Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Developing the Acid Reservoir at Tiwi Geothermal Field, Philippines

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Keywords: Tiwi, acid-sulfate fluids, Bariis, SoKap, alteration

ABSTRACT

The southwestern sector of the Tiwi Field - Bariis and South Kapipihan (SoKap) - has been developed since the late 1980s and many of the wells drilled in these areas proved to be acidic and could not commercially produce. However, successes in the re-drilling of B8 in 2005 and drilling of the big-hole producer B11 in 2008 suggest that the strategy employed to avoid the acid-sulfate fluids worked so that commercial drilling can resume in this sector. These two wells were completed with deep cemented liners set at ~900 meters below sea level (mbsl) and are currently two of the biggest producers in the field. The deep cemented liner strategy proved to be an effective solution in isolating the shallow acid-sulfate fluids in Tiwi.

Acid production has been encountered in 28 of the 156 wells drilled in the Tiwi Field, mostly in Bariis and SoKap. Eight of the 13 wells drilled in Bariis produced acidic fluids. These wells were completed with shallow production casing at ~500 mbsl. The shallow acid model describes the acid fluid as a product of the oxidation of H_2S exsolved from either the reservoir or ascending steam as it encounters oxygenated groundwater and condenses at the top of the geothermal reservoir. The zone defined from 840 mbsl to 900 mbsl in Bariis and 700 mbsl to 910 mbsl in SoKap is considered to be the primary (or known) acid-sulfate fluid entries in wells B8, K30, K31 and K32. These zones correlate with advanced argillic (acid) alteration zones logged in nearby wells B1, B2 and K28 (including K30), although several studies suggest that the advanced argillic zones are relict. Several inferred acid-sulfate fluid entries were also used in combination with the known acid-sulfate fluid entries and acid alteration zones to define a broader interval of acid-sulfate fluid zone for Bariis (670 mbsl to 1040 mbsl) and for SoKap (700 mbsl to 1,080 mbsl). Furthermore, a recent sulfur isotope study also reveals that the Tiwi acid-sulfate fluid has a non-magmatic origin but is influenced by shallow processes. This then leads to the proposal to set the cemented liner at ~1,100 mbsl to avoid the acid fluids and this deep cemented liner strategy will be applied in future make-up well drilling campaigns in southwest Tiwi.

1. INTRODUCTION

The Tiwi Geothermal Field is located in the municipality of Tiwi, Province of Albay, about 450 km southeast of Manila (Menzies et al., 2010). The production area (Figure 1) is divided into four geographic sectors - Naglagbong (Nag) to the east, where initial production took place in the early 1970's; Matalibong (Mat), which forms the northern boundary; Kapipihan (Kap), which is south of Matalibong; and Bariis (Bar), in the west-southwest. Production in the late 1980s was shifted to the west into the Mat-Kap sectors when cold meteoric fluids started to enter the Naglagbong reservoir.

The general geology and alteration in the Tiwi reservoir is discussed in Sugiaman, *et al*., (2004) and Moore, *et al*., (2000). The Tiwi geothermal reservoir is a liquid-dominated, fracture-controlled hydrothermal system with ~15 km^2 bean-shaped productive area (Sunio, *et al*., 2005). The southwest margin, however, has not been delineated yet thus the exploration efforts are focused on this location.

The Tiwi reservoir has an initial chloride concentration of about 4,300 – 5200 mg/kg, except for the outflow near the Naglagbong thermal area which had chloride concentrations of up to 6,400 mg/kg. The average initial reservoir temperature based on quartz and Na-K-Ca geothermometry is 260°C with a maximum measured temperature of 353°C (at K30) in the upflows (Sunio, *et al*., 2005). The more recent production make-up wells were drilled within Bariis and South Kapipihan (SoKap) areas in the southwest part of the production area, where two of the upflows - Bariis and SoKap - are inferred. These upflows are spatially associated with major faults - the Bariis Upflow being controlled by the Kagumihan Fault while the SoKap Upflow is controlled by the Tiwi Fault. Although both faults are pathways of fluid flow, they may also act as downflow conduits for shallow acid fluids, as well as barriers to flow across the fault blocks. Trends in measured temperatures, fluid chemistry, geothermometry and alteration mineralogy indicate that fluid from the upflows reaches shallow levels through the faults and generally outflows to the northeast (Figure 1) (Sunio, *et al*., 2005).

1.1 History of Acid-Sulfate Production in Tiwi

A total of 156 wells have been drilled at Tiwi since the field was first explored in 1971. Acid fluids have been encountered in 28 wells, mostly in Bariis and SoKap. In Bariis alone, eight of the 13 wells drilled turned out to be acidic and are now either suspended or have been plugged and abandoned. Because experience has shown that the minimum pH acceptable for production is 4.3, these results have discouraged further development of the Bariis sector. Some of the wells drilled in the Bariis sector have shown high-temperatures and good initial production, yet the acid character of the fluids has precluded their long term production due to excessive corrosion both within the wells and in surface facilities.

The successful recompletion of B8 in 2005 (Villaseñor and Vicedo, 2010), which effectively isolated the acid-sulfate production zone in the well, boosted the confidence that the hot, neutral-pH Bariis upflow can be produced with appropriate subsurface planning and wellbore design. The succeeding well, B11, drilled in 2008, was similarly completed with a deeper cemented liner set at 928 mbsl. These two wells are currently among the largest neutral-pH fluid producers in Tiwi delivering about 15 kg/s and 13 kg/s of steam, respectively. In the SoKap upflow area, K35 was also drilled in 2008 and is currently the biggest production well with 31 kg/s of steam despite a shallow production casing shoe at 725 mbsl. Other wells on the same pad as K35 are also neutral although wells on adjacent locations (i.e., K31 and K32) are acidic. This implies that the acid-sulfate fluids are localized, and may not be considered contiguous. This paper focuses on the acid wells in the Bariis and SoKap sectors, which are target areas for future make-up well drilling.

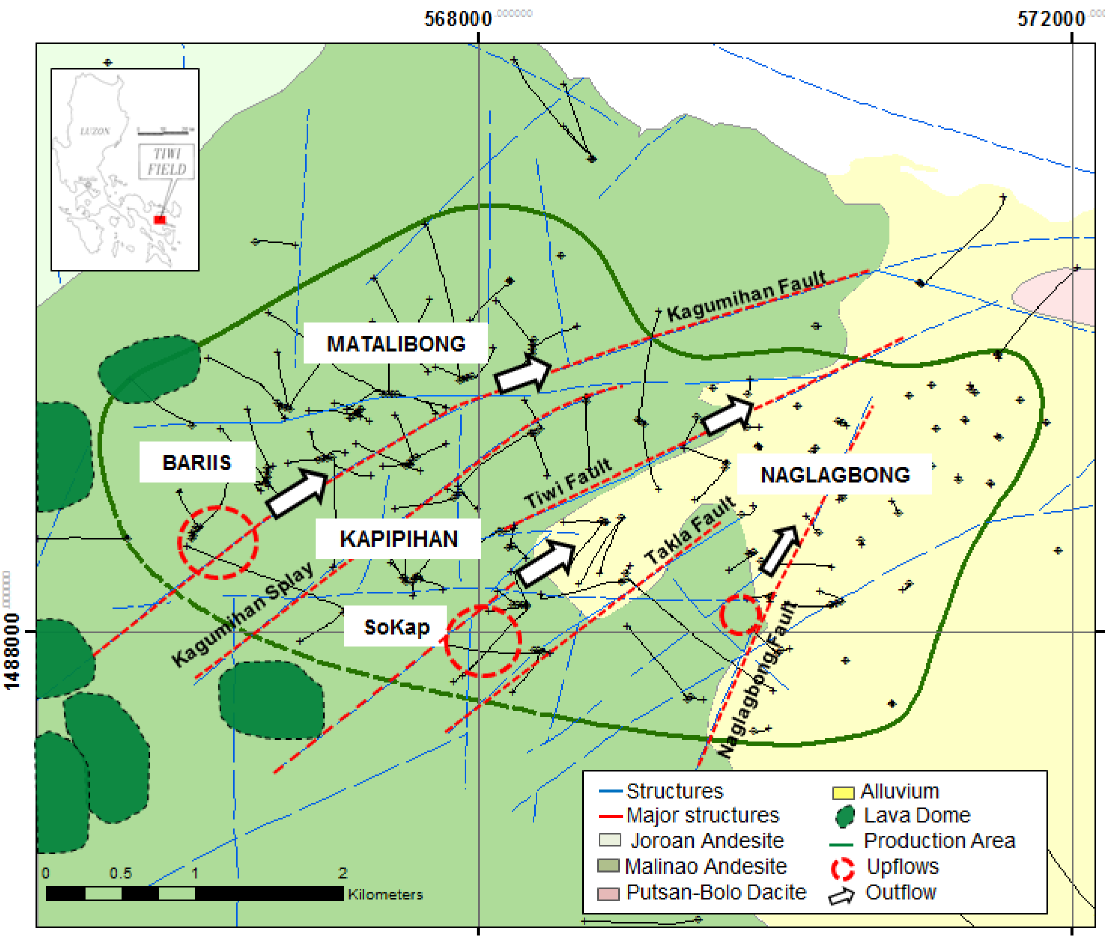

Figure 1: Location Map of Tiwi Geothermal Field Showing the Bean-Shaped Production Area (green solid/dashed line), Geographic Divisions, General Geology, Major Structures and Upflow Zones in Bariis and SoKap.

1.2 Acid-Sulfate Distribution in Tiwi

Exhaustive studies of acid fluids and mineralogy at Tiwi have been undertaken by previous authors (e.g. Moore and Lutz, 1994; Powell, *et al*., 1995; Stimac, 2000). This paper is a synthesis of findings from earlier studies and insights from new observations and interpretations. The authors reclassified the acid-sulfate zone distribution into (1) Known Acid-sulfate Fluid Zones; (2) Inferred Acid-sulfate Fluid Zones and (3) Advanced Argillic (Acid) Alteration Zones. Figure 2 shows the distribution in map view of the acid zones above and below 1,100 mbsl (the proposed casing depth for future wells, as discussed in succeeding sections), and it is obvious that most of the acid zones are located above this elevation.

At least four wells, namely B8RD, K30, K31 and K32, have proven acid producing zones in both Bariis and SoKap. Data from these wells, e.g., PTS-defined permeable zones, downhole samples, acid production history and evolution are compelling enough to provide high certainty on the vertical extent of the acid-sulfate zones. Inferred acid zones, as the name implies, were defined with less certainty because these are based on uncertain feed zone locations (i.e., permeable entries identified by Pressure-Temperature (PT) logs and lost circulation while drilling instead of the more accurate Pressure-Temperature-Spinner (PTS) logs) and absence of downhole samples or detailed acid production history. The acid alteration zones are defined by logged rock cuttings and cores exhibiting advanced argillic alteration assemblages, which may or may not correlate with the production of acid fluids.

Powell, *et al*., (1995) classified the advanced argillic alteration zones into two mineral assemblages: high-temperature minerals pyrophyllite + diaspore ± alunite ± dickite, which occurs within the main reservoir, and a low-temperature assemblage of kaolinite ± alunite ± jarosite found in clay-altered rocks. The distribution of the high-temperature acid-sulfate alteration in the reservoir and its association with acid production prompted further studies including detailed petrology and fluid inclusion analyses of both cores and rock cuttings.

Powell (1986) initially concluded that the acid alteration observed in several wells was relict. For example, the presence of pyrophyllite, stable at temperatures >300°C, in K30 was inconsistent with the lower measured temperatures in the well. Moore *et al.* (2000) corroborated this theory of relict acid alteration from fluid inclusion studies of anhydrite veins in B1 and K4. These studies concluded that the high-temperature advanced argillic mineral assemblage was deposited by the disproportionation of magmatic SO_2 to H_2SO_4 and not by the downflow of shallow acid-sulfate fluids. Furthermore, these minerals were formed at temperatures >300°C at the end stage of hydrothermal mineralization some 200,000 years ago, which is before the formation of the present-day geothermal system (estimated to have formed 10,000 to 50,000 years ago – Moore, *et al.*, 2000).

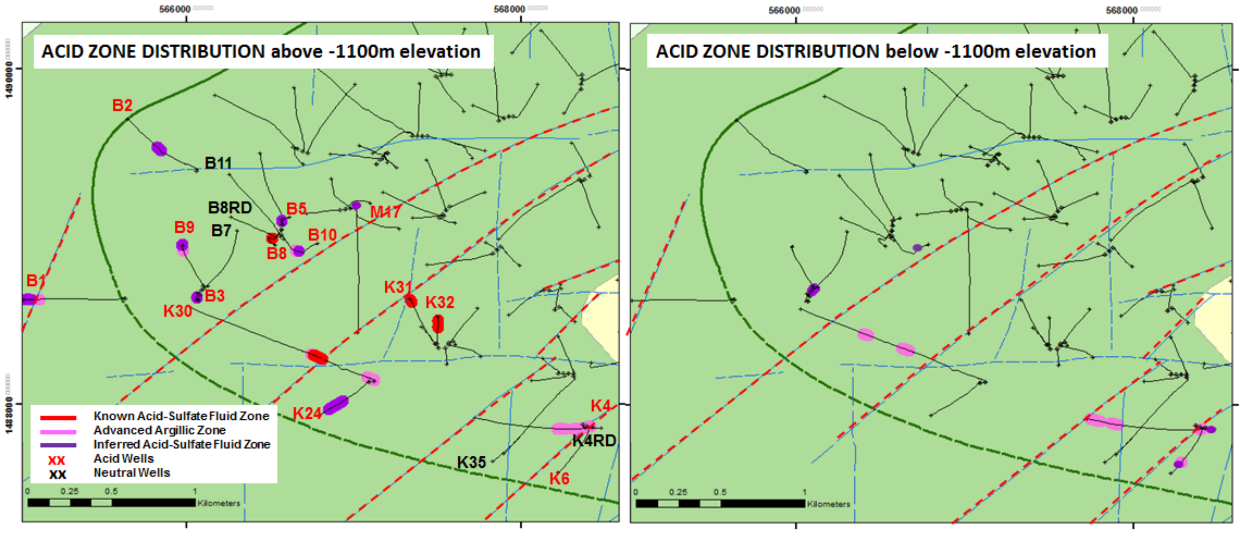

Figure 2: Distribution of Acid Entry Zones Above (left) and Below 1,100 mbsl (right). Note the abundance of acid producing zones above this depth.

The acid source in two of the deep acid wells in southwest Bariis has not yet been studied. The absence of reliable feed zone characterization in these two wells leaves open the possibility of deeper acid entries which could be magmatic in nature. A sulfur isotope study and review of alteration mineralogy will provide additional insights in characterization of these acid zones.

1.3 Theories on Acid-Sulfate Fluid Formation

Sugiaman, *et al*., (2004) defined the Tiwi acid fluid as a relatively cool and dilute (2,500 mg/kg – 3,500 mg/kg Cl) fluid with pH of 2.8 to 3.6, and concentrations of SO_4 of 300 to 700 mg/kg and Mg concentrations of 3 to 11 mg/kg. The lower enthalpy, dilute nature and elevated Mg suggested groundwater influence. Powell, *et al*., (1995) suggested that the acid-sulfate fluids could not be of magmatic origin because the isotope and helium data indicates very small magmatic contribution; SO_2 was also absent from any samples.

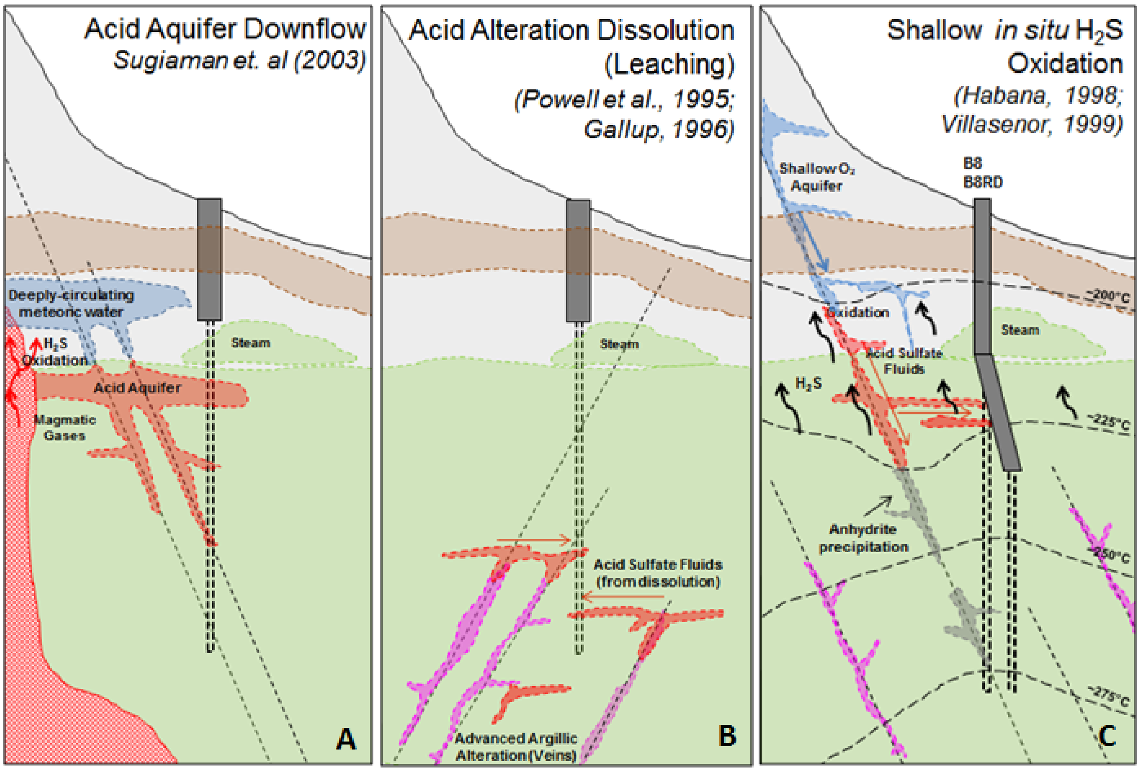

Figure 3: Theories on Acid-Sulfate Fluid Formation: A - Acid Aquifer Model; B - Acid Alteration Dissolution/Leaching Model; C - Shallow In-Situ H_2S Oxidation.

Several other theories on the formation of the acid-sulfate fluids in Tiwi have been presented. Early works stressed that the acid-sulfate fluids are localized in the southwestern margin of the field. The fluids were believed to originate from shallow oxidized aquifers draining the Malinao Crater (Rohrs, 1983; Hoagland and Bodell (1991) in Stimac, 2000). Powell, *et al*., (1995) suggested a model of acid-sulfate mineral dissolution wherein the benign reservoir fluids react and equilibrate with the relict advanced argillic minerals along steeply-dipping faults and fractures. The process also results to permeability enhancement along these structures (Figure 3). Sugiaman, *et al*., (2004) proposed the acid aquifer model where deeply circulated meteoric fluids mix with sulfur-rich gases from a magmatic heat source. In this model faults act as conduits for the downflow of these fluids to their present location (Figure 3).

Villaseñor and Vicedo (2010) suggested that the Tiwi acid-sulfate fluids are formed by the oxidation of H_2S derived from the geothermal reservoir by shallow oxygen-rich groundwater (potentially downflowing along faults). The oxidation of H_2S to H_2SO_4 may occur (1) beneath the steam cap which may or may not be a contiguous zone; (2) along faults or structures that conduct both separated steam to the surface and O_2-rich groundwater into the shallow reservoir; and/or (3) near shallow meteoric recharge zones. This shallow oxidation model suggests that the acid-sulfate fluids may have been formed in-situ with patchy distribution. Faults may also conduct these fluids to greater depths, e.g., Kagumihan and Takla Faults (Figure 3). This model of acid fluid formation and distribution near the top of the reservoir is currently the preferred model and is the foundation for designing wells that will produce from the deeper benign part of the reservoir.

In addition, Villaseñor and Vicedo (2010) modeled the chemistry of the discharged fluids of some of the acid-producing Bariis wells, i.e., B8 and B10, and observed that the SO_4 concentration in these wells declines with increasing temperature. The modeled anhydrite solubility for B8 showed that this mineral precipitates from acid-sulfate fluids at around 225°C as the SO_4-rich acid fluid mixes with the Ca-rich neutral-pH reservoir brine.

Both Sugiaman, *et al*., (2004) and Villaseñor and Vicedo (2010) suggested that these acid-producing wells are prone to anhydrite scaling particularly during shut-in conditions when mixing of the acidic and neutral fluids occurs. In general, the shallow feed zone contributes the acid-sulfate fluids while the deeper zone is the source of the hotter neutral-pH, chloride fluid. Anhydrite is precipitated when the cooler acid-sulfate fluid downflows at shut-in conditions and mixes with the hot neutral-pH reservoir brine as clearly demonstrated in the case of K4 and B8.

2. TIWI SHALLOW ACID - CASE HISTORIES

2.1 SoKap: K30

K30 is a long-throw well drilled in 1986 to a total depth of 3,095 m (2,384 mbsl) from the SoKap area into the deep Bariis sector. Its production casing shoe was set at 1,652 mbsl. The well initially had neutral but non-commercial production of 5.9 kg/s total mass flow, and a bottomhole temperature of 352°C. K30 was perforated at 741 mbsl to 879 mbsl in 1996 with the objective of tapping a potential steam zone which coincides with an advanced argillic alteration zone (Figure 4A) (Cabigon, *et al*., 1996). The perforation job did not improve the production of steam as the well started to produce fluids of pH 3.12 at non-commercial flowing wellhead pressure (FWHP). The result of the perforation job helped refine the extent of the acid-sulfate zone, at least for this area in SoKap. It was also observed that the acid zone coincided with the possible intersection with the Kagumihan Splay, which may have facilitated the formation and entry of the acid-sulfate fluid.

2.2 Bariis: B8

B8 was completed in 1995 to a total depth (TD) of 1,981 m measured depth (MD) (1,534 mbsl) with the production casing shoe at 900 m (463 mbsl) aimed at tapping both steam and deep liquid feed zones. It initially produced 35 kg/s of steam at 85% flash with a discharge fluid pH of 4.6- 5.2 (Villaseñor and Vicedo, 2010). The acid production in this well was attributed to a blockage at 870 mbsl which prevented flow from the deep benign feed zone and, thus, production from the shallow acid-sulfate zones only at 840 m – 860 mbsl and 870 m – 901 mbsl (Figure 4B). The blockage was believed to be anhydrite which formed with the downflow of the relatively cooler and dilute acid-sulfate fluids and mixing with the more Ca-rich neutral brine from the deep feed zone when the well was shut-in. Villaseñor and Vicedo (2010) concluded that anhydrite precipitated at about 225°C for some of the acidic wells in Tiwi.

In 2001, a corrosion mitigation system consisting of a corrosion-resistant capillary tube which injects a mild concentration of caustic soda was installed in B8 with the injection sub set just above the acid-sulfate entry. B8 was able to produce fluids with pH 4.5 – 5. However, scale formed around the injection sub (believed to be from the initial mixing of the caustic solution with the acid-sulfate fluids) and prevented the pull-out of the sub for maintenance. After eventually pulling-out the slotted production liner, heavily corroded sections just below the injection sub were observed while the liner above the sub did not show significant corrosion (Figure 5). Intensely corroded portions of the outside liner wall at ~910 mbsl were also observed providing strong evidence on the depth of the acid-sulfate zone (Villaseñor and Vicedo, 2010). Other acid-sulfate wells at Tiwi are documented in Table 1.

2.3 Sulfur Isotope Study

A sulfur isotope study was conducted in Tiwi to provide additional insights on the nature/origin of the acid-sulfate fluids. A total of 19 $BaSO_4$ ($\delta^{34}S_{SO4}$; $\delta^{18}O_{SO4}$) and 21 Ag_2S ($\delta^{34}S_{H2S}$) and 23 δD_{H20}-$\delta^{18}O_{H20}$ samples were collected from both neutral-pH and known acid producing wells, including six downhole samples. Results of this study reveal that the Tiwi acid-sulfate fluid has non-magmatic origin and has influence from shallow processes (Calibugan, *et al*., *in press*) hence the risk of encountering deep acid-sulfate fluids in the Bariis and SoKap areas is low except probably along the faults.

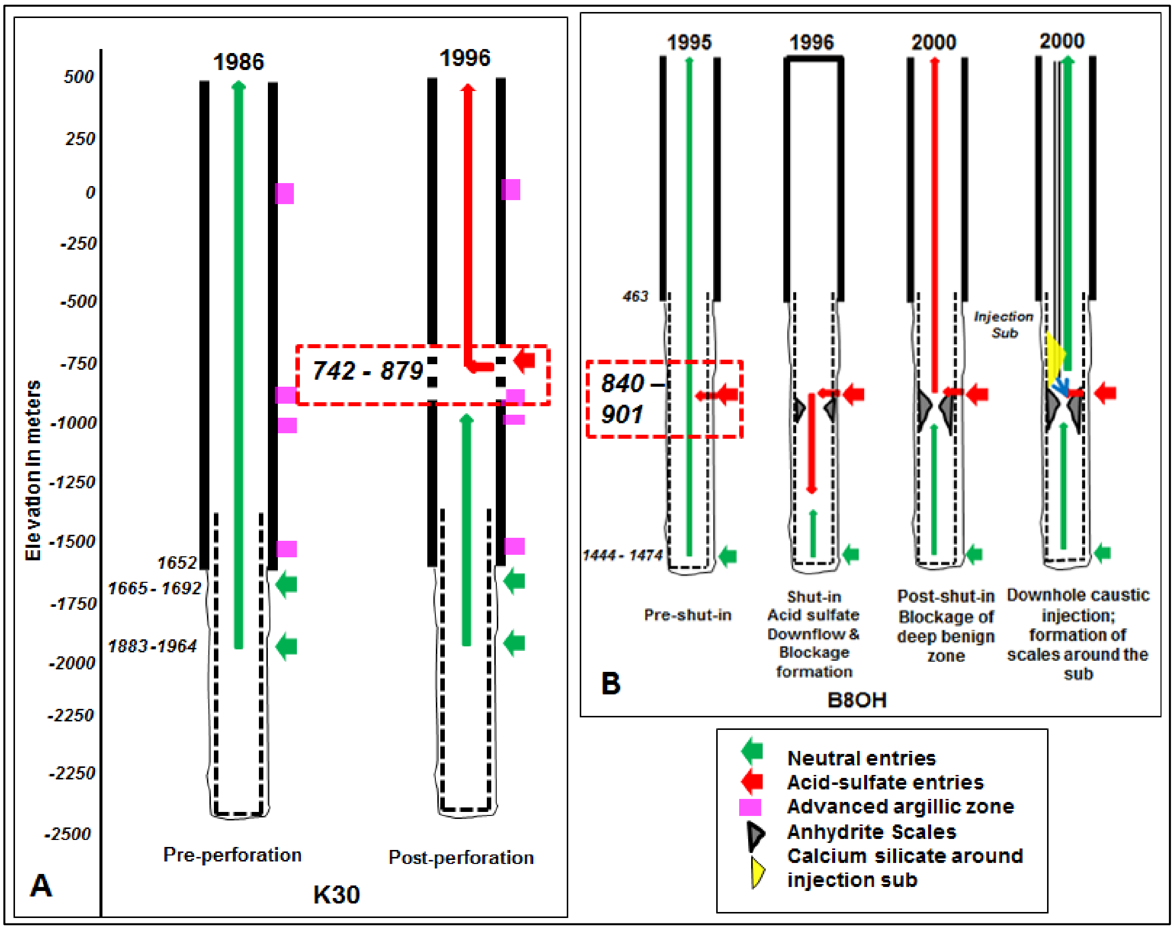

Figure 4: Simplified Pre- and Post-Perforation Wellbore Hydraulic Model of K30 Showing Acid Production at the Perforated Depths (A); Schematic Diagrams Showing the Acid-Sulfate Production and Evolution of B8 (B).

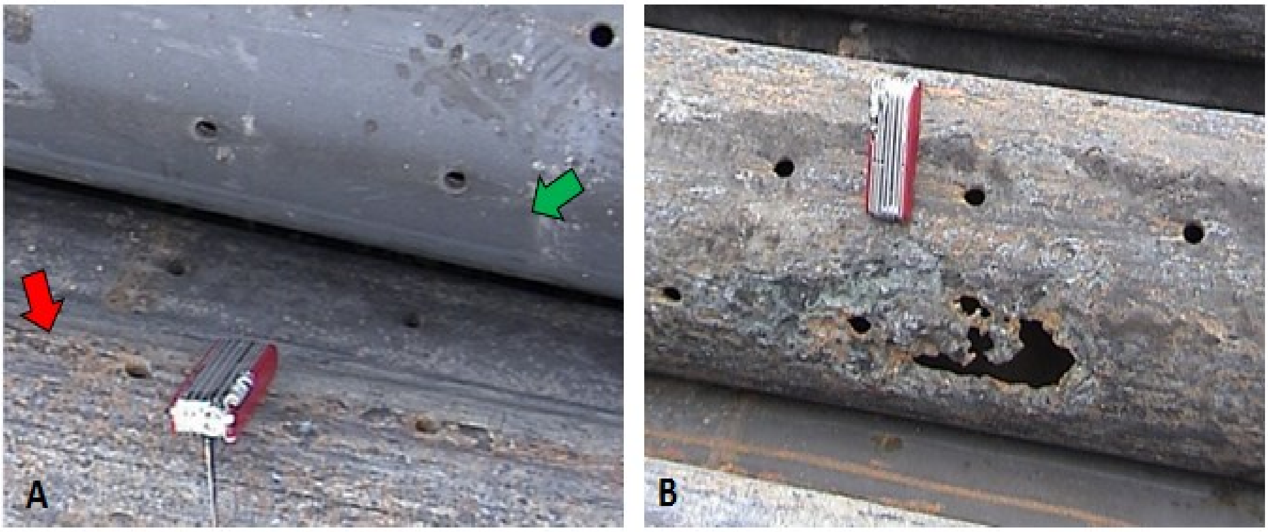

Figure 5: Photos showing the pulled-out liner of B8. Comparing the corroded sections (red arrow) believed to be above the acid entry zone and the non-corroded sections (green arrow), believed to be below the acid entry zone (A); Severe corrosion at the acid-sulfate entry zone (B).

3. MITIGATION OF ACID-SULFATE FLUID PRODUCTION

3.1 Well Recompletion

K4 produced acid-sulfate fluids with pH 3 – 3.4 during 1979 – 1983. This well was recompleted in 1984 to case-off the inferred shallow acid-sulfate entries at 691 mbsl and 1,360 mbsl by setting the bottom of the new 7-in cemented production liner at 1,508 mbsl. After re-drilling, the feed zone encountered at 1,568 mbsl – 1,738 mbsl produced neutral-pH fluids. K4RD was shut-in in 2001 but attempts to flow it in 2004 failed.

B8 was re-drilled and recompleted in 2005 with a deeper cemented production liner set at 907 mbsl that cased-off the shallow acid-sulfate zone at ~900 mbsl. Now, B8RD is producing ~16 kg/s of steam with neutral-pH brine. With the success and lessons learned in B8RD, production make-up well B11 was similarly completed in 2008 with a deep cemented liner at 928 mbsl and successfully produced with an initial production of ~25 kg/s of steam, one of the biggest neutral-pH producers in the field.

3.2 Operational Control

Wells B5, M17 and K31 initially started as single-phase steam producers, turned two-phase producers later and started producing acid fluids through time. Well B5 continued to produce acid fluids intermittently until 2006; the pH of the produced fluids increased to >4 when the well was throttled. Throttling the well is believed to suppress production from the inferred shallow acid-sulfate zones and allows production of more neutral-pH brine from the deep feed zone/s. Wells M17 and K31 were similarly throttled and have been producing neutral-pH fluids now.

Table 1: Acid-Sulfate Zone Occurrences at Depths Confined to 700 m – 1080 mbsl for Bariis and SoKap.

Well	Depth (m BSL)	Acid Zone	Basis	Others
B1	963m – 1016m	Inferred	Deeper permeable zone intersected a structure that potentially conducts acid-sulfate fluid (Stimac, 2000).	No downhole sample; no PTS survey; reservoir egde
B2	860 m – 897m 928m – 936m 967m – 975m	Inferred	Deeper permeable zones correlates with advanced argillic alteration zones (relict)	No downhole sample; no PTS survey; reservoir egde
B3	1004m – 1155m	Inferred	Intermediate zone correlates with nearby acidic well B9; The zone is relatively thick and extends below the current shallow acid model (see Section 4.1)	No downhole sample; no PTS survey; no further characterization due to very acidic fluid during flowtests
B5	816 m 907 m	Inferred	Operational control (See Section 3.2)	
B8			See Section 2.2	
B9	960 m – 991m 1021m – 1051m	Inferred	Intermediate zone correlates to nearby acidic well B3	No downhole sample; no PTS survey; no further characterization due to very acidic fluid during flowtests
B10	768m 1067m 1520 m	Inferred	Zone correlates with advanced argillic alteration zones (relict); Acid fluid samples identified by downhole survey (1998) suggests deeper acid entry below the current shallow acid model (see Section 4.1)	Could be related to downflow of acid-sulfate fluids through Kagumihan Fault
M17	822m – 847m9 901m	Inferred	Acid zones correlatable to those in B5; Operational control (See Section 3.2)	
K4	691m 1360m	Inferred	Recompletion (See Section 3.1) Deeper acid entry below the current shallow acid model	Could be related to Tiwi Fault intersection
K6	735m 1357m – 1377m	Inferred	Deeper acid entry below the current shallow acid model based on correlation with advanced argillic alteration (Powell, 1984)	
K24	760 m – 1046m	Inferred	Single permeable zone is highly uncertain, though fluid samples above this zone (from 2013 downhole survey) confirm existence of acid zone	No PTS survey
K30			See Section 2.1	
K31	706m – 740 m	Known	Well-defined permeable zones- one produces steam, the other produces acid; Produces all-steam when deeper zone is suppressed	Fluid samples from downhole survey confirm acid zone; Could be related to downflow of acid-sulfate fluids through Kagumihan Splay.
K32	880 m – 910 m	Known	Well-defined permeable zones (PTS) that started as neutral and turned acidic over time.	Fluid samples from K31 downhole survey (adjacent well) confirm acid zone

4. IMPLICATIONS ON WELL TARGETING

4.1 Acid Zonation

Most wells in this study were completed with cemented production casing shoe set at 400 m – 700 mbsl. These wells are producing from both the shallow steam (or two-phase) and the deep liquid reservoirs, with the exception of shallow steam wells B4, K17, K29 and K31, which were completed only to a total depth of about 650 mbsl.

Figures 6 and 7 show the vertical distribution of the acid-sulfate entries encountered by Bariis and SoKap wells, respectively, without considering the wells' geographic locations. The lighter red band represents the acid-sulfate fluid zone which combines all three types of acid zones, i.e., Known Acid-sulfate Fluid Zone (dark red band), Inferred Acid-sulfate Fluid Zone (purple vertical rectangles) and Advanced Argillic (Acid) Alteration Zone (pink vertical rectangles). Note that these schematics do not imply the presence of a continuous acid aquifer overlying this section of the field because the acid-sulfate zones are localized and not contiguous as clearly demonstrated by the neutral-pH fluids produced by wells B6, B7, K22 and K35, which were all drilled near acid wells. It is believed that some mapped structures at Tiwi, i.e., Kagumihan and Tiwi Faults and Kagumihan Splay, may be pathways of downflow of the acid-sulfate fluids to depths greater than those indicated in Figure 6 (e.g., ~1,500 mbsl in B10).

4.1.1 Bariis

In Bariis (Figure 6), 11 of the 13 (including M17) wells reviewed have shallow production casing shoe completion and eight of these wells produced acid-sulfate fluids. B6 and B7 seem to be "anomalies" as they are both neutral-pH fluid producers. Wells on the same pad with B7 are all acidic, except for B4 which is a single-phase steam producer (Figure 7). Wells on the same pad with B6 are all acidic as well. The neutrality of B6 and B7 is still a question and this may simply be due to the absence of permeability in the expected acid zone interval, again suggesting that the occurrence of the shallow acid-sulfate fluids is not contiguous.

Based on both the proven and inferred acid zones, the acid-sulfate zone in the Bariis area was delineated at 670 mbsl – 1,040 mbsl (Figure 6). This definition took into consideration the inferred acid-sulfate feed zones and advanced argillic alteration zones that appear to correlate with known acid-sulfate producing zones.

The pH 4.60 and 2.33 at 1,067 and 1,520 mbsl, respectively, from the 1997 downhole samples at B10 plotted deeper than the acid-sulfate horizon in the current model. This is believed to be caused by the downflow of the acid-sulfate fluids at the intersection of the well with Kagumihan Fault at 709 mbsl. This must be taken into consideration in case this structure is targeted with future make-up wells.

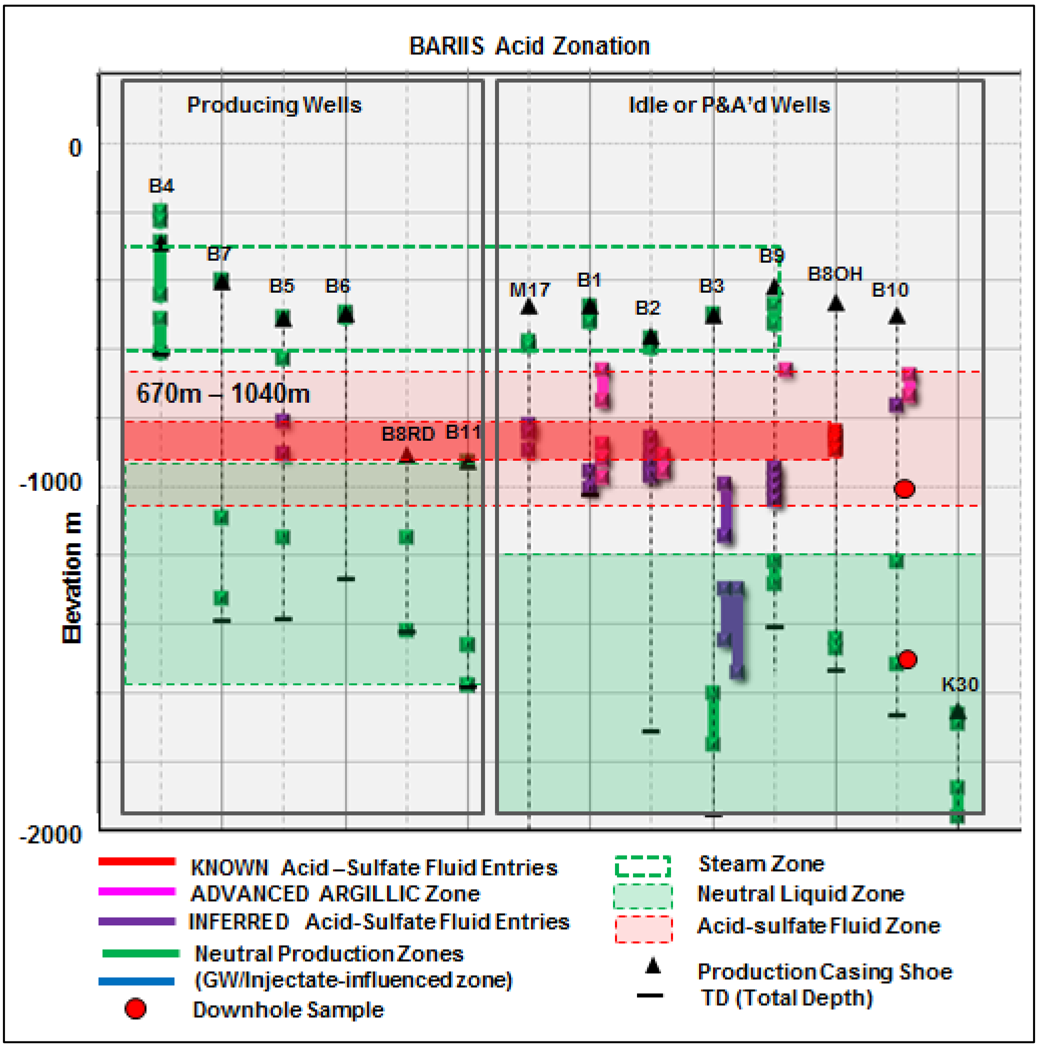

Figure 6: Schematic Diagram Showing Vertical Distribution of the Acid-Sulfate Fluid Zones in Bariis

4.1.2 SoKap

In SoKap (Figure 7), 12 of the 15 wells reviewed have shallow production casing shoe completion and five of these wells produced acid-sulfate fluids, except for K30 which has a deep casing shoe but was perforated (unfortunately) at the acid-sulfate fluid zone *(see Section 2.1)*. Both K22 and K35, located on an adjacent pad, some 500 m from the acid wells, were also completed with shallow casing shoe but proved to be two of the largest neutral producers in SoKap. This result is another evidence regarding the localized occurrence of the acid-sulfate fluids.

The acid-sulfate zone in SoKap area was delineated at 700 m – 1,080 mbsl, using the same considerations as in Bariis. Interestingly, wells K1, K19 and K33, which have permeable entries within the acid-sulfate zone, did not produce acidic fluids but, rather, fluids with a mixture of groundwater and injected brine.

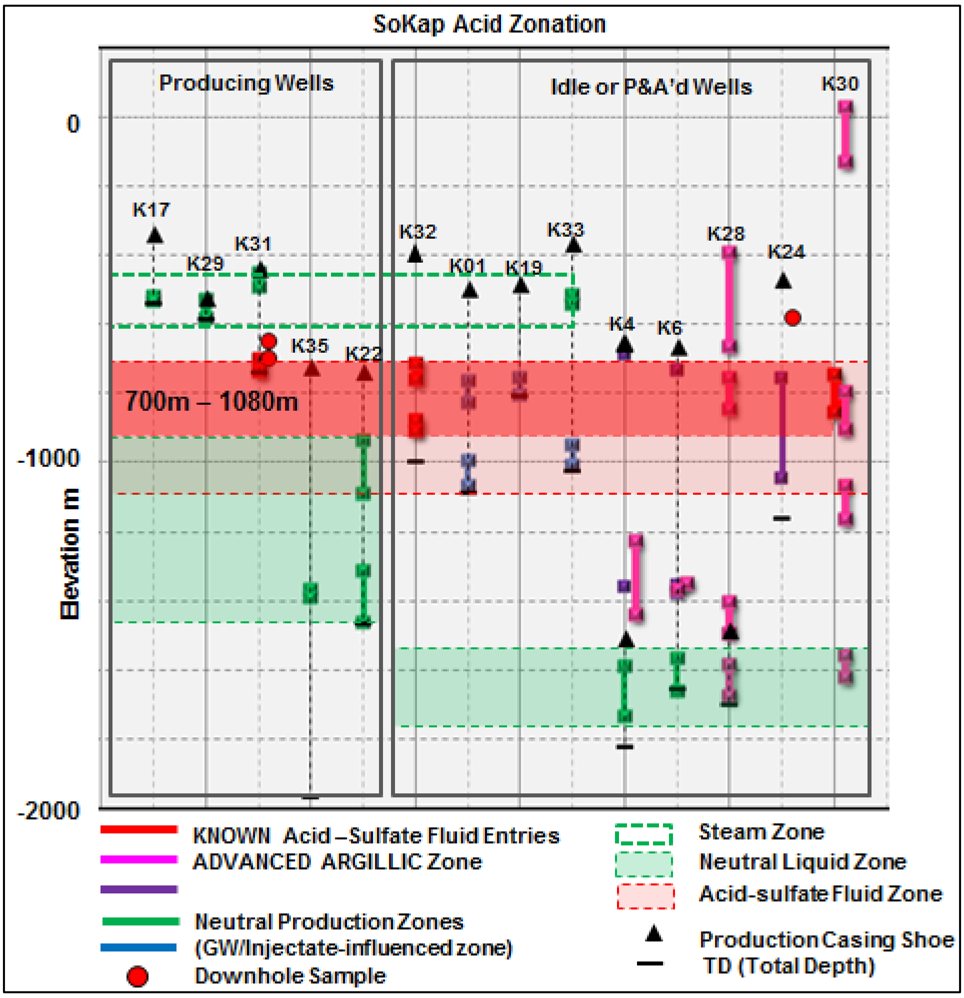

Figure 7: Schematic Diagram Showing Vertical Distribution of the Acid-Sulfate Fluid Zones in SoKap

4.2 Conceptual Model

The Tiwi geothermal system consists of two major upflow zones in Bariis and SoKap with measured bottomhole temperatures >300°C and significant steam deliverability. Future production make-up well drilling is geared towards development of these upflow zones.

The depths and distribution of the acid-sulfate zones are more-or-less defined with the shallow acid model at 670 m – 1,080 mbsl. Analysis of the acid-sulfate feed zones in southwest Tiwi supports the shallow acid model (or shallow *in-situ* H_2S Oxidation model) which suggests that the acid zones occur as localized "pods" below the steam zone (Figure 8). These pods of acid-sulfate fluids appear to be related with certain structures, e.g., Kagumihan and Tiwi Faults. Shallow oxygen-rich groundwater is believed to downflow along faults and reacts with H_2S to form H_2SO_4. Aside from providing pathways for groundwater downflow, these faults are also conduits for downflow of the acid-sulfate fluid as observed in B10.

The Kagumihan Fault is one of the major structures that control the flow of reservoir fluids from the Bariis Upflow. This study suggests that the Kagumihan Fault, at the depth intersected by B10, also facilitates downflow of shallow acid-sulfate fluids (Figure 8) thus this horizon should be avoided when targeting permeability related with this structure. The Kagumihan Splay, which is almost parallel to the main Kagumihan fault, may have a similar behavior. The acid-sulfate zones of K30 and K31 may be related to intersection with this structure (Figures 8 and 9). Further to the east, the Takla Fault is another structure believed to be the source of the shallow acid-sulfate fluids in wells K4 and K6.

4.3 Wellbore Design

The current strategy for future make-up well drilling is to complete certain wells shallow to produce from the steam zone only, and some wells deep into the neutral liquid reservoir with deep cemented production casing to case-off the shallow acid-sulfate zones. This study has delineated that acid-sulfate fluids are probably located at 670 mbsl – 1,040 mbsl and 700 mbsl – 1,080 mbsl in Bariis and for SoKap, respectively. Thus, the initial production casing shoe setting depth is at about 1,100 mbsl (Figure 9B).

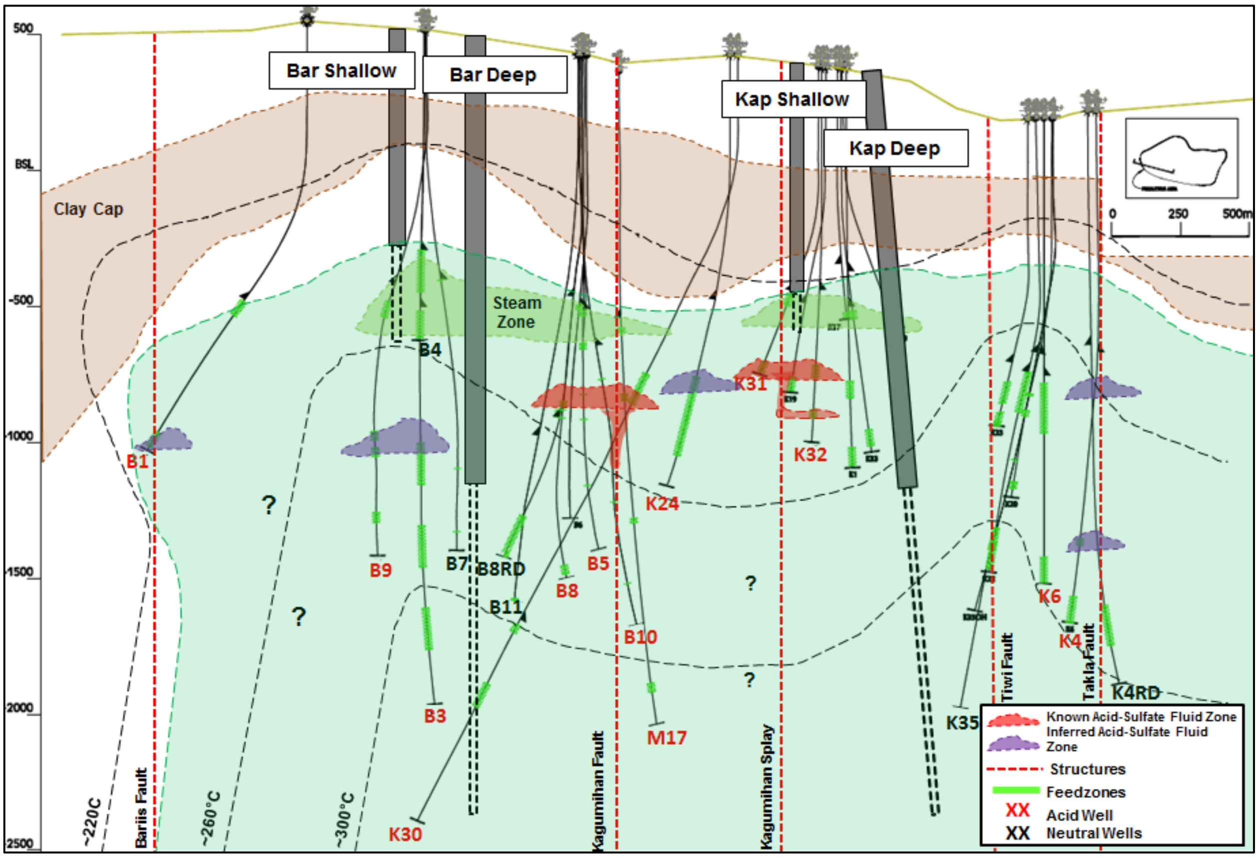

Figure 8: Conceptual Model of Bariis to SoKap Showing Distribution of Acid Zones and Proposed Shallow and Deep Make-up Wells.

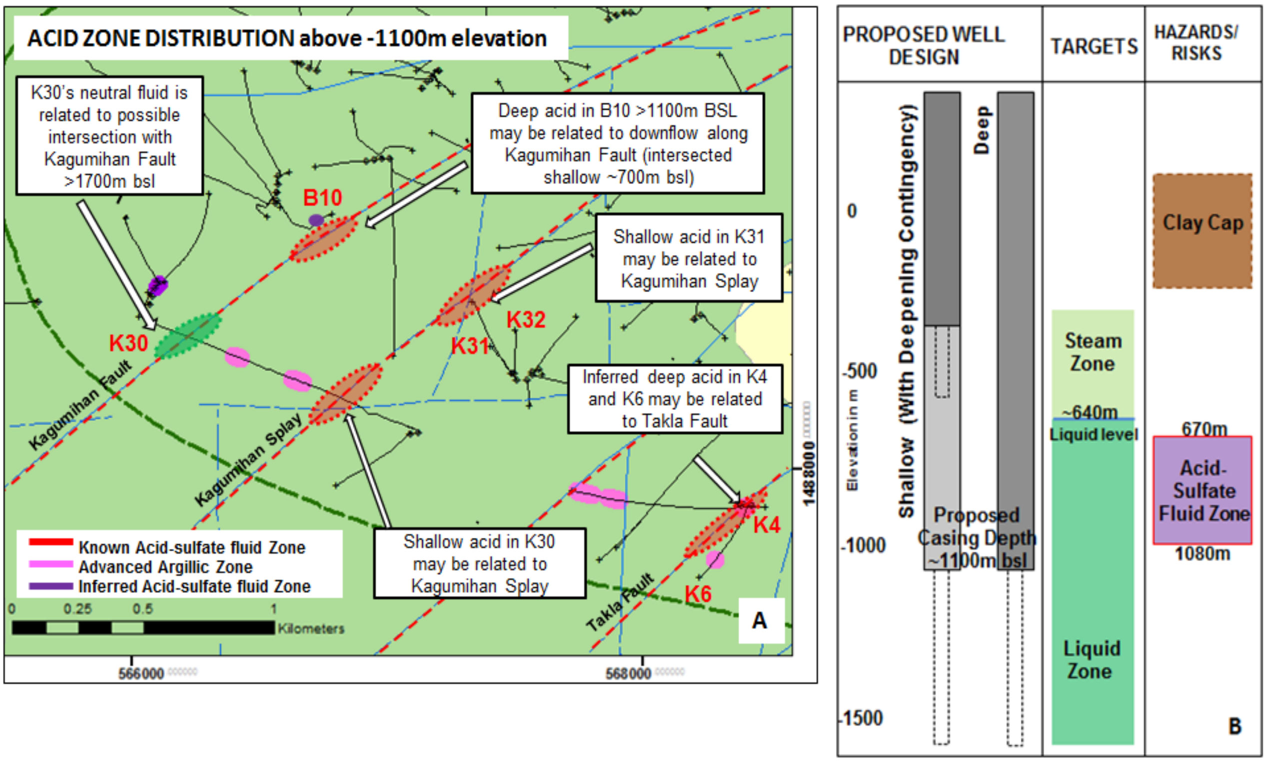

Figure 9: Implications of Acid-Sulfate Zones in Well Targeting. Certain segments of both Kagumihan and Takla Faults and Kagumihan Splay correlate with the acid-sulfate producing zones and must be avoided in targeting wells (A). Proposed wellbore completion for the shallow and deep make-up wells (B).

5. CONCLUSIONS

The favorable results of two recently drilled wells in the Bariis sector of the Tiwi field suggest that the existence of the acid-sulfate fluids is not as widespread as previously believed. Earlier studies, alteration mineralogy encountered in wells, recent downhole surveillance and production data show that the most of the acid-sulfate fluids are limited at shallow levels only, occur as isolated pods and can be cemented behind casing. Furthermore, certain mapped structures host acid-sulfate fluids at shallow depths but, at the same time, could also produce benign fluids at great depths. There is, however, still some uncertainty with regards to the presence of acid fluids at greater depths that may be related to the presence of magmatic fluids

The new production make-up wells to be drilled in the Bariis and SoKap areas will be designed with the cemented casing shoe set at about 1,100 mbsl or just below the "deepest" known occurrence of the acid-sulfate fluids. In areas with known steam cap, future make-up wells will be drilled shallow to produce steam only but will have contingency for deepening.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the approval and encouragement provided by Philippine Geothermal Production Company, Inc. and Chevron Geothermal Services Company to prepare and publish this paper.

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