EVALUATION OF RESERVOIR PROCESSES USING LIQUID GEOTHERMOMETRY AT AWIBENGKOK GEOTHERMAL FIELD, INDONESIA

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ABSTRACT

Understanding reservoir processes is critical to managing geothermal reservoirs. Production and re-injection of the produced brine cause pressure, temperature, enthalpy, and fluid chemistry changes in the reservoir. Monitoring the chemistry of the liquid being produced is an important surveillance activity that can provide information about these changes. In the Awibengkok (also known as Salak) geothermal field, routine geochemistry monitoring is conducted on a quarterly basis. Liquid geothermometry allows the temperature of reservoir fluid to be estimated from the fluid chemistry, especially at initial-state conditions. Comparing initial-state chemistry with historical changes shows that liquid geothermometers do not continually represent actual reservoir temperatures. However, the trends given by both the cation and silica geothermometers can be used to understand the processes occurring in the reservoir during production.

A comparison of the trends given by the silica and cation (Na-K-Ca) geothermometers was conducted in some wells at Awibengkok geothermal field. It was determined that the fluid temperature values diverged as the field is produced and, therefore, provide clues to the active reservoir processes present at specific times. From the preliminary evaluation of geothermometry trends, coupled with the historical time plots of enthalpy and reservoir chloride concentration, two main reservoir processes are believed to be active in the Awibengkok geothermal reservoir: boiling and injection breakthrough.

1. INTRODUCTION

The Awibengkok geothermal field is located about 60 km south of Jakarta on the island of Java, Indonesia (Figure 1). The original exploration contract area, including the current proven field, lies in the highlands on the southwestern flank of the Gunung Salak volcano (2211 m above sea level), for which the contract area was named. With a proven reservoir area of 18 km^2 and an installed capacity of 377 MWe, Awibengkok has a power density of about 21 MWe/km^2 despite substantial infield injection (Stimac et al., 2008).

Commercial power generation at Salak began in 1994 with an initial 110 MW (Units 1 and 2) and was expanded to 330 MW by 1998 when Units 3, 4, 5 and 6 were installed. Following the Asian Economic Crisis of 1997-1998, turbine output was increased to 377 MWe in 2002.

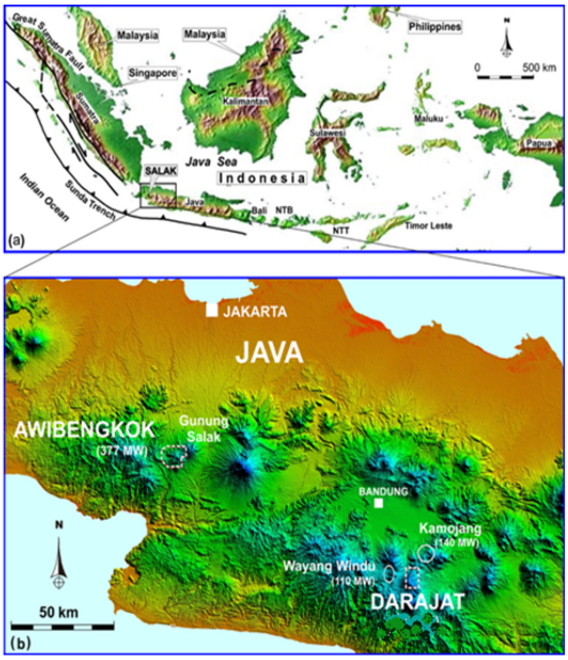

Figure 1: Location map of the Awibengkok Geothermal Field.

Periodic make-up drilling campaigns have maintained steam supply for full generation capacity since startup in 1994. At the end of 2009, 102 wells have been drilled with 69 wells used for production, 21 wells used for hot brine and condensate injection, five used as monitoring wells and seven wells plugged and abandoned. Currently, several additional production and injection wells are being drilled as part of the ongoing 2012-2013 Salak Drilling Campaign.

Chevron has developed an intensive reservoir monitoring or "surveillance" program collecting data for the Reservoir Engineering and Geoscience departments. Surveillance activities have been conducted routinely since 1994. This monitoring program is intended to document the changes in the reservoir brought about by production activities which are expected to be reflected in reservoir temperatures and fluid chemistry.

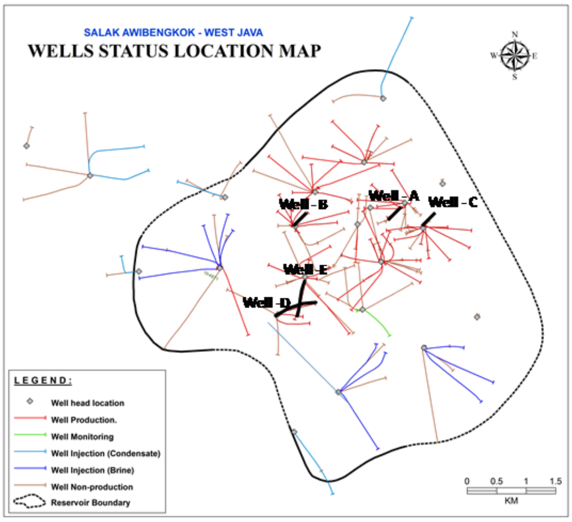

Figure 2: Map of well locations at the Salak geothermal field. The black bold lines show trajectory of the wells discussed in this study.

Quarterly geochemical data is used to monitor the changes in the reservoir. Historical liquid geothermometry is a geochemical tool used to evaluate reservoir temperature both at initial-state (baseline) condition and under continued fieldwide production. As the geothermal field is developed and produced, the mineral-liquid equilibrium will likely change with time. It is commonly known that the silica and the Na-K-Ca geothermometers equilibrate at different rates and react differently to reservoir processes. The application of comparative geothermometry to interpret reservoir processes has been established by Truesdell et al. (1990). Application of this methodology to the Awibengkok geothermal field has identified processes occurring in reservoir (e.g., liquid mixing and boiling).

2. METHODOLOGY

A series of continuous historical well data is needed to compare the liquid geothermometers and, ultimately, determined the active reservoir processes affecting the field. Geothermometers enable the temperature of reservoir fluid to be estimated from fluid chemistry. A pertinent chemical reaction is assumed to have attained equilibrium in order for a temperature estimate to be extracted from the fluid chemistry. There are three general classes of geothermometry available, namely, isotope, liquid, and gas. Liquid geothermometry is calculated from chemical analyses of liquid species collected under flowing conditions. The primary liquid geothermometers used are the silica (quartz adiabatic) and cation (i.e., Na-K-Ca). The equations for these two liquid geothermometers (Nicholson, 1993) are written below:

Na-K-Ca Geothermometer: $T\ (°C) = 1647 / \{\log (Na/K) + 1/3\ [\log (Ca^{0.5}/Na) + 2.06] + 2.47\} - 273$

Quartz (no steam loss) Geothermometer: $T\ (°C) = [1309/ (5.19 - \log SiO_2)] - 273$

Na-K-Ca values are dependent on the ratios of the cations when calculating liquid temperatures. The Quartz geothermometer (T_{Qtz}) uses silica concentration directly for the calculation. The more silica measured in a chemical sample, the higher the calculated temperature. These respective characteristics make the Na-K-Ca geothermometer ($T_{Na\text{-}K\text{-}Ca}$) less affected by processes such as boiling or mixing with dilute liquids than the Quartz geothermometer. These geothermometric differences combined with the trends of historical enthalpy and reservoir chloride concentration are used to determine the reservoir processes affecting the production wells.

Various techniques have been applied to measure the temperature of produced fluids in a geothermal field. Each technique may yield a different temperature depending on the condition of the fluids in the reservoir. The most conclusive technique to monitor the temperature is by direct measurement from flowing Pressure-Temperature (PT) or Pressure-Temperature-Spinner (PTS) surveys. Less direct techniques of temperature monitoring are more commonly used and include chemical liquid geothermometry and surface enthalpy measurements. Initially, a liquid reservoir shows general agreement amongst the different techniques. However, as extraction of mass from the reservoir continues, the values of reservoir liquid temperature obtained from the different techniques start to vary as boiling, re-circulation of injectate and influx of marginal recharge occurs. The different values extracted from each technique may reflect these different processes occurring in the reservoir (Figure 3).

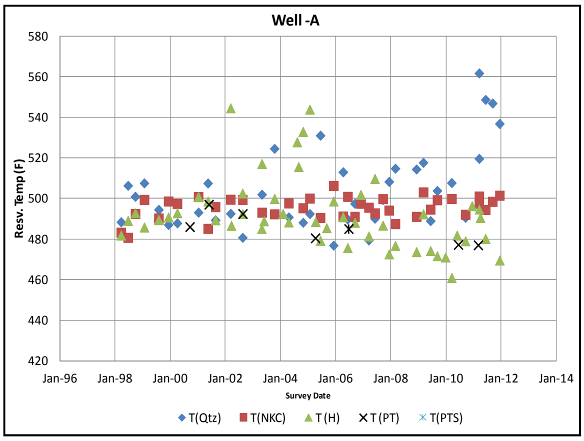

Figure 3: Example of comparison between different measurement techniques to estimate liquid reservoir temperature in Awibengkok. Historical data from this well shows the equilibrium state in initial condition where all of the measurement techniques shows agreement within 20°F.

This temperature comparison of wells in Awibengkok is an expansion of a previous study (Syaffitri et al., 2010). As with the previous study, the geothermometer data (T_{Qtz} and $T_{Na\text{-}K\text{-}Ca}$) from selected wells together with the produced fluid reservoir chloride concentration and enthalpy are used to determine the reservoir processes.

3. DISCUSSION

As the field undergoes sustained production, it is expected that reservoir condition changes with time. The reservoir temperatures often decrease due to mixing of cooler recharge liquids, both natural and injected, and as a result of boiling when a steam cap is developed.

Several wells in Awibengkok were selected as examples to illustrate the approach used in this study: Well-B, Well-C and Well-D (Figure 2). In addition, these wells represent different areas of the field and show various processes occurring in different parts of the reservoir.

3.1 Well – B : quick arrival of injectate

The western Awibengkok well, Well-B, shows a slow decline in Na-K-Ca temperature ($T_{Na\text{-}K\text{-}Ca}$) of about 10-15^{o}C with a significant drop in enthalpy (60 BTU/lb) over the past 13 years (Figure 4). This well produces from the liquid reservoir only. During its history, two periods of increased chloride concentration are evident, namely, in (1) 1999 to 2002 and (2) after 2011.

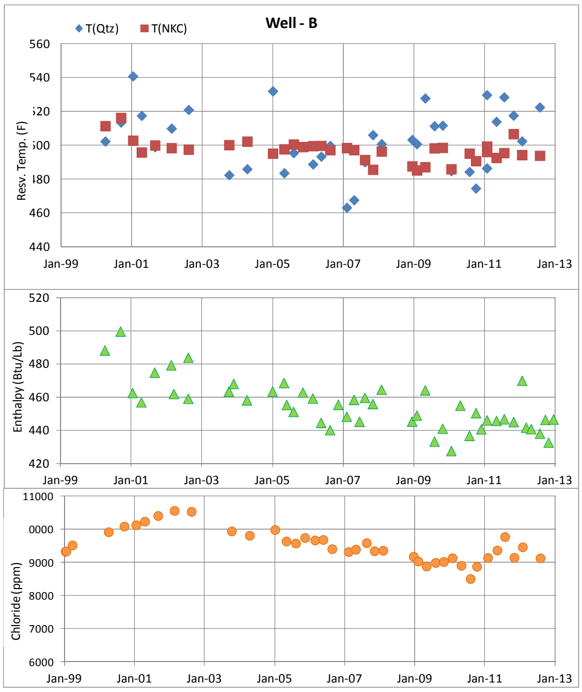

Figure 4: T_{QTZ} > $T_{Na\text{-}K\text{-}Ca}$ during the last three years combined with the decline in enthalpy and increasing Cl content suggest quick arrival of injected brine in Well-B.

In the early production of Well-B (1999 to 2002), the chloride concentration in the produced fluid has increased, coupled with a decline in fluid enthalpy. During this period, the T_{Qtz} > $T_{Na\text{-}K\text{-}Ca}$. These geochemical characteristics are consistent with increased influence from injection breakthrough. The quick arrival of the injected brine does not allow thermal re-equilibration along the flowpath, with the injected brine partially preserving the flashed brine conditions (i.e. high SiO_2) at the separator. This can result to a higher calculated T_{Qtz}.

Between 2002 and 2009, a change in injection strategy appears to have resulted to less impact of injected brine in this well. This period is characterized by T_{Qtz} < $T_{Na\text{-}K\text{-}Ca}$, a declining chloride trend and a slower decline in enthalpy.

After 2011, the two geothermometers show T_{Qtz} > $T_{Na\text{-}K\text{-}Ca}$, like in the early years of production. This trend is caused by the increase in hot brine injection at injection wells nearby as more additional brine is produced from newly drilled wells. During this same period, the chloride concentration started to increase and the enthalpy exhibits a more pronounced decline rate.

3.2 Well - C: boiling well

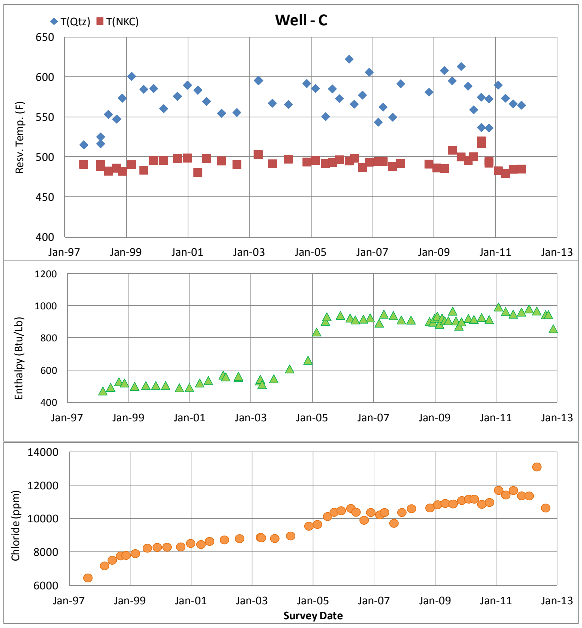

Figure 5: Consistently higher T_{Qtz} compared to $T_{Na\text{-}K\text{-}Ca}$, increasing in enthalpy and chloride indicates a continuously boiling process in this well.

The eastern Awibengkok well, Well-C had a dramatic increase in fluid enthalpy in 2005 with the chloride concentration showing the same rapid increase (Figure 5). Historically, T_{Qtz} is always higher than $T_{Na\text{-}K\text{-}Ca}$ in this well. $T_{Na\text{-}K\text{-}Ca}$ is relatively constant in most of the wells because the equation of this geothermometer (see above) contain ratios which makes less sensitive to changing concentrations caused to boiling or mixing in the reservoir. In addition, the $T_{Na\text{-}K\text{-}Ca}$ values are stable because of the significant injectate production. The consistently higher T_{Qtz} in this well can be attributed to a combination of two different process, injection breakthrough and continuous boiling in the well vicinity. The higher T_{Qtz} before 2005, is indicating a quick arrival of injectate into this well. However, the total flow enthalpy of this well does not show a decline trend accompanying Cl increase due to injection breakthrough. A simultaneous increase of NCG concentration in this well during the same period probably indicates higher contribution from the steam cap which then masked the effect of enthalpy decline from injection.

After 2005, the jump in enthalpy pointed to a boiling process happening in this well. The silica concentration in the fluid does not have time to re-equilibrate at a lower temperature after boiling and results in higher T_{Qtz} values compared to T_{NKC} and measured temperatures from PT and PTS.

Historical plot of the enthalpy (Figure 5) is consistent with partial production from the steam cap in this well as the enthalpy increases to >900 Btu/lb after 2005. The boiling hypothesis is also supported by the very high chloride concentration in this well (>11000 ppm) from 2009-2012. This chloride content is even higher than the chloride concentration in injected brine over the same time interval (~10,000 ppm Cl).

3.3 Well – D: Cycling Well

The southwestern Awibengkok well, Well-D, shows a gradual historical increase in $T_{Na\text{-}K\text{-}Ca}$ and reservoir chloride concentration, but with two periods of elevated enthalpy (Figure 6).

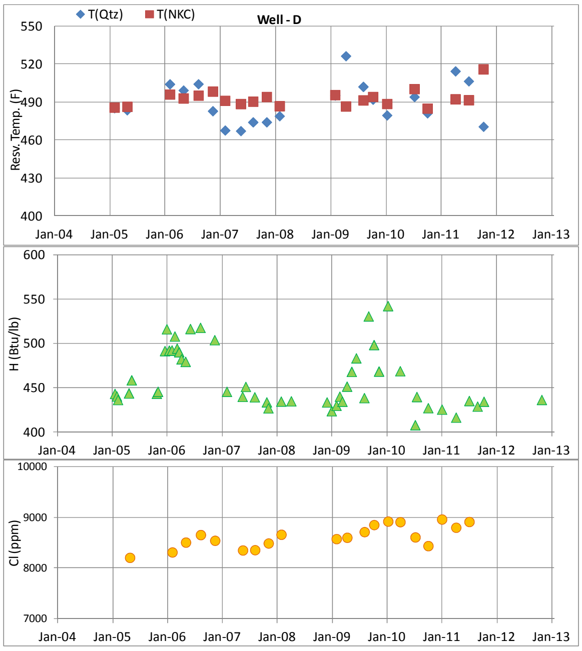

Figure 6: Cycling behavior observed in Well-D, characterize by the inconsistent relation between T_{Qtz} and $T_{Na\text{-}K\text{-}Ca}$.

Cycling behavior in this well can be identified from the relationship between T_{Qtz} and $T_{Na\text{-}K\text{-}Ca}$ which shows variation through time, supplemented by the two "spikes" of elevated enthalpy. Before 2007, the $T_{Na\text{-}K\text{-}Ca} \approx T_{Qtz}$ which suggests that an equilibrium condition exists. But from 2007 to 2008, $T_{Na\text{-}K\text{-}Ca} > T_{Qtz}$ and this is accompanied by decline in enthalpy and chloride concentration. This condition may be related to the influx of cooler dilute fluids into the wellbore which is also reflected by the drop in chloride concentration trend. At the end of 2009, the trend indicates a return to $T_{Na\text{-}K\text{-}Ca} \approx T_{Qtz}$ condition with enthalpy bouncing back to ~500 Btu/lb. These high enthalpy periods possibly show the original enthalpy of this well when it is not being impacted by influx of cooler dilute fluids. On the other hand, periods when low enthalpy is measured during 2007-2008 and after 2010 may show a condition where the well is being impacted by influx of cooler dilute fluids in the reservoir.

Cycling behavior in this well may also be a result of production interference with a nearby well. Declines in enthalpy in Well-D are observed when Well-E is shut-in. It is hypothesized that during the shut-in of Well-E, flow streamlines changed and preferential fluid flow was re-directed to the production zones of Well-D.

4. CONCLUSION

The reservoir processes in a developed and producing geothermal field can be assessed by combining the observed changes in fluid chemistry and temperatures. The use of geothermometry for actual reservoir fluid temperature determination can be limited and susceptible to error due to changes in reservoir condition brought about by field production. However, the cation and silica geothermometers are thermodynamically very different and provide different responses to reservoir processes. The comparison of the trends given by these two geothermometers coupled with the assessment in chloride concentration and enthalpy trends creates a powerful interpretive tool available for routine geothermal monitoring programs.

5. ACKNOWLEDGEMENT

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