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Tiwi Geothermal Field: Shifting Paradigms on Resource Management and Steam Field Operations

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ABSTRACT

Located in the province of Albay, Philippines, the Tiwi Geothermal field is operated by the Philippine Geothermal Production Company, Inc. Due to continued mass extraction, several challenges and prevailing reservoir processes have shaped the paradigms of operations in the field. The continued influence of injection returns, cooling inflows, acidic fluids, and wellbore scaling has greatly affected steam and brine production forecasts. In the last five years, these challenges were met with new well drilling programs to test the boundaries of the known resource by drilling deeper and closer to the known upflow zones, pilot studies of new technologies and significant well work activities. Next to the migration of cool water inflows, aggressive wellbore scaling remains as the biggest threat to maintaining stable and reliable operations of the wells. The Tiwi Geothermal Field sits on the edge of new frontiers for exploration and collaboration to maintain a sustainable energy source for this generation and the next.

1 INTRODUCTION

The Tiwi Geothermal Field is one of the oldest developed geothermal fields in the Philippines, located on the northeast flanks of Mt. Malinao in the province of Albay, approximately 450 km southeast of Manila (Figure 1). It is operated by the Philippine Geothermal Production Company, Inc., a 100% Filipino corporation. Commercial operations of the steam field started in May 1979, supplying steam to the first 55-MWe unit of the National Power Corporation (NPC) and eventually expanding to the full development of the geothermal field to supply steam to the total installed capacity of 330 MWe in 1982 (Menzies et al, 2009).

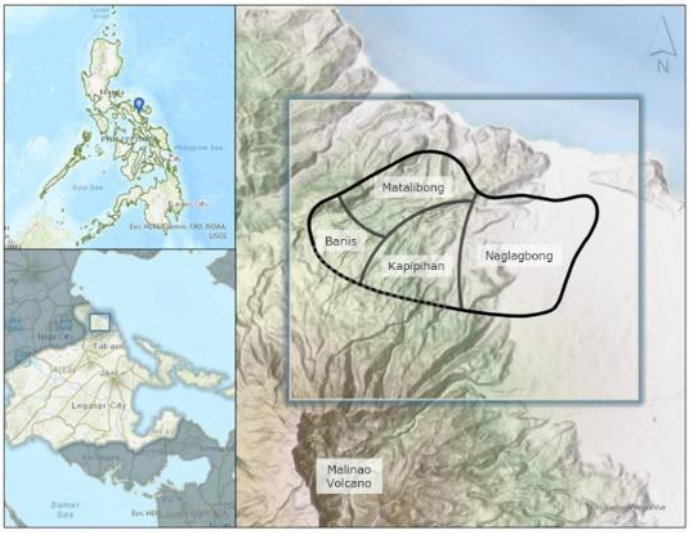


Figure 1. Location map of the Tiwi Geothermal Field.

The Tiwi Geothermal Field is a volcano-hosted, liquid-dominated geothermal system quartered into geographic sectors, Naglagbong, Kapipihan, Matalibong, and Bariis. The Kagumihan Fault and the Tiwi Fault are the two main faults that act as barriers and conduits to fluids that drive the reservoir processes observed in Tiwi. The Kagumihan Fault separates the field between the Kapipihan and Naglagbong sectors to the east from the Matalibong and Bariis sectors in the west. The Tiwi Fault further separates Kapipihan into the East and West

sectors. Both these faults act as partial barriers across their strike which facilitated the Northeast flow of fluids from the upflow zones to the outflow regions. (Sunio et al, 2004).

There are two main upflow zones that supply the field with natural recharge: one in Bariis and another in South Kapipihan. A minor upflow zone was also identified in South Naglagbong (Figure 2). The Naglagbong and Matalibong sectors are outflows of the South Kapipihan and Bariis upflows, respectively.

By the mid-80s, the steam zone that formed in the east during the early exploitation of Naglagbong collapsed due to the influx of marginal recharge, causing a drastic decline in steam output. This prompted the development of Tiwi to move westward and develop the other three sectors (Sunio et al, 2004).

There are two main injection sites in Tiwi: one in North Matalibong consisting of two hot brine reinjection wells that accommodates the brine from Matalibong, and the major injection site of Naglagbong which takes brine from Bariis and Kapipihan and is divided into two – the "infield" injectors and the "outfield" injectors. The infield injectors have provided mass and pressure support to South Kapipihan for decades and the current injection strategy is to retain injection in this sector but control it at a level that minimizes the risk of thermal breakthrough to the South Kapipihan production wells by balancing with the outfield injectors located in the southeast portion of the field.

The development and exploitation of the Tiwi field from 1979 to 2020 has been detailed in several papers and presentations by Gambill et al (1993), Sugiaman et al (2004), Sunio et al (2004), and Menzies et al (2009). Another paper by Mejorada et al (2020) provided an overview of the resource management strategies revolving around the reservoir processes observed from 2009 to 2020. This paper focuses on the last five years of resource management strategy and monitoring regarding these reservoir processes and how they are shifting the paradigms of how the field will be operated and the challenges it continues to face.

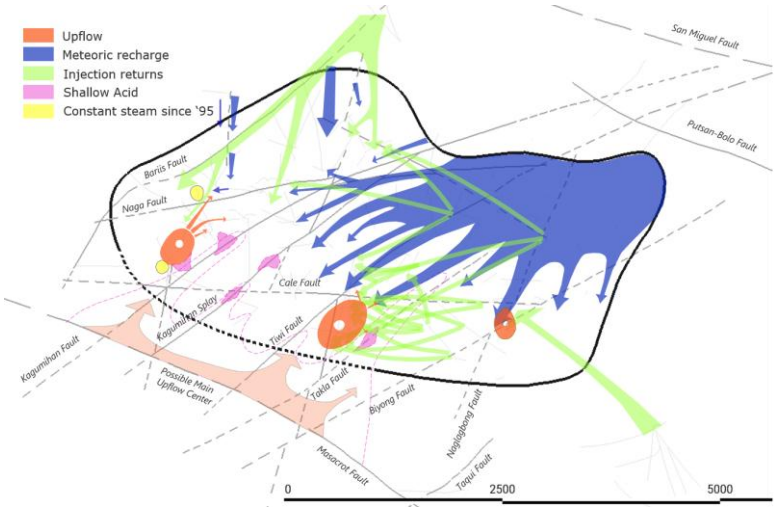


Figure 2. Major reservoir processes observed in the Tiwi Geothermal Field.

2 STATE OF THE RESERVOIR

At the beginning of 2020, the steam field was operating at 113 MW or 275 kg/s of steam (Figure 3), which is similar to what the field is producing in 2025. Although this suggests a low decline rate, it has required drilling of three new wells and a significant program of wellwork activities to maintain the steam supply. The rising liquid level in Matalibong, the nature of scaling in some wells in Bariis and Kapipihan, and the persistence of acidic fluids continues to create challenges in maintaining a sustainable steam decline rate. Among these issues, wellbore scaling has been the main driver in the accelerated decline of several large two-phase wells.

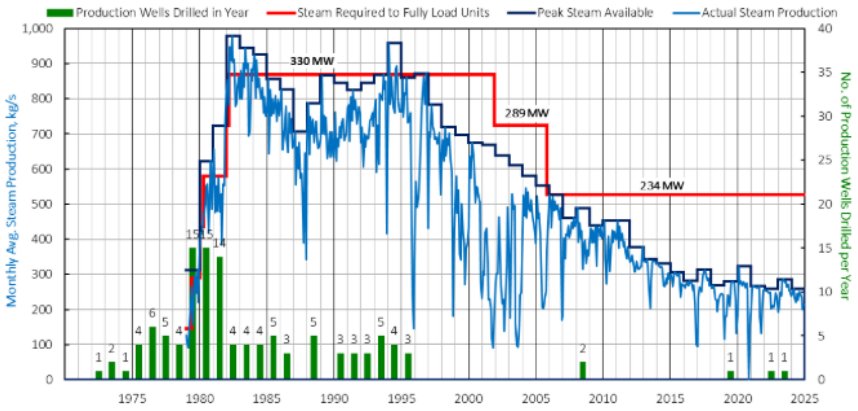


Figure 3. Tiwi steam supply, the available plant capacity, and the number of wells drilled.

2.1 Pressure Drawdown and Matalibong Liquid Level Rise

The effects of mass extraction are most evidently observed in Matalibong as shown by the initial decline in both shallow steam and deep pressures from 1980 to ~1994 and then the increase in deep liquid pressure and stabilization of shallow steam pressure from 1996 to 2023 (Figure 4). The combination of these pressure responses has resulted in the continuous shallowing trend of the water level in Matalibong (Figure 5) since 1994. These trends are due to a combination of a decline in overall production from the field since the mid-1990's (Figure 3) and also fluid recharge that has been continuously supplying the Matalibong sector with mass support.

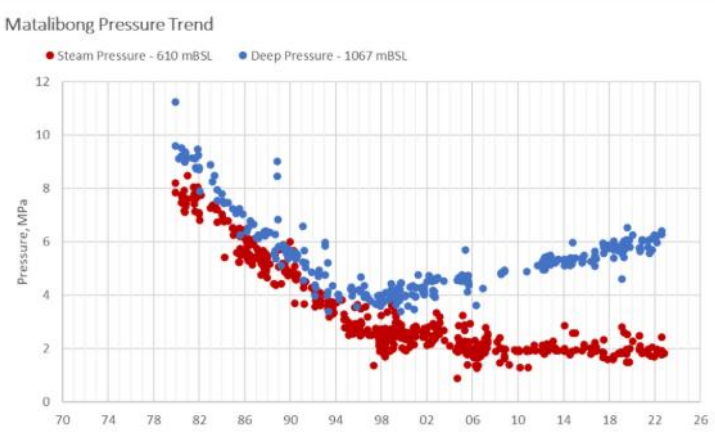


Figure 4. The Matalibong pressure trends at 610 and 1067 mBSL.

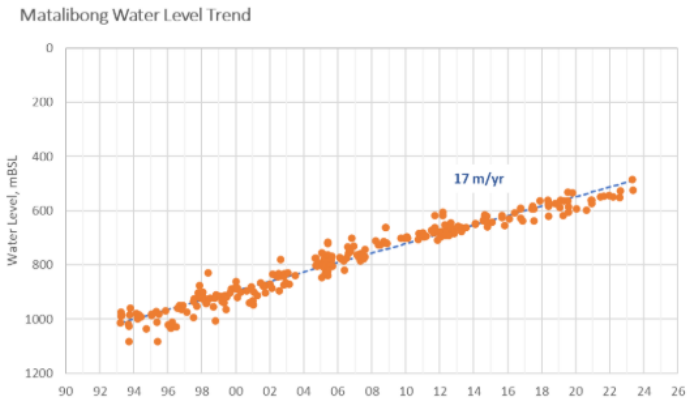


Figure 5. Matalibong water level trend.

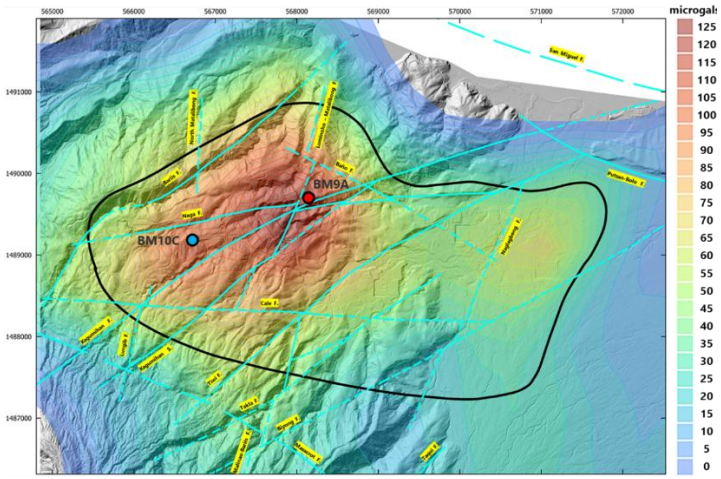


Figure 6. Tiwi smoothed gravity change contour map from 2014 to 2024. Color scale is in microgals (µgals), with red colors indicating regions of maximum gravity increase, while blue colors represent minimum gravity increase.

Contours of smoothed free-air gravity changes between the latest survey in 2024 with respect to 2014 is presented in Figure 6. Although the average fieldwide gravity change across all benchmarks is about +40 µgals, the western production area where the Matalibong sector is located exhibits a notably higher gravity change with more than 100 µgals (red areas). This region is regarded as a positive gravity anomaly forming a bull's eye pattern which encompasses Matalibong sector during this period. The anomaly is possibly linked to migration of cooler, denser fluids into the reservoir, triggering a combination of re-saturation and temperature effects on gravity that result in a net mass gain over the 10-year span. Re-saturation or decrease in steam saturation is a result of the mass influx that has also caused the rise in water level, thereby increasing local fluid density.

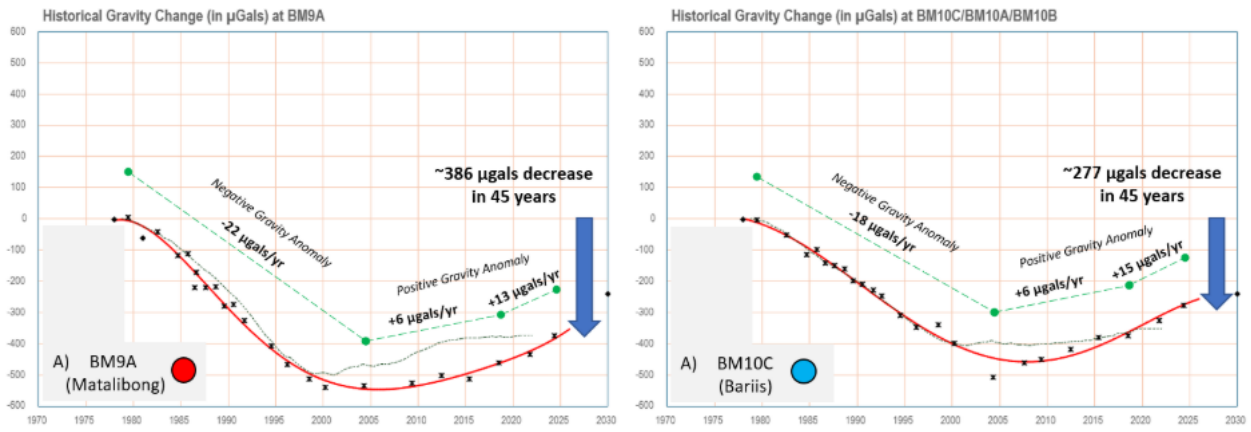


Figure 7. Gravity changes over time at A) BM9A and B) BM10C located in the Matalibong and Bariis sectors, respectively. X represents observed gravity data and the simulated gravity response derived from TOUGH2 reservoir simulator is depicted as the black dashed line (data until mid-2022 only).

The historical changes in gravity for BM9A and BM10C (Figure 7) are consistent with earlier findings that reported a gravity depression (negative gravity anomaly) in the western production area, which includes the Matalibong and Bariis sectors. This negative anomaly was due to the decline in pressure and formation of an extensive steam zone, which persisted from the start of commercial operations until approximately 2004. BM9A, the index benchmark in the Matalibong sector, exhibited a relatively steady steep gravity decrease from the early 1980s until 2004, averaging about −22 µgals/year. Following 2004, this pattern shifted, and gravity began rising at approximately +6 µgals/year until 2018. Between 2018 and the most recent 2024 survey, the rate of gravity increase accelerated to +13 µgals/year, more than twice the previous rate. Nearby benchmark in the Bariis sector, BM10C, mirrored this trend but with less pronounced changes, suggesting that similar processes influencing gravity in Matalibong may be occurring in Bariis, possibly with a slower progression, delayed onset, or occurring at a later stage.

Due to the steeper gravity decline experienced in the early years, the Matalibong Sector has accumulated a greater overall gravity decrease over 45 years of commercial operation, approximately 386 µgals compared to 277 µgals in the Bariis Sector. The greater the historical decline, the higher the tendency for available peripheral fluids to recharge or replenish the lost mass resembling a gravity rebound effect. The simulated gravity from TOUGH2 reservoir simulator roughly matches this pattern of gravity decline and rise, particularly the inflection points in the early 2000's.

The source of this recharge has been recently identified as marginal recharge and is more closely correlated to the shallow aquifers of Matalibong rather than the previously thought injection breakthrough from North Matalibong injectors. The SO_4 vs Cl discrimination diagram (Figure 8) is used to identify which secondary fluid predominantly influences each well in the Matalibong sector—either injection returns (IR) or marginal recharge (MR). An increase in brine Cl concentration indicates the influence of IR, as injectates are typically enriched in chloride. Conversely, an increase in brine SO_4 concentration accompanied by a relative decrease in Cl concentration suggests the contribution of MR. Since SO_4 concentration is temperature-dependent, only wells with comparable reservoir temperatures are included in this discrimination analysis. The Bariis upflow represents the pristine reservoir chemistry, unaffected by either IR or MR. The chemistries of both hot and cold injectates are also plotted as references to illustrate the potential effects of IR. As shown in the diagram, the Mat wells deviate rightward from the Bariis upflow composition, indicating an increasing MR contribution, while the Bar-Mat wells deviate upward, reflecting a greater influence of IR. These findings indicate that the Mat wells are strongly impacted by MR processes.

These shallow aquifers surrounding Matalibong have contributed to the overall decline in enthalpy of this sector, changing the once extensive all-steam resource into a liquid-dominated one, as seen in Figures 4 and 5 wherein the current steam-water interface sits at almost 525 mBSL, and is continuously rising by 17 m/year.

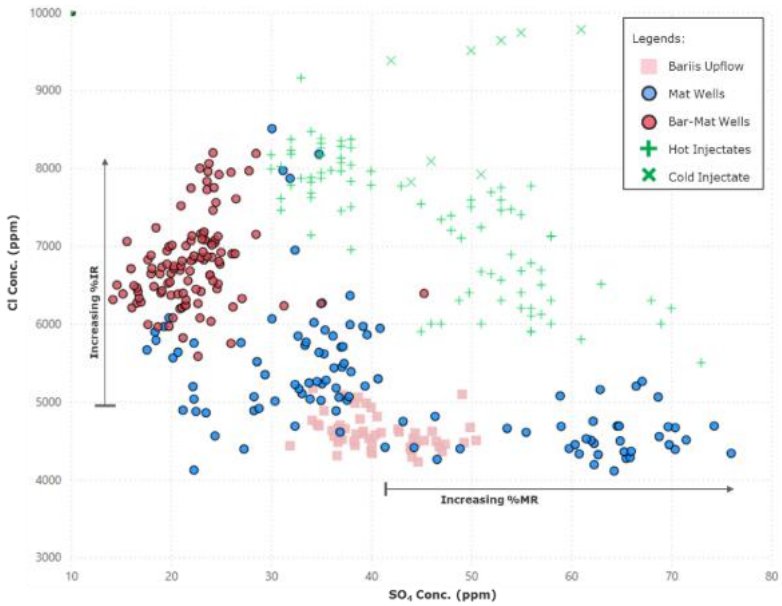


Figure 8: Sulfate (SO4) vs Chloride (Cl) plot.

The lack of a strong natural heat source, or at least a direct upflow source in Matalibong, combined with the large aquifer sources, provides a challenging task in maintaining steam field production through conventional methods.

In Bariis and South Kapipihan, the deep liquid pressures show increasing trends since the mid-1990's (Figures 9.a and 9.b), which is similar to that noted for Matalibong. This is despite the increase in mass extraction since most fluids produced in the past years were from these sectors, including from the three additional production wells drilled in 2019, 2022, and 2023 (Figure 10).

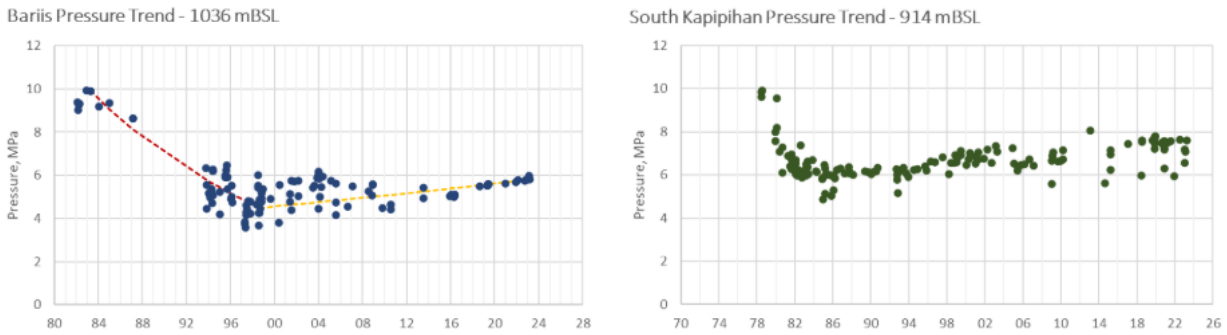


Figure 9.a. Bariis pressure trend at 1036 mBSL. b. South Kapipihan pressure trend at 914 mBSL.

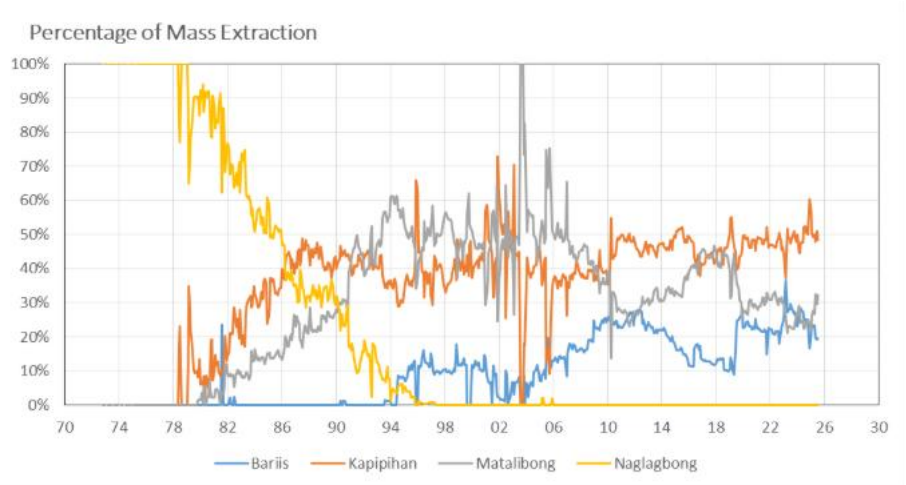


Figure 10. The distribution of mass extraction of the Tiwi field in percentage of total mass flow.

2.2 Injection Returns

In response to the increase in brine production from the drilling of new wells, old idle wells in Naglagbong were converted to infield injectors in 2019. The results of the tracer injection test conducted in 2021 show that there is connection between the Naglagbong injection wells and the South Kapipihan production wells. Frequent microearthquakes clustering in South Kapipihan area based on recent monitoring campaign continue to observe evidence of ongoing thermal contrast and heat exchange caused by these injection wells. Continued careful monitoring of the injection loading Naglagbong is required to manage and prevent thermal decline. The successful drilling of a new reinjection well in the outfield area (NRI-4) in 2023 plus the 2024 injection workover campaign, which revived the injection capacities of old injectors – both active and idle injectors, has provided an opportunity to shut-in some infield injectors that were identified to have potential thermal breakthroughs if not mitigated (Figure 11).

In Matalibong, the revival of injection well MRI-1 through a scale drillout and acidizing workover has provided a more beneficial alternative for injection from the Bariis-Matalibong production wells since its injection returns are not as severe as MRI-2. From 2019 to 2024, MRI-2 was the sole hot brine injector for Matalibong after MRI-1's capacity declined significantly when it was briefly converted as an injector for cold brine.

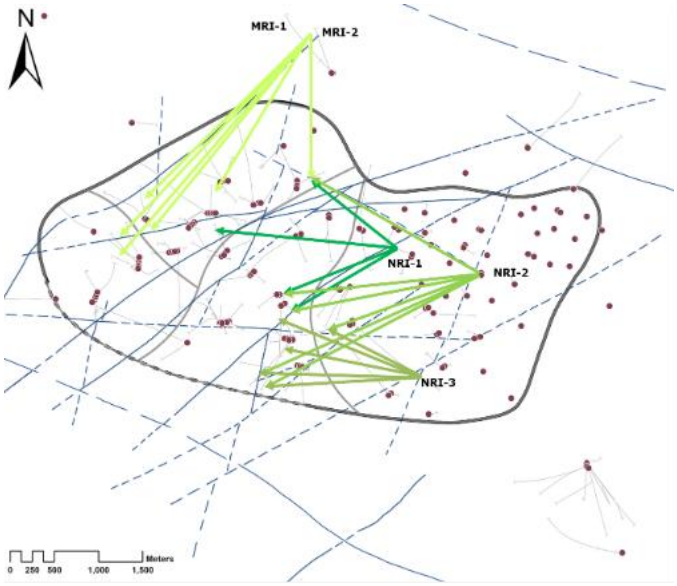


Figure 11. Results of 2021 tracer test showing the reinjection breakthrough potential from re-injection wells.

The commissioning of the Tiwi Binary Plant in 2024 provided an additional 17 MWe capacity for the Tiwi field. The binary plant utilizes the remaining heat from the brine produced from Bariis and Kapipihan before it is reinjected in the Naglagbong injectors. There is an ongoing monitoring of pressure and temperature in the South Kapipihan sector which is directly affected by these injectors, especially the infield injectors of Naglagbong.

2.3 Cool Water Inflow

Aside from injection returns, marginal recharge from the peripheries of the reservoir and shallow aquifers continues to migrate towards the production areas, especially in the Matalibong sector. This is observed in the pressure changes, liquid level rise in Matalibong, the microgravity data and the geochemistry data (Figures 4 to 8). The geology of the area also plays a vital role in managing this reservoir challenge given the presence of several conduits in the area and the weak upflow support from Bariis.

Decreasing Cl and increasing SO_4 concentrations are common indicators of cooler water inflow as mentioned in the previous section. Based on these parameters, it has been observed that the marginal recharge from Naglagbong (Nag MR) continues to affect the central and E-NE portions of the Kapipihan Sector. Evidence also suggests that Nag MR may have penetrated the southern portions of the Matalibong Sector and the E-SE of the Bariis Sector. Nevertheless, reservoir geothermometry (Tnkc) indicates that this chemical breakthrough does not correspond to a thermal breakthrough, at least in the upflow zones.

The migration of these fluids to the productive areas of the reservoir like Matalibong and Kapipihan wells that lie West of the Tiwi Fault has caused the huff-and-puff behavior. With declining enthalpy, the flowing of these wells through conventional methods, i.e. through artesian flow and into a conventional steam turbine, can be challenging due to the reduction in maximum discharge pressure. Other means of flowing these huff-and-puff wells may require technological interventions in the future.

2.4 Wellbore Scaling

One of the main drivers for the recent decline in steam production in some Tiwi production wells is wellbore scaling, wherein the chemical compositions of the fluids produced are favorable for the formation of scale. Calcite ($CaCO_3$) is a notorious example of this process, such that it easily forms when supersaturated liquid flashes, either in the reservoir or more commonly, in the wellbore.

Another common type of scale observed in the field is anhydrite ($CaSO_4$), which typically forms when hot brine with high calcium and sulfate concentrations undergoes boiling, cooling, or mixing with another cooler fluid, leading to $CaSO_4$ oversaturation.

Silica scaling, usually amorphous, commonly develops in injection pipelines and wells and sometimes in production wells, due to pressure drop, flashing and associated cooling of the geothermal fluids, which reduces silica solubility and causes precipitation at lower temperatures.

Depending on the chemistry and thermodynamics in the well, these common types of scales mentioned above can form at the same time in a single production well.

This issue has been mitigated through the years through scale drillout and acidizing programs both using a rig and utilizing other methods like broaching and scale dissolution. These methods have had varying degrees of success, especially broaching, which has been tried on a number of production and injection wells in Tiwi. The results of these broaching campaigns are discussed further in section 4.1.

2.5 Acidic Fluids

In Bariis and in the west of the Tiwi Fault, an acid horizon rests at the shallow waters of the reservoir. This acid horizon is defined from 840 to 900 mbsl in Bariis, and 700 to 910 mbsl in South Kapipihan (Crisostomo, et al., 2015). The migration of this acidic fluid is a constant threat for several wells and has led to plug and abandonment for some of the Bariis wells in its early development. The strategy in the recent drilling campaigns has been to set the casing deep to isolate the acid horizon. However, for old wells that are open to the shallow section, this threat remains true.

Several theories have been proposed in the past to address the origin of acid sulfate fluids in Tiwi. Two of the currently preferred models include the: (a) migration or downflow of acid fluids from aquifers through faults (Sugiaman, et al., 2004); and (b) in-situ formation of acid sulfate from the mixing of H_2S and shallow oxygenated ground waters (Villasenor and Vicedo, 2010). Both models further suggest that acid-producing wells are prone to anhydrite scaling, especially during shut-in conditions. This results in wellbore obstruction and the restriction of deeper neutral zones, leading to acidic production from shallower acid-sulfate zones.

Zonal isolation, opening up deep neutral feedzones, suppressing acid inflow through valve manipulation, and, more recently, chemical intervention have been strategies employed to ensure that acidic production is prevented or mitigated. The details and results of the pilot study on the chemical intervention are discussed in section 4.2.

3 DRILLING PROGRAMS

Three (3) production wells and one (1) multilateral re-injection well have been drilled in Tiwi since 2019 and after more than a decade since the last make-up well program. The drilling of these wells aimed to explore the deep resource of Tiwi in Bariis and South Kapipihan. A deep casing program (to below ~1300 mbsl) was implemented in these new wells to isolate the effects of acid and cold water inflow which occur at relatively shallow depths (Figure 12).

In South Kapipihan, three (3) make-up wells (SK-1, SK-2 and SK-3) were able to prove the existence of highly permeable feedzones in the deep sections of this sector and is closely correlated to the upflow due to its high temperature. On the other hand, in Bariis (B-1), the deep exploration has discovered high temperatures and moderate permeabilities. Unfortunately, scaling, which appears to be predominantly calcite, has been observed to affect the continuous production of these wells. Mitigating scale formation through frequent scale removal and scale inhibition techniques are currently being explored to ensure steam availability.

A multilateral re-injection well (NR-4) was also drilled as part of the recent campaign to handle the produced brine from these wells. To mitigate the effects of the aforementioned injection returns, NR-4 was drilled in the outfield sector of the field.

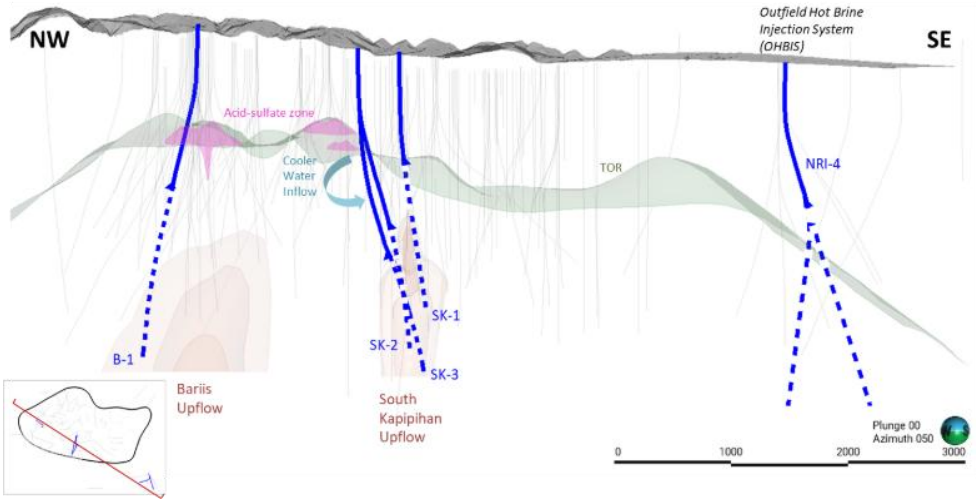


Figure 12. Cross section of the Tiwi Resource from northwest to southeast with the recently drilled wells (in blue).

As mentioned above, several workover campaigns were conducted to combat wellbore and formation scaling. Steam decline is mostly wellbore-related and not reservoir-related since the production from these scaling wells return close to their initial production rates post-workover.

The largest scale drillout and acidizing workover program in Tiwi was executed on several injectors in 2024 to rehabilitate the injection system. All injectors in the campaign were successfully drilled out and acidized and were able to increase injection capacity by as much as 125% in Naglagbong injection wells. The full details of the benefits of the acidizing campaign are still being studied due to the introduction of a confounding variable – the lower temperature of brine from the Tiwi Binary plant that also appears to be a factor in the improved injection capacities.

4 PILOT STUDIES

Aside from rig activities, several pilot studies are also being conducted to provide solutions to the above-mentioned reservoir and wellbore issues.

4.1 Broaching

As a low-cost alternative to scale drill outs using a rig, broaching was tested in several wells in Tiwi with varying degrees of success. The main challenge encountered in broaching is if the well has a high degree of inclination, which imposes access restrictions for the broaching assembly to successfully penetrate scales. Since this is a mechanical wireline activity, the driving force to push past the scale is relatively limited, especially below the water level.

Another limitation is the hardness of scale. The probability of success decreases as more minerals other than soft calcite are present in the scale formation. From the campaigns conducted in Tiwi, broaching is recommended for recently formed soft scales as a routine maintenance activity but a well inclination threshold must be imposed to guarantee effectivity (Figure 13).

4.2 Scale Inhibition System and Acid Well Utilization

Broaching and scale drillouts alone cannot solve the issue of wellbore scaling. Chemical intervention systems are now commonly deployed in many geothermal fields across the globe to overcome well challenges and limitations, two of which were tested in Tiwi in the last 3 years.

The calcite scale inhibition system was tested in one Bariis well. The system uses a proprietary chemical from a supplier that utilizes a chelating agent to bind calcium ions (Ca^{2+}) effectively inhibiting the formation of calcite scale ($CaCO_3$). However, there have been some operational challenges encountered that resulted in the capillary tubing being lost downhole. The pilot study will continue once the scaling inhibition system is back online.

The acid well utilization (AWU) system, on the other hand, uses capillary tubing to deliver a neutralizing base to produce the acidic fluids at an acceptable pH. This project was able to provide an additional 3 MW when a Matalibong well previously open to the acid horizon flowed safely to the system in 2023 (Figure 14).

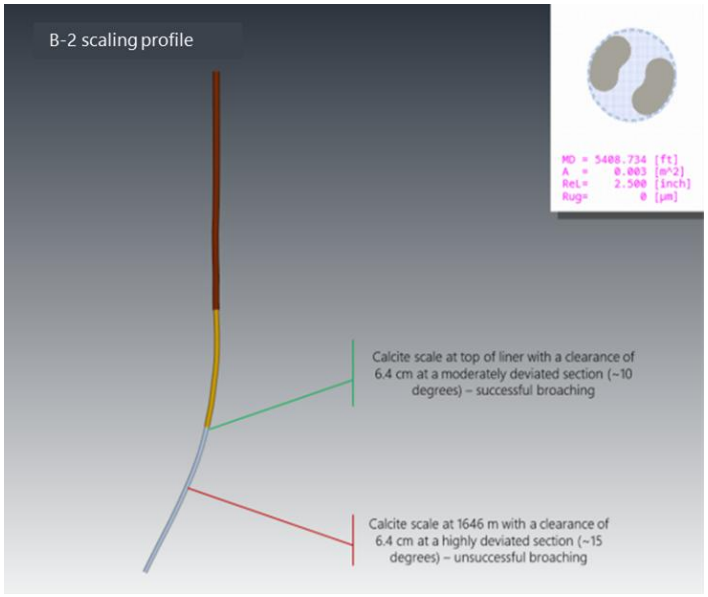


Figure 13. B-2 scaling profile and the well track showing the deviated sections where the scales were tagged.

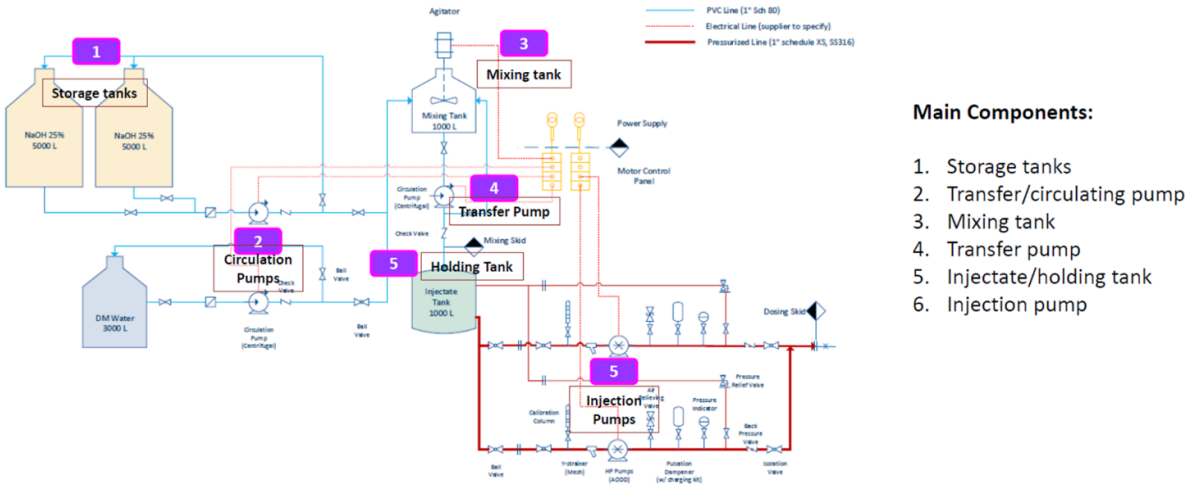


Figure 14. Schematic diagram of the acid well utilization system.

The main challenge in maintaining the AWU system is the inadvertent formation of by-product scales which are hard to remove and may result in a stuck tubing incident. Ongoing mitigation studies and well interventions (e.g., sulfide scale dissolution, optimization of tubing maintenance schedule, etc.) are being evaluated to be able to deploy this technology to other acidic wells in the field.

5 WAY FORWARD

After more than four decades of continued mass extraction, the Tiwi field has developed several reservoir and wellbore issues that are not new to this industry. In the long history of Tiwi's development and production, continuing operations through conventional methods have been more challenging in the previous years. This is simply but a testament of the aging reservoir and managing this resource requires looking into novel technologies outside of the existing paradigm. Chemical intervention delivered through capillary tubing, low-cost alternatives for scale removal, and new methods for isolating wellbore sections are only a few of the myriad advances in well intervention over the past decade alone. These issues are not unique to a singular field and the universal goal to produce at a steady decline remains a collective struggle.

PGPC Reservoir Management team, and the Technology and Innovations team are currently investing efforts to remove scale using air hammer technology and scale dissolution, to ensure safe and stable production by continuing pilot studies on chemical intervention techniques, to probe further the boundaries of the Tiwi production area through drilling programs, to refine and update the conceptual model through geologic studies

and numerical modeling, and to overcome low enthalpy fluid migration through the applications of electrical submersible pumps and zonal isolation.

The prevailing reservoir processes and the introduction of new parameters like lower brine temperature from the Binary plant have created fertile ground for innovation. As the oldest operating geothermal field in the Philippines, the Tiwi reservoir has had its share of challenges and is bound to show signs of wear and tear but through comprehensive drilling and wellwork campaigns coupled with new technologies, it remains as a steadfast source of clean energy to support this generation and the next.

Acknowledgements

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