# THE GEOCHEMICAL MODEL OF TONGONAN GEOTHERMAL FIELD PRIOR TO FULL COMMISSIONING OF 450 MWE POWER PLANTS

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## ABSTRACT

*Tongonan production field encompasses the five produetion sectors of Upper Mahiao, Mahiao, Sambaloran, South Sambaloran and Malitbog, Mamban and Bao sectors separate the Tongonan from Mahanagdong field. This updated geochemical model of Tongonan Geothermal Field was based from the baseline well chemistry during discharge tests and the present production chemistry after more than a decade of Mahiao-Sambaloran operations.*

*The upflow sector is inferred to be situated in Upper Mahiao, particularly in the vicinity of 407 and 410. Towards the south and southeast, that is in the general direction of Malitbog, mineralization, temperature and gas concentrations decrease. These directions are the major natural outflow of the system. Discharge tests and commercial production indicate the presence of secondary fluids in the periphery of Tongonan system. Cooler waters in northeast of Upper Mahiao characterize the well discharges of 411D, 4160 and 4170. Likewise, the 5RB wells in southwest of Malitbog exhibit less mineralized and coolerjluids. Northeast of Malitbog, however, there is a presence of sulfate-rich type of cooler waters as seen in the discharge of 505D. Acid fluids are also identified in 402, which appears to be confined only west of Upper Mahiao-Mahiao sectors. Notably, the exploitation of the Mahiao-Sambaloran sectors for Over a decade has brought about the massive migration of reinjection jluids from the southwest, which is the reinjection sink of Mahiao and Sambaloran.*

## 1.0 INTRODUCTION

Tongonan geothermal field lies in north-central Leyte island (Fig. 1) within Ormoc City and Kananga town. It covers a northwest trending 15 $km^2$ area of rolling and rugged topography. Seven sectors comprise the Tongonan geothermal field, namely Mahiao, Sambaloran, Upper Mahiao, South Sambaloran, Malitbog, Mamban and Bao. A **112.5** MWe Tongonan-1 power plant in the Maluao and Sambaloran sectors has been operating since **1983.**

In the coming next two years, three more power plants will be installed in the different sectors of Tongonan geothermal field as part of interconnecting Leyte electric grid with Luzon and Cebu grids. These events signal the utilization of the field in its full power capacity estimated at 536 MWe. Designed to Operate for 25 years, this massive commercial operation will not only deliver electricity but will also cause changes in the natural state of the Tongonan geothermal reservoir.

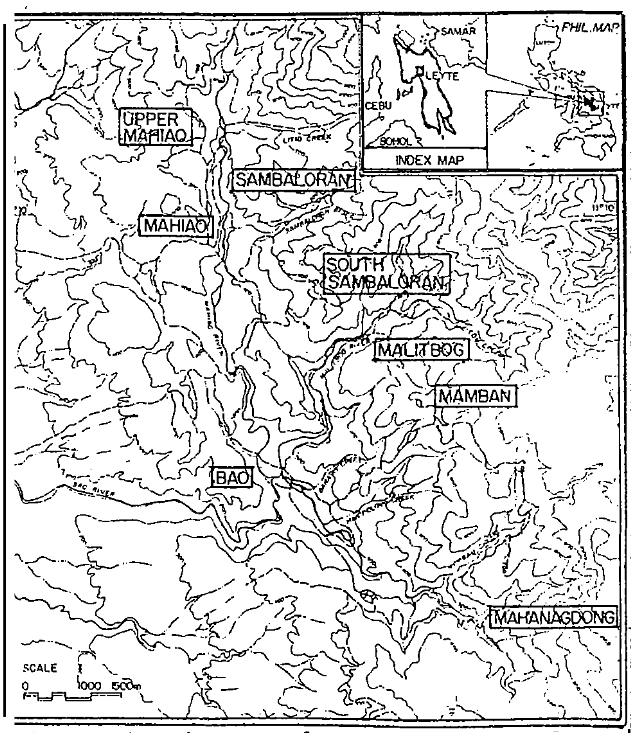


**Figure 1. Location Map of Tongonan geothermal field.**

The primary aim of this paper is to present an updated geochemical model of Tongonan geothermal field based from the baseline well chemistry during the discharge tests and the present production chemistry after more than a decade of Mahiao-Sambaloran operations. An assessment on the impact of areas posing potential problems during full operation of all power plants in Tongonan geothermal field is also presented.

## 2.0 CHEMICAL TRENDS ACROSS THE FIELD

### Trend of $Cl_{res}$ across the field

The distribution of the calculated reservoir chloride are shown in the iso-$Cl_{res}$ contour maps in Figures 2-1 and 2-2. The pre-exploitation (1982) iso-chloride contour shown in Figure 2-1 indicates highly saline fluids (>9,000 mg/kg) at the vicinity of well 410 and 407. This region also corresponds to the hottest part of the field and is believed to be the upwelling zone where the parent fluids emanate. Chloride concentrations gradually decline towards the south-southeast and southeast at Sambaloran and Malitbog sectors interpreted to be the outflow regions. The Contour configuration appears to follow a northwest trend which correspond to the major structural framework of the area bounded by the Litid North fault, East Fault Line and Central Fault Line. This indicates that the flow is most likely controlled by these *structures.* Conspicuous contour depressions in the vicinity of 411D-416D, 102402 and 5R4-509 areas could indicate dilution of the hot reservoir brine with a low-chloride cooler fluid which are likely cooler meteoric waters.

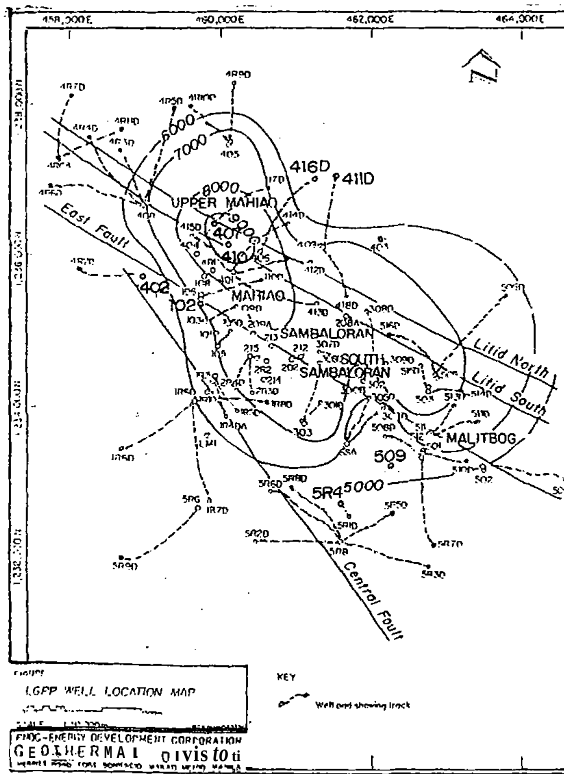


figure 2-1. Baseline iso-Clres contour map across Tongonan geothermal field.

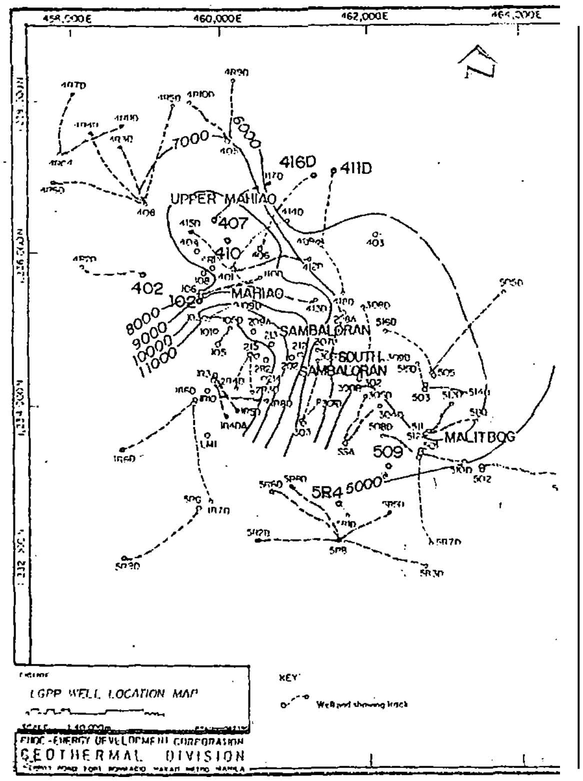


Figure 2-2. Present iso-Clres contour map across Tongonan geothermal field.

The entry of cold (<180°C) and highly saline (>11,000 mg/kg Cl) reinjection fluids during the exploitation of TIPF has significantly alter the pre-exploitation iso-$Cl_{res}$ contour. In Figure 2-2, chloride enrichment of >10,000 mg/kg at the southwest sector of the Tongonan-1 production field, indicate the encroachment of reinjection fluid towards the north and northeast of the T1PF. The reinjection fluid flow appears to follow the northsouth trending Mahiao graben and the northeast trending Urangon and Sambaloran faults. These structures are likely conduits of reinjection fluid towards the production Sector (Alincastre, 1991).

Contour depression observed in the vicinity of wells 102, 106, 108 and 402 is attributed to cold water mixing. Entry of low chloride cold meteoric water was evident in wells 102, 106 and 108 when utilized at highly throttled discharge conditions (Salonga et al., 1996). Significant decline in chloride contents associated with decreasing $T(SiO_2)$ and enthalpies indicate the inflow of cold water in these wells.

### Trend of $T(SiO_2)$ across the field

The calculated reservoir temperature of each discharging well based on $T(SiO_2)$ are plotted and contoured. The iso-$T(SiO_2)$ contour of the Tongonan field prior to exploitation in 1982 and the present temperatures are shown in Figures 2-3 and 2-4, respectively.

In Figure 2-3, the hottest region with silica temperature of >300°C is situated in the vicinity of well 410. This well also registered the hottest measured temperature of 329°C at 2200mVD and 312°C at the major feed zone at 1600mVD. The $T(SiO_2)$ values correspond well with the measured downhole temperature indicating fluid-rock equilibrium state. The $T(SiO_2)$ declines gradually towards the southeast at Sambaloran and Malitbog sectors. The decrease in temperature is also associated with the decline in chloride concentrations confirming an outflow of the hot reservoir fluids in this region. Iso-$T(SiO_2)$ contour depressions noted in the north-northeast (411D-416D) and west (108-402) of the field are attributed to mixing with cooler meteoric waters.

The present $T(SiO_2)$ contour map after commercial operations in T1PF is shown in Figure 2-4. Silica geothemometers of the newly dnlled wells in Mahiao and Upper Mahiao sectors (109D, 110D and 413D) have caused the expansion of the 300°C iso-$T(SiO_2)$ contour. Distinct iso-$T(SiO_2)$ contour depression still exist in the north-northeast and west. However, the decline of $T(SiO_2)$ in the west as reflected in wells 106 and 108 is the effect of cold water inflow due to exploitation. The low temperature gradient in the southeast is attributed to the cold fluid dilution as reflected in well 505D. While the contour depressions in the south and south-southeast at the vicinity of the T1PF production wells are attributed to reinjection fluid breakthrough.

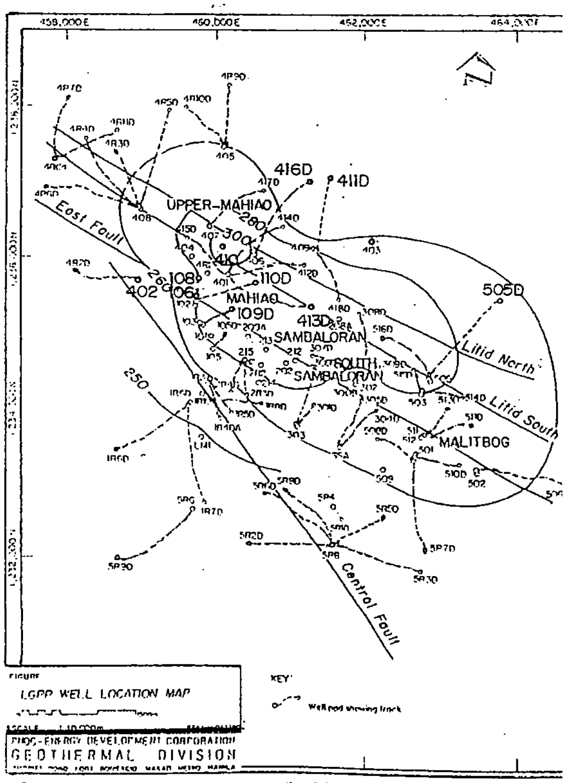


Figure 2-3. Baseline iso-$T(SiO_2)$ contour map across Tongonan geothermal field.

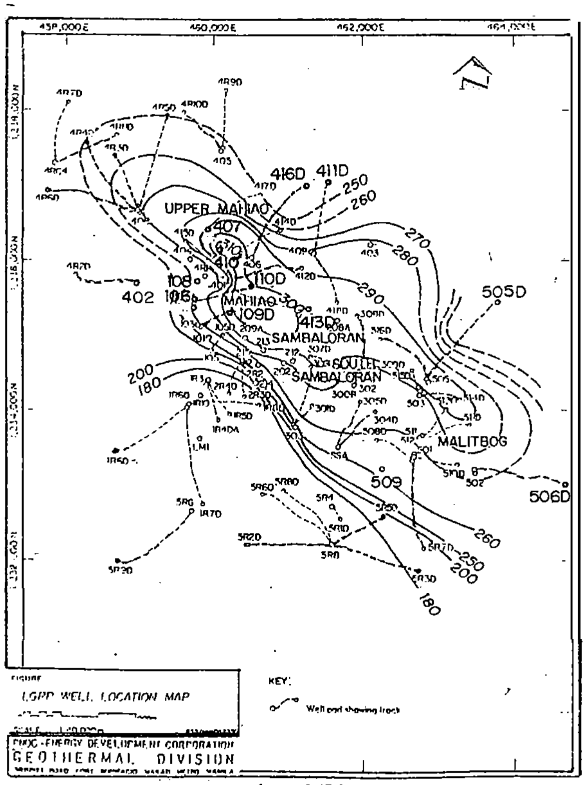


Figure 2-4. Present iso-$T(SiO_2)$ contour map across Tongonan geothermal field.

## Trend of $CO_{2td}$ and iso-$\delta^{18}O$ across the field

**Figure** 2-5 shows the field distribution of $CO_{2td}$ across Tongonan field $CO_{2td}$ is highest in Upper Mahiao sector which is in the order of 200 to 500 mM/100M. This area is thought to be the resident of the parent fluids (wells 407 and 410), the reason for the high gas contents of this area. Moreover, the wells in Mahiao were noted to be undergoing localized drawdown which induced addition of steam to overall discharges.

There are three areas where $CO_{2td}$ appears to have a decreasing trend The first area is toward the northern part of Upper Mahiao sector marked by wells 411D and 416D where $CO_{2td}$ dropped to 100-200 mM/100M. A possible explanation is the presence of cooler and diluted type of fluids in the bottom section of these wells (Auman, 1996). Temperature reversals by as much as 40°C were also noted in these wells. The second area where $CO_{2td}$ has declined is towards the reinjection sink of TIPF because of the presence of degassed injected fluids. The third area is towards the Malitbog and Bao sectors in the southeast which is the natural outflow of the Tongonan geothermal system.

In the area west of Mahiao, well 402 discharged acid fluids with $CO_{2td}$ of greater than 1000 mM/100M. Except for the high salinity, the fluids from the well has chemical affinity with the Kapakuhan fumarole. It is possible therefore that the fluids from well 402 is a product of mixing deep thermal brine with shallow *steam* condensates.

The baseline iso-$\delta^{18}O$ contoured across Tongonan geothermal field shown in Figure 2-6 indicates $\delta^{18}O$ enrichment of more than -0.30‰ at the vicinity of wells 407 and 410. This isotopically enriched sector corresponds to the upwelling region of the Tongonan geothermal system. The isotopic trend gradually depletes towards Sambaloran and Malitbog sectors which are the natural outflow regions.

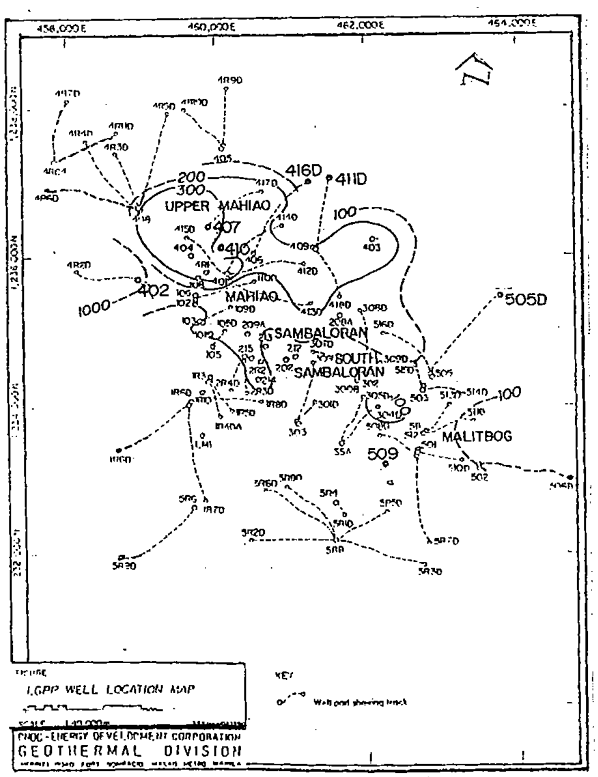


**Figure 2-5. Present $CO_{2td}$ contour map across Tongonan geothermal field.**

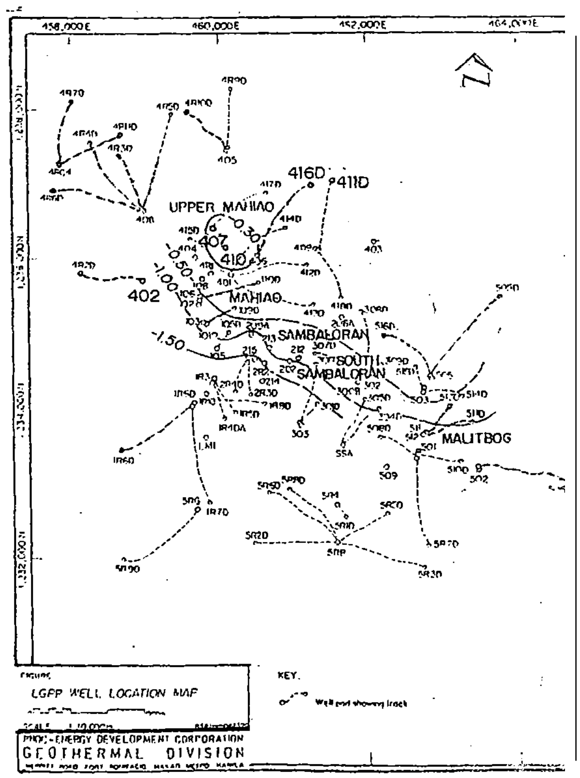


**Figure 2-6. Baseline $\delta^{18}O$ contour map across Tongonan geothermal field.**

### HOMOGENEITY OF TONGONAN FLUIDS

The iso-Cl/B contour of the Tongonan geothermal field is illustrated in Figure 2-7. Cl/B ratio values of 12 to 16 units characterised the fluids in the Upper Mahiao to Sambaloran sectors. while the Cl/B ratio values ranging from 17 to 24 were observed in the South Sambaloran and Malitbog areas. Further south in Bao valley, the neutral-pH chloride springs of Bao and Banat-i have Cl/B ratios of 30 to 33 units. The increasing Cl/B trend towards the outflow region in Sambaloran-Malitbog sectors could be attributed to boron depletion due to absorption in clays developed in colder regions where the hot fluids flows (Lovelock, et al ,1982; PNOC-EDC, 1993).

A plot of Cl/B molar ratio and reservoir chloride concentrations of the Tongonan thermal fluids is shown in Figure 2-8. Increasing CUB molar ratio due to boron depletion is exhibited by wells in South Sambaloran, Malitbog and Bao sectors indicating a natural outflow. Decreasing chloride concentration due to steam and steam condensate dilution is evident in high enthalpy wells in Upper Mahiao. Chloride enrichment without wide changes in Cl/B ratios attributed to reinjection fluid breakthrough are reflected in most of the T1PF production wells.

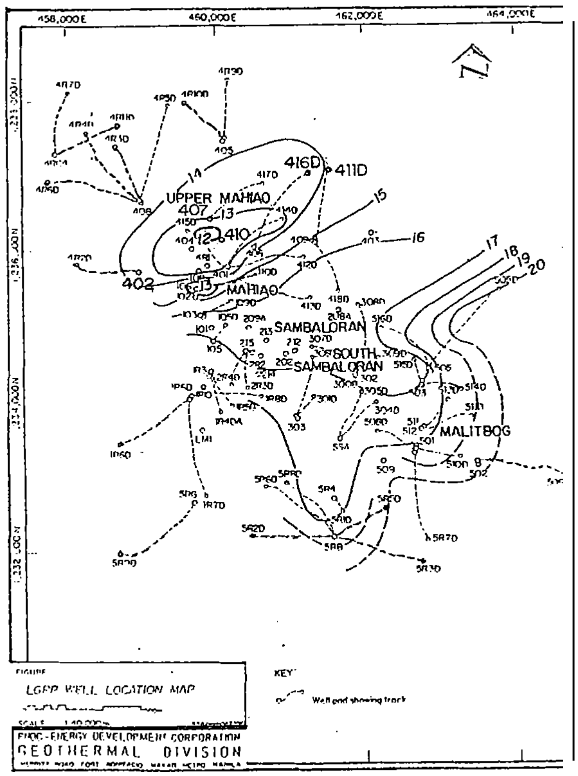


Figure 2-7. Present iso-Cl/B ratio contour map across Tongonan geothermal field.

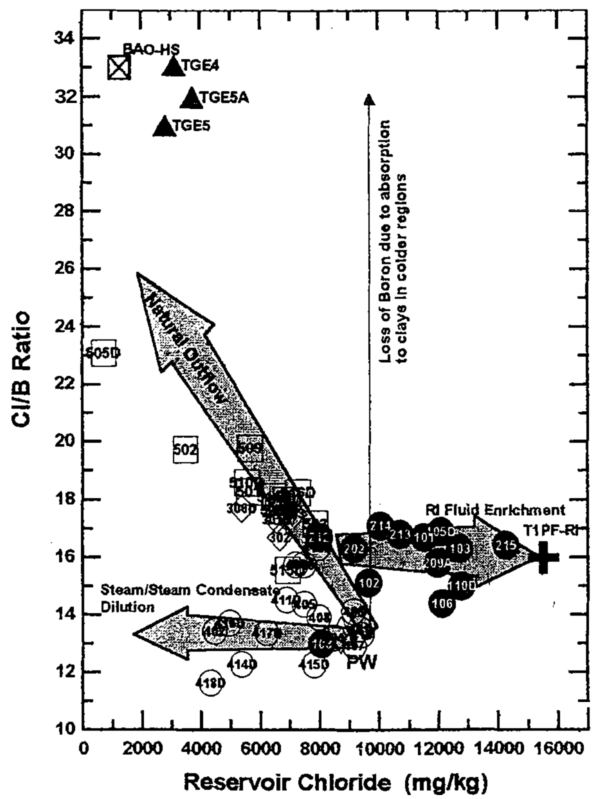


Figure 2-8. Clres vs. Cl/B crossplot in Tongonan geothermal field.

### 3.0 RESERVOIR PROCESSES

A cross plot of $Cl_{td}$ and enthalpy is one of the simple yet effective tool in evaluating the geochemical processes occurring in the geothemal system. A $Cl_{td}$-enthalpy cross plot of each discharging Tongonan wells is shown in Figure 3-1. Distinct linearity of plots are evident where certain processes can be deduced.

Based on geothermometers, the parent fluid is interpreted to have a temperature of about 320°C (equivalent to liquid enthalpy of 1400 kJ/kg) and reservoir chloride concentration of about *8,500* mg/kg. This type of fluid is represented by the discharge of well 407.

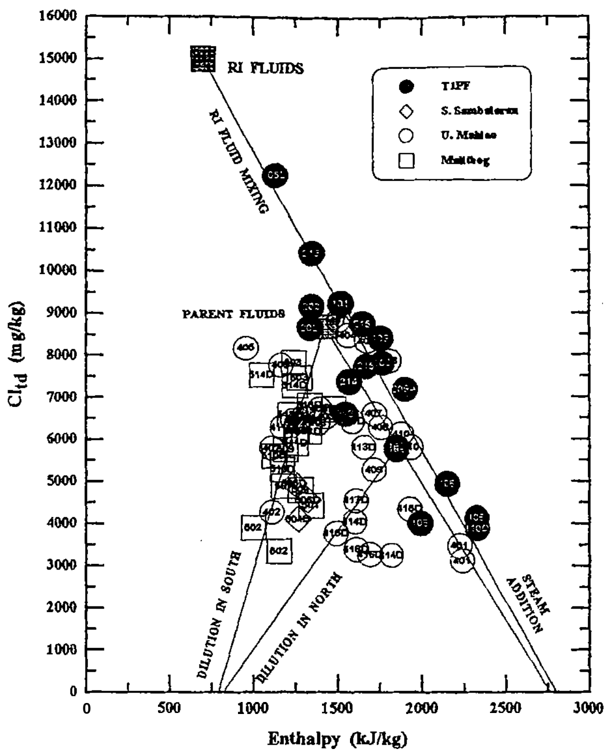


Figure 3-1 . Cltd vs. Enthalpy cross plot in Tongonan geothermal field.

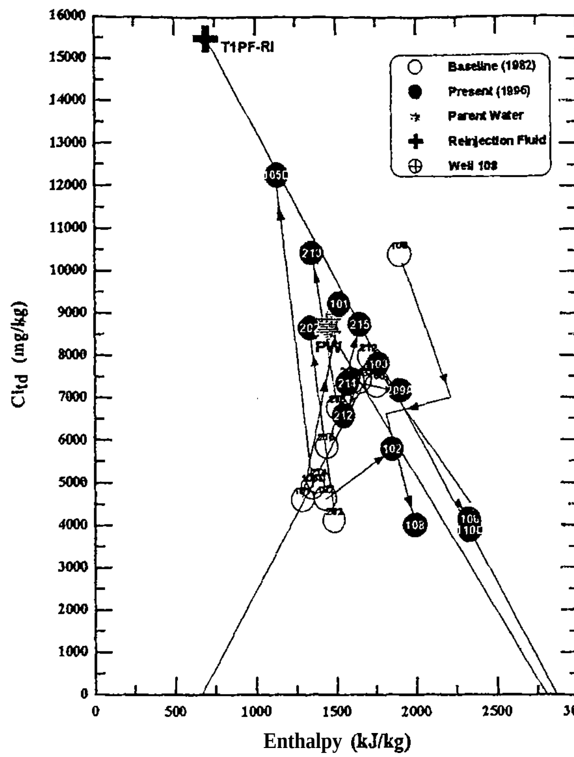


Figure 3-2. Cltd vs. Enthalpy of TlPF production wells.

In the present state of the Tongonan reservoir illustrated in Figure 3-1, at least two cooling-dilution lines are invoked which could be due to mixing with cooler meteoric waters. The discharge fluids of the Sambaloran and Malitbog wells fall along the dilution line in the south representing the natural outflow trend The dilution line in the north represents fluids which has undergone boiling and dilution with cooler meteoric waters. Discharge fluids in some of the high enthalpy wells in the north of Upper Mahiao (409, 414D, 416D and 417D) are likely the result of this process. Wells 401,407,408 and 410 discharged fluids fall along the steam addition line indicating that these fluids have undergone considerable adiabatic boiling.

An apparent shift of the steam addition line to the right is attributed to the gain in field enthalpy due to pressure drawdown. Most of the Tongonan-1 production wells lie along this line which is connected to the box representing the reinjection fluids.

Plots of $Cl_{td}$ and enthalpy of Tongonan-1 production wells showing their pre-exploitation and the present state are shown in Figure 3-2. Significant shift of TlPF well fluids towards.the reinjection line from their pre-exploitation state manifests the reinjection fluid breakthrough in wells 101, 103, 105D, 202, 213, 214 and 215. Wells 105D and 213 are most affected by reinjection fluid returns due to their proximity to the TlPF reinjection sink.

On the other hand, wells 106, 108 and 110D and 209A depict wells whch have experienced substantial boiling. Several processes may also have occurred throughout the utilization of well 108. As illustrated by the shift of its fluid characteristics from 1982 to present, well 108 may have experienced significant boiling from 1982 to 1988 and a substantial cooling as a result of dilution with cooler meteoric waters between 1988 to 1990. The entry of cooler water in this well was induced during utilization at highly throttled discharge (Salonga, et al, 1996). Boiling was again experienced from 1990 to present when well 108 was utilized at full bore condition, hence, preventing the entry of cooler fluids. Likewise, well 212 in Sambaloran sector exhibits cooling due to dilution with cooler meteoric waters.

The FT-HSH equilibria is based on Fischer-Tropsch (Eqn. 3-1) and in the reaction of pyrite with $H_2$ (Eqn. 3-2) (D'Amore et al., 1993):

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \qquad \textit{Eqn. 3-1}$$

$$H_2 + 3/2FeS_2 + 2H_2O \rightarrow 3H_2S + \tfrac{1}{2} Fe_3O_4 \qquad \textit{Eqn. 3-2}$$

The essential features of this approach are summarised in a grid diagram (Fig. 3-3) where the temperature and steam fraction of the reservoir fluids are indicated.

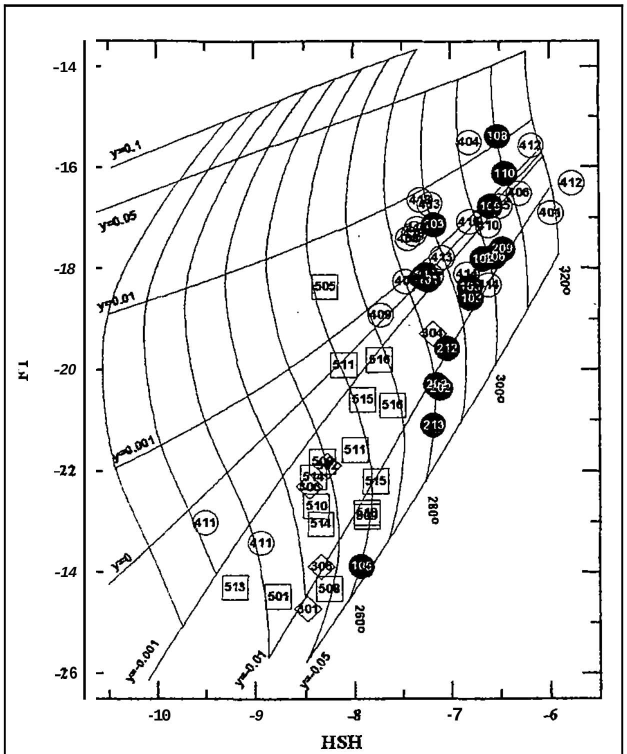

Figure 3-3. FT-HSH grid diagram of gases in Tongonan geothermal field. Symbols' same as in Fig. 3-1.

In Figure 3-3, the data points of wells from Upper Mahiao sector plotted on equilibration temperature between 280-320°C with reservoir steam fraction of +0.01 to -0.001. These values indicate that parent fluids at Upper Mahiao sector are dominantly composed of liquid-phase. Well 411D, however is an exception which plotted instead on equilibration temperature of 240°C. This can be explained by the presence of cooler fluids at the bottom section of the well.

TlPF data pints showed two general trends. Wells with high discharge enthalpy, such as wells 108 and 110D, have gained steam of about 0.001 to 0.01. The steam addition can be related to the localised drawdown of liquid reservoir in the sectors tapped by these wells. The wells with lower enthalpy showed loss of steam from -0.001 in wells 102 and 106 at temperature of 290-300°C, to about -0.01 and -0.05 in wells 105D and 213 at equilibration temperature of 260-280°C. The entry of injected fluids in these wells possibly caused the apparent steam loss and temperature decline in these wells.

Towards South Sambaloran and Malitbog, the data points are scattered below the pure liquid line suggesting progressive degassing process towards the southeast. Moreover, the data points have indicated equilibration temperature of 240-280°C.

## 4.0 FLOW MODEL

Figure 4-1 illustrates the updated geochemical flow model of the Tongonan geothermal field showing the upflow and outflow sectors.

### The Upflow Sector

The center of Tongonan geothermal field can be logically placed in Upper Mahiao sector, that is within the general area of Wells 407 and 410, on the basis of the following evidences:

1. high temperature of up to 315°C as indicated by direct downhole measurements, mineral alteration, fluid inclusions, and solute and gas geothermometers;

2. highly saline fluids **with** $Cl_{res}$ of about 9,000 mg/kg;

3. **high** gas levels with $CO_{2td}$ of **around** 200 to 500 mM/100M *steam;* and

4. isotopically enriched waters with $\delta^{18}O$ of greater than -0.30 ‰.

The **deep** parent ***fluid*** is mostly composed of liquid-phase as proven **by** the studies in *gas* equilibria. At present, there exists a ***steam*** horizon capping the deeper liquid reservoir which is *evinced* on the highly two-phase discharges of most of the Upper Mahiao wells and on the nearly **pure** ***steam*** nature of the discharges of wells 109D and 110D in Mahiao. The expansion of the ***steam*** cap is thought to be **caused by** the drawdown ***of*** the reservoir water level **as a** result ***of*** commercial **operations** in Tongonan-1 production field.

## The **Natural Outflow**

The Tongonan geothermal reservoir has two natural outflow directions. The first one is towards the northwest which is in the direction of Pad 4RC. Owing to the limited permeability directly north of wells **407** and 410, this outflow direction did not develop to be as extensive **as** the major outflow.

The major **natural** outflow is towards the southeast passing **through Sambaloran and** Malitbog sectors, and unto the Bao and Banat-i thermal **springs.** The following are the chemical and physical changes **in** the thermal **fluids** from Upper Mahiao to Malitbog sector:

1. decline in fluid temperature **from** 315°C to about 270°C;

2. transition **from** highly two-phase to liquid-saturated **state;**

3. decrease in fluid salinity from 9,000 mg/kg to about 5,000 mg/kg;

4. increase in Cl/B ratios from 11 to 20;

5. decline in $CO_{2td}$ from 500 to less **than** 100 mM/100M;

6. increase in $CO_2/H_2S$ ratios from *25* to 40; and

7. depletion of heavy isotopes from -0.30‰ $\delta^{18}O$ to less **than** -3.00‰.

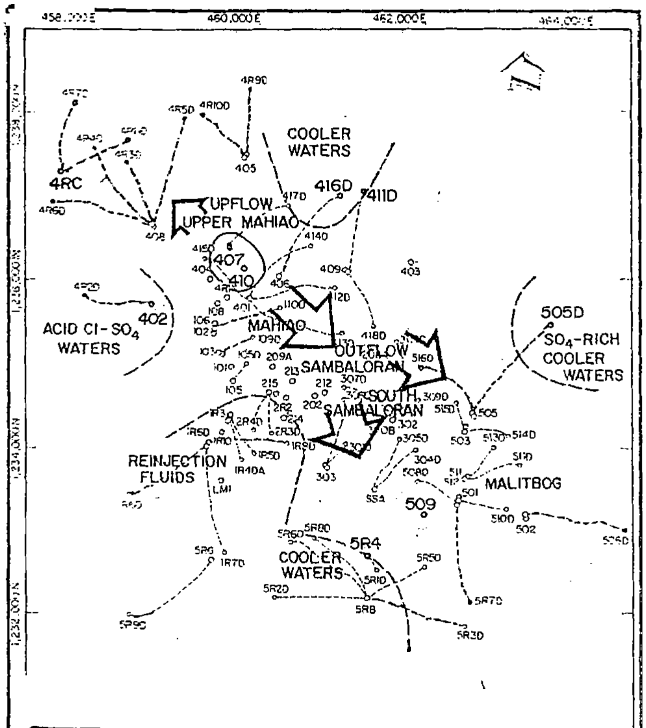


**figure** 4-1. Geochemical flow model of **Tongonan** geothermal **field showing** areas posing potential problems during full **operations of power** plants.

The flow of thermal **fluids** at depths possibly terminate at Mamban sector where there is a marked decrease in reservoir permeability and temperature. Instead, the deeper fluids ascend through the porous rock layers. The fluids **boiled** to around 100-180°C and **mixed** with **as** much **as** 20-40% meteoric waters. The resulting **fluids are those** found in **TGE-4** and 5A, and in Bao and Banat-i **springs.**

## **5.0 POTENTIAL PROBLEMS**

Figure 4-1 also presents the areas posing potential problems **during** full commercial operations of all power plants in Tongonan geothermal field. The following sections present the **impact *of*** these problem **areas** to the field

### The Cooler Waters

Temperature reversals by as much as 40°C occur in wells 411D and 416D which are situated directly north of the center of Tongonan reservoir. These wells also delivered diluted fluids which are believed to be mixture of the thermal brine and deeply circulating fresh waters from the north. These cooler waters are the possible meteoric recharge of the geothermal reservoir. The structures channeling these fluids are Balabag and Balabag-A faults.

During full operations of the Upper Mahiao sector, the decline in the reservoir pressure at the center of the field may possibly invite inflow of these cooler waters from the north. If these happen, the production wells in Upper Mahiao may suffer quenching-effects and eventually become liquid-saturated.

### The Reinjected Fluids

The three areas where influx of reinjected waters are expected to occur are the present reinjection sink in TIPF, the reinjection sink in Upper Mahiao sector, and the reinjection sink in Malitbog sector. The reinjected fluids in TlPF have already invaded the production wells lying within 1.5 km radius which also included well 303 in South Sambaloran sector. Tracer tests have proven that the main conduits of the waste brines are the Urangon, Sambaloran and Mahiao East faults.

In the north, there is an apparent poorly permeable Mock separating the center of the resource fiom the reinjection sink in Pad 4RC. If this block indeed exist, it will provide a barrier from invasion of injected fluids unto the production sector. However, if there will be massive reinjection returns from pads 405,408 and 4RC4, the main conduits will be Litid South and Litid North faults and the likely affected wells will be 407, 410 and 415D.

In Malitbog sector, there was no detected reinjection fluid breakthrough during the four month-long pre-commissioning testing of Malitbog power plant. However, it remains uncertain whether the waste brine will eventually return to production sector with prolonged field production. The probable conduits of the injected fluids are the Bayabas and Caticlan faults and the likely affected wells are 501 and 509.

### The Acid Fluids

Acid $Cl-SO_4$ fluids were detected in wells 402, 1R3 and 1R5D ail of which lie west of Mahiao sector. Although the presence of acid fluids pose a potential problem to Mahiao sector, there has been no detected migration of this type of fluids in TlPF production wells even after almost 15 years of commercial operations. This could be due, either, to the absence of a direct channel connecting the acid fluids and the TlPF production wells, or to the pressure support provided by the reinjected fluids in TlPF reinjection sink

In the eastern part of the field, cooler waters with $SO_4$ levels of about 200 to 300 mg/kg, were discharged by wells 505 and 516D. The waters, however, have near neutral-pH level of above 5.5. Based on the marked decline in permeability in this part of the field, the reservoir of this high-$SO_4$ waters in the east may not occur extensively. In the event of a movement of this type of fluids to the production sector, it may possibly cause acidity or quenching effects in wells 503, 515D and 514D.

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