COMPARISON BETWEEN TWO CONTRASTING GEOTHERMAL FIELDS IN MEXICO: LOS AZUFRES AND LOS HUMEROS

J. César Viggiano-Guerra and Luis C.A. Gutiérrez-Negrín

Comisión Federal de Electricidad
Alejandro Volta 655. Morelia, Mich. C.P. 58290, Mexico.

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ABSTRACT

A comparison between the Los Azufres and the Los Humeros geothermal fields in the Mexican Volcanic Belt (MVB) is made. The Los Azufres geothermal field is located ut the center of the MVB, und is a typical boiling system lying entirely within Pliocene and Quaternary volcanics. This field has been subdivided in two zones, namely: North and South. At the center of the field lies a rhyolitic dome which permits fluid to discharge in thew two directions. Thus the fluid mows-up from the aquitard, which contains only compressed liquid, to the producer aquifer, where it flashes in situ to constitute a two phase zone, and later, above the level of alkali chloride water, steam segregates in pockets to discharge as fumaroles and hot springs. In some places the steam condenses to produce intense alteration wirh kaolinite and residual silica. On the dher hand. the Los Humeros geothermal field is located ut the Eastern side of the MVB. Its lithology is more complex, being grouped into four units including hornblende and augite andesites, basalts, ignimbrites. limestones, granirir rocks, marbles, hornfels and diabases. Thus although this system is also a high relief one, its hydrology is quire different from Los Azufres. Here fluid of variable composition, moves-up from the aquitard {local basement) to the aquifer (Unit III) to constitute a narrow compressed liquid zone, with temperatures near to critical, bur steam does not separate in-situ Its superficial discharge is rhus very low.

INTRODUCTION

The Los Azufres and the Los Humeros geothermal fields are both situated in the Mexican Volcanic Belt (MVH). The former is located almost in its center and the latter in the eastern border of the belt (Figure 1). The MVB is a volcanic chain with many central edifices and calderas of Plio-Quaternary calc-alkaline activity. apparently originated by the subduction of the Cocos Plate beneath the North-American one.

In spite of both fields having a number of features in common, they present many distinct characteristics. This paper focuses on a practical comparison of conceptual models of both fields, based mainly on petrologic studies and on direct evidence derived from reservoir engineering.

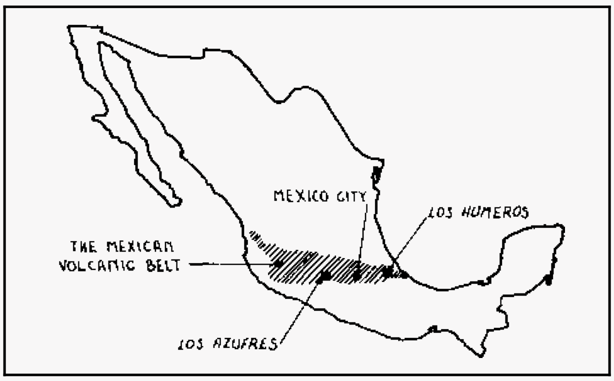

Figure 1.- Location of Los Azufres rind Los Humeros.

THE LOS AZUFRES GEOTHERMAL FIELD

This field has an installed capacity of 98 MWe with 12 generating units. It is a typical boiling system (of high relief) lying entirely within Pliocenic and Quaternary volcanics (López, 1991). Since exploration began the field was subdivided into two zones, North and South, based upon a geological basis. This has hydrological implications, because at the center of the field lies a Quaternary rhyolitic dome which permits fluid to discharge in those two directions This results in two upflows with a common feed zone (Viggiano, 1987). The common feed zone is hosted by Quaternary and Tertiary andesires which underly, *sensu lato*, the rhyolitic dome. These andesitic rocks are practically homogeneous in terms of their lithology and hydrological behavior.

Superficial Hydrothermal Activity

An area of about 8 km^2 of outcropping Quaternary rhyolites and in minor proportion of Quaternary dacites and andesites have been intensely altered, as a consequence of the discharging fluids. Hydrothermal manifestations art: represents d hy hot springs, some with temperatures up to 90°C --especially through faults where the fluid surpasses the vadose zone--, fumaroles, steaming soil, mud pools and even small thermal lakes. The thermal features are mostly located along faults or lineations suggesting a fracture control.

The hydrothermal minerals ohscrved are kaolinite predominantly + pyrite + smectite ± tridymite + alunite ± alunogen ± smectite (Izquierdo, 1994). This alteration is being produced by acid (pH ≈ 1-2) sulfate steam heated waters derived from boiling chloride fluid. The ascending steam carries H_2S and other gases fractionated from the hotter liquid (Hedenquist et *al.*, 1992). The water table is located, according to pressure logs, at about 400 m depth although it varies (Figure 2).

Subsurface Hydrothermal Activity

Underground hydrothermal activity can be divided into two types: acid sulfate (near surface) and alkali chloride, below the water table.

Hydrothermal minerals here are: kaolinite ± chlorite/smectite + pyrite + silica + anhydrite They have the same origin as those found on the surface. Separation of steam from the boiling alkali chloride water provides steam to some shallow wells in the Southern Zone,

It is very difficult to locate the isotherms at the boundary between the vadose zone and the water table, but it is between 150 and 200°C (Figure 2). There is no a indicator mineral of such a change. However, the shallowest occurrence of hydrothermal calcite can be regarded as that index, hy assuming that this mineral was formed hy boiling of a two-phase hut liquid dominated fluid. Furthermore, this mineral is at some places ohscrved ahnve the

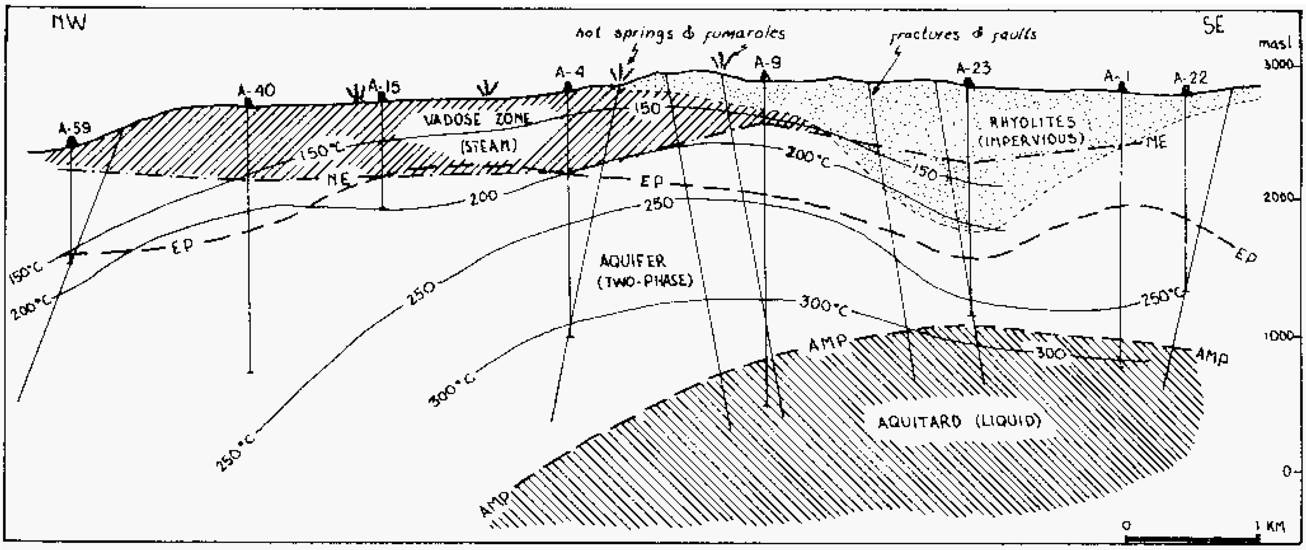

Figure 2. *- NW-SE section in the Los Azufres geothermal field*

NE: Static level, EP: First appearance of epidote, AMP: First appearance of amphibole.

present water table, meaning its surface has fluctuated (maybe because of strong uplift).

Alkali chloride activity, on the other hand, is generated, beneath the alkali chloride water table. The prograde metamorphism of the original magmatic phases gives way to calc-silicate minerals and clays as well as either CO_2-rich or H_2S-rich minerals. The distribution of calc-silicate alteration zones is as follows:

Zeolite zone.- It is located in a transitional zone between the vadose or steam dominated zone and the alkali chloride surface. Minerals are: the first appearance of calcite ± anhydrite + pyrite + smectite + chlorite + quartz (chalcedony) and zeolites (heulandite and laumontite). It is also common to see kaolinite as a proof of the changes in the level of the water table. The zeolite zone is found below 400 m depth on average Measured temperature ranges between 150 and *250°C* (Figure 2) and pressure is less than 60 bars. The rock density is 2.40 g/cm^3 and the rock porosity is 12.7% on average.

Epidote zone.- Is composed by epidote + wairakite + chlorite (penninite) + quartz + illite/smectite + illite + calcite + pyrite ± prehnite. It is located between 400 and 2000 m depth (Figure 2). *This* zone is the most important because it constitutes the producing aquifer, with temperatures that range between 250 and 285°C. The measured fluid pressure ranges between 50 and 170 bars and the rocks have a density of 2.40 to 2.45 g/cm^3 and a porosity of 9.0% on average. Fluid raises from the deeper aquitard to this zone.

Amphibole zone.. This zone is featured by the first occurrence of hydrothermal amphibole but also observed arc the following minerals: epidote ± wairakite + biotite ± illite ± chlorite ± garnet ± diopside. In some places it is possible to verify the disappearance of calcite (calcite-out). This zone is located below 2200 m depth with remperatures up tu 285°C (Figure 2) and pressures over 170 bars. Because the porosity is less than 3%, the anhydrous minerals appear and the thermal regime is forced convective or even conductive. The conspicuous disappearance of calcite means, on the other hand, that boiling is not prominent. Furthermore, no well penetrating this zone is producing. For these reasons, it is assumed that this zone is an aquitard with alternating regimes from conductive to convective or viceversa And the must imponant is that it channels fluid to the aquifer.

As seen above, the petrophysical properties (porosity and density among others) reflect the influence of water/rock interaction and the increasing temperature and pressure. On the other hand, the theoretical P-T stability fields (see for instance Bird *et al.*, 1983) agree well in general with those measured in-situ. Exceptions are in zones were self-sealing has occurred, especially in the Northern Zone.

THE LOS HUMEROS GEOTHERMAL FIELD

This field is now producing 35 MWe hy 7 back-pressure units. It is located 280 Km east of Mexico City and lies in the eastern sector of MVB (Figure 1). 33 wells have been drilled in a volcanic caldera known as the Los Potreros Caldera which is located within the Los Humeros Caldera. Inside of Los Potreros Caldera are located two circular structures also important: the so called Central Collapse and the phreatic crater named Xalapazco Mastaloya. Both are intersected by the northwest striking Los Humeros normal fault, which together with another NW regional structure (only inferred in the basement and without superficial trace) are the most important structures.

Subsurface rocks drilled by the wells fall into four lithological units as follows (see Figure 3, above): Unit I, which is formed mainly by augite andesite interbedded with basalts and some tuffs, of post-calderic events (less than 0.5 My in age); basalrs are more abundant in the uppermost parts. Unit II is constituted of lithic and vitreous ignimbrites (0.5 My in age) that contain fragments of andesite, basalts and, in much minor amounts. limestones, hornfels and intrusive rocks; the ignimbrites were produced by calderic events. Unit III is featured by augite andesites in the upper part and hornblende andesites in the lower one; these andesites were erupted by pre-calderic Miocenic to Pliocenic events. Unit IV is the basement, which is formed by Cretaceous limestones that were in some sites metamorphosed to marble and hornfels. Granitic post-Cretaceous intrusions that produced the metamorphism are also observed within this unit, and much less frequently diahascs were detected.

Superficial Hydrothermal Activity

An area of about 3 km^2 has been altered to mainly kaolinite and residual silica This alteration is observed around the well H-4, at the Central Collapse. Thermal features associated with the alteration are scarce steaming soils or else ephemeral fumaroles Ry the way, the word "humeros" means smoky because of the large amount of visible steam which is conspicuous due to the weather which is wet and cold.

The above mentioned alteration must have originated from an acid (pH ≈ 3) sulfate steam heated waters derived from a boiling chloride fluid ascending from deeper parts. This is even more likely because the field is about 1000 m above the surrounding Perote

Valley, in which the water table is at shallow depths (about 10 meters).

Subsurface Hydrothermal Activity

Deposition of newly-formed minerals occurs mainly in Unit III, indicating that water/rock interaction has been more intense there. Conduits related to deposition arc regional faults, fractures and microfractures, including lateral permeability features such as contacts. unconformities, etc. Units I and II have also been altered but, due to their lower permeability, their intensity of alteration is low and, therefore, they act as relatively impervious rocks.

Lack of permeability in Unit II (ignimbrites) does nut allow the formation of a vadose zone. although it perhaps was present at former time, as the presence of kaolinite and residual silica on the surface seems to indicate. In fact, both minerals form in a vadose zone. so Unit II could have lost its permeability due to sealing. Anyway. this lack of present permeability in Unit II has allowed the formation of a "cold" aquifer in Unit I, which has been confirmed by recent shallow boreholes. This "cold" aquifer contains meteoric water heated by conductive heat from Unit II.

Of course, the presently impermeable rocks ot Unit II also act as an efficient cap-rock for the deeper reservoir in Unit III.

Hydrothermal minerals in the underground rocks have been produced by alkali chloride water and gave rise to a calc-silicate mineral zoning together with H_2S-rich and CO_2-rich minerals (Viggiano y Robles. 1988a). This zoning is as follows (Figure 3, below):

Zeolite zone.- This has temperatures from SO to 150°C. It includes zeolites other than wairakite, + hematite + calcite + pyrite + chlorites and quartz. This mineralogy affects the andesites, basalts, air-fall tuffs and ignimbrites.

Epidote zone.- This zone affects essentially the Tertiary andesites of Unit III. It has been divided into: *Epidote* sub-zone, with temperatures from 150 to 200°C and the presence of hematite + calcite + pyrite + rutile + titanite + clays + chlorites + quartz and epidote (there are also relics of amphiboles and garnet); and *Epidota-wairakite* sub-zone, with temperatures from 200 to 300°C and: hematite + calcite + anhydrite + pyrite + rutile + titanite + clays + chlorites + quartz + epidote + wairakite and prehnite. The epidote sub-zone is associated with low permeability, while the epidote-wairakite one is in the production zone of the reservoir in Unit III.

Amphibole zone.- This zone displays temperatures of 300°C or even higher. It is characterized by an assemblage of pyrite + chlorites + quartz + epidote + prehnite + amphiboles + potassium-mica + biotite + garnet + diopside and wollastonite (these three last minerals have been identified also as primary

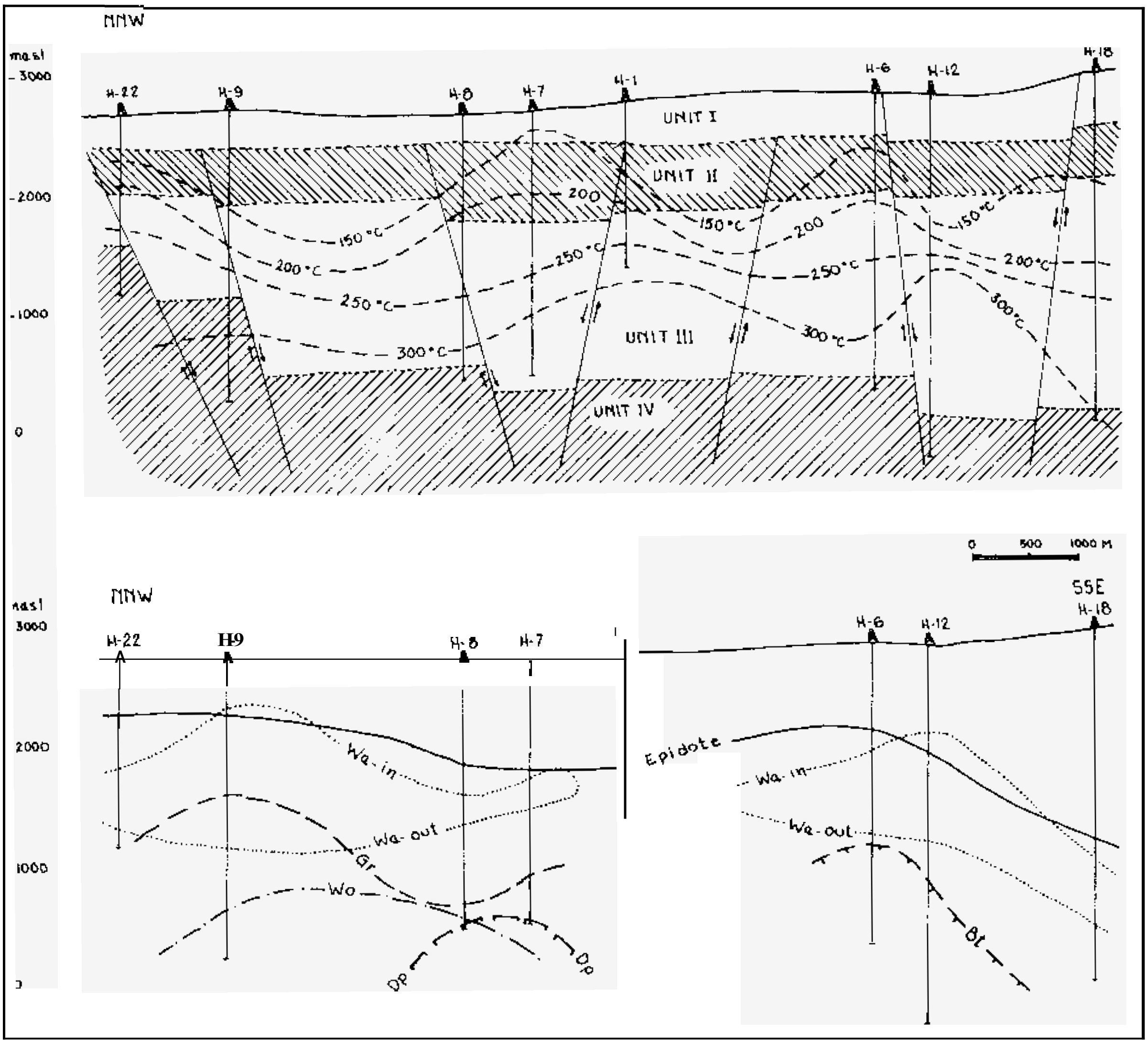

***Figure 3**.- NNW-SSE sections in the Los Humeros geothermal field.*
Above: Lithological units, faults and isotherms.
Below: Hydrothermal mineralogy. Lines mark the first appearance of: biotite (Bt), diopside (Dp), garnet (Gr), wairakite (Wa) and wollastonite (Wo).

minerals in the metamorphic rocks of the basement). The amphibole zone affects the lower parts of the Tertiary andesites in Unit III and some portions of the basement rocks.

Clay minerals have been above mentioned in general, but X-Ray studies by Prol and Browne (1987) determined that montmorillonite, interlayered illite-montmorillonite and illite occur in the reservoir, at progressively increasing temperatures.

Three zones where fluids rise can be recognized; these seem to be related to intrusions into the basement and probably control the mineral chemistry One of them appears to he the most important and is linked to the Central Collapse, another is in the Xalapazco Maztaloya, while the third perhaps feeds wells H-8 and H-9 (see Figure 3). In this later case, intrusions have not been identified at drilled depths, hornfels being the underlying rocks in both wells (Viggiano y Robles. 1988b).

The above mentioned lithological units act as successive aquifers and aquitards, which allow the commercial exploitation of the reservoir. Therefore, Unit I is a "cool" aquifer, Unit II is an aquitard, Unit III contains the producing aquifer, and Unit IV is also an aquitard but acts as the feed zone.

Corrosion and Scaling

Severe problems of corrosion and scaling (calcite and some silica) occur in wells located at the Central Collapse area in the Los Humeros geothermal field (Gutiérrez and Viggiano. 1990). The wells showing this troublesome situation are H-11, H-15, H-16, H-17, H-29, and H-30. Most agree that pH decreases strongly at depth. which is confirmed by the mineral assemblage found in the subsurface (Viggiano, in progress).

Some wells were deviated to produce from a shallower aquifer (around 1500 meters depth), which presumably should have a higher pH, and be less likely to cause scaling or corrosion In fact, production conditions in those deviated wells are improving regarding both pH and scaling rate. but the production rates and temperatures are lesser than before deviation.

By assuming that scaling in wells of the Central Collapse seems to be a consequence of mixing of shallow and deep fluids in the same well, it would be necessary to isolate the shallower production zone, which apparently produces less fluid. Production would then just from the deeper zone. Thus scaling could be avoided with probably little loss of production, as has been suggested (Gutiérrez and Viggiano, 1990).

CONCLUSIONS

In Table 1 are presented several comparative parameters of the fields dealt herein. Some sources of the information are already mentioned, the rest being unpublished data and files of the Comisión Federal de Electricidad (CFE).

There seems to be a direct relationship between the altered surface of the field and the volume of the reservoir: the larger the altered area. the higher the production of the system. The relative lithological homogeneity of tucks in Los Azufres results in a less complicated field, which is without must problems found in Ins Humeros In contrast, the heterogeneity of rocks in the Los Humeros field does not allow the fluid to separate easily and the conceptual model is more complicated. Scaling and corrosion problems occur in some of its wells. but not at Los Azufres

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Table 1.- Comparative parameters for both fields

FEATURE	LOS AZUFRES	LOS HUMEROS
INSTALLED CAPACITY	98 MW	35 MW
MINIMUM VOLCANIC AGE	140 X 10³ YEARS	40 X 10³ YEARS
CLASSIFICATION	HIGH RELIEF	HIGH RELIEF
RELATED-STRUCTURE AND VOLCANIC SETTING	CENTRAL. STYLE. CALC ALKALINE	CALDERA, CALC-ALKALINE
ALTERED SURFACE AREA	8 km²	3 km²
VOLUME OF RESERVOIR	4.55 km³	1.9 km³
SUBSURFACE LITHOLOGY	RHYOLITES AND ANDESITES	ANDESITES, BASALTS, TUFFS. IGNIMBRITES. LIMESTONES. GRANITIC ROCKS, MARBLES. HORNFELS AND DIABASES
PRODUCING ZONE	ANDESITES	ANDESITES AND, LESS COMMONLY THE BASEMENT
INDEX MINERALS	EPIDOTE. WAIRAKITE. CALCITE. PYRITE	EPIDOTE, WAIRAKITE. CALCITE PYRITE
MAXIMUM MEASURED TEMPERATURE	358°C (A-47)	400°C (IN UNIT IV)
POROSITY IN THE PRODUCING ZONE	ϕ = 9% (LOW STANDARD DEVIATION)	ϕ = 12.27% (HIGH STANDARD DEVIATION)
PRODUCTION CHARACTERISTICS	STEAM IN THE VADOSE ZONE STEAM DUE TO FLASHING DURING WELL OPENING	STEAM DUE TO FLASHING DURING WELL OPENING STEAM (UP TO CRITICAL POINT)
PROBLEMS	NONE	CORROSION AND SCALING IN THE CENTRAL COLLAPSE AREA
REMARKS	GOOD LIQUID SEPARATION	NO VADOSE OR VAPOR DOMINATED ZONE

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