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# DEVELOPMENTS IN GEOTHERMAL ENERGY IN MEXICO—PART FOUR: EVALUATION OF GEOTHERMAL RESOURCES. MULTIDISCIPLINARY STUDIES OF THE LOS AZUFRES FIELD, MEXICO

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**Abstract**—The effective utilization of geothermal energy is dependent on a knowledge of the total amount and character of the heat available in a particular geothermal field. The development of a conceptual model of a hydrothermal resource is essential for estimating its value and the proper mode of exploitation. This paper describes results of studies leading to the construction of a model for the Los Azufres (Mexico) hydrothermal system. The geometry of the system is found to correspond to a dome-shaped structure, distorted by two columnar zones of natural fluid discharge, which give rise to two areas of surface manifestations. A vertical progression is observed, from a hot liquid phase at depth to an intermediate two-phase liquid-dominated zone, and then to a relatively shallow two-phase vapour-dominated zone.

## INTRODUCTION

The effective utilization of geothermal energy is dependent on a knowledge of the total amount and character of the heat available in a particular geothermal field. It is specially important to be able to estimate the spacial distribution of the vapour to liquid mass, and of their respective enthalpies, within the system.

Of several types of geothermal resources [1], hydrothermal reservoirs are the only ones which are being currently exploited for the production of electricity. A hydrothermal reservoir is a geological system consisting of a volume of rock, permeated by water and heated by a relatively shallow magma intrusion. Both the heat and the fluid sources are essential features of this type of system, which is usually bounded laterally, and on the top by zones of low vertical permeability. This zone is sometimes referred to as the 'cap zone'.

The early evaluation of a hydrothermal resource selected for exploitation constitutes a formidable problem, given the intrinsic complexity of this type of system. However, critical financial decisions based on the value of the resource must be made, particularly during the initial stages of development. Therefore, it is extremely important to obtain a conceptual model of the system as early as possible, and to complement and modify it as new evidence becomes available. In order to allow the estimation of the stored thermal energy, the model must define the general features of the geometry of the system, as well as the distribution of temperatures and heat capacity per unit mass of the host rock. Likewise, in order to estimate the mass of the stored fluid, the distribution of rock porosity and the specific volume of the fluid must be known. The initial model should also incorporate evidence from the chemical and isotopic characterization of fluids produced by the geothermal wells, in order to probe the hydrological structure of the reservoir and detect possible processes of mixture of more than one fluid, which in turn would indicate the existence of more than one area of recharge.

In order to estimate the fraction of the energy which can be extracted from the system, and the optimal rate of extraction, subsequent versions of the conceptual model should provide additional information, such as the distribution of fracture and matrix permeabilities, the storativity ratio (ratio of available fracture vs pore volumes), and non-condensable gas concentrations. With such a model, it would be possible to do numerical simulations of heat and mass transport, matching historical data of production and of reservoir pressure drawdown, thus obtaining estimates of fluid recharge into the system, and predicting its behaviour under selected modes of exploitation.

The present contribution describes the advance made in the characterization of the Los Azufres hydrothermal reservoir, through the collaboration between the Instituto de Investigaciones Eléctricas (IIE) and the Comisión Federal de Electricidad of Mexico (CFE). The Los Azufres geothermal field is in the high part of the mountain range of the same name. The mountains reach elevations of more than 3,200 meters above sea level (m.a.s.l.). The elevations of the wellheads vary between approximately 2,750 and a little more than 3,200 m.a.s.l. The neighbouring valleys are several hundred meters below the average elevation of the field. Two well-defined zones of steam discharge can be distinguished: Maritaro in the north and Tejamaniles in the south. The discharge zones are separated by several kilometers of terrain with essentially no surface manifestations (Fig. 1). The primary subsurface geology, as well as initial studies of hydrothermal mineralogy have been reported elsewhere [2].

The following section describes results obtained through the application of geochemical, mineralogical and reservoir engineering techniques, and the integration of these results in a conceptual model of the Los Azufres hydrothermal system.

## RESULTS AND DISCUSSION

### *Mineralogical and geochemical studies*

The first phase of a detailed study of the mineralogy of hydrothermal alteration in samples of drill cores and cuttings from Los Azufres has been completed. The results of this study were reported in the literature [3], and the principal conclusions were as follows.

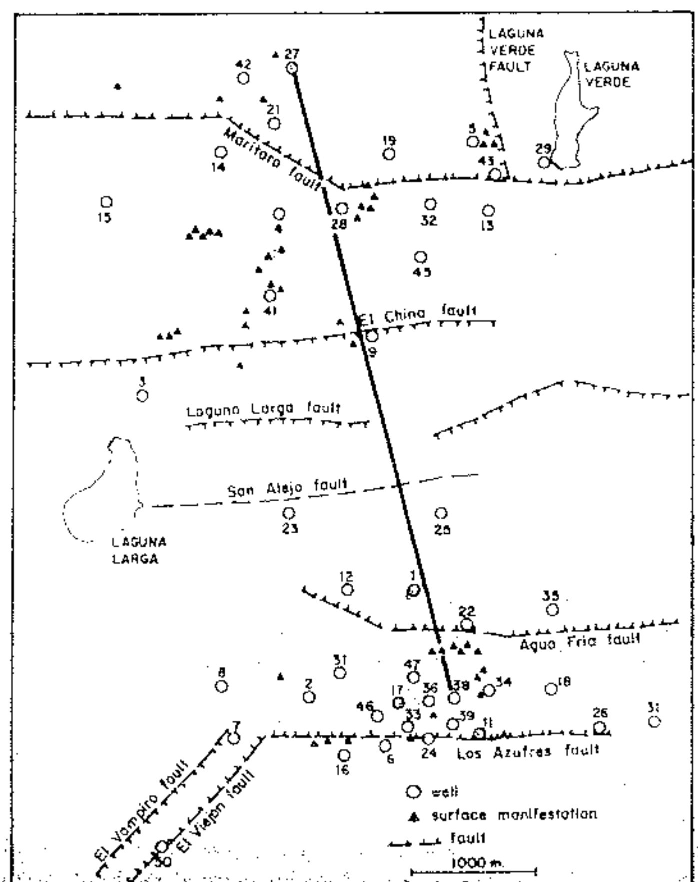


Fig. 1. Map of Los Azufres geothermal field, showing the main geological faults, and the location of geothermal wells and surface manifestations.

The absence of evidence of retrograde metamorphism indicates that the Los Azufres reservoir is a young hydrothermal system in the heating stage. A rather regular sequence of mineral associations was observed, with increasing temperature and depth. The information obtained from each of the wells studied was integrated into a three-dimensional distribution map of minerals hydrothermal alteration. This map allows the definition of the general features of the geometry of the reservoir. Figure 2 shows the distribution of a number of alteration minerals in a northeast–southeast transverse cross section, corresponding to the line marked in Fig. 1. Profiles of temperature and primary mineralogy are also shown. The geometrical form of the distribution of minerals reflects the superposition of two factors. One of these is the effect of the high local thermal gradient, which produces a distribution with the form of a dome. The second factor, which tends to distort this dome structure, is the effect of hydrothermal alteration produced by the ascending fluids in the two principal zones of circulation and discharge. This circulation zones produce the two areas of thermal manifestations observable at the surface (Maritaro in the north and Tejamaniles in the south). The continuity of the distribution of some alteration minerals, such as chlorite and epidote, indicates the existence of a single aquifer at depth.

Horizontal cuts at different depths [3], show that the southern circulation zone consists of a well-defined columnar structure, with aureoles of hydrothermal alteration which decreases with increasing distance from a quasi-vertical axis. The circulation zone observable in the north has a greater average diameter. The available information was insufficient to define the horizontal extent of the alteration associated with the zone, specially in the north and southeast directions. Figure 3 is a schematic diagram of the reservoir.

A study was done based on a compilation of chemical, isotopic, and production parameter data from the Los Azufres wells, with the purpose of defining the condition of the fluid in the reservoir [4]. It was found that most of the wells are fed a mixture of liquid and steam, which implies a two-phase state of the fluid in the reservoir. This observation was extended and quantified by other

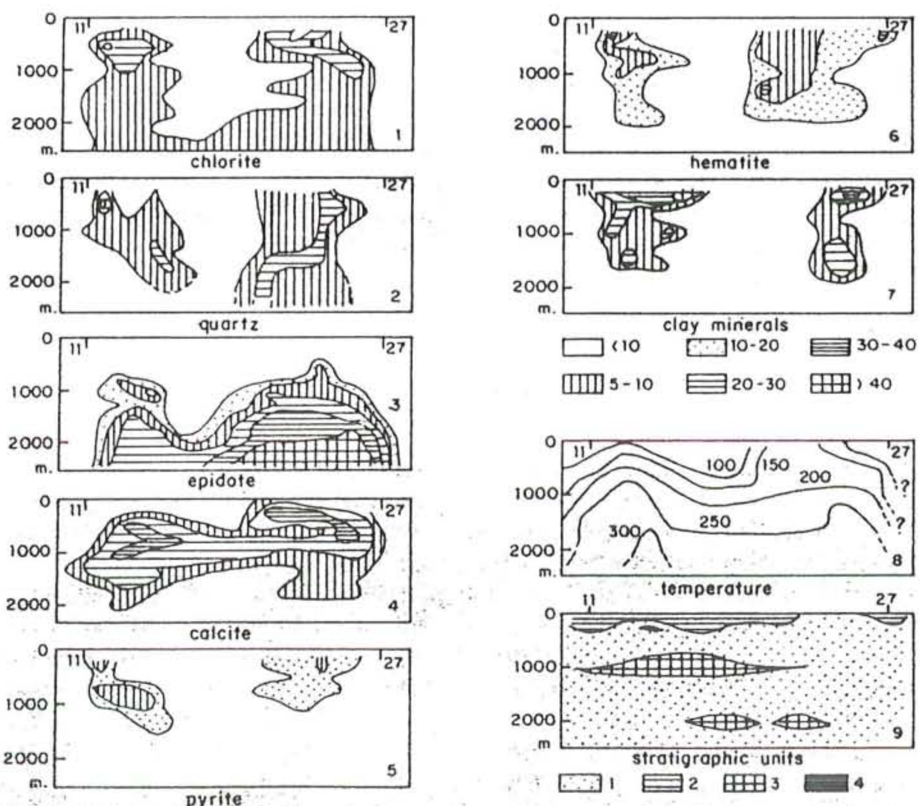


Fig. 2. Cross-section along the line joining well A-11 with well A-27, showing the distribution of hydrothermal minerals (segments 1 to 7), temperature (segment 8) and stratigraphic units (segment 9). Numbers assigned to stratigraphic units are as follows: (1) microlithic andesite; (2) rhyolites and ignimbritic tuffs; (3) porphyroblastic andesite and (4) dacite. After Cathelineau *et al.* [3].

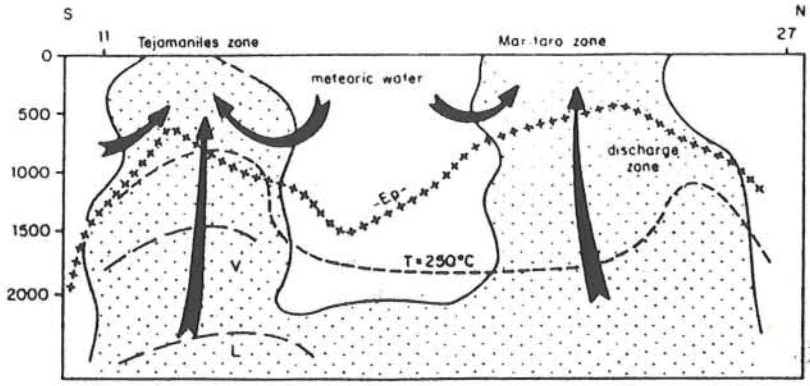


Fig. 3. Schematic representation of the main area of hydrothermal alteration (dotted area) in the cross-section corresponding to Fig. 5. Arrows show the pattern of fluid circulation. The broken line represents the 250°C isotherm and the crossed line follows the level of first appearance of epidote. Dashed lines show the location of hypothetical boundaries of the two-phase (labeled V) zone, above single-phase liquid (labeled 1) zone, in the Tejamaniles section. After Cathelineau et al. [3].

means [5, 6]; see below. The existence of two phases in the reservoir complicates enormously the interpretation of the composition of the well discharges, since it becomes necessary to calculate the distribution of chemical and isotopic species among the two phases. A process was implemented for calculating the chemical and isotopic composition of the liquid phase in the reservoir, and revealed an appreciable heterogeneity in the composition. Recent calculations using more precise measurements of specific enthalpy, and assuming that these values prevailed at the time when the samples for isotopic analysis were gathered, show less but still appreciable heterogeneity in the liquid phase [7]. This heterogeneity implies the ocurrence of a process of mixing among at least two isotopically different waters. The isotopic compositions of fluids produced by steam wells A-17 and A-6 correspond to steam separated from liquid phase with compositions that are included in the calculated distribution. The great temporal variability in the isotopic composition of the fluid from well A-6 indicates the possibility that this well is fed from more than one zone of the reservoir.

*Petrophysical properties*

The properties of the reservoir host rocks are of great importance for characterizing and evaluating the reservoir. These properties were studied at IIE by means of two different but complementary techniques: several physical properties of interest were measured in the laboratory and well tests were analyzed in order to deduce important properties of the reservoir rocks. The laboratory determinations were made on drilling cores extracted from 4 wells of Los Azufres. Density, permeability, compressibility, thermal conductivity, thermal diffusivity, and specific heat [8] were measured. All the samples studied turned out to be andesites with different types of textures, colours, mineralogical content, and degrees of hydrothermal alteration. The densities and porosities measured varied from 2260 to 2740 $kgm^{-3}$ and from 1 to 17.8%, reflecting the wide range of hydrothermal alteration depicted by the samples. Not that the upper end of the porosity values is comparable to the values typically found in geothermal reservoirs of sedimentary type, such as Cerro Prieto. This is somewhat surprising, given the extrusion origin of the rocks studied, and it illustrates the powerful effect of hydrothermal alteration.

Compressibility was measured at 25°C and at 250°C, between 70 and 400 bar. In these temperature and pressure ranges, the volumetric coefficient of compressibility varied between $8.7 \times 10^{-6}$ and $2.22 \times 10^{-5}\ bar^{-1}$. The observed range of variation is attributed mostly to the different degrees of hydrothermal alteration of the samples.

The thermal properties mentioned below were measured in a single specimen, the one that showed the greatest degree of hydrothermal alteration among the samples studied. The measurements were made on a dry sample subjected to a confining pressure of 80 bar. The thermal conductivity was measured at 25, 150, and 250°C, varying in this range from 1.97 to 1.75 $Wm^{-1}K^{-1}$. The thermal diffusivity at 250°C was equal to $0.66 \times 10^{-6}\ m^2s^{-1}$. The heat capacity per unit mass of the same sample was 1.16 $kJkg^{-1}K^{-1}$. The measured values are reasonable when compared with the values published in the specialized literature.

Permeability was measured in the laboratory by means of a gas permeameter. The results were corrected for the Klinkenberg effect [9] and represent absolute permeability. The measurements were made at ambient conditions. The measured values vary from less than $1.9 \times 10^{-18}$ to $1.8 \times 10^{-16}\,m^2$, with the exception of one sample which, due to the existence of a microfracture in the direction of the flow, showed a permeability of $2.2 \times 10^{-15}\,m^2$. It is interesting to note that these low permeabilities of the rock matrix are representative even of the samples that were the most altered hydrothermically, (those with porosities of up to nearly 18%).

As for the pressure tests, we present here results from 6 tests in 4 wells [10]. Obviously, this relatively small amount of information cannot warrant that the present results are representative of the whole reservoir. The analyses were made according to the technique of Bourdet and Gringarten [11] for reservoirs, with double-porosity behaviour. The derived fracture permeabilities range from $1 \times 10^{-15}$ to $2.5 \times 10^{-14}\,m^2$, and those of the matrix between $3 \times 10^{-18}$ and $5 \times 10^{-15}\,m^2$. These results are consistent with those obtained in the laboratory when it is considered that the matrix permeabilities deduced from the pressure tests are subjected to considerable uncertainty, due to poorly known porosities and block shape parameters. The storativity ratio (the parameter that describes the ratio between the storativity of the fracture system and the storativity of the rock matrix) inferred from these tests is consistently about 0.01. This indicates that this small fraction is insignificant for fluid reserve estimates. The results of the pressure tests also indicate that the reservoir presents a clear double-porosity behaviour (as suggested by the geologic and drilling data), that the fluid reserves are almost exclusively in the pores of the matrix rock, and that the fluids are conducted to the wells almost exclusively through the fracture system.

*One-dimensional vertical model*

A considerable amount of data corresponding to 25 wells was analyzed in order to determine the undisturbed thermodynamic state of the fluid of the reservoir [5]. As a by-product of this effort a relatively simple method for determining the undisturbed enthalpies from data routinely obtained in deliverability tests was developed [6]. The results of the analysis were assembled in a one-dimensional vertical model of the undisturbed reservoir fluid [5]. This model shows that in the reservoir there is a deep (below 1,200 m.a.s.l.), hot (enthalpy of the deep brine equal to $1317 \pm 103\,kJkg^{-1}$), and extensive aquifer, covering an area of about $30\,km^2$. These conclusions are supported by results independently obtained by other authors, from geochemical data [12] and mineralogical data [3]. The existence of this aquifer may prove important for the commercial success of this geothermal resource.

The model shows that there is no significant recharge of the reservoir from the surface of the field. This is consistent with conclusions derived from isotopic studies of local fluids [13]. The abundant local rainfall (about $1400\,mm\,yr^{-1}$), the existence of several lakes at the surface of the field, and the existence of shallow cold perched aquifers of meteoric origin in the field, together with the lack of significant recharge from the surface, strongly suggest the existence of a caprock over most of the reservoir surface. This caprock should be significantly fractured in the geothermal steam discharge zones (Maritaro and Tejamaniles).

Los Azufres is a hydrothermal system that is unusually interesting in the sense that the transition between a water-dominated zone and a steam-dominated zone is observable. The model shows the existence of a deep compressed liquid that ascendes until about 1,200 m.a.s.l. where it starts boiling. This conclusion, based exclusively on pressure and enthalpy data, is reinforced by the mineralogical–petrographic model of Cathelineau *et al.* [3], which shows that calcite appears only above a level corresponding to about 1,200 m.a.s.l., it is well known that the redistribution of carbonates on the liquid phase upon phase separation leads to precipitation of calcite (calcium carbonate). The subsequent two-phase water-dominated region extends vertically to about 1,700 m.a.s.l., where saturated steam becomes the pressure controlling phase. The steam-dominated two-phase region extends upwards until, at about 2,500 m.a.s.l., a region of dry or superheated steam, that presumably flows to the surface in the natural discharge zones (Maritaro and Tejamaniles) takes over. The characteristics just described are illustrated schematically in Fig. 4.

The wide variation in the thermodynamic conditions of the fluid in the reservoir in turn causes a peculiar variation among the chemical compositions of the different wells. In particular, there are differences of nearly two orders of magnitude in the content of non-condensable gases in the

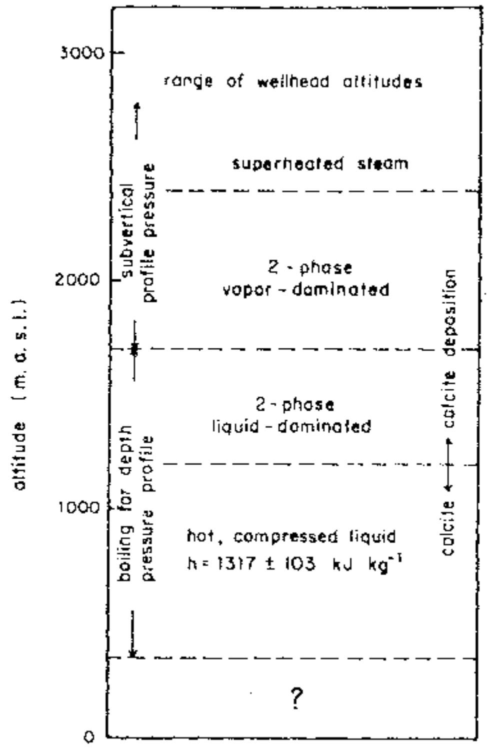


Fig. 4. Schematic cross-sectional diagram of one of the discharge zones of the reservoir.

total discharge. This variability originates from the fact that the fluid entering a wellbore has a composition which does not necessarily correspond to that of the steam/liquid mixture prevailing in the undisturbed reservoir. The mixture flowing towards the entrance to the wellbore may be enriched or partially depleted of the steam phase, and thus of volatile components. A method was recently developed for estimating the fraction of excess steam in the fluid feeding a geothermal well [14]. The calculated fraction does not correspond to the total amount of steam, but to the fraction that is constituted by the inflow of steam in equilibrium from the reservoir. The procedure was modified to make it applicable to cases of high excess of steam, and its application to Los Azufres indicates a correlation between the variability of gas content and a corresponding variability of excess steam in the fluids feeding different wells [15].

Finally, from the vertical model it can be concluded that the so-called 'steam dome' is actually a two-phase fluid zone dominated by high-quantity steam. This result implies that the reserves of fluid in this zone are somewhat larger than expected if there were only steam in this zone of the reservoir.

The one-dimensional vertical model of Iglesias *et al.* [5] also suggested some speculations which, if confirmed by new studies, would yield important knowledge for the characterization of the reservoir. These speculations indicate that Los Azufres is probably a young hydrothermal system (about 30,000 yr old) that is in approximately steady state. The speculations are based on a comparison of the results of the one dimensional model with predictions of the natural evolution of a geothermal reservoir by Pruess and Truesdell [16], and in the work of Cathelineau *et al.* [3] who found that the hydrothermal alteration in the Los Azufres reservoir corresponds to that of a young system subject to prograde metamorphism. An important practical consequence of these speculations is that it would be possible to estimate the natural recharge of the system from the natural discharge.

The information obtained from this work is important for several activities related to the use of this geothermal resource, including drilling, assessment of reserves, development, and refining of mathematical models of the reservoir.

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## REFERENCES


1. R. DiPippo, Geothermal energy as a source of electricity: a worldwide survey of the design and operation of geothermal power plants, U.S. Department of Energy, Report: DOE/RA/28320-1 (1980).
2. A. Gutiérrez-Negrin and F. Aumento, The Los Azufres (Michoacán, Mexico) geothermal field, *J. Hydrol.* **56**, 137–162 (1982).
3. M. Cathelineau, R. Oliver, D. Nieva and A. Garfias, Mineralogy and distribution of hydrothermal mineral zones in Los Azufres (Mexico) geothermal field, *Geothermics* **14**, 49–57. (1985).
4. D. Nieva, L. Quijano, A. Garfias, R. M. Barragán and F. Laredo, Heterogeneity of the liquid phase and vapor separation in Los Azufres (Mexico) geothermal field, *Proc. Ninth Workshop on Geothermal Reservoir Engineering*, Stanford University, pp. 253–260 (1983).
5. E. Iglesias, V. Arellano, A. Garfias, C. Miranda and A. Aragón, A one-dimensional vertical model of the Los Azufres, Mexico, geothermal reservoir in its natural state, *Geothermal Resources Council Trans.* **9** (in press) (1985).
6. E. Iglesias, V. Arellano, A. Garfias, C. Miranda and A. Aragón, The natural thermodynamic state of the fluids in the Los Azufres geothermal reservoir, *Proc. Tenth Workshop on Geothermal Reservoir Engineering*, Stanford University, pp. 241–246 (1985).
7. L. Quijano, Personal communication (1985).
8. E. Contreras, E. Iglesias and R. Oliver, Determinación de propiedades fisicas y estudios petrográficos de núcleos de perforación del campo geotérmico de Los Azufres, Instituto de Investigaciones Electricas, Cuernavaca, Report: IIE/11/3753/I 01/F, (1984).
9. L. J. Klinkerberg, The permeability of porous media, *Drilling and Production Practices*, American Petroleum Institute (1941).
10. E. Iglesias and V. Arellano, Segundo informe de avance del proyecto: apoyo en ingenieria de yacimientos para el campo geotermico de Los Azufres, Instituto de Investigaciones Electricas, Cuernavaca, Report: IIE/11/1864/I 02/P, (1984).
11. A. Bourdet and C. Gringarten, Determination of fissure volume and block size in fractured reservoirs by type-curve analysis, *Proc. Fifty-fifth Ann. Technical Conf. Soc. Petroleum Engineers of AIME*, Dallas, Texas (1980).
12. C. Rodriguez, F. J. Villa and L. Quijano, Modelo geoquimico del campo geotérmico de Los Azufres, Michoacán, Comisión Federal de Electricidad Mexico, Gerencia de Proyectos Geotermoeléctricos, Report: 10–84 (1984).
13. W. F. Giggenbach and L. Quijano, Estudio isotópico de las aguas del campo geotérmico de Los Azufres, Comisión Federal de Electricidad Mexico, Gerencia de Proyectos Geotermoeléctricos, Internal Report (1980).
14. W. F. Giggenbach, Geothermal gas equilibria. *Geochim. Cosmochim. Acta* **44**, 2021–2032 (1980).
15. D. Nieva, J. González and A. Garfias, Evidence of two extreme flow regimes operating in the production zones of different wells from Los Azufres, *Proc. Tenth Workshop on Geothermal Reservoir Engineering*, Stanford University, pp. 233–240 (1985).
16. K. Pruess and A. H. Truesdell, A numerical simulation of the natural evolution of vapor-dominated hydrothermal system, *Proc. Sixth Workshop on Geothermal Reservoir Engineering*, Stanford University, pp. 194–203 (1980).