APPLICATION OF GEOCHEMICAL TECHNIQUES IN EVALUATING THE RESERVOIR RESPONSE TO EXPLOITATION AT PALINPINON GEOTHERMAL FIELD, PHILIPPINES

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ABSTRACT

Geochemical monitoring techniques have provided significant contributions in assessing the effects of field exploitation at Palinpinon since steam production was initiated in 1983. Reservoir processes such as reinjection fluid returns, pressure drawdown and acidic fluid inflows were recognized through the application of these techniques.

Water chemistry data such as chloride, calcium and Cl/Ca ratio were used to trace the mass breakthrough of reinjection fluids. Thermal decline *caused* by reinjection fluid returns was recognized by silica geothermometry and sulfate concentration. The effect of pressure drawdown in the reservoir was clearly illustrated by gas chemistry though the FT-HSH diagram. A hydrological model of the field during exploitation was defined by the evaluation of stable isotope chemistry data.

1. INTRODUCTION

The Palinpinon geothermal field, situated at the flanks of a dormant Cuernos de Negros Volcano, consists of three major sectors, viz: Fuhagan, Nasuji-Sogongon and Baslay-Dauin (Figure 1). At the Puhagan sector, the 112.5 MWe Palinpinon-I power plant has been operating since June 1983. A total of 30 production wells and 15 reinjection wells were completed in this sector. These wells, which are mostly deviated, were drilled to a measured depth (MD) of around 3000 m or 2900 m vertical depth (VD). Four units of 20 MWe modular power plants will be developed at Nasuji-Sogongon. The first &-lar unit was commissioned in March 1994. Only two wells were drilled at Baslay-Dauin and both are non-commercial.

The deep fluid is believed to be upflowing southwest of Puhagan (Amistoso et al., 1990) within the vicinity of Lagunao dome (Figure 1). Fluid geothermometers indicate an increasing temperature trend towards this sector. An enthalpy-chloride diagram suggests a pre-exploitation reservoir temperature of 328°C and a chloride concentration of 4150 mg/kg (Jordan, 1983). This fluid tenperatme is quite close to the maximum temperature of 329°C measured at PN-20D. From the postulated upflow zone, the reservoir fluid outflows towards Puhagan and Nasuji-Sogongon through a series of northeast and northwest trending fault structures.

Mass breakthrough of reinjection fluids was observed in most production wells since the commissioning of the Palinpinon-I power plant at Puhagan in 1983 (Harper and Jordan, 1985). Due to the proximity of the production sector to the reinjection area, rapid return of reinjection fluids was encountered resulting in thermal deterioration in several proauction wells (Harper, 1988). Nonetheless, thermal recovery in most of these wells occurred when wastewater injection was shifted farther north to the Ticala/Malaunay sector (Figure 1) from Puhagan in October 1989 (Seastres, 1993). A major increase in mass withdrawal in October 1990 due to the interconnection of the nearby Panay island (Figure 1) to the Negros power grid caused field pressure drawdown in the reservoir. Acidic fluid inflows were detected on the eastern part of Puhagan during the early stage of exploitation in 1985. However, these acidic inflows were suppressed when reinjection fluids were induced to the southeastern production wells from the Ticala sector in 1991.

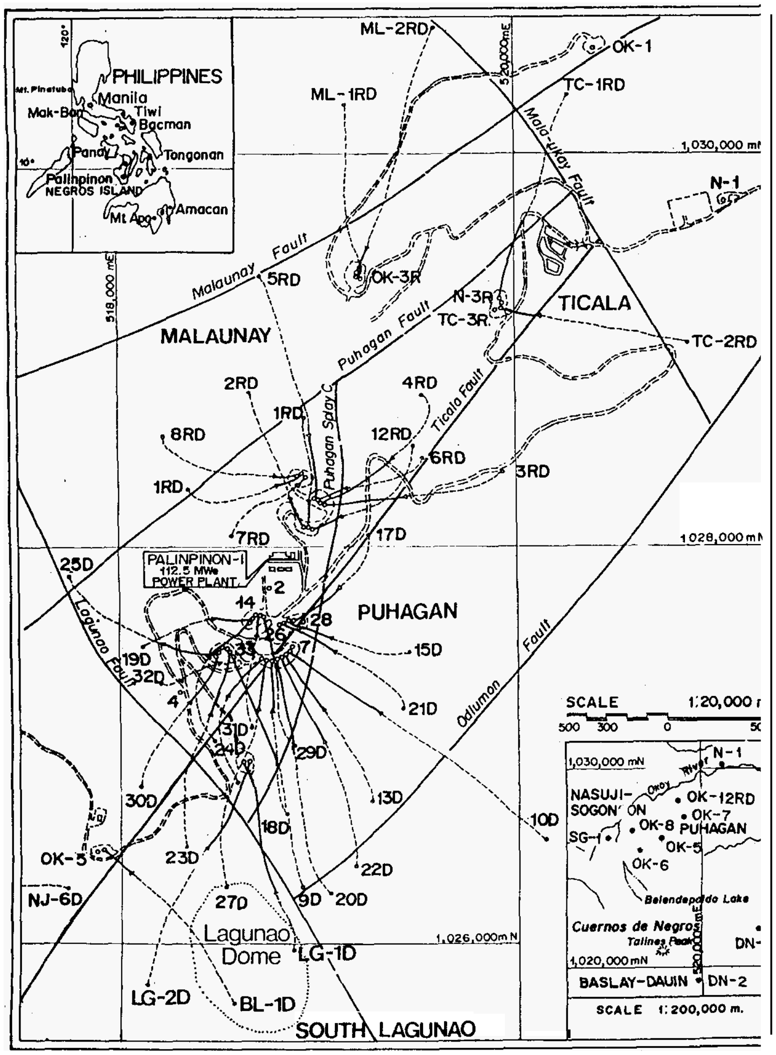
Geochemical monitoring techniques were formulated in evaluating the reservoir changes that were encountered at Palinpinon during field exploitation. Applications of these techniques have recognized the mass and thermal effects caused by reinjection fluids, field pressure drawdown induced by massive fluid withdrawal and acidic fluid inflows in the production sector. The evaluation of these chemical processes has significantly contributed in the adoption of an effective field management strategy at Palinpinon.

2. REINJECTION FLUID BREAKTHROUGH IN THE RESERVOIR

Reinjection fluid returns were observed at Puhagan, Palinpinon since the initial exploitation period in 1983. The field chloride level obtained from the reinjection line has consistently increased from 5750 mg/kg in 1983 to as high as 11400 mg/kg in 1989 (Figure 2). *Such* increase in chloride concentration indicates the return of reinjection fluids that have been progressively concentrated upon flashing at the separator station prior to injection. Recognition of reinjection fluid returns, however, is not that simple since *increase* in chloride mineralization due to boiling in the reservoir or recharge from highly mineralized fluids may mask the effect of reinjection fluid breakthrough. To completely characterize the presence of reinjection fluids, chemical parameters such as the Cl/Ca ratio and CO_2 *gas* composition were correlated.

In addition to the distinct increase in chloride amcentration, a corresponding decline in Cl/Ca ratio manifests the existence of reinjection fluids in the reservoir since the calcium concentration increases in greater proportion than the corresponding increase in reservoir chloride concentration at the Pubagan reinjection sector, This phenomenon is attributed to the dissolution of calcium bearing minerals by relatively cold reinjection fluids (165°C) in this *sector*. Moreover, the declining CO_2 *gas* composition reflects the inflow of reinjection fluids which have been progressively degassed at the separator station.

The chloride concentration, Cl/Ca ratio and CO_2 gas composition were routinely utilized in assessing the breakthrough of reinjection fluids at Palinpinon production wells. Massive reinjection fluid returns were observed in several production wells (PN26, PN28, PN19D, PN29D and OK7) when wastewater injection was confined near the production sector at Puhagan. Well PN26 illustrated the major incursion of reinjection fluids (Figure 3) which reached as high as 90% in



Pig. 1. Location of Puhagan production sector, Palinpinon geothermal field. Production wells that were deviated are marked with a D. Injection wells are marked with an R. Lower inset in the figure shows the three main sectors (Puhagan, Nasuji-Sogongon and Baslay-Dauin) found at the periphery of Cuernos de Negros volcano. upper inset shows the location of Palinpinon within Negros Island, Philippines.

discharge fluids of this well (Harper and Jordan, 1985). Recently, the presence of a reinjection fluid component in the production wells was further distinguished by stable isotope composition (Gerardo et al., 1993). Several proauction wells were enriched in stable isotopes due to mixing with isotopically enriched reinjection waters. The baseline mixing line (Figure *8)* of parent fluid with meteoric water defined by $\delta^{18}O = 8.16 \times 10^{-4}$ Cl $-$ 7.9 has shifted primarily towards the reinjection water (upper *end* member) and the acidic steam condensate fluid (lower *end* member) ***during*** exploitation.

The return of reinjection fluids to the production sector is relatively rapid covering a fluid transit time from one day to almost two weeks based *on* radioactive and sodium-fluorescein tracer testing results (Urbino et al., 1986). *Such* relatively rapid fluid communication *does* not allow effective reheating as thermal deterioration *caused* by reinjection fluid returns was encountered in the production wells. Geochemical indicators of thermal decline due to reinjection fluids consist of silica (quartz) tenperatme. silica breakthrough and sulfate breakthrough.

The *quartz* geothermometer is widely used at Palinpinon to monitor thermal changes in the reservoir *since* its calculated temperature is closest to the measured tenperatme among the fluid geothermometers. This condition is due to its rapid reequilibration with changes in fluid temperature (Fournier and Potter, 1982). Silica breakthrough occurs when the measured tenperatme differs substantially from the calculated silica *(quartz)* geothermometer indicating that *quartz* solubility no longer controls the concentration of silica. The silica concentration is now governed by a relatively lower temperature silica polymorph (e.g. cristobalite). On the other hand, sulfate breakthrough is encountered when the reservoir sulfate concentration *exceeds* its baseline level in response to a temperature decline (Harper. 1988; Seastres and Reyes, 1989). This phenomenon is a function of the reverse solubility of anhydrite with fluid temperature.

Thermal deterioration was mainly encountered when the bulk of wastewater was injected near the Fuhagan production sector from 1983 to 1989. A decrease in fluid temperature was detected in several production wells.

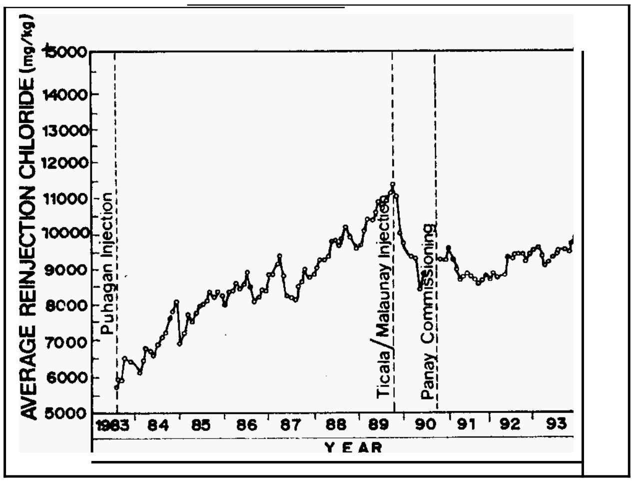


Fig.2 Monthly average reinjection line chloride at Puhagan production sector, Palinpinon geothermal field.

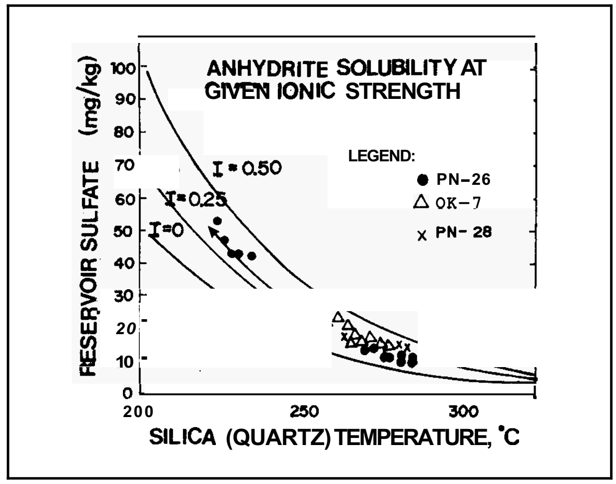


Fig. 4 Sulfate breakthrough curves of selected Puhagan production wells. Measured temperatures were used in PN-26 instead *of* quartz temperature since silica breakthrough was encountered in this well.

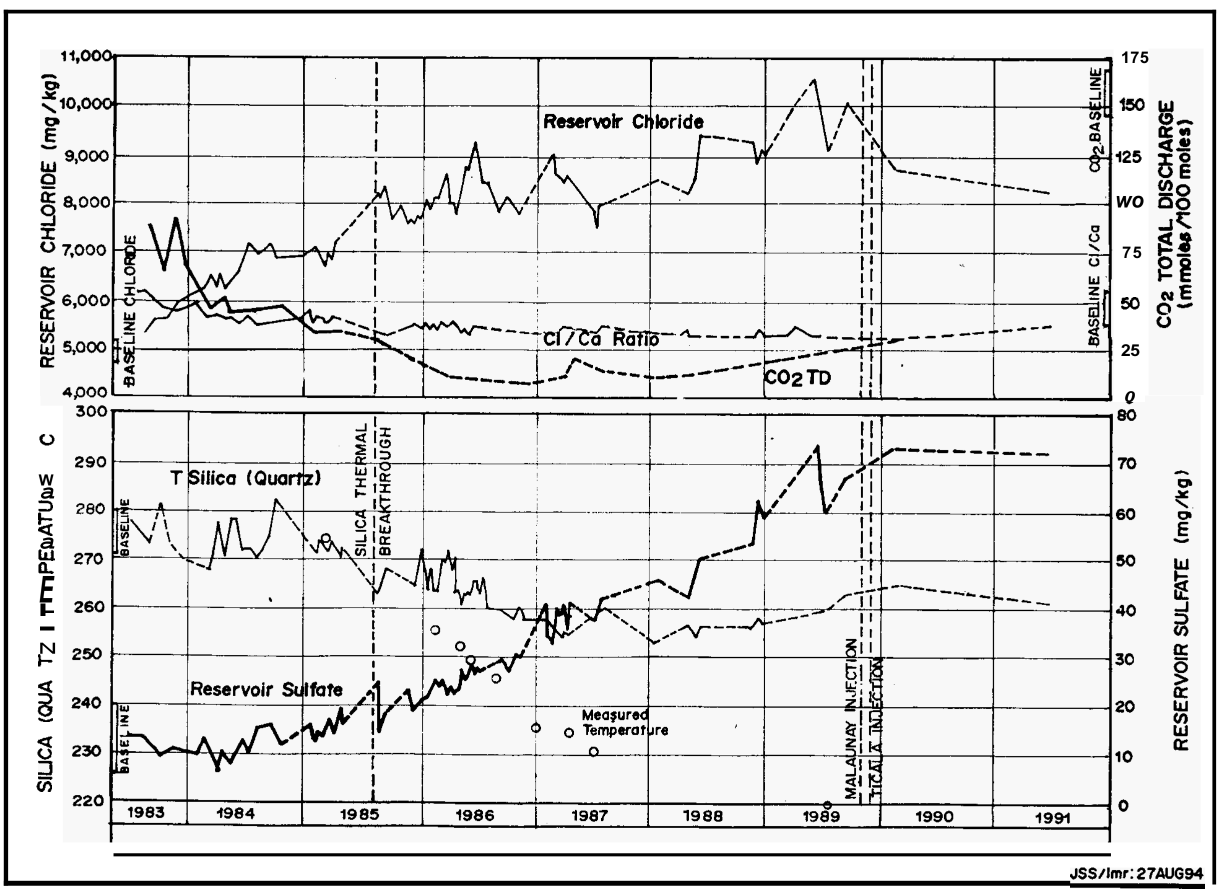


Fig. 3. Geochemical indicators of reinjection fluid returns applied in a production well, PN-26.

A typical *case* is that of well **PN26** which illustrated a progressive increase in reinjection fluid returns causing a consistent decline in borehole **temperatures** from **300°C** to **220°C. An** increase in reservoir sulfate concentration ***exceeding*** its baseline level of **20 mg/kg occurred** in **1985** (sulfate **breakthrough**; Figure **3). The** anhydrite solubility curve of **PN26** illustrated a typical decrease in fluid temperature caused by reinjection fluids (Figure **4).** The sulfate concentration reached as high as 70 **mg/kg** corresponding to a fluid temperature of **220°C.**

Although silica **(quartz)** temperature decline was observed **due** to the **breakthrough** of reinjection fluids, it ***appears*** that quartz does not **anymore govern** the solubility of silica (silica **breakthrough)** at a temperature of **260°C (e.g. PN26;** Figure **3). The** silica stability field of **PN26** has in **fact** moved towards **a** cristobalite (Figure 5).

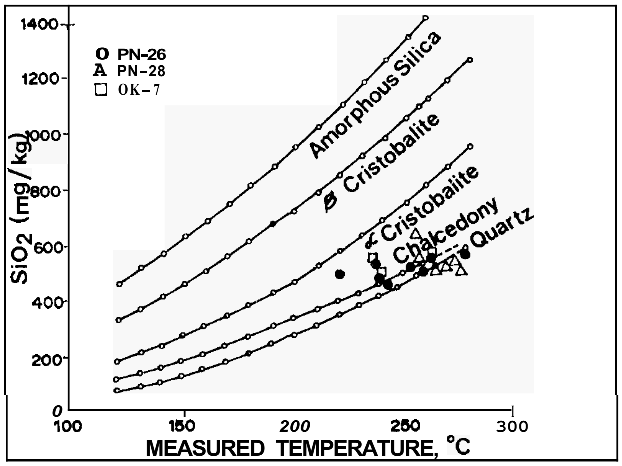


Fig. 5 Silica breakthrough curves of Puhagan production wells, Palinpinon geothermal field.

When reinjection fluid returns **based** on field chloride decreased to as low as **8400 mg/kg** in **1990** (Figure **2)** from a **peak** of **11400 mg/kg** in response to the shift of fluid injection from **Puhagan** to the **Ticala/Malaunay** sector, several production wells showed an *increase* in fluid temperatures by as **much** as **20°C.** Field deterioration in fluid temperatures, was therefore, arrested when wastewater injection was reduced at Puhagan ***since*** **1989.**

3. SUPPRESSION OF ACIDIC FLUID INFLOWS

The southeastern part of the Puhagan reservoir **(OK10D, PN13D, PN20D, PN22D)** is characterized by the presence of acid-sulfate fluids detected ***during the*** early stage of exploitation in **1985.** These fluids have been diluted by the neutral-pH reservoir fluids found at **deeper** levels allowing utilization **of these** wells for **power** production. **However, the** acid-sulfate waters often deposited anhydrite that eventually clogged up these proauction wells. The commissioning of reinjection well **TC2RD** in **1991** has induced **changes** in the fluid chemistry at the southeastern Puhagan wells.

Well TC-2RD has facilitated *the* inflow **of** reinjection fluids in some of the acidic wells at southeastern Puhagan **through** the **Odlumon** fault (Figure **1). Geochemical** indicators of reinjection fluid returns (Cl, Cl/Ca ratio, CO_2 *gas* composition) attested to the **presence** of reinjection fluids which *suppressed* acidic fluid inflows in **OK1OD and PN13D. The** fluid **chemistry** of these wells has shifted from the acid sulfate-parent fluid **mixing** line to the acid sulfate-reinjection fluid **mixing** line (Figure **6).** Stable isotopic composition shared that the acidic steam condensate fluid ***mixing*** with OK10D reservoir fluid **in 1991** (Figure **8) has** been **subsequently suppressed by** isotopically enriched reinjection waters ($\delta^{18}O$ =-3.8°/oo).

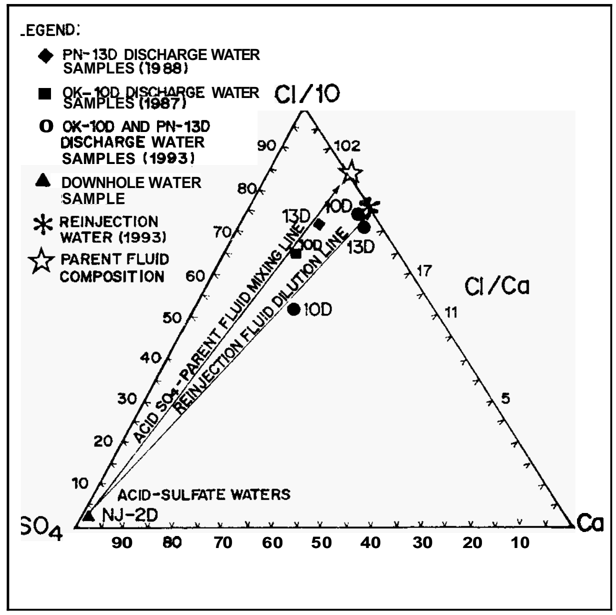
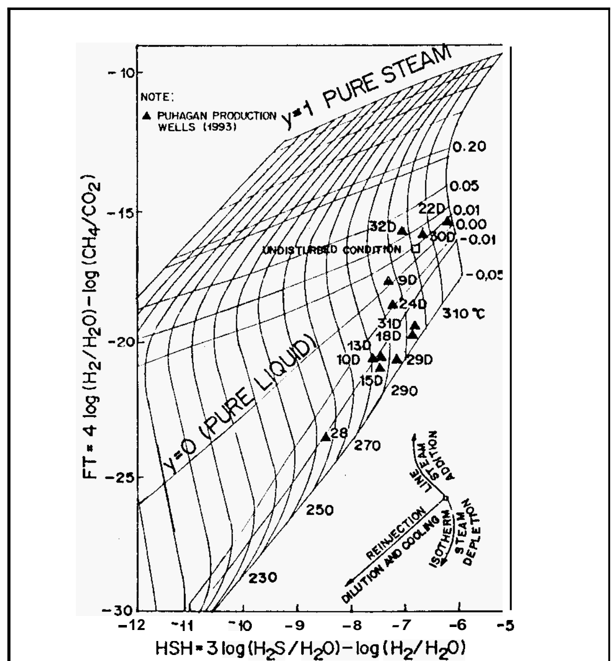


Fig. 6 Chloride-calcium-sulfate mixing model.



i .7 FT-HSH grid diagram for gas composition of

Despite the major incursion of reinjection fluids in **OK10D** and **PN13D,** their fluid temperatures **remained** within **260°C** which suggest that the reinjection fluids have **been** reheated **upon** migrating to the production **sector.** The induced flow of reinjection fluids to these wells has resulted to a sustained proauction of near-neutral pH reservoir fluids at southeastern Puhagan. Fluid pH of acidic wells prior to the entry of reinjection fluids decreased to as low as **4.10.**

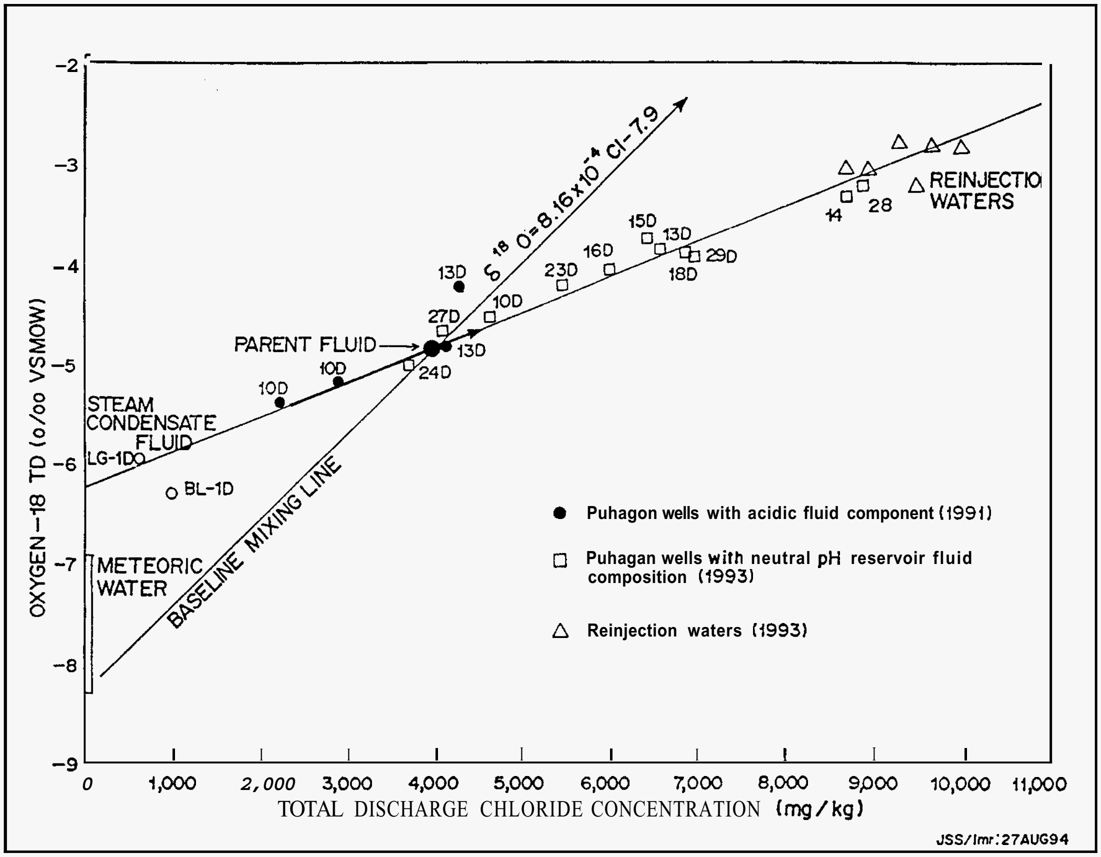


Fig. 8. Chemical processes affecting the reservoir during exploitation.

4. EFFECT OF FIELD PRESSURE DRAWDOWN

In **October 1990,** the nearby Panay island (Figure **1) was** interconnected to the **Negros power** grid producing a major *increase* in energy production to as high as **110** MWe. With **increased** monthly mass withdrawal to **1890 x 10^3 tons** from 1400 x 10^3 tons coupled with reduced **mass** injection at Puhagan *during* this period, field pressure drawdown was further enhanced in the reservoir. The shut-in pressure of a monitor well, **PN25D,** decreased **from 9** MPa to **6** MPa as an effect of pressure drawdown. This physical change induced an increase in average field enthalpy **from 1500** kJ/kg to **1640** kJ/kg and gas concentrations **of** several production wells (Seastres, **1993).**

Production wells that are highly affected by drawdown are **PN20D, PN22D** and **PN30D** which have relatively low percentage of reinjection fluid returns (<30%). The discharge enthalpies of these wells increased from **<1350** kJ/kg **(1983** baseline condition) to **>2000 kJ/kg (1993** exploitation level) in response to drawdown. **A** corresponding *increase* in total discharge gas concentration from **<200 mmoles/100moles** to as high as **460 mmoles/100moles** was encountered in these wells. The **FT-HSH** diagram **(D'Amore** et al., **1982)** applied in modeling the behavior of *gases* at Palinpinon (Figure 7) indicated that the steam fraction **of** these wells **has** been enriched (y = **0.010)** from an originally liquid reservoir fluid *(y* = 0). Well **PN32D,** drilled in July **1990,** tapped **the expanded** two-phase zone (i.e. produced by field pressure d r a m) in the Palinpinon reservoir which is characterized by a highly positive steam fraction (y = **0.025).**

5. DISCUSSION

The baseline fluid chemistry of the production wells at Puhagan has been altered *during* field exploitation. **Most** of these wells were affected by reinjection waters. Stable isotope modeling **of** the field exploitation hydrology (Figure **8)** indicates that wells in the central part **of** the reservoir (e.g. **PN28, PN14)** are **most** affected by reinjection fluid returns. **These** wells are highly enriched with reinjection waters **($\delta^{18}O$** = **–3.22 o/oo,** total *discharge* chloride = 8900 mg/kg) indicating a direct fluid communication with the reinjection area. Moderately saturated **with** reinjection fluids are those wells located at the **southern** and southwestern part **of Puhagan** (e.g. **PN24D, PN31D, PN18D, PN29D, PN23D and** PN27D). The FT-HSH diagram (Figure 7) suggests that the production wells saturated with reinjection fluids are highly **degassed** (y = **–0.01).** This characteristic is consistent with dilution of reservoir fluids with steam depleted reinjection water. **According** to the stable isotope model, well PN28 is severely affected by reinjection fluids. The **FT-HSH** diagram (Figure 7) illustrated a progressive temperature decline from **southern** Puhagan within PN24D **(300°C)** towards the reinjection **sector** near **PN28 (250°C).**

Wells within the periphery of the **Puhagan** production field (e.g. **PN22D,** PN30D) encountered massive pressure drawdown **due** to a minor component of reinjection fluids **recharging** in these wells. ***Steam*** condensate fluids downflowed in **some** production wells as induced by drawdown. These fluids as detected in shallow well **LG1D** (i.e. **–695 m** b.s.l. relative to **–2100 m** b.s.l. of most Puhagan wells) are acidic **(pH t4.5)** with low chloride **(<1000** mg/kg) **and** high sulfate **(>200 mg/kg).** However, at the **southeastern** production **sector which** is closer to the reinjection area, the acidic fluid **component** detected **in 1985** in **some** wells (OK10D, PN13D) has been **suppressed** by reinjection **waters** from the Ticala sector in **1991.**

6. CONCLUSIONS

Application of geochemical monitoring techniques at Palinpinon since field exploitation **started** in **1983** detected the presence of reinjection fluids in the production sector. Thermal deterioration **caused** by reinjection fluid returns was recognized and the shift from infield injection near **Puhagan** to the outfield injection at **Ticala/Malaunay** sector was **subsequently** implemented in **1989.** This strategy facilitated thermal recovery in several production wells and the flow of reinjection fluids to the southeastern production sector that resulted in the suppression of acidic fluids in some wells (OK10D, PN13D). Evaluation of the gas chemistry (FT-HSH diagram) indicates that some wells (PN22D, PN30D) were highly affected by steam addition produced by pressure *drawdown.* Inflow of acidic steam condensate fluids, however, was encountered farther south of Puhagan (i.e. *sector* unaffected by reinjection fluid returns).

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