



UNITED NATIONS
UNIVERSITY

GEOTHERMAL TRAINING PROGRAMME



LaGeo S.A. de C.V.

CHEMICAL RESPONSE MONITORING DURING PRODUCTION

Patricia Jacobo and Francisco E. Montalvo,

LaGeo S.A. de C.V.

15 Av. Sur, Col. Utila, Santa Tecla,

EL SALVADOR

pjacobo@lageo.com.sv, fmontalvo@lageo.com.sv

ABSTRACT

The chemistry of geothermal fluids plays an important role in the knowledge of the conceptual natural state model of the geothermal field at the initial steps of development, and in the conceptual dynamic model taking into account the evolution against time due to the extraction-reinjection regimes. The geochemical parameters along with the thermodynamic data are periodically and systematically monitored, following the reservoir response to production. A case study for Ahuachapan geothermal field is presented but some particular examples for Berlin geothermal field are also included. Development of the Ahuachapan field has resulted in changes in the chemistry of the discharged fluids, induced by the reservoir's pressure drawdown. The pressure decline in Ahuachapan wells is mostly located at the central part of the field, where boiling and inflow of a cold recharge is found, resulting to the increase of the shallow steam (steam cap). Influence of peripheral waters is observed in the new southern producing zone, where wells with calcite scaling potential are located.

1. INTRODUCTION

The way a reservoir changes with time has been described as its response to the production load. Geothermal reservoirs change with time as a result of their exploitation. In the natural state, there is a balance of recharge and discharge flows. Through these flows reservoir pressures are kept in dynamic equilibrium with surrounding aquifers. When a reservoir is exploited, the quantity of fluid produced greatly exceeds natural discharge and pressures in the reservoir decrease (or are “drawdown”) so that they are no longer in equilibrium (D’Amore, 1991).

Pressure drop with a cold recharge into the reservoir causes alterations in the geothermal system at some extent. In the most extreme condition, cold recharge may cause the reservoir to become unproductive, but only moderate changes are usually observed, e.g. decrease in well discharge, changes in surface activity, water level decline, increased boiling, increased recharge (usually cold water), surface subsidence, changes in fluid chemistry and temperature/enthalpy variations.

Therefore, reservoir monitoring is a key factor in the development and sustainability of geothermal resources. It should start prior to the commencement of exploitation (baseline) and continue throughout its productive life, providing the most valuable source of information to define the best management strategies such as the extraction-reinjection regimes and well operation points.

2. RESERVOIR MONITORING PROGRAMME

The parameters to be measured are different from one system to another, because a particular exploitation regime applied in a particular reservoir will affect differently the chemical, physical and thermodynamic properties of fluids. However, major aspects for monitoring in almost every reservoir include: a) production properties of wells (water and steam flow-rate, well-head pressure, separation pressure, discharge enthalpy, b) chemical composition of discharged fluids, c) downhole pressure and temperature profiles.

Each of the analyzed components provides information on changes in the reservoir conditions. An integrated assessment of available chemical and thermodynamic data from production wells provides understanding of likely downhole processes e.g. boiling and dilution; reinjection effects and evolution of mineral scaling potential.

3. MONITORING CHEMICAL AND THERMODYNAMIC PARAMETERS

Chemical and thermodynamic data from production and injection wells are necessary for the understanding of main flow-pattern of deep fluids and likely downhole processes. Chemical studies of produced fluids from geothermal wells provide information on the temperature, salinity, physical state and flow of fluids in the reservoir. In the case of wells sunk into a boiling geothermal aquifer, chemical composition of discharged fluids also contribute to the assessment of the reservoir response to the production load as regards recharge and enhanced boiling.

Changes in the chemical composition of water and steam discharged from wells in exploited geothermal systems provide information on the response of the reservoir to the production load with respect to the source of the water recharging producing aquifers (Arnórsson et al., 2000). Data on fluid composition may also provide useful information on the depth level of producing horizons of individual wells. Gas compositions can be used to estimate the initial steam fraction in the aquifer fluid (Arnórsson, 2000), i.e. the steam fraction in the aquifer fluid beyond the depressurization zone that forms around producing wells.

3.1. Geochemistry in the first geothermal development stage

With the new wells, it is necessary to carry out chemical surveys prior to their operation (as a base line), in order to assess the natural reservoir chemistry of the fluids, and thus estimate the type of fluids, the thermal potential, the main operation points (e.g. separation pressure) and the mineral scaling and corrosion potentials of the fluids. Amongst key chemical parameters to be monitored are chloride, Tquartz, TNaKCa, gas content and enthalpies, along with the production characteristics and thermodynamic data.

For instance, according to the results for the Berlin well TR-9 downhole samples from 1991 (Figure 1), chloride content showed a possible feed zone at 1700 m depth, in agreement with temperature data giving a maximum temperature of 290°C. In most cases, measured temperature was close to quartz temperature and higher than Na/K and Na-K-Ca temperatures.

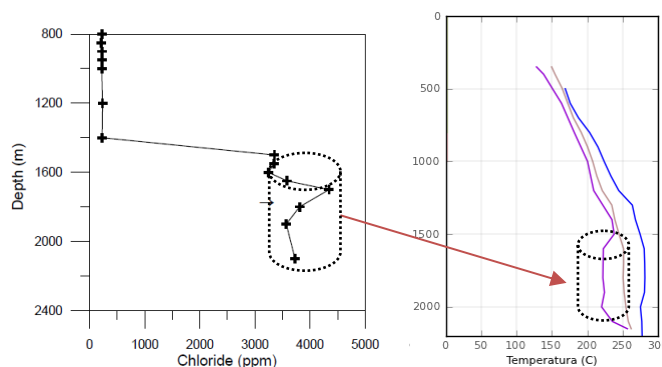


FIGURE 1: Chloride content vs. depth and thermal recovery for well TR-9

3.2 Geochemistry during the exploitation

Periodic chemical sampling of production wells is necessary to evaluate the evolution of the reservoir's fluid composition. The chemical composition of the total well discharge is estimated through the chemistry of collected samples of both water and steam at the measured separation pressure, and the corresponding steam fraction.

Calculations are carried out as follows:

If the heat content of the total well discharge and its composition is the same as those of the water entering the well, then the mass of any component “*i*” is:

$$m_{i,1}^d = m_{i,1}^s Y_1 + m_{i,1}^w (1 - Y_1) \quad (\text{Arnorsson, 2000})$$

In this equation m^d , m^s and m^w stand for the mass of the *i* component in the total discharge, steam and water, respectively. Y_1 is the steam fraction at a particular pressure P_1 , and $(1 - Y_1)$ the water fraction at that pressure. When availability of chemical data is limited, a practical assumption for solving the former equation is that dissolved solids are negligible in the separated steam phase, as well as non-condensable gases in the separated water phase.

3.2.1 Geothermometry

In a producing field, downhole temperatures may be conveniently estimated through the use of chemical geothermometers, which constitute a very important tool during exploitation in monitoring the response of geothermal reservoirs to the production load.

Fluid geothermometers depend on temperature sensitive reactions of fluids with rock minerals or fluids components. Thus, in a producing field, downhole temperatures may be conveniently estimated through the use of geothermometers applied to analyses of produced fluids, provided the geothermometer reaction is in equilibrium at downhole conditions.

Water geothermometers may be broadly classified into two groups: (1) those which are based on temperature-dependent variations in solubility of individual minerals, e.g. silica, and (2) those which are based on temperature-dependent exchange reactions, which fix ratios of certain dissolved constituents, such as the Na-K-Ca geothermometer.

3.2.2 Chemical changes with time.

Monitoring of the chemical composition of water and steam discharged from wells in exploited geothermal fields provides information about the response of the reservoir to the production load. For this purpose, time evolution plots of geochemical and thermodynamic parameters are normally used.

Since geothermometers are based on reactions with specific kinetic rates, comparison of some geothermometer temperatures may indicate reservoir processes such as boiling or mixing. For instance, different rates of response of the Na-K-Ca and quartz geothermometer combined with the discharge enthalpy provide indications of fluid state and of fluid temperature near and far from wells. Aquifer chloride provides additional indications for dilution and boiling processes. (Truesdell A.H. et al, 1989).

Decrease in the Cl concentration in the discharged water indicates relative increase in recharge into producing aquifers of colder water; however, an increase in Cl indicates recharge from hotter zones. When a well discharges (consisting of components with different temperatures), the result is a

discrepancy between geothermometers. The cause of discrepancy may also be a variable departure from equilibrium for individual geothermometers (Arnorsson, 2003).

3.2.3 Boiling and dilution

Geothermal reservoir in the natural state has a balance of recharge and discharge flows. Through these flows, reservoir pressures are kept in dynamic equilibrium with surrounding aquifers. When a reservoir is exploited, the quantity of fluid produced greatly exceeds the natural discharge and pressures in the reservoir decrease (or “drawdown”) so that they are no longer in equilibrium. The volume of fluid removed must be replaced by inflow of colder waters outside of the reservoir or by boiling and formation of vapor. Whether cold water entry or boiling occurs, it usually depends on the permeability of channels to other aquifers. If channels are tight (relatively impermeable), the fluid boils; if they are open, cooler water will enter the reservoir (D’Amore, 1991).

Extensive boiling modifies the composition of the water, which occurs in response to steam formation and degassing, in addition to changes in temperature and pressure, leading to changes in the saturation state of the water with respect to minerals (Arnorsson, 2003).

Boiling and dilution can be estimated through geochemical indicators such as chloride content, and comparison of geothermometers with discharge enthalpy.

3.2.4 Mineral saturation and scaling potential

The mineral scaling potential of geothermal fluids is commonly estimated through the mineral saturation index of aqueous speciation for the aquifer fluid composition at a selected temperature. Based on this approach, oversaturated waters are likely to result on mineral deposition, whereas unsaturated waters are believed to be without scaling potential.

Mineral saturation indexes are calculated with the computer programs specifically suited to handle chemical data (liquid, vapor, gases) from two-phase wells.

3.2.5 Isotopic composition of geothermal fluids

Isotope studies in geothermal contribute to identify the recharge, discharge zone and also other physical processes like boiling, dilution or mixing with inflow of colder waters or reinjection fluids.

As an example, the baseline of the water’s isotopic composition at initial conditions in the Berlin geothermal field (see Figure 2) reflects that the water-rock interaction process yields more positive values of $\delta^{18}O$ with respect to the isotopic composition of the groundwater. Because of interaction with silicates of andesitic rock instead of carbonic sediments, this process is not locally predominant. For most of the wells with respect to hot springs, the observed slope of δ^2H vs. $\delta^{18}O$ is positive. The plot also shows the evolution of new wells towards the reservoir’s area. Reinjection wells are located to the right hand side of the plot, clearly apart from production wells, indicating reinjection has no influence in the producing area.

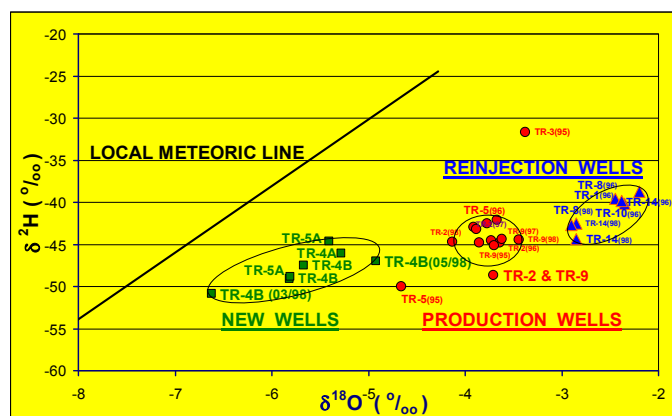


FIGURE 2: Water’s isotopic composition at initial conditions in the Berlin geothermal field

4. CASE STUDY: THE AHUACHAPAN GEOTHERMAL FIELD

4.1 General features

The Ahuachapán geothermal field (AGF) came on line in 1975, and was the first geothermal power plant in Central America. The AGF is located in the northwest part of El Salvador (Fig. 1) in a weak tectonic zone, where the movements of fluids are conducted mainly by a fault structure system. The production well field covers an area of 4 km² with 53 drilled wells with varying depths between 591 and 1,645 m. Their average elevation is around 800 m a.s.l.

The Ahuachapán reservoir is still considered as liquid dominated. The initial salinity prior to exploitation was 22,000 ppm and the measured fluid temperatures ranges from 214 to 250 °C, with inferred minimum recharge temperatures of 245-250 °C, based on discharge fluid geothermometry (Aunzo et al., 1989).

Since the initial commercial exploitation of the AGF, a monitoring programme of chemical and thermodynamic properties of productive wells has been carried out. Through years, such source of information has been used to improve the understanding of the Ahuachapan reservoir, estimate the reservoir response to changes during exploitation, select potential expansion areas, decide the number of new wells to be drilled to fulfill production requirements, and forecast the most promising production scenarios that guarantee a sustainable use of the geothermal resource.

4.2 Conceptual model

In general, the conceptual model of the geothermal system indicates that hot fluids recharge the reservoir from the S-SE; possibly the upflow zone is found beneath the Laguna Verde volcanic complex. The hot fluids feed the field through major faults, and flows laterally along the permeable Ahuachapán andesites. Some of the geothermal fluids discharge initially through surface manifestations in the Ahuachapán-Chipilapa area; the main discharge of geothermal mixed fluids occurs at El Salitre springs some 6 km N of Ahuachapán field (Figure 3).

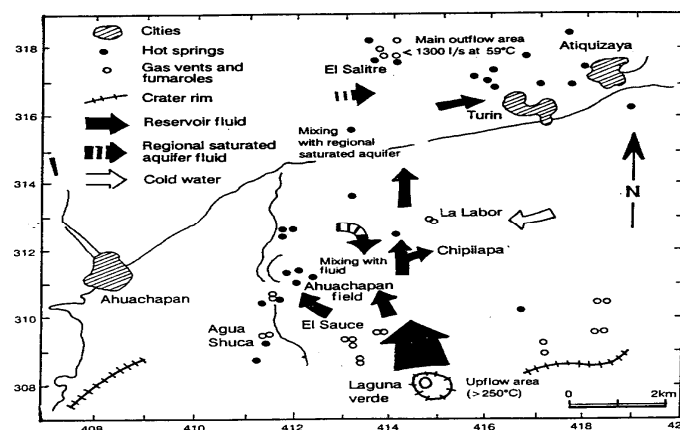


FIGURE 3: The Ahuachapan Hydrological Model in the Natural State (from LBL, 1988)

According to the geological model, there are 3 main faults (La Planta, Buenavista and Agua Shuca) responsible for the upflow to the production reservoir and other secondary faults that control the outflow in the geothermal system. The geothermal reservoir is pressurized with respect to the shallow aquifer and the saturated regional aquifer. This is the reason why, a colder downflow fluid has been identified in the fluid monitoring (geochemical data) during the history of the field, especially in the first years of exploitation.

4.3 Pressure drawdown

Prior to exploitation, the pressure in the geothermal reservoir was near-uniform (about 36 bar-g). Later on, the intensive mass extraction during the early exploitation of the field resulted to large changes in the thermodynamic conditions of the reservoir, mainly a significant pressure drawdown and temperature decline. All changes in the reservoir have been mainly produced by the drop of the initial reservoir's pressure from 34 bar-g to about 20 bar-g in 1989, and to 18.4 bar-g at present (Figure 4). The stabilization of the reservoir's pressure achieved in recent years is attributed to a more conservative extraction strategy, as well as the injection of residual waters into the Chipilapa Field.

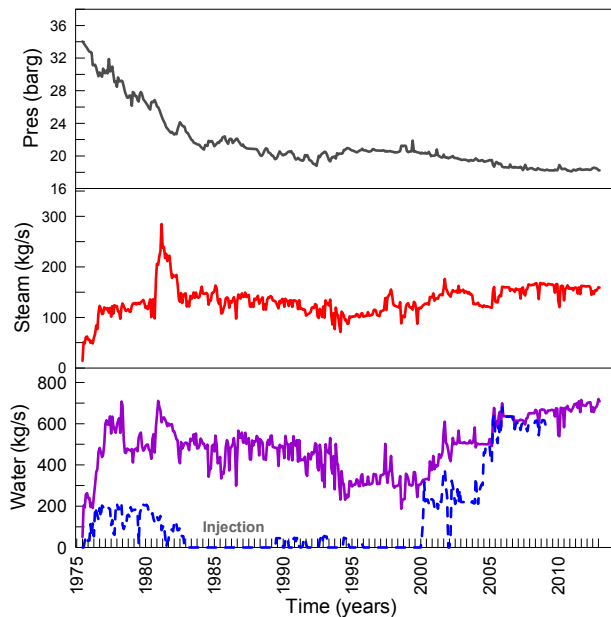


FIGURE 4. Pressure and mass extraction rate in the the Ahuachapan geothermal field

conservative extraction strategy, as well as the injection of residual waters into the Chipilapa Field.

4.4 Production history and reservoir response

It has been established that the dominant physical processes governing the evolution of the reservoir over time, mostly in the first 10 years of operation, consist of boiling in shallower parts of the reservoir (with development of excess enthalpy), and dilution due to recharge of peripheral lower salinity fluids. Estimation of these downhole processes is carried out through interpretation of geochemical and thermodynamic parameters e.g. time comparison of geothermometers,

enthalpies, chloride, gas content; distribution of conservative elements; stable isotopes profiles.

4.4.1 Enthalpy vs. time

In the case of the Ahuachapan production wells, estimation of likely downhole processes such as boiling or dilution is carried out through a time series comparison of the temperature indicators Na-K-Ca cation geothermometer, quartz-saturation geothermometer, and discharge enthalpy.

The chemical indicator sequences applied are based on those proposed by Truesdell et al. (1989), except for the use of enthalpies instead of temperatures. The enthalpies are abbreviated as H-NaKCa, H-Sil and DH indicating Na-K-Ca, quartz and discharge enthalpies, respectively.

The enthalpy patterns of some wells such as AH-6 and AH-23 suggest fluid boiling during flow to the well in response to decrease in well bottom pressure ($DH > H-NaKCa > H-Sil$). According to the results, well AH-6 is a dominant boiling well greatly affected by the depressurization zone with high and constant discharge enthalpy values, whereas well AH-23, whose discharge enthalpies have persistently declined during the last years, is also presently affected by mixing with cooler water. Well AH-31's evidence of dilution, with a dominant pattern $HNaKCa > HSil > DH$, likely caused by the entry of cooler water into the well through a shallow feed zone, where it mixes with the reservoir fluids. (Figure 6).

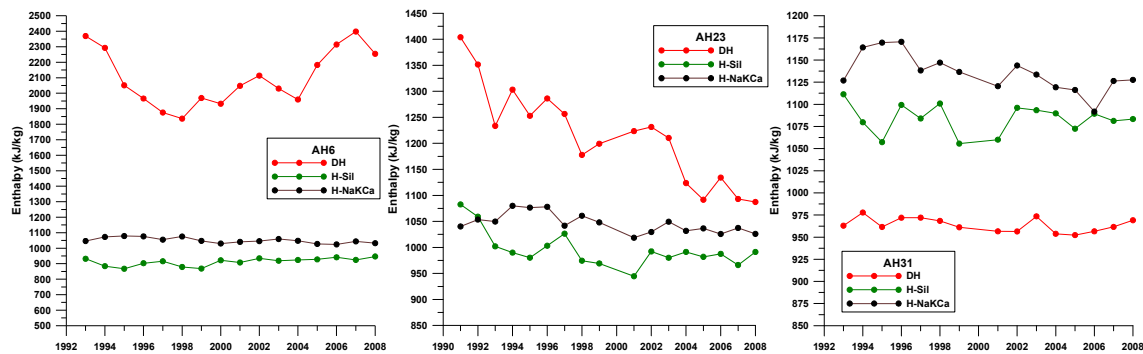


FIGURE 6: Enthalpy vs. time plots for wells AH4Bis, AH-21 and AH-31. Abbreviations: Discharge enthalpy (DH), Quartz enthalpy (H-Sil), Na-K-Ca enthalpy (H-NaKCa)

4.4.2 Water and gas chemistry vrs.time.

Besides geothermometers, other chemical species and ratios are plotted against time using the chemical data collected in the wells, from the start of exploitation until the present.

A decrease of conservative elements such as chloride indicates dilution or mixing of reservoir waters with a cooler recharge, while an increase of chloride is usually related to boiling. When the increase of chloride is accompanied by temperature reduction, some reinjection effect should also be considered.

For example, since year 1999, well AH-6 has shown a clear aquifer chloride increase, suggesting boiling is the main downhole process. On the contrary, well AH-23 has exhibited some decrease of chloride, probable related to the intrusion of less saline water. As mentioned earlier, this well has also experienced a decrease in its discharge enthalpy, a further evidence of dilution. Well AH-31 has shown aquifer chloride declining during the last ten years, probably due to the decreased pressure in the central part of the field, which allows the breakthrough of less saline and cooler water (Figure 7).

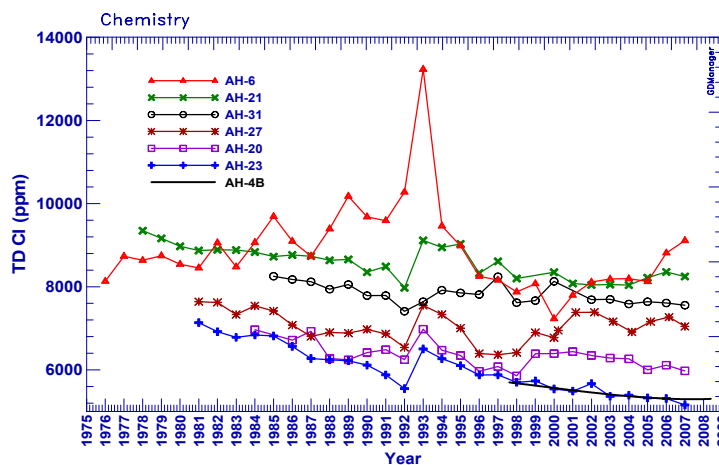


FIGURE 7: Total discharge chloride vs. time for wells AH-6, AH-21, AH-31, AH-27, AH-20, AH-23 and AH-4Bis

In the Ahuachapan geothermal field, the average T Na-K-Ca has decreased over time, suggesting downflow of cooler fluids from the overlying regional saturated aquifer due to pressure decline. On the other hand, CO₂ content has not declined after thirty years of exploitation, suggesting an open system with constant inflow of deep geothermal fluids (Figure 8). Chloride and O16 distribution through the geothermal field show a general gradient from southeast to west. The higher values

suggest deep reservoir fluids in the central western part of the field. To the east, a cold water inflow lowers the chloride and isotope contents (Figure 9).

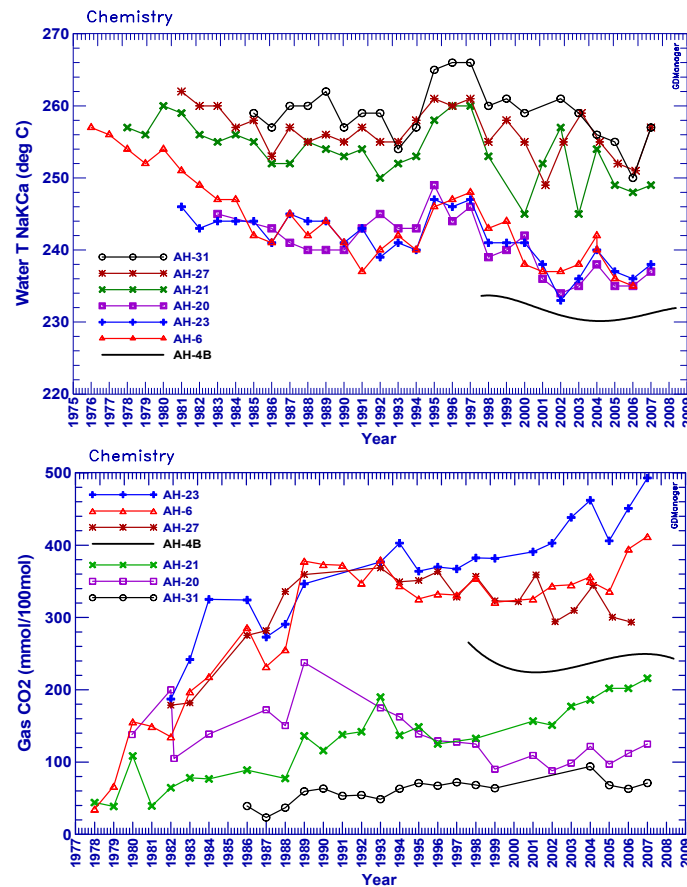


FIGURE 8: Evolution of Na-K-Ca temperature and CO2 content in production wells of the Ahuachapán geothermal field

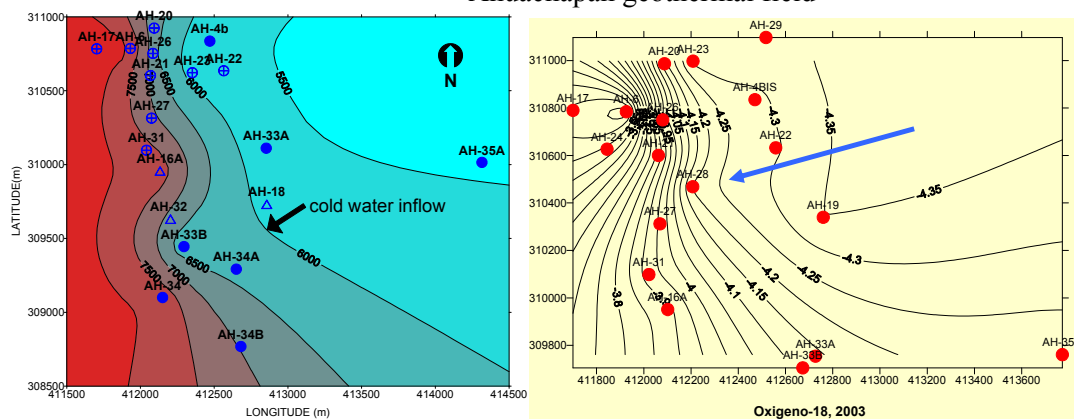


FIGURE 9: Left hand side: Chloride distribution through the Ahuachapán geothermal field. Right hand side: O18 profile in AH production wells

4.4.3 Mineral saturation and scaling potential

Mineral saturation indexes are calculated with the software Watchworks. This allows the study of the chemical changes due to boiling within the well up to surface conditions (100°C,) and how these changes affect the solution/mineral equilibria. The mineral saturation indexes are computed as $\log(Q/K)$, where negative values indicate undersaturation, zero stands for equilibrium, and positive values suggest oversaturation (except for calcite, with a scaling potential starting at $IS > 0.3$).

The major expected minerals in Ahuachapan production wells are anhydrite, calcite, amorphous silica and quartz (Figure 10). According to the results, all fluids are unsaturated with respect to anhydrite and amorphous silica at wellbore conditions. Quartz is in equilibrium within the aquifer, and becomes oversaturated while discharge waters cool down during boiling. Only calcite exhibits different behaviour through the field, with saturated values for southern wells AH-33B, AH-35A, AH-35B and AH-35C, but unsaturated or equilibrium values for the rest of the wells (Figure 10).

All the wells with calcite scaling potential are located in the new expansion area at the southern part of the field. They operate with calcite inhibition systems in order to prevent calcite blockage (Figure 11).

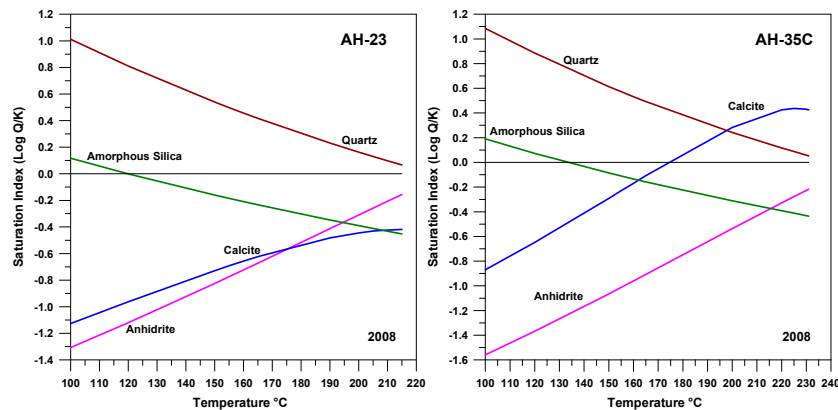


FIGURE 10: Mineral saturation indexes in discharged fluids from wells AH-23 and AH-35C

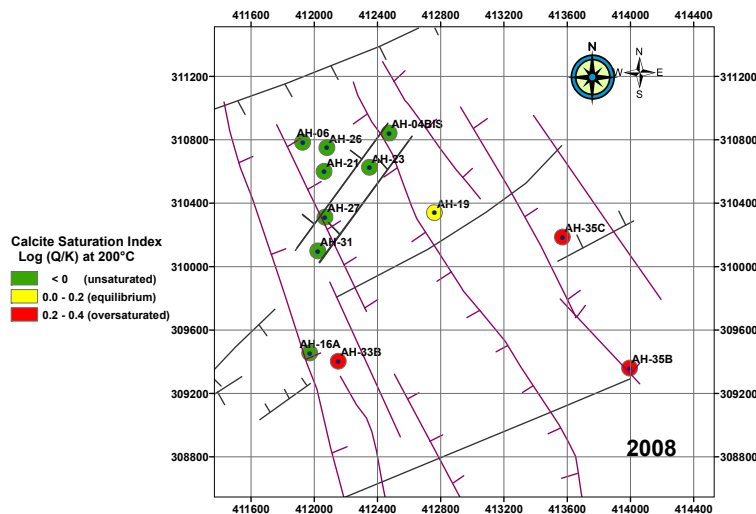


FIGURE 11: Distribution of Calcite saturation indexes through the Ahuachapan wellfield. Wells in red color are calcite oversaturated at 200°C, and are likely to result on calcite scaling if are operated without any calcite inhibitor

The only reported case of a silica scaling problem in the production area occurred in 1990, specifically in well AH-17, a dry steam well. The origin for silica scaling problems only can be related to the contamination of the upper steam zone by the lower liquid feed zone above, but due to the lack of chemical history it is not possible to do a detail analysis. After cleaning in 1992, well AH-17 has being operating at higher well-head pressure and without any evidence that the problem has returned. Figure 12 shows the well head pressure decline during the scaling problem.

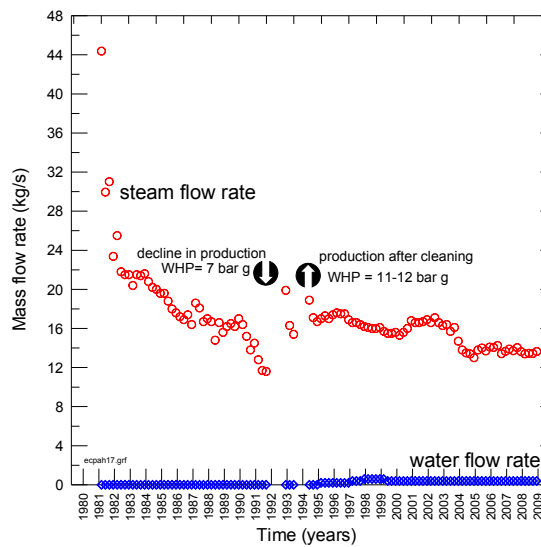


FIGURE 12. Decline in steam flow rate due to the pressure drawdown and scaling problems

4.4 Hydrogeological conceptual model under exploitation

Through the years, the extraction of fluids has affected several geochemical parameters. Significant changes occurred mainly in the early years of operation due to dilution, as the reservoir chlorides decreased from 9000 to 6000 ppm and the content of silica was lowered from 600 to between 350 and 500 ppm. However, some wells exhibited a boiling process as chlorides increased above 9000 ppm and the content of non-condensable went from 0.3 up to 1 wt%. The cationic geothermometers have remained rather constant but that of silica has decreased in recent years in most wells, ranging from 215-220 °C, in accordance with the measured temperatures and as a result of cooling caused by the aforementioned processes. The average temperature measured in the reservoir has dropped between 15-20 °C.

Wells located at the western and northwestern parts of the field discharge a mixture of fluids from a hotter feed zone and a cooler feed zone, the first ones likely related to the steam cap. Presently, the depressurization zone has extended to most of the shallow and old wells in the field and it seems to promote boiling and mixing; some wells exhibit both processes.

Geochemical data suggest dilution in a north-south trending zone that coincides with several major faults suggesting downflow of cooler fluids from the overlaying saturated aquifer. The chloride content and geochemical thermometers show higher values in the western part of the production field (about 8000-9000 ppm and 260 °C) than in the eastern part (about 7000 ppm and 240 °C), suggesting that the dilution process occurs mainly from the N-NE direction. However, a diluted fluids supersaturated with calcite has been founded at the S-SE part, despite the fact that the highest measured temperature (250°C) is also registered in the new expansion area (Figure 13).

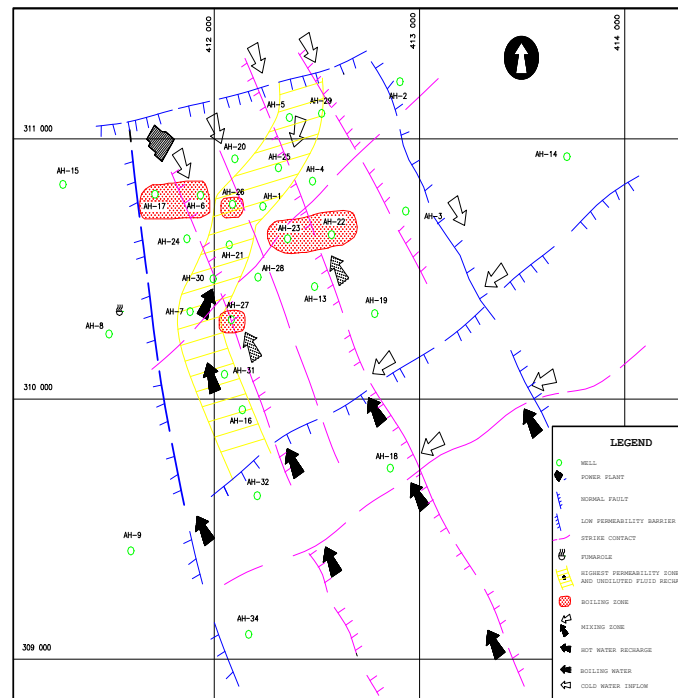


FIGURE 13. Hydrogeological Exploitation Conceptual Model of the Ahuachapan geothermal field

5. CONCLUSIONS

The normal behavior of a liquid dominated reservoir is to reduce the reservoir pressure during the early stage of exploitation, this it is not a dramatic situation if there is injection into the system and a complete monitoring is available. The monitoring must include at least mass extraction and injection, chemistry of fluid, reservoir pressure monitoring, tracer tests and geothermal surface monitoring. Two main processes are affecting the reservoir of the AGF: a) boiling is present in the shallow part of the system, characterized by increasing enthalpy in the production wells, higher gas and water chemical content; b) dilution or cold water inflow occurs in some part of the reservoir where the declining pressure induce inflow from neighboring aquifers (lateral or above).

The injection could produce effects like boiling and dilution together, and must be carefully analyzed and monitored. Tracer test could be helpful to determine how the injection process is affecting the neighboring wells; chemical and isotopic monitoring must also be undertaken.

REFERENCES

- Aunzo, Z., Bodvarson, G.S., Lippmann, M.J., Steingrimsón, B., Truesdell, A.H., and Witherspoon, P.A., 1989: The Ahuachapán Geothermal Field, El Salvador - Reservoir Analysis -Volume I: Text and Main Figures. LBL, Berkeley, Ca, report.
- Arnórsson, S. (ed.) 2000, *Isotopic and chemical techniques in geothermal exploration, development and use. Sampling methods, data handling, interpretation*. International Atomic Energy Agency, Vienna, 351 pp.
- Arnórsson, S., Gudmundsson B., 2003: Geochemical monitoring of the response of geothermal reservoirs to production load –examples from Krafla, Iceland. *Proceedings of the International Geothermal Conference, Reykjavik, Sept. 2003*.

D'Amore, F., and Truesdell, A.H., 1985: *Calculation of geothermal reservoir temperatures and steam fraction from gas compositions*. *Geoth. Res. Council, Trans.*, 9, 305-310.

D'Amore F. (coordinator) 1991. *Applications of Geochemistry in geothermal Reservoir Development*. UNITAR. Rome, 408 pp.

Montalvo, F., Tenorio, J., 2009: Geochemical monitoring practices in El Salvador. *Presented at "Short Course on Surface Exploration for Geothermal Resources"*, organized by UNU-GTP and LaGeo, in Ahuachapan and Santa Tecla, El Salvador.

Montalvo, F., 1994: Gechemical evolution of the Ahuachapan geothermal field, El Salvador C.A. Report 9 in: *Geothermal training in Iceland in 1994*. UNU-GTP, Iceland.

Moore, J., 2011: *Fluid Geochemistry*. Energy & Geoscience Institute, University of Utah, June, 2011.

Monterrosa, M., and Montalvo, F., 2010: Sustainability analysis of the Ahuachapán geothermal field: management and modeling. *Geothermics*, 39-4, 370-381.

Renderos, R., 2002: Chemical characterization of the thermal fluid discharge from well production tests in the Berlin geothermal field, El Salvador. Report in: *Geothermal training in Iceland in 2002*. UNU-GTP, Iceland.

Truesdell A.H., Aunzo Z., Bodvarsson G., Alonso J., Campos A. 1989: The use of Ahuachapan fluid chemistry to indicate natural state conditions and reservoir processes during exploitation. *Proceedings 14th Workshop on Geothermal Reservoir Engineering, Stanford University, USA*, 273-278.

Wanjie, C., 2012: Geochemical monitoring of reservoir response to production. *Presented at "Short Course VII on Exploration for Geothermal Resources"*, organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, 2012.