Modeling the reservoir fluids of acidic geothermal wells in Mahanagdong, Leyte, Philippines

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Abstract

Some production wells of the high-temperature and liquid-dominated Mahanagdong Geothermal Field discharge low pH (<4 at 25 °C) fluids. The acidic discharges pose challenges to operations due to corrosion and scaling on the wellbore and surface facilities. The low-pH discharges have high salinity, and have either high or low sulfate concentrations. To elucidate the nature and mechanism of the acidic discharges, equilibrium and boiling simulations were conducted with the aid of SOLVEQ-XPT and CHIM-XPT geochemical software, taking into account the apparent “excess enthalpy” discharged by the wells and assuming that aluminum levels in the solution are in equilibrium with secondary minerals at depth. The reservoir fluids of the high sulfate acidic fluids have a high concentration of \( \text{HSO}_4^- \) species, which dissociates at lower temperatures and yields acidic discharges at the wellhead. In comparison, the low sulfate fluids are very acidic in the reservoir, with high levels of HCl inferred to be a major contributor to the acidity of the fluids at depth.

1. Introduction

Mahanagdong is in the southern part of the Greater Tongonan Geothermal Field lying along the Philippine Fault in the island of Leyte, Philippines (Fig. 1). Relative to the northern Tongonan field, Mahanagdong is characterized by lower enthalpy and lower salinity fluids, with discharge pH ranging from neutral to acidic [1]. Geothermal development in the north and northeastern part of Mahanagdong tapped acidic fluids. These discharges introduce constraints to operations due to corrosion and scaling on both wellbore and surface facilities. These fluids need further characterization since these portray

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differences in sulfate concentrations: the high-sulfate group in the north and the low sulfate group in the northeast.

![Map of the Philippines and the island of Leyte, which hosts the Mahanagdong Geothermal Field.](image)

**Fig. 1.** Map of the Philippines and the island of Leyte, which hosts the Mahanagdong Geothermal Field.

### 2. Mahanagdong and Low-pH Discharges

Expansion of the Mahanagdong field in the north and northeast area show highly mineralized fluids with reservoir chloride of 4000–5000 mg/kg and high temperatures based on quartz geothermometry at ~300-320 °C. Stable isotope data also shows these fluids to be enriched in isotope relative to nearby fluids at -1.0‰ δ¹⁸O (VSMOW). Gas levels of the low-pH wells range from 400-800 mmol/100M. These values are comparable to the gas values of neutral wells. Based on geochemical data, the acidic fluids are likely of hydrothermal origin with no active magmatic input similar to the neutral wells of the field [2].

The low-pH discharges have pH₂₅°C ranging from 3.0 to 4.0. Based on reservoir modeling and boiling simulations, the high-sulfate group in the north have high reservoir sulfate >100 mg/kg and near-neutral pH at depth which significantly decreases as the fluid ascends to the wellhead. On the other hand, the low-sulfate group with low reservoir sulfate < 100 mg/kg, is considerably acidic at depth (pH_res ~3.5) which only slightly increases as fluid ascends to the wellhead thereby yielding pH₂₅°C <4.

### 3. Methods

For this study, programs SOLVEQ-XPT and CHIM-XPT were used to model the low-pH fluids of Mahanagdong. Both programs have the ability to model mineral equilibria with CHIM-XPT that is able to compute reactions through continuous variations in temperature and pressure up to 600 °C and 5kbar, respectively [3]. Wells with “excess enthalpy”, where discharge enthalpy is greater than the enthalpy of liquid water at reservoir temperature (i.e., H_TD > H_res at T_qtZ), were interpreted to have a two-phase reservoir (i.e. gas and liquid).

In dealing with wells discharging “excess enthalpy”, heat titration is performed using CHIM-XPT. Heat titration is performed until the simulated enthalpy at the sampling condition is equal to the discharge enthalpy. Forced equilibrium with aluminum (Al³⁺) is performed since this parameter is commonly lacked due to difficulty in analysis. Forced equilibrium is performed at aqueous phase with reservoir pH and temperature. For neutral waters, k-feldspar, microcline and albite are used while kaolinite or muscovite
goes well with acidic waters [4]. For this paper, kaolinite and muscovite minerals were used since the pH25°C of waters is in the range 3.0-5.0.

4. Results and Discussion

4.1. Equilibrium plots

The minerals used for equilibrium calculations are based on minerals encountered during drilling. The plots show good convergence for all wells with the acid alteration minerals. The plots show good convergence at 260 °C and 320 °C, consistent with the inferred reservoir temperature range of the low-pH wells as determined from downhole surveys. Equilibrium calculations were performed using SOLVEQ-XPT with forced equilibrium of aluminum, and are shown in Fig. 2.

![Equilibrium plots showing convergence of acid alteration minerals of (a) high-sulfate well on the left at 260°C and (b) low-sulfate well on the right at 300-320°C.](image)

4.2. Minerals and species trends during boiling

4.2.1. Low-pH, high-sulfate wells

Boiling calculations show that reservoir fluid pH values are near-neutral but with a significantly decreasing trend as fluid ascends to the wellhead. HSO₄⁻ species concentration is higher compared to other acid contributing species such as HCO₃⁻. This is the major contributor to the wells’ acidity and occurs when HSO₄⁻ dissociates to SO₄²⁻ and H⁺ especially at lower temperatures. The increase in SO₄²⁻ concentration may also be caused by H₂ redox reaction at the early stage of boiling, however, dissolution of anhydrite must also be taken into account. Increasing Fe²⁺ from reservoir to wellhead is primarily due to adiabatic boiling of the fluid, which concentrates non-volatile components in the liquid phase.

4.2.2. Low-pH, low-sulfate wells

The modeled reservoir fluids of low-sulfate wells revealed acidic pH waters below 4.0 and very low sulfate concentration. As shown in Fig. 2b, there is a decrease in Fe²⁺ during the later stage of boiling coinciding with the formation of pyrite. Pyrite scales were also documented attached to the walls of the casing and the wellhead. Additional supply of Fe comes from dissolution of the casing due to corrosion and reacts with available H₂S to saturate pyrite at the wellhead. Simulations show high HCl concentrations (at ~10⁻⁴⁰, one unit higher than HCl concentrations in the high-sulfate group) possibly
contributing to the fluid acidity of the low-sulfate group. The nature of relatively higher HCl in these acidic fluids still needs to be further evaluated considering that geochemical evaluation indicates no active magmatic input [2]. Reservoir H2S concentrations are comparable with the high-sulfate group.

Fig. 3. Figures show the minerals and derived species of high-sulfate well (left) and low-sulfate well (right).

5. Conclusions

SOLVEQ-XPT and CHIM-XPT are useful in modeling acidic fluids including wells with “excess enthalpy”. The acidic fluids are at equilibrium with acid alteration minerals at reservoir temperatures. High-sulfate acidic fluids have near-neutral pH at depth and the pH decreases as fluids rise to the wellhead. Boiling precipitates anhydrite and pyrophyllite. The high reservoir level of HSO4− is the major cause of surface acidity due to dissociation to SO42− and H+. Modeling of the low-sulfate group shows that higher level of HClaq contributes to the low reservoir pH. Boiling only slightly increases the fluid pH thus still yielding a surface pH25°C of <4. Pyrite is significantly precipitated during boiling.

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References