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CHARACTERIZATION OF THE DEEP GEOTHERMAL RESOURCE IN TONGONAN GEOTHERMAL FIELD (LEYTE, PHILIPPINES)

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ABSTRACT

The past 6 years saw rapid changes in the Tongonan geothermal reservoir as the field underwent full commercial operations starting in 1996 from 112 MWe to 550 MWe gross generation. The most prominent among the changes is the transformation of the discharge of production wells, mostly from the center of the field, from being liquid-dominated to steam-dominated.

In order to properly manage and sustain the reservoir, a geochemical evaluation was made of the deeper resource untapped by the production wells. The result showed that the reservoir is sustainable as the deeper part of the resource still hosts more than 90% of the hot geothermal liquid. The gas-mineral equilibria tool (FT-HSH2) developed by D'Amore gave an estimate of the steam fraction and temperature at the central region at 1-5% steam (or 95-99% liquid) and 290-310°C, respectively. A consistent temperature of 280-300°C of the same region was extrapolated from the Na/K geothermometer.

At the outflow region of the reservoir where production wells still have a liquid fraction in their discharge, a steam loss of 1% is estimated in areas with inflow of cooler peripheral waters and injected brine while a 5% steam fraction was noted in areas having higher-enthalpy production wells. The same gas-mineral equilibria method gave good agreements with the quartz geothermometer for the low-enthalpy wells signifying its fast re-equilibration. In dry wells, the method reflected higher temperatures indicating that the last re-equilibration of the participating species is far from the wellbore, probably at the point where water containing the reacting minerals is still present.

1.0 INTRODUCTION

The full commercial operations of the Tongonan geothermal field starting in 1996 brought about rapid changes in the reservoir. The initial operation, which began in 1983, involved only a 112.5 MWe power plant. By 1996-1998, the commissioning of new power plants raised the total generation to around 500 MWe. By 2000, this increased further to around 550 MWe when Tongonan started to augment the steam requirement of the neighboring Mahanagdong geothermal field (Fig. 1) through a steamline interconnection. The production history in terms of the monthly net mass extraction (i.e. total mass extraction less mass injected back to the reservoir) is presented in Figure 2. The figure shows the huge increase in the mass extracted during the full operations of the field, about 7 times the initial rate.

The most prominent among the changes in the reservoir to maximized exploitation is the transformation of the discharge of the production wells, mostly from the central part or near the upflow region, from liquid-dominated to steam-dominated. Majority of these wells are found in the Upper Mahiao and Tongonan-1 sectors (Fig. 1). Their discharge enthalpies increased sharply from 1600-1900 J/g to 2400-2700 J/g (Fig. 3) indicating two important related points: the reservoir is undergoing extensive boiling and there is limited or no natural recharge at all from the northern periphery of the field (Dacillo, 2003). Even the brine returns from the injection sinks of Tongonan-1 and Upper Mahiao did not persist because the separated brine decreased appreciably when the discharge enthalpies of production wells continued to increase.

The major outflow region, the South Sambaloran and Malitbog sectors, had an opposite response. Pressure drawdown drew in cooler meteoric waters inferred to be from the eastern and western periphery of South Sambaloran. This

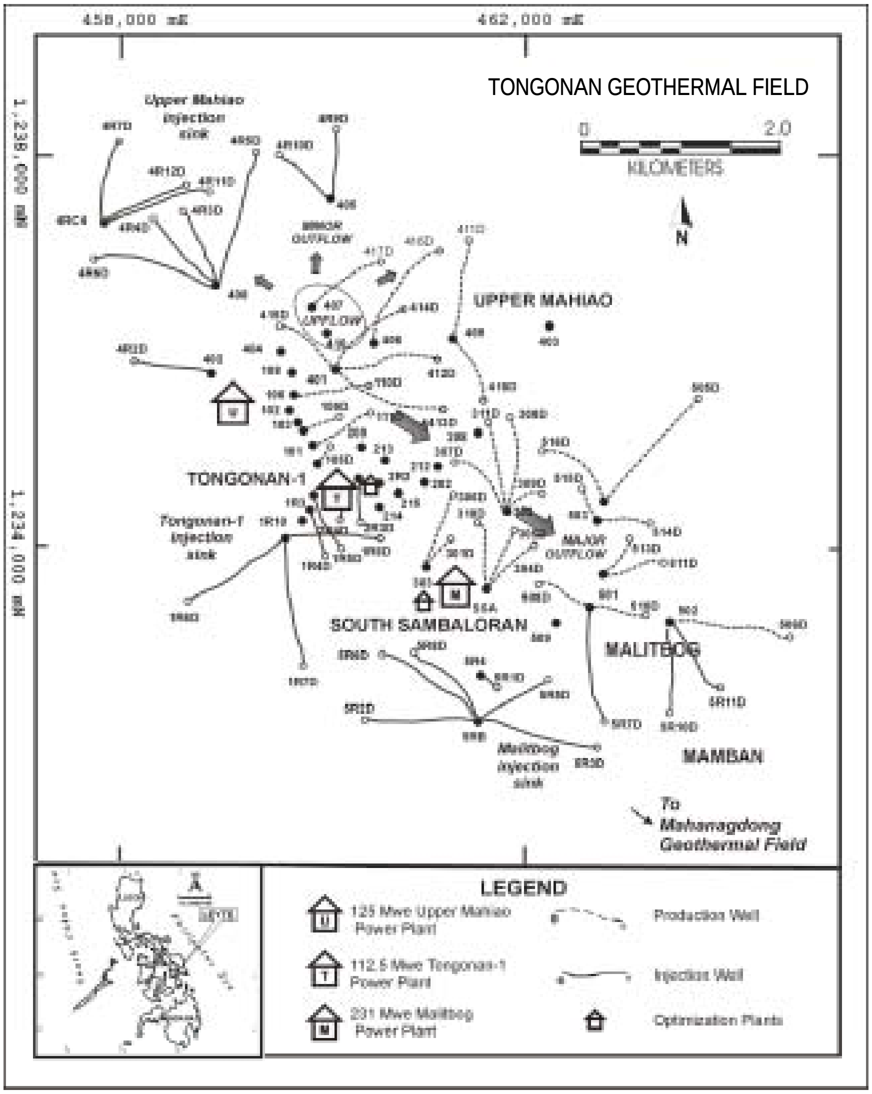

Figure 1. Map of Tongonan Geothermal Field subdivided into the sectors of Upper Mahiao (w/ 400-series name wells), Tongonan-1 (100&200-series wells), South Sambaloran (300-series wells) and Malitbog (500-series wells). Inset map: the Philippines.

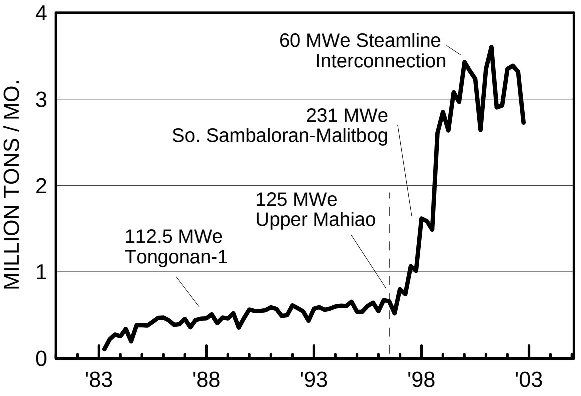

Figure 2. Historical trending of net mass extraction rate (i.e. total mass extracted less mass injected back to the reservoir).

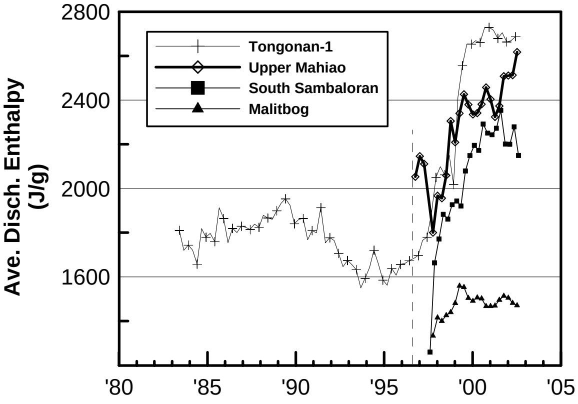

Figure 3. Plot of average enthalpy per sector with time.

kept the discharges of production wells at the margin of the sector at liquid enthalpies. Those located in the more central part have enthalpies closer to Upper Mahiao and Tongonan-1. In Malitbog, the production wells in the south have considerable inflow of the injected brine from the Malitbog injection sink. This artificial recharge maintained the sector's average enthalpy at less than 1600 J/g.

The concern on the sustainability of the reservoir encouraged this geochemical evaluation of the deeper aquifer. Characterization of the deeper parts of the resource has become important considering that the depth tapped by most of the existing production wells became dry. Specific parameters like the deep temperature and water fraction of the reservoir were sought using the FT-HSH2 method as the main tool in the evaluation. These and additional geochemical data were used to give a clearer picture of the deep fluids feeding the dry production wells in the north and the cold water-encroached wells in the south. The evaluation however, is limited only to the reservoir beneath the Tongonan geothermal field and does not include the reservoir of the Mahanagdong geothermal field. The resources of the two fields are separated by the cold and impermeable Mamban block (Alvis-Isidro *et al*., 1993).

2.0 METHOD

The use of geochemical tools based on water chemistry has been very efficient in monitoring the reservoir of Tongonan since the start of production in 1983. This is because the Tongonan reservoir is water-dominated. By 1996-1998 however, water chemistry became obsolete for most of the production wells in the northern half of Tongonan (Tongonan-1 and Upper Mahiao sectors) that eventually produced dry steam. Thus, different techniques developed using gas chemistry would be very helpful.

Two methods of calculating the reservoir steam fraction are known by this author, one from the group of D'Amore (D'Amore and Celati, 1983; D'Amore and Truesdell, 1995), the other from Arnorsson (1995). D'Amore's work revolves on various gas-mineral reactions that are assumed to have attained full equilibrium in the reservoir. The end parameters that are calculated from his method are the temperature and the steam fraction in the reservoir where thermodynamic and chemical equilibrium of the reactions are attained.

Siega *et al.* (1999) used D'Amore's method which are based on the different gas-mineral equilibria and evaluated their applicability of each in the different geothermal fields in the Philippines. The gas-gas and gas-mineral equilibria considered were the following:

$$FT : CH_4 + 2H_2O = CO_2 + 4H_2 \quad (1)$$

$$HSH1 : H_2 + 2H_2O + 3/2\, FeS_2 = 3H_2S + 1/2\, Fe_3O_4 \quad (2)$$

$$HSH2 : 5/4\, H_2 + 3/2\, FeS_2 + 3/4\, Fe_2O_3 + 7/4\, H_2O = 3H_2S + Fe_3O_4 \quad (3)$$

$$HSH3 : FeS_2 + H_2 = FeS + H_2S \quad (4)$$

where FT, HSH1, HSH2 and HSH3 are the symbols used to denote each reaction. However, only the combination of FT and HSH2 will be used in this paper since it is the most applicable and consistent for the mature hydrothermal system in Tongonan (Siega *et al.*, 1999). Expressing the above reactions in terms of the equilibrium constant equation and applying the law of mass action, equations 1 and 3 yield:

$$FT = 4 \log (H_2/H_2O) + \log (CO_2/H_2O) - \log (CH_4/H_2O) \quad (5)$$

$$FT = \log K_{FT} + 4 \log A_{H2} + \log A_{CO2} - \log A_{CH4} - 2 \log P_{H2O} \quad (6)$$

$$HSH2 = 3 \log (H_2S/H_2O) - 5/4 \log (H_2/H_2O) \quad (7)$$

$$HSH2 = \log K_{HSH2} + 3 \log A_{H2S} - 5/4 \log A_{H2} \quad (8)$$

The derivation of final equations 5 to 8 is detailed in Siega *et al.* (1999) and the guiding assumptions and limitations are found in D'Amore and Truesdell (1995) and D'Amore and Celati (1983). Equations 6 and 8 generate a "grid" while equations 5 and 7 are computed based on total gas compositions in the discharge of production wells. The values of the reservoir temperature and steam fraction become known by plotting the calculated values from equations 5 and 7 inside the "grid".

Arnorsson (1995) proposed a different approach to the estimation of the reservoir steam fraction. His method takes into account the possible segregation of the flowing water and steam in the aquifer. Such segregation will cause the discharge composition of gases to differ from that of the parent reservoir fluid. This is the main difference in the two methods since one of the basic assumptions of D'Amore and Celati (1983) is that no mass is gained or lost as the reservoir fluid is transferred to the wellhead. The reservoir steam fraction calculated from Arnosson's method is always lower than that of D'Amore and Truesdell. Examples given in Arnorsson's paper (1995) showed a range of 1-25% from D'Amore's method for Cerro Prieto in Mexico and Hveragerdi, Nesjavellir and Namafjall in Iceland whereas Arnorsson obtained -0.01 to 0.35% for the same fields.

For the purposes of this paper, the method of D'Amore (FT-HSH2) will be used considering that the author is looking for the widely-used method that would give the lowest reservoir water fraction (~the highest steam fraction), the worst picture that could be painted for the Tongonan reservoir. It is also already outside the scope of this paper to compare and validate, in the Tongonan setting, the two methods that have been discussed above.

3.0 RESULTS AND DISCUSSIONS

3.1 FT-HSH2

Figure 4 is a plot of gas data from all production wells before (pre-1997) and during (2002) the full exploitation of the field. The decline in reservoir pressures caused a general shift of data points towards higher reservoir steam fraction. This reflects the present condition of the reservoir: Extensive boiling which expanded vertically and laterally to form a shallow steam cap. Even the lower temperature wells exhibited increases from negative to close to zero steam fractions. These wells are those found in the margins of the southern major outflow. Their previous negative steam fraction values is due to mixing with the highly degassed injected brine from the injection sinks and, in some, by inflow of cooler meteoric waters with negligible gas content.

3.1.1 Upper Mahiao and Tongonan-1 Sectors

Aside from the general shift towards higher steam fraction, the year 2002 data appears to have clustered into two groups (Fig. 4). The first group has higher temperature and steam fraction. The second has lower temperature, and although a little dispersed, data plotted closer to zero steam fraction. If plotted by sector (Fig. 5a), the first group of data points belongs mostly to production wells from Upper Mahiao and Tongonan-1 which are presently discharging dry steam or an enthalpy above 2500 J/g. In the pre-1997 data, these two sectors have scattered data points. Those production wells with injection returns from the Tongonan-1 and Upper Mahiao injection sink plotted in the vapour loss region while those in the center of the sector plotted slightly above the single-phase liquid line reflecting the presence of the natural, shallow steam-cap in the reservoir.

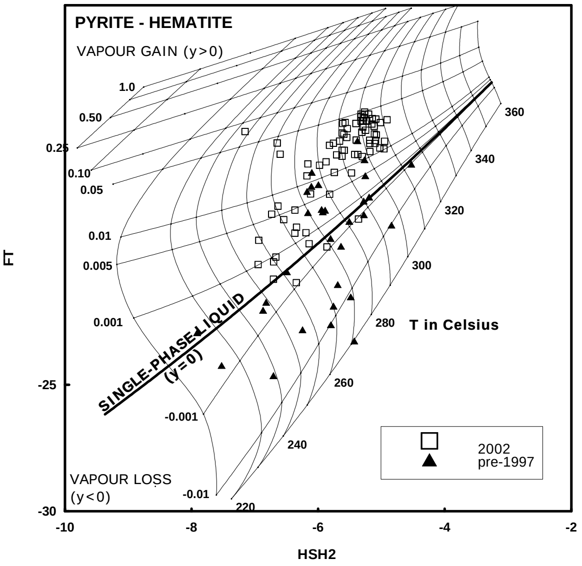

Figure 4. FT-HSH2 of all production wells in Tongonan Geothermal Field before (pre-1997) and during full exploitation (2002).

In the 2002 data wherein full exploitation has commenced and injection returns have declined, it appears that pressure drawdown forced the data points of the two sectors to cluster inside the 290-310°C isotherms and 1-5% steam fraction. This is about the same as the baseline temperature that has been measured in two Upper Mahiao wells, wells 407 and 410, considered to have hit the upflow region of the reservoir because both have the highest temperature (>300°C) among all production wells. Geochemical and isotopic data support the location of the upflow within this area (Salonga *et al.*, 1996).

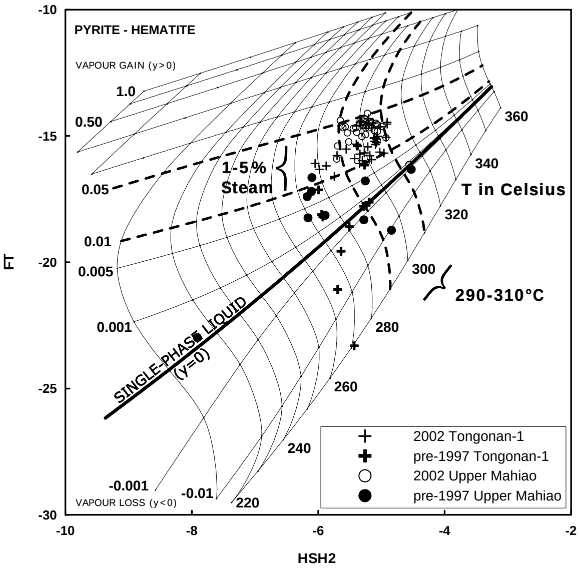

Figure 5a. FT-HSH2 of all Upper Mahiao and Tongonan-1 wells before (pre-1997) and during full exploitation (2002).

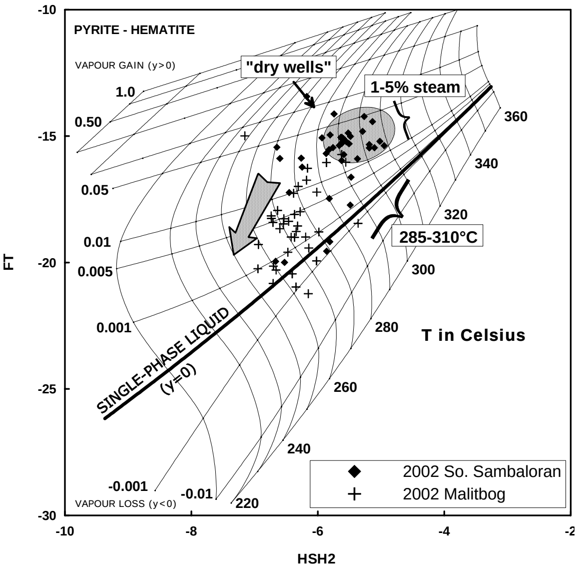

Figure 5b. FT-HSH2 of South Sambaloran and Malitbog wells during full exploitation (2002).

The year 2002 temperature is also about 10-20°C higher than the average temperature in the pre-1997 data suggesting that the gaseous and aqueous mineral species considered in the FT-HSH2 reactions have equilibrated deeper into the hotter regions of the reservoir and farther away from the lower temperature boreholes. This is consistent with the observed increase in steam fraction and discharge enthalpies which indicated that the geothermal waters bearing the dissolved participating minerals have receded deeper in the reservoir.

Moreover, the uniform temperature suggests that no further re-equilibration is taking place as the dry steam is being transported towards the minor outflow in Upper Mahiao to the north. What is “remembered” in the gas composition of the dry wells is the temperature information possibly of the hottest area, the liquid upflow, where the last re-equilibration is assumed to have taken place.

With this temperature and steam fraction of 1-5%, the deeper part of the resource beneath the Tongonan-1 and Upper Mahiao sectors still hosts around 95-99% hot geothermal liquid.

3.1.2 South Sambaloran and Malitbog Sectors

Unlike Upper Mahiao and Tongonan-1, the data points of Malitbog and South Sambaloran sectors are dispersed over a wider range of temperature from 245 to 310°C (Fig. 5b). It is interesting to note that the dry wells of South Sambaloran have plotted between the 285-310°C isotherms and 1-5% steam fraction, which is similar to the dry wells of Tongonan-1 and Upper Mahiao. What this means is that the dry South Sambaloran wells are drawing steam from the same area as that of Tongonan-1 and Upper Mahiao even though this sector is already far from the upflow. The other South Sambaloran data points with 1-5% steam fraction but with lower temperature at 260-280°C, may have fluid contribution from deeper source at the area with lower temperature near or beneath South Sambaloran.

For the rest of the South Sambaloran and Malitbog data points, there is a gradual decline in temperature as well as in the steam fraction. This reflects the gradual cooling of geothermal fluids as they flow from the upflow towards Malitbog-South Sambaloran outflow and mix with the cooler meteoric waters and injection brine. Also, the FT-HSH2 geothermometer has good agreement with the quartz geothermometer for the watery production wells of Malitbog (Fig. 6). This means that the participating species in the FT-HSH2 method seem to re-equilibrate as fast as quartz as long as all these species are present. In the case of the low enthalpy wells of Malitbog, the dissolved minerals and the gases are there so that the temperatures reflected are those near the wellbore.

In the case of dry wells of Upper Mahiao, Tongonan-1 and South Sambaloran, the participating species have equilibrated deeper or far from the wellbore, probably at the point where the water bearing the minerals is still present. Only the gases, which retained the thermal impression of the area of the last equilibration, have reached the wellbores.

As to the value of the steam fraction which is close to zero (or water fraction of ~100%), it would initially look as if the sustainability of the sector is not in question because the deep fluids flowing into the Malitbog sector have not dried out like in the case of Tongonan-1 and Upper Mahiao. However, the real problem lies in the magnitude of inflowing cooler waters. This is discussed more clearly in the following section.

3.2 Water Chemistry Data

In addition to the FT-HSH2 method, water chemistry data from the remaining few watery wells in South Sambaloran were also used to further characterize the deeper fluids feeding the production wells. Figure 7 is a geochemical trending of well 309D, which has been encroached with cooler, dilute waters from the eastern side of South Sambaloran.

The well initially experienced boiling as evidenced by the increase in discharge enthalpy from 1400 to 2200 J/g in 1997 to 1998. With the continued decline in reservoir pressure however, the well drew in cooler, dilute waters as indicated by the decline in enthalpy, reservoir chloride and quartz geotemperature starting in year 2000. By the early part of 2002 however, the influx of cooler waters appears to have equilibrated as shown by the leveling off of the T-Quartz at 275°C, reservoir chloride at 8000 mg/kg and discharge enthalpy at 1600 J/g. The fact that these significant parameters did not continue to decline towards the cold and dilute meteoric end-member means that there is still hot and saline geothermal liquid flowing towards the South Sambaloran and Malitbog sectors. This is not clearly seen in Upper Mahiao, Tongonan-1 and in the dry areas of South Sambaloran because of the thick dry steam cap that is present at the depths of the production wells. The geothermal liquid flowing under the steam cap from the upflow to the outflow region manifested only in some production wells in South Sambaloran and in majority of the wells in Malitbog where the steam cap is thin (y<1%). In addition, the geothermal liquid obviously has higher temperature (>275°C) and salinity (>8000 mg/kg Cl) than the mixed fluids in well 309D.

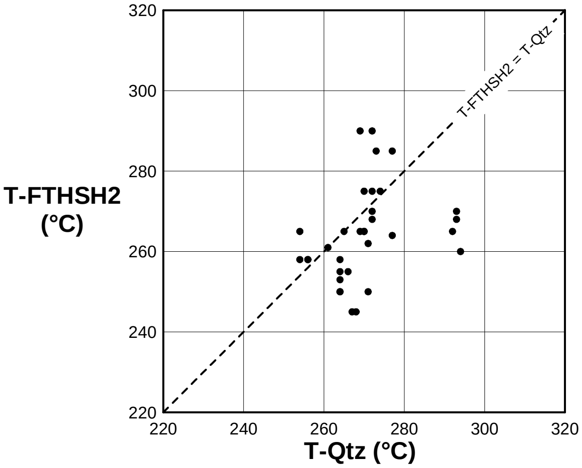

Figure 6. T-FTHSH2 vs. T-Qtz (2002) of the watery wells of Malitbog.

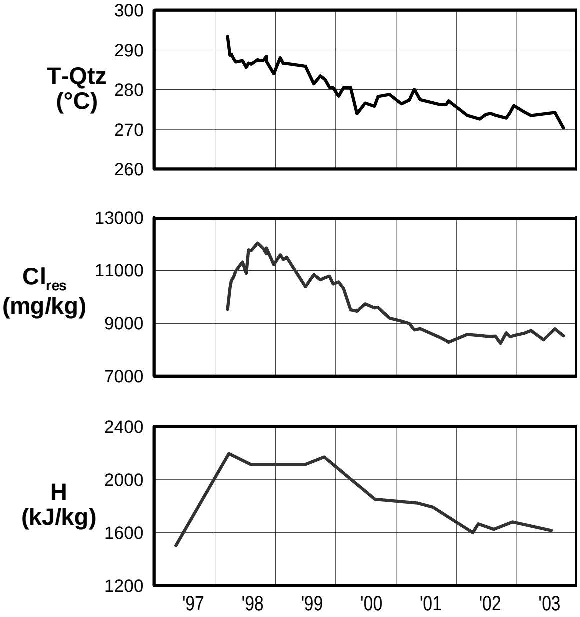

Figure 7. Geochemical trend of Well 309D which is encroached with cooler, dilute meteoric waters.

3.3 Na/K Geothermometer

The results of the FT-HSH2 for the Malitbog sector and the watery areas of South

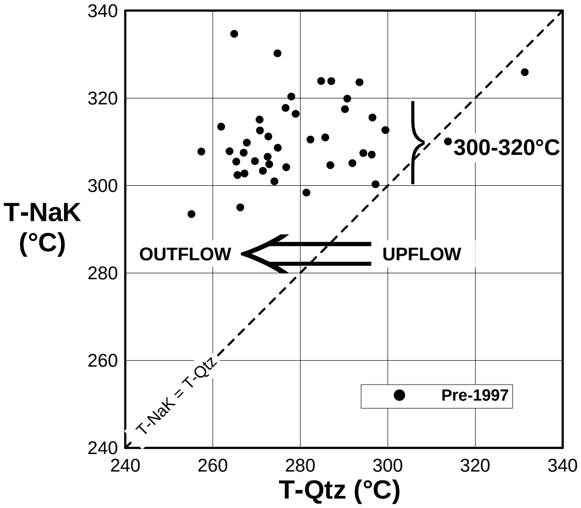

Figure 8. Pre-1997 Na/K geotemperature of all wells in Tongonan Geothermal Field.

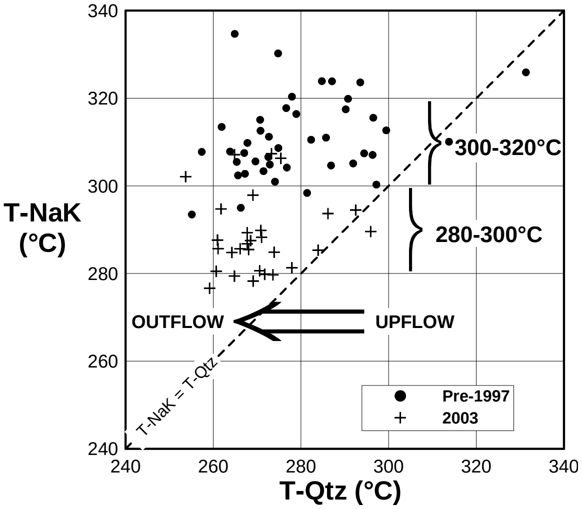

Figure 9. Na/K geotemperature before (pre-1997 data of all wells in Tongonan Goethermal Field) and during (2003 data of Malitbog and the remaining watery wells in South Sambaloran) full exploitation of the field.

Sambaloran have been somehow validated by the water chemistry data. As for Tongonan-1, Upper Mahiao and the dry wells of South Sambaloran, the Na/K geothermometer is utilized.

Due to the slow response of the Na/K geothermometer to the prevailing temperature in the different section of the reservoir, the Tongonan experience is that the values obtained from this geothermometer remains relatively constant from the upflow to the outflow. This is shown in Figure 8 where the Na/K temperatures are plotted with the fast-equilibrating quartz temperature using the pre-1997 data when the production wells of the whole field still have considerable water fraction at the wellhead. The Na/K geothermometer retained the 300-320°C temperature of the parent fluids from the upflow region all the way to the outflow whereas quartz temperature declined from 300 to 260°C. The Na/K geothermometer was virtually unaffected by cooling due to conduction and gradual mixing of cooler meteoric waters and returns of the injected brine.

Using this understanding, the 2002 water chemistry data of the only remaining watery wells in outflow region of South Sambaloran and Malitbog sectors were used to extrapolate the temperature of the parent fluids under the Upper Mahiao sector. In Figure 9, results show that the Na/K geothermometer of 280-310°C is comparable to the 290-310°C temperature of FT-HSH2. This independently validated the temperature estimated by the FT-HSH2 method. Also, the 2002 data is lower by about 20°C than the pre-1997 data which is probably due to pressure drawdown.

4.0 SUMMARY AND CONCLUSIONS

Pressure drawdown and limited recharge in the northern half of the field transformed the discharge of production wells in Upper Mahiao, Tongonan-1 and the central part of South Sambaloran from liquid-dominated to steam-dominated during the full exploitation of the field. The reservoir though is still sustainable as the FT-HSH2 method estimated 95-99% geothermal liquid with a temperature of 290-310°C present beneath the expanded steam cap that is feeding the dry production wells. The extrapolated Na/K geothermometer independently validated the presence of 280-300°C parent fluids.

Most of the dry wells of South Sambaloran is drawing the more mobile steam boiled off from the upflow zone with less contribution from the liquid that is flowing from the upflow to the outflow under the steam cap. The outflowing geothermal liquid is not seen in the production wells of Upper Mahiao, Tongonan-1 and the central part of South Sambaloran because of the expanded steam cap present at the depths of the production wells. It manifests only in the margins of South Sambaloran and the whole Malitbog sector where steam cap is thin (y<1%). The remaining watery wells in South Sambaloran and Malitbog showed that the outflowing geothermal liquid has high temperature (>275°C) and salinity (>8000 mg/kg) before mixing with the cooler peripheral waters (meteoric and injection returns) in these sectors.

The same gas-mineral equilibria method gave good agreements with the quartz geothermometer for the low-enthalpy wells signifying its fast re-equilibration. In dry wells, the method reflected higher temperatures indicating that the last re-equilibration of the participating species is far from the wellbore, probably at the point where water containing the reacting minerals is still present.

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