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Geothermal Energy Potential of a Promissory Area in the Central and Eastern Zones of Sonora, Mexico: A Preliminary Geochemical Study

Erika Almirudis, Mirna Guevara, Edgar Santoyo, Ignacio S. Torres-Alvarado+, Francisco Paz-Moreno

Instituto de Energías Renovables, UNAM, Priv. Xochicalco s/n, Temixco, Morelos, 62580, Mexico

erale@ier.unam.mx; mygg@ier.unam.mx; esg@ier.unam.mx

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ABSTRACT

Geothermal energy is an important renewable energy resource in Mexico, and the evaluation of the energy potential of promising geothermal systems has been defined as an important task for defining the future energy portfolio of the country. For achieving such general goal, a preliminary geochemical study for the evaluation of promissory geothermal zones located in the Central and Eastern of Sonora was carried out. Evidence of previous geological and geochemical exploration studies on the Northwestern zone of Mexico have delimitated some promissory low-to-medium temperature geothermal areas, and suggest that these systems are related to the pull-apart basin dynamics of the Gulf of California hydrothermal systems. The present study was specifically focused to characterize the origin of thermal fluids sampled in the Central and Eastern zone of Sonora, to identify water-rock interaction processes, and to develop a preliminary geochemical model. A field survey was carried out for collecting representative geothermal fluid samples. Chemical analysis of major and minor components in these samples indicated the presence of calcium bicarbonate waters in the Central zone, whereas sulphate-sodium waters were typified for the eastern part. Deep equilibrium temperatures were calculated using new and improved solute geothermometers, and the estimated mean temperature was 150°C. A preliminary geochemical modeling of water-rock interaction processes was also performed using the chemical composition of thermal springs at the expected temperature. Mineral assemblages involving minerals such as muscovite, clinochlore, laumontite, prehnite, kaolinite, and albite were found to be in equilibrium with the geothermal fluids. A deep fluid circulation with the presence of a hydrothermal system characterized by low-to-medium temperatures (T<200°C) seems to dominate in this geothermal system. However, a more detailed study requires to be conducted in the future for a better understanding and characterization of these geothermal resources.

1. INTRODUCTION

The scientific and technological research is currently in continuous development for exploration and exploitation of renewable energy resources. Mexico is currently the fifth largest producer of electricity from world geothermal resources with an effective installed capacity of 850 MW (Flores-Armenta, 2013). A large portion of the Mexican territory is privileged with the presence of volcanic and tectonic activity that has contributed to the forming of hydrothermal systems. There are four high-temperature geothermal fields currently under exploitation: Cerro Prieto (CP) in Baja California; Los Azúfres (LA) in Michoacán; Los Humeros (LH) in Puebla; and Las Tres Vírgenes (LTV) in Baja California Sur, with effective installed capacities of 570 MWe, 191.6 MWe, 78.4 MWe and 10 MWe, respectively. An additional site, the Cerritos Colorados project has an evaluated potential of 75 MWe (Santoyo & Torres-Alvarado, 2010). The situation of low-to-medium temperature resources (T<200ºC) in Mexico is quite different, being the installed capacity of ~156 MWt in 2010 (Gutierrez-Negrín et al., 2010). The primary use of these resources is related with balneology, and for electricity generation purposes, these sources have not yet presented a significant development in the last decade, despite that low- to-medium temperature resources are more abundant than the high-temperature geothermal systems (Iglesias, 2003). The evaluation of the energy potential of these geothermal systems acquires a particular relevance, and therefore, the geological, geochemical and geophysical prospecting studies are crucial to characterize either Low-Temperature Hydrothermal Systems (LTHS) or Enhanced Geothermal Systems (EGS). Thus, the exploration and exploitation of these geothermal systems could multiply the energy potential of the geothermal resources in Mexico.

According to previous geothermal exploration campaigns carried out in the Sonora state (located in Northwestern Mexico): Figure 1, 154 hydrothermal manifestations with mean temperatures ranging between 28 and 88ºC have been reported (Verdugo-Mariscal, 1983; Iglesias et al., 2011). These thermal manifestations, along with the Quaternary and recent volcanism (Paz-Moreno et al., 2003), the relative geographical proximity with the CP and LTV geothermal fields, and the active tectonics of the Gulf of California (Prol-Ledesma & Canet, 2004), identify to Sonora state as an attractive region with a promissory geothermal potential. The geochemical characterization of the Sonora hydrothermal systems is therefore a new contribution to the updating map of geothermal resources of Mexico. The present work has the objective of proposing a preliminary geochemical model based on the chemistry of geothermal fluids, and the thermodynamic concepts governing the chemical equilibrium of the fluid-rock interaction processes existing at shallow thermal manifestations of central and eastern Sonora.

2. STUDY AREA, THERMAL SPRINGS AND LITHOLOGY

The study area is located approximately 50 km in straight line to the East of Hermosillo city (the state capital), in the mountain portion of the Central Sonora (see Figure 1), where 12 localities were identified with geothermal activity in association with thermal springs. The study area was divided in four zones, the NE zone contains the most ancient rocks corresponding to a detritus-carbonated sedimentary sequence from the Lower-Cretaceous, consisting mainly of arenites, orthoquartzites, and limestones with fragile and ductile deformation and with early metamorphism evidenced by marmol and tourmaline eyes. The sequence has been correlated with the El Aliso and Agua Salada Formations of Aptian age (González-León, 1988), which are cut by volcanic rocks from the Upper Cretaceous. These volcanic rocks are composed of andesites, rhyolitic tuffs, and traquites, correlated with the Tarahumara Formation (Wilson & Rocha, 1946).

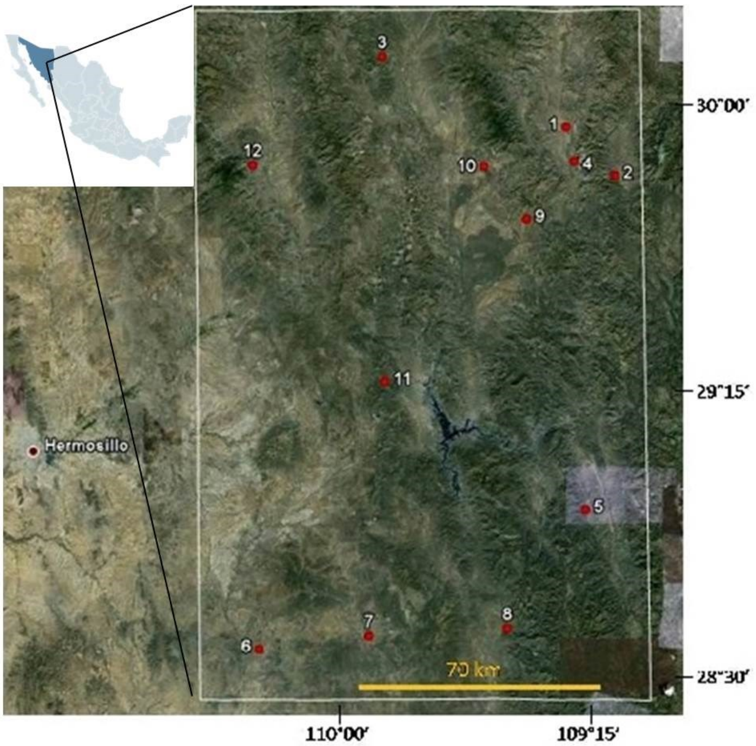

Figure 1: Geographic map showing the location of 12 geothermal hot springs. Northwest zone (NW): Aconchi (ACH, 12) and Cumpas (CMP, 3); Northeast zone (NE): Tonibabi (TNB, 10), Huasabas (HSB, 1), Divisaderos (DVS, 9), Granados (GRN, 4), and Bacadehuachi (BCD, 2); Center zone (C): Matape (MTP, 11) and Arivechi (ARV, 5); and South zone (S): San Marcial (SMR, 6), Tecoripa (TCP, 7) and Tonichi (TCH, 8).

Both sedimentary and volcanic sequences are intruded by a series of plutonic rocks, from granodiorites to granites (Roldán-Quintana, 1994) and, to the south of the NE zone, by small mafic outcrops altered by low temperature hydrothermalism with presence of tourmaline and actinolite (Almirudis, 2010). These igneous bodies are in turn cut by a microdiorite stock, and mafic to lamprophyre dikes of NW-SE preferential orientation of presumably Tertiary age (Almirudis, 2010). Upon these dikes Tertiary rocks are found: acid tuffs, rhyolites, and ignimbrites, correlated with the Upper Volcanic Complex (Cochemé, 1985). The basins are filled by alluvium and sediments from the Baucarit Formation, and particularly the Moctezuma valley by the basalts forming the Moctezuma Quaternary field. The remaining three zones from the study area (NW, C and S zones) present a similar lithology to the NE zone, particularly in the sequences from the Cretaceous to recent, without the presence of the Quaternary volcanism. Furthermore, some of their outcrops correspond to more ancient rocks composed mainly by carbonated sedimentary rocks (limestones and dolomites) and arenites.

4. WORK METHODOLOGY

4.1 Fluid sampling and analytical methods

The work methodology was divided in three major stages: (i) the geological reconnaissance and locating of the thermal manifestations; (ii) the *in-situ* measurement of the main physicochemical parameters of the hydrothermal fluids; and (iii) the representative sampling of hydrothermal fluids. For each locality, temperature, electrical conductivity, and pH were measured at the hydrothermal emission source with ten replicates to estimate reproducibility and uncertainty. For that purpose, a HACH® portable multimeter and a HANNA® portable potentiometer were used. Carbonate and bicarbonate concentrations in the sampled fluids were determined *in-situ* by triplicate, following the volumetric method proposed by Merchand-Reyes (2010). Two fluid samples were collected in each thermal spring for further chemical analysis of cations and anions. Samples for cation analysis were previously acidified with ultrapure HNO_3 (pH <3). Major cations in acidified samples were analyzed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and some samples with high cation concentrations (Na, K, and Sr >25 ppm, Ca, Mg, and Si >100 ppm) by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Non-acidified samples were used to analyze anions by Ion Chromatography (IC). A third group of samples of non-acidified thermal fluids were analyzed for stable isotopes ($^{18}O/^{16}O$ and D/H) by using a Gas Source Isotope-Ratio Mass Spectrometry (IRMS). Ionic balances were computed in each thermal spring sample for evaluating the quality of the chemical analyses.

4.2 Water-rock interaction approach

Deep equilibrium temperatures were estimated by applying the SolGeo software (Verma et al., 2008). The solute geothermometers used for estimating the equilibrium temperatures were the Na/K and Na/Li geothermometers from Verma & Santoyo (1997), which include the determination of the associated uncertainties, and the Na-K-Ca proposed by Fournier & Truesdell (1973). Besides knowing the chemical affinity of the geothermal fluids, their equilibrium temperature, and their origin, it was important to understand how these fluids interact with the reservoir rocks (minerals), and during their path towards the surface. The local equilibrium state between these geothermal fluids and the hydrothermal mineral phases was also examined using chemical thermodynamics, by comparing the fluids' composition together with the solubility of specific minerals (Torres-Alvarado, 2002).

Based on chemical equilibrium assumptions, these models consider a closed system at specific temperature and pressure. The equilibrium state is referred as the state of maximum stability towards which the physicochemical system addresses through irreversible processes (Bethke, 2008). These models result in the prediction of the chemical species distribution in the fluid, the saturation indexes of the mineral species, and the gas fugacities. In this work, we use the software 'The Geochemist's Workbench Standard 8.0$^{©}$' (GWB), particularly the subroutines React and Act2 (Bethke, 2009). The GWB uses a comprehensive thermodynamic database created in the Lawrence Livermore National Laboratory (Delany & Lundeen, 1990).

The set of equations that completely describe the equilibrium state of a geochemical system are known as the governing equations. For establishing the governing equations of this approach, it was necessary to determine the independent chemical reactions that probably occur among chemical species, minerals, and gases in the system, as well as the mass action equation that corresponds to each reaction. This set of mass action equations are substituted in the mass balance equations derived from each chemical component in the system. The resulting equations correspond to the governing equations, which are solved directly for the equilibrium state (Bethke, 2008). This non-linear equations system is solved for a multicomponent equilibrium, being numerically evaluated by iteration with the GWB software, based on the Newton-Raphson method.

Input data for this software require the knowledge of the initial system and the reaction path that modifies that system (Bethke & Yeakel, 2010). In the present study, the reaction path was defined to varying the system temperature from $\xi=0$ with a value of $T=T_{sup}$ (temperature measured in each thermal spring) up to $\xi=1$ with $T=T_{eq}$ (mean equilibrium temperature from the geothermometric estimates). Calculations were done by assuming a T=150°C as equilibrium temperature, according to the estimated Na/K equilibrium mean temperature (from $T_0=150$ °C to $T_f=T_{sup}$). Once the species distribution in the fluid during the reaction path was calculated, the saturation degree of the fluid with respect to the mineral species was additionally determined. The variation of saturated mineral species in the system was obtained as function of temperature, indicating which minerals could precipitate from the fluid composition during its ascent to the surface. The results were clustered by zones within the study area and plotted in mineral precipitation-temperature diagrams. The precipitated amount of each mineral (in mg) was obtained after calculating its corresponding logarithmic value.

Finally, the ionic activity ratios for Na/H, K/H, Mg/H, Ca/H, and SiO_2 (aq) were used to generate stability diagrams at T=150 ºC and P=1atm of systems with the components Na_2O, K_2O, MgO, CaO, SiO_2, Al_2O_3, and H_2O. Such activity diagrams were plotted under the following four assumptions: (i) an aqueous solution is always available for the reaction; (ii) the aluminum (Al^{3+}) content in the minerals is represented as a solid phase; (iii) the silica concentration is fixed by the quartz saturation; and (iv) the pressure and temperature of the system are kept constants. The ionic activities in solution that were compared in the activity diagrams correspond to the thermal springs whose equilibrium state could be obtained considering their charge balance. The results from the geochemical modeling were interpreted with caution because they do not include the gas phase composition. This lack of information implies that the chemical composition of the geothermal fluids is not completely represented.

5. RESULTS AND DISCUSSION

5.1 Geothermal Fluids Geochemistry

The sampled thermal springs were classified in two groups: (1) according to the lithology for which emanated the fluid spring, and (2) according to the geographic location in the study area. According to field observations, TCH, TNB, ACH, and TCP thermal springs were related with laramide granitoids, and, except for the TCP spring, they were located over NW-SE oriented regional faults, at the basin limits. Salt precipitations forming crusts on dikes and fractures were observed close to the TCH thermal spring. The faults that seem to feed the ACH and DVS thermal springs contained travertine crusts, indicating the presence of ancient hydrothermal activity. CMP and DVS springs emerged in ignimbrites from the SMO and from fractures and secondary faults. The DVS spring contained a large quantity of gases with a constant bubbling. The MTP spring emerged on sediments, which covered a regional fracture of more than 10 km length, in limestones in contact with ignimbrites. HSB, BCD, GRN and SMR springs emerged directly from alluvium, the HSB from ancient alluvium correlated with the Baucarit Formation. Finally, the ARV thermal spring emerged on limestones from older Formations (Cambrian and Mesozoic).

Higher surface temperatures were measured in springs that were emerging from granite, with values ranging between 41.5 and 63.1º C. Other hot spring temperatures varied from 30 to 46º C. The pH values logged were mainly neutral, slightly alkaline, with values between 6 and 9. The electrical conductivity (EC) showed higher variability ranging from 400 up to almost 4000 S/cm. The percentage ionic balance at each locality was lower than 5% for most of the hot springs.

5.2 Equilibrium Temperatures

The estimated equilibrium temperatures are shown in Figure 2. The estimated temperatures by the geothermometers Na/K, Na-K-Ca, and Na/Li, and the superficial temperature values measured *in-situ* as an indicator of the minimum temperature at each thermal site are included.

According to the Na-K-Ca geothermometer, the highest equilibrium temperatures estimated were of 321.3 °C in CMP and 229.1 °C in TNB, and the lowest of 52.4 °C and 21.7 °C in HSB and MTP, respectively. Without considering these two last springs, the mean temperature estimated by the Na-K-Ca geothermometry was T=166.7±70.0 °C. The highest equilibrium temperatures estimated by the Na/K geothermometry were of 327.9±61.5 °C and 461.6±86.7 °C in ARV and BCD, respectively, and the lowest of 27.7±21.8 °C and 68.8±25.9 °C in HSB and BCD, respectively. In general the HSB and BCD thermal springs do not seem to fulfill the constraints of the geothermometers because the estimated equilibrium temperatures were closed to the superficial ones. The estimated temperatures in the ARV and BCD thermal springs were greater than those values obtained for the rest of the springs. This behavior was only observed for this geothermometer. By excluding the HSB, BCD, ARV, and MTP thermal springs, the mean temperature predicted by the Na/K geothermometry was T=142.3±15.7 °C. Finally, the equilibrium temperatures inferred from the Na/Li geothermometer were very similar to those estimates inferred from the Na/K geothermometers, including the MTP, ARV and BCD springs with estimates of 144.9 °C, 104.5 °C and 101.1 °C, respectively.

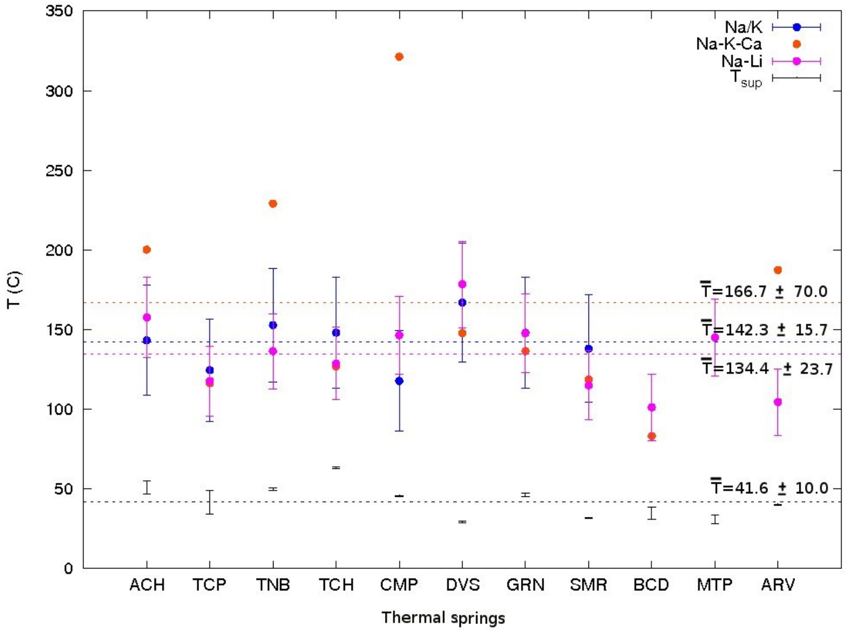

Figure 2: Estimated equilibrium temperatures by chemical geothermometers in thermal springs of Central Sonora: Na/K and Na/Li from Verma & Santoyo (1997), Na-K-Ca from Fournier & Truesdell (1973). Sample labels as in Figure 1. Dotted lines represent mean estimated temperatures by each geothermometer. T_{sup}: temperature measured in each thermal spring.

Considering all springs, except the HSB with a T=56.6 °C, the mean temperature predicted from Na/Li geothermometry was T=134.4±23.7 °C. By comparing the mean temperature estimates of Na/K and Na/Li with their standard deviations, it was concluded that there are no significant statistical differences among them.

All the calculations of the equilibrium temperatures considered the following assumptions (Fournier et al., 1974; White, 1970): (a) the chemical concentrations of the used species are derived from water-rock interaction reactions at equilibrium conditions, and are dependent of temperature; (b) there is mineral abundance in the water-mineral interaction of the geothermal system; (c) there is no re-equilibrium during the fluid flow path through the surface; and (d) there is no fluid mix or dilution with cold or hot water. The differences observed in the temperature estimates, inferred from distinct geothermometers, are probably due to either partial equilibrium, or lack of equilibrium (ARV, MTP, and HSB springs), which do not satisfy the fundamental condition of each geothermometer.

Large differences among the temperature estimates computed in a single spring were only obtained for the ARV and MTP (Central zone) springs, which were characterized by calcium-bicarbonate waters. The concentration of Mg in the fluids of Central Sonora varied from 0 to 3.38 mg/kg, except for the ARV, MTP, and DVS springs where they reach values of 19.7 mg/kg, 32.3 mg/kg, and 58.4 mg/kg, respectively. These relatively high concentrations of Mg may suggest a possible mix of these fluids with underground waters. DVS spring samples exhibit an anomalous behavior with ionic concentrations greater than the rest of the NE zone thermal springs, particularly of HCO_3, Na, K, SO_4, which could be influenced by the interaction of fluids with saline sedimentary bodies. These deposits have been previously reported in the Divisaderos-Tepache Valley and, near to the sampled spring, in La Salada towards the East and in Cretaceous Sedimentary rocks towards the Southeast (Herrera-Urbina & Bartolini-Navarro, 1981).

The main mineral phases that control the presence of the alkaline metals Na^+ and K^+ in the thermal fluids are feldspars, potassium micas (sericite mainly), and potassium clays as illite (Izquierdo-Montalvo et al., 1995). This mineral assemblage supports the use of Na/K geothermometer. From the equilibrium temperature inferred from this geothermometer, it was possible to establish that the Central Sonora geothermal systems are characterized as low-to-medium enthalpy reservoirs with a mean temperature of T=150 °C. Finally, it is important to pointed out that the use of the Na/K geothermometer is reliably recommended for temperatures greater than 200 °C (Díaz-González et al., 2008). Thus, lower temperature estimates than 160 °C should be considered with special caution. These geothermometers usually tend to overestimate systematically the equilibrium temperatures for low-to-medium enthalpy systems. This limitation is basically explained by the lack of reliable data in geochemical databases, which are used for the derivation of new geothermometers (Díaz-González et al., 2008).

5.3 Geochemical Modeling

The reservoir temperature considered for the geochemical modeling was given by a mean temperature of T=150 °C. According to the obtained results, the minerals that are in equilibrium with geothermal fluids at this temperature are given by laumontite, clinochlore, prehnite, and muscovite (Figure 3).

According to mineral stability diagrams plotted at T=150 °C, the Na_2O-K_2O-Al_2O_3-SiO_2-H_2O system exhibits an ionic exchange of Na/K that seems to be dominated either by the albite/muscovite interaction or the albite/K-feldspar interaction in metastable equilibrium. This reflects the possible hydrothermal alteration of primary plagioclase in agreement with the following reaction:

$$\text{Plag-Na} + K^+ + H^+ \leftrightarrow \text{mica-K} + Na^+$$

The discharge composition tends to be placed along an extension from either the albite/K-feldspar limit through the muscovite field, or through phases chemically similar like sericite and illite (Hedenquist, 1991). This behavior can be interpreted as the result of the primary dissolution of feldspars in the reservoir with an equilibrium condition given between albite and K-feldspar under a metastable equilibrium condition (Torres-Alvarado, 2002). For T=100 °C, the geothermal fluids seem to be keep in equilibrium with muscovite, close to the muscovite/kaolinite boundary. In contrast for T=200 °C, the fluids are placed close to the muscovite/albite equilibrium line.

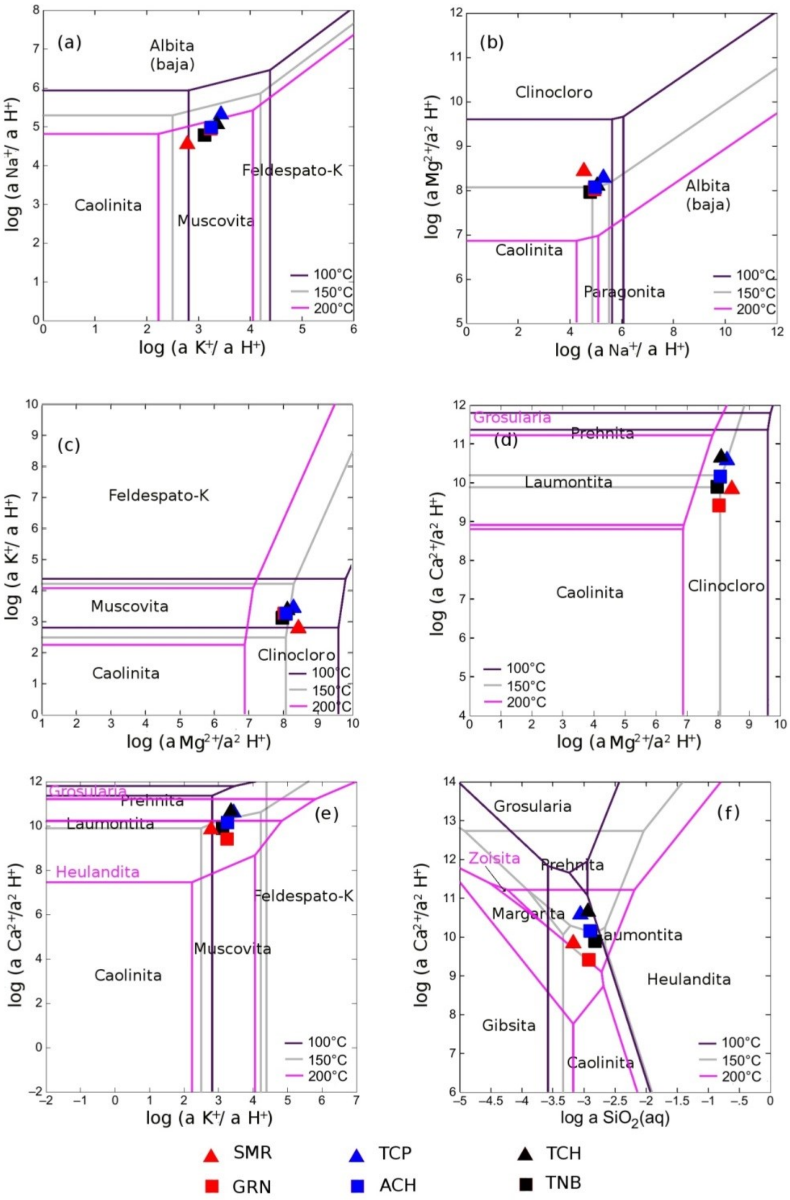

Figure 3: Activity diagrams for mineral phases at different temperatures: (a) Na_2O-K_2O-Al_2O_3-SiO_2-H_2O, (b) Na_2O-MgO-Al_2O_3-SiO_2-H_2O, (c) K_2O-MgO-Al_2O_3-SiO_2-H_2O, (d) CaO-MgO-Al_2O_3-SiO_2-H_2O, (e) CaO-K_2O-Al_2O_3-SiO_2-H2O, (f) CaO-SiO_2-Al_2O_3-H_2O. Sample labels as in Figure 1.

For the K_2O-MgO-Al_2O_3-SiO_2-H_2O system, the ionic exchange of K/Mg seems to be dominated by the muscovite/clinochlore interaction. This indicates that the processes involving chlorites are in agreement with the following reaction:

$$3\text{Clinochlore} + 2K^+ + 28H^+ \leftrightarrow 2\text{Moscovite} + 24H_2O + 3\text{Quartz} + 15Mg^{2+},$$

Such a chemical reaction could be controlled by the presence of Mg^{2+} and K^+ in the spring samples, as was previously reported for the Los Azufres geothermal field (Giggenbach, 1986). For T=100 °C, the fluids are in equilibrium with muscovite, close to the muscovite/kaolinite limit, whereas for T=200 °C, the fluids are in equilibrium with clinochlore.

For the CaO-MgO-Al_2O_3-SiO_2-H_2O system, the ionic interchange of Ca/Mg seems to be dominated by a prehnite-laumontite-kaolinite/clinochlore interaction. This geochemical system supports the application of Na/K and Na-K-Ca geothermometers in the geothermal fluids produced in Central Sonora. Laumontite is a Ca-rich zeolite typically observed in some geothermal fields at temperatures between 170 and 250 °C (Torres-Rodríguez, 2000). The fluids in that mineral stability field could indicate the existence of reservoir temperatures greater than 150 °C. The equilibrium of the fluids with muscovite and prehnite is observed in the activity diagrams for minerals characterized by potassium and calcium, particularly for the system $CaO-K_2O-Al_2O_3-SiO_2-H_2O$, which depends on the K^+/H^+ and Ca^{2+}/H^{+2}. In this system the fluids are in equilibrium with the triple point muscovite/prehnite/laumontite.

With respect to the equilibrium existing between minerals with sodium and magnesium, for the system $Na_2O-MgO-Al_2O_3-SiO_2-H_2O$, the fluids are placed in the paragonite/clinochlore limit. This indicates that the magnesium activity seems to be controlled by the chlorites, as the sodium activity controlled by Na-micas. However, in absence of paragonite, and given that this does not correspond to a stable mineral phase for the fluids in the diagram of Figure 3a, the sodium activity seems to be controlled by albite, reinforcing the metastable equilibrium condition of the fluids with muscovite. For T=100 °C, the fluids are in equilibrium with kaolinite, whereas for T=200 °C, the fluids are in equilibrium with clinochlore.

For the system $CaO-Na_2O-Al_2O_3-SiO_2-H_2O$, the equilibrium of minerals with sodium and calcium (as function of the relations Na^+/H^+ and Ca^{2+}/H^{+2}) is observed between the thermal fluids with laumontite and paragonite. In this system, the SMR, GRN, ACH, and TNB springs are placed in the triple point laumontite/paragonite/kaolinite. In absence of paragonite, the fluids are placed near the boundary with albite. For T=100 °C, the fluids are found in equilibrium with K-feldspar, closed to the K-feldspar/kaolinite equilibrium line, whereas for T=200 °C, laumontite is not stable and its field is not present, as two new minerals appear, heulandite and grossularite. For this temperature, the fluids are found over the heulandite/prehnite boundary, being the SMR and GRN springs towards the heulandite field, and the TCP and TCH towards the prehnite field.

Finally, for the $CaO-SiO_2-Al_2O_3-H_2O$ system, the equilibrium phases for minerals with silica and calcium are represented as function of the Ca^{2+}/H^{+2} and SiO_2 (aq) relations. According to this diagram, the fluids are in equilibrium with prehnite, laumontite and kaolinite. For T=100 °C, the fluids are in equilibrium with kaolinite, close to the kaolinite/heulandite limit, whereas for T=200 °C, the fluids are in equilibrium with laumontite, being the SMR and GRN springs over the laumontite/margarita equilibrium line.

According to the reaction path simulation results, the minerals that could precipitate from the sampled thermal fluids are: quartz, fluorite, calcite, anhydrite, dolomite, and talc (Figures 4 and 5). It is also indicated that these fluids are in equilibrium with muscovite, clinochlore, laumontite, prehnite, kaolinite, and albite. Most of these minerals correspond to a mineral assemblage of low grade metamorphism. This may indicate that, according to the regional geology of the study are, the fluids are reaching the chemical equilibrium in the contact zones between the Laramie granitoids and the tectonic basins. That is, in the regional fault zones over the influence of such granitoids and rocks with low grade metamorphism. The regional rocks that represent this last characteristic are the intermediate to acidic rocks from the Tarahumara Formation. Even, the Tertiary mafic rocks associated to the Baucarit type basins, where the presence of this intermediate to mafic rocks might represent the main Ca and Mg source of the fluids.

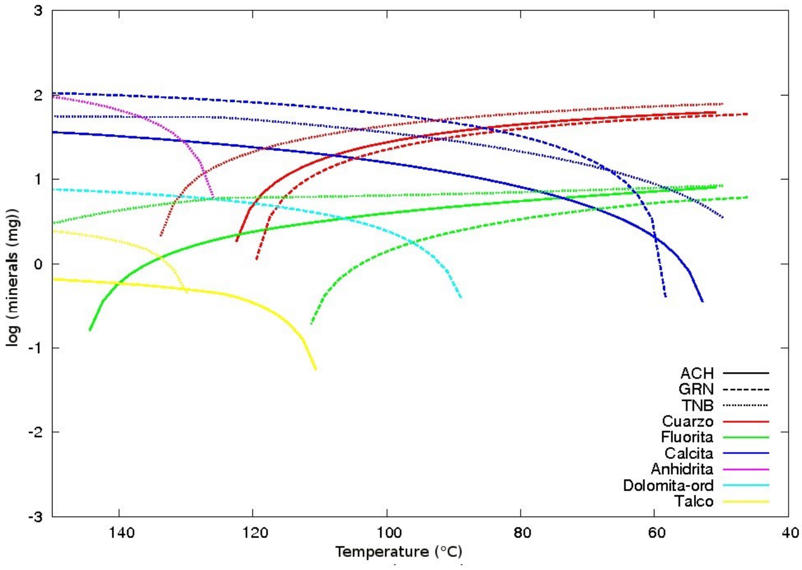

Figure 4: Mineral precipitation as a function of temperature (T) in hydrothermal fluids from the NW and NW zones.

6. CONCLUSION

The presence of a series of thermal manifestations, Quaternary volcanism, and tectonic activity at the Central-East Sonora state, Mexico, motivated a field sampling campaign. The aim of this research was to propose a preliminary geochemical model of the hydrothermal system.

The physicochemical parameters measured in the field showed that higher surface temperatures are obtained in thermal springs emanating from granite rocks (in the basin-range limits marked by regional faults), whereas the lowest surface temperatures are found in hot springs that emanate from recent sediments within the valleys.

The estimated equilibrium temperatures showed that the hydrothermal fluids resulting from medium temperature reservoirs. The Na-K-Ca geothermometers predicted higher temperatures ranging from 229 to 321°C in the TNB and CMP springs, respectively. The temperature estimates inferred from Na/K and Na/Li geothermometers are in agreement with values of 150 °C for the ACH, TNB, DVS, TCH, and GRN springs. This temperature value was used as the mots suitable equilibrium temperature for the geochemical modeling simulations. According to the temperature estimates inferred from the Na/K geothermometer, geothermal fluids emerged from the Central zone exhibited the highest equilibrium temperatures. The lowest estimated temperatures were found in the sediments emanating springs, particularly in the HSB and BCD springs.

From the geochemical modeling at 150°C, it was observed that the main minerals that probably precipitate from the thermal fluids are quartz, fluorite, calcite, anhydrite, dolomite, dolomite-ord, talc, and in some cases tremolite. Considering the ionic activity ratios, the thermal fluids are in equilibrium with muscovite, clinochlore, laumontite, prehnite, kaolinite, and albite. Therefore, these minerals are the main source of Na^+, K^+, Mg^{2+}, and Ca^{2+}.

Finally, it is concluded that the thermal fluids of Central Sonora, especially the TCH, TNB, ARV, TCP, CMP, and GRN sites, have the potential to be used not only for heat direct use, but for electricity production through binary cycle plants, which are usually used for fluids with temperatures between 100 and 180 °C.

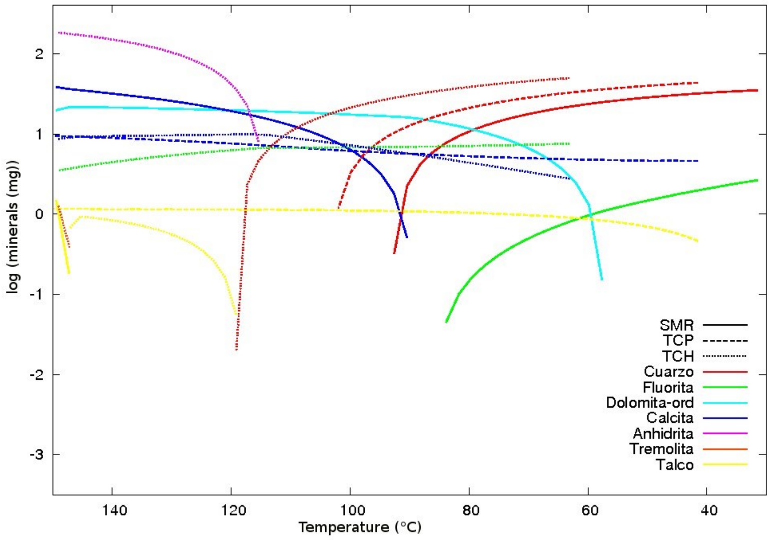

Figure 5: Mineral precipitation as a function of temperature (T) in hydrothermal fluids from the S zone.

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