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MAJOR GEOCHEMICAL CHANGES IN THE TONGONAN GEOTHERMAL RESERVOIR (LEYTE, PHILIPPINES) DURING ITS TWENTY YEARS OF OPERATION

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ABSTRACT

After 20 years of exploitation, three major reservoir processes have been experienced in the Tongonan reservoir. The first is the encroachment of cooler injected brine into the production wells. Production wells near the Tongonan-1 injection sink displayed increasing salinity with accompanying declines in geotemperatures, gas levels and discharge enthalpies. As a mitigating measure, the injection load was distributed between the two injection sectors of Tongonan. This led to the recovery of most of the production wells.

The second involved the transformation of the reservoir from a liquid to a steam-dominated field during the commissioning of additional power plants bringing the total installed capacity from 112.5 to 500 MWe. The resultant field enthalpy and the available steam increased significantly. The different sectors of the field however responded differently. The northern section continued to show increase in enthalpy because of limited recharge. In contrast, the southern section induced influx of cooler waters from the periphery of the field which is regarded as the third major reservoir process experienced in Tongonan.

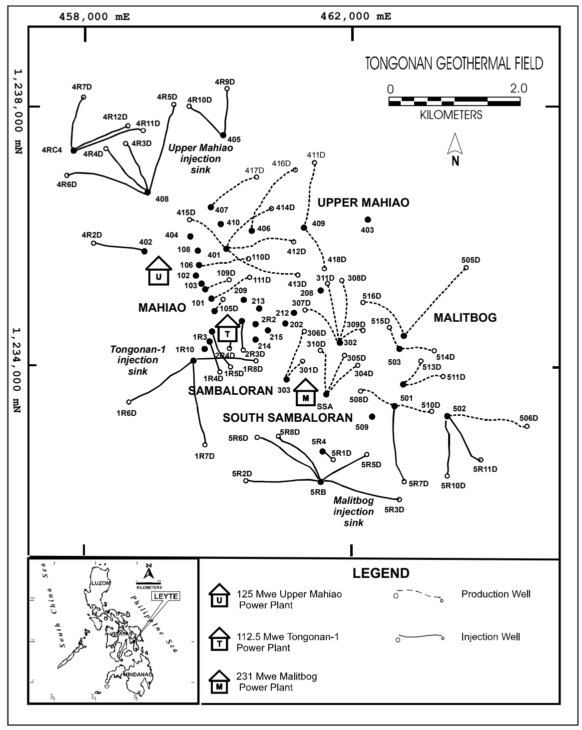

Figure 1. Welltrack map of production and injection wells of Tongonan geothermal field. Inset is the map of the Philippines.

1.0 INTRODUCTION

In the past two decades, the Tongonan geothermal field has been the centerpiece of PNOC-EDC's energy development program. It is found in a large geothermal reservation in Leyte in the central region of the Philippines (Figure 1) along northwest trending structures of the Philippine fault that cut across the Leyte island. The field occupies about 15-km^2 of rolling to rugged topography and has three production sectors namely, Upper Mahiao (UM), Tongonan-1 (TGN-1) and Malitbog-South Sambaloran (MB-SS).

The Tongonan-1 production sector encompasses the two geographic areas of Mahiao and Sambaloran. The production and injection wells in these areas are assigned the 100 and 200-series codenames, respectively and were drilled to supply the steam requirement of the 112.5 MWe power plant.

In Upper Mahiao, the 14 production wells that have the 400-series codenames were drilled to provide the steam requirement of the 125 MWe power plant. There are 9 injection wells located in the northwestern margin of the field for the disposal of separated brine and power plant condensate.

The South Sambaloran and Malitbog production wells, with 300 and 500-series codenames respectively, supply steam to the 231 MWe power plant located in Malitbog. At present, the interconnection of steamlines and brinelines across the three sectors provide flexibility of supplying excess steam from one sector to another and the disposal of separated brine to the sector where mass recharge is needed.

Since the field's operation in 1983, the extraction of geothermal fluids for power generation has brought several changes in the reservoir. Baltasar and Solaña (1983-1995) did numerous geochemical works and groundwater tracer studies of Tongonan. Papers by Siega, et al. (1998), Salonga, et al. (1999), Maturgo, et al. (2001) and Dacillo and Siega (2002) have also been written documenting and investigating the major geochemical changes in the reservoir. It is the primary aim of this paper to consolidate these major observations over the twenty-year history of the field and assess options that would ensure the sustainability of the reservoir, hopefully, for another twenty years.

2.0 PRODUCTION HISTORY

In the two-decade operation of Tongonan geothermal field, its production history can be roughly divided into two major periods: (a) the single operation of the 112.5 MWe main power plant in Tongonan-1 from 1983 to 1995 and (b) full exploitation of the field starting in 1996 up to present with the commissioning of the 125 MWe Upper Mahiao power plant (1996), the 231 MWe Malitbog power plant (1996-1997) and the 50 MWe SLI or steamline interconnection (2000) which pipes the excess steam of Tongonan to the neighboring Mahanagdong geothermal field.

With only one power plant in operation, the extraction rate from 1983 to 1989 started only at 0.5 to 1.1 million tons per month (Figure 2). Of the total amount, about 0.1 to 0.5 million tons of separated waters are injected back into deep wells in compliance with the zero-waste surface disposal policy of brine by the national government. Extraction was concentrated mainly in the center of the field using the Mahiao and Sambaloran production wells while brine injection was done in the sink located about a kilometer southwest of the production sector (Figure 1).

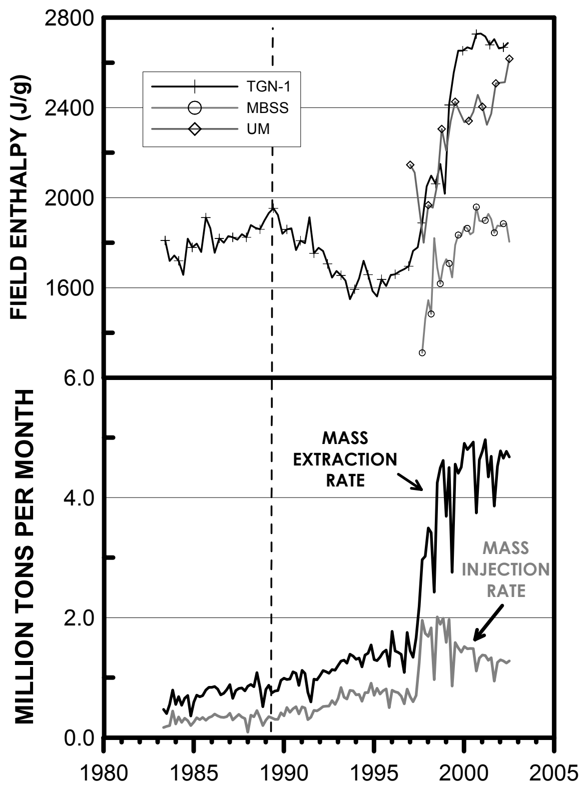

Figure 2. Total mass extraction and injection rate of Tongonan geothermal field. Graph above shows time trend of field enthalpies of the three production sectors.

By the early 1990's, there was a national program to produce more electricity from indigenous energy sources to mitigate the escalating power crisis in the country. The general scheme was to produce around 500 MWe of electricity from Tongonan geothermal field that could be transmitted to the main island of Luzon and the industrial island of Cebu through Leyte-Luzon and Leyte-Cebu interconnections. This was realized in 1996-1998 during the commissioning of the Upper Mahiao and Malitbog main power plants and the 18 MWe and 14 MWe optimization plants in Tongonan-1 and South Sambaloran, respectively. The monthly extraction rate during this period increased significantly from 1.3 millions tons in 1995 to 4.5 million tons in 1998. This peaked to around 5 million tons during the commissioning of the SLI. The optimization plants utilize only the excess heat of steam going into the main power plants or the brine from the separator vessels.

3.0 MAJOR RESERVOIR GEOCHEMICAL CHANGES

3.1 Injection Returns

The continuous fluid extraction from the Tongonan-1 sector from 1983 to 1995 led to the decline in reservoir pressure by about 3 MPa across Tongonan-1 and a uniform pressure drawdown of less than 1 MPa over an area extending towards the Upper Mahiao and Malitbog sectors (Siega et al., 2000). Production wells in the Mahiao and Sambaloran areas experienced local boiling as evidenced by the gradual rise of the sector's enthalpy from 1700 J/g in 1983 to 1900 J/g in 1989 (Figure 2).

Starting in 1989 however, the extraction rate and the corresponding injection rate gradually increased due to increase in power demand. The higher load in the Tongonan-1 injection sink resulted to the extensive incursion of cooler (~180°C as compared to the in-situ fluids with 260-300°C temperature), highly saline injected fluids into the adjacent production wells.

The migration and mixing of injected fluids from the injection sink to the production sector of Tongonan-1 is depicted in the decline of the sector's average enthalpy from 1900 J/g to 1600 J/g. This is also manifested in the distribution of the chemical species in the southwestern part, that is, the sector became highly saline, about 1000-2000 mg/kg higher than the natural state concentration of the upflow region with the entry of the injected fluids (Figure 3). The reservoir chloride contour shows the movement of highly saline fluids (>11,000 mg/kg Cl) from the injection sink towards the production sector.

Figure 4 also illustrates the change of heavy isotope (^{18}O) composition as a result of mixing with the isotopically enriched injected fluids. Reservoir chloride and isotope data points of affected wells have shifted above the baseline regression line and towards that of the injected fluids. Based on the same figure, the encroaching injected fluid is estimated at 40-60% in the local reservoir of affected production wells.

The position of affected wells relative to the injection sink suggests that the encroaching fluids appear to follow the northerly and northeast trending structures toward the production sector. The process has been considered extensive since the injected fluids have already reached well 212, which is already relatively far from the injection sink. The

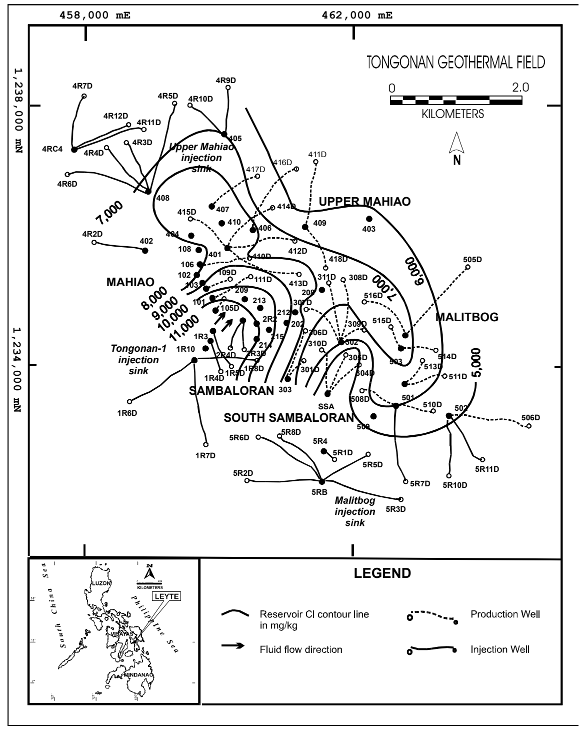

Figure 3. Movement of highly saline injected fluids is indicated by the indentation of high chloride contour lines in the southwestern section.

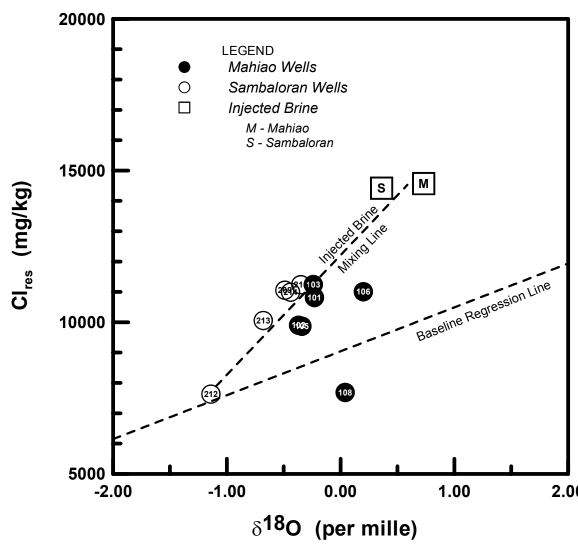

Figure 4. Crossplot of ^{18}O and Cl_{res} showing the enrichment of heavy isotope and chloride of affected production wells as a result of mixing with injected brine.

temperature and output of the most adjacent production wells have also been significantly affected (Solaňa and Macambac, 1995).

To avert further cooling and decline in output, an optimized injection scheme was implemented in September 1995. The total injection load of wells 2R3D and 2R4D of Sambaloran, the injection wells nearest to the production sector, was reduced from 140 kg/s to 90 kg/s. The rest of the load was piped to Mahiao injection wells -- 1R3, 1R4DA, 1R5D and 1R8D. The scheme resulted to the significant recovery of affected wells.

3.2 Field-wide Boiling

The decrease in the injection load and the significant increase in mass extraction across the whole field of Tongonan in 1996-1998 period resulted to reservoir-wide pressure drawdown. This led to extensive boiling. The liquid level receded deeper into the reservoir while the upper steam-zone thickened and expanded laterally towards Upper Mahiao in the north and South Sambaloran in the south.

This process is characterized by the steep increase of field enthalpy of Upper Mahiao and Tongonan-1 as shown in Figure 2. Production wells in the Tongonan-1 sector, especially the shallow-ones that tapped the expanded steam cover, discharged ‘dry’ steam causing the sector’s average enthalpy to shoot up to 2700 J/g and the separated brine injected to the Tongonan-1 injection sink to decline considerably.

The field enthalpy of Upper Mahiao had the same initial trend but it leveled off in 2400 J/g in 1999 when the injected fluids from pad 408 encroached the area of production well 410. Apparently, these highly saline and cooler injected waters were drawn towards the production sector when the reservoir pressure was declining. This process was considered minor because it did not persist for a long time. By year 2001, boiling was still progressing in the sector causing the liquid level in the reservoir to recede deeper and the amount of brine discharged by wells to decline significantly. As a consequence, the separated brine injected into pad 408 wells decreased and so the progressive boiling in the production wells affected by injection returns resumed.

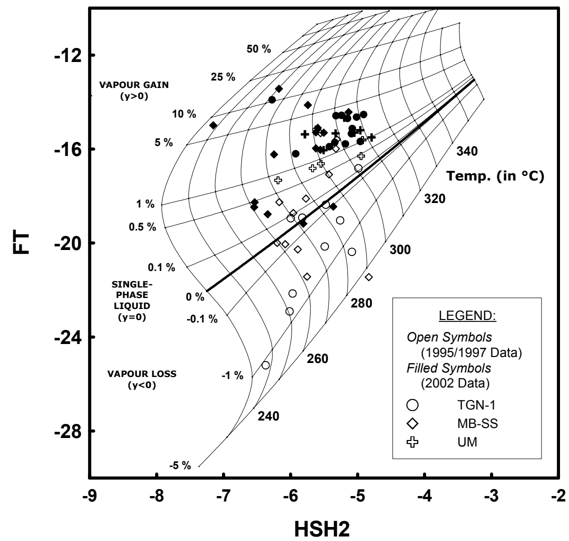

Figure 5. The general shift of data points to the vapor gain side depicts the extensive boiling in the reservoir resulting to expansion of the shallow steam zone.

With the disappearance of the liquid phase, the use of gas chemistry tools became very important in monitoring the changes in the reservoir. One tool called the FT-HSH2 employs the equilibrium reactions between CO_2, H_2S, CH_4 and H_2 (Siega et al., 1999) providing a graphical presentation of the deep aquifer’s temperature and steam fraction (Figure 5). The general shift of the data points towards the vapor gain side illustrate the present condition of the field, that is, the formation of more steam on the shallow region of the reservoir. A number of production wells, especially in the Malitbog area, still plotted close to the liquid equilibrium line due to the considerable influx of peripheral waters. On the other hand, the 1995 data points for Tongonan-1 plotted on the vapor loss side indicating the presence of highly degassed-liquid recharge coming from the injection sink.

Another gas chemistry tool called SNHC elucidates further the process of decline in reservoir pressure of Tongonan during the significant increase in mass extraction. This tool, developed by D’Amore, simultaneously calculates for the deep temperature, steam fraction and partial pressure of carbon dioxide (PCO_2) where equilibrium of six reactive gases has been reached. It has found fairly successful applications in Tongonan geothermal field in terms of monitoring of reservoir processes (Dacillo et al., 1998) and assessment of sustainability of the upper steam zone of the Tongonan reservoir (Salonga and Siega, 1999).

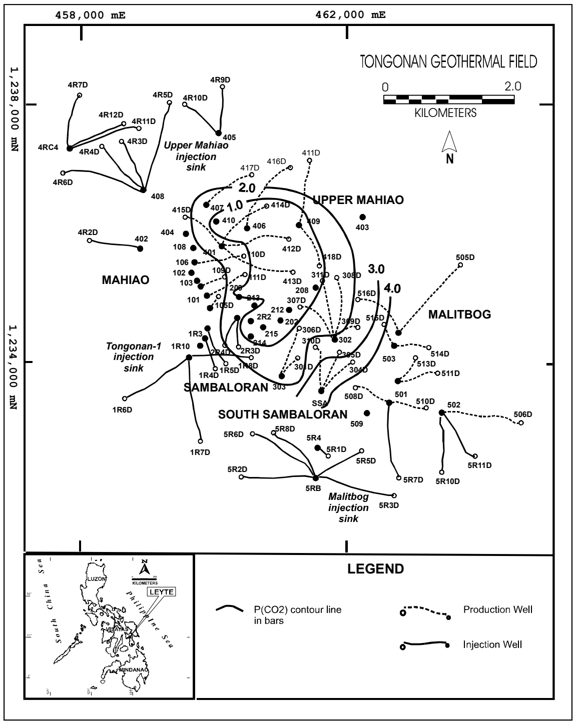

Figure 6. Field contour of PCO_2 in 1996. The central region is marked by lower PCO_2 due to continuous loss of CO_2 from the liquid phase since start of extraction in 1983.

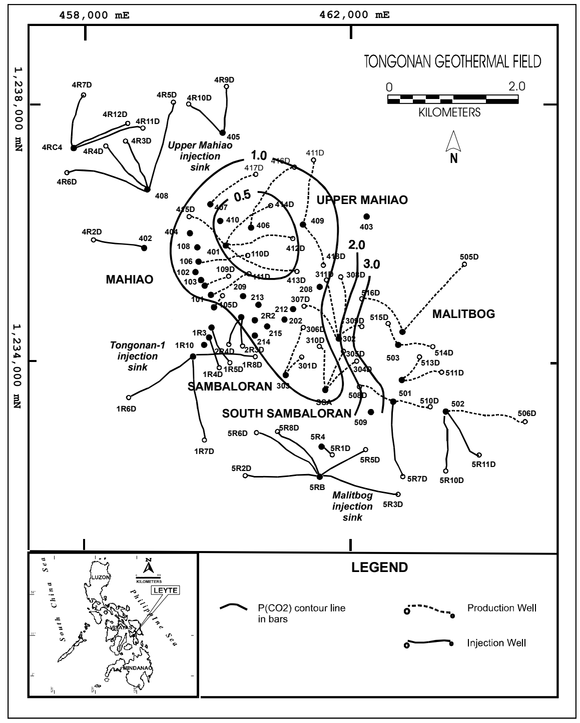

Figure 7. Present field contour of PCO_2. The lower PCO2 values compared to the contour in 1996 reflects indirectly the decline of reservoir pressure due to the significant increase in extraction.

Figure 6 shows the fieldwide contour of PCO_2 in 1996. The central region is marked by a lower PCO_2 of 1 bar due to continuous extraction since 1983. The calculated PCO_2 becomes greater towards the less-exploited outflow region of Malitbog.

The present contour (Figure 7) shows that the depressurized 1 bar PCO_2 area have extended from Upper Mahiao to South Sambaloran sector corresponding to the areas where production wells are already discharging dry steam. Moreover, the present PCO2 values are lower compared to values in 1996. This depicts the lateral expansion of the shallow steam cap towards South Sambaloran and the decline of the reservoir pressure associated with exploitation.

3.3 Inflow of Cooler Waters

When the Malitbog power plant went into full operation in 1998, the whole Malitbog-South Sambaloran sector also experienced boiling. Production wells displayed increase in enthalpy just like the wells in Upper Mahiao and Tongonan-1. This was short-lived for the wells in the periphery of the sector though since cooler waters from the surrounding areas were drawn in as the reservoir pressure declined.

While the field enthalpy of Upper Mahiao and Tongonan-1 increased rapidly and almost continuously to 2800 J/g, the average field enthalpy of Malitbog-South Sambaloran leveled off at 1800-1900 J/g (Figure 2). This reflects the abundance of peripheral liquid recharge in the southern region of the whole Tongonan field.

Two types of cooler peripheral waters are seen encroaching the Malitbog-South Sambaloran region. These are the injected brine coming from the Malitbog injection sink and dilute waters coming from the northeastern and southwestern sides of South Sambaloran.

The increasing mineralization, declining gas content and liquid enthalpy of production wells near the Malitbog injection sink manifest the incursion of injected brine into the production sector. Figure 8 presents the crossplots of the reservoir chloride, CO_{2TD} and deep liquid enthalpy (based on quartz geothermometer) of the affected production wells. Based on the direction of the shift of data points, it is clear that the cooler, highly saline and highly degassed brine from the Malitbog injection sink are mixing with that of the affected production wells.

Cooler, dilute waters are also flowing from the northwestern area to the production sector of Malitbog-South Sambaloran. The area of wells 505D and 516D (Figure 1), hosts cooler, sulfate-rich waters that are also slightly acidic compared to the waters in the main reservoir (Figure 9). These are the same cooler waters that rendered the two wells unproductive – their wellhead pressures cannot reach the 1.2 MPa commercial level. These are believed to be the waters encroaching the adjacent production wells, 309D, 503 and 515D. Its influence on the chemistry of the affected production wells is seen in Figure 10. The in-situ waters of the production wells become cooler, less saline, in terms of chloride, and have lower Cl/SO_4 ratio.

The same type of waters are also encroaching the other side of South Sambaloran. Production wells 303 and 310D also exhibit the same declining trends in Cl, Cl/SO_4 and deep liquid enthalpy. However, their source of cooler waters appears to be coming from the southwestern side, which is more dilute than that in the northwestern area. The incursion of cooler waters in the southwestern side started only in year 2001 and caused well 303 to have the present chloride level of 5000 mg/kg. The inflow in the northwestern side started earlier in year 2000 and at present, the chloride level of well 309D in that area, leveled off at 8000 mg/kg. If the source area have been only in the northwestern side, well 309D should had a chloride level lower that that of well 303.

4.0 MEASURES TO SUSTAIN THE RESERVOIR

Since the start of massive extraction in 1996-1998, it has become apparent that the northern and southern sections of the field are in complete contrast. The northern section has limited fluid recharge from the periphery or from the deep hot upflow so that the reservoir in the Upper Mahiao and Tongonan-1 area responds to massive extraction by expanding the steam zone. On the other hand, the southern section has ample supply of cooler peripheral fluids that

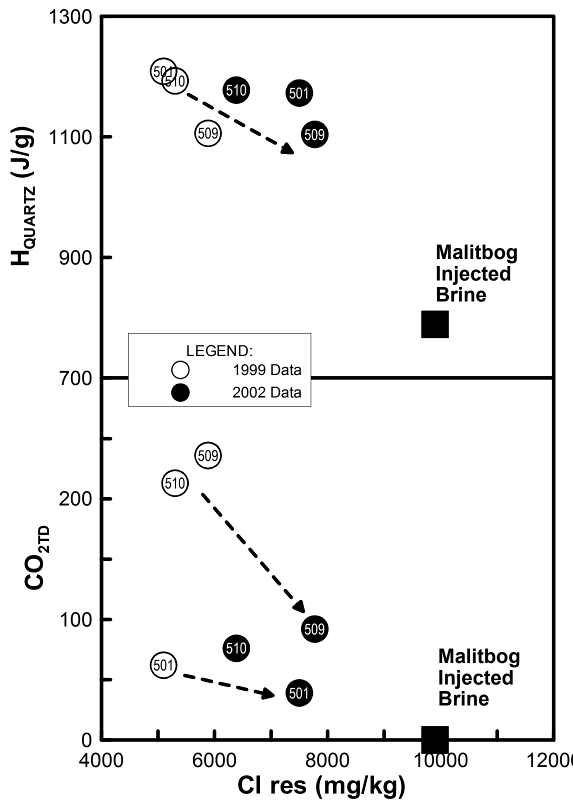

Figure 8. Crossplots of CO_{2TD} and deep liquid enthalpy (based on quartz geothermometer) against reservoir chloride reflects incursion of injected brine into the affected production wells.

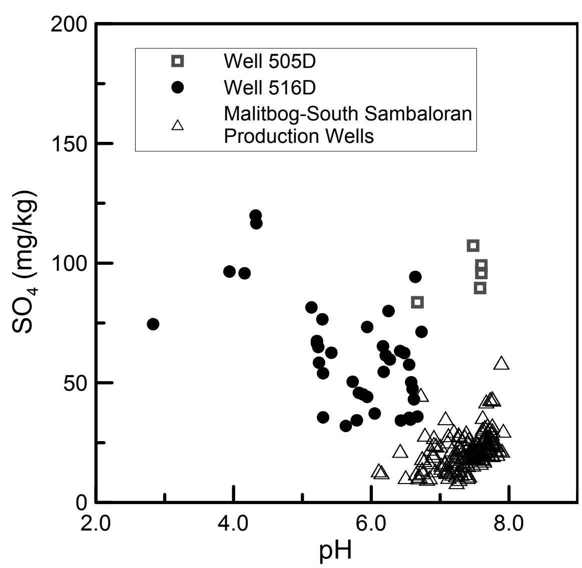

Figure 9. Plot showing the elevated SO4 content and slightly acidic nature of cooler fluids in the area of wells 505D and 516D in the northwestern side of South Sambaloran.

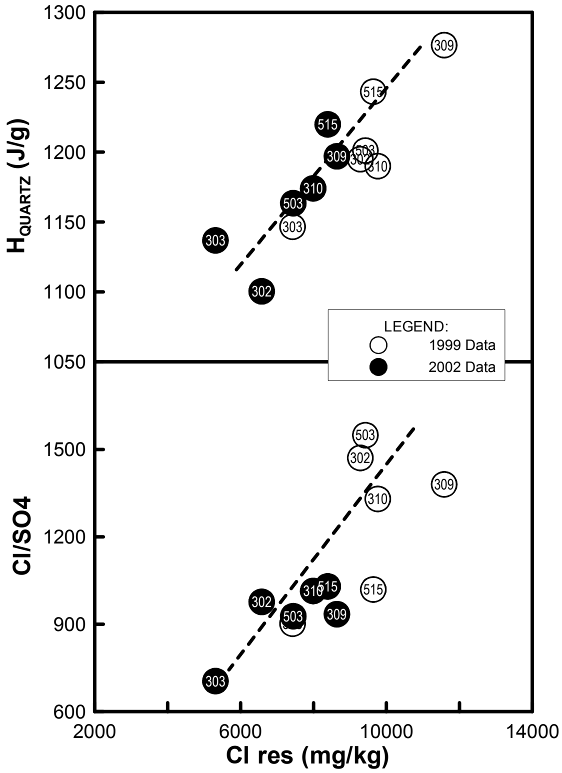

Figure 10. Plots showing the dilution and cooling of peripheral production wells caused by inflow of cooler, sulfate-rich waters.

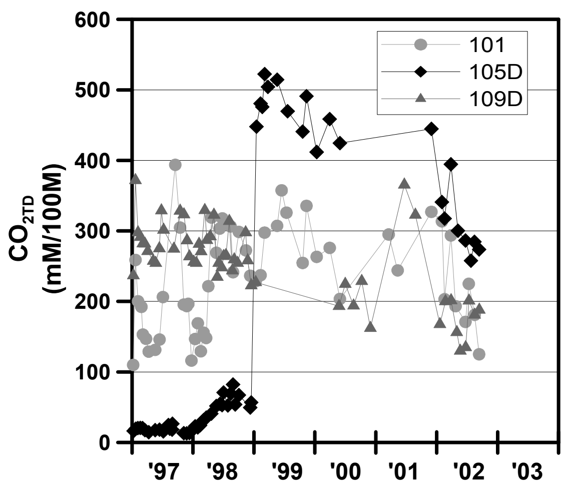

Figure 11. The continuous decline of CO2TD of production wells near the Tongonan-1 injection sink indicate incursion of the highly-degassed injected fluids.

recharges the Malitbog-South Sambaloran sector. In both pictures, there are factors that threaten the sustainability of the reservoir.

In the northern section, steam availability could decline if the mass recharge or pressure support would remain limited while in the southern section, the inflowing cooler waters could quench the production wells.

Certain measures have already been introduced to address these concerns. The separated brine from South Sambaloran, which was previously being disposed to Pad 4RC in Upper Mahiao, was diverted to Tongonan-1 injection sink in August 2001. This was done to provide mass recharge and pressure support to Tongonan-1 whose production wells are already discharging dry steam. Operationally, it is also advantageous in mitigating silica deposition since the residence time of the brine in the pipeline to Tongonan-1 is very much lower than to Upper Mahiao.

Evidence of the injected fluids returning to the production sector is manifested in the decline of the gas contents of production wells north of Tongonan-1 injection sink. Continuous decline of CO_2 concentration was observed since the first quarter of year 2002 (Figure 11). This indicates mixing of the degassed injected brine with the in-situ fluids of the affected production wells. Periodic tracer flow measurements of these wells showed no significant decline in enthalpy so that the injected fluid is considered as beneficial as mass recharge to production sector. The absence of significant drop in enthalpy also suggests that the injected fluids are probably boiled off before reaching the affected wells. Redistribution of the brine load among injection wells will be conducted once the cooler injected fluids become detrimental to the production wells.

Come January 2003, the cold (<60°C) condensate from the Upper Mahiao power plant will be injected to Pad 4RC in compliance with the environmental policy on zero-waste disposal to the surface. Hopefully, the move will also provide mass recharge to the production sector but it could also quench the reservoir since injection rate is high at 290 kg/s and temperature of the fluids is very low. Tracer test will be conducted to assess rate of return and the percentage of returns in the production sector.

In the Malitbog-South Sambaloran sector, the discharge enthalpy of the production wells affected by injection returns is still above or within its baseline level. The injection returns are therefore still considered beneficial as mass recharge. Once the returns become detrimental, the injection load will be redistributed to other injection wells to minimize the thermal impact of the most affected production well.

As for the dilute waters in the northeastern and southwestern sides of South Sambaloran, its influx to the production sector can only be minimized by reducing the extraction from the peripheral wells most adjacent to the sources. In this way, the decline in reservoir pressure that would eventually dictate the hydrological flow of cooler waters can be regulated.

5.0 CONCLUDING REMARKS

The Tongonan geothermal field has been in operation for twenty years and within this period, its reservoir underwent changes that are mainly in-response to field utilization. The reservoir experienced three major processes: (a) injection returns that led to decline in output of production wells near the Tongonan-1 injection sink, (b) extensive boiling that resulted to the lateral and vertical expansion of the shallow steam zone and (c) influx of cooler peripheral waters that threatens to quench the production sector of the southern section of the field.

From these processes, it has become apparent that the northern half of the field has limited recharge from the periphery and from the deep upflow. The southern half, on the other hand, has ample supply of peripheral fluids that recharges the Malitbog-South Sambaloran sector. But these waters are cooler and can potentially quench the production wells.

The present concern, however, is to guarantee the sustainability of the field. Some measures are already being implemented. The separated brine from South Sambaloran has been diverted to Tongonan-1 to provide mass recharge to the latter. The power plant condensate will be injected in Pad 4RC to recharge the dry wells of Upper Mahiao. Furthermore, numerical simulation will also be conducted to determine the optimum extraction rate that would regulate the inflow of cooler waters in the southern section of the field.

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