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# Fluid Flow Pattern in the Reservoir of Cerro Prieto Geothermal Field using Quartz Geothermometry

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**ABSTRACT**

The knowledge of a reservoir fluid flow pattern is of vital importance during the development and exploitation of a geothermal system. A methodology based on the quartz geothermometry is developed to calculate geothermal reservoir temperature and vapor fraction. This procedure was applied in the Cerro Prieto geothermal field in 1993 and 2003.

It was discovered that there is an infiltration and a movement of geothermal fluid in the reservoir towards the N-E region. Similarly, the increase in the vapor fraction in the N-E region is a consequence of extensive exploitation.

## 1. INTRODUCTION

Geochemical studies of geothermal systems provide a framework to understand the physiochemical processes responsible for their origin and evolution. The chemical composition of fluids (separated vapor and water), collected from fumaroles, hot springs and drilled wells is determined in the laboratory. Using quartz geothermometer and the conservation of mass, energy and alkalinity, the chemical concentrations are converted to the reservoir conditions in order to predict the state of water-rock interaction and reservoir processes like boiling, condensation, mixing with other fluids, mineral dissolution-precipitation, etc. (Verma, 2002).

Verma (2003) presented the preliminary results on the development of a computer program, *QrtzGeotherm* for estimating temperature and vapor fraction in a geothermal reservoir. Four representative types of quartz solubility: *(i) a quadratic regression equation of 1/T(K) and P(MPa). (ii) a linear equation relating log $SiO_2$ to the inverse of absolute temperature, (iii) a polynomial of absolute temperature including logarithmic terms* and *(iv) temperature as a polynomial of $SiO_2$ including logarithmic terms* were programmed. The algorithm was written using the Newton-Raphson method. The fundamental problem with this algorithm is that the initial guess value of a reservoir's temperature should be close to the real value. To resolve the above problem Verma (2008) reprogrammed the ActiveX *QrtzGeotherm* using the trial and error method for solving the equations.

The quadratic regression equation fits well to all of the experimental solubility data in pure water along the saturation curve and provides better agreement between the calculated and measured down-hole temperatures in the case of Cerro Prieto (Verma et al., 2006).

In this article we present the calculation of downhole temperature and vapor fraction in the production wells at the Cerro Prieto geothermal field using the quartz geothermometry. The temperature and vapor fraction contours are used for the estimation of a fluid flow pattern.

## 2. QUARTZ GEOTHERMOMETRY

The quartz solubility geothermometry is based on the regression equations of experimental quartz solubility data in pure water along the saturation curve. Geothermal reservoir conditions are generally along the liquid-vapor saturation and there may be any proportion of vapor from 0 to 100% in the reservoir. Silica dissolves only in liquid phase. The total discharge fluid from a well represents both liquid and vapor phases in the reservoir. Initially, the quartz geothermometer has been applied on the total discharge composition with an assumption that the reservoir fluid is only in the liquid phase. However, it is observed in many cases that the total discharge enthalpy (i.e. reservoir enthalpy) is higher than that of liquid water at the reservoir conditions. In other word there exist both vapor and liquid in the reservoir.

Therefore, the application of quartz geothermometer to the total discharge silica concentration may provide an incorrect value of reservoir temperature, which could significantly depart from the real reservoir temperature depending on the amount of vapor present or lost from liquid phase within the reservoir. Here an algorithm based on the conservation of enthalpy and silica is developed to estimate temperature and vapor fraction in a geothermal reservoir.

There may be multiple inlets to the feed zone of a well and segregation of phases within the well, which may affect considerable the results of geothermometry. Similarly, adiabatic condensation can produce misleading liquid composition. However, the following assumptions are made here: single feed zone, liquid or liquid-vapor along the saturation curve in the geothermal reservoir and homogeneous flow in the well. These assumptions are made in general in geochemical modeling calculations.

$$H_{res} = yH_v + (1-y)H_l \quad (1)$$

where H is enthalpy, y is the fraction of vapor by weight in the reservoir and sub-indices res, v and l stand for reservoir, vapor and liquid, respectively. All the geochemical calculations are performed with the assumption of conservation of enthalpy (iso-enthalpy flow both in reservoir and wellbore). According to the conservation of enthalpy, the reservoir enthalpy ($H_{res}$) is equal to the total discharge enthalpy ($H_R$).

Similarly, the equation for the conservation of silica is written as

$$SiO_{2,TD} = (1-y)SiO_{2,l} \quad (2)$$

Where $SiO_{2,TD}$ is the total discharge concentration of silica and $SiO_{2,l}$ is the silica concentration in liquid phase in the reservoir. From equation 2, the fraction of vapor in the reservoir is

$$y = 1 - \frac{SiO_{2,TD}}{SiO_{2,l}} \quad (3)$$

Let the temperature in the reservoir be T. The value of T (and the corresponding saturated pressure (P) for the quadratic regression equation) is substituted in the regression equations to calculate the silica concentration of the liquid phase in the reservoir. This silica concentration ($SiO_{2,poly}$) is substituted for $SiO_{2,l}$ in equation (3) to calculate y. The value of y together with the values of $H_l$ and $H_v$ at T are used to calculate the reservoir enthalpy ($H_{res}$) from equation (1). $H_{res}$ must be equal to the measured reservoir enthalpy ($H_R$), if T is equal to the reservoir temperature. Since we do not know the correct value of reservoir temperature, the values of $H_{res}$ are calculated for each temperature and plotted in an enthalpy versus temperature plot to find the temperature for $H_{res} = H_R$.

An alternative approach to solve the equations 1 and 2 is applying the trial and error method. There may be multiple solutions in case of a quadratic equation; therefore the guess value of the reservoir temperature is crucial in the case of a quadratic equation. This will be explained later.

## 3. IAEA COMPARISONS OF SILICA ANALYSIS IN GEOTHERMAL WATERS

With interlaboratory comparisons of isotopic analysis ($\delta^{18}O$ and $\delta D$) of natural waters the International Atomic Energy Agency (IAEA), Vienna has created successfully a worldwide network of laboratories for good quality analysis (see Verma et al., 2010). The chemical and isotopic data are complementary to understand the geochemistry of natural water system. Therefore, the IAEA has also conducted various interlaboratory comparisons for geothermal waters within the framework of the project "*Coordinated Research Program on the Application of Isotope and Geochemical Techniques in Geothermal Exploration*". The results are reported in the internal reports: (i) 22 laboratories from 19 countries, (ii) 15 laboratories from 7 countries, (iii) 26 laboratories from 10 countries, (iv) 35 laboratories from 16 countries, (v) 38 laboratories from 23 countries and (vi) 31 laboratories from 18 countries.

Figure 1 presents a relation between the laboratory number and concentration of $SiO_2$, analyzed in thirteen samples during the IAEA interlaboratory comparison program. There is a wide spread in the analytical data ever after the removal of outliers. Verma et al. (2002) found that the higher uncertainty in the analysis of high concentration $SiO_2$ samples was associated with analytical problems. Combining all the analytical errors in measuring $SiO_2$ and reservoir enthalpy, the total error in the calculated temperatures with quartz geothermometry is ±20ºC.

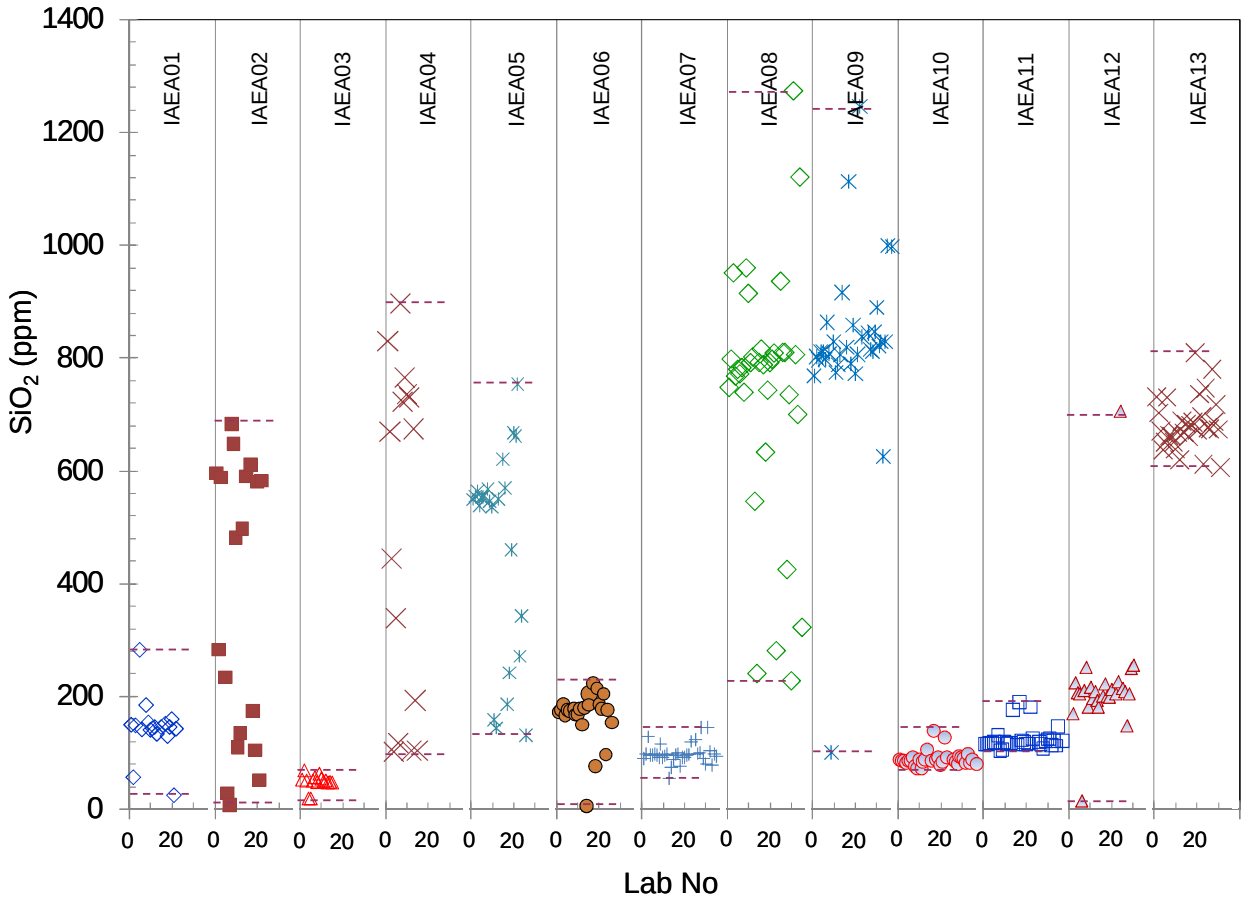


**Figure 1: A relation between the laboratory number and $SiO_2$ analyzed in thirteen samples as a part of IAEA interlaboratory comparison program during 1982 and 2004. The dashed lines indicate the lower and upper bounds of the results.**

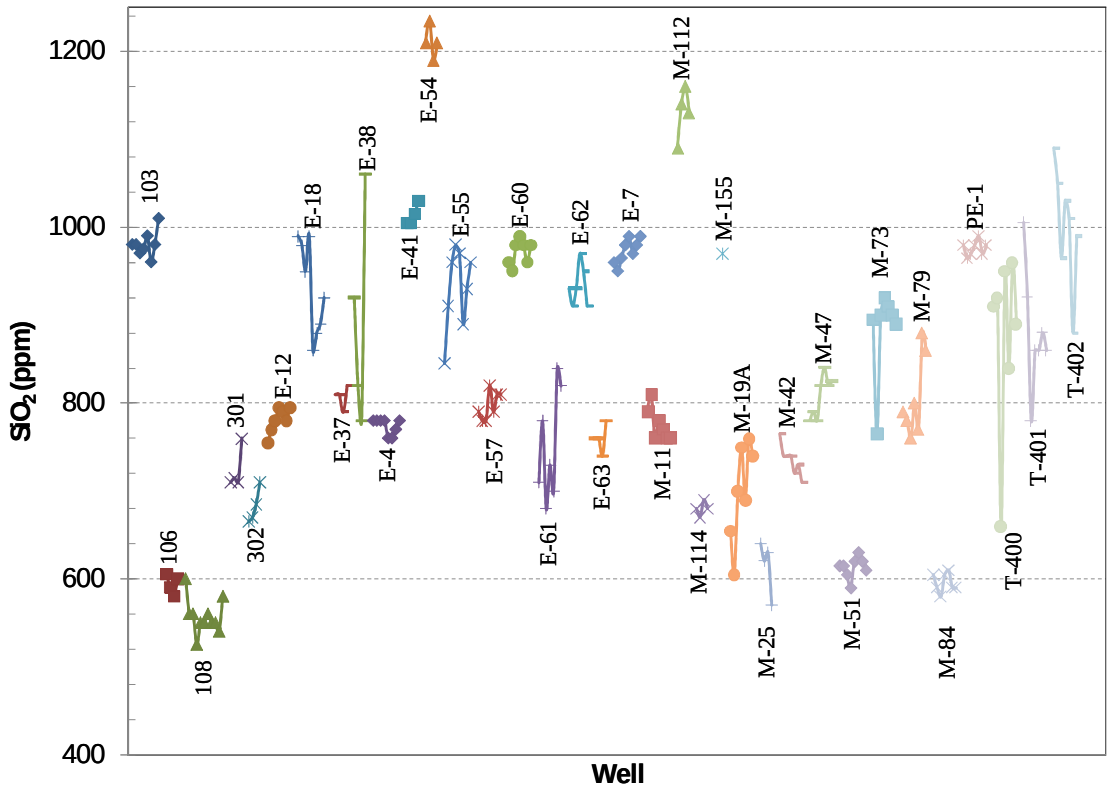


**Figure 2: Variation of silica concentration in the separated water at atmospheric conditions from thirty five production wells in the Cero Prieto geothermal field in 1993. There is a high fluctuation in silica concentration in some wells. The averaged values are considered here.**

## 4. FUILD FLOW PATTERN IN CERRO PRIETO

We present the preliminary results on the application of quartz geothermometry to estimate the temperature and vapor fraction in the Cerro Prieto geothermal reservoir. Figure 2 shows the variation of silica concentration in the separated water at atmospheric conditions, obtained from thirty five production wells in 1993. The fluctuation in the silica concentration for some wells like E-38 and T-400 is very high. It may be associated with analytical uncertainty or some reservoir process. We considered the averaged values of $SiO_2$ for each well.

Figure 3 shows contours of temperature and vapor fraction in the Cero Preito geothermal reservoir in 1993 and 2003, calculated on the basis of quartz geothermometry. There are no appreciable changes in the temperature distributions in the reservoir after 10 years of geothermal production except there are more details in 2003. This is associated with an increase in the number of production wells (i.e. 146 instead of 35).

The variation in the reservoir vapor fraction is drastic (Figure 3). There was about 40% vapor in the reservoir along the S-W to N-E direction in 1993. In 2003 there is practically no vapor in the S-W region; whereas the vapor fraction has increased to 60% in the N-E region.

The reservoir processes like cold water entrance, extensive exploitation, and fluid migration may contribute to such behavior. The cold water entrance reduces vapor fraction as well as temperature. Since there is no appreciable temperature variation in the reservoir, the contribution of cold water entrance is not significant. However, there is an increase in vapor fraction in N-E which also implies a decrease in pressure. So, there may be some fluid flow towards the N-E region.

In the N-E region the increase in the vapor faction may be a consequence of extensive exploitation. The extensive exploitation may change the reservoir characteristics from liquid dominant to vapor dominant.

In this preliminary work we did not consider the depth of each well. To understand the effect of well depth we have to compare our result with an alternative approach like numerical well simulation. The quartz geothermometer calculates the temperature in the geothermal reservoir, whereas a well simulator can provide the values of temperature and vapor fraction at the bottom of the well (Verma et al., 2006, Arellano et al., 2010). The movement of fluid from the reservoir to the bottom of a well reduces temperature as well as pressure. The pressure reduction produces some extra vapor. Therefore, the calculation of temperature and vapor fraction by both the techniques is necessary to study the effect of well depth.

## 5. CONCLUSIONS

The procedure to estimate temperature and vapor fraction in a geothermal reservoir with quartz geothermometry is a reliable tools; however the quality of analytical determination of silica in waters is crucial.

Its application in the Cerro Prieto geothermal reservoir indicates that there is an infiltration and movement of geothermal fluid towards the N-E direction. Similarly, the increase in the vapor fraction in the N-E region is a consequence of extensive exploitation.

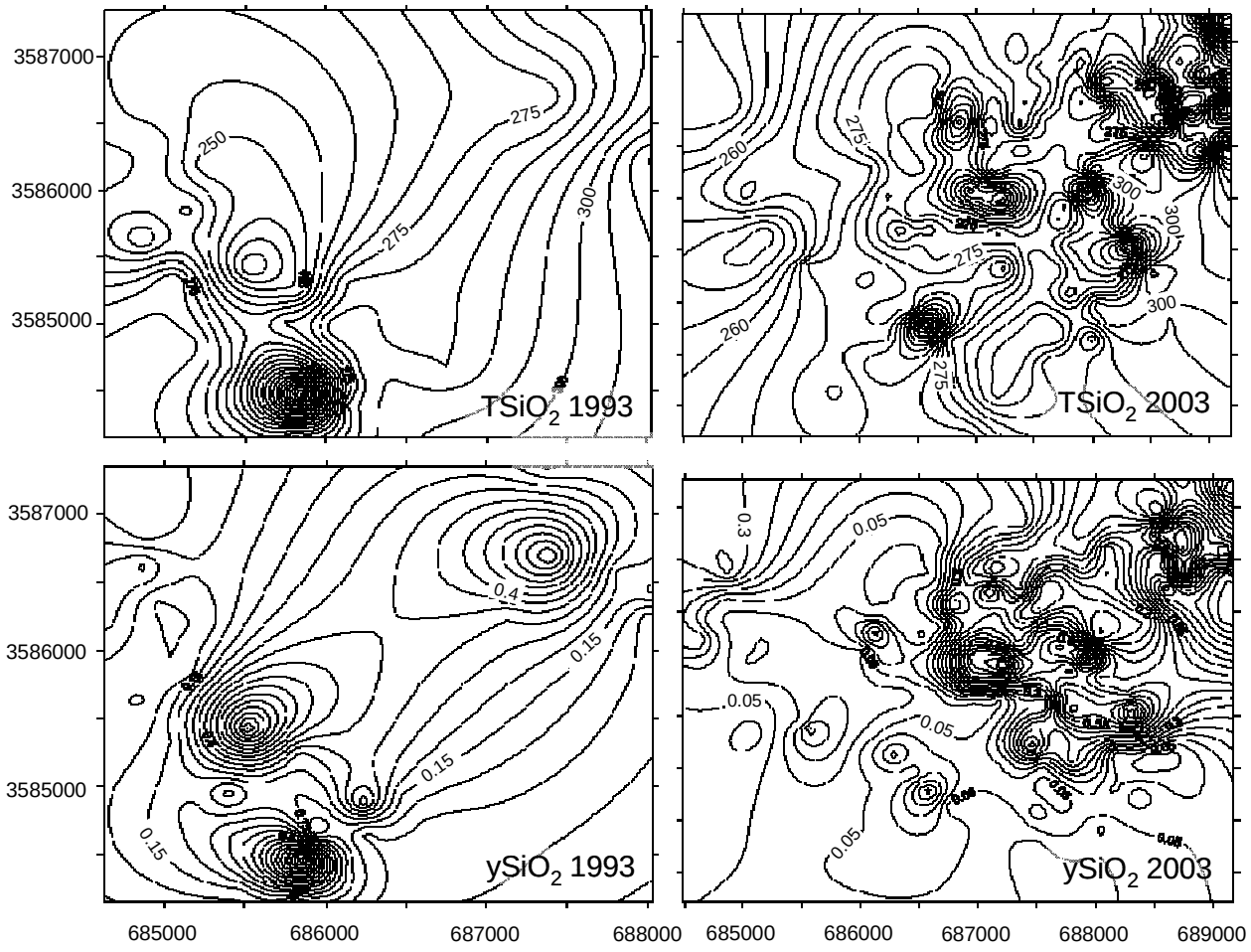


**Figure 3: contours of temperature and vapor fraction in the Cero Preito geothermal reservoir in 1993 and 2003, calculated on the basis of quartz geothermometry.**

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**REFERENCES**

Arellano, V.M., Barragán, R.M., Aragón, A., Izquierdo, G., Portugal, E., Rodríguez, M.H. and Pérez, A.: Reservoir Characteristics and Exploitation-Related Processes at the CP IV Sector of the Cerro Prieto (México) Geothermal Field, *Proceedings*, 4th World Geothermal Congress, Bali, Indonesia, (2010).

Verma, M.P.: Geochemical techniques in geothermal development. In: D. Chandrasekharam and J. Bundschuh (eds.) Geothermal Energy Resources for Developing Countries. Swets & Zeitlinger Publishers, The Netherlands, (2002), 225-251.

Verma, M.P.: QrtzGeotherm: a computer program for the quartz solubility geothermometer in moderately saline brines up to 370ºC. *Proceedings* Geothermal Research Council Transactions, (2003), 341-345.

Verma, M.P.: *QrtzGeotherm*: An ActiveX component for the quartz solubility geothermometer. Computers & Geosciences, (2008), 1918-1925.

Verma, M.P., Arellano, V.M. and Aguilar, K.M.: QrtzGeotherm: An ActiveX component for the quartz solubility geothermometers, *Proceedings* NZ Geothermal Workshop, (2006).

Verma, M.P., Birkle, P. and Sanchez, D.: Theoretical and Analytical Aspects of Carbonic Species Determination in Rain, Ground, Geothermal and Petroleum Waters, *Proceedings*, 4th World Geothermal Congress, Bali, Indonesia, (2010).