TELEMETERED MICROSEISMIC STUDY
OF THE GREATER TONGONAN GEOTHERMAL FIELD

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Abstract

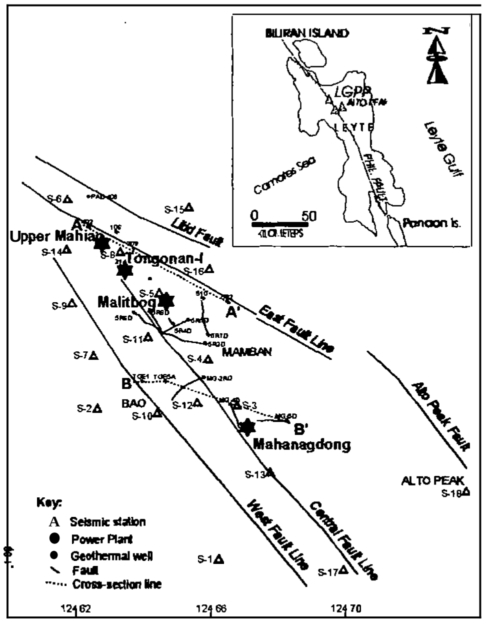
A microearthquake telemetry monitoring network was installed in Tongonan geothermal field and operated from February, 1996 to July, 1997 to detect and locate small earthquakes occurring in the area. In the 18 month period, more than six hundred fifty events were detected. The hypocentral depths ranged from <1 km to 12 km with over 40 % deeper than 5 km. The present study confirms the results of earlier microearthquake studies, that seismicity of the area is relatively high and believe to be tectonic events related to the Philippine Fault. It also showed that induced seismic occurred during initial injection at wells 5R3D/5R5D/5R7D and MG-2RD while conducting Malitbog power plant test and hydraulic fracturing of MG-2RD.

A three-dimensional velocity structure was obtained from local earthquake tomography. A low velocity zone, generally oriented in NW-SE direction coincide with the structural trends on the surface. At 1.5 km depth, the low velocity zones coincide with the hot fluids upwelling at Mahiao and outflowing at -1000 msl along the unconformable contact of Mahiao Sedimentary Complex (MSC) and Mamban Formation (MF). Remarkably, the high velocity zones correlate very well with the impermeable pre-Tertiary serpentinitic basement rocks and Mahanagdong Claystone.

Fault plane solutions were obtained for 89 events. Based on FPS, the most frequent focal mechanisms are of two types: strike-slip (left lateral) and dip-slip (normal faulting) mechanisms with strike oriented N46°W. The strike of the source fault plane follows the average trend of the major faults which are principally left lateral strike-slip faults and which are aligned sub-parallel to the general trend of the Philippine Fault.

1.0 Introduction

A telemetered microearthquake monitoring network was installed in the Greater Tongonan geothermal field (GTGF) and operated from February, 1996 to July, 1997 to detect and locate small earthquakes occurring in the area. The network consisted of eighteen stations, five out of which are three component sensors and the remaining are single vertical component sensors (Fig. 1). Eleven of the stations were installed from October to November, 1996 and from June to July, 1997 to enlarge the data base on the area's seismicity. The enhanced microearthquake monitoring system was established in preparation for the commissioning of several power plants which might increase the local seismicity as a result of massive fluid extraction and injection. In addition, a hydraulic fracturing experiment in MG-2RD was programmed which necessitated careful seismic monitoring to track the



network were vertical component seismometer, seismometer amplifier , transmitter , an accurate clock , and 12V car battery. The output signal from the seismometer was conditioned and amplified at the field station and converted for telemetry transmission to the central recording station. Data from the 13 remote stations were telemetered directly to the central recording station located at the Geoscientific Building and were stored and recorded in digital audio- tape. The network was terminated in the mid- July, 1997 after the completion of hydraulic fracturing experiment.

2.0 Seismotectonic and Geothermal Setting

The Greater Tongonan Geothermal Field is situated in north central Leyte where the Philippine Fault passes and bifurcates into several branches (Fig. 1). On the basis of field observations and radiometric dating, (Aurelio 1993) proposed an average velocity of 20 mm/yr for the Philippine Fault in northern Leyte. Repeat geodetic measurements using a dense (GPS) network in northern Leyte indicated a non-tectonic ***(creep)*** displacement of 2-3 cm/yr along the fault (Duquesnoy, 1997).

Two separate hydrothermal systems occurred in the GTGF. The Mahiao system upwells in the Upper Mahiao sector around wells 101/106 with **maximum** reservoir temperature of 320°C (Delfin *et* al. 1995). The system outflows largely to the southeast with production coming mainly from the Mahiao Sedimentary Complex-Mamban Formation unconformity (Fig. 2a). The Mamban block separates the Mahiao from the Mahanagdong system. The latter is centered in **MG-3D/MG-.4D** (Fig. 2b), with reservoir temperature of 310°C and permeability controlled largely by faults and fractures.

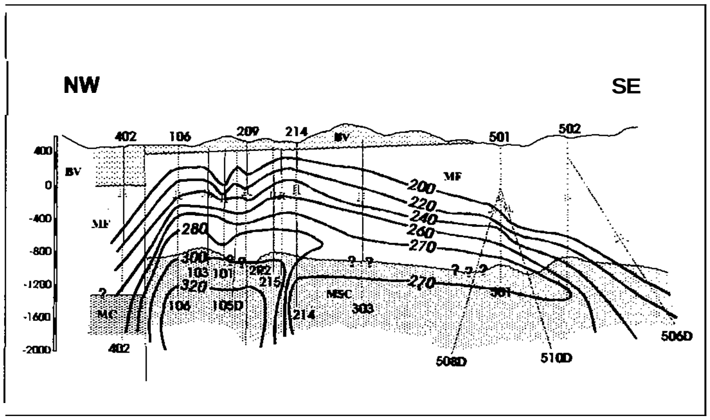


Figure 2a. Correlation of stratigraphy and stable isotherms along line A-A'.

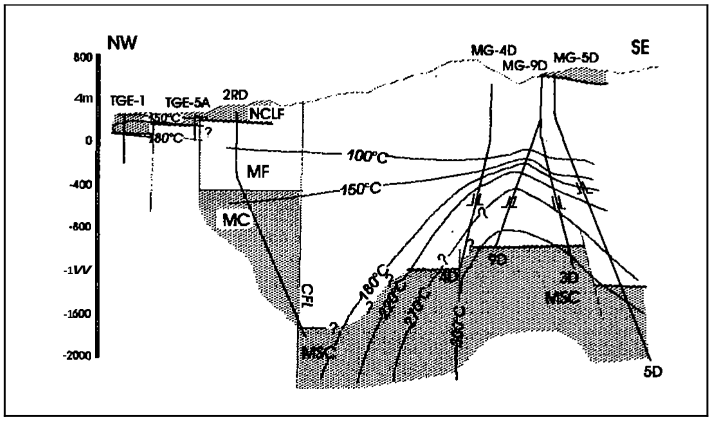


Figure 2b. Correlation of stratigraphy and stable isotherms along line B-B'

To exploit power from these hydrothermal system, several power stations have been recently built in addition to 112.5 MWe Tongonan-1 which has been operational since 1983. The 125 MWe Upper Mahiao and 77.5 MWe Malitbog power plants (Fig. 1) exploit the Mahiao resource and was commissioned in July, 1996 for Leyte-Cebu Interconnection project. Also exploiting the Mahiao resource is the 155 MWe South Sambaloran power plant which will be in full operation by April, 1998 along with the Mahanagdong A (120 MWe), B (60 W e) and optimization plants (50 MWe).

Microearthquake monitoring activity in (GTGF) was started in November, 1980. A single permanent seismic monitoring station was installed near the Administration building to monitor any changes in baseline seismicity that might result from future geothermal exploitation. The equipment used is Kinemetrics analog recorder with seismometer having a natural frequency of 1.0 Hertz. From April to May, 1981 and from September to November, 1982 short-term epicentral studies had been conducted, using four portable seismographs(Bromley and Rigor, 1987). The recorded events typically occur in swarm or cluster with an average rate of six events per week. From 1981-1982, before the Tongonan-1 power plant was commissioned a total of 325 events were recorded. The average rate is 162 events per year. From 1983 to 1985 after the Tongonan -1 power plant was commissioned a total of 770 events were recorded. The average rate is 256 events per year which is 58% higher than 1981-1982 baseline data.

3.0 Data Inversion Technique

In an effort to determined the tectonic association of the seismicity recorded in GTGF, we examined 650 events occurring between February, 1996 to November, 1996 and June-July, 1997. The well recorded data in this period were chosen in locating the events. For locating the earthquakes we used the HYPOINVERSE computer code (Fred W. Klein 1978). The *crustal* model applied in locating the earthquakes is similar to that used by Mrs. Catherine Dorbath in her 1996 preliminary study of Tongonan (Table 1).

P wave velocity (km/sec)	Layer thickness (km)
3.56	0.00
3.75	1.50
4.33	3.00
5.20	5.00
6.20	10.00
8.00	40.00

Table 1 Crustal Model (from C. Dorbath, Nov., 1996)

In the second stage of processing, the latest version of the program adapted by Eberhart Philips(1986) from the method developed by *Thurber* (1983) has been used. We simultaneously inverted earthquake travel time data from the local earthquakes to determine both locations of earthquakes and the 3-dimensional seismic velocity structure of the earth beneath the seismic array. The damped least squares technique were use for simultaneous inversion. For the inversions we choose events using restrictive criteria to retain only the best quality data. We first selected the events meeting the following criteria : RMS <.20 s , horizontal standard error < 1.5 km, vertical standard error < 2.5 km, number of stations >10. In *Thurber's* (1983) inversion method the veiocity structure is parametrized by assigning velocity values at discrete points of a 3-D grid and linearly interpolating between these points. The study zone is a rectangular region 10 by 20 km inside Tongonan geothermal field. The initial velocities at the grid nodes were adopted from onedimensional *P* velocity model used for Tongonan earthquake location.

4.0 Results and Discussions

4.1 Seismicity *during Power plant testing*

From March, 27 to August 25, 1996 testing activity in 77 MWe power plant in South Sambaloran/Malitbog was undertaken prior to full operation in June 1996. A total of 0.155 ton/sec of brine from nine production wells will be needed in energizing the power plant and 0.496 ton/sec of waste water will be injected from seven reinjection wells. These wells are **5R1, 5R4, 5R8D**, 5R6D, 5R3D, 5R5D, and 5R7D. The testing of the

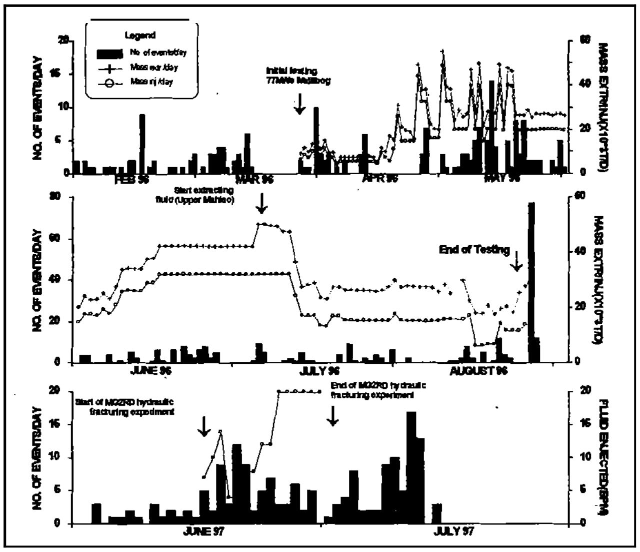


Figure 3. Histogram of daily number of events as recorded by the network.

125 MWe Ormat power plant in Upper Mahiao was conducted almost at the same time from May to August 25, 1996. This power plant required 0.3394 ton/sec of fluid from thirteen production wells and a reinjection load of 0.2736 todsec water which were to be disposed in Pad 408 reinjection wells. But during testing of this power plant, waste water was dumped into upper Mahiao thermal pond.

Figure 3 correlates the volumes of fluid extracted and injected into the wells during testing against the number of earthquakes detected. One month before testing of the power plant a total of twenty-seven microearthquakes were recorded. The epicenters of these earthquakes are located in Mahiao, Bao, south Mamban and Mahanagdong (Fig. 4). During the first month of recording, thirty eight events were located (Fig. 4). Of these thirty-eight events, located only one of lie near the vicinity of the injection well 5R8D, the others are scattered in Mahanagdong. During this period, no direct relationship between the fluid injection and earthquake occurrence was noted. In the mid- April to end of May, the volume of fluid injection increased to a maximum 0.220 ton/day. During this period, an increase in seismicity was observed clustering the bottom of injectors 5R3D/5R7D. Epicenter of these events appear to propagate in eastward while the others are scattered in Mahiao and south Mahanagdong areas (Fig. 5). Testing activities were ended in the mid-August, 1996 and two weeks after this activities, a series of felt events were recorded in the 25th and 26th of August, 1996. Epicenters of all the events are found mostly south of Mahanagdong several kilometers away from the injectors (Fig. 5).

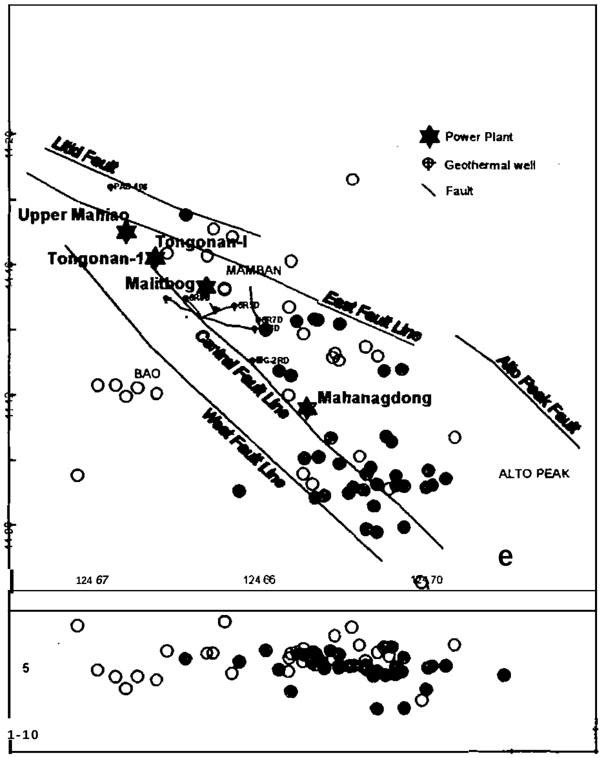


Figure 4. Epicenter distribution of microearthquakes located by the network. Open circles are events before initial injection and closed circle are events during injection.

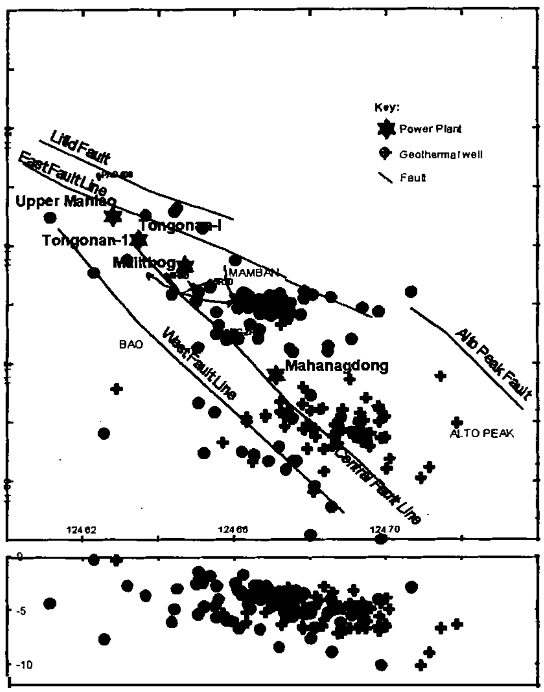


Figure 5. Epicenter distribution of microearthquakes located during and after injection. Closed circles are events during injection and crosses are events after injection.

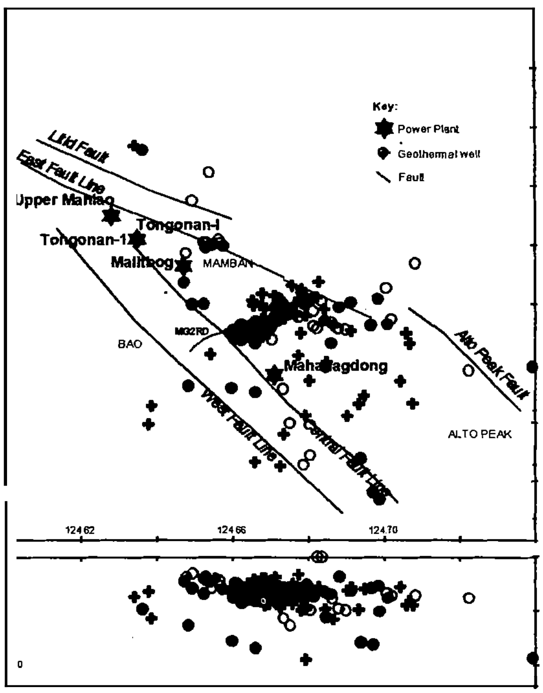


Figure 6. Epicenter distribution of microearthquakes located before, during and after hydraulic experiment. Open circles are events located before fracturing, closed circles and crosses are during and after fracturing.

4.2 Seismicity during Hydraulic fracturing of MG-2RD

MG-2RD, the second injection well in the Mahanagdong, was drilled to a depth of 2695m MD. Poor permeability, was indicated by the absence of drilling losses and low injectivity index (13l/s-MPa at 6 MPa well head pressure), made the well unusable for injection. In order to see if the well can still be utilized, a new hydraulic stimulation technique involving sustained water injection was performed on the well (Comey, 1998). In June 18, 1997 a massive hydraulic fracturing experiment of MG-2RD was carried out. Injection of water proceeded in different steps starting at 4 bpm (10.6 l/s) and ending at 20 bpm (53 l/s). Each step involved a constant injection flow rate period of 48 hours. The last step was the injection of 20 bpm lasted for 96 hours. Before, during and after hydraulic fracturing of the well seismicity was monitored. A total of one hundred sixty-six events were recorded (Fig. 6). Cluster of events are noted in Malitbog and Mamban area. In June 18, 1997 at 1715 hrs when the first injection was started, the volume of injected water was 4 bpm (10.5 l/s) and lasted for 48 hours. In this first injection, no seismicity response was immediately detected. There was a delay of nineteen hours. This delay may be linked to the volume of fluid injected. A certain excess pore pressure may have to be exceeded over a certain surface area of fractures before induced seismicity begins; such an area will be related to the volume of fluid injected. Following to this test, injection was increased from 4 bpm (10.5 l/s) to 20 bpm (53 l/s). In this period more than fifty-nine microearthquakes were recorded. Epicenters are clustered near the bottom of MG-2RD and the distance of epicenters from the injection well increase gradually towards east direction (Fig. 6). July 30 1997 when the hydraulic fracturing experiment was terminated and after the experiment more than seventy six events were plotted northeast of the injector less than kilometer distance from the bottom of the injector (Fig. 6). The pattern follows the model of a propagating front of increased pore pressure (Healy, et al.. 1968). When injection stopped this front would continue to over pressure pore spaces at greater distances from the injection site thereby continuing to induced seismicity, while pore pressures in the immediate vicinity of the injection site would drop below the critical level causing a return to normal level of seismicity near the well.

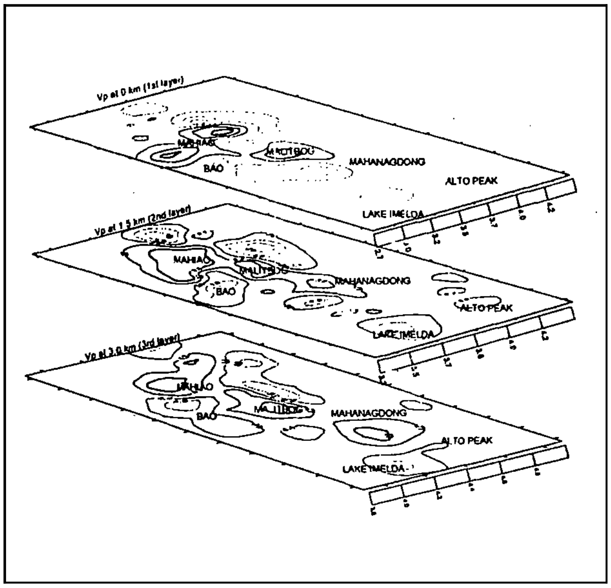


Figure 7. Three-dimensional velocity model for Tongonangeothermal field.

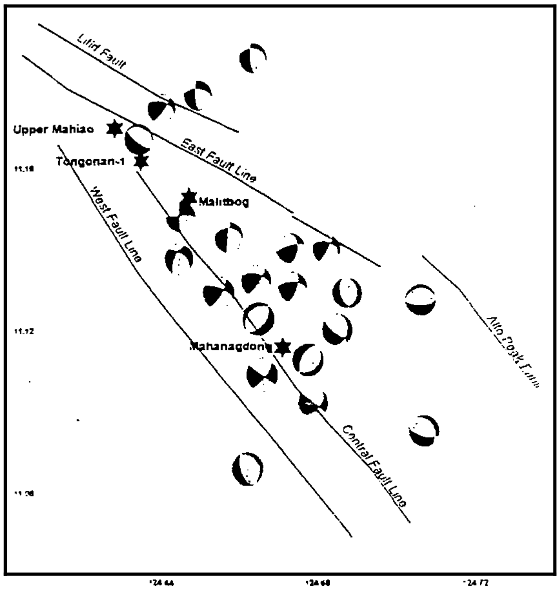


Figure 8. Selective focal mechanism solutions. Diagrams represents the lower hemisphere of focal sphere with shaded quadrants for compressions and white for dilatations.

4.3 Velocity structure

During the period of monitoring more than six hundred fifty events were located. Most of these have magnitude of <3.5 with hypocentral depths ranging from 0 km to 12 km (Figs. 4-6). The epicenters are lies to the center of the geothermal field, between Central Fault Line and East Fault Line. Three dimensional velocity solution in the first three layer is presented in Figure 7. The velocity model found in this study can be compared to the stratigraphy and stable temperature contours of Tongonan Geothermal Field. The lowest velocities are observed directly beneath Mahiao, Malitbog and Mahanagdong. In the upper most velocity layer, two pockets of low velocity zone are observed directly beneath Mahiao and Malitbog. Immediate below this layer a significant low velocities of <3.5 km/sec were observed. This prominent feature is a NW-SE low velocity zone sandwiched by high-velocity areas bounded between East and West Fault Lines, coincide with the structural trend of major faults. This low velocity body is wider in Mahiao area and becoming thinner towards Mahanagdong area. Stratigraphic section with superimposed stable temperature from well 402 to well 502 is presented in Figure 2a. In this figure low velocity zone is closely related to the hot fluids upwelling at Mahiao and outflowing at -1000 mRSL along the unconformable contact of Mahiao Sedimentary Complex (MSC) and Mamban Formation (MF)(Delfin F.G et al., 1995). In addition the shape of low velocity zone coincided with the stable temperature contours at -1000 mRSL. High velocity values ranging from 3.8 to 4.0 km/s are observed in the Northern and Eastern part of Mahiao, Bao valley, Lake Imelda and AltoPeak. In these areas, no flow of high temperature fluid exists at -800 to -1000 mRSL within the impermeable pre-Tertiary serpetinitic basement rocks and Mahanagdong Claystone (M.Z Delfin, pers. comm., 1998).

4.4 Focal mechanisms

Fault plane solution were obtained for 189 events with 5 or more polarities and with location qualities A or B. The source mechanisms indicates strike-slip (left lateral) and dip-slip (normal faulting) mechanisms with strike oriented N 46°W (Fig. 8). The strike of the source fault plane follows the average trend of the major faults which the principally left lateral and are aligned sub-parallel to the general trend of the Philippine Fault.

5.0 Conclusion

The results of operating microearthquakes monitoring network in Tongonan Geothermal field confirm the result of earlier studies that seismicity of the area is relatively high. The magnitudes of these events are generally less than three and believed to be tectonic events related to the Philippine Fault.

A microearthquake survey showed induced seismicity occurred during initial injection at wells 5R3D/5R5D/5R7D and MG2RD while conducting Malitbog plant test and hydraulic fracturing experiment in MG2RD.

The low velocity body inside Tongonan geothermal field is most likely related to the hot fluids upwelling at Mahiao and outflowing at -1000 mRSL along the unconformable contact of Mahiao Sedimentary Complex (MSC) and Mamban Formation (MF). High velocity zones correlate closely with the impermeable Basement Complex rocks and Mahanagdong Claystone.

Focal mechanisms are strike-slip and dip-slip faulting with an average strike of N46°W.

6.0 Acknowledgments

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7.0 References

Aurelio, M.A., Pagado, E. S., and Tebar, H. T. (1993) Kinematics of the Philippine fault system at the Tongonan Geothermal Field, N. Leyte: Implications for the geothermal exploration and development, J. Geol. Soc. Phil., v. 48, nos. 1-2, 1993.

Bien, O.C. 1986. Microseismic Monitoring of Leyte Geothermal Project. PNOC EDC internal memorandum.

Bromley, C.J., Pearson, C. F., and Rigor, D.M. (1987). Microearthquakes at the Puhagan Geothermal Field, Philippines - A case of induced Seismicity . J. Volc. and Geoth. Res., 31, pp. 293-311.

Dorbath C., Oppenheimer D., Amelung F., King G., Seismic tomography and deformation modelling of the junction of the San Andreas and Calaveras faults, J. Geophys. Res., 27 917-27,941, 1996.

Eberhart-Phillips, D., Local earthquake tomography: Earthquake source regions, in Seismic Tomography: Theory and Practice, edited by H.M Iyer and K. Hirahara, pp. 613-643, Chapman and Hall, New York 1993.

Klein, F. W., User's Guide to HYPOINVERSE, a program for VAX computers to solve for earthquake location and magnitude, U.S. Geol. S w . Open File Rep., 89-314, 49 pp.. 1989.

Lee, W.H.K and Lahr, J.C. (1972). HYPO71: A computer program for determining hypocenter, magnitude and first motion pattern of local earthquakes. U.S. Geological Surveys, Open File Report.

Saw, V.S., 1996 Bi Monthly Reservoir Report of Leyte Geothermal Project. PNOC EDC internal memorandum.