Distribution of Hydrothermal Alteration in the Cerritos Colorados Geothermal Field, Mexico

D. A. Rocha Ruiz[1,2] and R. Hernández Zúñiga[2]

[1]Facultad de Ingeniería, Universidad Nacional Autónoma de México, Cd. Universitaria, México D.F.
[2]Inter-American Development Bank (IDB)- Energy Ministry, SENER, México, D.F.
david.rochar9@gmail.com • drocha.perge@energia.gob.mx

Keywords

Mexico, Cerritos Colorados, hydrothermal alteration, SWIR reflectance spectroscopy, alteration suite, geochemical distribution, magmatic fluids

ABSTRACT

The study and analysis of rock samples from wells drilled in the Cerritos Colorados geothermal field (Mexico) allowed determining the distribution and zonation of alteration minerals in the system. Reflectance spectroscopy in the short-wave infrared range (SWIR) was used on the samples (cores and cuttings) to identify hydrothermal alteration minerals by comparing their spectra against those given in a US Geological Survey database. The main features used were common absorption peaks, shape of the spectrum, percent reflectance and wavelength, which provided guidance to identify mineral suites. The zoning and geochemical distributions of the identified minerals in the system, in general correlated with observed lithology and hydrothermal alteration. As a result, four main alteration associations (argillic, phyllic or sericitic, propylitic and advanced argillic) were defined, which reflected the temperature, pressure, fluid chemistry, and other conditions influencing the presence of characteristic mineral associations.

1. Introduction

An important part of a geothermal exploration project is the determination of hydrothermal alteration patterns since they are the result of processes that are affected by temperature, permeability and fluid chemistry.

The mineralogy of alteration of the hydrothermal reservoir can be characterized by analyzing rock samples collected from drilled wells. That data help determine lithology, water chemistry, pressure and temperature. Estimates of subsurface temperatures inferred from the association of alteration minerals provide relevant information on the thermal regime of a geothermal field. These data are useful to define reservoir conditions and estimate the field's potential for geothermal development and exploitation.

Since the mid 1970's, the Comisión Federal de Electricidad (CFE), Mexico's National Utility, began a series of geological, geochemical and geophysical studies in the Cerritos Colorados geothermal area, which was previously known as La Primavera since it is located within La Primavera Caldera, near the city of Guadalajara (Jalisco). The purpose of the work was to assess the area's geothermal potential, given its recent (some 25,000 years ago; Mahood, 1981a) volcanic activity and the presence of surface manifestations (fumaroles, hot springs and hydrothermal alteration zones).

The data obtained from deep exploration wells determined the existence of an important geothermal resource in the Cerritos Colorados area. Further drilling identified a geothermal reservoir with an estimated capacity of 75 MWe. The reservoir had a stable pressure and fluid saturation behavior during long well tests. This was validated by an independent evaluation by the Japan International Cooperation Agency (JICA) based on numerical reservoir simulation studies that used geological, geophysical and geochemical data obtained by CFE.

The main objective of the present study is to determine the distribution and zonation of alteration minerals in the Cerritos Colorados geothermal system, and to define possible changes in the hydrothermal activity by the presence of minerals having ranges stability ranges dissimilar to those presently observed in the system. The alteration minerals in the area were identified by analyzing their spectral signatures.

2. Regional and Local Geology of Cerritos Colorados

The Cerritos Colorados geothermal field is located in central Mexico west of the Mexican Volcanic Belt and at the intersection of three regional geologic structures: the N-S striking Colima rift, the E-W Chapala rift and the NW-SE trending Tepic-Zacoalco rift (Fig. 1).

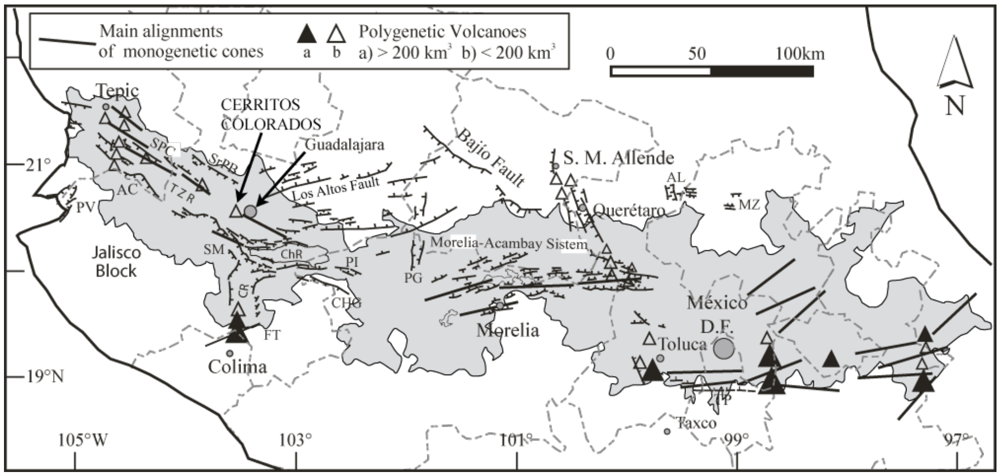

Figure 1. Major fault systems and Miocene-Quaternary volcanism of the Trans-Mexican Volcanic Belt. TZR: Tepic-Zacoalco rift; PV: Puerto Vallarta graben; SPC: San Pedro-Ceboruco graben; AC: Amatlán de Cañas semigraben; SrPB: Santa Rosa - Plan de Barrancas graben; SM: San Marcos fault; CR: Colima rift; FT: Tamazula fault system; ChR: Chapala rift (Modified after Gómez-Tuena et al., 2005).

The Trans-Mexican Volcanic Belt is defined as a belt of active, dormant and dead volcanoes and volcanic complexes of recent formation that crosses the country from east to west (Fig. 1), where 79% of Mexico's known thermal anomalies are found (Venegas et al., 1985).

The Cerritos Colorados geothermal field is within a volcanic center related to a caldera structure. The geology and eruptive history of La Primavera (Fig. 2) has been reported by Mahood (1981a,b). The generalized lithological column of the area is based on exploration well data. At shallow depths rhyolitic rocks predominate, however, the deep reservoir is mostly in andesitic strata interlayered with lithic tuffs (Gutiérrez-Negrín, 1991).

Hydrogeological studies done in the Cerritos Colorados area show that groundwater flow is mainly controlled by fractures and faults associated with the regional tectonic regime, both at shallow and deep levels. Hydrogeological data, obtained from CFE exploration wells, have shown a system composed by at least two aquifers (Fig. 3):

1. A local shallow aquifer (< 150°C), for the most part contained in the Tala tuff.
2. 2. A deep regional aquifer (> 200°C), related to the geothermal reservoir (at more than 1000 m depth) located in the lower andesites, with fluid flowing through NW-SE striking faults, lithological lithologic contacts and fractures, which are the result of western Mexico's regional tectonic regime.

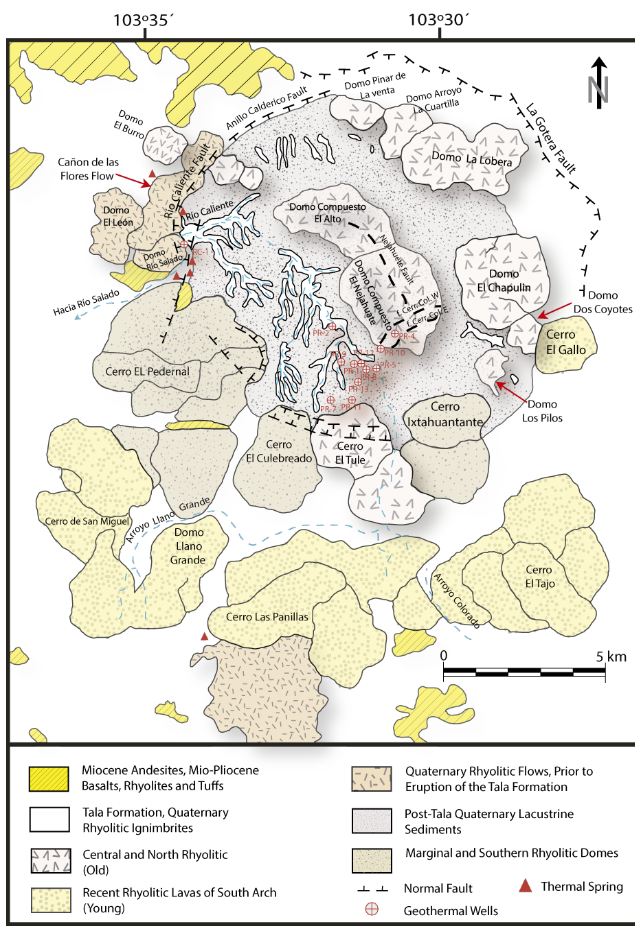

Figure 2. Geology of the Cerritos Colorados geothermal area. Modified after Mahood (1980).

3. Methodology and Distribution of Hydrothermal Minerals

An ASD-LabSpec Pro spectrometer, with a wavelength range of 0.35-2.5 µm, was used to measure the spectral signatures of the rock samples. In this study, however, we focused on the reflectance response in the short-wave infrared range (SWIR; 1.0 - 2.5 µm), to detect the main features of the hydrothermal alteration minerals (i.e., phyllosilicates, carbonates and sulfates). A total of 276 ground rock samples from 12 wells in the Cerritos Colorados geothermal field were analyzed to identify specific mineral associations considering the abundance and stability of hydrothermal minerals as kaolinite, dickite, montmorillonite, illite, smectite, tridymite, epidote and chlorite. Minerals were identified by correlating absorption peaks and the shape of the spectral signatures of the samples with those from the database of the US Geological Survey (USGS) spectral digital library (Clark et al., 2008; Fig. 4).

The post-processing of data that helped define the parameters to characterize the reservoir included the analysis and comparison of spectra responses. As an example, the data obtained for well PR-5 are plotted according to depth and lithology (Fig. 5).

The results for the other wells that were studied are shown in Figures 7 and 8. These geologic cross sections were constructed using data from JICA (1989); their location is given in Figure 6.

3.1 Vertical Distribution of Mineral Alteration (Cross section X-X′)

The alteration mineralogy observed in the Cerritos Colorados geothermal field, supplemented with information from JICA (1989), allowed to identify five zones primarily along section X-X’. The section includes wells PR-2, PR-9, PR-1, PR-12, PR-8 and PR-5 and crosses the field from the NW to eastern portion of the field (Fig. 6). The alteration zones that could be identified are:

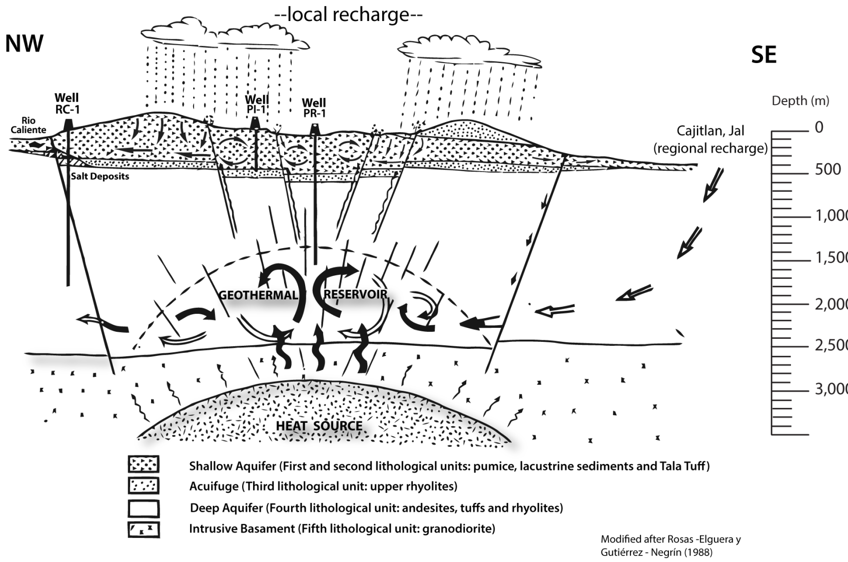

Figure 3. Conceptual hydrological model of the Cerritos Colorados geothermal field. (Modified after Rosas-Elguera and Gutiérrez-Negrín (1988).

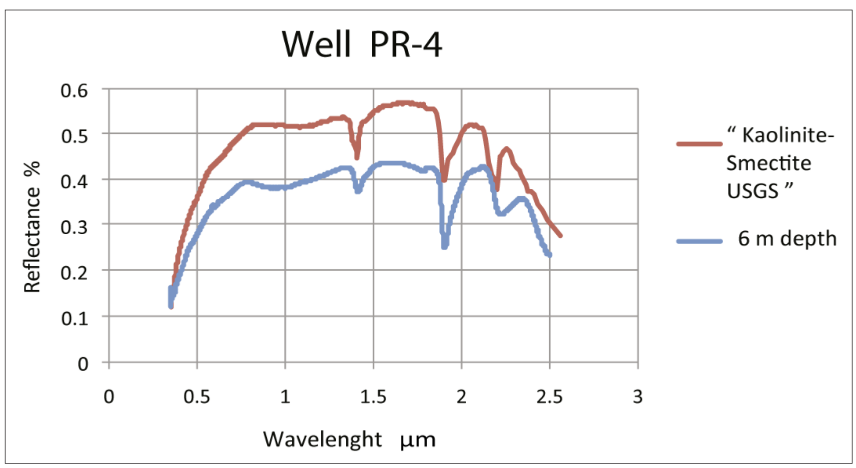

Figure 4. Comparison of spectral signatures. In blue is the spectrum for a sample from well PR-4 collected at 6 m depth; in red is the standard spectrum for a kaolinite-smectite mixture from the USGS library.

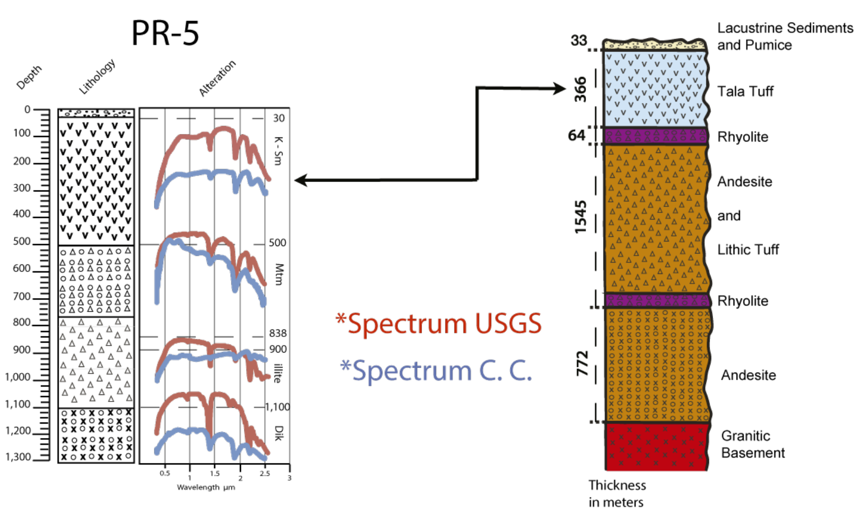

Figure 5. Right: Lithologic column of well PR-5; Left: Lithology and the spectral response of the analyzed samples plotted against depth. C.C.: Cerritos Colorados.

1) Argillic (Kaolinite-Smectite) Zone. – This mineral association, found mainly in rhyolites and lithic tuffs, is present in shallow (20-30 m depth) samples of practically all the wells drilled in the field, and also at less than 800 m in wells PR-1 and PR-2.

2) Argillic (Montmorillonite) Zone. – On average, this zone starts at approximately 800 m depth, close to the geologic contact between andesites and lithic tuffs. In well PR-12 montmorillonite is observed at shallow depth (between 530-700 m) and at 500-838 m in PR-5. This similarity may be due to PR-12 being located at the center of an uplifted area that creates fractures and possibly generates an upflow that communicates with well PR-5 via the Los Muertos and El Embalse faults. This suggests that subsurface hydrothermal thermal activity increases towards the southeast in the direction of PR-5 and into the La Primavera Caldera. The montmorillonite in these two wells (PR-12 and PR-5) is found in rhyolites, lithic tuffs and andesites.

3) Phyllic Zone. – Illite occurs in PR-2 and PR-9 at similar depths; i.e., at 1034 and 1000 m, respectively (Fig. 7), in the transition zone between lithic tuffs and andesites. In both of these wells illite is present at great depths. It was identified at 1914 m in well PR-2, and only in one PR-9 sample at 2590 m depth, in association with chlorite.

4) Propylitic Zone. – This zone predominated by chlorite and calcite, was identified below the phyllic association in wells PR-2, PR-9, PR-1, PR-12.

5) Advanced Argillic (Dickite and Alunite-Pyrophyllite) Zone. – This mineral association is found in PR-12, PR-8 and PR-5, wells located in the high-temperature area. These three wells and PR-1, allowed JICA (1989) identify the center of the resurgent caldera, which presents many fractures and faults that facilitate the rise of the geothermal fluid from the hottest parts of the reservoir. This upflow is inferred from the mineral associations observed in these wells, as the high temperature-low pH association (pyrophyllite alunite) occurs at 2010 m depth in PR-12. In well PR-5 dickite replaces pyrophyllite at 1100 m depth (Fig. 7). The stability range for these minerals indicates acid conditions (pH <4) with temperatures between 250° and 300° C and are the product of extreme hydrolysis, perhaps due the possible rise of magmatic fluids.

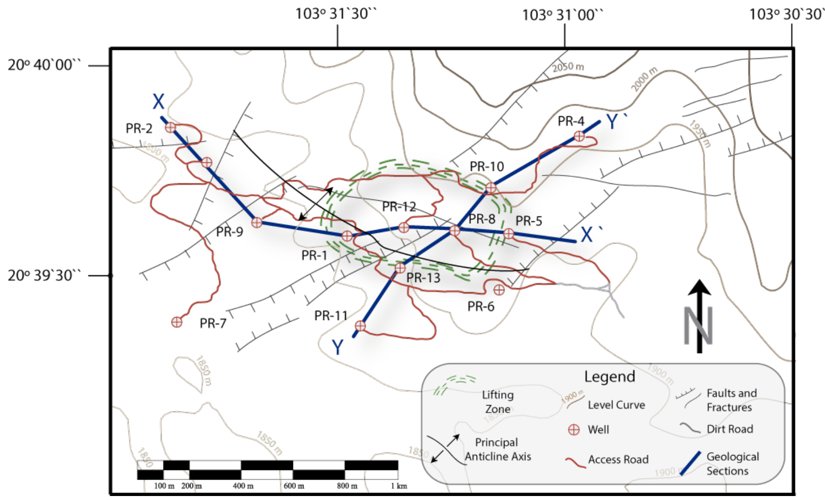

Figure 6. Location of sections X-X′ and Y-Y′, and wells in the Cerritos Colorados geothermal field., as well as some structural data.

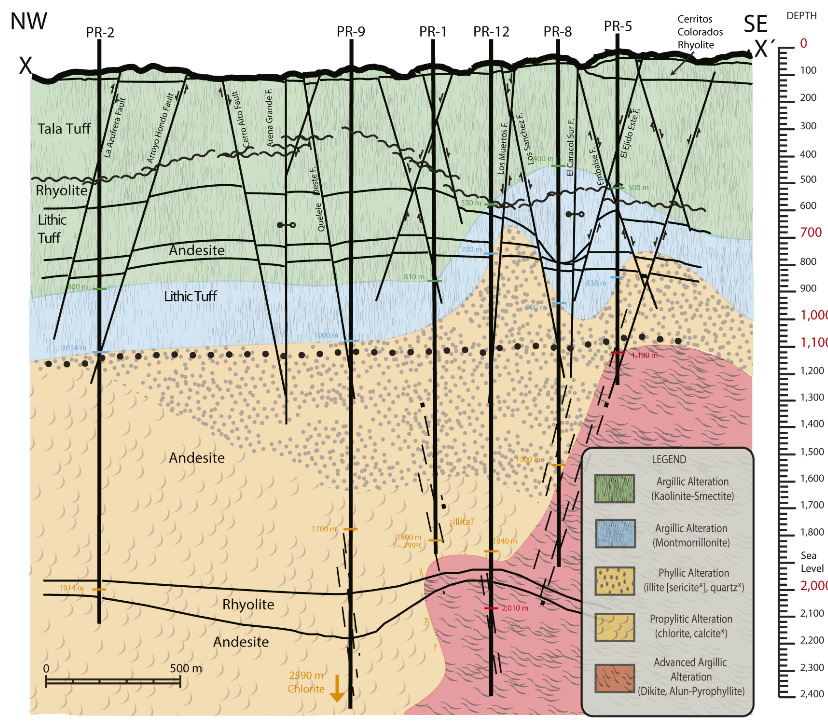

Figure 7. Vertical distribution of hydrothermal mineral associations along section X-X′. The presence of high-temperature argillic alteration at depth coincides with the central part of the La Primavera Caldera.

As shown in Fig. 7, in section X-X’ the argillic alteration represented by the association kaolinite-smectite, occurs at shallow depths, while montmorillonite predominates at greater depths. This type of alteration is characterized by the replacement of plagioclase and feldspars by clays in rhyolites and andesites. Phyllic and propylitic alterations occur between 900 and 1000 m depth. On average illite is present in greater proportion within this zone. At greater depths, the presence of advanced argillic alteration that grades from dickite-alunite to alunite-pyrophyllite, indicates acidic-high temperature conditions in the central part of the field.

3.2 Vertical Distribution of Mineral Alteration (Cross section Y-Y')

Section Y-Y' (Fig. 8) that includes wells PR-11, PR-13, PR-8, PR-10 and PR-4 crosses the field from the SW to the NE and intersects section X-X' at well PR-8 (Fig. 6). In this section the propylitic zone is missing; only the following four zones were identified as:

1) Argillic (Kaolinite-Smectite) Zone. – This zone is present in very shallow samples, the maximum depth recorded by spectroscopy was at 610 m in well PR-4 and at 510 m in PR-13. In most of the Cerritos Colorados wells the kaolinite-smectite association is found within the Tala Tuff. JICA (1989) indicates that the hot water produced by PR-4 by way of NE-SW fractures is gradually influenced by mixing with surface water. An analysis of fractures in well PR-13 reveals that circulation losses at less than 600 m depth corresponds to tensional fractures in Tala Tuff. This may explain the predominant kaolinite-smectite association at these depths within the rhyolites and lithic tuffs.

2) Argillic (Montmorillonite) Zone. – Montmorillonite was identified in PR-11 at 240 m depth almost at the contact between the Tala Tuff and the rhyolite. In well PR-13 this zone occurs deeper and is more abundant in lithic tuffs. In PR-10 the distribution of montmorillonite is similar to that in PR-8; it is found between 500 and 1100 m depth in rhyolites, andesites and partly in lithic tuffs.

3) Phyllic (Illite) Zone. – Along this cross section, illite is present at greater depths towards NE (Fig. 8). The shallowest samples with illite occur in PR-11 within the lithic tuffs, from 400 m to below 1850 m depth in andesites and rhyolites. Well PR-8 presents abundant illite from about 900 m to 1850 m where the temperatures reported by JICA (1989) are 231 ºC at 1750 m depth; PR-10 shows a similar illite distribution. In both wells illite is observed both in lithic tuffs and andesites.

4) Advanced Argillic (Alunite-Pyrophyllite) Zone. – In the Y-Y' section advanced argillic alteration is only observed in wells PR-8 and PR-10 at depths between 1810 m to 2200 m, but it probably extends deeper in the system. The stability range for pyrophyllite indicates temperatures above 250 °C and acid pH (Browne, 1984), this may indicate that both wells are located in the high-temperature upflow zone. The pyrophyllite-alunite association is limited to the andesites.

As shown in Fig 8, argillic alteration occurs in the SW portion of the Y-Y' section at and near the ground surface and deepens toward the NE. The distribution of phyllic and propylitic alterations was supplemented by data from JICA (1989). In addition, Hernández-Lombardini (1996) reported the presence of quartz, tridymite, calcite, epidote, chlorite, sericite, pyrite, hematite and chalcopyrite. Information on hydrothermal alteration and its distribution with depth in the geothermal field is given by Prol-Ledesma et al. (1999) and Alcala-Montiel (1999). All of these data were used to establish the location of the phyllic and propylitic alteration zones. Therefore, it is evident that this section Y-Y' has a low degree of hydrolysis in relation to that shown in section X-X'.

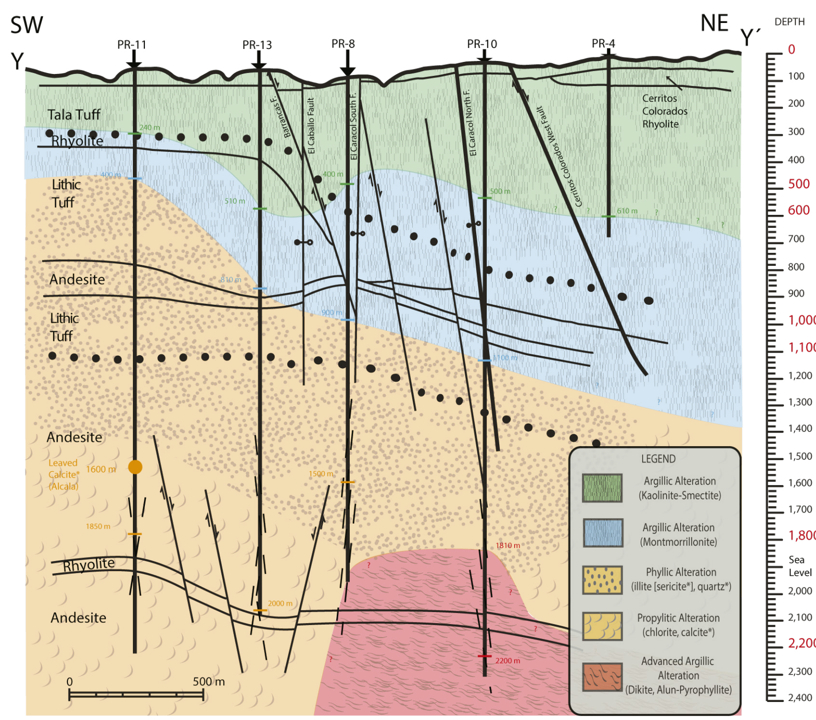

Figure 8. Vertical distribution of hydrothermal alteration in the Cerritos Colorados geothermal field along section Y-Y' (see Fig. 6).

4. Conclusions

The distribution of hydrothermal minerals in the Cerritos Colorados geothermal field has allowed identifying alteration associations that reflect the geological characteristics of the site and the hydrothermal processes that have occurred and still are occurring in the system.

Summarizing, the presence of kaolinite-smectite in section X-X' is limited to shallow depth levels. Except for well PR-12, montmorillonite is observed in association with kaolinite at intermediate depths, while in PR-8 and PR-5 it occurs at depths where the rock has intermediate composition (andesites). In wells PR-2 and PR-9, illite is present in rhyolites and andesites at depths greater than 1000 m, while in PR-1, PR- 12, PR-8 and PR-5 it is found at less than 1000 m.

Both cross sections (X-X' and Y-Y') were used as reference to study and classify the hydrothermal alteration in the geothermal field. Mineral assemblages defined predominant alteration zones, which reflect the nature of the fluids and their pH (either acid and/or neutral). The observed pattern corresponds to a typical grading with depth, from argillic to propylitic alteration. One important contribution of this study is that in the section X-X', an area of advanced argillic alteration was identified at depth, where the alunite-pyrophyllite association in wells PR-8 and PR- 10, may be indicating the presence of high temperature-acidic conditions.

The hydrothermal activity in the Cerritos Colorados geothermal field seems to be confined mainly to the central collapse area, which corresponds to the most important regional fracturing system having a predominant NW-SE direction which, together with the caldera events, contributed to create preferential hydrothermal fluid flow paths.

Acknowledgements

We thank the Gerencia de Proyectos Geotermoeléctricos of the Comisión Federal de Electricidad of Mexico for kindly providing us with samples and field data.

References

Alcalá-Montiel, E., 1999. Análisis geoestadistico de metales y elementos traza para determinar patrones de depositación en las rocas del campo geotérmico de La Primavera, México. Tesis, F. I. UNAM, 72 p.

Browne, P. R. L., 1984. Lectures on Geothermal Geology and Petrology: Islandia, National Energy Authority and United Nations University (UNU), Geothermal Training Programme, 93 p.

Gómez-Tuena, A., Orozco-Esquivel, M.T, and Ferrari, L., 2005. Petrogénesis ígnea de la Faja Volcánica Transmexicana. Boletín de la Sociedad Geológica Mexicana, Vol. LVII, No. 3, p 227-283.

Gutiérrez-Negrín, L.C.A., 1991. Recursos geotérmicos en La Primavera, Jalisco. Ciencia and Desarrollo. Vol. XVI, No. 96, p 57-69.

Hernández-Lombardini, S. I., 1996. Variaciones en la composición geoquímica de las rocas de La Primavera, Jalisco, como resultado de la alteración hidrotermal. Tesis, F. I. UNAM, México, 62 p.

JICA, 1989. Evaluación del yacimiento geotérmico en La Primavera. Internal report, 122 p.

Mahood, Gail A., 1981a. A summary of the Geology and Petrology of the Sierra La Primavera, Jalisco, México. Journal of Geophysical Research, Vol. 86, p 10137-10152.

Mahood, Gail A., 1981b. Chemical Evolution of a Pleistocene Rhyolitic Center: Sierra La Primavera, Jalisco, México. Contributions to Mineralogy and Petrology, Vol. 77, p 129-149.

Prol-Ledesma, R. M.; Lozano-Sta. Cruz, R.; Juárez-Sánchez, F.; Alcalá-Montiel, E.; Cruz-Casas, V.A.; Hernández-Lombardini, S.; Canals, A. and Cardellach, E., 1999. Precious and base metal deposition in an active hydrothermal system, La Primavera, México. Proceeding of the 9th International Symposium on Water-Rock Interaction, WRI-9, A.A. Balkema, Rotterdam, Taupo/New Zealand, p 649-652.