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GEOCHEMICAL EVALUATION OF THE RESERVOIR RESPONSE TO EXPLOITATION OF THE MINDANAO-1 GEOTHERMAL PRODUCTION FIELD, PHILIPPINES

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ABSTRACT

Mindanao-1 production field has been operating commercially for almost two years. Nine (9) production wells were tapped to supply steam for the 52 MWe power plant. Significant changes in the physical and chemical characteristics of the producing wells were observed and are attributed to the response of the reservoir to continued exploitation. Variations in the geochemical parameters of the producing wells from its initial production were used to describe the effects of continued exploitation.

Decline in discharge enthalpy with corresponding increase in waterflow were observed in wells along the Marbel Corridor. Slight increase of reservoir chloride and apparent decrease in $TSiO_2$ were also experienced and are likely due to dominance of the liquid-saturated bottom feed zone in the discharge and the likely ingress of the reinjection fluid. The declining output of APO-1D, APO-3D and SP-4D is attributed to calcite deposition.

To avert the ingress of reinjection fluid and calcite deposition in the production wells, reinjection load at present sink should be reduced and diverted farther north of the field and antiscalant injection system is being progressively installed in the affected production wells.

1. INTRODUCTION

Mindanao geothermal production field is situated at the northwestern flank of Mt. Apo, in southern Mindanao, Philippines. The geothermal field has a known productive area of approximately 8.4 km^2 (Fig.1) and is referred as the Mindanao-1 production field (M1GPF). PNOC-Energy Development Corporation (PNOC-EDC) started commercial exploitation of the field with the commissioning of a 52 MWe power plant in March 1997. The 50 MWe Mindanao-2 geothermal production field (M2GPF) upstream of M1GPF, was commissioned in June 1999 bringing the area's total generating capacity to 102 MWe.

Three (3) production areas comprise the Mindanao geothermal production field: the Sandawa Collapse, Marbel Corridor and Matingao Block (Fig. 1). Nine (9) production wells drilled within the Marbel Corridor supply the required steam for the 52 MWe Mindano-1 power plant. Four (4) reinjection wells located in the Matingao Block accommodate the separated hot brine from two separator vessels of the Mindanao-1 production field. Another well is also dedicated for the disposal of cold condensate from cooling tower and drainpots.

The M2GPF is supplied by seven (7) production wells drilled in the Sandawa sector and two (2) wells in the Marbel Corridor. The separated brine of the wells at Sandawa sector is injected at KN1RD while brine from APO2D and MD1D, is reinjected at the M1GPF reinjection wells.

This paper evaluates the chemical changes observed in M1GPF production wells during continued exploitation of the field since March 1997. Based on the observed chemical changes, we infer some processes occurring in the reservoir and recommend steps for appropriate field management.

2. NATURAL STATE OF THE RESERVOIR

Fluid chemistry of the production wells during medium term discharge (MTD) testing was the basis in establishing the initial chemical state of the field. The geothermal reservoir of the M1GPF and M2GPF are referred singly as the Mt. Apo reservoir.

2.1 Pre-exploitation Fluid Chemistry

Three (3) distinct types of fluid exist in the Mt. Apo geothermal reservoir. Neutral-pH brine with chloride concentration ranging from 2,000 to 5,000 mg/kg exists predominantly at the Marbel Corridor production sector. An acid-sulfate fluid with pH of 3.0 to 5.0 and chloride concentration of more than 5,000 mg/kg is present in the deep portion of the Sandawa Collapse. Lastly, neutral-pH to slightly acidic sodium-sulfate fluid is present in the upper steam dominated zone of the reservoir.

Fieldwide geochemical trends illustrate the lateral changes in reservoir chemistry. Iso-chloride trend shown in Figure 2 depicts highest chloride values of more than 6,000 mg/kg in the vicinity of well KN-3B. Chloride concentration progressively decreases towards the northwest across the Marbel Corridor and further down to Matingao Block. A steep decline is likewise observed southeast of KN-3B. Temperature distribution across the field based on the expanded $TSiO_2$ (Fournier and Potter, 1982) is illustrated in Figure 3. A highest temperature of more than 300°C depicted in well KN-3B likely indicates the location of the upwelling zone. Temperatures gradually decrease towards the northwest across the Marbel Corridor and Matingao Block (Nogara, et al., 1999).

The chloride-enthalpy mixing model (Fig. 4) shows that the parent water of the Mt. Apo reservoir is compositionally closest to KN-3B fluid. Fluids discharged by the Marbel Corridor wells such as APO-1D, APO-3D, SP-4D and SK-4D can be produced by groundwater dilution of the parent water. Wells SK-1D and TM-3D represent discharges affected by extensive steam addition.

Wells drilled at Sandawa sector discharge high chloride with relatively higher enthalpy representing their close affinity with the deep parent fluid less affected by dilution. These wells namely, KN-3B, SK-3D, SK-5D, SK-6D, TM-1D, and TM-2D comprise this fluid type. Wells in the Marbel Corridor represented by APO-1D, APO-3D, SK-4B, SP-4D, MT-1RD, MT-2RD and the chloride springs are the more diluted members.

2.2 Hydrological Flow Model

Figure 5 illustrates the 2-dimensional picture of the hydrological flow model of the Mt. Apo geothermal system. Hot brine appears to upflow in the vicinity of well KN-3B. The upwelling geothermal fluids with temperature of 300-320°C and chloride concentration of 5,500-6,400 mg/kg undergo boiling. The separated vapour accumulates in the shallow reservoir that is being tapped by wells SK-1D and also present in the upper feed zone of KN-1D (Gonzalez, 1994).

Geothermal fluids flow laterally towards the Marbel Corridor and Matingao sectors along permeable northwest trending faults. Along the outflow, the fluids undergo continued degassing and dilution resulting in progressive decline in temperature, chloride concentration, gas content and enthalpy. This type of fluid with temperatures of 220-260°C is being tapped by the production wells at the Marbel Corridor.

Significant temperature inversion in wells APO-2D, KL-1RD and KL-2RD drilled at Matingao Block indicate cold meteoric water incursion at depth. This is considered the deep reservoir water recharge occurring at deeper levels of the Matingao Block and Marbel Corridor.

3. WELL UTILISATION

Utilisation scheme of production and reinjection wells for the Mindanao-1 production field is shown in Figure 6. In nearly two years of continued operation, the power plant and fluid collection and disposal system (FCDS) of Mindanao-1 production field have undergone regular Preventive Maintenance Service (PMS) between March 30-April 20, 1998. Due to decrease in steam availability of some production wells, all of the wells are currently utilised at full capacity.

3.1 Production Wells

Nine (9) production wells drilled at three (3) multi-cellar pads are utilised to supply the steam requirement of the 52 MWe Mindanao-1 power plant. An average of 450 kg/s of total mass is being extracted to supply the required steam. The intermittent use of production wells in the early stages of operation corresponds to the performance test of the Mindanao-1 FCDS and power plant prior to their commercial operation in March 1997.

Due to reinjection well constraints at the start of operation, medium to high enthalpy wells were prioritised and low enthalpy water-dominated wells APO-1D, APO-3D and SP-4D were used sparingly. This utilisation strategy minimized the amount of separated brine for reinjection (Esberto, et al., 1998). Choking problem experienced by well SK-4B upon its commissioning compelled the utilisation of low enthalpy wells APO-1D and SP-4D. However, declining massflow experienced by these wells resulted to the utilisation of another low enthalpy well APO-3D. Well APO-1D and SP-4D underwent work-over operations twice in March to May 1998 and April to May 1999 to clear the well of calcite blockages. From then on, the well utilisation scheme was maintained until April 1999 at full power plant load of 52 MWe.

3.2 Reinjection Wells

M1GPF has a total of ~350 kg/s separated brine disposed through hot reinjection to four (4) reinjection wells drilled in RA and RI pads. One well is also being used to accommodate condensate fluids from the cooling tower and steam-line drain pots for cold injection. Well KL-3RD was used for cold injection since the start of operation until October 1998. However, due to the increasing amount of separated brine in mid-1998, cold injection scheme was shifted to KL-1RD.

4. RESERVOIR RESPONSE TO EXPLOITATION

Variations in the discharge chemistry of production wells in M1GPF were observed after almost two years of operation. Monitored chemical parameters like chloride, $TSiO_2$, CO_{2td}, and discharge enthalpy showed significant changes attributed to the response of the reservoir to continued exploitation.

4.1 Chemical Changes

Changes in the discharge chemistry are evident in wells APO-1D, APO-3D, SP-4D, SK-1D, SK-2D and SK-5D. Relative to their baseline chemistry, significant increase in chloride concentration with corresponding decline in the discharge enthalpy was observed in wells APO-1D, APO-3D and SP-4D. Reservoir chloride of well APO-3D increased significantly from 4,000 to 4,900 mg/kg with corresponding decline in discharge enthalpy from 1179 to 1013 kJ/kg. Likewise, CO_2td, although in small amount, decreased from 40 to 22 mmoles/100moles of steam. Similarly, APO-1D and SP-4D's reservoir chloride increased by about 600 mg/kg while discharge enthalpy declined by about 130 kJ/kg. Both wells currently discharge single-phase fluid compared with their initial two-phase discharge.

General chemical trends of production wells can be represented on a chloride-enthalpy diagram shown in Figure 7. Reinjection fluid with chloride concentration of 5,200 mg/kg and 714-kJ/kg enthalpy is also plotted for comparison. Changes in physical and chemical characteristics of wells with time are evident in most of the production wells. The trend observed in well APO-3D likely indicates the incursion of a more saline, low enthalpy and more degassed reinjection fluid. The continued increasing mineralisation with corresponding decline in CO_2td and discharge enthalpy points to mixing with reinjection fluid. Similar trend is also observed in wells APO-1D and SP-4D. The absence of temperature decline as indicated in the stable $TSiO_2$ of these wells suggest that the reinjection fluid could have undergone sufficient heating as it enters the production sector. This also indicates that the breakthrough of reinjection fluid to the production sector is neither massive nor rapid.

Reinjection fluid currently disposed in wells MT-1RD and MT-2RD constitute about 75% of the total reinjection fluid of the M1GPF. The proximity of MT-1RD and MT-2RD to production wells APO-1D, APO-3D and SP-4D could likely enhance the entry of reinjection fluid returns.

The mineralisation in well SK-2D is observed to be increasing since October 1997 to present. However, with the increasing trend of $TSiO_2$ from 240°C to 250°C and the consequent increase of discharge water could be attributed to the increasing contribution of the single-phase lower feed zone. The declining contribution of the hotter two-phase feed at the upper zone is reflected in the decrease of the discharge enthalpy from 1164 to 1063 kJ/kg. The influx of a hot and mineralised fluid at SK-2D could suggest the inflow of fluids coming from TM-1D and TM-2D sector (Alincastre and Sambrano, 1998). This type of fluid is found in TM wells drilled at the southwest of the Sandawa Collapse near the production zone of well SK-2D is near.

Well SK-5D shows declining reservoir chloride from 4,800 to 4,100 mg/kg and $TSiO_2$ from 252 to 242°C. Although the discharge enthalpy appears to stabilize, the influx of this low chloride and lower temperature fluid may suggest that well SK-5D could be drawing Marbel fluids (Alincastre and Sambrano, 1999).

Wells SK-1D, SK-4B and SK-6D showed relatively stable discharge chemistry. The slight changes observed in these wells could be attributed to changes in the operating wellhead condition. The occurrence of water discharge in the steam-dominated well SK-1D is likely due to the intermittent inflow of brine at the bottom of the well. However, the well appears to have maintained its initial physical and chemical characteristics.

4.2 Calcite Formation

Wells drilled in Marbel sector intersected rocks with abundant calcite minerals dominantly occurring as vein minerals. Calculations of calcite saturation index of the fluid from these wells showed highly supersaturated levels in the "flashed" state (Fig. 8). Wells APO-1D, SP-4D and APO-3D fluid showed potential calcite development upon boiling.

Calcite formation in wells APO-1D, APO-3D and SP-4D was detected during their initial medium-term discharge testing and even prior to their utilisation. It is believed that flashing within the wellbore induces the formation of calcite. Work-over operations were conducted in both wells to clear the calcite blockages that had significantly reduced its output. Although calcite scales similarly formed in APO-3D, there was no significant change in the mass output that necessitates remedial work-over.

5. POTENTIAL PROBLEMS

The current mass extraction experienced by the Mindanao production field indicates significant changes in the fluid flow of the Mt. Apo geothermal reservoir. Changes observed in the chemical characteristics of some of the wells suggest progressive incursion of cooler fluids in the reservoir. If the continued exploitation results in depressurization of the production sector, cooler peripheral fluids will most likely affect the peripheral production wells in the Marbel Corridor.

Similarly, reinjection fluid may further ingress to the Marbel Corridor production sector. Although temperature deterioration has not yet occurred, it is most likely that thermal degradation could succeed the chemical front. Similarly, the high carbonated and cooler meteoric observed north of the Marbel Corridor will likely inflow towards APO-1D, APO-2D and MD-1D.

The acid-sulfate fluid at the southeast of the Sandawa sector may also pose similar problem to the production wells drilled within the Sandawa Collapse. Wells KN-2D, KN-4B and TM-3D will likely be affected by the entry of this acidic fluid. The anticipated problems that will likely be experienced are illustrated in Figure 9.

6. SUMMARY AND RECOMMENDATIONS

Variations in the geochemistry of the discharged fluids of all production wells indicate significant changes in the chemical and physical characteristics of the Mt. Apo geothermal reservoir as a result of continued exploitation.

The increasing mineralisation with corresponding decline in discharge enthalpy in well APO-3D indicates reinjection fluid breakthrough. The excess chloride concentration relative to its baseline level suggests about 27% of reinjection fluid in APO-3D's discharge. Although thermal deterioration has not yet been experienced, it is believed that continued entry of this cooler reinjection fluid could induce decline in fluid temperature. Thus, disposal of this cooler reinjection fluid should be reduced at the present reinjection sink (MT-1RD and MT-2RD) and shift some injected fluids farther north to minimise dispersal towards the production sector. An additional reinjection well drilled north of RI could address this disposal concern.

The encroachment of a more saline and hotter fluid in well SK-2D likely indicates the incursion of the fluid from the south west of the Sandawa sector, i.e. at the vicinity of the production wells at pad F. The withdrawal of this fluid type by well SK-2D, however, could be stopped as a result of the continued production of wells TM-1D, TM-2D, TM-3D and TM-4D for Mindanao-2 production field.

The significant variation of the discharge chemistry observed in well SK-5D indicates the inflow of a less saline and cooler fluid likely originating from the Marbel production sector. The current discharge chemistry of the SK-5D fluid is very similar to well SP-4D drilled in the Marbel Corridor. Furthermore, the current production of well MD-1D at Site B will likely induce withdrawal of the fluids in the Marbel Corridor. Thus, entry of peripheral cooler fluid will likely be enhanced. The observed fluid flow in different production sectors reflected from current discharge fluids is illustrated in Figure 9.

Calcite scales are believed to have formed during the flashing of the calcite–saturated fluid in wells APO-1D, APO-3D and SP-4D. The progressive formation of calcite blockage in the wells resulted in significant decline in well's output and caused successive work-over operations. The frequent mechanical clearing of APO-1D and SP-4D from calcite blockage could be detrimental to the stability of the casing. Hence, to avert the formation of calcite blockages and prevent successive work-over operation anti-scalant injection is currently done in well SP-4D. Similarly, well APO-1D and APO-3D are also programmed for this anti-scalant injection.

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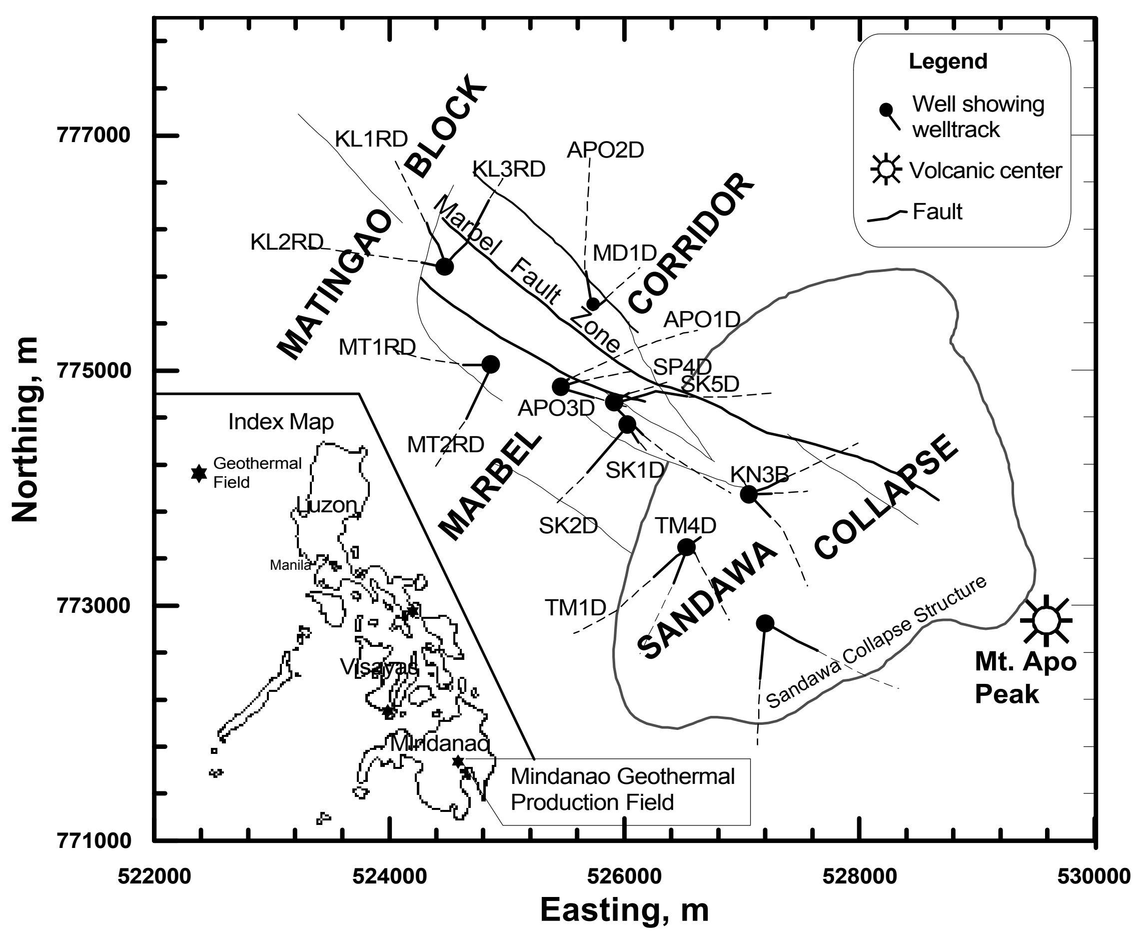

Figure 1. Map of the Mindanao geothermal production field showing structures, well tracks and production sectors.

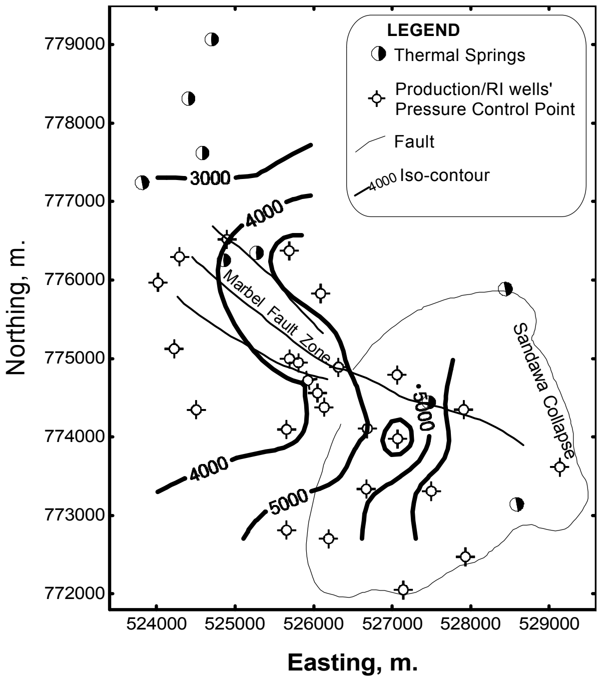

Figure 2. Iso-chloride contour across Mindanao geothermal field.

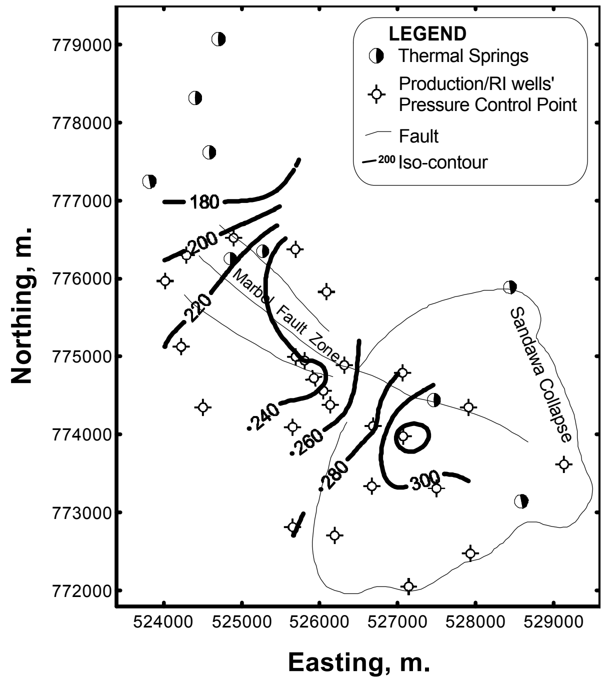

Figure 3. Iso-$TSiO_2$ contour across Mindanao geothermal field.

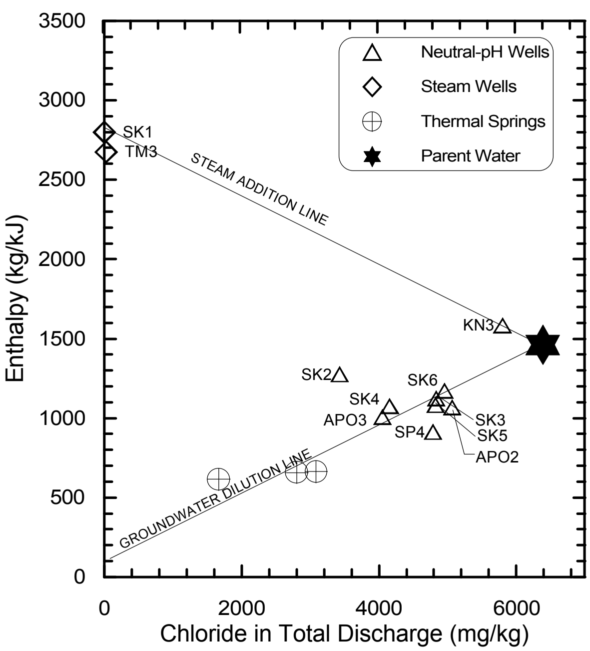

Figure 4. Chloride – enthalpy diagram showing the pre-exploitation fluids of selected wells and thermal springs. (after Nogara, et al.,1999)

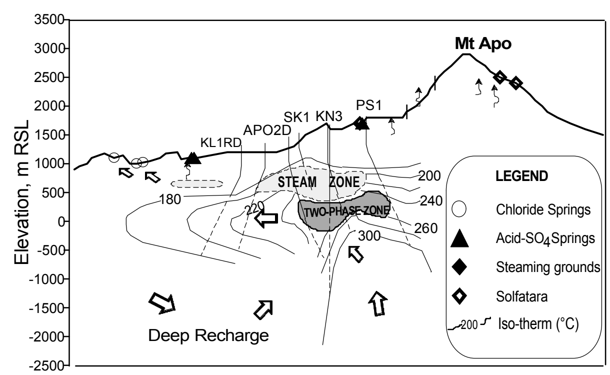

Figure 5. The hydrological model of the Mt. Apo geothermal system. (after Gonzalez, 1994)

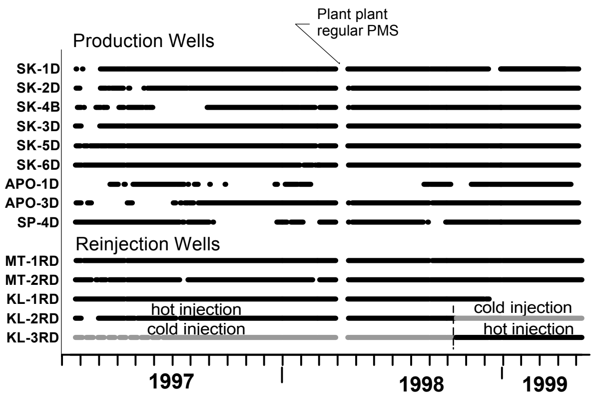

Figure 6. Production and reinjection well utilisation diagram for Mindanao-1 geothermal production field.

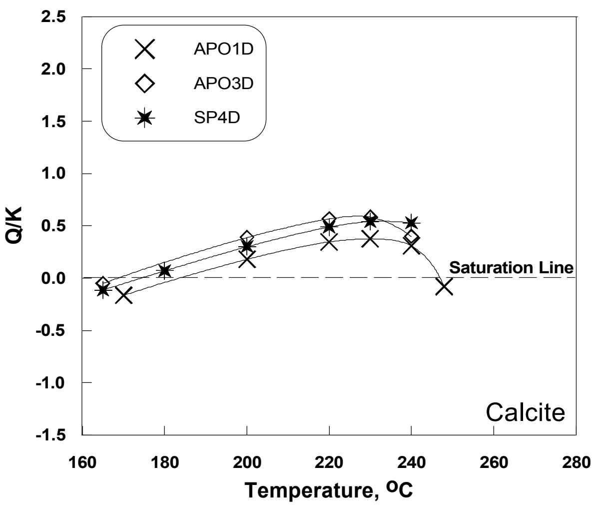

Figure 8. Simulated calcite saturation index of selected production wells boiled from 250°C to 165°C. (after Nogara, et al., 1999)

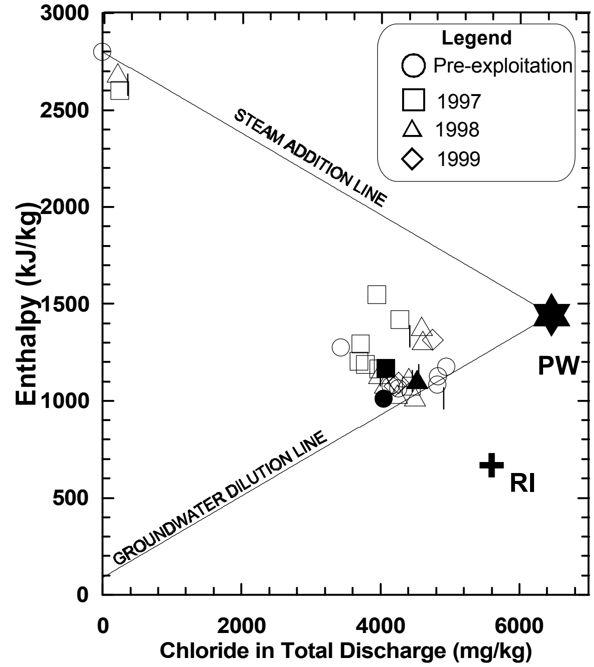

Figure 7. Chloride – enthalpy diagram showing Mindanao-1 production wells fluid chemistry trend during continued exploitation from 1997 to March 1999. Filled figures represents well APO-3D fluids. Open figures represent production wells in the Marbel Corridor.

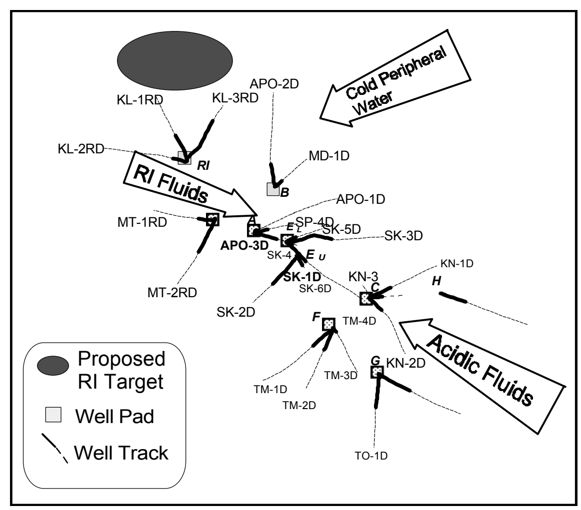

Figure 9. Mindanao production field showing interpreted geochemical fluid flow and proposed reinjection target sector.