TRENDS OF FLUID ENTHALPY BASED ON SOLUTE GEOTHERMOMETERS AS INDICATOR OF RESERVOIR PROCESSES IN TONGONAN GEOTHERMAL FIELD, LEYTE, PHILIPPINES

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ABSTRACT

The trends of enthalpy based on physical measurement and solute geothermometer of T(SiO_2) and T(Na-K-Ca) are used as indicator of near-well reservoir processes in Tongonan production wells that have been utilized since 1983. The application of this method on selected wells shows promising results since identified reservoir processes based on enthalpy trends are consistent with that observed from other chemical parameters such as Cl trends.

*The identified reservoir processes include the following: (1) no boiling or mixing indicated by E-meas = E-nkc = E-silica and exhibited by production wells located near the outflow region in Malitbog sector such as well **501**, uhich is characterized by liquid-dominated discharge with stable fluid chemistry; (2) localized pressure drawdown indicated by E-meas > E-nkc > E-silica and observed in production wells 102, 106, 110D and 401 located near the upflow region in Upper Mahiao sector; (3) reinjection fluid mixing indicated by E-nkc > E-meas = E-silica and observed in production wells 105D and 212 located near the reinjection sink of Tongonan-1; **(4)** reservoir-wide drawdown indicated by E-meas > E-nkc = E-silica and exhibited by production wells located in Sambaloran sector such as well 212; and **(5)** mixing of cooler meteoric water indicated by E-nkc > E-silica > E-meas and observed in wells 508, 102 and 106.*

1.0 INTRODUCTION

The Tongonan geothermal field, located in north-northwest Leyte, has three installed power plants with total generating capacity of 468 MWe (Fig. 1). The expected commercial operation of these power plants will definitely cause adverse changes in Tongonan reservoir (Salonga et al., 1996). It is then necessary to effectively assess these changes through geochemical monitoring of individual wells. The use of enthalpy trends is believed to indicate near-well reservoir processes. This approach has been applied in selected Tongonan wells with the objective of identifying major reservoir processes within the field.

2.0 DATA REDUCTION AND EVALUATION

There are nine production wells used for this evaluation, namely, wells 102, 105D, 106 and 110D in Mahiao, wells 212 and 213 in Sambaloran, well 401 in Upper Mahiao, and wells 501 and 508 in Malitbog. Water samples were collected in these wells at frequent interval since 1978 and analyzed for selected chemical parameters such as Na, K, Ca and SiO_2.

The needed chemical geothermometers, namely, quartz and Na-K-Ca geothermometers, from 1978 to 1997 in each well were collated. Using steam table data for pure water, these temperatures are converted to enthalpy of reservoir liquid for comparison with measured enthalpy values. These quantities are abbreviated as E-mas, E-quartz and E-nkc, indicating enthalpy values from Bore Output Measurements (BOM) or Tracer Flow Testing (TFT), quartz and Na-K-Ca geothermometers, respectively.

The collated enthalpy data from selected wells in Tongonan are plotted with time. These are evaluated through established pattern by Truesdell (1995) and summarized in the table below.

·esponding interpretation.

Process #	Pattern	Interpretation
1	E-meas = E-nkc = E-silica	All-liquid, fully-equilibrated reservoir fluid with no boiling or mixin
2	E-mas > E-nkc > E-silica	Fluid boiling during flow to well in response to localized pressure drawdown
3	E-nkc > E-meas = E-silica	Mixing with cooler water near *the* well with reequilibration of silica
4	E-meas > E-nkc = E-silica	Reservoir-wide boiling with phase segregation and separate entries of steam and water, mixing of equilibrated liquid with steam formed from boiling
5	E-nkc > E-silica > E-meas	Inflow of shallow, cooler, more dilute water into a well

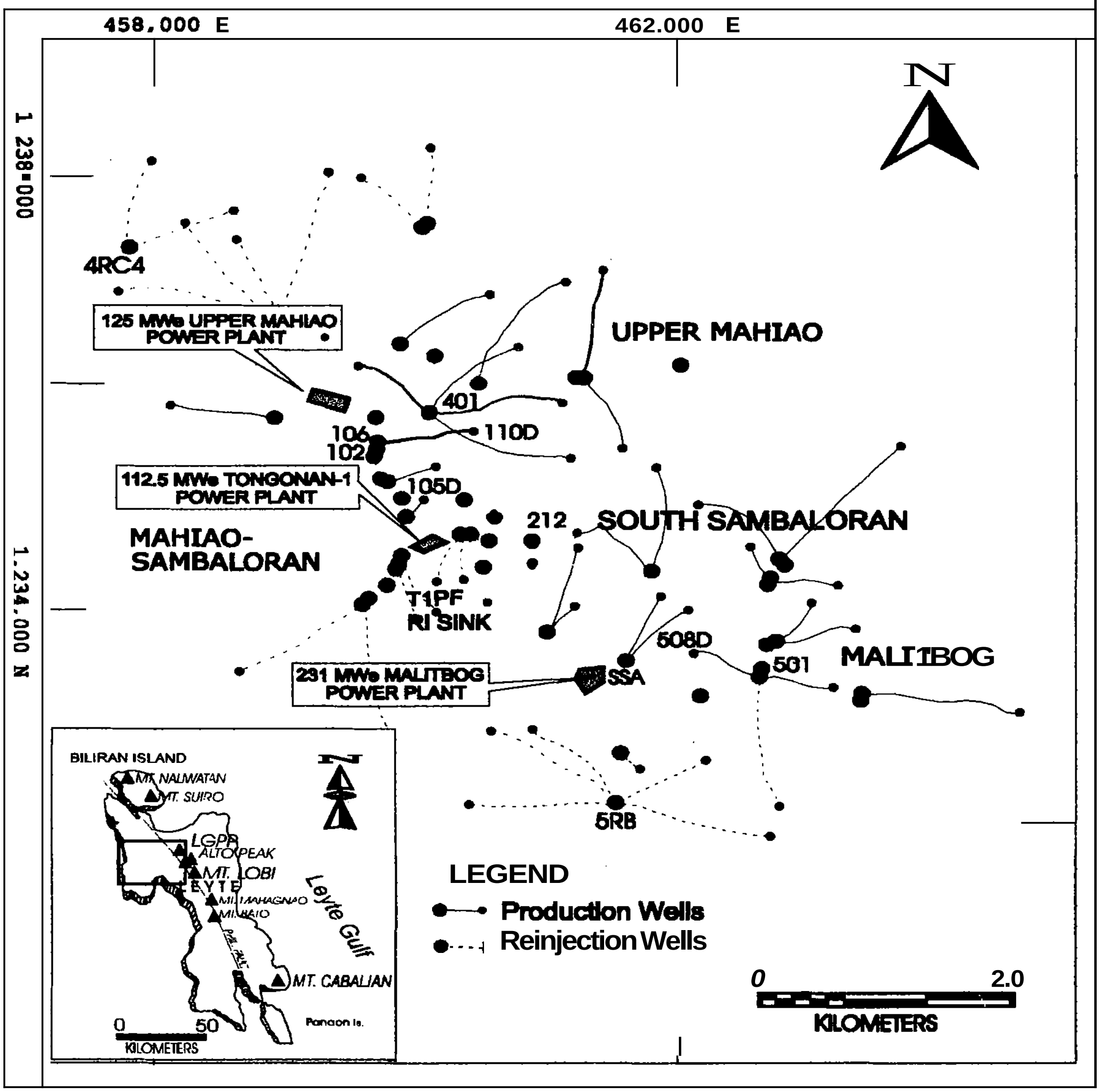


Figure 1. Map of Tongonan Geothermal Field showing the location of the production and reinjection wells and the existing power plants.

3.0 RESERVOIR PROCESSES

Monitoring of changes in selected geochemical parameters such as Cl_{res}, $T(SiO_2)$, CO_{2td} and Cl/Ca ratio in Tongonan wells have identified major reservoir processes such as localized and field-wide drawdown. and presence of reinjection fluid returns (Siega et al., 1996-97). The trends indicated by enthalpy likewise provided evidence on the present fluid state **and** temperature. The identified reservoir processes since 1983 were reconciled with the results of enthalpy trends in the following sections.

Wells with fully equilibrated fluids

Figures 2 shows the fluid enthalpy trends of well 501 in Malitbog sector. The pattern in well 501 is E-meas = E-nkc = E-silica indicating production from equilibrated liquid reservoir with no boiling or **mixing.** Production well chemistry monitoring conducted in Malitbog sector indicates most of the wells having stable fluid chemistry with liquid dominated discharge.

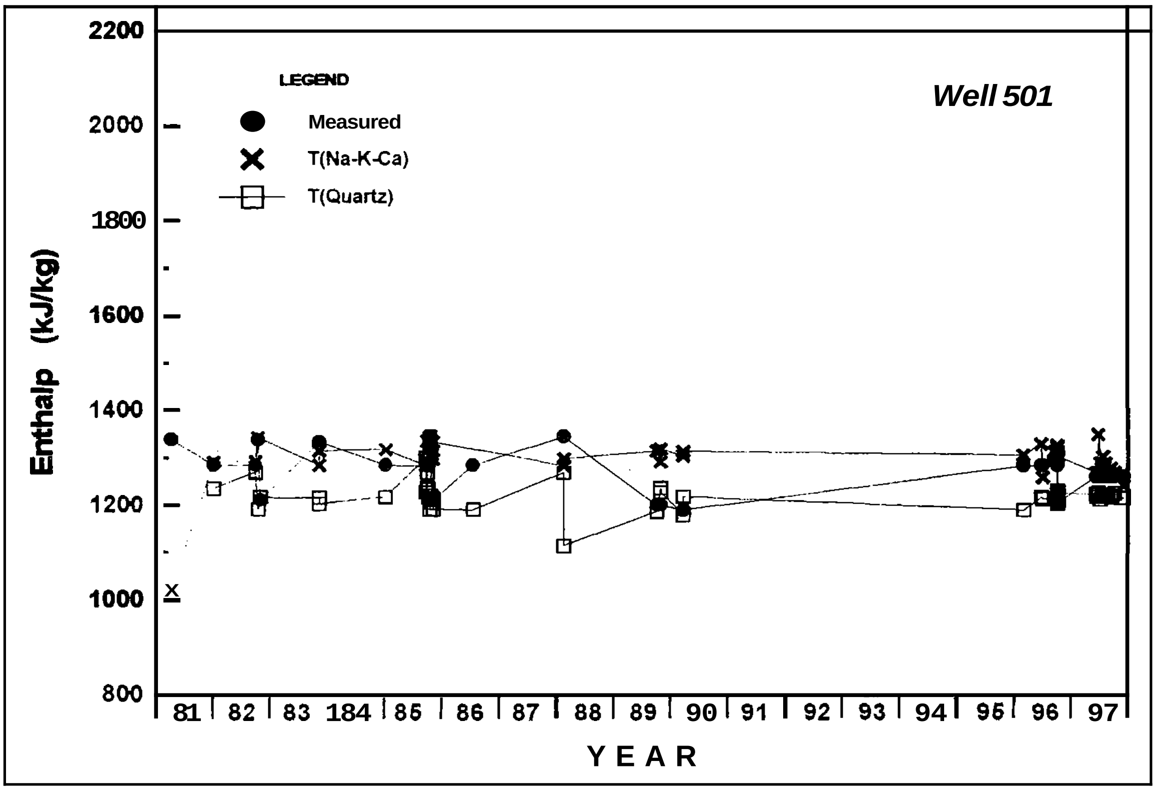


*Figure 2. Malitbog well **501.** The pattern in well 501 **is E-meas** = Enkc = E-silica indicating production from equilibrated liquid with no boiling **or** mixing.*

Reinjection fluids mixing

The fluid enthalpy trends of well 105D in Mahiao sector is presented in Figure 3. The pattern before 1983 is E-meas = E-nkc = E-silica indicating equilibrated liquid with no boiling and mixing. With the **start** of commercial operation of Tongonan-1 power plant and cut-in of well 105D, the pattern becomes E-meas>E-nkc>E-silica suggesting fluid boiling during flow to the well in response to decrease in well-**bottom** pressure. After 1991, E-meas declined to a value equal to E-silica and producing the pattern E-nkc>E-meas=E-silica. The trend usually results from mixing with cooler water near the well with the re-equilibration of E-silica but not E-nkc. This **period** is believed to be the onset of reinjection fluid breakthrough into the production sector as RI load in Tongonan sink was increased in 1989.

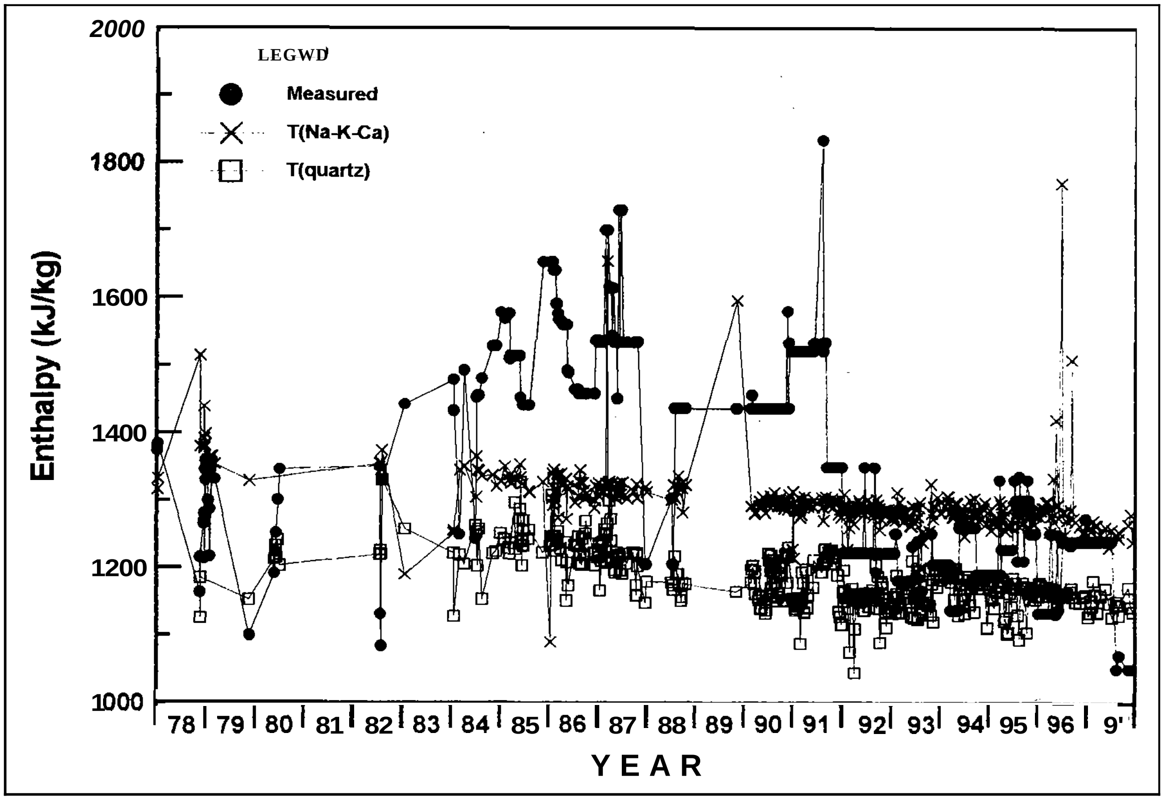


Figure 3. Mahiao well 105D. Changes with time ofjluid enthalpies. The pattern before 1983 suggests equilibrated liquid with no boiling and mixing. From 1983-1991, the pattern indicates local boiling and after 1991, inflow of cooler RI fluid caused the pattern of E-nkc > E-meas = E-silica.

Similar trends can be observed in Cl shown in Figure 4. Increase in Cl from 1983-88 is attributed to local boiling which apparently receded in 1989. The increase again in Cl starting 1991 coupled with the decline in measured enthalpy is attributed to presence of reinjection fluid returns in well 105D.

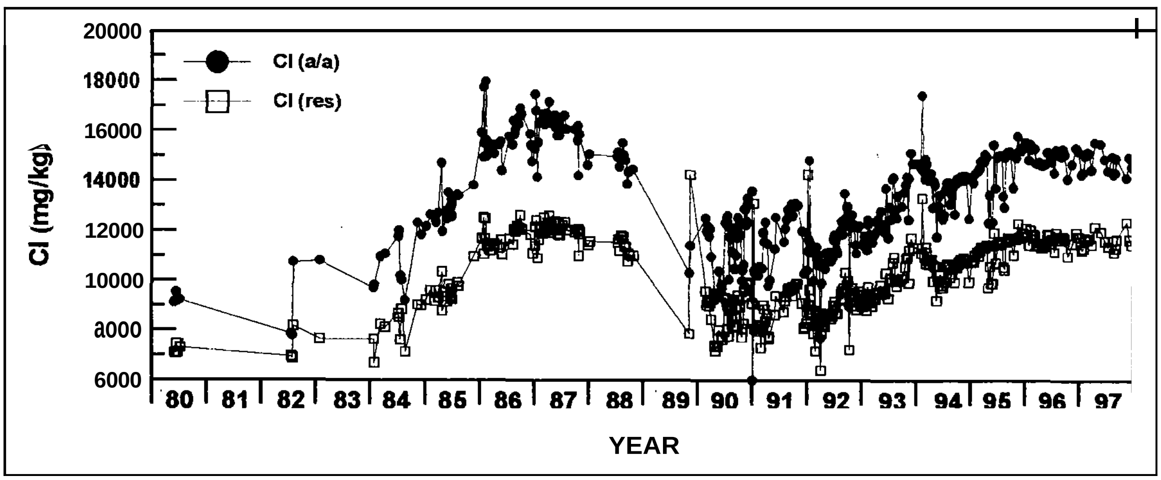


Figure 4. Mahiao well 105D. Chloride trends with time indcating several processes affecting the well. The increase in Cl from 1983-88 is attributed to localized drawdown while after 1991 is due to presence of reinjection fluid.

Well 508 enthalpy pattern before 1996 is E-nkc > E-silica > E-meas suggesting mixture in the well of cooler more dilute water with the equilibrated liquid (Fig. **5)**. However, with the start of reinjection at Malitbog RI wells in 1996, possible presence of RI fluids in the vicinity of well ***508*** could have **caused** the enthalpy pattern of E-nkc > E-meas = E-silica. **This** pattern indicates mixing with cooler water near the well with the re-equilibration of E-silica. The Cl trend with time of well **508 shown** in Figure 6 indicates slight increase in Cl level in 1996, which coincide with the enthalpy pattern.

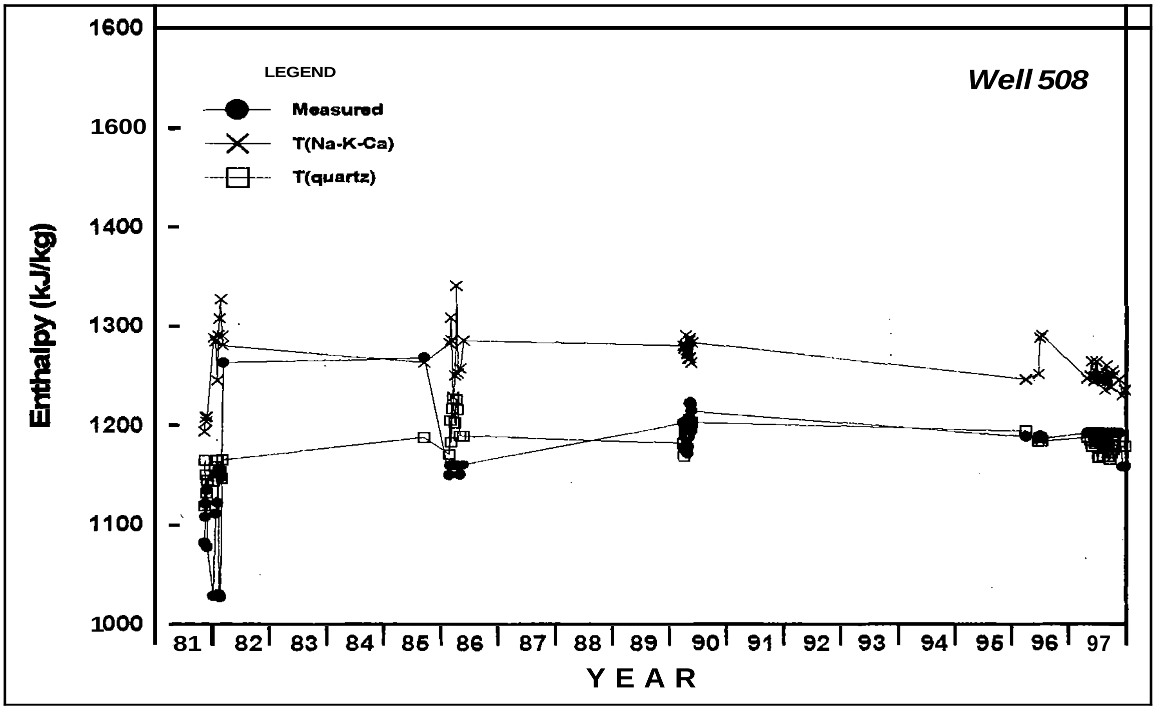


Figure 5. Malitbog well 508. Well 508 enthalpy trends before 1996 suggest mixing of cooler dilute water with equilibrated liquid. After 1996, the trend becomes E-nkc > E-meas = E-silica possibly due to mixing with cooler water with re-equilibration of silica.

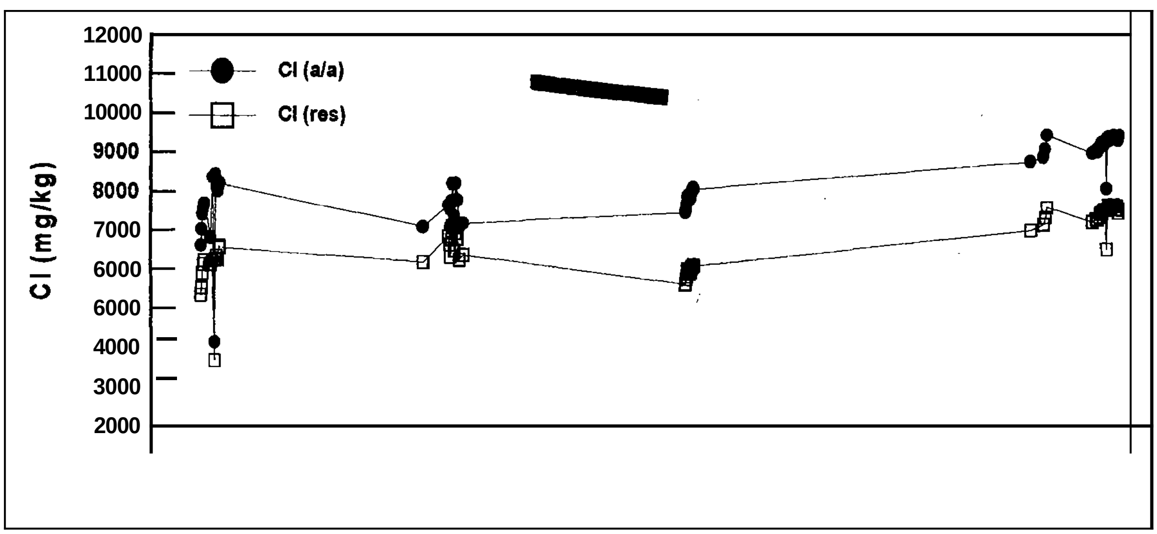


Figure 6. Well 508 Cl trend with time. Slight increase in Cl level is observed in 1996 which coincide with the enthalpy pattern of E-nkc>E-meas=E-silica.

Localizedpressure drawdown

The pattern shown by wells 102 and 106 before 1994 is E-meas > E-nkc > E-silica whch indicates local boiling in response to decrease in well-bottom pressure (Fig. 7). These wells are located on the same pad and proximate to the identified upflow region in Upper Mahiao sector.

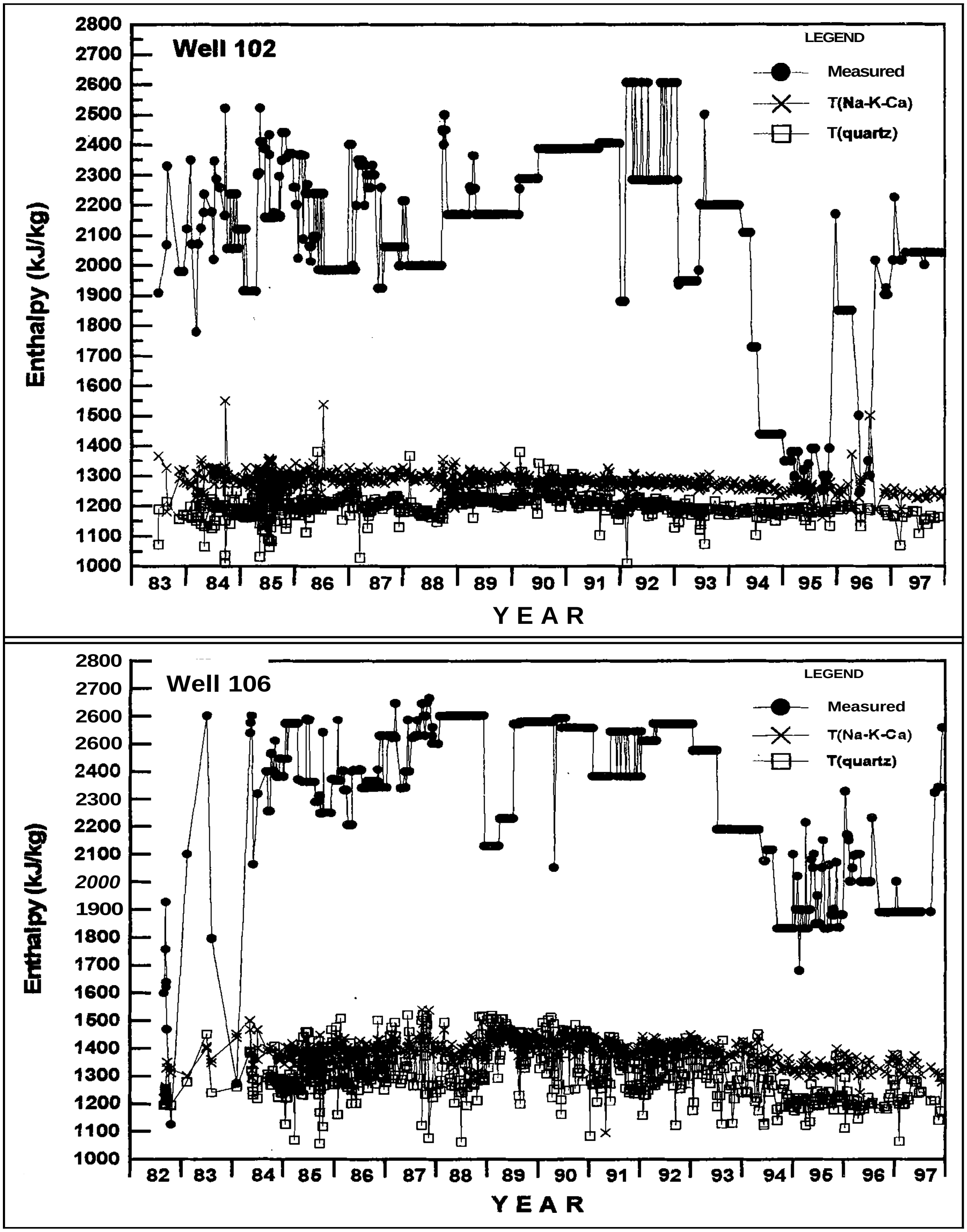


Figure 7. Wells 102 and 106 in Mahiao sector. Fluid enthalpy values indicate localized near-well boiling from 1983-1994 which apparently stabilized in 1995.

After 1994, the pattern in well 102 becomes E-meas = E-nkc > E-silica. This usually indicates that local boiling experienced by well 102 may have gradually slows and stops. One plausible explanation for this is the inflow of cooler fluids from the north-northwest area of the field. The inflow could have stabilized the well-bottom pressure and halts further expansion of the boiling zone. Within this zone, temperatures equilibrate and heat is no longer transferred so excess enthalpy disappears resulting to the observed decline in measured enthalpy. Similar trend could be observed in well 106 although local boiling has not completely stops. With the utilization of wells in Upper Mahiao, wells 102 and 106 again showed the same pattern as in the period 1983-1994.

The changes observed in aquifer chloride likewise suggest similar reservoir process affectingthese wells (Fig. 8). The boiling experienced by wells 102 and 106 in 1983-1994 could account to the increase in chloride. However, as both wells showed stabilized condition in 1994, corresponding decline in chloride is observed.

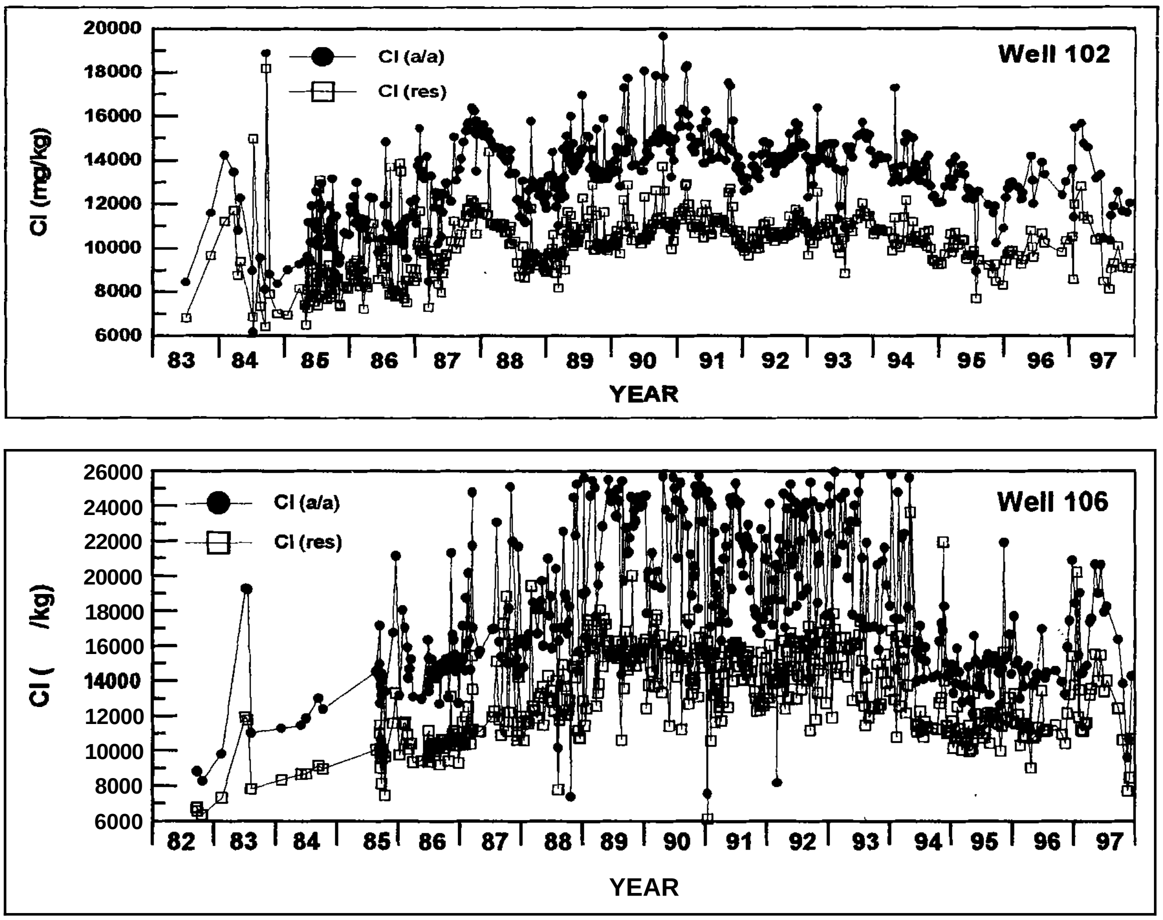
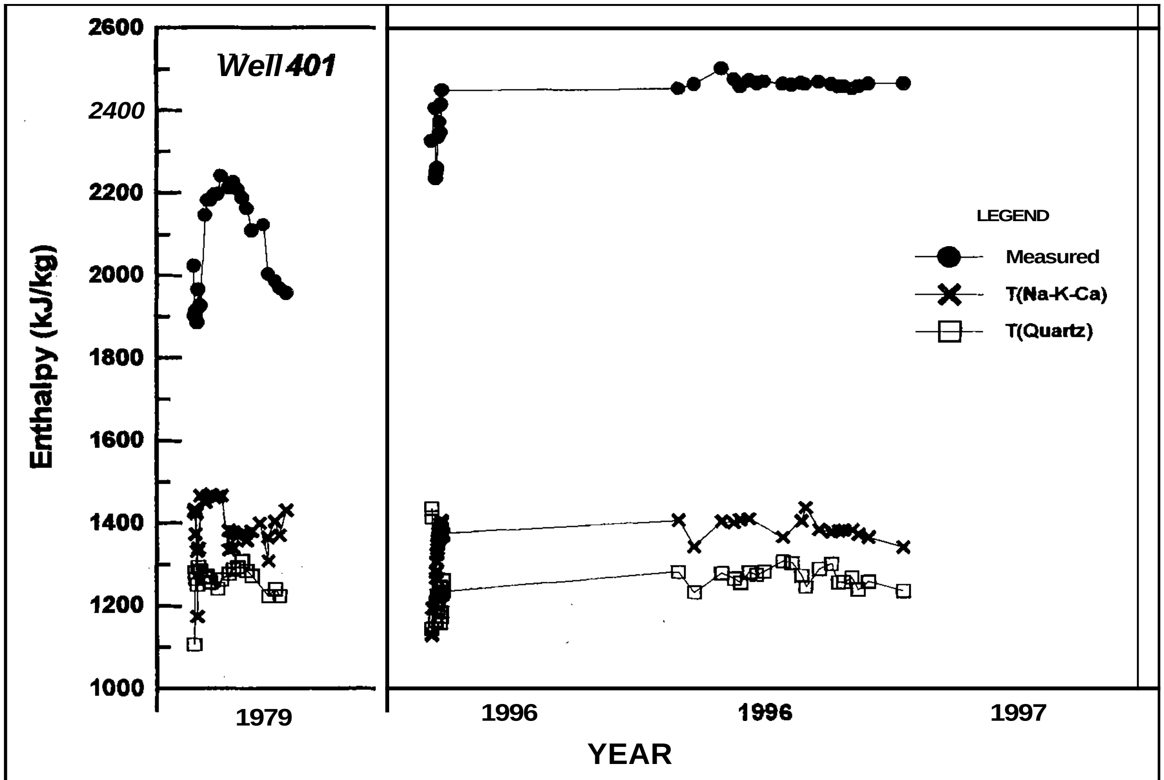


Figure 8. Mahiao wells 102 and 106 Cl trends. Increase in Cl in both wells starting from 1983 up to 1994 is attributed to localized near-well boiling.

Wells 401 and 110D, which are located near the upflow region of Tongonan and believed to have well-well connection, show similar enthalpy pattern as in wells 102 and 106 (Fig. 9). This would indicate that these wells are also experiencing localized near-well boiling. Present chemistry monitoring showed increase in mineralization in well 401 (Siega et al., 1996-97). Towards the end of 1996, well 1101) showed significant decline in output and enthalpy. The go-devil survey conducted in this well confirmed blockage at its lower zone, which would explain the increase in measured enthalpy and decline in enthalpy based on cations and silica geothermometer. The trend suggests production mainly from steam-dominated upper zone.



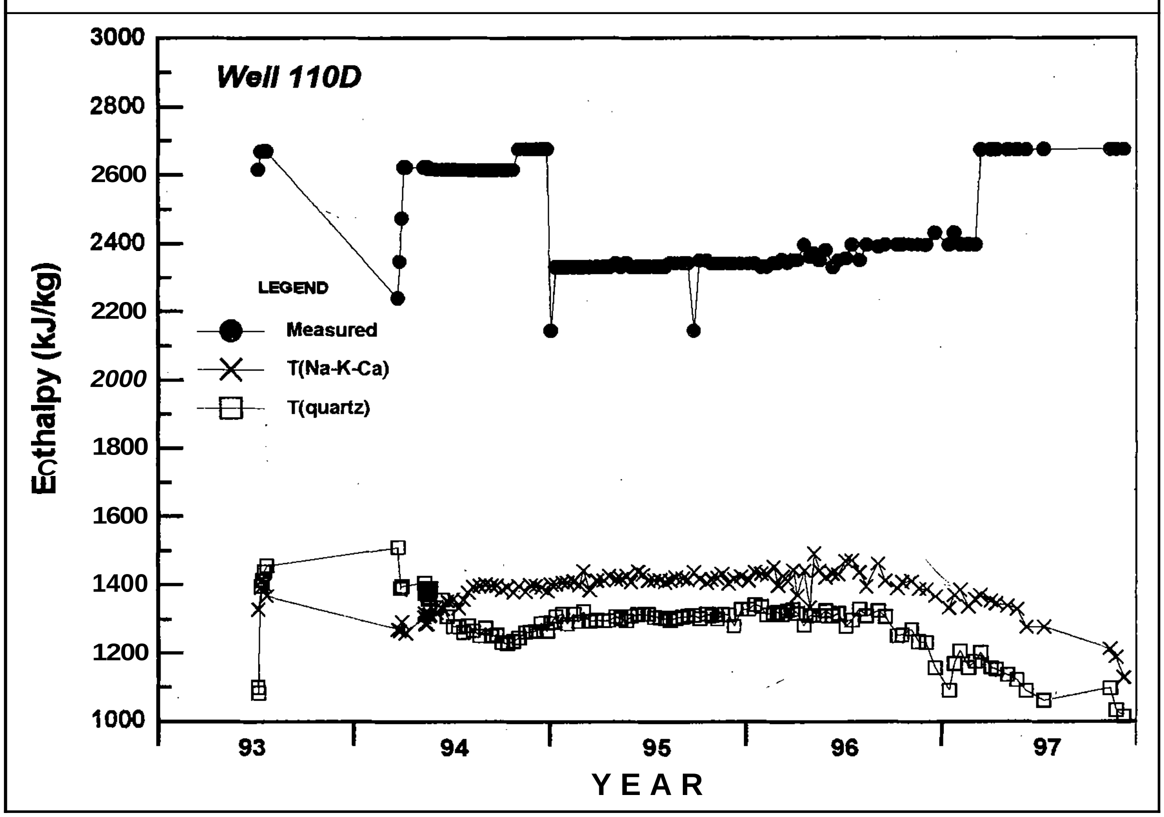


Figure 9. Wells 401 and 11OD. The enthalpy pattern shown by these wells indicate localized near-well boiling. Both wells are located near the upflow region of Tongonan and observed to have well-well connection.

Reservoir-wide drawdown

The general enthalpy trend in well 212 from 1983-1987 indicates local boiling which coincide with the observed increase in Cl level (Fig. 10-11). In 1992-94, apparent equlibration of enthalpy values is observed which could be attributed to the influence of reinjection returns in Sambaloran sector. The presence of RI returns may have halt the further expansion of the boiling zone. With the reduction in reinjection load at TlPF sink in 1995, significant increase in measured enthalpy and decline in E-nkc and E-silica could be observed in 1997. This trend is attributed to the extensive boiling happening in Sambaloran sector from 1996-97, which possibly expand the two-phase zone and caused steam dilution. The Cl trend likewise showed this process where in the period 1995-97, increasing and subsequent decline in Cl level can be observed. The trend shown by well 212 in the later part of 1997 could not be correlated with the enthalpy patterns tabulated in Table 1 possibly since it was already discharging pure steam.

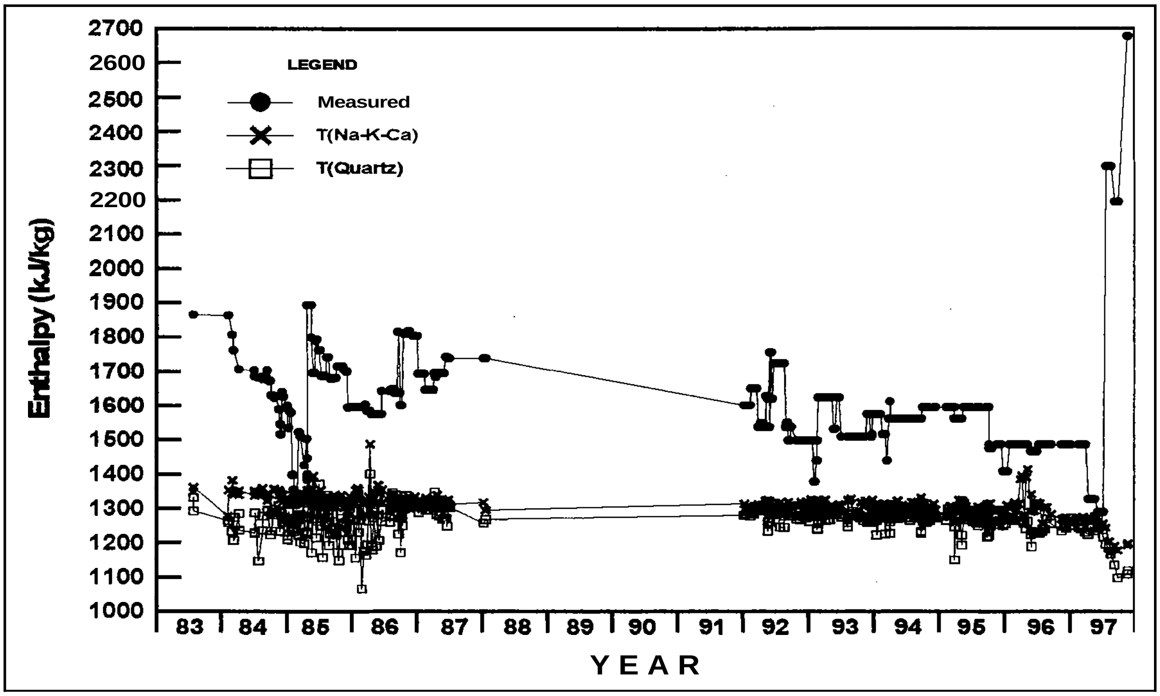


Figure 10. Well 212 in Sambaloran. General enthalpy pattern observed in 1983-87 is E-meas >E-nkc > E-silica indicating localized drawdown. The apparent equilibration of enthalpy values in 1992 until 1996 suggests the stabilization of the boiling experienced by well 212 possibly due to influence of RI returns.

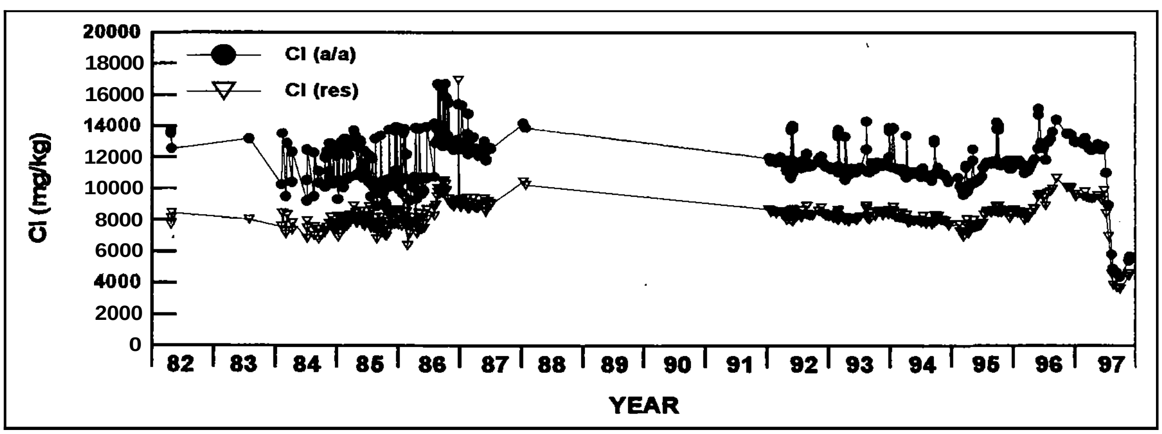


Figure 11. Well 212 Cl trend Increase in Cl in 1983-87 is attributed to local boiling. Presence of RI returns caused the stabilization of Cl level in 1992-94. Increase and subsequent decline in Cl in 1995-97 is attributed to extensive boiling due to reduced RI load at TlPF sink and steam dilution.

4.0 SUMMARY

The wells located in Malitbog sector typically exhibited the pattern E-meas = E-nkc = E-silica (pattern 1 of Table 1) suggesting production from all-liquid, fully equilibrated reservoir fluids. The present chemistry of these wells in Malitbog showed single-phase liquid dominating the discharge.

The second pattern E-meas > E-nkc > E-silica is a result of localized near-well boiling in response to the decrease in well-bottom pressure. This lowers near-well fluid temperatures and causes heat transfer from deep hotter rock to increase E-meas values. The silica re-equilibrates with the change in temperature thereby causing E-silica values to decrease. E-nkc remained relatively stable since the slower equilibration of cations with aluminosilicate minerals does not occur as the conduits are lined with quartz. This process, which was present during the first five years (1983-1988) of Tongonan-l operations, are exhibited by wells 102, 105D, 110D, 106 and 212.

When well-bottom pressures gradually stabilized and expansion of the boiling zone ceased, the order then becomes E-meas = E-nkc > E-silica. This happens when the pressures are controlled by a constant pressure boundary, and within the stabilized boiling zone, temperatures equilibrate and heat is no longer transferred so excess enthalpy decreases and E-meas equals E-nkc. E-silica still shows lower values since near-well boiling and temperature decrease continues. This trend is indicated in some of the Mahiao and Upper Mahiao wells, whch based on other chemical parameters, are affected by local boiling since 1983.

The mixing of cooler water near the well with re-equilibration of E-silica but not E-nkc is indicated by enthalpy pattern of E-nkc > E-meas = E-silica. Production wells located near the T1PF sink affected by reinjection returns show this pattern.

On the other hand, enthalpy pattern of E-meas > E-nkc = E-silica indcates widespread boiling with phase segregation and separate entries of steam and water into a well. This process is usually shown by Mahiao and Sambaloran wells where there is an observed increase in enthalpy and steam fraction, and decline in waterflow and mineralization possibly as a result of mixing between equilibrated liquid with steam formed by extensive boiling in the reservoir.

Wells with inflow of shallow, cooler, more dilute water show the pattern E-nkc > E-silica >E-meas. The lower E-silica values result from dilution without reequilibration. E-nkc is not significantly affected. Leakage of cool water into a well from casing break can give similar indications. This was the pattern exhibited by wells 102 and 106 in 1994 when there was an inflow of cooler meteoric waters into the wells.

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