	0.0
3.7	0.2
4.2	1.0
5.0	2.5
6.0	10.0

Depth (km)	**P-velocity (km/s)**
0.0	----------------------------
	2.0
0.2	----------------------------
	3.7
1.0	----------------------------
	4.2
2.5	----------------------------
	5.0
10.0	---------------------------
	6.0

Magnitude calculation is performed by a formula provided by Lee and Lahr's (1975), based on the duration of the record:

$$M = -0.97 + 2\log(c) + 0.00325\,d \tag{1}$$

where d = Distance to the epicentre (km); and
c = Duration of the seismic signal (s).

No magnitude values greater than 3 have been observed, but micro-earthquakes with magnitudes of less than two are predominant in the geothermal system.

5. SEISMIC MONITORING RESULTS

In this report, a four year database is presented (July/1996 - June/2000). The network has operated continuously, except for some short periods of time used to rearrange the network in order to increase operational reliability, and for maintenance of the equipment. The monitored area is about 325 km^2 and the data base consists of 903 local events with Ts-Tp < 3 s.

5.1 Spatial and temporal distribution of seismicity

5.1.1 Spatial distribution

Figure 5 shows the spatial distribution of epicentres and the main geological structures that form the local tectonic framework. The seismicity is basically concentrated in two areas, Lempa river zone in the northwest and Berlín geothermal area in the southeast. Both seismic zones are located in the E-W tectonic structure of El Salvador, called the Central American graben, formed by the subduction process.

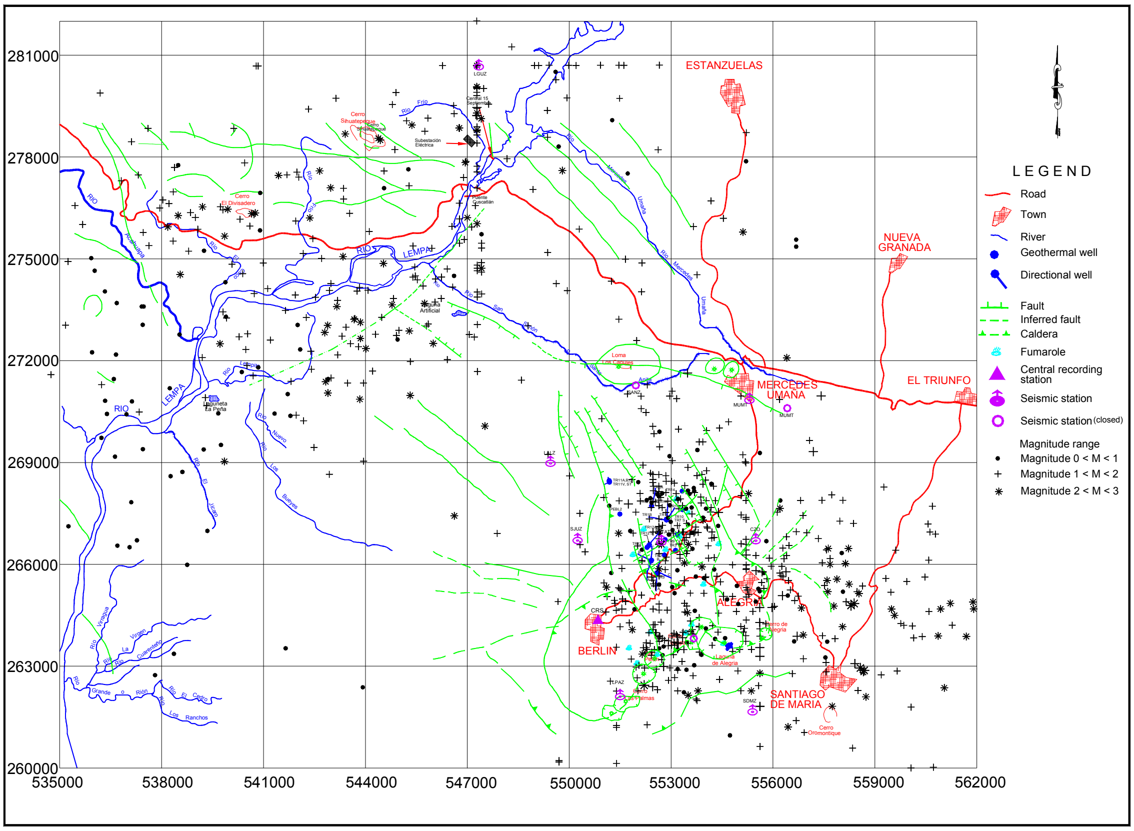


FIGURE 5: Spatial distribution of the local seismicity recorded by STNB in the period July 1996 - June 2000. Nine hundred and three local events with Ts-Tp < 3 s. Magnitude range; (·) 0 ≤ M d < 1, (+) 1 ≤ Md < 2; (*) 2 ≤ Md < 3

The hypocentral depth of this seismicity is less than 25 km and the magnitudes are in a range between 0 and 3. This shallow seismicity is typical in the graben and in the chain of Quaternary volcanoes that extend from Guatemala to northern Costa Rica (Bommer et al., 1997). Three kinds of symbols are used to represent three different ranges of magnitude. Note that the higher magnitude earthquakes, denoted with (*) are located in the Lempa river zone and north of Santiago de María city (northwest and southeast in Figure 5, respectively).

5.1.2 Temporal distribution

As mentioned earlier, the network has recorded 903 local events at least at three stations, with magnitude values lower than 3 (Md < 3). The temporal magnitude distribution of the earthquakes is shown in Figure 6. Figure 7 shows the number of seismic events per month in the whole area and in the geothermal system. Over 44 months of effective operating network time, the frequency average of microearthquakes with Ts-Tp < 3 s

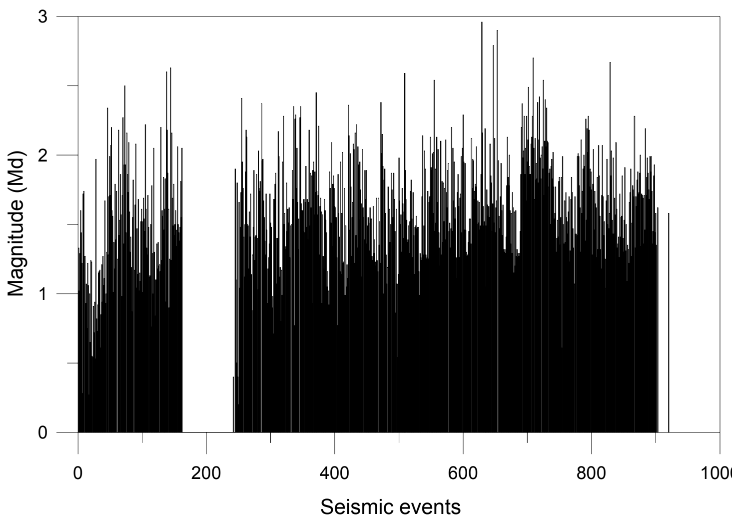


FIGURE 6: Chronogram of magnitude values of the local seismicity for the period July 1996 - June 2000, nine hundred and three seismic events

is 20 events per month (see Figure 7, black bars). Approximately one third of these events is within the exploitation area, and the volcanic zone hosting the heat source of the Berlin field (Figure 7, grey bars).

The histogram in Figure 7 shows that there have been 7 months, where the average frequency (20 events/month) was strongly exceeded. In the periods of above average activity (September 1996, January and August 1997, April and November 1998, March and July 1999), the activity is seen as a clusters of events, some of which took place in the Lempa river (1996,1997,1998) and Santiago de María zones (March 1999). There was a cluster in the geothermal system in July 1999. The network was out of operation from December 15, 1996 to January 15, 1997 and from May 15 to August 31, 1998. This is why few, if any, events appear in those months.

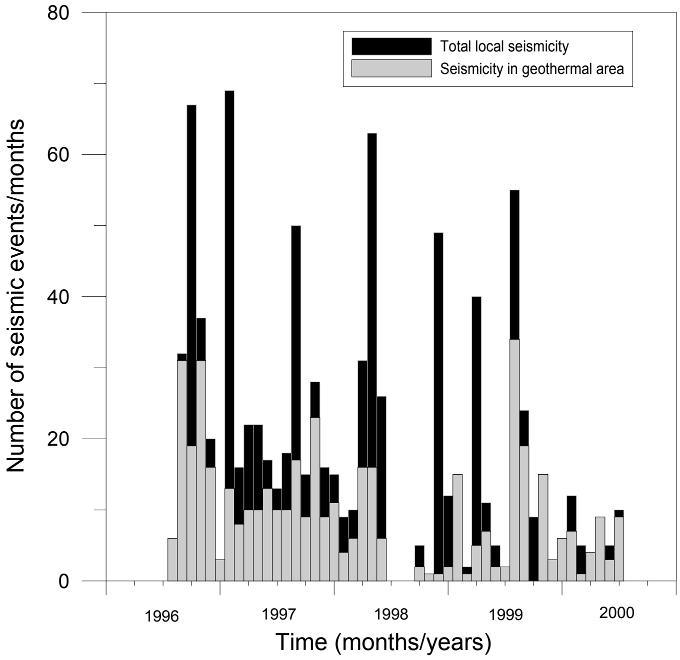


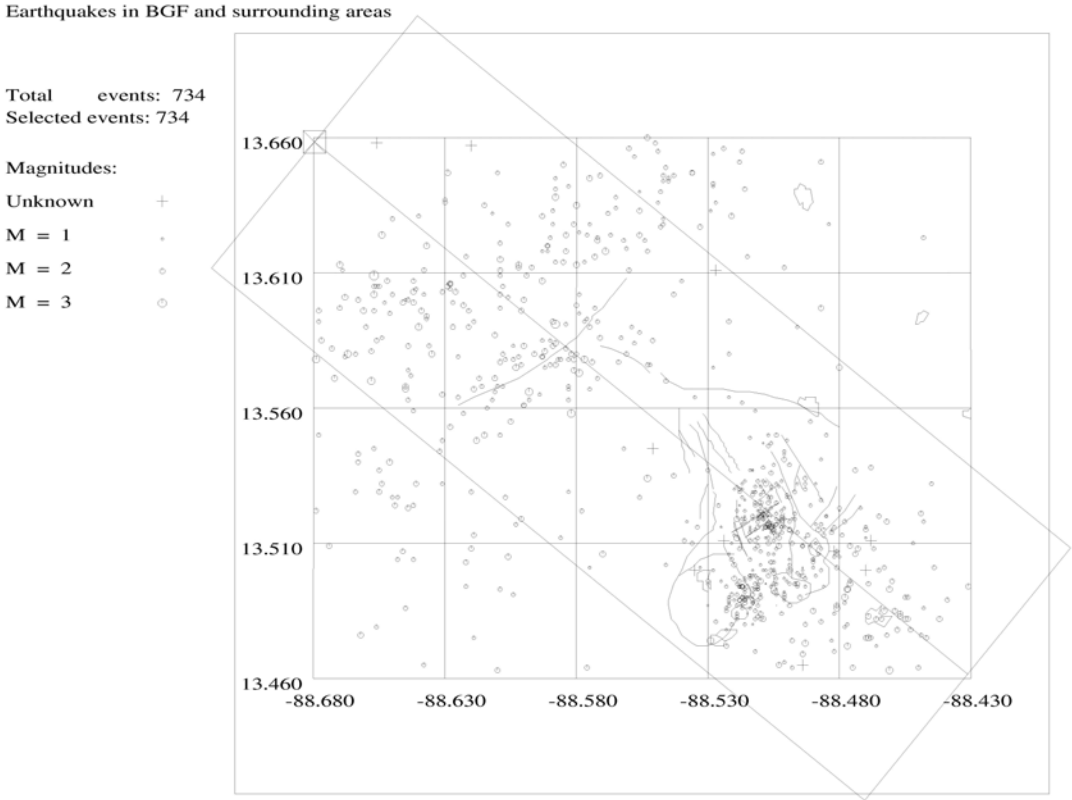
FIGURE 7: Number of seismic events per month in the whole area and in the geothermal system

In November 1998, a cluster was observed in the Lempa river area three weeks after hurricane Mitch caused damage in the area. During the last week of November 1998, 45 seismic events took place. The cluster observed in March 1999 could have been influenced by the seismic activity recorded and located by the *National seismological network* in the San Vicente area (approximately 25 km west of Lempa river). Two shallow earthquakes (10.3 and 9.1 km depth) with magnitudes (Md) 4.6 and 4.5, respectively, were followed by numerous small earthquakes, 71 of which were felt by the population in San Vicente (Torres et al., 1999).

5.2 Seismicity in the Lempa river zone

The concentration of epicentres in the northwest, in Figure 5, is located in the vicinity of Lempa river. The "15 September" dam is located in this area (approximate coordinates 547750, 278000). These seismic events represent 50% of the observed seismicity (about 450 events) and are possibly related to a fault running almost parallel to the river (NE-SW, dashed line). Earthquakes with higher magnitude values (2< Md <3) are located on this inferred fault. There are some few events with similar values of magnitude located on the Sihuatepec and El Divisadero hills. A small group of events to the southwest of this distribution, with lower magnitude (0<Md<1), has been observed in a geothermal area named "Obrajuelo", but the depth of this seismicity (10-20 km) indicates that it is not related to the geothermal activity.

Figure 8 shows a map with the total local activity and a profile from northwest to southeast. The profile gives a general view of the depth of the local seismicity. It shows that in the northwest part (left), the hypocentre concentration in Lempa river could correspond to a fault with a small dip to the northwest. A seismic gap is observed between Lempa river and the geothermal area. In the Lempa area some local faults are probably activated as a response to the stress generated by the subduction process and the seismicity can be interpreted as a reaction of the crust to the subduction process and releasing of regional stresses. In order to gain more information on the seismicity in the Lempa river area, one or two additional stations are needed, because the uncertainties are quite big. Only one seismic station (LGU) sited 3 km to the north of the dam, covers this area (Figure 5). An additional station at coordinates (536,000 m, 273,000 m) would improve the coverage considerably.



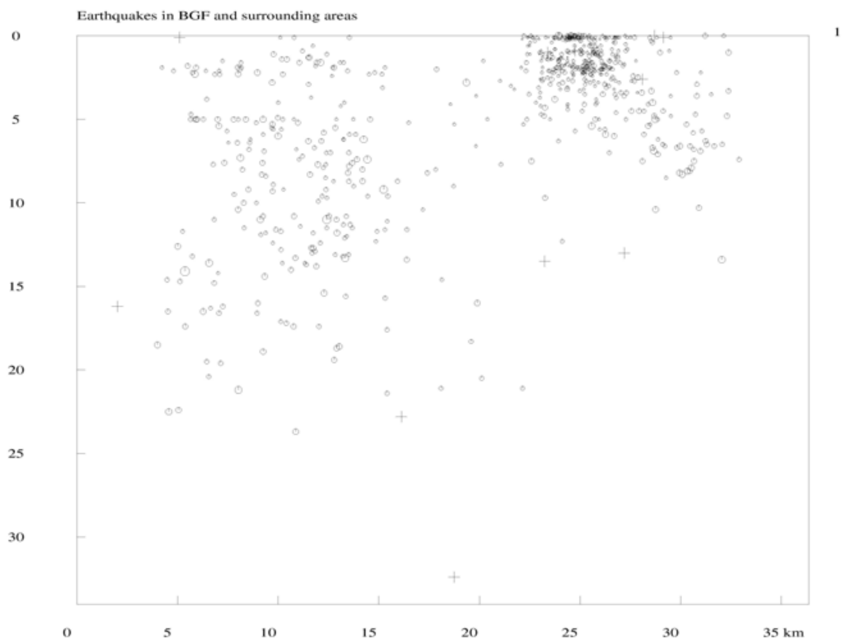


FIGURE 8: Spatial distribution of local seismicity located with SEISAN software

5.3 Seismicity in the Berlín geothermal field

Figure 5 shows high seismicity in the southeast, in an area of about 150 km^2 and covering the Berlín geothermal field. Seven of the eight seismic stations of the network are in and around the geothermal system. This distribution of epicentres constitutes the second half of the registered local seismicity (453 events). The structures related to the geothermal activity are mainly in an area defined by coordinates (549000, 261000), (549000, 271000), (557000, 271000) and (557000, 261000). A number of dispersed events (about 150) are observed to the east and southeast of this area. This activity is on the north flank of El Tigre hill, located to the northeast of Santiago de Maria city, and will not be discussed further in this report.

The power plant, production and reinjection wells are located within an area defined by coordinates (551000, 265000), (551000, 269000), (554000, 269000) and (554000, 265000). One third of the total seismic activity is concentrated in this area, which is considered to have the highest subsurface temperatures (Monterrosa, 1993). The Berlín-Tecapa volcanic complex is found to the south of this area. All the studies carried out indicate that the heat source of the geothermal system underlies this volcanic complex (GESAL, 2000). A more detailed discussion of the seismicity in the Berlín geothermal field will be given in Chapters 5.5 and 6.

5.4 Comparison of the processing results using SWS and SEISAN software

A part of the study described in this report was to implement and test the *Earthquake analysis software* SEISAN developed at the University of Bergen, Norway (Havskov and Ottemöller, 1999) and compare to the software that has been used up to now. The database between July 1996 and December 1999, was converted from the HYPO71 (SWS) format to SEISAN format (Kinemetric format to Norway format). All the input files and the most important geological structures of the area, necessary for relocation and reference, were included. Figure 8 shows the spatial distribution of the earthquakes (upper part) and a profile (lower part) obtained with SEISAN (the box on the upper part of Figure 8 shows which hypocentres have been projected onto the profile). The area represented in Figure 8 is the same in Figure 5. Both figures reproduce very well the main distributions of seismic events. There are some differences in the clusters in the south of Lempa river and to the southeast of the geothermal area. Despite these differences SEISAN was used for calculation of the b-value of the Richter frequency-magnitude relation, and to evaluate the *Vp/Vs* ratios and Poisson´s coefficients.

The profile in Figure 8 shows the depth distribution of the hypocentres. The left part of the profile (northwest) shows the hypocentres related to the structures of the Lempa river area (depth < 25 km). The seismicity, between 20 and 25 km along the profile, is in the geothermal system (depth < 5 km). At the southeast end, there are some seismic events (depth < 10 km) possibly generated, by a tectonic structure located in this area or by El Tigre hill, northeast of Santiago de Maria city.

Processing with SWS gave smaller residual times, and smaller horizontal and vertical errors than SEISAN. The reason is that the database was systematically processed with this software. The SEISAN results are less accurate because the relocation was made in blocks by periods of time and some changes were made in the original array of the network, so there are some uncertainties in coordinates, names and dates when these changes took place. The SEISAN program offers more flexibility and simple options for displaying results. Furthermore, this software has additional tools for earthquake analysis.

Generally speaking, the characteristic of the distribution of the seismicitiy obtained by SEISAN are similar to the results of SWS, except for some clusters which are located in areas where the network has no capability of giving good accuracy, that is to the south of Lempa river zone and southeast of the geothermal area.

5.5 Seismicity and exploitation activities

The first idea about induced seismicity being due to a water injection process in the ground was introduced by Healey et al. (Allis, 1987). The first evidence for this was found during the pumping of waste water into a 3.8 km deep well in the Rocky Mountain arsenal during the 1960s. In analysing the data, Healey at al. attributed the anomalous seismic activity to increased pore pressure at depth. Subsequently, there have been many similar reports of induced seismicity, and the use of high pump pressure tests to induce hydrofracturing and to determine the magnitude of stress in the crust (Allis, 1987). There are reports about induced seismicity in Wairakei in New Zealand (Sherburn, 1984; Allis et al., 1985) and several geothermal fields in Italy, including Torre Alfina, Latera, Cesano, Larderello-Travele (Batini et al., 1980 and 1985). Focal depths were relatively shallow (depth < 3 km) and concentrated around the reinjection wells (generally less than 2 km distance). The maximum magnitudes exceeded 3. In the Alfina field, most of the induced seismic events occurred when the wellhead pressure exceeded about 5 bars. There has, however, been no observed correlation between anomalous seismicity and production and reinjection of fluids in the Tongonan field in the Philippines (Bromley et al., 1985).

High pore pressure is not the only way of triggering earthquakes. Both loading of the earth´s surface with large water reservoirs (dams) and unloading in large mines or quarries may also induce seismicity. In fact, any activity that changes the stress regime in the earth is likely to induce earthquakes.

As a general rule, reinjection of geothermal fluid into the ground is liable to cause induced seismicity. The principal mechanism is the increase in pore pressure that occurs at injection depths, which reduces the effective normal stress acting on faults planes (Allis, 1987). It appears that production of geothermal fluids (as opposed to reinjection) does not cause induced seismicity. The reason for this is that the pore pressure declines with fluid extraction.

With the objective of looking for a possible temporal and spatial correlation between seismicity and some exploitation activities, the seismic distribution in Berlín geothermal field was plotted for every year (see Appendix I) and the cumulative seismicity is presented in Figure 9. It shows that the main concentrations of epicentres are in the production–reinjection area, and in the volcanic complex which hosts the heat source of the geothermal system.

The seismic activity correlates closely in space with steam producing wells (TR-2, TR-3, TR-4, TR-5, TR-9) and reinjection of waste fluids (TR-1s, TR-8, TR-14). There is no spatial correlation with reinjection wells at TR-11, located at the northwest limit of the field (Figure 9a). The observed annual activity (Figures in Appendix I) shows a lateral expansion in the cluster of events over time especially in the reinjection area. In Figure 9a, some seismic events are aligned with the La Pila, Los Rivera and Guallinac faults, very close to re-injection wells. These alignments and the expansion of epicentres in the re-injection area suggest that the fluids are moving out from the reinjection area along faults in a NW-SE direction. The observed alignment in the northern part of the well zone, could represent the extension of the Guallinac or Los Rivera fault. It is likely, if this seismicity continues, that permeability will increase in this area in the future.

The number of seismic events located in the production and reinjection zones, have been plotted against extracted and reinjected mass (see Figure 10). The pressure measured in well TR-10 in the reinjection zone is also plotted. The Berlín geothermal field was exploited at a low scale from 1992 to 1998. The production was around 5 MWe for the first 3 years and up to 8 MWe between 1995 and 1998, using the back pressure power plant with 10 MWe installed capacity. Under this low scale exploitation, 21 Mtons of fluid were extracted over 6 years, 16 of which were water. The water was reinjected mainly in two wells, TR-8 and TR-14 (Montalvo and Axelson, 2000).

The seismic moni-toring started in July 1996 and in the database there is a record of 143 events until December 1998 in the exploitation area (a record of 27 months, with an average of 5 seismic events per month), and 297 including the volcanic zone. In February 1999, exploitation was increased by a new

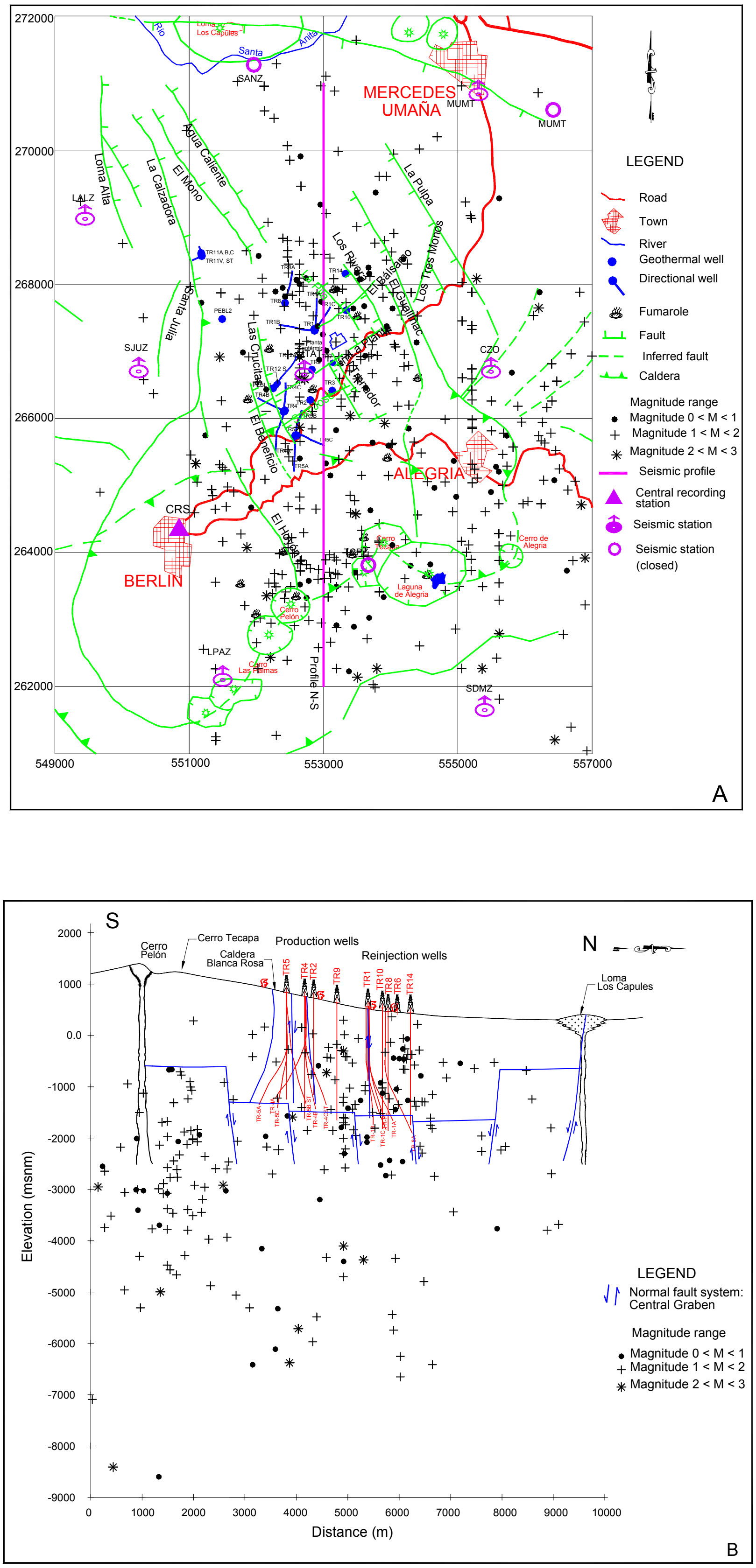


FIGURE 9: Seismicity in Berlín geothermal field and surrounding area; a) Epicentres' distribution map; b) N-S profile in coordinate 553,000 m, for the period July 1996 - June 2000

condensing power plant. More mass is being extracted and reinjected and the geothermal system has been disturbed on a much larger scale. During this period of time (February 1999 - June 2000), seismic activity decreased. During the operation of the new power plant (17 months), 45 micro-earthquakes occurred in the production-injection area (an average of 2 events per month), and 142 events including the volcanic zone. Figures 10a and 10b show the extracted and injected mass and the number of seismic events located in each area. The figures also show the pressure in the reinjection zone.

Figure 10 shows the seismic activity in relation to extracted and reinjected mass. The amount of extracted and reinjected mass stayed fairly constant until 1999. The production and injection increased gradually in 1999 and then sharply at the end of 1999. In this period, little changes were observed in the number of seismic events, and if any, then seismicity increased in the production area but decreased in the injection area, which is the opposite to what would be expected. No clear correlation is seen between seismicity and reservoir pressure change. Hence, the conclusion is that no obvious correlation is seen between the number of recorded seismic events and the rate of production and reinjection.

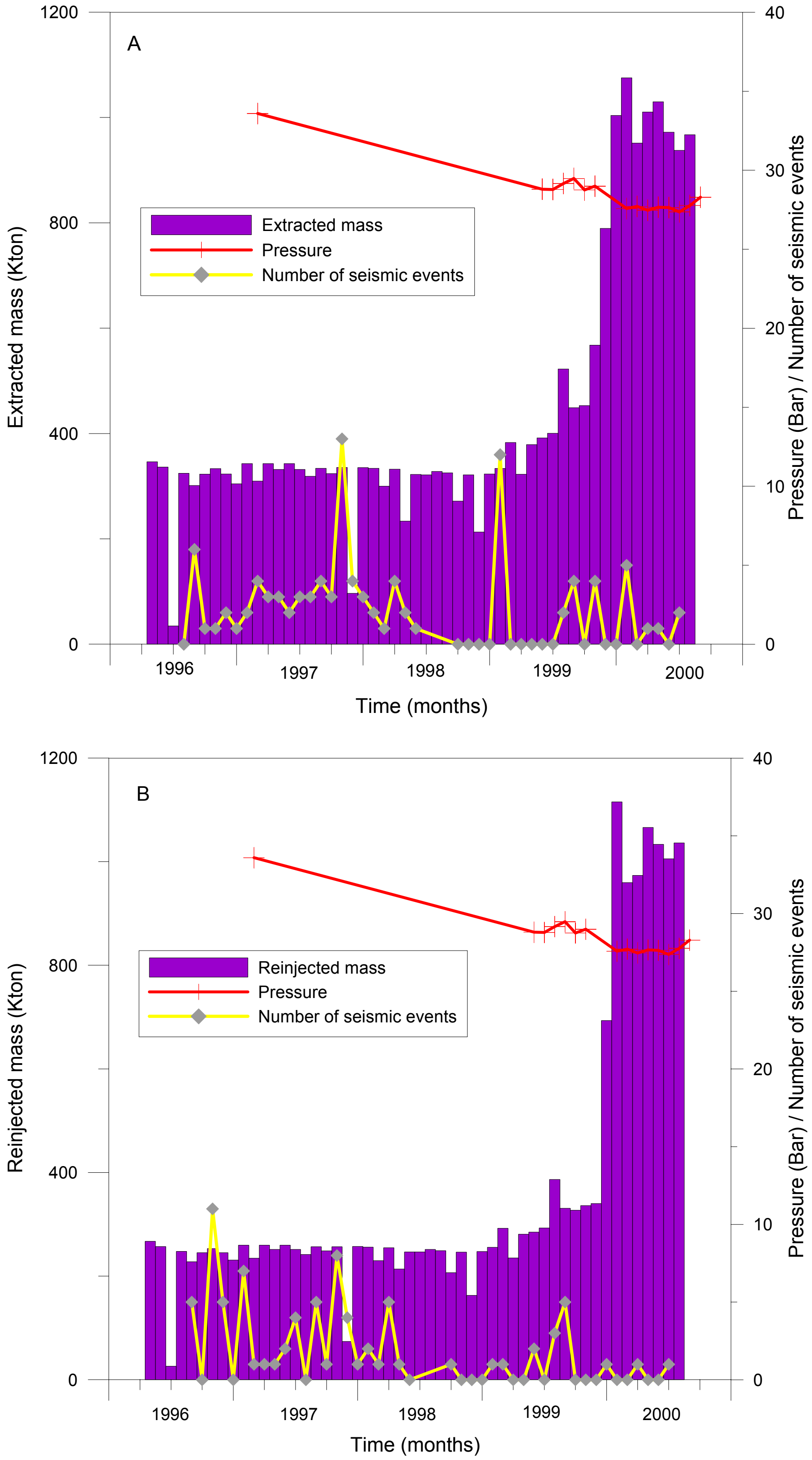


FIGURE 10: Comparison of number of seismic events with exploitation activities in the field; a) Seismic events in the production zone vs. extracted mass-pressure; b) Seismic events in the reinjection zone vs. reinjected mass-pressure

5.6 Frequency - magnitude relationship and Poisson´s ratio

5.6.1 Frequency - magnitude relationship: *b*-value

It has been shown experimentally that earthquake magnitude, M, is a random variable, with a cumulative distribution function, F.

For $M > 0$

$$F(M) = 1 - e^{-\beta M} \tag{2}$$

This distribution was first proposed by Omori in the late 1800's and later by Gutenberg and Richter (1954) in the form

$$Log_{10} N(M) = a - bM \tag{3}$$

where N = Number of earthquakes with magnitude greater than M;
a = The logarithm of the number of earthquakes with magnitude greater than zero; and
b = Slope of a fitted straight line to the logarithm of the number of earthquakes with magnitude higher than M.

The deviations from the straight line in this relationship are assigned to the lack of completeness in the series of earthquakes, that is to say, not all the earthquakes of a certain magnitude range were included. The constant b normally has a value between 0.6 and 1.5. (Udías and Mezcua, 1986). This parameter is related to the physical characteristics of the rocks in each region. A high value of b implies that small magnitude earthquakes are predominant, and therefore, the region has little resistance to stress. A low b-value means that earthquakes with greater magnitudes are predominant, indicating that the rocks can accumulate large stress.

In order to evaluate the stress level of the geothermal field and to have an idea of the rock's resistance to accumulate stress, the b-value was calculated for every seismic region, that is to say the production, the re-injection, the volcanic and the Lempa river areas. The b-value was calculated using the seismicity in four different periods of time (one year), with the objective of seeing the evolution over time. Finally, it was calculated using the whole period, which is more representative. Table 3 shows the results.

TABLE 3: The *b*-values for the four different zones; production, reinjection, volcanic and Lempa river zones

Period	Production area	Reinjection area	Volcanic area	Lempa river zone
199607-199705	2.09	1.15	1.61	0.7
199706-199803	1.15	1.81	1.67	1.84
199804-199901	1.28	1.81	1.06	1.1
199902-199912	1.19	1.88	1.66	0.93
199607-199912	**1.35**	**1.48**	**1.83**	**1.31**

Table 3 indicates that the obtained b-values vary considerably with time for all the four areas. It is, however, questionable whether these variations are real, because the number of seismic events per year is not high enough to allow a reliable determination of the b-value. The first period (199607-199705) seems to give somewhat anomalous values for the production, reinjection and Lempa river areas, as compared to the following years. Apart from these anomalies, the production area shows the lowest b-values and the reinjection area the highest ones. This could indicate that the production area can accumulate greater stress than the reinjection area, in agreement with that reduced pressure increases the strength of the rocks. Increased pore fluid pressure can cause the rocks to release stress more continuously and by smaller earthquakes in the reinjection area. The *b*-values for the volcanic area are in between those of the production and reinjection areas. The *b*-values obtained for the Lempa river area vary greatly and are therefore not conclusive.

In conclusion, the seismicity in the monitored area is relatively low. Earthquakes with magnitude lower than 3 are predominant and the values of *b* are larger than 1. The absence of earthquakes larger than magnitude 3 may be explained by the low stress state at the sources and by circulation of fluid in the fractures of the geothermal system and the Lempa river zone.

5.6.2 The ratio of P-wave and S-wave velocities and Poisson´s ratio

One of the critical aspects of a geothermal system is whether phase separation between water and steam has occurred. Phase separation is controlled by temperature, pressure, fluid saturation, and the composition of advecting fluids (Simiyu and Malin, 2000). Geothermal reservoirs are classified into fluid-dominated or vapour-dominated systems depending on whether phase separation has occurred or not. The ratio of P-wave and S-wave velocities (*Vp/Vs*) can indicate the saturation conditions in the reservoirs. The presence of a vapour phase, porosity, fractures, temperature, and rock type are parameters which control the velocity and attenuation of elastic waves passing through a geothermal reservoirs. Measurements of velocity and wave amplitude will, therefore, contain important information about the reservoir.

The velocity of the two types of body waves (P- and S-waves) are given by the following equations:

Compressional wave.

$$Vp = ((k + 4/3\,\mu)/\rho_w)^{1/2} \tag{4}$$

Shear wave.

$$Vs = (\mu/\rho_w)^{1/2} \tag{5}$$

where k = Bulk modulus;
μ = Shear modulus; and
ρ_w = Wet density.

These elastic parameters are related to the linear elastic deformation of an elastic body.

Poisson´s ratio can be expressed in terms of the elastic parameters and elastic velocities as

$$\sigma = (3k - 2\mu)/2(3k + \mu) = (Vp^2 - 2\,Vs^2)/2(Vp^2 - Vs^2) \tag{6}$$

Poisson´s ratio, σ, can therefore be expressed in terms of the ratio of the elastic-waves velocities (Goldstain, 1998)

$$\sigma = \frac{\gamma^2 - 2}{2(\gamma^2 - 1)} \tag{7}$$

where γ = *Vp/Vs*.

Typically, σ is in the range of 0.25 to 0.30 for normal saturated rocks. Anomalously low values of 0.15 were observed at Coso geothermal field area (Combs and Rotstein, 1975) and over the steam production area at Geysers (Majer and McEvilly, 1979). Abnormally high values of σ, around 0.4, have been observed over two geothermal reservoirs in the Salton trough, the East Mesa (McEvilly et al., 1978) and Cerro Prieto (Albores et al., 1980) reservoirs.

The effect of elevated temperature is to increase the compressibility, which will reduce the bulk modulus of the rocks, hence *Vp*, and consequently *Vp/Vs* and σ will be lower in areas of higher temperatures (Simiyu, pers. comm.).

The velocity ratio (*Vp/Vs*) increases from vapour-saturated (low pore-pressure) conditions to liquid-saturated (high pore-pressure) conditions (Ito et al., 1979). Studies of *Vp/Vs* ratio, carried out on several geothermal systems (McEvilly et al., 1978; Majer and McEvilly, 1979, Foulger et al., 1997, Julian et al., 1996, 1998), show that water-dominated systems such as in East Mesa, USA and Cerro Prieto, Mexico have high ratios, 1.55-1.68. These fields were also found to have low reservoir draw down during exploitation. Steam-dominated fields such as Geysers and Coso hot springs, USA have lower ratios, and high reservoir drawdown.

Similar studies were made in the Northeast field in Olkaria, which is a high-pressure liquid-dominated field, and the East production field, which is a relatively low-pressure steam-dominated field. The values of *Vp/Vs* reported in these studies vary from 1.58 in the East production field to 1.71 in the Northeast field. The very low ratio in the East production field is due to phase changes during production. The higher value in the Northeast field is due to the reservoir being liquid-dominated (Simiyu and Malin, 2000). The East production field has been exploited for 18 years, but a power plant is under construction in the Northeast field (C. Karingithi, pers. comm.).

The recorded seismicity was used to calculate the *Vp/Vs* and the Poission's ratio in the different areas within the Berlín geothermal system, and the Lempa river area to the northwest. The values of *Vp/Vs* and σ were calculated for similar periods as used in the determination of the *b*-value, with the objective of evaluating the changes over time, but in most cases the standard deviations turned out to be large because the number of seismic events used was too few. Therefore, only values for the whole recording period are given in Table 4.

TABLE 4: *Vp/Vs* and Poission's ration in the different areas in the Berlín geothermal field

	Vp/Vs	σ
Volcanic zone	1.74 ± 0.08	0.25
Production zone	1.76 ± 0.16	0.26
Reinjection zone	1.89 ± 0.04	0.31
Lempa river zone	1.85 ± 0.03	0.29

The difference in the values obtained for volcanic and production zones, is within uncertainties, but the lower value in the volcanic area could indicate presence of more steam than in the production area. Both values are high and both areas are predominantly liquid-saturated, in agreement with estimated enthalpy (1300-1400 kJ/kg) in the reservoir using well data. This enthalpy corresponds to 300˚C, similar to measured temperatures, which implies that the reservoir is in liquid phase but close to boiling (GESAL, 2000).

The reinjection area is less than 1 km from the production area. It seems that the injected water has influenced the area and reduced the S wave velocity (*Vs*), resulting in higher values of *Vp/Vs* and σ. The *Vp/Vs* value in the reinjection area seem to be a little higher than in the Lempa river zone. A possible explanation for this could be that the waste water is injected at depth in the wells, but in the Lempa river area, the infiltration is from the surface. In conclusion, the *Vp/Vs* ratios indicate the presence of some steam phase in the production and volcanic areas, but no conclusive evidence is found for increased steam fraction due to exploitation.

6. SEISMIC MONITORING AS AN EXPLORATION TOOL

Several surveys have been carried out in Berlín geothermal field in order to determine its size and the boundaries of the reservoir. The results of geological, geochemical and geophysical surveys as well as data from drilled wells contributed to the development of the field for economical exploitation. Several geophysical methods, such as different DC-resistivity methods, MT and gravity measurements were used for exploring the geothermal field. Seismic monitoring started in 1996 and its database has been used for both monitoring and exploration. The seismic spatial distribution shows numerous micro-earthquakes concentrated in the centre of the geothermal field, close to the wells, and in the volcanic chain where the temperature is high. Outside the field where the temperature is lower, some few seismic events were observed. In the lower temperature area, the events are of higher magnitude and are deeper. This implies that the number of earthquakes and their magnitude vary with rock temperature. This observation could be used to estimate reservoir boundaries and reservoir size in advance of drilling (Simiyu and Malin, 2000).

6.1 Seismicity and Schlumberger soundings

Schlumberger soundings have revealed a resistive anomaly which has a good correlation with thermal alteration, and the formation temperature derived from temperature logs (Santos, 1995). Figure 11a shows the topography and epicentre distribution of the local seismicity. The seismicity in the lower part is in Lempa river zone. The concentration of epicentres at intermediate elevation is located in the production and reinjection areas. The highest temperatures were found in this area. The epicentres at the higher elevation are in Berlín-Tecapa volcanic complex.

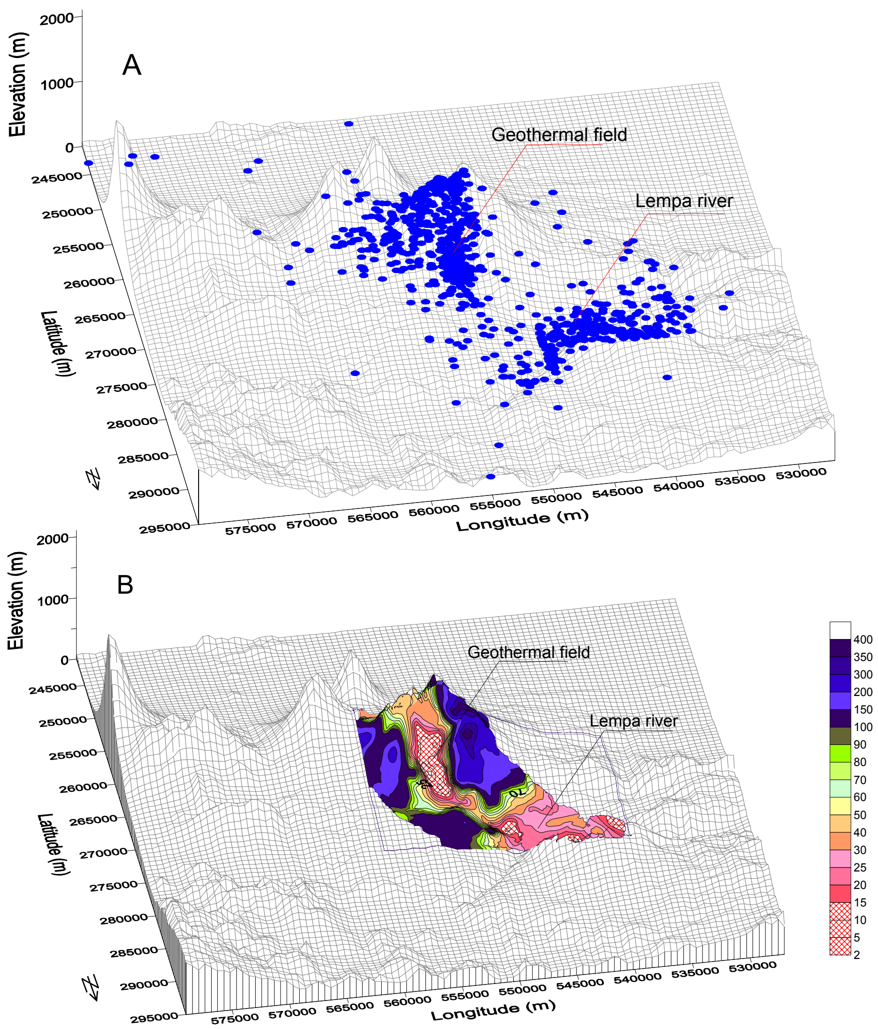


FIGURE 11: Comparison of seismicity and resistivity revealed by Schlumberger soundings; a) Seismicity distribution; b) Apparent resistivity map for AB/2 = 1000 m

The area defined by apparent resistivity values lower than 15 ohm-m coincides very well with the seismicity at intermediate elevation. The seismicity in the volcanic area is in a zone with higher values of resistivity, between 15 and 50 ohm-m. Only a few seismic events were observed in areas where the resistivity is larger than 50 ohm-m. Both resistivity and seismicity show a good correlation with hydrothermal alteration and temperature.

Figure 12a shows a N-S seismicity profile. Earthquakes located within 1 km of the profile have been projected onto the section. Figure 12b shows a N-S resistivity cross-section based on Schlumberger

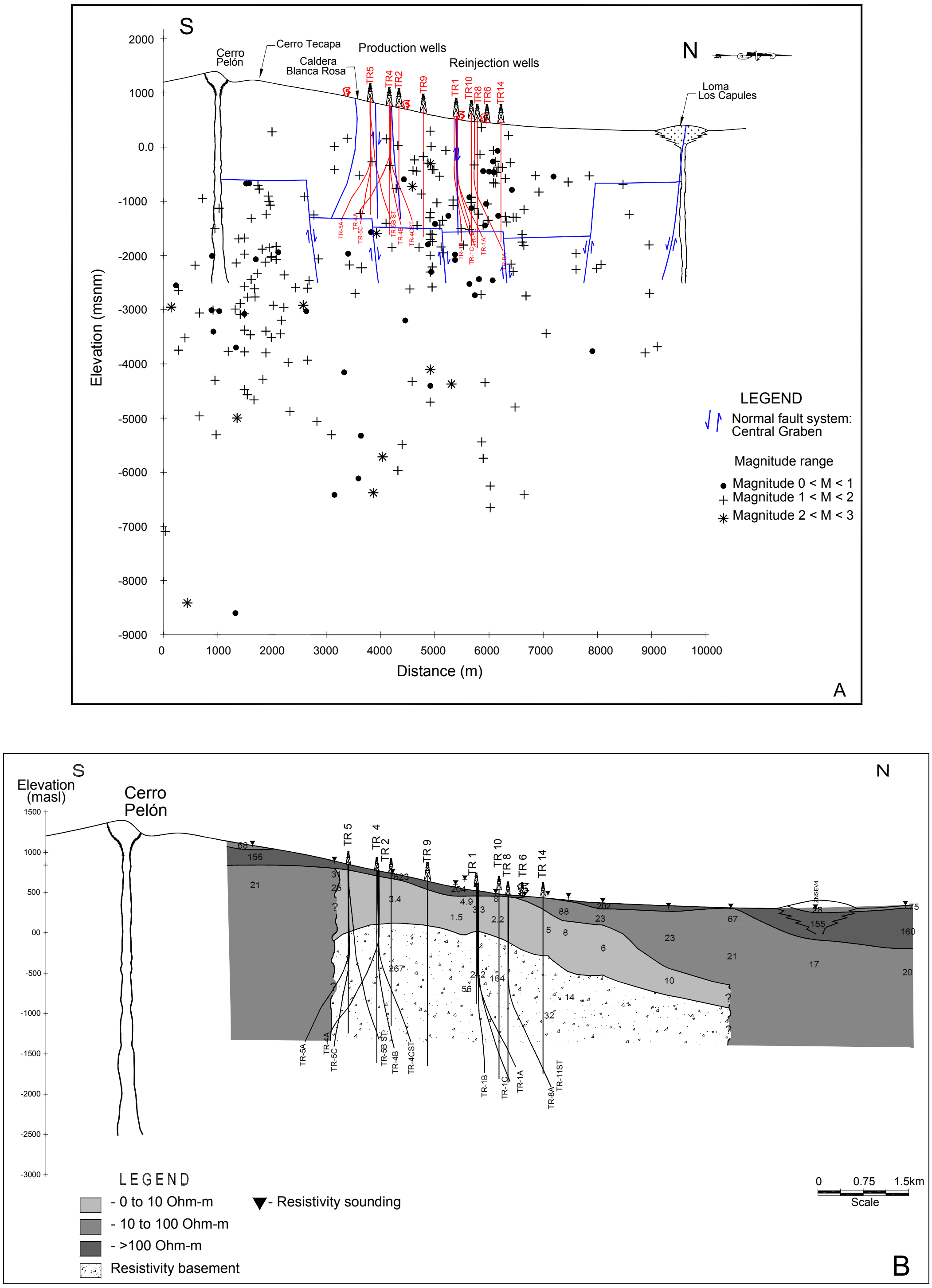


FIGURE 12: Seismicity and resistivity N-S profiles in the Berlín geothermal field; a) Distribution of hypocentres; b) Resistivity cross-section

soundings. Both seismicity and resistivity profiles run along the Lambert coordinate 553,000 longitude, starting in the volcanic area, passing through production wells (TR-5s, TR-4s, TR-2 and TR-9) and reinjection wells (TR-1s, TR-10, Tr-8s and TR-14) and extend to the limit of the Central American graben in the north.

The profiles of Figure 12 show that there is a cluster of events close to the production and reinjection wells. Some shallow events are distributed in the area with low resistivity values (< 15 ohm-m). Most of the events (from –500 to –2500 m) are located in the highly resistive core underlying the conductive layer. The resistive core delineates the high-temperature reservoir with temperatures exceeding 230˚C (Santos, 1995). It is noteworthy that there are more hypocentres concentrated in the reinjection area. This might indicate that some of these events were triggered by increasing pore pressure at depth.

Studies carried out in different geothermal fields affirm that clustering of microseismicity around the production and injection wells is characteristic of induced or triggered seismicity (Fabriol et al., 1997, in Berlín, El Salvador; Romero et al., 1994, Fabriol and Munguía, 1997). The cause of these microearthquakes is commonly ascribed to pressure changes causing fracturing and fracture movement in response to geothermal production and reinjection (PB Power, GENZL Division, 2000).

The seismicity in the southern part of the profile (left) is within the volcanic complex. The hypocentres are located between -700 and -5500 m a.s.l., deepening to the north, towards the production area. The seismicity in the volcanic chain can be interpreted as an effect of a transition from a brittle (pressure-controlled) seismogenic zone to a ductile (temperature-controlled) zone (Kohlstedt et al., 1995). Earthquakes are generally restricted to a zone of brittle deformation and the maximum depth of seismicity delineates the brittle-ductile transition zone (Meissner and Strehlau, 1982). The depth limit of earthquake activity is, therefore, related to temperature. The lower seismic boundary (the brittle-ductile transition) can, therefore, be an indicator of the existence of the heat source, as suggested for other geothermal fields, such as Cerro Prieto, Mexico (Lippmann et al., 1997).

6.2 Seismicity and head-on resistivity profiles

Some alignments of seismic events have been observed, which can be related to faults in the geothermal field visible at the surface. For some alignments of the epicentres, there is no surface evidence of faults. In order to investigate the possible existence or extension of known faults, the head-on method was applied. This method is used to detect faults and about 60% of the known faults in the Berlín geothermal field were identified with this method (Santos and Rivas, 1999).

Figure 13 shows the seismicity, head-on resistivity profiles and inferred faults. The figure shows that the epicentres are centred in a tectonic arc from south to north, from the volcanic area and limited to the west and east by the caldera limits. Seismicity is abundant in the volcanic area and is related to the heat source of the system. The assumed upflow zone at the northern flank of the volcanic complex has less seismicity. In the production area between latitudes 265,000 and 267,000 m, events are dispersed but appear more abundant in the east and southeast of the production wells. Two head-on profiles (HO1 and HO2) were carried out in this area and they showed that the area is highly fractured. Both seismicity and head-on profiles indicate a highly fractured zone in this area, which could be a promising target for future development.

The reinjection zone is between latitudes 267000 and 268250 m. In this area the epicentres look more concentrated, and there are alignments of seismicity which follow the direction of some faults. It seems like the earthquakes are associated with injected fluids moving in the graben formed by the La Pila and Los Rivera faults, from TR-8 and TR-14 wells which have the highest injection capacities. These two faults have NW-SE direction and a cluster of epicentres is located along this direction, indicating the extension of these faults. There is no surface evidence indicating that these faults continue to the

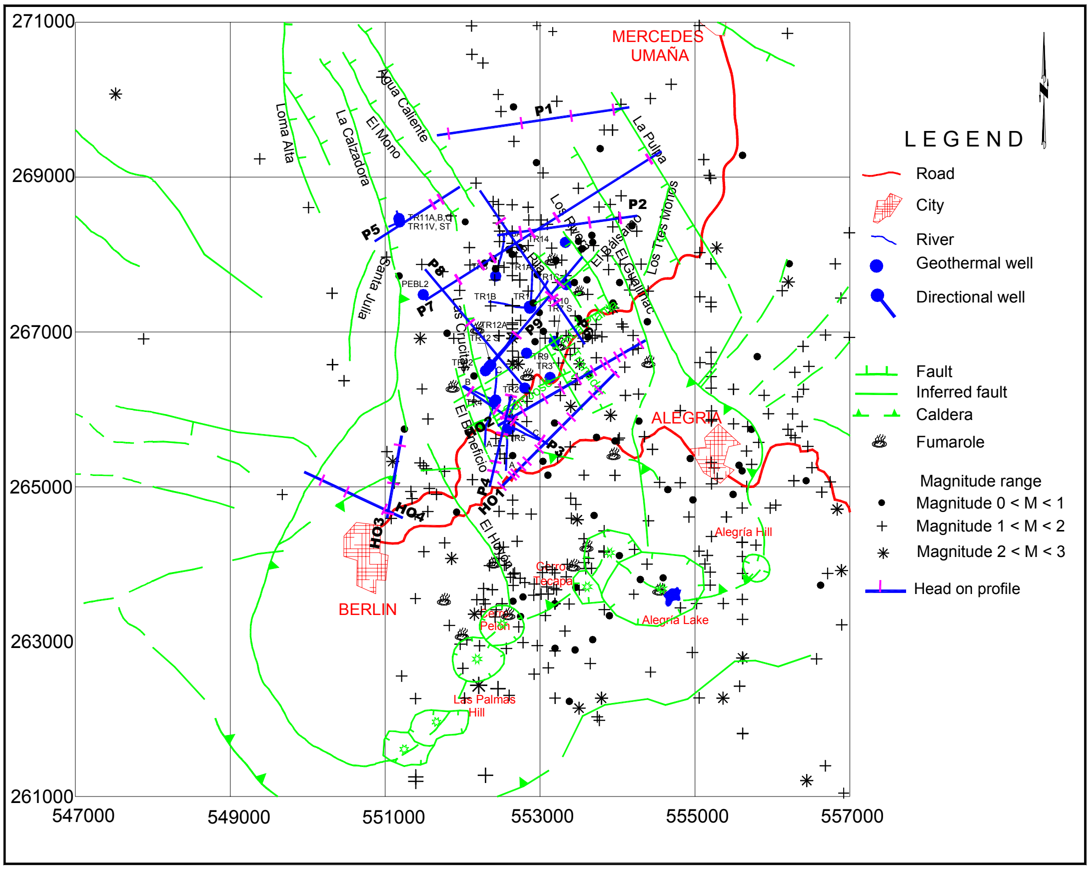


FIGURE 13: Seismicity and inferred faults from head-on profiles in the Berlín geothermal field; hyphens over the profile lines relate to possible faults

northwest and southeast, but head-on profiles indicate that this is the case. According to that, it is expected that the cluster of events will extend to the northwest in the future. It is also possible that part of the injected fluid is going to the southeast through the faults mentioned above and will help maintaining pressure in the reservoir.

There are no seismic events related to the faults located in the area north of the reinjection zone, such as the Agua Caliente, El Mono and La Calzadora faults. Possibly, this is because the faults there are sealed. This is further indicated by some wells drilled there (TR-11s), showing low permeability. There is, however, a trend of epicentres in the direction of the Guallinac fault. Head on resistivity profiles indicate structures that might be the extensions of the Los Rivera, Guallinac and La Pulpa faults. In this area, faults dip to the southwest and this alignment of epicentres is most likely related to an extension of the Guallinac fault. This alignment of epicentres may indicate a good choice for future injection wells.

In conclusion, the results of seismology and electrical resistivity (Schlumberger and head-on) give anomalies which are related to elevated temperature, hydrothermal alteration and the main structures of the geothermal system. Similar results have been found using gravity and MT surveys.

The geophysical methods applied in the Berlín geothermal field defined its main structural features. The seismicity is confined to these structures, helping to define the boundaries of the geothermal system and identifying which faults are the main flow paths of the geothermal fluids.

7. FUTURE DEVELOPMENT

As Geotérmica Salvadoreña has planned for developing new prospects (e.g. Cuyanausul and Obrajuelo), it is important that the seismic monitoring of these areas begins while the areas are still in their natural state. The network installed in the Berlín geothermal field could monitor the Obrajuelo area, located in the vicinity of Lempa river, by implementing some small changes or extending the network using one or two stations more. The Cuyanausul, is located to the east of the Ahuachapan-Chipilapa geothermal field. It is possible to monitor Cuyanausul with the same seismic network planned for monitoring the production-reinjection activities in Ahuachapan-Chipilapa area. Both networks can work independently but the data can then be integrated in the same database and processing system.

It is necessary to carry out experiments for detecting induced seismicity related with production and reinjection activities. For this purpose, seismic stations should be installed closer to these areas, during the testing period. This experiment would confirm if induced seismicity occurs and under which conditions it is triggered.

8. CONCLUSIONS AND RECOMMENDATIONS

The main results of this study and the installation of a seismic network in Berlín geothermal field may be summarized as follow:

- The recorded local seismicity is basically concentrated in two areas, Lempa river zone and Berlín geothermal field and its surrounding areas. Both seismic zones are located in the E-W tectonic structure of El Salvador named the Central American graben, formed by the subduction process. The depth of the local seismicity is less than 25 km in Lempa river zone and less than 10 km in the geothermal area. The magnitudes are lower than 3 on the scale based on signal duration.

- The seismic distribution in the Lempa river zone corresponds to a fault with a small dip to the northwest. This small dip can explain the seismic gap observed between the two seismic areas. The fault runs NE-SW, almost parallel to the river. The seismicity is unevenly distributed in time with some periods of high seismic levels per month which seems to be a normal pattern in the area.

- Both mass extraction and reinjection in the Berlín field increased progressively from February to November 1999 and at the same time, seismicity decreased. Comparison of the temporal evolution of the seismicity, extracted and reinjected mass, and pressure in reinjection well TR-10 does not show, apart from a general decline of seismicity, any detailed correlation with exploitation. In the structures close to the reinjection zone there are, however, events that could have been triggered by increased pore pressure and stress regime change in this area. This could indicate the direction of the motion of fluids.

- The absence of earthquakes larger than magnitude 3, and high *b*-values, may be explained by low stress state of the source and by the circulation of fluid in the fractures of the geothermal reservoir and the Lempa river zone. Therefore, it is expected that many seismic events with low magnitude may occur in the region every year.

- The high *Vp/Vs* values and Poisson´s ratios indicate that the low-scale exploitation in the Berlín geothermal field during the first six years and the increased exploitation in the last year have not substantially affected the phase separation of the reservoir. The lower *Vp/Vs* value in the volcanic area might be explained by higher temperatures and by some steam fraction in the pore spaces.

- The spatial distribution of epicentres identified the most active areas in and around the geothermal system. The seismic network determined the seismicity prior to large-scale exploitation, and contributed to a better definition of the reservoir, its boundaries and heat source. Seismicity can possibly be used to estimate the top of the heat source, below the deepest seismicity at -7000 m a.s.l. The seismic distribution shows a very good correlation with higher temperatures and low resistivity in the southernmost part of the area.

- Relocation of recorded seismic events by the program SEISAN basically gives the same results as obtained by the program SWS, except for some clusters in areas where the network does not have the capability to give good accuracy, such as to the south of Lempa river and Santiago de Maria area.

- Aligned seismic events to the north of the reinjection wells, where the temperature and the permeability are low, could be related to the extension of Los Rivera or Guallinac faults. This alignment of epicentres and the possible extension of these faults may indicate that permeability is higher in this direction and that it can be a good choice for future injection wells.

- The magnitudes of the seismic activity in the Berlín geothermal field have been low due to low accumulation of tectonic stress in the rocks. The seismicity in the Berlín area is, therefore, not of great environmental concern and poses little threat to the community. There is, nevertheless, a good reason for continuous network operations, both for monitoring of the geothermal system and for public safety.

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REFERENCES

Albores, A., Reyes, A., Brune, J.N., Gonzalez, J., Garcilazo, L., and Suaraz, F., 1980: Seismicity studies in the region of the Cerro Prieto geothermal field. *Geothermics, 9 -1/2*, 5-77.

Allis, R.G., 1987: *Induced seismicity due to geothermal exploitation*. Notes for N.Z.-M.F.A. Geothermal Seminar in Indonesia - Feb. 1987, D.S.I.R., Geophysics division, Wairakei, N.Z.

Allis, R.G., Currie, S.A., Leaver, J.D., and Sherburn, S., 1985: Results of injection testing at Wairakei geothermal field, New Zealand. *International Symposium on Geothermal Energy, Geoth. Res. Council, Transactions, Internat. Vol.,* 289-294

Ambraseys, N.N., and Adams, R.D., 1996: Large central american earthquakes 1898-1994. *Geophys. J. Int., 127*, 665-692.

Batini, F., Bufe, C., Cameli, G.M., Console, R., and Fiordelisi, A., 1980: Seismic monitoring in Italian geothermal areas I and II. *Proceedings of the 2nd DOE-ENEL Workshop for Cooperative Research in Geothermal Energy*, 20-85.

Batini, F., Console, R., and Luongo, G., 1985: Seismological study of Larderello-Travale geothermal area. *Geothermics, 14,* 255-272.

Bommer, J.J., Udías, A., Cepeda, J.M., Hasbún, J.C., Salazar, W.M., Suarez, A., Ambraseys, N.N., Buforn, E., Cortina, J., Madariaga, R., Mendez, P., Mezcua, J., and Papastamatiou, D., 1997: A new digital accelerograph network for El Salvador. *Seismolog. Res. Letters, Seismolog. Soc.Am.*, *68-3*, 426-437.

Bromley, C.J., Pearson, C.F and Rigor, D.M., 1985: *Induced seismicity at Southern Negros, geothermal field, Philippines*. Abstract for Symposium of N.Z. Geophysical Society,Wellington, N.Z.

Combs, J., and Rotstein, Y., 1975: Microearthquake studies at the Coso geothermal area, China Lake, California *Proceedings of the 2nd U.N. Symposium on the Development and Use of Geothermal Resources*, *San Francisco, 2,* 909-916.

Dewey, J.W., and Suarez, G., 1991: Seismotectonics of Middle America. In: Slemmons et al. (eds.). *Neotectonics of North America*. Geological Society of America, Decade Map, I, 309-321.

ELC, 1993: *Resource evaluation of Berlín geothermal field, final version*. Electroconsult, internal report CGB-2-ELC-R-11994, submitted to CEL (in Spanish).

Fabriol, H., and Beauce, A., 1997: Temporal and spatial distribution of local seismicity in the Chipilapa-Ahuachapán geothermal area, El Salvador. *Geothermics, 26-5/6*, 681-699.

Fabriol, H., and Munguía, L., 1997: Seismic activity at the Cerro Prieto geothermal area (Mexico), from August 1994 to December 1995, and its relationship with tectonics and fluid exploitation. *Geophys. Res. Lett.*, *24-14*, 1807-1810.

Fabriol, H., Rivas, J.A., Handal, S., and Correia, H., 1997: *Microseismicity and geothermal exploitation: The case of Berlín (El Salvador*). CEL, unpublished report, 12 pp.

Foulger, G.R., Grant, C.C., Ross, A., and Julian, B.R., 1997: Industrially induced changes in earth structure at the Geysers geothermal area, California. *Geophys. Res. Lett., 24-2*, 135-137.

GENZL, 1995: *The Berlín geothermal field, geoscientific studies*; *Part 6, integrated report*. Geothermal Energy New Zealand Ltd., report submitted to CEL (In Spanish), 29 pp.

GESAL, 2000: *Updated conceptual model of the Berlín geothermal field*. Gerencia de Proyectos, internal report (in Spanish), 19 pp.

Goldstain, N.E., 1988: Subregional and detailed exploration for geothermal-hydrothermal resources. *Geotherm. Sci. & Tech., 1*, 303-431.

Gutenberg, B., and Richter, C.F., 1954: *Seismicity of the earth and associated phenomena.* Princeton University Press, Princeton.

Havskov, J., and Ottemöller, Lars, 1999: *SEISAN: The earthquake analysis software.* Institute of Solid

Earth Physics, University of Bergen, Norway.

Ito H., DeVibris, J., and Nur A., 1979: Compressional and shear waves in saturated rock during water-stream transition. *J. Geophys. Res.*, *84*, 4731-4735.

Julian, B.R., Pitt, A.R., and Foulger, G.R., 1998: Seismic image of a CO_2 reservoir beneath a seismically active volcano. *Geophys. J. Int., 133,* F7-F10.

Julian, B.R., Ross, A., Foulger, G.R., and Evans, J.R., 1996: Three-dimensional seismic image of a geothermal reservoir. *Geophys. J. Int., 23*-6, 686-688.

Kohlstedt, D.L., Evans B., and Blackwell, S.J., 1995: Strength of the lithosphere: Constraints imposed by laboratory experiments. *J. Geophys. Res., 100 -B9,* 17587-17602.

Lahr, J.C., 1997: *HYPOLLIPSE/Version 3.0. A computer program for determining local earthquake hypocentral parameters, magnitude and first motion pattern.* U.S. Geological Survey Open file report, 99 pp.

Lee, W.H.K., and Lahr, J.C., 1975: *HYPO71 (revised): A computer program for determining hypocenter, magnitude and first motion pattern of local earthquakes*. U.S. Geolological Survey, Open file report, 75-3N, 113 pp.

Lippmann, M.J., Truesdell, A.H., and Gutierrez H., 1997: What will a 6 km deep well at Cerro Prieto find? *Proceedings of the 21st. Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, Ca,* 19-28.

Majer, E.L., and McEvilly, T.V., 1979: Seismological investigations at The Geysers geothermal field. *Geophysics*, *44*, 246-269.

McEvilly, T.V., Schechter, B., and Majer, E.L, 1978: *East Mesa seismic study.* Annual Report, Earth Science Division, Lawrence Berkeley Laboratory. University of California, 26-28.

Meissner, R., and Strehlau, J., 1982: Limits of stress in the continental crust and their relation to depth-frequency distribution of shallow earthquakes. *Tectonics*, *1,* 73-89.

Montalvo, F., and Axelsson, G., 2000: Assessment of chemical and physical reservoir parameters during six years of production-reinjection at Berlín geothermal field (El Salvador). *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan*, 2153-2158.

Monterrosa V., M.E., 1993: *A 3-D natural state modeling and reservoir assessment for the Berlín geothermal field in El Salvador, C.A.* UNU G.T.P., Iceland, report 11, 45 pp.

Monterrosa V., M.E., 1998: Present status of geothermal development in El Salvador and contribution of UNU Fellows in the geothermal scenario and management. In: Georgsson, L.S. (ed), *Geothermal Training in Iceland, 20th Anniversary Workshop 1998*, UNU G.T.P., Iceland, 21-28.

PB Power, GENZL Division, 2000: *Berlín geothermal field, MT-reinterpretation and resource assessment.* Geothermal Energy New Zealand Ltd., report submitted to Geotérmica Salvadoreña S.A. de C.V., 63 pp.

Rivas, J.A., 1996: *Seismic telemetry network of the Berlín geothermal field.* Gerencia de Recursos Geotérmicos, Comisión Ejecutiva Hidroeléctrica del Río Lempa (CEL), internal report (in Spanish), 27 pp.

Romero, A.E., Kirkpatrick, A., Majer, E.L., and Peterson, J.E., 1994: Seismic monitoring at The Geysers geothermal field. *Geoth. Resourc. Council, Trans.*, *18*, 331-338.

Santos, P.A., 1995: One- and two-dimensional interpretation of DC-resistivity data from the Berlín geothermal field, El Salvador. Report 11 in *Geothermal Training in Iceland*. UNU G. T. P., Iceland, 269-302.

Santos, P.A., and Rivas, J.A., 1999: *Geophysical methods applied in the detection of faults in the Berlín geothermal field* (in Spanish). Presented at the Geophysical Seminar, IPGH-CIG (MOP), El Salvador, 9 pp.

Sherburn, S., 1984: Seismic monitoring during a cold water injection experiment, Wairakei geothermal field. Preliminary results. *Proceeding of the 6th New Zealand.Geothermal Workshop*, *Geothermal Institute, Auckland, N.Z.,* 129-134.

Simiyu, S.M., and Malin, P.E., 2000: A "volcanoseismic" approach to geothermal exploration and reservoir monitoring: Olkaria, Kenya and Casa Diablo, USA. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan,* 1759-1763.

Torres, R.E, Escobar, C.D., and Hernández, D.A., 1999: *Seismic Activity in San Vicente between March and April 1999* (in Spanish). Departamento de Investigaciones Sismológicas, Centro de Investigaciones Geotécnicas, Ministerio de Obras Públicas, Internet page: (http://www.geotecnico.com/Sismologia/1vicentedoc.htm).

Udías A., and Mezcua, J., 1986: *Fundamentals of geophysics* (1st edtion. in Spanish). Alhambra, S.A. Madrid, Spain, 419 pp.

White, R.A., 1991: Tectonic implications of upper-crustal seismicity in Central America. In: Slemmons et al. (eds.), *Neotectonics of North America*. Geological Society of America, Decade Map, I, 323-338.

APPENDIX I: Annual seismicity distribution and profiles from July 1996 to June 2000

Profiles were drawn at coordinate 553,000 m longitude, and the epicentres located 1 km on each side of the profile are included.

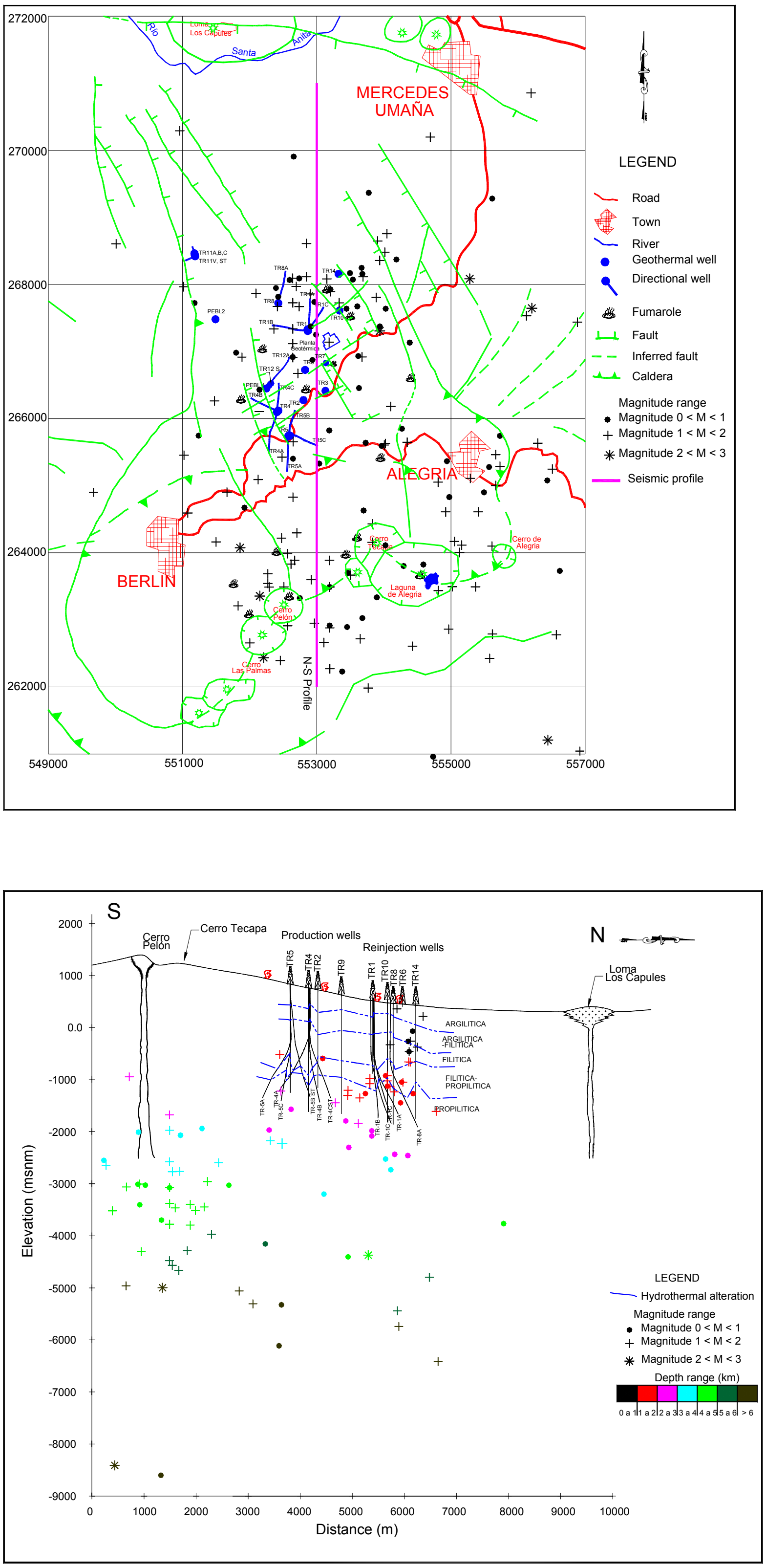


FIGURE 1: Map of seismicity and seismicity profile during July/96 - June/97

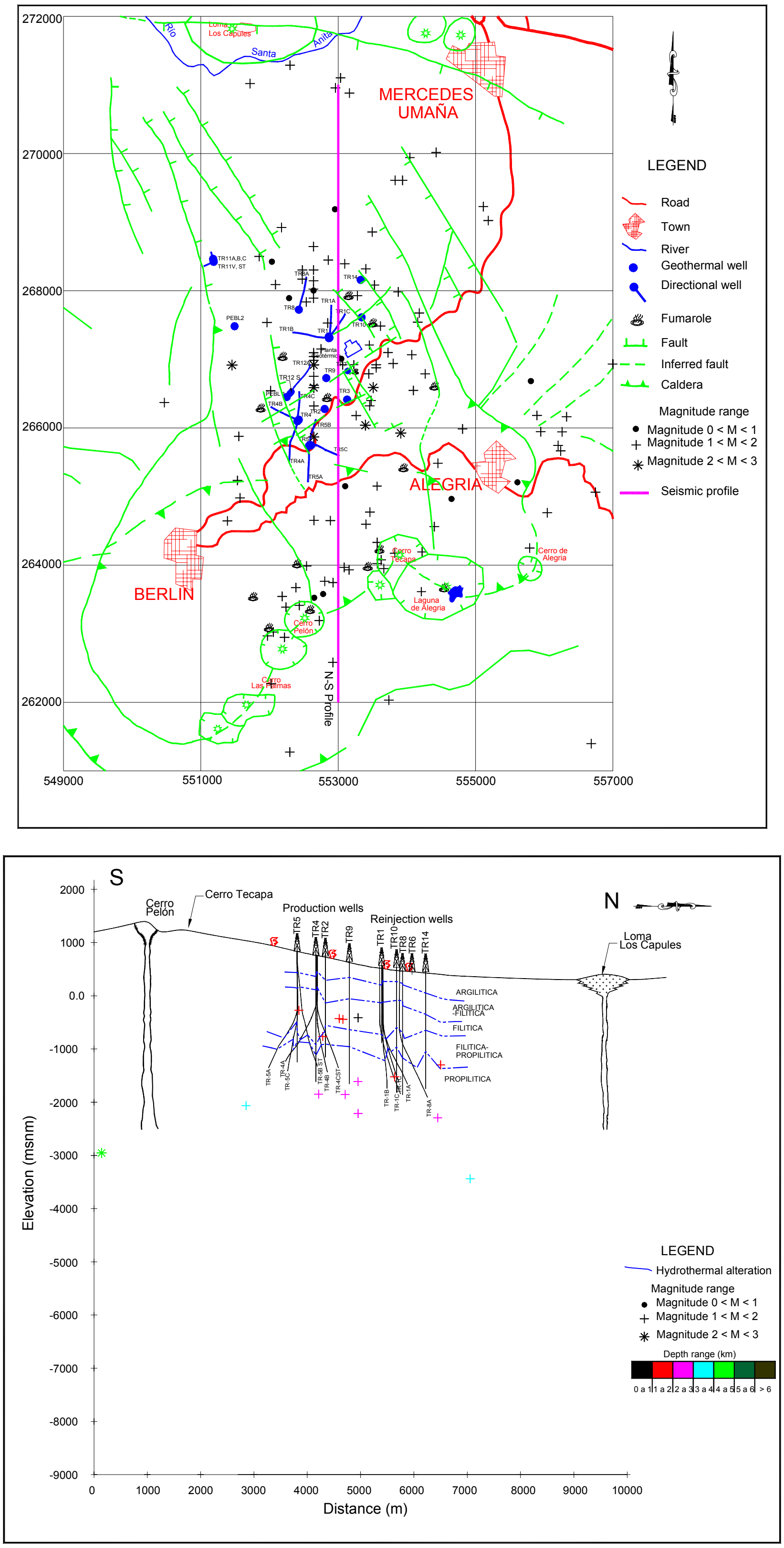
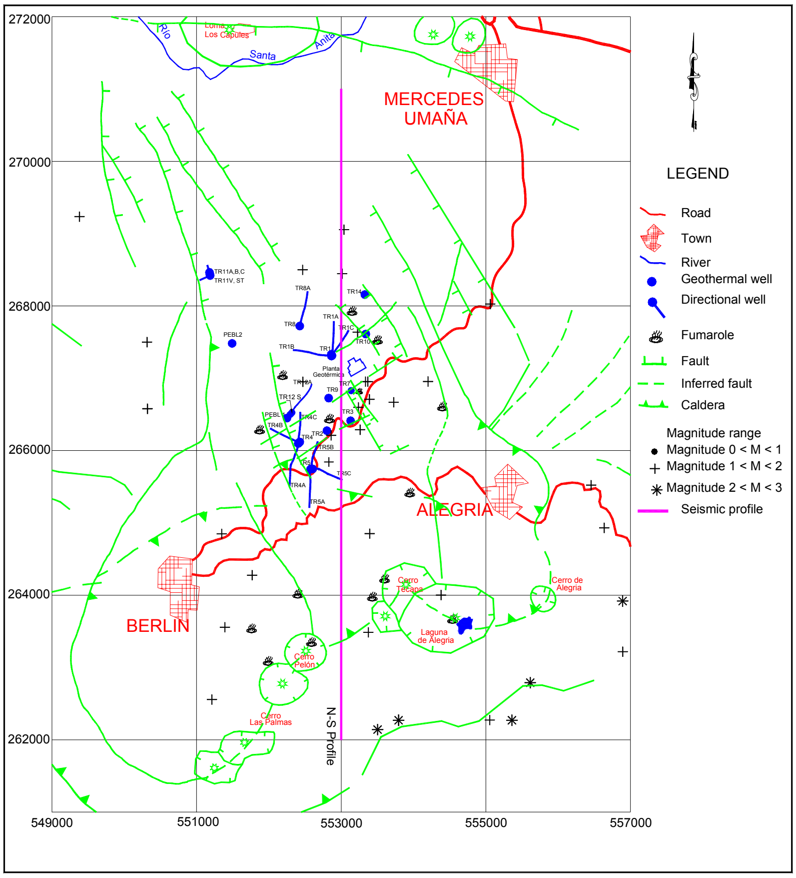


FIGURE 2: Map of seismicity and seismicity profile during July/97 - June/98



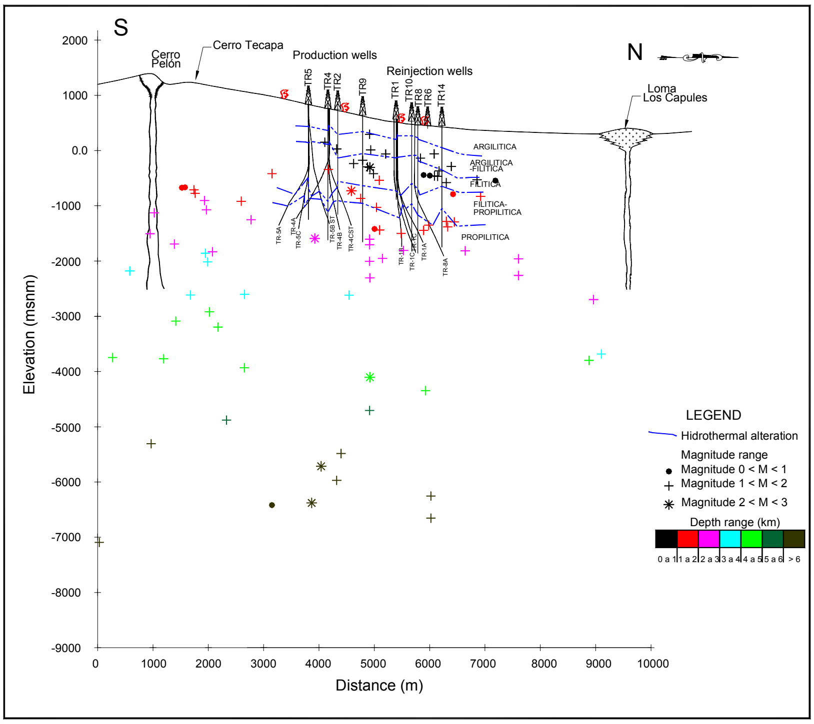
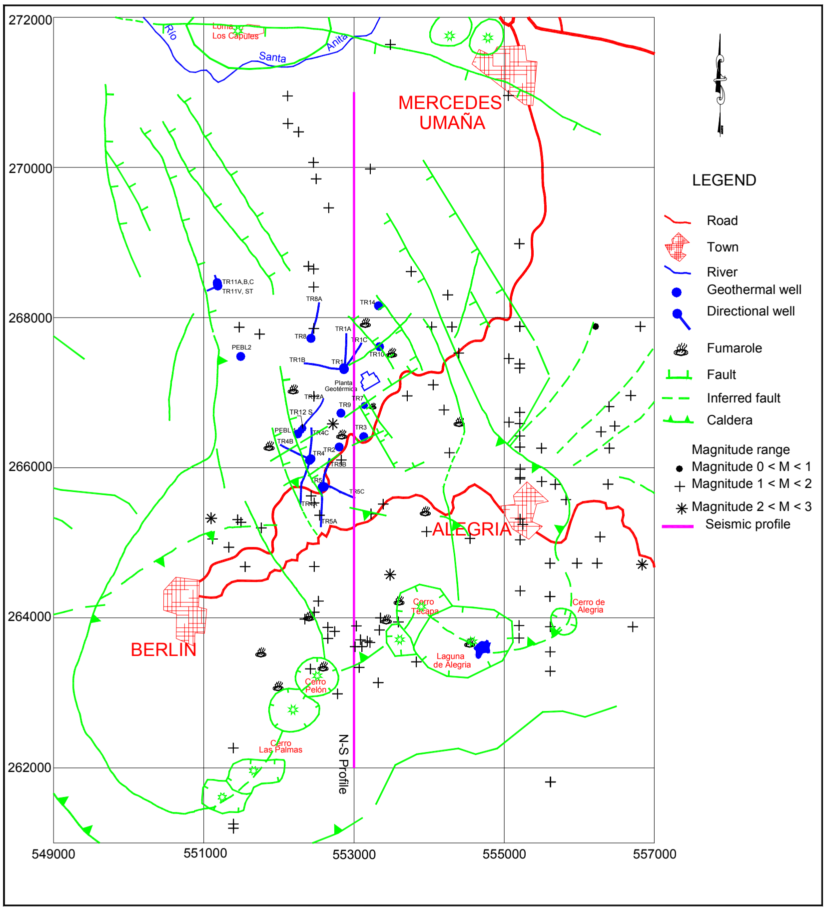


FIGURE 3: Seismicity map and seismicity profile during July/98 - June/99; during July/98 – June /99 the network was not operating for three months



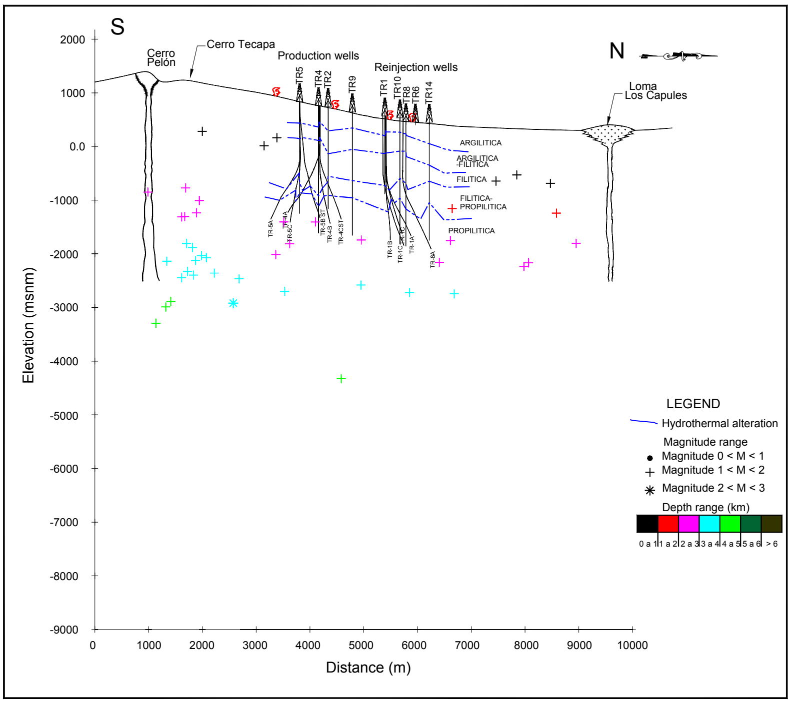


FIGURE 4: Seismicity map and seismicity profile during July/99 - June/00