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The Use of Ahuachapan Fluid Chemistry to Indicate Natural State Conditions  
and Reservoir Processes during Exploitation

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ABSTRACT

Chemical analyses of production fluids from Ahuachapan, El Salvador, have been used to indicate natural state reservoir fluid temperatures and chloride concentrations and reservoir processes resulting from exploitation. Geothermometer temperatures (Na-K-Ca and SiO<sub>2</sub>) and calculated aquifer Cl for early flows show a gradient from about 265°C and 9000 ppm Cl in the western part of the well field to 235°C and 6000 ppm Cl in the eastern part. The geochemical temperatures are 10-20°C higher than early downhole measurements. Since exploitation started, pressures have declined over most of the drilled area with boiling and excess-enthalpy discharges in the eastern and western parts. In the center of the field, a number of wells show mixing with cooler, less-saline water. These wells are nearly coincident with a major NE-SW oriented fault that may be the conduit for downward recharge of cooler fluids from an overlying aquifer.

INTRODUCTION

In 1987-88 a collaborative study of the Ahuachapan, El Salvador, geothermal reservoir was started by the Comision Ejecutiva Hidroelectrica del Rio Lempa (CEL), the Lawrence Berkeley Laboratory (LBL), and the U.S. Geological Survey (USGS) through a subcontract with the Los Alamos National Laboratory (LANL). Part of this study consists of interpretation of the chemical and gas analyses of Ahuachapan well fluids collected and analyzed by CEL. Chemical studies of produced fluids from geothermal wells provide information on the temperature, salinity, physical state, and flow of fluids in the reservoir. Extrapolation to the time of first production provides estimates of initial conditions, and changes in fluid composition indicate reservoir processes, including boiling, entry of different (usually cooler and less saline) fluids, and conductive heat transfer. The initial study of Ahuachapan well discharges concentrated on the interpretation of geothermometer temperatures and aquifer chlorinity as a function of time. These time-series diagrams have been used to indicate initial conditions and identify reservoir processes.

GEOOTHERMOMETRY

Fluid geothermometers depend on temperature-sensitive reactions of fluids with rock minerals or fluid components. In a producing field, downhole temperatures may be conveniently estimated through the use of geothermometers applied to analyses of produced fluids, provided the geothermometer reaction is in equilibrium at downhole conditions (Mahon, 1966). Geothermometer reactions differ in kinetic rates, that is in how rapidly they re-equilibrate in response to a change in conditions. If the temperature of the fluid flowing to a well changes by boiling, by passage through hotter or cooler rocks, or by mixing with hotter or cooler fluids, or if the fluid has specific enthalpy higher than that expected for liquid at the prevailing temperature, then comparison of geothermometer temperatures may indicate reservoir processes. A particularly useful set of temperature indicators for this purpose includes the Na-K-Ca cation geothermometer, the quartz-saturation geothermometer, and the calculated "enthalpy temperature."

Cation geothermometers use temperature-dependent cation exchange reactions with rock aluminosilicates to indicate temperature. Some of these reactions are either too slow or too rapid to be of interest in reservoir studies. The most generally useful one is the empirical Na-K-Ca geothermometer developed by Fournier and Truesdell (1973) that depends on the exchange of K<sup>+</sup> ion for Na<sup>+</sup> and Ca<sup>++</sup> on aluminosilicate minerals. The kinetics of this reaction are strongly dependent on the salinity of the fluid and on the amount and type of mineral surfaces present. With high-salinity fluid a large amount of mineral transformation is required to change fluid compositions. If no aluminosilicate surfaces are available (as might occur if channelways are mantled with quartz) then the cation exchange will not occur. Because of these factors the Na-K-Ca geothermometer is slow to respond to changes in temperature of even moderately saline fluids (e.g., Cl > 2000 ppm) and responds particularly slowly to decreases in temperature accompanied by quartz precipitation. Most changes in fluid temperatures involve cooling so mantling of surfaces by quartz (or other silica minerals) is very common.

Silica geothermometry uses the experimentally determined solubility of quartz and other silica minerals to indicate temperatures. In high-temperature reservoirs ( $> 200^{\circ}\text{C}$ ), quartz is the stable polymorph of silica. At these temperatures the precipitation and solution of quartz are relatively rapid (hours at  $> 260^{\circ}\text{C}$ ; days at  $> 220^{\circ}\text{C}$ ) and dissolved silica remains in equilibrium with quartz through most reservoir processes including mixing and boiling induced by exploitation. Thus the quartz geothermometer indicates temperatures close to those at the well bottom unless mixing occurs in the wellbore. Further discussion of quartz and cation geothermometry may be found in Fournier (1981).

"Enthalpy temperature" is the temperature of liquid water calculated from the enthalpy of the total fluid, assuming that there is no vapor entering the well. If, in fact, the fluid that enters the well is entirely liquid with no vapor, then the enthalpy temperature is the same as the actual inflow temperature. If there is excess steam, the enthalpy temperature will be higher than the actual inflow temperature. The comparison of geothermometer and enthalpy temperatures can indicate excess steam or mixture with cooler water. Enthalpy temperature is calculated from steam tables, using data for temperature and enthalpy of vapor-saturated liquid. For this calculation, both liquid and vapor phases must be present, so there is some inaccuracy for compressed liquid conditions. This error is small because the enthalpy of water is a weak function of pressure. A more serious limitation is that enthalpies exceeding that of water at the critical point (2100 kJ/kg at  $374^{\circ}\text{C}$  for the pure water steam tables used) cannot be represented by enthalpy temperatures since vapor-saturated liquid cannot exist with these enthalpies.

#### AQUIFER CHLORIDE

Chloride is a conservative element in geothermal fluids. It is not an essential constituent of any minerals normally found in geothermal systems and is not affected by temperature-sensitive reactions with rock. Concentrations of chloride are affected by boiling and mixing and may be used to identify these processes. Changes in aquifer chloride concentration may, for example, provide indications of the chemical breakthrough of less-saline water or of the amount of boiling and steam loss. Chloride concentrations in surface samples are strongly affected by boiling and steam separation, so for quantitative comparisons the aquifer chloride concentration must be calculated.

Water from geothermal wells is usually sampled from the weirbox of the silencer or from the separator through a cooling coil. If the enthalpy of the aquifer liquid is known, the fraction of steam separating and the change in solute concentrations can be calculated. Using enthalpy and chemical balances,

$$\begin{aligned} \text{Cl}_1 \text{, aquifer} &= \text{Cl}_1 \text{separator} \times \text{WFsep} \\ \text{WFsep} &= (\text{Esteam, sep} - \text{Ewater, aqu}) / \\ &(\text{Esteam, sep} - \text{Ewater, sep}) \end{aligned}$$

for samples collected from the separator through a cooling coil. For weirbox samples there are the additional equations:

$$\begin{aligned} \text{Cl}_1 \text{separator} &= \text{Cl}_1 \text{weirbox} \times \text{WFsilencer} \\ \text{WFsilencer} &= (\text{Esteam, sil} - \text{Ewater, sep}) / \\ &(\text{Esteam, sil} - \text{Ewater, sil}), \end{aligned}$$

in which WF is the water fraction, and the enthalpy of steam and water at separator (sep) and silencer (sil) pressures are obtained from steam tables. For wells with no excess steam, the measured enthalpy is assumed equal to the aquifer liquid enthalpy for calculating aquifer chloride.

For excess-steam wells, the measured total enthalpy is not equal to the enthalpy of the reservoir liquid so another method is used. Because the liquid enthalpy of most interest to us is that at a distance from the well unaffected by near-well boiling, liquid enthalpy based on the Na-K-Ca temperature is used for calculations of aquifer chloride presented in this paper. An advantage of this procedure is that excess enthalpy produced by near-well boiling without reequilibration of Na-K-Ca temperatures does not affect calculation of aquifer chloride concentrations away from the well. A possible disadvantage is that the chloride values do not help to distinguish between sources of excess enthalpy.

#### TEMPERATURE-CHLORIDE-TIME PLOTS

The chemical indicators discussed above are combined as temperature-time and chloride-time plots that are interpreted to indicate reservoir processes. Na-K-Ca temperatures are assumed to represent the temperature of the fluid at a distance from the well not affected by mixing and boiling near the well. This relatively distant fluid is assumed to have remained at its indicated temperatures long enough to be fully equilibrated. Silica (quartz-saturation) temperatures are assumed to represent near-well temperatures and are usually fully equilibrated. For several wells at Cerro Prieto, calculated well-bottom temperatures (Goyal et al., 1981) have been shown to agree reasonably well with quartz-saturation geothermometer temperatures (Truesdell, 1988 and unpublished data, 1982). Finally, enthalpy temperatures indicate either the actual temperature of the liquid if only liquid enters the well or indicate the relative amount of excess steam. In this second case, the indicated temperature does not correspond to any real reservoir temperature.

#### INITIAL CONDITIONS

Geothermometer and aquifer chloride versus time plots allow reasonable estimates of initial reservoir fluid temperature and chloride. The drilling and development of

wells disturbs reservoir conditions in various ways. Drilling water may locally dilute reservoir fluids, and pressure decrease from extensive testing may cause boiling or cold-water entry. Analysis of fluids produced at low flow during well development may be affected by cooling from both wellbore heat loss and boiling. These data cannot then be used to calculate quartz-saturation temperatures or aquifer chloride because the amount of steam loss is not known, although Na/K and usually Na-K-Ca geothermometers are applicable.

For these reasons, chemical and enthalpy measurements for the first year or so of full flow production are usually best for estimating initial conditions. The Na-K-Ca geothermometer has a long memory and aquifer chloride is unlikely to change rapidly. Often a trend in data can be extrapolated to the start of major production. Examples of these estimations will be given later.

#### CHEMICAL PATTERNS

As noted earlier, the different rates of response of the Na-K-Ca and quartz geothermometer combined with the enthalpy temperature provide indications of fluid state and of fluid temperature near and far from wells. Aquifer chloride provides additional indications for dilution and boiling processes. These indicators are most useful when a relatively long history is available with data collected at frequent intervals. These numerous data are needed for the interpretation of certain processes such as cold-water sweep and allow errors to be estimated. This interpretive method has been applied to Cerro Prieto (Truesdell, et al., 1979, 1984; Truesdell, 1988) and is applied here to Ahuachapan. Although only some of the possible sequences have been observed at Ahuachapan, we will for completeness and possible application elsewhere also include those found at Cerro Prieto. The temperatures are abbreviated as TNaKCa, TSil and TE indicating Na-K-Ca, quartz and enthalpy temperatures, respectively.

1. TNaKCa = TSil = TE indicates all-liquid fully equilibrated reservoir fluid.
2. TE > TNaKCa > TSil indicates fluid boiling during flow to the well in response to decrease in well-bottom pressure. Boiling lowers near-well fluid temperatures (and TSil values) and causes heat transfer from hotter rocks. If pressures are controlled by a constant pressure boundary, well-bottom pressures gradually stabilize and expansion of the boiling zone slows and stops. Within the stabilized boiling zone, temperatures equilibrate and heat is no longer transferred so excess enthalpy decreases slowly and disappears. TSil is still depressed because near-well boiling and temperature decrease continues. The order then becomes TE = TNaKCa > TSil.
3. TNaKCa > TE = TSil results from mixing with cooler water and reequilibration of TSil but not TNaKCa.

4. TE > TNaKCa = TSil indicates mixture of equilibrated liquid with steam formed by boiling away from the well. Wells with two inlet zones may show this pattern.
5. TNaKCa > TSil > TE shows mixture in the well of cooler more dilute water with equilibrated liquid. The lower TSil results from mixture without reequilibration with TNaKCa not significantly affected by moderate dilution. Inflow of shallow cooler water into a well with multiple fluid entries could produce this pattern.
6. TE = TSil > TNaKCa indicates chemical breakthrough of cooler water. TNaKCa still partly retains the memory of equilibration at lower temperatures although the fluid has been heated by flow through hot rock. Aquifer chloride will also indicate chemical breakthrough.

Other cases can occur by combination of these processes; for example, boiling in the reservoir could be combined with cool water entry into the well. Some of these combinations produce ambiguous indications. Consideration of changes in aquifer chloride is of value in sorting out these processes.

#### AHUACHAPAN INDICATORS

Ahuachapan wells usually exhibit either pattern 2 or 5 and less often 3 and 4, with pattern 1 found in the earliest production. Examples of typical behavior are shown in Figures 1-4.

Well AH-23 (Fig. 1) generally shows excess enthalpy and low silica temperature (pattern TE > TNaKCa > TSil). The initial temperature of 245°C is best indicated by Na-K-Ca. Early calculated silica temperatures were probably depressed by the presence of drilling fluid or by wellbore heat loss as indicated also by low enthalpy temperatures.

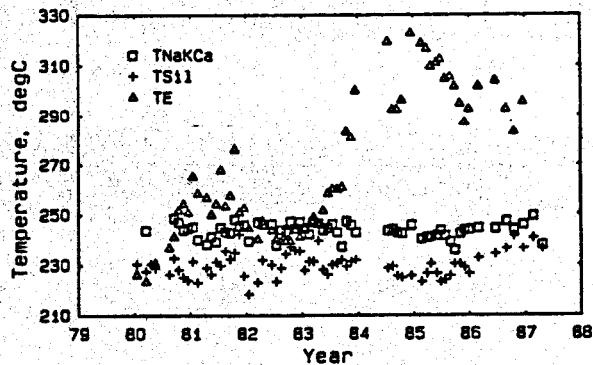


Figure 1. Temperature indicators versus time for Ahuachapan 23 generally showing boiling and excess enthalpy. Symbols: square, TNaKCa; plus, TSil; and triangle, TE.

Well AH-28 (Fig. 2) shows generally low fluid temperatures (shown by enthalpy temperature), but more or less constant Na-K-Ca temperatures and intermediate silica temperatures (TNaKCa > TSil > TE). This pattern is caused by the entry of cooler water into the well,

probably through a shallow feed zone where it mixes with the reservoir fluid. The temperature of the "hot" reservoir fluid is about 245°C, similar to its initial temperature. The temperature of the mixture in the well is about 220°C. If the mixing had occurred away from the well, then the silica-temperature would also be near 220°C. The initial Na-K-Ca, silica (except two earliest values affected by conductive cooling), and enthalpy temperatures are all 250 ± 5°C.

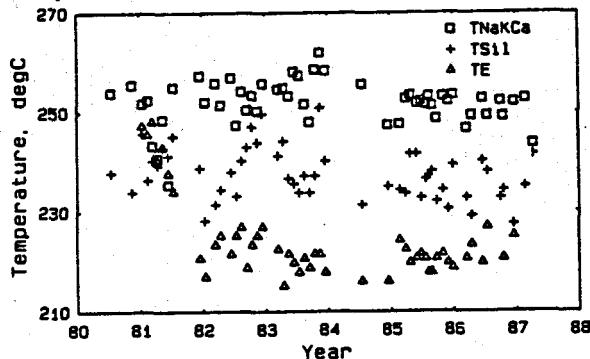


Figure 2. Temperature indicators versus time for Ahuachapan 28 showing mixing with cooler water near the well. Symbols as in Figure 1.

Well 21 (Fig. 3) shows the result of mixing further from the well with mostly TNaKCa > TSil = TE indicating equilibration of silica after mixing. Mixing occurred so early in the history of this well that only TNaKCa can be used to indicate the initial temperature of 260°C.

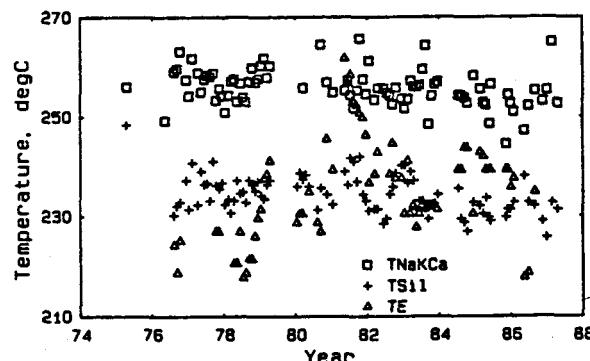


Figure 3. Temperature indicators versus time for Ahuachapan 21 showing mixing with cooler water farther from the well. Symbols as in Figure 1.

The aquifer chloride of well AH-22 (Fig. 4) shows chemical breakthrough in 1981 with aquifer chloride decreasing from about 7000 mg/kg to 6300 mg/kg by 1987. This breakthrough was in response to decreased pressure in the central part of the field, which caused flow from the east where fluids were less saline. Geothermometer temperatures for this well showed immediate (1976) over-all boiling (TE > TNaKCa > TSil) independent of the later chemical breakthrough.

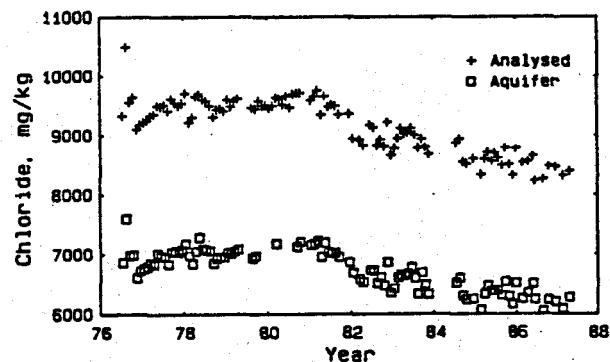


Figure 4. Chloride concentrations versus time for Ahuachapan 22 showing breakthrough of less-saline water. Symbols: plus, Cl concentrations as analyzed; square, aquifer Cl concentrations calculated using TNaKCa for reservoir temperature.

#### INITIAL TEMPERATURE AND CHLORIDE AT AHUACHAPAN

Using initial geothermometer and aquifer chloride values, or values extrapolated from early production, maps have been prepared with contours of the natural reservoir conditions (Figs. 5 and 6). These maps show a clear increase in both temperature and aquifer chloride concentration from east to west. Liquid enthalpy values (calculated from temperature) are almost linearly related to chloride concentration (Fig. 7), suggesting mixing between a more-saline, hotter water and a more-dilute, cooler water. The low-temperature end member cannot be defined from these data but is not surface water (compare data for Cerro Prieto in Grant et al., 1984).

The Na-K-Ca geothermometer temperatures indicate that fluids produced from the wells were equilibrated with rock minerals at temperatures ranging from above 260°C in the west to below 235°C in the east. These temperatures are uniformly 10–20°C higher than the downhole measured temperatures in the same wells (see Lakey et al., this volume). One possible explanation is that the Na-K-Ca geothermometer is not accurate for Ahuachapan fluids. This is unlikely because the Ahuachapan fluids are in no way chemically unusual and because other geothermometers give similar temperature indications (Table 1). Another possibility is that by the time downhole temperatures were measured, pressure drawdown had already affected temperatures either through boiling with resulting temperature decrease or through cold-water mixing.

#### RESERVOIR PROCESSES AT AHUACHAPAN

A map can also be drawn showing predominant reservoir processes for each well. A well may show different processes during its history but one process usually predominates. In response to pressure drawdown, high-temperature reservoirs either boil or are flooded with cooler recharge from the top or sides of

the field. In a large reservoir, evidence of boiling or dilution may be delayed unless the well is close to the location of boiling or cold-water entry. In these reservoirs local boiling may occur immediately but evidence of dilution is usually delayed. At Ahuachapan large amounts of fluid were irregularly discharged from wells during extended field development. This discharge may have caused some early drawdown. The relatively early appearance at Ahuachapan of boiling or cold-water mixing may result from extended field development or may indicate that fluid entries are near the top of the reservoir where pressure drawdown effects are first manifest. The response to exploitation at Ahuachapan has either been immediate boiling or immediate dilution. The locations of wells with these behaviors are shown in Figure 8. The wells have been divided into "boilers" (solid circles) and "diluters" (solid squares), simply according to whether  $TE > TNaKCa$  or  $TNaKCa > TE$ .

The pattern shows a band of diluters running N-S through the center of the field with boilers on both sides. Comparing this map with Figure 9, the fault map of Laky et al. (this volume), we see a remarkable coincidence of the band of diluters with faults 8 and 7. These faults are among the youngest in the field and probably allow hydrologic communication between the reservoir and the overlying Saturated Aquifer, which contains cold water.

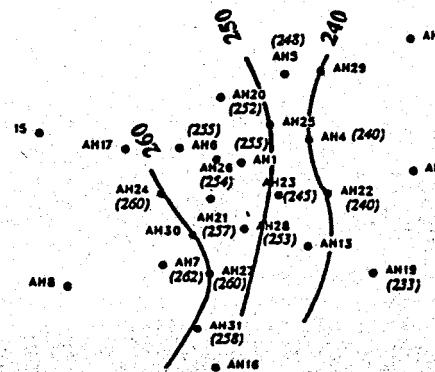


Figure 5. Natural state reservoir temperatures for the Ahuachapan field.

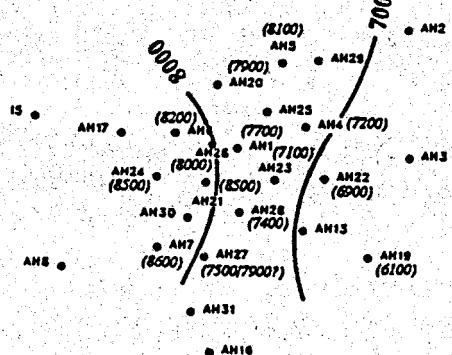


Figure 6. Natural state reservoir chloride concentrations for the Ahuachapan field.

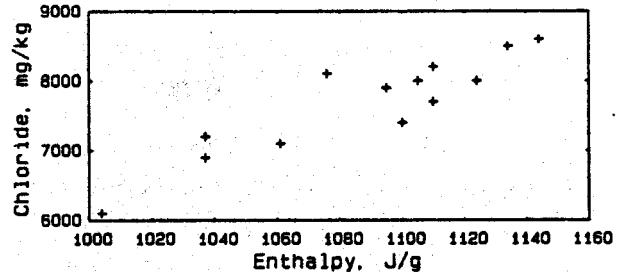


Figure 7. Enthalpy-chloride contents for natural state Ahuachapan reservoir fluids.

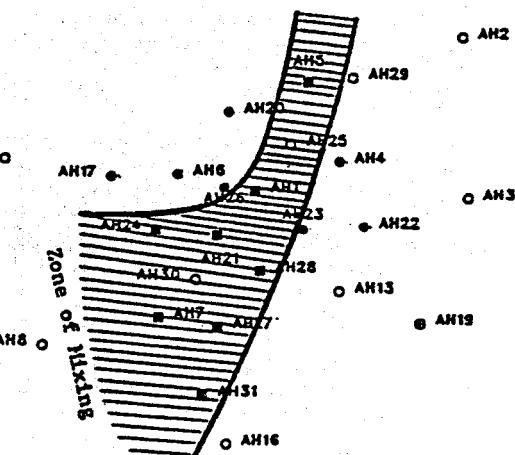


Figure 8. Simplified map of response of Ahuachapan wells to exploitation. See text for explanation.

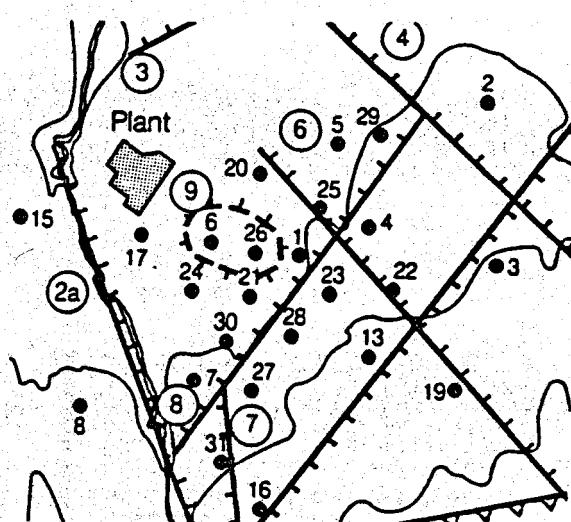


Figure 9. Fault map for the Ahuachapan field from Laky et al. (1989).

IMPLICATIONS FOR THE AHUACHAPAN CONCEPTUAL MODEL

The geochemical interpretations provide major constraints on the natural state model of the field. As described by Laky et al. (this volume) and Steingrimsson et al. (this volume), the behavior of the field is controlled by the major faults (Fig. 9). The main faults believed to feed the Ahuachapan reservoir are faults 6, 2a and 10. In the natural state, mixing of the geothermal fluids with cooler, less-saline fluids occurs in the eastern part of the well field. These cooler fluids probably come from the north via fault 4; another possibility is downward recharge from the overlying Saturated Aquifer, which has a higher hydraulic potential than the main reservoir. This mixing explains the observed gradients in geothermometer temperatures and chloride concentrations across the field.

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Table 1. Early Geothermometer Temperatures for Ahuachapan Well Discharges in °C.

Well	Date	TNaKCa	TSi1	TNaK(1)	TNaK(2)
AH-1	07/74	256	251	247	263
AH-4	06/75	246	237	237	256
AH-5	02/72	248	---	242	259
AH-6	07/74	257	246	252	266
AH-7	04/75	262	256	260	272
AH-16	03/87	240	238	231	251
AH-19	03/85	233	228	218	241
AH-20	07/76	255	234	250	268
AH-21	04/75	256	248	250	265
AH-22	07/76	239	237	226	247
AH-23	09/80	249	233	243	260
AH-24	09/78	262	252	260	273
AH-26	09/76	253	229	246	262
AH-27	10/80	263	246	262	274
AH-28	07/80	254	239	249	264
AH-31	04/85	260	250	257	270

TNaK(1) is the Ellis-White Na-K geothermometer from Truesdell (1976). This usually indicates minimum temperatures. TNaK(2) is the Na-K geothermometer from Fournier (1979), which usually indicates maximum temperatures.

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