HYDROTHERMAL ALTERATION MINERALS IN LOS AZUFRES GEOTHERMAL FIELD, MICHOACAN, MEXICO

G. Izquierdo and V.M. Arellano

Instituto de Investigaciones Electricas. UR de Geotermia. Av Reforma 113. Col. Palmira, 64490
Temixco, Morelos. Mexico. e-mail gim@iie.org.mx

Abstract

X-ray powder diffraction, electron microprobe analyses and classical optical methods were used to identify hydrothermal minerals in Los Azufres geothermal field. The information obtained from individual wells was used to integrate a distribution map of alteration minerals. Observed patterns of alteration have been correlated with homogenization temperatures. According to their formation conditions, authigenic minerals in Los Azufres may define three thermal zones. The low thermal zone defined by: Amorphous silica + native sulphur + smectite + gypsum + alunite + kaolinite. The intermediate zone represented by: Calcite + wairakite + quartz + chlorite + anhydrite. The high temperature zone is represented by: Quartz + microcline + prehnite + epidote. A brief description of main characteristics of the most common hydrothermal minerals is presented below.

1.0 INTRODUCTION

The Los Azufres geothermal field (LAGF) presently is the second geothermal resource within the Republic of Mexico. The first well was drilled by the Comision Federal de Electricidad (CFE) of Mexico in 1976. Since then, 62 wells ranging in depth between 600 to 3544 m (A44) have been drilled in an area of almost 40 km^2.
Most of the wells are located along and between two well defined mnes of steam discharges. These are the Maritaro zone (close to the Maritaro Fault, F.M.) in the north; is characterized by water-steam mixture wells and the Tejamaniles zone (between the Tejamaniles and Agua Fria Faults, F.A.F.) in the south with dry-steam wells (Figure 1)

The exploitation of energy in the LAGF started en 1982 when a 5 MW wellhead generator unit was installed (Alonso-Espinoza, 1985). At present the field has a total installed capacity of 90 MW. The LAGF has given an excellent opportunity to perform a variety of scientific studies through its exploration, development and exploitation stages. Mineralogical and fluid inclusion studies were camed out in order to establish the distribution of hydrothermal mineral zones and thermal profiles in different sections of the field (Cathelineau et al., 1985 and Cathelineau et al., 1989). Phyllosilicates formed as products of hydrothermal alteration in active geothermal areas are of great interest, since their Occurrence is related to the temperature their formation. Previous studies of Phyllosilicates at LAGF have focussed on their dependence on temperature and rock composition (Izquierdo and Cathelineau, 1987), their characterization (Izquierdo, 1989) and their application as geothermometers (Cathelineau and Nieva, 1985; Cathelineau and Izquierdo, 1988).

2.0 STUDY AREA

The Los Azufres Geothermal Field is located in The Sierra de San Andres in the Michoacan State of Mexico. It is in the geological province known as Mexican Volcanic Belt (see inset in Figure 2). The geology of the LAGF has been described by several authors (Camacho, 1979; Gutierrez and Aumento, 1981; Dobson and Mahood, 1985 among others). The lithologic successions consists of an andesitic basement overlain by rhyolitic and dacitic domes and flows, and a volcano-sedimentary sequence with interlayered ashes and pumices (Fig. 2). Thus, most rocks at depth are andesites with a thin cover of rhyolites mostly in the range 0-500 m depth in the central part of the field. Although they have been encountered in some wells down to 1 km (well A23). These rocks belong to the calkalkaline series of the Mexican Volcanic Belt.

Based on their chemical composition the reservoir waters in Los Azufres have been classified as alkali-chloride and sodium waters. The widespread occurrence of calcite in most of the deep altered rocks is a good indicator of the occurrence of neutral to alkaline thermal waters at depth in Los Azufres geothermal area.

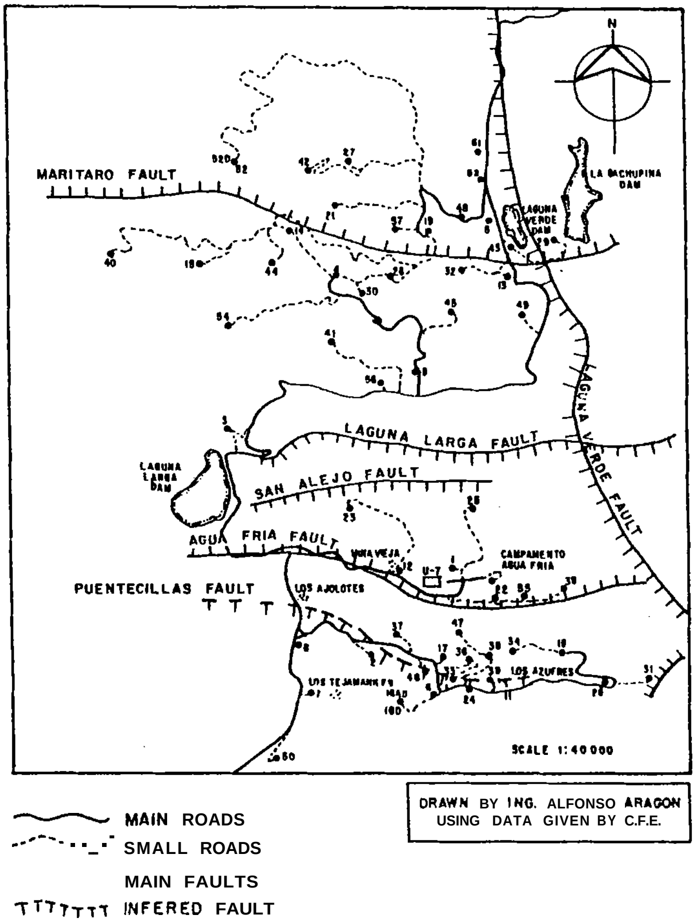

Figure 1. Well location in the Los Azufres geothermal field.

3.0 EXPERIMENTAL TECHNIQUES

3.1 X-ray diffraction

Selected fragments of well defined minerals such as zeolites, anhydrite, prehnite and clay minerals where identified by X-ray diffraction using the powder method. Al samples were analyzed in a Siemens D500 diffractometer with Ni-filtered Copper radiation.

3.1.1 Clay minerals determination

The phyllosilicates present in the clay fraction of the cuttings, were characterized by X-ray diffraction at every 50 to 100 m intervals, depending on availability.

In order to eliminate contaminant drilling mud, cuttings were carefully washed with distilled water. Clay minerals were separated mechanically in an ultrasonic bath and by repeated sedimentation. Oriented preparations were produced by pipetting the clay slurry onto glass slides. Samples were saturated in an ethylene glycol atmosphere at *60°C.* All samples were analyzed in the air dried and saturated forms. To ensure clay identification some samples were heated et 350° and 500°C. After each treatment, the samples were X-rayed. Estimation of the relative percentages of each clay mineral was made by measuring the linear **peak** height intensity of the I„ of the phyllosilicates present in the clay fraction.

3.2 Microthermometry of fluid inclusions

CFE provided cuttings obtained during the drilling of the well. Fluid inclusions were analyzed systematically in authigenic transparent minerals which were separated manually under a binocular microscope. The tiny fragments were, **as** much **as** possible, doubly polished. **When** cores were available thick polished sections were prepared. Fluid inclusions were studied mainly in authigenic quartz, using a Chaix-Meca heating-cooling stage. The stage was calibrated for temperatures higher than 25°C **using** the melting point of organic **standards** and for temperatures below 0°C with natural **and** synthetic fluid inclusions. As the fluid trapped in authigenic minerals at Los Azufres is a diluted, gas-poor water only two parameters were determined for each fluid inclusion: the melting temperature of ice (T_{mi}) and the bulk homogenization temperature (T_h). One important characteristic of most fluid inclusions in Los Azufres is that they are very small and therefore it is frequently difficult to observe the T_{mi}.

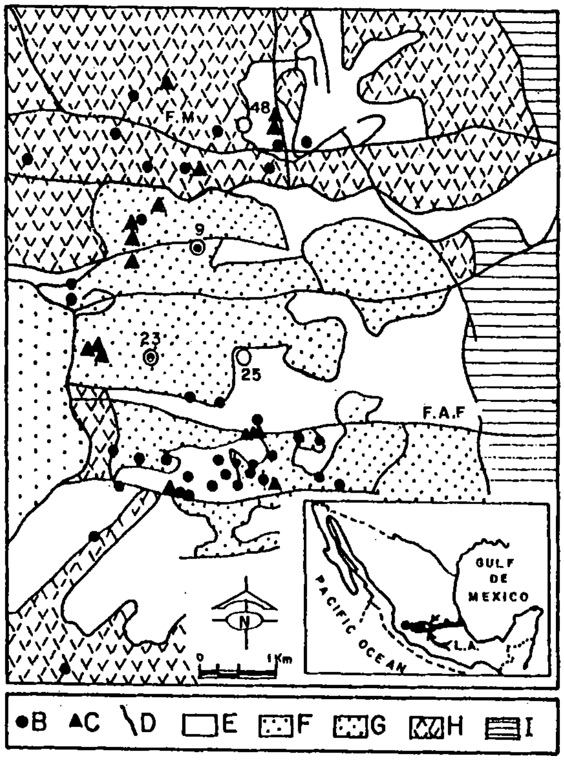

Figure 2. Simplified geological map of the Los Azufres Geothermal Field. It shows the locations of wells A23 and A9. The inset depicts the Mexican Volcanic Belt, where the study area is located. The symbols **correspond to:** Drilled well (B), surface emission (C), major fault (D), tuffs (E), vitreous rhyolite, flow rhyolite (G), andesite (H) and dacite (I).

3.3 Scanning electron microscope and electron microprobe.

To characterize the morphology and chemical composition of **some** authigenic minerals, scanning electron microscopy **(SEM)** and simultaneous energy - dispersive elemental X-ray (EDX) analyses were camed out on freshly fractured samples using a Cambridge stereoscan 250 microscope coupled to a PGT system III ED spectrometer.

Thin polished sections were prepared from cores and cuttings in order to characterize mineral assemblages and to obtain quantitative chemical analysis of specific minerals. Analysis were carried out on an automatic electron microprobe Camebax at the University of Nancy (France)

4.0 HYDROTHERMAL MINERALS IN LOS AZUFRES

A brief description of main features of most common hydrothermal minerals in Los Azufres is presented below.

Calcite is widespread at intermediary levels and disappears after certain depth (around 1800 m), yielding a flat circumscribed zone of appearance. It forms xenoblastic to subidioblastic crystals, dispersed in the matrix or in small vugs, but also can fill up veins accompanied by anhydrite, chlorite, wairakite, and less often by epidote.

Anhydrite is abundant, and appears generally as automorphic crystals, as ultimate mineral to crystallize in vugs (epidote cavities, A3-2300 for instance) in veins (accompanied by calcite and anhydrite A3-1242) or in the clayed matrix (A12-700).

Quartz is a very common authigenic mineral. It ,crystallizes in veins, vugs and fissures. It occurs as xenoblastic to idioblastic crystals up to 2 mm. It is mainly encountered in the two defined discharge columns of the field. It is present in almost all wells and at all depths.

Epidote-clinozoisite solid solutions are generally very abundant in deeper levels. They form small prismatic crystals, sometimes aciculares forming radiating aggregates. Colours are pale to intense yellow-green. Usually are encountered in association to calcite, wairakite and chlorite; to quartz and chlorite at deeper levels and sporadically to amphibole, prehnite or garnet. Epidotes in Los Azufres as in other geothermal fields show large chemical variations.

Diopside is encountered occasionally and is difficult to determine because of the small size of the crystals. It has been found accompanying amphiboles and epidote.

Chlorite. Apart from smectite and quartz, chlorite is a major component of the hydrothermal mineralogy. It is present in almost all the wells at the deepest levels. It is present as little intergranular patches in the upper levels, with increasing temperature it crystallizes in a variety of automorphic shapes (radial aggregates, booklets) . Chlorite is the main alteration of Fe-Mg minerals (pyroxenes), but it is also encountered in veinlets and vugs in association to epidote, wairakite, calcite and anhydrite.
Regular variations of two parameters indicators of solid solution have been related to temperature.

Clay minerals are the most common hydrothermal minerals in bore holes and cuttings from Los Azufres geothermal field. They have been identified mostly by X-ray diffraction of the clay fraction of a large number of samples from different wells.

Kaolinite. It is restricted to the shallower levels were acidic rock composition (rhyolites) and acid waters are encountered. Usually kaolinite is found with little amounts of smectite, alunite, native sulphur and gypsum. In the clay fraction the relative proportion of kaolinite is inverse to the relative amount of smectite. A kaolinitic deposit under exploitation is near to well A23, were the largest extension of the rhyolitic dome is located.

Smectite. It is by far the most abundant mineral from shallow levels up to 1000 m depth. Whatever their depth of sampling, their X-ray diffraction pattern exhibits very little changes. Usually the glycolated samples show a very similar pattern for pure smectite as it has been reported by Reynolds (in Brindley and Brown, 1980). The most probable variety of smectite occurring in LAGF is montmorillonite. According to its d_{001} it has been assigned, under dry condition, as Na-smectite (d_{001} between 12 and 13 Å) and as Ca-smectite (between 14.5 and 15.5 Å). Na-smectite is the most widespread specie From shallow levels to deep levels. Ca-smectite is less common and usually it is found at depth.

Mixed layer minerals. They are relatively rare compared to the abundance of other clay minerals. These minerals correspond mainly to interstratification of illite and smectite. Very occasionally chlorite/smectite was encountered. Estimation of the amount of the expandable phase in the mixed layer minerals was carried out by comparing real d-spacing values against theoretical data by Reynolds and Hower (1970).

Illite. In rhyolites illite becomes the main clay mineral formed by the effects of hydrothermal alteration. For example in well A23, which crosses the thick pile of rhyolites, illite constitutes more than 90% of the clay fraction and it is accompanied by small amounts of smectites (depending on the temperature).
Well A23 is a good example to show the rock composition dependence of clay minerals formation. From surface to 1200 m illite is the main component of the clay fraction. As the change from rhyolites to andesites occurs, chlorite appears and is the dominant phase as temperature and depth increase.

Zeolites are not very abundant in Los Azufres. They have been found filling vugs and fractures. Large crystals of mordenite clinoptilolite have been found in the core sample of the well A42 at a depth of 305 m. Radial white crystals of laumontite were separated from cuttings of well AR50-1384m

Wairakite occurs commonly in vugs and veinlets at different depths. For example in well A27A wairakite has been found at 200, 620, 980 and 1940 m. In other wells it is limited at deep levels. It appears as xenomorphic crystals as filling vugs with calcite-epidotechlorite. Often with anhydrite and calcite as euhedral shape with isometric symmetry (truncated cubes). Common features, such as those described by Steiner (1977) in Wairakei are observed sets of twin lamellae, low birefringence (never equal to zero) and vague twinning cleavage.
Chemical data for wairakites from Los Azufres do not show considerable compositional variation. Compared to wairakites, from other geothermal fields, percentages of Na and Ca are rather low. Its composition is close to the stoichiometric wairakite $CaAl_2Si_4O_{12}.2H_2O$. Chemical data are comparable to data from Steiner (1977) and others.

Prehnite. It is not very abundant in Los Azufres, it has been encountered in various wells for example A27A-980. Chemical analysis show it is almost a pure stoichiometry in contrast to the large compositional variation observed in Cerro Prieto.

Fe-Ti phases

Primary ilmenite and magnetite are not stable in the altered zones, they have been replaced by pyrite and titanite below very shallow levels

Titanite forms authomorphic crystals, in some cases associated to authigenic albite in shallow levels (200 to 900 m deep).
Anatase is the most widespread Ti-mineral and dispersed as numerous tiny xenomorphic shapes.

Pyrite is abundant in shallow and intermediate levels. It has been found in association to kaolinite, ,calcite, illite and quartz. It disappears below 1000 m depth and reappears together to other sulphides at great depth (chalcopyrite, for instance).

Hematite is widespread in the altered rocks, it is in equilibrium with epidote. In accordance with observations in other fields the amount of hematite decreases at deeper levels.

5.0 CONCLUSIONS

Hydrothermal alteration in the Los Azufres geothermal field is mainly controlled by temperature, permeability, fluid composition and host rock crystallinity and composition.
Most of the hydrothermal minerals in LAGF precipitated from hydrothermal fluids in open spaces such as vesicles and fractures.

In most of the drilled wells the amount and intensity of alteration generally increase as a function of depth and temperature. The distribution zones of some of the alteration minerals follow quite closely the distribution of isotherms in the field.
Three thermal zones in Los Azufres have been defined:
Below 150 °C, the low thermal zone defined by: Amorphous silica + native sulphur + smectite + gypsum + alunite + kaolinite.
The intermediate zone, between 150 and 260 "C, is represented by: Calcite + wairakite + quartz + chlorite + anhydrite
And the high temperature zone, above 260 "C, is represented by: Quartz + microcline + prehnite + epidote

Finally, hydrothermal minerals distribution has been used to provided a picture of the general geometry of the field. According to Cathelineau et al., 1983, there appears to be a main aquifer at depth, which discharges through two main circulation zones (Tejamaniles and Maritaro).

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