THE ORIGIN AND MECHANISM OF THE ACIDIC DISCHARGE OF PRODUCTION WELL BL1D, SOUTHERN NEGROS GEOTHERMAL FIELD, CENTRAL PHILIPPINES

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ABSTRACT

Production well BLlD is one of the wells supplying steam to the 20 MWe Balas-balas modular power plant of the Southern Negros Geothermal Production Field Central Philippines. BLlD's discharge pH sharply declined to 3.5 in 1997 to 1998, from its former stabilized pH range of 4 to 5, resulting to the rapid corrosion of its surface and sub-surface equipment.

Sulfuric acid (H_2SO_4) is mainly responsible for the changes in the discharge pH of well BLlD in the periods 1991 to 1993, and 1997 to 1998. The acid enters the well fiom the shallower, two-phase feed zones (1075-1200 mMD and 1397-1600 mMD), and mixes with the neutral liquid feed coming from the deeper feed zones (2200 mMD and below). The chemistry of this acid-SO_4 fluid is inferred to be akin to the Kaipohan waters. The reduction of the liquid feed from the deeper zones, especially during 1997 to 1998, because of well blockage, resulted to the shift of chemistry to the two-phase feed where the acid-SO_4 dominates, causing the pH to decline. The mechanical work-over conducted in July 1998 succeeded only in opening up partly the permeable zone at 1397 to 1600 mMD, where the feed is still two-phase. The chemistry did not change significantly, because the blockage at 1557 mMD was not cleared to allow the neutral liquid feed from the bottom to re-contribute.

1.0 INTRODUCTION

Since the start of its commercial operation in 1983, the Southern Negros Geothermal Production Field (SNGPF), located in Negros Island, southern Philippines, has been hosting a number of wells with acidic discharge. These wells present a special problem to field management because of their liability to form blockage fiom mineral and corrosion-product deposits, and to corrode and erode surface and sub-surface equipment. Various chemical and physical monitoring techniques have been adopted by the site technical staff of the Philippine National Oil Company-Energy Development Corporation-- owner and operator of the geothermal field-- primarily to assess the viability of these wells, and to prolong their life when possible. In some cases, like those in the Nasuji sector (e.g. NJ1D and NJ2D), wells were put out of use, after acidity brought severe erosion and corrosion of the wellhead assembly and discharge pipeline. In other cases, like in the eastern part of Puhagan (e.g., OK10D, PN20D, and PN22D), wells continue being used after their initial, acidic discharge was diluted by neutral reinjection fluids returning to the field. The distribution of wells with acidic discharge in SNGPF, along with the wells' present status, is found in Figure 1.

One of the wells with acidic discharge, well BLlD, is found in the Balas-balas sector (Figure 1), where it supplies steam to one of the four 20-MWe modular plants being operated by the National Power Corporation in SNGPF. It started supplying steam to the power plant in 1994, at an output of 10 to 11 MWe, which decreased to 8 to 9 MWe in 1996, and finally to around 7 MWe in 1997. This output decline was associated with the blockage detected since 1996, just below the production-casing shoe at 1076 mMD. Analyses of the scraper samples revealed mineral deposits including rock fiagments, clay, and corrosion products.

The discharge pH of well BLlD stabilized in the range 4 to 5, during its medium term discharge fiom 1991 to 1993. Despite the low pH, it was decided to utilize the well for production, because of its low water-fraction discharge. In the years 1994 to 1996, the injection of river water was done extensively on well BLlD, in order to mitigate the very high total suspended solids in its discharge. During this period, river water dilution caused the pH to vary erratically.

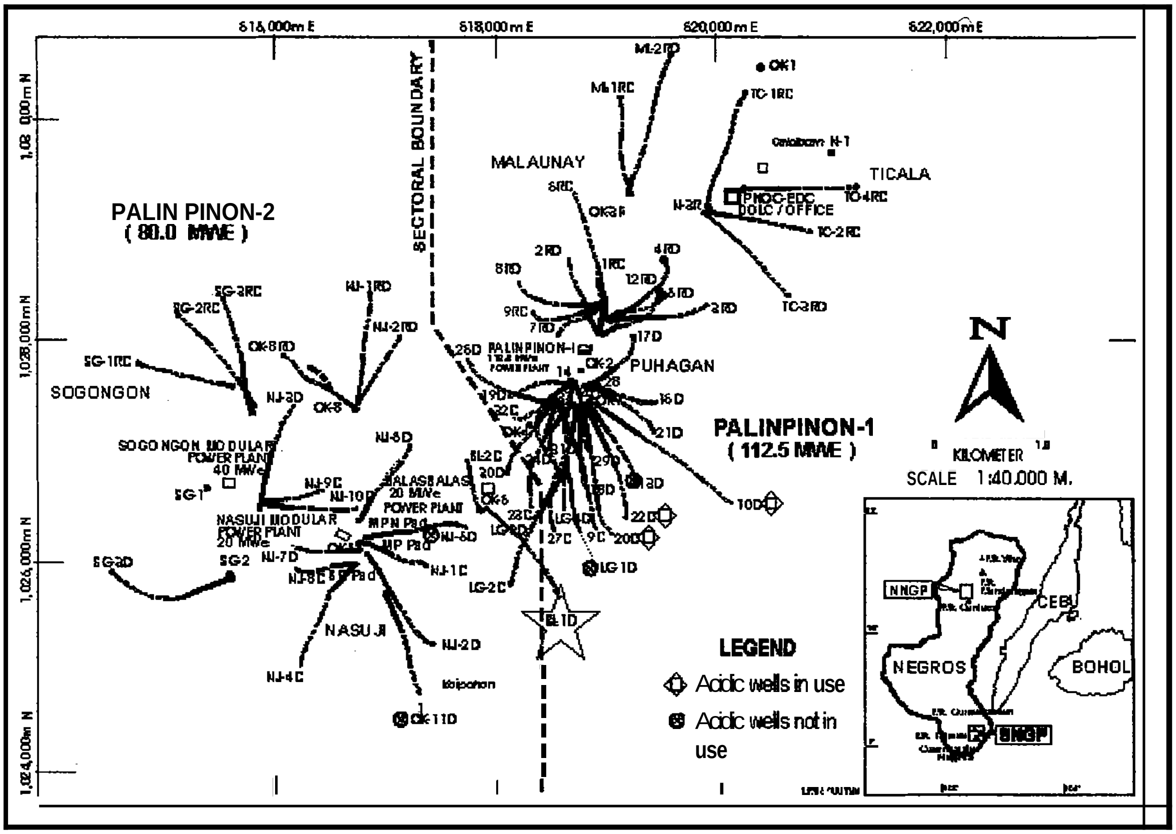


Figure 1. **Map of** the Southern Negros Geothermal Production Field showing well **tracks.** Inset **is** the location **map.**

Starting the first quarter of 1997, BL1D's discharge pH dropped consistently to around **3.5.** A gradual increase in the total line Fe concentration followed, which peaked to 60 to 80 mg/kg starting October of 1997. Thereafter, the wellhead tee had to be replaced twice within a four-month period, first with a temporary, built-up tee in November 1997, and later with a new one in January 1998.

The sudden and consistent decline in BL1D's discharge pH, coinciding with the increase in virulence and corrosivity of the well's discharge, is investigated in this study. More specifically, the acid that controls the pH of BL1D's discharge, and by what mechanism the acid concentration varies inside the well, are determined. The inference that a well blockage has caused the pH decline is validated with the results of a mechanical work-over, conducted in July 1998. As a result, the existing well model is modified, and the implication of the change to the field hydrological model assessed.

2.0 HYDROLOGICAL FLOW MODEL OF THE SOUTHERN NEGROS GEOTHERMAL FIELD

The Southern Negros Geothermal Production Field is located on the northern slope of the Cuernos de Negros Complex, a dormant andesitic volcano related to the west-facing Negros Arc. Geochemical and geophysical assessment of the field has delineated the hydrological upflow area beneath the vicinity of the Lagunao Dome, with outflow tongues radiating towards the northwest in Sogongon-Nasuji, and the northeast in the Lower Okoy Valley reaches. The flow is generally controlled by secondary permeability associated with northeast and northwest trending faults, and to a lesser degree, by contact permeability related to dikes. Thermal springs are to be found along the postulated hydrological flow, grading outward fiom acid bicarbonate-sulfate springs to near-neutral bicarbonate springs to neutral chloride springs. Likewise, wells with acidic discharge are found near the hydrological upflow. This is exemplified by acidic wells LG1D and BL1D, both found in the vicinity of the Lagunao dome. Figure 2 illustrates the hydrological flow model of SNGPF.

Several authors have presented often-conflicting theories on the mechanism of acid generation in certain sectors of the field. Most of the studies made dealt with the origin of SO_4, and differed mostly in their interpretation of isotope data (Robinson et al, 1987; Bayon, 1997; Hermoso et al, 1998). At least two theories of the origin of well acidity have emerged as a result of these studies. The first contends that well acidity is magmatic in origin, and that sulfate is being derived from the disproportionation of SO_2 to H_2S and SO_4 in the deep portions of the reservoir (Bayon, 1997). The second contends that well acidity has a shallow origin, and that sulfate is derived from the oxidation of H_2S to SO_4 in perched aquifers– shallow, oxidizing zones from where the acidic fluids percolate downwards because of pressure drawdown (Seastres et al, 1995). The latter has been incorporated to the hydrological flow model (Figure 2) currently used by the site geochemistry staff.

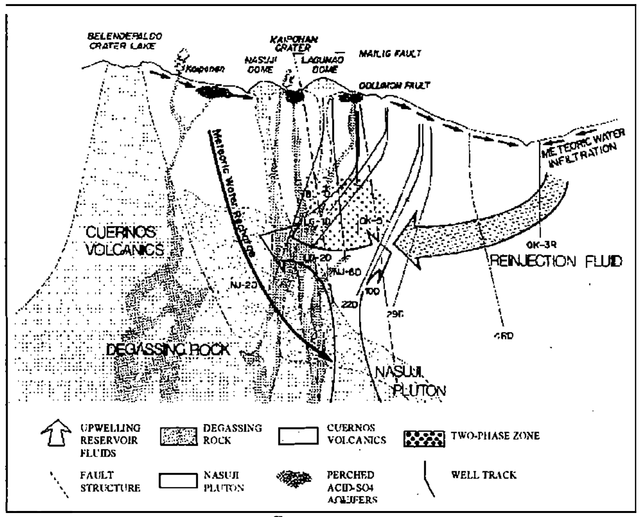


Figure 2. Hydrological flow model of the Southern Negros Geothermal Field showing shallow oxidation of H_2S in perched aquifers as primary source of acid-SO_4 waters (Seastres et al, 1995).

3.0 MEDIUM-TERM-DISCHARGE WELL MODEL

Well BL1D was drilled from July to October 1990, to a total depth of 2694 mMD[1], and deviated southeast of the OK-5 wellpad where the postulated upflow area is believed to lie beneath. It intersected three geologic units: the Southern Negros Formation (SNF), the Okoy Sedimentary Formation (OSF), and the intrusive igneous rocks believed to be associated with the Lagunao Dome. Drill cuttings taken from the SNF reflected an alteration mineral assemblage that was dominantly neutral chloride suites, with rare diaspore found at some levels. Beyond 1710 mMD (the SNF is believed to extend up to 2000 mMD), the well was drilled blind. Circulation losses encountered were mainly attributed to the well's intersection with various permeable zones: Okoy-D Fault (418 - 2130 mMD), Odlumon Fault (1720 – 1840 mMD), and Balas-balas Fault (2020 mMD to bottom of liner) based on the structural correlation of Hermoso et al. (1991) and Pamatian (1998).

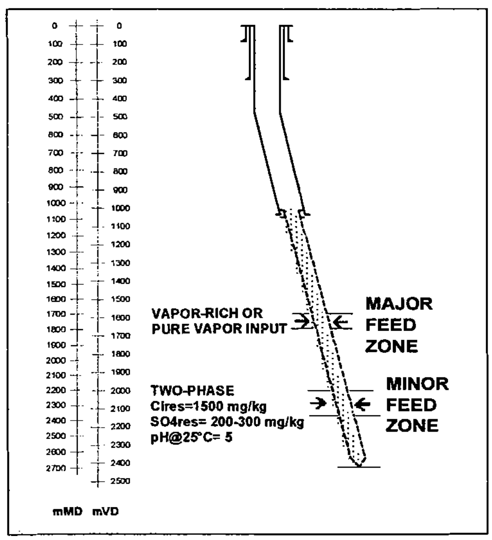


Figure 3. Well BL1D, based on medium-term discharge test (Bayon, 1994)

Completion testing indicated a major permeable zone at 1700 to 1800 mMD and a minor permeable zone at 2200 to 2380 mMD. Analyses of downhole samples yielded conflicting results, but were nevertheless used, together with back-pressure plate test results, as basis for characterizing the feed zone chemistries of the well in a well model by Bayon (1994) (Figure 3). According to the model, fluid from the main feed zone is vapor-rich or pure vapor, and has a higher CO_2/H_2S ratio than the lower minor feed zone. The minor feed zone, on the other hand, is two-phase, slightly acidic at pH 4 to 5, and has low Cl ($\approx$1500 mg/kg) and high SO_4 (200 - 300 mg/kg). Bayon postulated that BL1D tapped only the slightly acidic, high-enthalpy induced steam cap above the upflowing neutral-Cl liquid reservoir - the reason why Cl in BL1D is much lower than the 4,000 mg/kg Cl of the parent water (Bayon, 1994).

[1] All depths reported by this paper are measured depths from the casing head flange (CHF), unless indicated otherwise.

4.0 ACIDS IN THE DISCHARGE WATER OF WELL BLlD

Acids in geothermal waters in the Southern Negros Geothermal Field include H_2CO_3, H_2S, H_2SO_4, and H_3BO_3. Acids like HCl, HF, H_4SiO_4, and HCO_3^-, are not expected to contribute much to pH lowering since physical and chemical characteristics of SNGPF's geothermal waters are unfavorable either to their dissociation or occurrence. Monosilicic acid (H_4SiO_4) and HCO_3^- are acid contributors in waters that are dilute, of low temperature, and with high pH (at least alkaline). Consequently, nil concentrations of $H_3SiO_4^-$ and CO_3^{2-} were obtained for BLlD fluid using the WATCH speciation program.

Hydrochloric acid, which is a very strong acid, may be carried by superheated steam in vapor-dominated, high-Cl, and low pH reservoirs, or rarely, may be present in acid Cl-SO_4 waters with excess chloride, possibly fiom a volcanic origin (Truesdell, 1991). In the case of BLlD, a comparison between chloride and the sum of major cations (Na^+ plus K^+) yields no excess chloride.

Hydrofluoric acid is another acid associated with active volcanism, or deep magmatic input. Figure 4 is a conventional plot for classifying gas discharges according to their sources. Well BLlD plots between crustal and air concentration, suggesting a crustal source which has been variably contaminated with air. Gases plotting on this region indicate long residence time in the crust (Giggenbach, 1992). Without evidence of recent, deep magmatic input, HF is unlikely present in significant amounts.

Concentrations of the analyzed components of the four acids, H_2CO_3, H_2S, H_2SO_4, and H_3BO_3, in well BLlD's water discharge are plotted against time and compared with the trend of BLlD's discharge pH at 25°C (Figure 5)[2]. Discharge pH varied almost symmetrically to the variations in the concentration of SO_4 in the BLlD water[3]. Table 1 shows the correlation factor between the concentration of each acid component of BLlD water, and the pH measured during the periods 1991-1993 and 1997-1998, when the well chemistry was free of the effects of river water dilution. All showed negative-value correlation, meaning that an increase of these acids' concentration in the discharge is correlated to a decrease in the pH. Of all, SO_4 showed the greatest absolute value. Inferring from the graph and correlation factors in Table 1, H_2SO_4 appears to be the acid with the greatest influence on the change of BLlD's discharge pH.

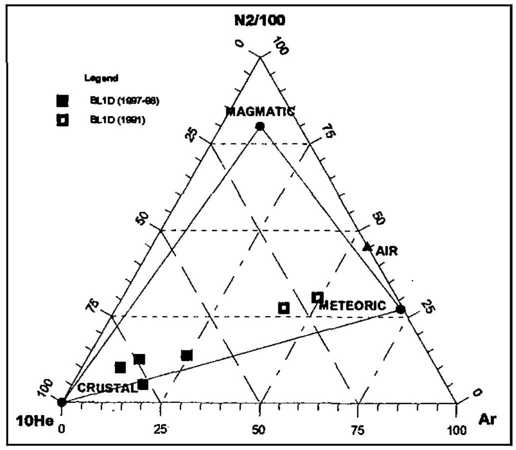


Figure 4. Relative N_2, He and Ar contents of BLlD gases, plotting between *crustal* **and meteoric corners (Giggenbach, 1992).**

Table 1. Correlation between acid concentrations and H.

Acid Components	Correlation r^2 w/ H 25°C
H_2SO_4 as SO_4	-0.73
as B	
as tCO_2	-0.35
	-0.15

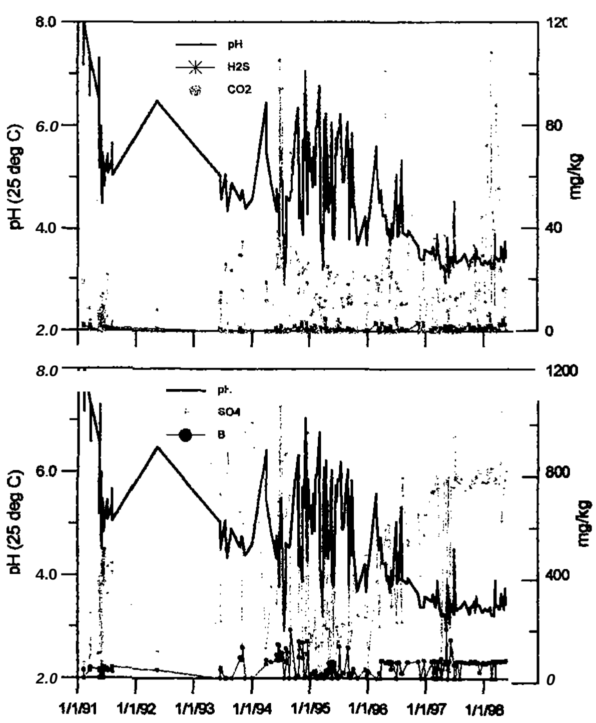


Figure 5. BLlD pH, SO_4, B, CO_2, and H_2S trends with time, showing the near-symmetrical relation of pH to SO_4.

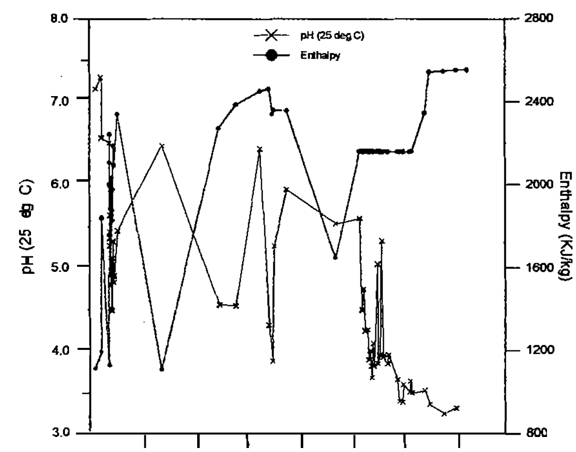
[2] **All pH values reported are taken at 25°C,** unless **otherwise** indicated.

[3] **SO_4 (without the** valence **sign)** will be used **throughout** to **denote the sum of HSO_4^-** and **SO_4^{2-} ion as they are analyzed; these ions are produced by the** primary and **secondary dissociation** of **H_2SO_4,** both **of which liberate H^+, thus** decrease **the** pH.

It is clear fi-om Figure *5* that H_2SO_4 far exceeds the other three acids in concentration, and this is because H_2CO_3 and H_2S partition readily to the gas phase *upon* boiling, while H_3BO_3 is a conservative component of geothermal fluids, controlled mainly by reservoir **geology,** which is essentially constant **when** considering reservoir exploitation time. The supply of H_2SO_4 on the other hand is highly variable, and controlled by processes such as those illustrated in the field hydrological model (Figure 2). The next section will tackle on the manner that this acid, H_2SO_4, varies in concentration in well BLlD.

5.0 MECHANISM OF THE ACID INFLOW IN WELL BLlD

5.1 Discharge Enthalpy as a Function of Feed Distribution Among BL1D's Producing Zones



BL1D's discharge pH strongly relates to its discharge enthalpy, as shown in Figure 6. Looking at the data ffom 1991 to 1993 and from 1997 onwards, the pH values rise and drop inversely with the discharge enthalpy. Ambivalent changes in pH relative to enthalpy, observed between late 1993 to late 1996, are attributed to the river water injection in well BL1D during this period.

BL1D's discharge enthalpy generally increased with time, its excess enthalpy reaching up to 1600 kJ/kg. In order to infer the mechanism of excess enthalpy, Arnorsson et al (1990) suggested looking at the solute and gas trends with discharge enthalpy. Figure 7 shows trends of Cl in water and Cl in total discharge, with the discharge enthalpy of BL1D. If the excess enthalpy is brought about by evaporation of the liquid water, then with increasing discharge enthalpy, Cl in water will increase, and Cl in the total discharge will remain unaffected. *On* the other hand, if the excess enthalpy is the result of steam addition, then Cl in water will be unaffected, and the Cl in total discharge will decline. The trends shown by BLlD agrees with the latter (i.e., Cl in water remains unchanged, and Cl-td steadily decreases), suggesting that the main mechanism for the excess enthalpy in BLlD is steam addition. The increase in H_2S concentration, both in steam and in total discharge, is another indication that the above mechanism is at work in BLlD's increasing discharge enthalpy.

In wells that have multiple feed zones with different physical characteristics, steam addition may be interpreted as the increase in contribution of the more vapor-saturated feed, relative to the less vapor-saturated feed. In the medium term discharge model of BLlD (Figure 3), two distinct **feed** zones were identified: a deeper, two-phase feed zone, and a shallower, steam-rich feed zone (Bayon, 1994). The basis for characterizing the deeper feed zone as two-phase, albeit 'wetter', was the result of back-pressure plate tests, that showed discharge enthalpy declined with throttling, while leaving a still high excess enthalpy of 600 to 900 kJ/kg. This assumed that

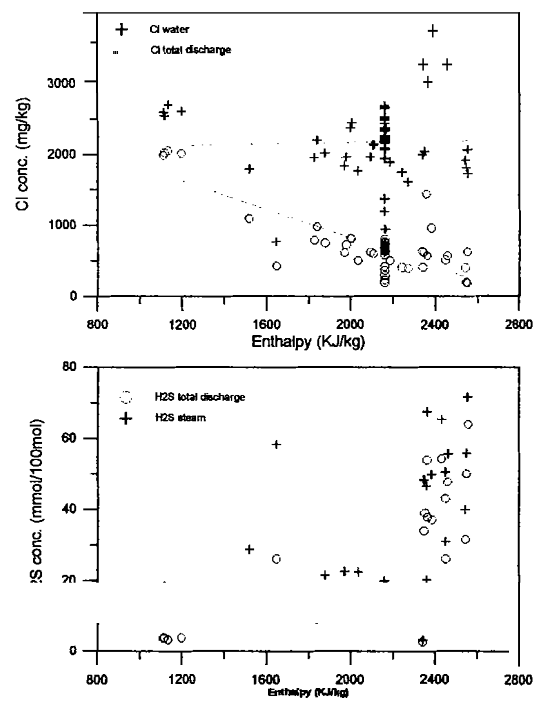


Figure 7. BLlD Cl (water and total discharge) and H2S (steam and total discharge) trends with discharge enthalpy, showing signature trends of steam addition.

BL1D's deeper feed zone wholly dominated the well discharge at the throttled condition, although such was never confirmed.

Instead, temperature and pressure surveys indicate more strongly the presence of a liquid feed from the bottom. Below around 2000 mMD, a pressure-depth curve is shown in the pressure profile taken from a flowing survey in June 1991, with pressures reaching up to as high as 11 MPag to the bottom, where the indicated temperature is 280 to 300°C, suggesting that a liquid column was formed along this length. Corresponding to these depths, a temperature inversion showed up in the temperature profiles from both shut and flowing surveys, indicating an inflow of liquid feed.

Thus, the increasing contribution of the shallower , vapor-rich zones, over that of the deeper liquid zone, caused BLlD's discharge enthalpy to increase with time. In the extreme case where the deep zones no longer contribute, such as in the event of a blockage, the discharge enthalpy may then be expected to come close to that of saturated steam at the two-phase zone temperature indicated by the flowing survey-- around 260°C, roughly equivalent to 2800 kJ/kg for saturated steam. This may be the case recently, when BLlD enthalpy went to as high as 2680 kJ/kg in June 1998.

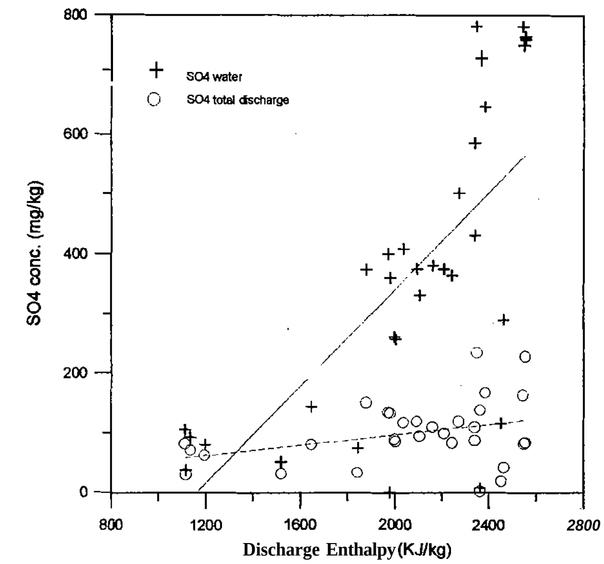


Figure 8. BLlD SO4 (water and total discharge) trends with discharge enthalpy, showing a different signature to that of Cl.

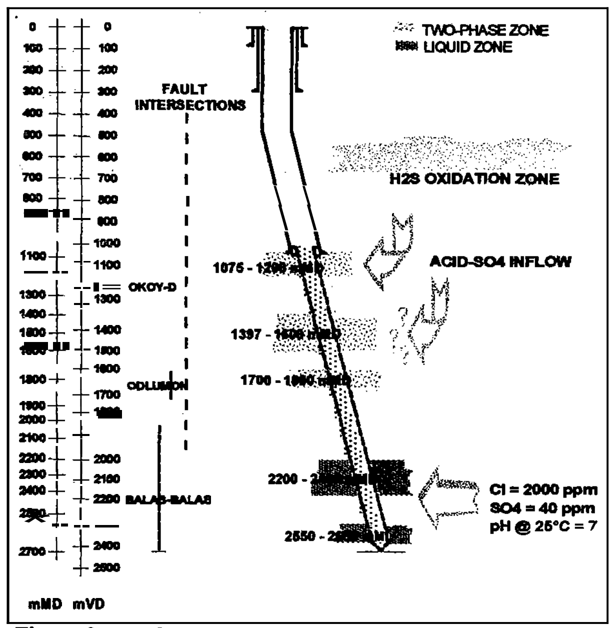


Figure 9. BLlD geochemical well model (after Bayon. 1994).

5.2 Shallow-Zone Entry of BL1D's Acid-SO_4 Component

In the MTD model (Figure 3), the lower feed is characterized as more acidic, bearing with it the excess SO_4. This is not, however, what is indicated by a similar analysis of SO_4 trends with discharge enthalpy. The SO_4 in water tends to increase with increasing discharge enthalpy, unlike Cl in water, which does not (Figure 8). SO_4-td shows also a slightly rising trend, as opposed to Cl-td's downward trend The implication is that SO_4 (i.e., the bulk of the SO_4 in the discharge) could not have been born into the well by the same liquid feed that carries the bulk Cl, as was postulated by the MTD model, or both (SO_4 and Cl) would have shown similar trends with discharge enthalpy. Indeed, the SO_4 trend follows more closely the H_2S trend, suggesting that a SO_4-rich fluid is carried into the well by the vapor-rich feed from the shallower zones. This explains the good correlation between pH decline and enthalpy increase (Figure 6). A modified model of the well showing the various feed zones, with their inferred chemistries and structural correlation is shown in Figure 9.

The initial discharge of BLlD showed a fairly mature chemistry (Cl=2600-2800 ppm, SO_4=50-110 ppm), which, with time, became less mature. This phenomenon was earlier deemed unexplainable (*Bayon, 1994*), when in fact, wells normally pass through a period of liquid—thalpy discharge before forming a local boiling front that induces excess enthalpy (thus acidity, as the case in BL1D). The synchronous emergence of excess enthalpy and well acidity, is already proof that the acid-SO_4 signature is not related to the original deep liquid feed.

Using a Cl-SO_4-Ca ternary plot (Figure 10), the dilution path taken by well BLlD fluid may be traced to a possible end-member (an acid dilutant) akin to the Kaipohan waters[4]. Other acidic wells in SNGPF also plot along this dilution line. Very apparent is the shift of the recent BLlD chemistry nearer to the postulated acid dilutant.

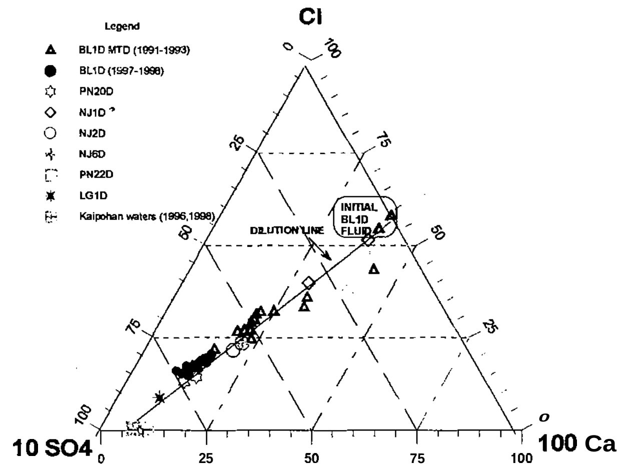


Figure 10. Dilution path taken by BLlD fluid in a Cl-Ca-SO_4 ternary plot, showing a connection with Kaipohan waters.

6.0 RESULT OF THE MECHANICAL WORK-OVER OF WELL BLlD

Well BLlD underwent a mechanical work-over fiom 28 June to 6 July 1998, with the objective of clearing the borehole of blockage; thus, recover lost output, and hopefully, improve the discharge chemistry. It was found during the operation that the top of liner (TOL) had lowered by 44 m, creating a 15-m open hole section between the production casing shoe at 1076 mMD and the new TOL at 1091 mMD. This open section is within BL1D's uppermost permeable zone (1075 – 1200 mMD), which is tagged as the main conduit for the acid inflow. It is postulated that severe corrosion may have caused the liner to break at certain points along this section, and cause the debris to slide down the borehole (Hermoso et al, July 1998).

Obstructions were encountered at 1219 mMD and 1557 mMD, where lead impression block survey indicated a parted liner. The 1557 mMD blockage could no longer be cleared; and the work-over had to be abandoned at this point.

The resulting chemistry is shown in Figure 11. It will be seen that the stabilized post-work-over chemistry of BLlD differs very slightly to the pre-work-over chemistry. Very critical, however, was the slight reduction in SO_4 concentration, to around 600 – 700 ppm, fiom the 800 ppm right before the work-over. The pH also increased from an average of 3.4 to an average of 3.6, considering the last six data points. It is reasonable to assume these last six points as representative of the stabilized chemistry, from observations of the Cl and CO_2 level during this period. The initially low Cl was the result of dilution by drilling fluids, and the initially high CO_2 was the result of a gas pocket that had been formed while the well was being shut during the work-over. The return to their normal values (i.e., values before the work-over) indicates the well has sufficiently stabilized.

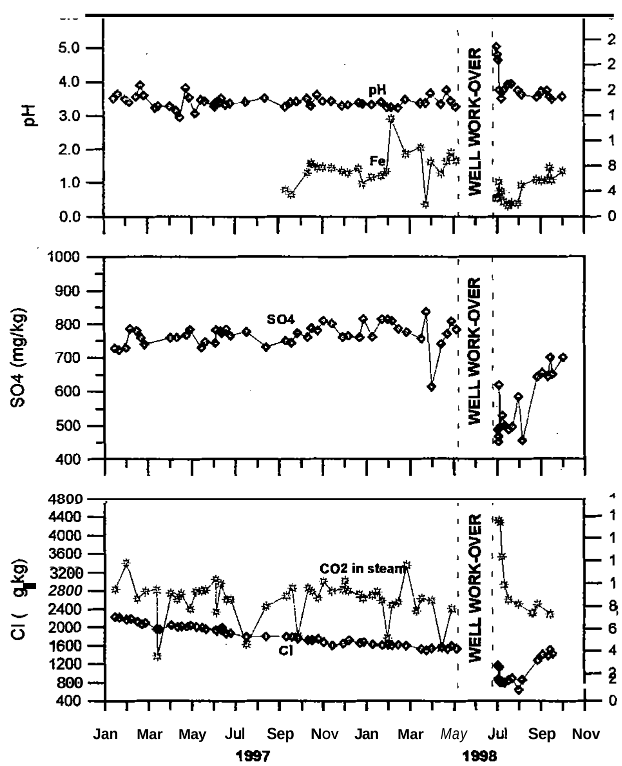


Figure 11. BLlD water and gas chemistry trends with time, showing very slight improvement after the mechanical work-over.

[4] Kaipohan craters are found between the Nasuji and Lagunao domes. Gas seepage in this area is high in H2S concentration. Consequently, Kaipohans are characterized by cool, bubbling acid-SO_4 pools, and dead vegetation and wildlife.

The slightly improved chemistry could also be seen in Fe, where the values after work-over ranged fiom 50 to 70 ppm, unlike before the work-over, when values reached up to as high as 80 to 110 ppm. There is, however, no assurance that the chemistry of BL1D will not further deteriorate to the original level with time.

Considering that the wellbore was cleared up to 1557 mMD, including the blockage tagged at 1219 mMD, it is assumed that the permeable zone at 1397 to 1600 mMD has been partly opened. The only indication, however, that contribution from this zone has increased, came from observations that the steam blow-off and peak load in the Balas-balas modular plant has slightly increased, which could not be attributed to the only other on-line well, OK5 ***(Orizonte et al, September 1998).*** The increased contribution from this zone might have effected the slight improvement in the discharge chemistry, although the magnitude of the chemistry change is too small to suggest a significant differentiation between the chemistry of this zone, and that of the uppermost zone. The former is believed to also contribute a two-phase fluid, and basing on the mechanism of the acid-SO_4 entry, may itself be a contributor of the acid-SO_4 in BL1D's discharge. In any case, the blockage at 1557 mMD has likely suppressed the liquid feed fiom the deeper zones (1850 mMD downwards), which was earlier relied on to dilute the acid-SO_4 component.

7.0 CONCLUSIONS

Correlation between acid concentration and BL1D's discharge pH strongly points to H_2SO_4 as the acid mainly responsible for the recent decline in BL1D's discharge pH. Re-evaluation of the medium term discharge model of well BL1D, along with evidences of Cl and SO_4 trends with discharge enthalpy, leads to the conclusion that the acid-- mainly H_2SO_4, with chemistry akin to the Kaipohan waters-- enters the well fiom the shallow permeable zones (1075-1200 mMD and 1397-1600 mMD), where the feed is two-phase. A liquid feed, which dominated the well during the initial discharge, and which mixed variably with the acid dilutant during the medium term discharge from 1991 to 1993, enters the well at the deeper permeable zones (2000 mMD and below). This feed is effectively blocked in the period 1997 to 1998, resulting to a shift in chemistry to the two-phase feed where the acid-SO_4 dominates the water chemistry. This resulted to the drastic decline in BL1D's discharge pH. The mechanical work-over of BL1D in June 1998 was unable to clear the blockage at 1557 mMD, **and** succeeded only in partly opening up the feed zone at 1397 to 1600 mMD, where the feed is two-phase. Consequently, very little change in chemistry was achieved by the work-over, since the neutral, liquid feed fiom the bottom zone has not been regained.

The above conclusions imply the adoption of a strategy to drill deep when drilling into the Lagunao area, **and** to avoid or case off shallow intersections with permeable structures in this area, especially Okoy-D, and possibly, Odlumon Fault. **A** theoretical implication is that H_2S oxidation to SO_4 in shallow aquifers would appear the more feasible mechanism of acid-SO_4 generation, as compared to SO_2 disproportionation ***or*** direct magmatic influx, thereby buttressing the hydrological flow model presently adopted by the site geochemistry staff.

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