

The BacMan Geothermal Field, Philippines: Geochemical Changes and Challenges After Twenty Years of Operation

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ABSTRACT

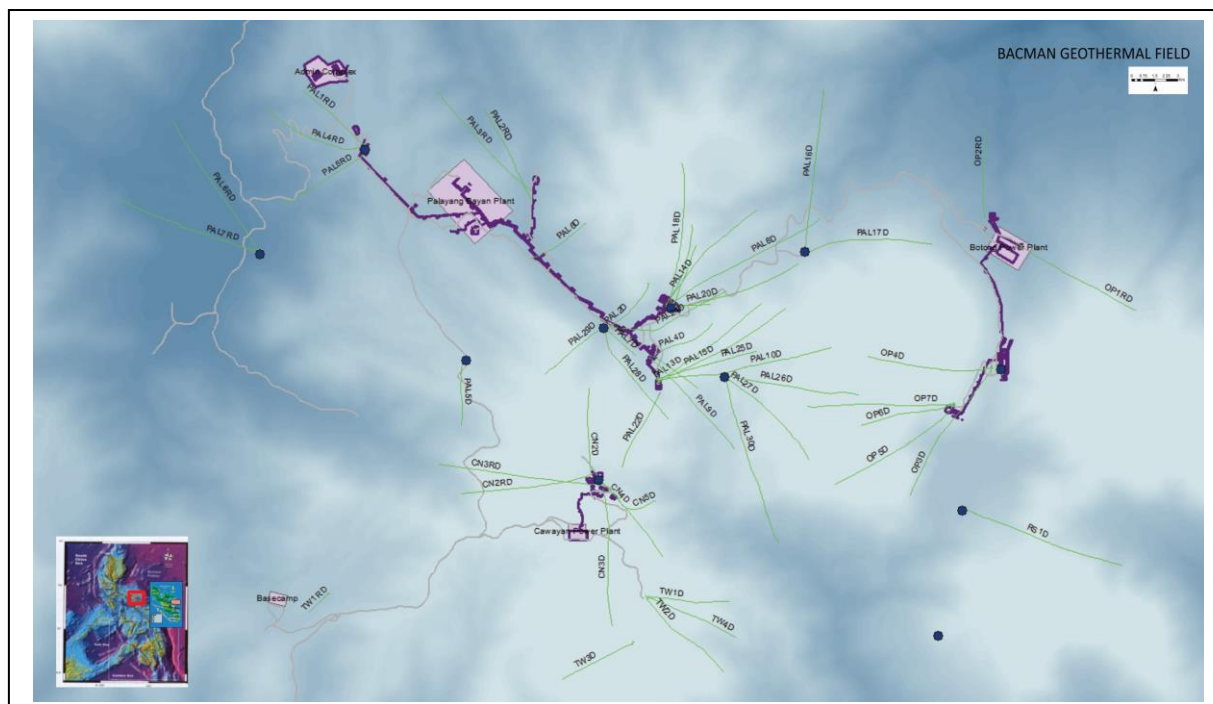
After twenty years of operation, the Bacman geothermal field has undergone geochemical changes that lead to operational challenges unique to the field. Since the start of its commercial operation in 1993, continuous long-term full extraction was not attained due to power plant problems. This condition has somewhat preserved the steam supply of the field. The historical steam flow rate decline is relatively low at ~ 7.5 kg/s/year or < 3.0 % of the field capacity. Since 1993, the average pressure drawdown across the field was also relatively low at ~ 1.21 MPa. Average reservoir fluid temperature decline based on TQuartz is about 2°C in 10 years (1999-2009). Geochemical monitoring for the past twenty years showed relatively stable trends with time.

Geochemical processes include reservoir boiling, acid fluid inflow and anhydrite deposition, injection fluid returns, calcite deposition, and cooler fluid inflows. These processes are expected to continue once the field operates again at full extraction rate. The geochemical responses were mostly benign, and adverse processes such as acid fluid inflows, injection returns, and mineral scaling have been very manageable. Sufficient recharge fluids, albeit cooler than the in-situ near well-bore fluids have sustained the output of the production wells.

Sound reservoir management strategy, intensive and pro-active geochemical monitoring, and the application of practical and innovative solutions to operational problems encountered resulted to a well-managed, stable, and sustainable resource.

1. BACKGROUND

The Bacon-Manito (BacMan) Geothermal Production Field is situated in a 25,000-hectares reservation area in the Pocdol Mountains between the town of Manito, Albay and Sorsogon City, Sorsogon in Bicol Region. The Pocdol Mountains is part of the northwest-southeast trending Bicol Volcanic Arc. Bacman is subdivided into three production sectors: Palayan Bayan, Cawayan and Botong (Figure 1). Expansion projects in the adjacent areas of Tanawon, Rangas, and Tikulob are currently in different stages of development while the Botong sector is not productive since 2009. A total of thirty-one (31) production wells constitute the 150 MWe installed capacity of Bacman-1 and four production wells in the 20-MWe Cawayan power plant.



There are two infield injection (Pads RA and RC/RD) and one outfield injection (Pad RE) sinks in Palayan Bayan sector while one infield injection sink is located in Cawayan sector to accommodate the separated brine. Commercial operations started in 1993 with the commissioning of the 110 MWe Bacman-1 Geothermal Power Plant in Palayan Bayan sector. After a year, the 20-MWe Cawayan Modular Power Plant was commissioned. By 1998, the total installed gross capacity of Bacman increased further to 150 MWe when Botong power plant was commissioned. In 2010, the acquisition by EDC of the power plants from NPC, which is a government owned institution, paved the way for the rehabilitation of the Palayan Bayan and Cawayan power plants. The Bacman steam augmentation program (BSAP) also ensued with the drilling of eight (8) additional wells in the Palayan Bayan sector. Further development in the whole field were also continuously being undertaken with the expansion projects in the Tanawon sector which started in 2001, in the Rangas sector wherein exploratory well were drilled in 2012-13, and in Tikulob area wherein an exploratory well is being planned.

Mass extraction started at around 0.51 million tons per month in 1993 during the commercial operation of 110 MWe Palayan Bayan, with about 69% of the mass injected back. Extraction increased significantly in 1996 to about 2.5 million tons per month. No considerable increase in the mass extraction in 1998 during the commissioning of the Botong power plant with extraction rate at about 2.02 million tons/month and injection rate at around 59% of mass extracted. However, mass extraction continuously declined thereafter, from 1.18 million tons per month to 0.83 million tons per month while the mass injected increased from 61% to 71% of the extracted mass. Continuous long-term full extraction was not attained because the Bacman power plants were frequently operated at low loads, or shut condition. Cawayan and Botong power plants were completely shut down in 2005 and 2009, respectively, due to power plant and geohazards problems. Cawayan power plant resumed operation in 2013 while the Botong power plant turbine and ancillary units were permanently transferred. This paper consolidates all the major reservoir processes in response to mass extraction and how these challenges were managed in the past 20 years.

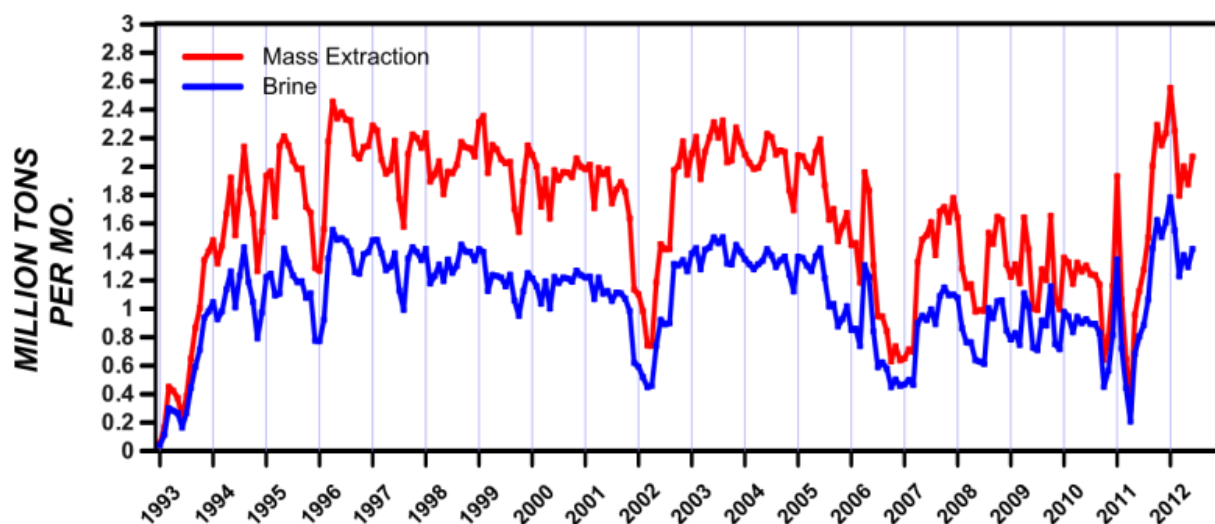


Figure 2: Monthly total mass extraction and injection in million tons per month

2. RESERVOIR RESPONSE

Increase and decline in mass extraction and injection rates from 1993 onwards manifested in the changes observed in the geothermal reservoir. In general, the eastern portion of the field exhibited significant boiling while the central and southwestern portion manifests entry of external recharge from the peripheral areas (Figure 1). The major reason for the sustained boiling in the eastern portion is that the area has no direct contact with the cooler fluids in the periphery of the resource since it is located in the upflow part of the field. The presence of the two major structural trends that have significant control on the permeability of the Bacman field may have also influenced the incursion of the cooler peripheral fluids. The convergence of the WNW-ESE Bacman fault zone and prominent NW-SE trending faults known as Pocdol Belt provide excellent permeability for the Bacman geothermal system (Figure 3). However, permeability is reduced evidently along the margins of this structural intersection, as in the case of Botong wells which are located in the edge of the Pocdol Belt.

2.1 Pressure Drawdown

Downhole pressure monitoring near the center of the field (Fajardo, 2003) showed that the highest rate of decline at 0.02 MPa/g per month occurred from 1993 to 1996 (Figure 4). The increased pressure drawdown during the early periods of commercial operation translates to increase in discharge enthalpy. However, the pressure trend with time (Figure 4) indicates periods of pressure increase brought about by peripheral fluid inflow in Palayan Bayan sector and decline in mass extraction. Palayan Bayan area average field enthalpy declined from 1600 kJ/kg to 1400 kJ/kg. In Cawayan sector, pressure trend with time is relatively stable coupled with stable average field enthalpy at ~ 1300 kJ/kg. Botong sector on the other hand, show variations in the average field enthalpy due to effects of changes in well configuration during low power plant load or shutdown (Gamez, 2012). Botong enthalpy remained high discharging high-enthalpy two-phase fluids. The wells tend to recover in terms of water flow but the prevailing process is still boiling and two-phase expansion (Gamez, 2012).

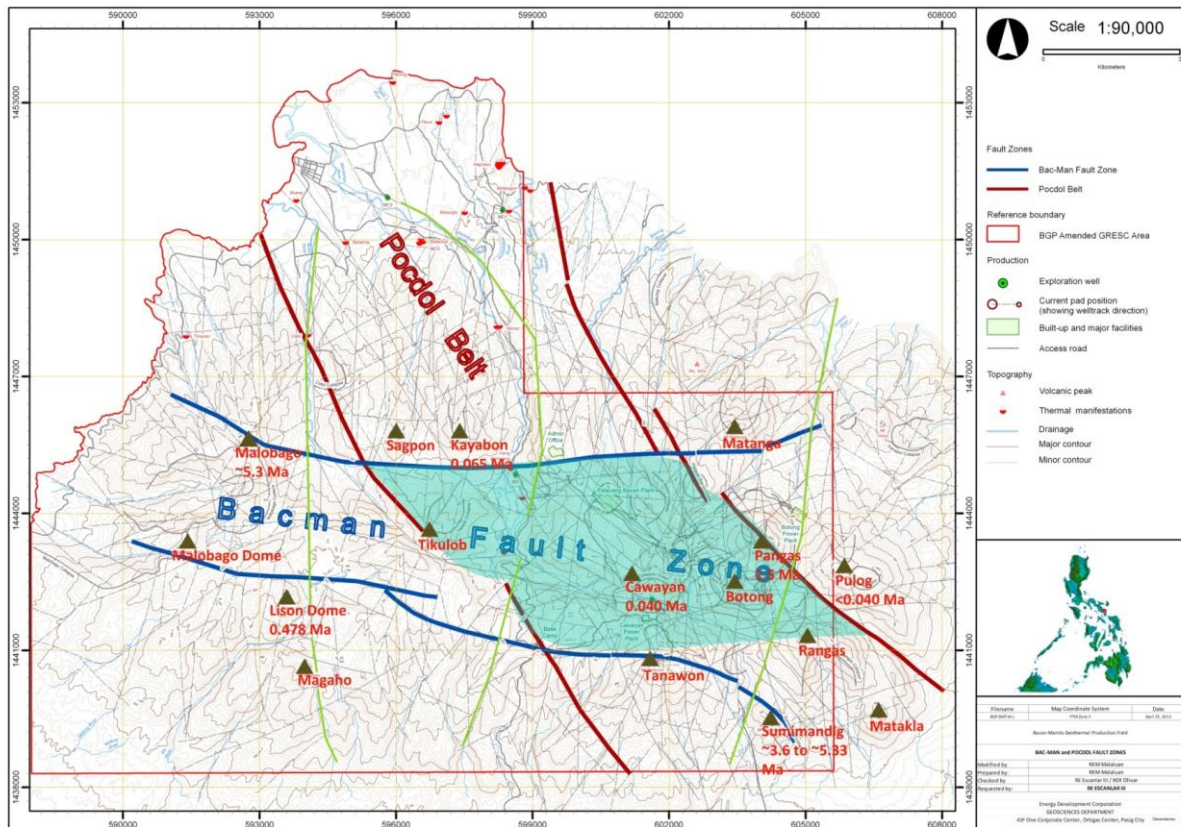


Figure 3: Identified and exploited geothermal system in Bacman lies within the intersection of these structural complexes.

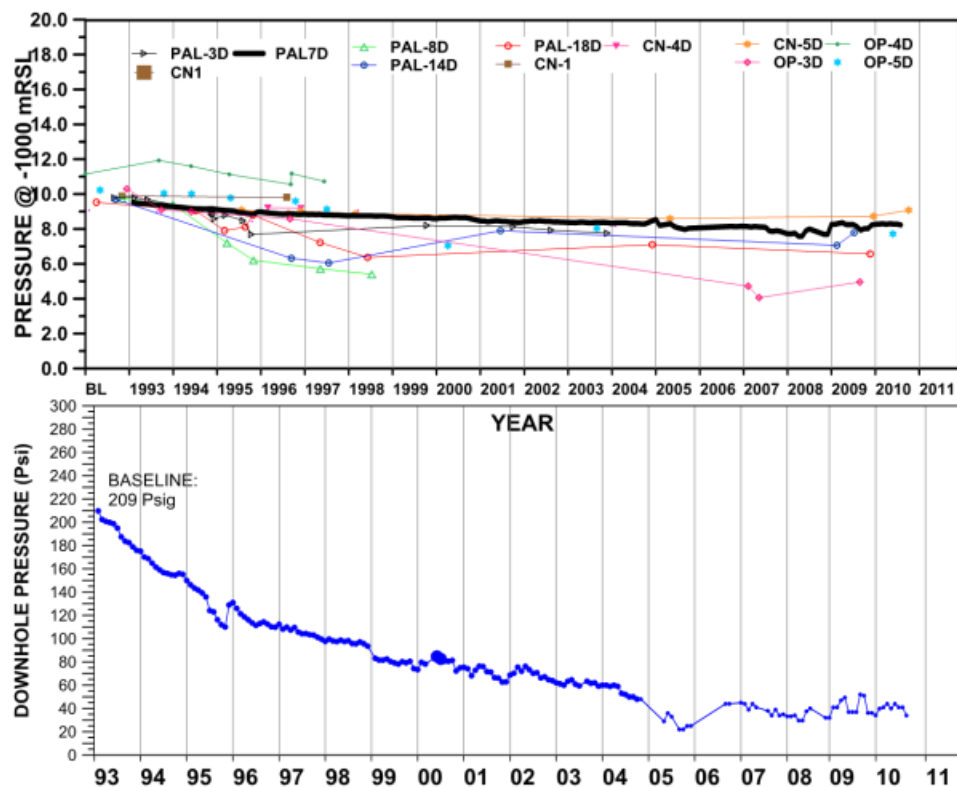


Figure 4: Measured Downhole Pressure Trend with Time of Bacman production wells at -1000mRSL and PAL7D Interference Test

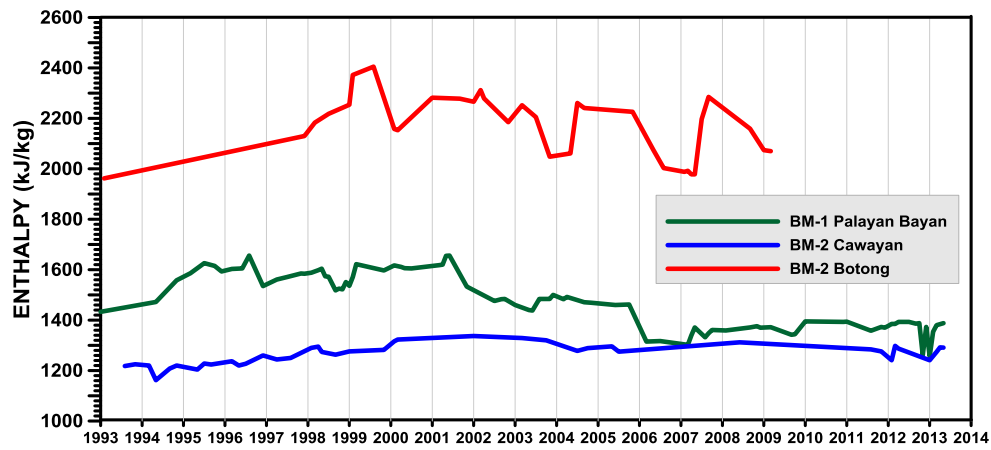


Figure 5: Average enthalpy of the different sectors of Bacman geothermal field

2.2 Cooler Fluid Inflow

Relatively cooler, dilute fluids with low boron content flowed from the western area of the field to the production sector of Palayan Bayan. The western portion of the field hosts relatively cooler, boron-depleted waters compared to the waters in the main reservoir. Fluids in the western sections have low boron because it is absorbed in alteration minerals of the Pocdol Volcanic Formation while the high boron content in the eastern portion of the field particularly characterized by the Botong wells is attributed to the sedimentary units of the Gayong Sedimentary Formation. Since the start of production in 1993, the movement of the in-place boron-depleted fluid from the western region to the central and southern Palayan Bayan was observed. Its influence on the chemistry of the affected production wells is shown in Figure 6. The in-situ waters of the production wells exhibit slight decline in temperature, less saline, and have higher Cl/B ratio. The migration of the low-boron fluid is traced by using mixing plots and end-member fluids to characterize the inflowing water. In this case, chemistry of idle wells PAL-5D, PAL-6D and PAL-7D drilled in the western section of the field was used to characterize the low-boron waters. Production well data shift towards PAL-5D and PAL-6D fluid chemistry signatures.

The influx of relatively cooler low-boron waters has been manageable. Although the affected wells have shown decreases in enthalpies, these have stabilized, attributed to the pressure support into the reservoir. However, it may be detrimental to the output of the field if the influx of the low-boron waters would advance further into the eastern portion of the field overlain by wells with high-enthalpy discharges.

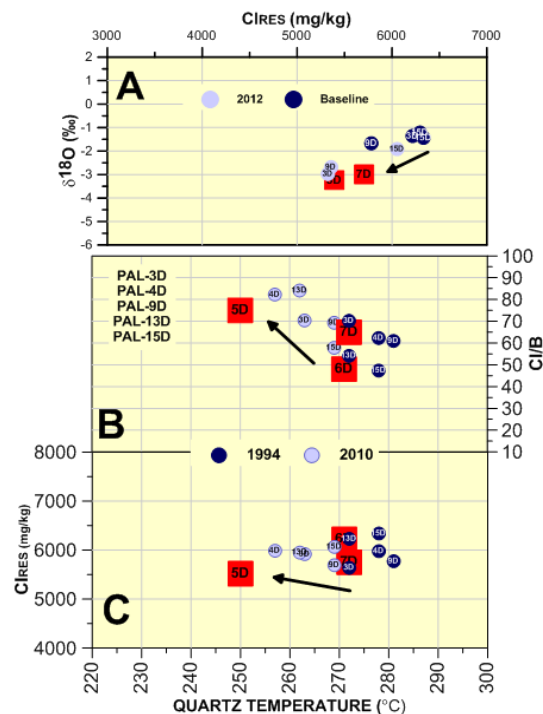


Figure 6: Crossplots of (A) $\delta^{18}\text{O}$ against reservoir chloride; (B) Cl/B ratio against quartz temperature; and (C) reservoir chloride against quartz temperature showing encroachment of the low-boron fluids to the Palayan Bayan production wells using chemistry of wells drilled in the western section of the field as end-member fluids

2.3 Injection Fluid Returns

2.3.1 Palayan Bayan Sector

The onset of injection breakthrough in the northern Palayan Bayan sector from in-field injection sink was suspected in 2001-2003. The increasing mineralization, declining gas content and discharge enthalpy of the production wells manifest the incursion of the injected brine into the production sector. Evidences of this incursion are reflected in Figure 7, which show cross plots of the reservoir chloride, CO₂TD and enthalpy based on quartz temperature. Production well data shift towards the cooler, highly saline and highly degassed brine from the in-field Palayan Bayan injection sink. Wells affected indicated increases in Cl with corresponding decrease in CO₂ and discharge enthalpy. A multiple-reservoir tracer test was conducted in December 2009 by injecting NDS tracers in wells PAL-3RD and PAL-1RD to confirm the injection fluid returns, establish flow paths, rate and magnitude of influx of the injection fluids. Tracer test included NDS injection at idle well PAL-16D located in the northeastern portion of the field which was temporarily used as cold injection in 2008-2009 to augment the injection capacity of the Botong cold injection wells. Results of the tracer test (Figure 8) confirmed the hydrological connection between PAL-3RD and production wells PAL-18D and PAL-14D; between PAL-1RD and production wells PAL-18D, PAL-14D, PAL-12D, PAL-19, PAL-10D, PAL-11D, PAL-23D; and between PAL-16D and most of the Palayan Bayan production sector. The highest total tracer mass recovered was calculated at only about 9% or 36 kg of the 400 kilograms 1,5-NDS injected from PAL-3RD. However, full extraction of the field during the NDS tracer return monitoring was not implemented. The earliest tracer breakthrough started about three months after injection and extended to about two years without returning to the baseline concentration.

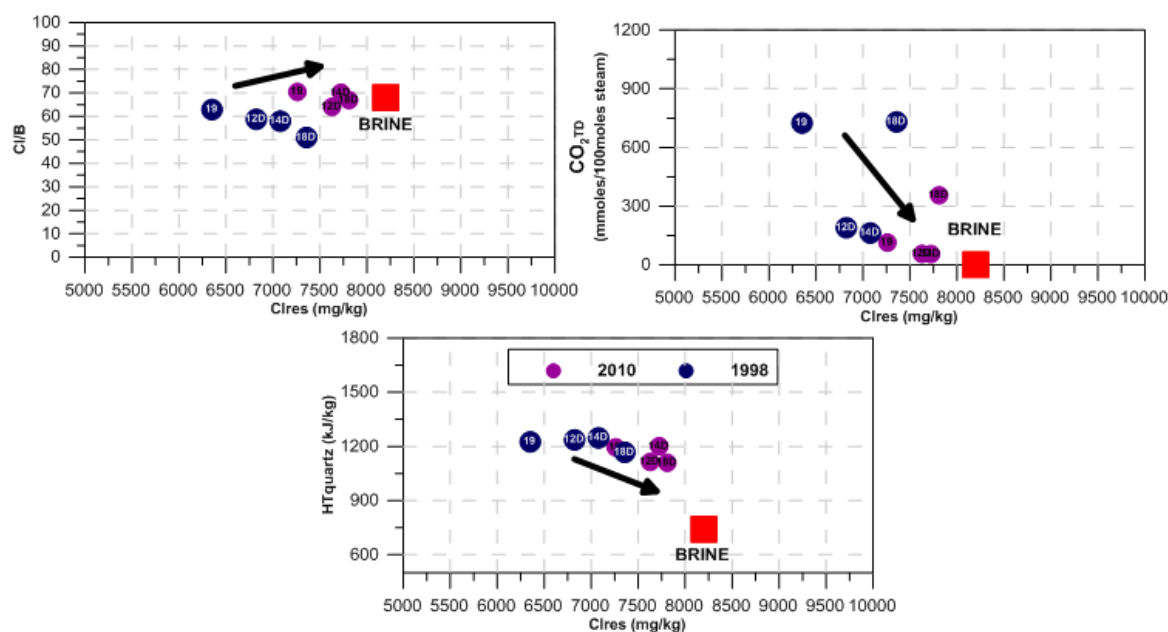


Figure 7: Crossplots of Cl/B ratio, CO₂TD and fluid enthalpy based on quartz temperature against reservoir chloride indicate incursion of in-field Palayan Bayan brine

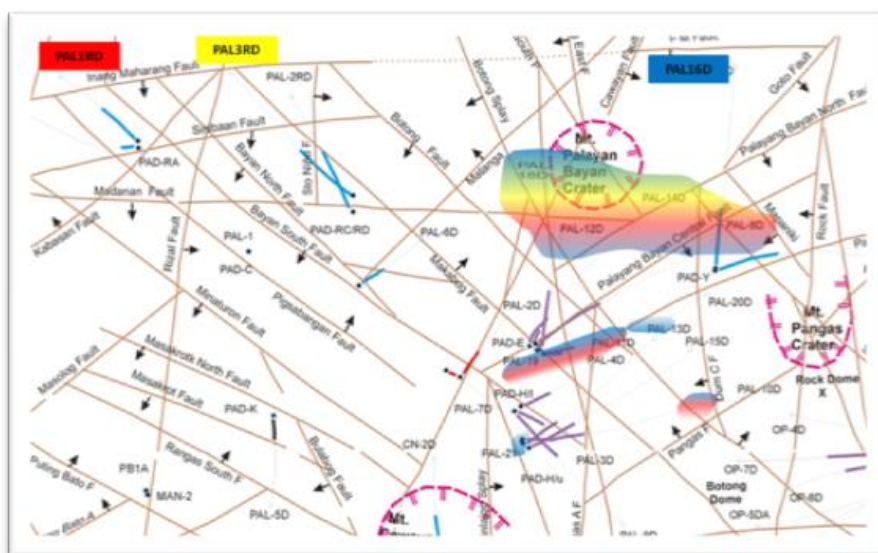


Figure 8: Tracer test returns from PAL-3RD (yellow area), PAL-1RD (red area), and from PAL-16D (blue area)

Based on the results, out-field injection strategy was implemented by drilling two injection wells outfield which is part of the reinjection well complement for the BSAP production wells. In 2012, the bulk brine load (360 kg/s) was transferred to outfield wells PAL-6RD and PAL-7RD and the balance brine load was accommodated by the in-field injection wells. The CO₂TD, quartz and Na-K geothermometers increased with corresponding increase in the enthalpy were observed thereafter indicating recovery from inflow of injection fluid returns. Also, the recovery is attributed to non-utilization of well PAL-3RD due to zero acceptance of the well.

2.3.2 Cawayan Sector

Since start of commercial operation, injection returns was the only major reservoir process occurring in wells CN-4D and CN-5D. This is reflected in the steady increase in reservoir chloride, calcium and declining CO₂TD. However, from 1994 to 2005, the temperature based on quartz and NaK geothermometers remain generally stable. This is also reflected in the stable discharge enthalpy with time (~1300 kJ/kg). The stable enthalpy suggests that the injection fluid encroachment towards wells CN-4D and CN-5D is still beneficial since it still provides mass recharge and pressure support through in-field injection.

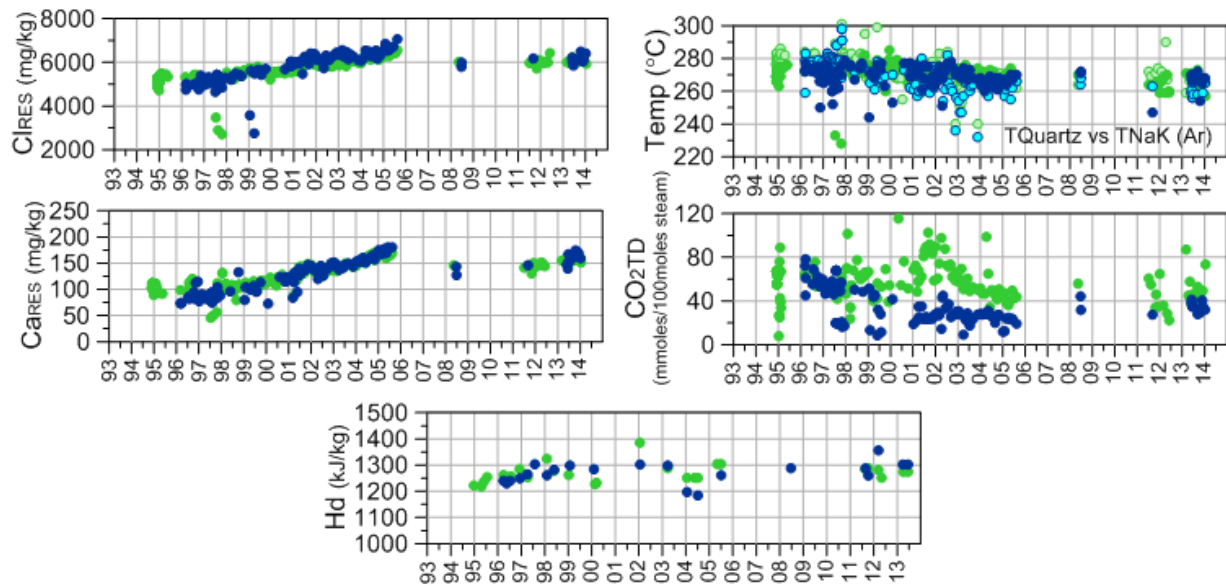


Figure 9: Selected physical and chemical parameters of wells CN-4D and CN-5D indicating signatures of injection returns

2.4 Mineral Deposition

Calcite deposition was particularly active in well PAL-21 located south of the Palayan Bayan sector. Figure 10 shows the calculated calcite saturation indices and total mass flow with time. The well underwent four mechanical work-over and could be used for about two years before it ceased to flow. The main strategy implemented which is the most practical and economical during the period was to conduct regular mechanical work-over and discharge the well only during steam augmentation is needed since Palayan Bayan power plant is operating at low load. However, a chemical anti-scalant will be implemented during full operation of the Palayan Bayan power plant.

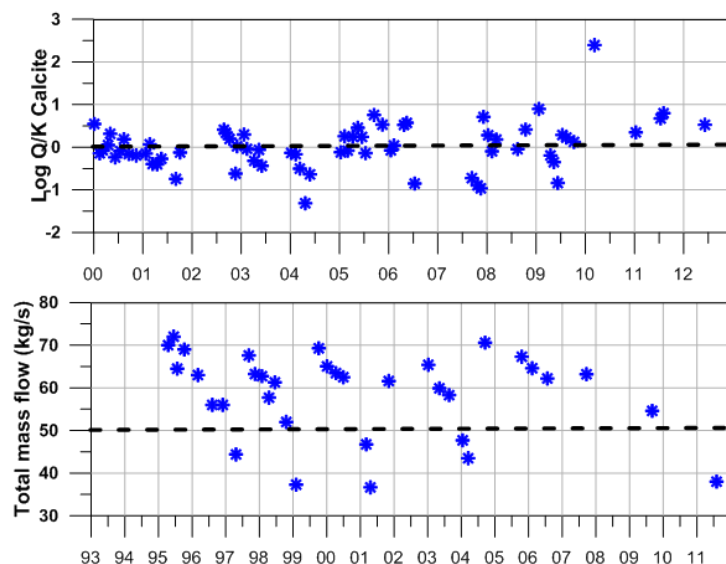


Figure 10: Well PAL-21 calcite saturation index and total mass flow with time

Anhydrite deposition in a number of production wells in Bacman develops in the wellbore when the high-SO₄ fluid mixes with upflowing deep fluid (See, 1995). As the mineral deposits grow, this progressively isolates the hotter, neutral, deeper fluids until the discharge fluid becomes acidic, dilute and cooler. The chemical trends with time of well CN-1 as well as its total mass flow with time are shown in Figure 11. Remedial measures include mechanical cleaning by means of a drilling rig, maintain the well at full-bore condition to prevent down flow, deepening the production casing shoe of new wells to case-off or avoid acid feed zones, calcium chloride injection during drilling and use of corrosion-resistant casing at detected active acid depths. Other technique being considered is the use of chelating agents to dissolve anhydrite blockages instead of mechanical cleaning using drilling rigs.

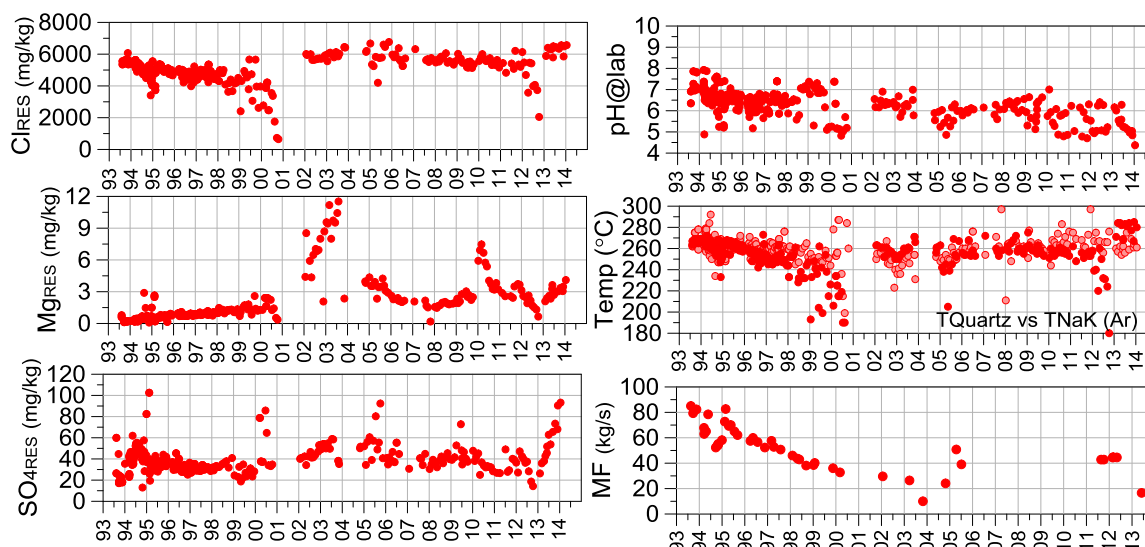


Figure 11: Selected geochemical trends of well CN-1 and its total mass flow trend with time reflect the dominance of cooler low-pH fluid and cause decline in total mass flow due to anhydrite blockage

2.5 Reservoir Temperature Decline

In Palayan Bayan sector, predominant cooling mechanism is due to boiling wherein the significant drop in quartz temperature of about 6°C occurred during the period 1993-1999 wherein the major reservoir process is boiling. However, from 1999 to 2009 the quartz temperature has stabilized, and the total drop in temperature during this period was relatively low at about 2°C. This period correspond to the episode wherein the Palayan Bayan production sector started to draw-in peripheral fluids such as the low-boron waters and injection fluid returns. The quartz temperature trend is also consistent with the enthalpy trend with time which confirms that the inflow of these peripheral fluids has been manageable also due to low mass extraction.

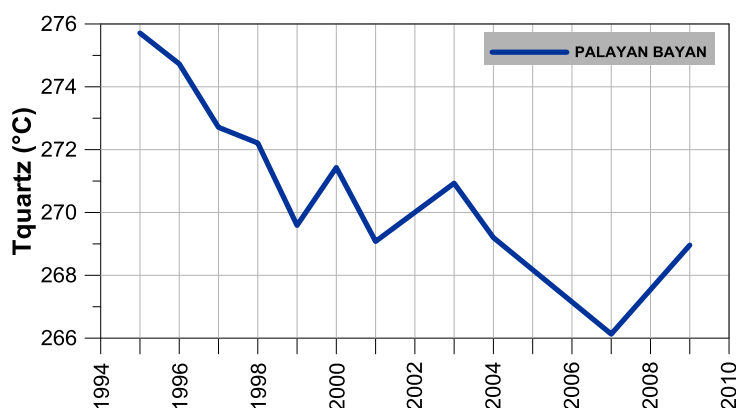


Figure 12: Average Palayan Bayan deep fluid temperature based on quartz with time

3. STEAM AVAILABILITY

In Palayang Bayan, boiling as an early response to mass extraction indicates significant increase in steam flow to ~1400 tons per hour (Figure 13). Continuous decline in steam flow ensued from when the production sector started to draw in peripheral fluids. The steam flow decline is also attributed to acid inflows at the shallow portion of the well, mineral deposition and variable utilization of the Bacman field. In 2011, with the drilling of the BSAP wells in the Palayang Bayan sector, the steam availability increased significantly. Current steam availability is around 1100 tons per hour, more than enough to supply the 110 MWe power plant.

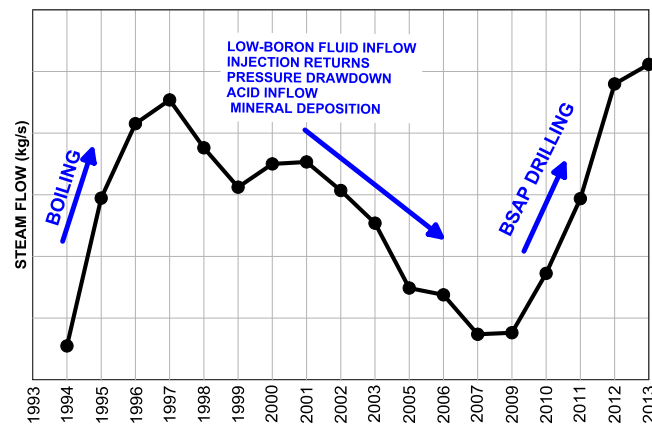


Figure 13: Total steam flow trend of Bacman geothermal field correlated with major reservoir processes during the period

4. RESOURCE MANAGEMENT STRATEGY

During the past twenty years of operating the field, various resource management and well intervention procedures have been implemented to prevent further decline of the steam flow which include: 1) cut-out or optimized loading of injection wells; 2) develop out-field brine injection strategy; 3) convert idle wells to production wells; 4) work-over and/or acidizing of wells with mineral deposition and conduct vertical clearing discharges; 5) maintain wells at discharge condition to prevent down flow of acid fluids; and 7) target M&R wells with low NCG.

5. SUMMARY AND CONCLUSION

The Bacman Geothermal Field operation for the past 20 years has somewhat preserved the steam supply of the field due to highly variable resource extraction rate and continuous long-term full extraction was not attained. However, the resource management strategies implemented have also been effective in attaining the optimum performance of individual production wells. Operational and reservoir challenges based on the past production of the field are expected to continue. Historical data and trends generally indicate that Bacman geothermal resource could be considered as currently in good condition, i.e. pressure drawdown is minimal, temperature decline is relatively low, and geochemical responses are mostly benign; adverse processes such as cooler and acid fluid inflows and injection returns have been manageable. With the rehabilitated Bacman power plants, addition of the newly-drilled BSAP wells and the development of the expansion projects, the present challenge in the field is to how to anticipate the changes as a response to maximum field operation and be able to effectively sustain production at the required loads of the power plant.

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