Geothermal Resources Council TRANSACTIONS, Vol. 19, October 1995

# HYDROTHERMAL CHARACTERISTICS OF THE WELL A-29 AT THE LOS AZUFRES GEOTHERMAL FIELD, MEXICO

Julio C. Viggiano-Guerra and Luis C.A. Gutiérrez-Negrín

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

## ABSTRACT

Three distinct hydrothermal zones can be identified in the well A-29, located at the northeastern border of the Los Azufres, Mexico, geothermal field. They are the zeolite, epidote and amphibole-garnet zones. High temperatures (over 300 °C) were measured, but the well did not produce mass flow. This can be explained by a self-sealing process as a result of three trends recognized in the evolution of geothermal fluids: boiling, boiling and gas losses, and dilution. A certain cooling of at least 25°C seems to be happening in the well, especially in the epidote zone and in the upper portions of the amphibole-garnet zone.

## INTRODUCTION

The Los Azufres, Michoacán, Mexico, geothermal field is a typical boiling geothermal system (high relief) lying entirely within Pliocene and Quaternary volcanics, at the center of the Mexican Volcanic Belt (Figure 1).

Since its exploration began, the field was divided in two zones: north and south. This division was mainly based upon geologic data, but presents hydrological implications. Rhyolitic domes lie at the center of the field, which permit the fluid to discharge in two directions giving as a result two discharges, north and south, with a common deep source (Viggiano, 1987).

Host rocks, predominantly andesites and subordinate basalts, dacites and pyroclastics, are being strongly metamorphosed by sodium chloride near neutral pH brine at temperatures up to 350°C, giving rise to the greenschist facies in some places.

More than sixty wells have been drilled in the field. Well A-29, located at the northeastern border (Figure 1), displays some interesting features:

- ☐ The well does not produce mass flow, even though a high temperature was measured (over 300°C).
- ☐ The paragenesis of authigenic minerals embraces some minerals that have not been seen elsewhere in other wells of the field (like garnet, biotite and amphibole).
- ☐ The well is located at the boundary of the field.

In addition to petrological studies and temperature and pressure logs, some fluid inclusion determinations were carried out on cuttings and core samples from the well A-29. This paper focuses mainly on the interpretation of fluid inclusions and hydrothermal mineralogy, in order to establish the thermal regime and the relation between the progressive appearance of calc-silicates and the fluid composition. This could improve the knowledge of the reservoir characteristics by means of the correlation of the fluid inclusions, hydrothermal mineralogy and temperature and pressure data.

## HYDROTHERMAL MINERALOGY

Well A-29 cut through 2900 meters of both high and low-silica has reported andesites, belonging to the Mil Cumbres Andesite, which ages varying from 18 to 1 *m.a.* after superficial dating (Razo *et al.*, 1989). A simplified lithological column is depicted in Figure 2a (modified from Viggiano, 1983). Together with the primary minerals, authigenic phases were identified by microscopy. Striking features on these are as follows:

- ☐ Intensity of alteration is low from surface to 300 meters depth, where it increases sharply and is constant to well-bottom. Total alteration becomes interesting where calc-silicates appear, around 1000 meters depth. Convective fluid has interacted with those rocks from 300 meters depth to well-bottom much stronger than in the shallower rocks.
- ☐ Chlorite and hematite are the most common widespread secondary minerals in the well, though in small amounts. Quartz was found from 300 meters depth to well-bottom, as was calcite. The calcite concentration however decreases as depth increases, and disappears at the well-bottom. Pyrite appears from 650 meters to well-bottom (Figure 2b). The presence of calcite and pyrite seem to indicate degassing due to boiling processes.
- ☐ Clay minerals were observed throughout the well, but they are absent from 1850 to 2250 meters, They are replaced by K-mica which has a coarser grain size (Figure 2b).
- ☐ The prograde metamorphism which increases with depth and temperature is reflected in the calc-silicate mineral zoning (Viggiano, 1989).

Ranges of measured temperatures, depths and typical associations encountered in the mineral zones are as follows (Figure 2b):

*Zeolite zone.*- This zone is found below 300 meters in depth, at measured temperatures between 100 and 215°C. Observed mineral assemblages in this zone include:

Quartz + chlorite + calcite (often hematite)
Quartz + zeolites (except wairakite) + calcite + hematite (often pyrite).

*Epidote zone.*- This extends from the depth of first appearance of epidote, at 950 meters, to 2250 meters, with measured temperatures between 215 and 285°C. Typical mineral associations are:

Epidote + quartz + chlorite (penninite)
Calcite + chlorite (penninite) + quartz
Quartz + epidote + chlorite + pyrite
Unidentified clay minerals + quartz
Calcite + wairakite + quartz + pyrite
The latter was observed only in the interval between 910 and 920 meters. Epidote and pyrite are quite oxided.

*Amphibole-garnet zone.*- The first downhole occurrence of hydrothermal amphibole characterizes the upper limit of this zone. It occurs from 2250 meters depth, at 285°C, to well-bottom (2900 meters), at >300°C (Figure 2b). The mineral assemblages are:

Epidote + amphibole + pyrite
Amphibole + garnet + epidote + K-mica
Epidote + pyrite + garnet
Chlorite + K-mica + amphibole + epidote + garnet
Epidote + chlorite + amphibole + hematite
Hydrothermal biotite occurs from 2790 to well-bottom (2900 meters) (Figure 2b). Young generations of calcite were observed within this zone, probably indicating some boiling took place.

The expected temperature for calc-silicates formation are higher than those measured at the well, so that a cooling of at least 25°C on average is suggested. However, because of the evident self-sealing, this temperature decline is rather low indicating that it was not enough to define a conductive zone.

The observed hydrothermal alteration was produced by alkali chloride waters of near neutral pH. Temporary acid conditions can be inferred at the amphibole zone, where K-mica was recognized, thus indicating that there was a changing fluid in this zone in terms of aca/a H ratio and of $CO_2$ behavior (see Bird *et al.*, 1983). On the other hand, the presence of calcite implies that altering water also contained a considerable amount of dissolved $CO_2$ which decreases with depth. Additionally, the geothermal fluid also had $H_2S$ as indicated by the presence of pyrite.

## FLUID INCLUSIONS

Most of the fluid inclusions reported in this study were taken from González *et al.* (1989). The rest were performed during a sabbatical visit of one of the authors to the Geothermal Institute of the University of Auckland, New Zealand (Figures 3 and 4).

González's measurements were carried out in epidote, quartz and calcite crystals from seventeen points, but only fifteen of those are used in this paper (Figure 3). Results indicate that (temperature of homogenization) values increase with depth, displaying a large range especially between 1000 and 2300 meters depth, where the epidote zone occurs. Tm (temperature of ice melting) values also show a large range (see Figure 4). Those temperatures variations would be due to variations in liquid/vapor ratios as well as in the $CO_2$ content, both characteristic products of boiling. By contrast, below 2300 meters depth both Th and Tm values present a narrow range, probably indicating that boiling did not occur or it was less common.

Viggiano's samples include only three sample locations (Figures 3 and 4).

Secondary inclusions in quartz were observed at 1150 meters depth, with different liquid/vapor (L/V) ratios and even pure vapor inclusions. The homogenization temperatures range from 160 to 212°C with a mean value of 181°C. The ice melting temperatures vary from -0.6 to -0.7°C. These values imply variations in solute molalities in terms of $CO_2$ in the geothermal fluid, as was mentioned before.

Small liquid-rich fluid inclusions in calcite were analyzed, with Th values ranging between 208 and 292°C and Tm values from -1.1 to -2.6°C. This indicates that the $CO_2$ content is high, and in turn it could be interpreted as the boiling rate was variable thus yielding different rates of $CO_2$ in the trapped bubbles.

Some liquid-rich fluid inclusions in hydrothermal quartz at 2750 meters depth were also studied by González *et al.* (1989). Their Th fluctuate from 287 to 330°C, and their Tm vary from -0.4 to -0.5°C. These relatively low variations suggest that geothermal fluid partition in terms of liquid plus vapor, if any, was poor.

## SOME INTERPRETATIONS

As was mentioned before, based on Figure 3 it is possible to detect a cooling of 25°C at least, assuming 250°C as the formation temperature for epidote, and 300°C for amphibole and garnet (Bird *et al.*, 1983). This cooling, however, seems to decrease below the amphibole-garnet zone: the measured, Tm and calc-silicates (garnet) formation temperatures tend to be coincident at the well-bottom.

The cooling is probably due to the fact that $CO_2$ in the geothermal fluid influences the boiling temperatures, especially when NaCl predominates (Hedenquist and Henley, 1985). Thus, above the upper limit of the garnet-amphibole zone different rates of $CO_2$ were trapped into the fluid inclusions during boiling, which is reflected by the melting temperatures. In contrast, low partition of $CO_2$ is observed within the garnet-amphibole zone, reflecting lack or scarce boiling.

That systematic decrease of calcite (Figure 2b), which is formed by a degassing process deeper in the well, seems to provide additional supporting evidence for the boiling model proposed: the deeper the depth, the less boiling. Besides, the mineral assemblages containing garnet, found in the garnet-amphibole zone, imply a low $CO_2$ pressure at over 300°C (Giggenbach, 1981) which is the theoretical temperature in this zone. The presence of other minerals such as epidote, K-mica and even some calcite, found together with garnet, indicate that boiling was also present there, but was minor.

On the other hand, according to Hedenquist and Henley (1985) the fluid evolution can be found out by plotting measured Tm versus Th, as is shown in Figure 4. The apparent salinities were taken form Simmons and Browne (1990). The hydrothermal zoning based on calc-silicates expected temperatures has also been depicted in that figure.

Despite the values appear to be very scattered, three paths can be noted: boiling and gas loss, boiling, and dilution. All of them lead to cooling as the fluid moves up.

Based on those patterns, it can be inferred that the calc-silicates (minerals from the epidote and amphibole-garnet zones) were formed in the absence of boiling. So, the high salinities of this zones, obtained from measured Tm, could represent the unboiled fluid. Some lower values are observed, however, indicating a very dilute unboiled fluid in the amphibole-garnet zone.

The boiling and gas loss process produces the remnant fluid which is depleted in $CO_2$, with the resultant mentioned cooling. So, the fluid inclusions trapped during this time display varying amounts of $CO_2$. This process occurred at depth, above the amphibole-garnet zone, and perhaps took place during fracture opening and communication of geothermal fluid with the surface.

Another significant trend of the fluid is dilution. The fluid coming from the amphibole-garnet zone cools as it ascends to the surface, and becomes more dilute due to cool water inflow. The systematic decrease of measured Th and Tm reveal that dilution.

These processes caused the hydrothermal minerals to precipitate suddenly, which reduced the permeability and the zone was self-sealed. The thermal regime once convective became conductive, but because the process was rather fast, the temperatures are still high in the well.

Distribution of the geothermal fluid in this zone of the field seems to be closely linked with the hydrothermal zones. So, the fluid zonation includes a *vapor rich zone*, located above the first occurrence of hydrothermal epidote. This zone has been defined with petrophysical support (Viggiano and López, 1990). The following *two-phase zone* is found within the epidote zone, and a *single phase liquid zone* is found within the amphibole-garnet zone.

On the other hand, Tm values of nearby wells A-13 and A-43, which are producing from the epidote zone, were plotted on Figure 4. These values support the fact that in the epidote zone Tm is due to $CO_2$, although this gas was depleted in those wells because the analysis were made from degassed production fluids, but Tm was calculated from the NaCl content, which remains in the fluid even in degassing conditions. Thus, the apparent high salinities in the epidote zone must be explained by $CO_2$-enriched fluid inclusions during boiling, rather than itself high salinities fluids. Table 1 summarizes the estimated data of wells A-29, A-13 and A-43.

## CONCLUSIONS

The salinity of the unboiled fluid for the case of well A-29 can be estimated from fluid inclusions in the amphibole-garnet zone. Boiling occurs seldom and $CO_2$ is still absent in this zone, and then the measured Tm values are due to salinity. This zone seems to contain only liquid but does not produce, and seems to behave as an aquitard.

By contrast, within the epidote zone the salinity can not be estimated from measured Tm, because boiling is intense and $CO_2$ is the predominant solute. This zone contains two phases being, in other wells of the field, the main producing aquifer.

## ACKNOWLEDGEMENT

Authors wish to thank Stuart Simmons for his comprehensive critic and valuable suggestions on the first version of this paper.

## REFERENCES

Bird, D.K., Schiffman, P., Elders, W.A., Williams, A.E., and McDowell, S.D., 1984. Calc-silicate mineralization in active geothermal systems. *Economic Geology*, 79, pp. 671-695.

Giggenbach, W.F., 1981. Geothermal mineral equilibria. *Geochimica and Cosmochimica Acta*, 45, pp. 393-410.

González P., E., Nieva G., D. y Barragán R., R.M., 1989. Estudio detallado de Las inclusiones fluidas en el sistema hidrotermal activo del campo geotérmico de Los Azufres, Mich. *Geotermia*, Vol. 5, No. 1.

Lemieux, M.N., Moore, J.N., González P., E., Izquierdo, G., and Huitrón E., R., 1989. Chemistry of Los Azufres reservoir fluids; data from fluid inclusions. *Proceedings of Symposium in the field of geothermal energy*. San Diego, CA.

Razo M., A., Huitrón E., R., Moore, N.J., Tripp, C.A., and Lemieux, M.N., 1989. Stratigraphy of the Los Azufres geothermal reservoir. *Proceedings of Symposium in the field of geothermal energy*. San Diego, CA.

Simmons, S.F., and Browne, P.R.L., 1990. Mineralogic alteration and fluid-inclusion studies of epithermal gold-bearing veins at the Mt. Muro prospect, Central Kalimantan (Borneo), Indonesia. *Journal of Geochemical Exploration*, 35, pp. 63-103.

Viggiano G., J.C., 1982. Petrografía, mineralogía primaria y mineralogía hidrotermal en los pozos A-9 y A-29 (Los Azufres): Evidencias de autosellamiento. *Primera Reunión Interdisciplinaria de Actividades sobre el Campo Geotérmico de Los Azufres, Mich.*, pp. 38-42.

Viggiano G., J.C., 1987. Régimen de flujo en base a mineralogía autigénica en el campo geotérmico de Los Azufres, Mich. *Geotermia*, Vol. 3, No. 3.

Viggiano G., J.C., y López de N., M., 1990. Volúmenes de fluido y régimen de flujo en la zona sur del campo geotérmico de Los Azufres, Mich. CFE, Internal report. Unpublished.

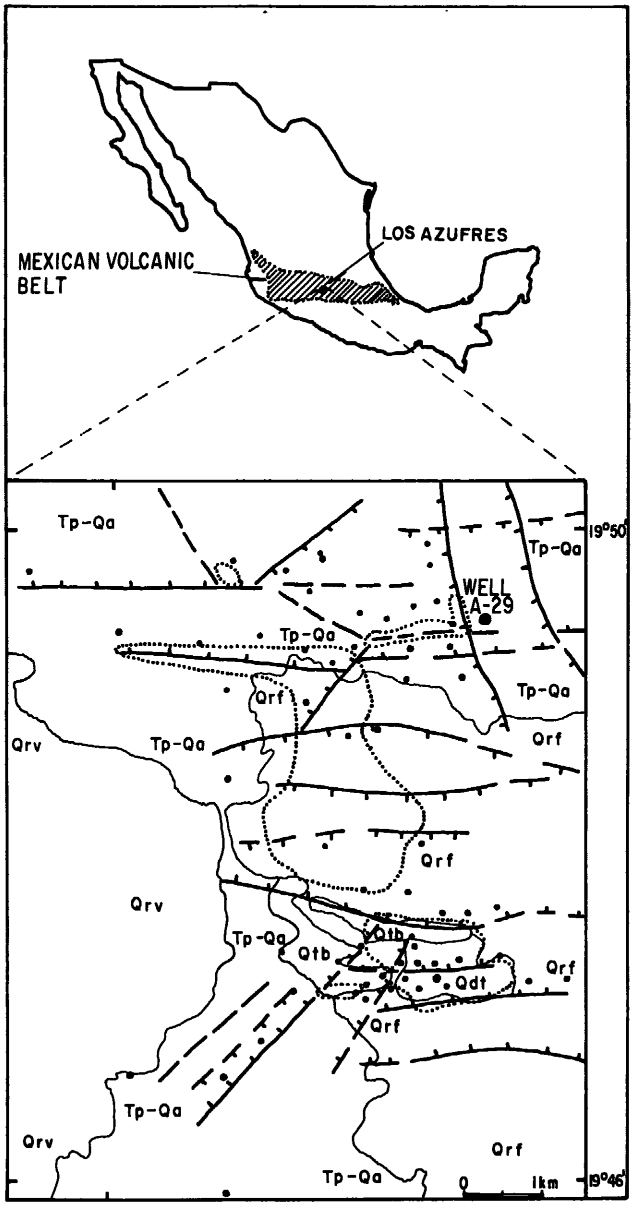

Figure 1 - Location of the Los Azufres field and of the well A-29

Fault, Fracture, Alteration zone, Well. Qrv: Yerbabuena Rhyolite, Qrf: Agua Fría Rhyolite, Qtb: Agua Fría Tuffs, Qdt: Tejamaniles Dacite, Tp-Qa: Basement andesites.

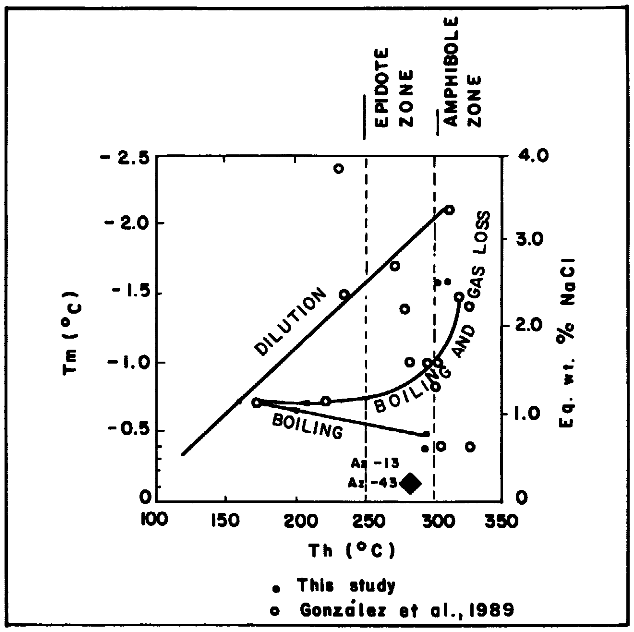

Figure 4 - Ice melting temperatures (Tm) against homogenization temperatures (Th) showing several fluid paths in the well A-29

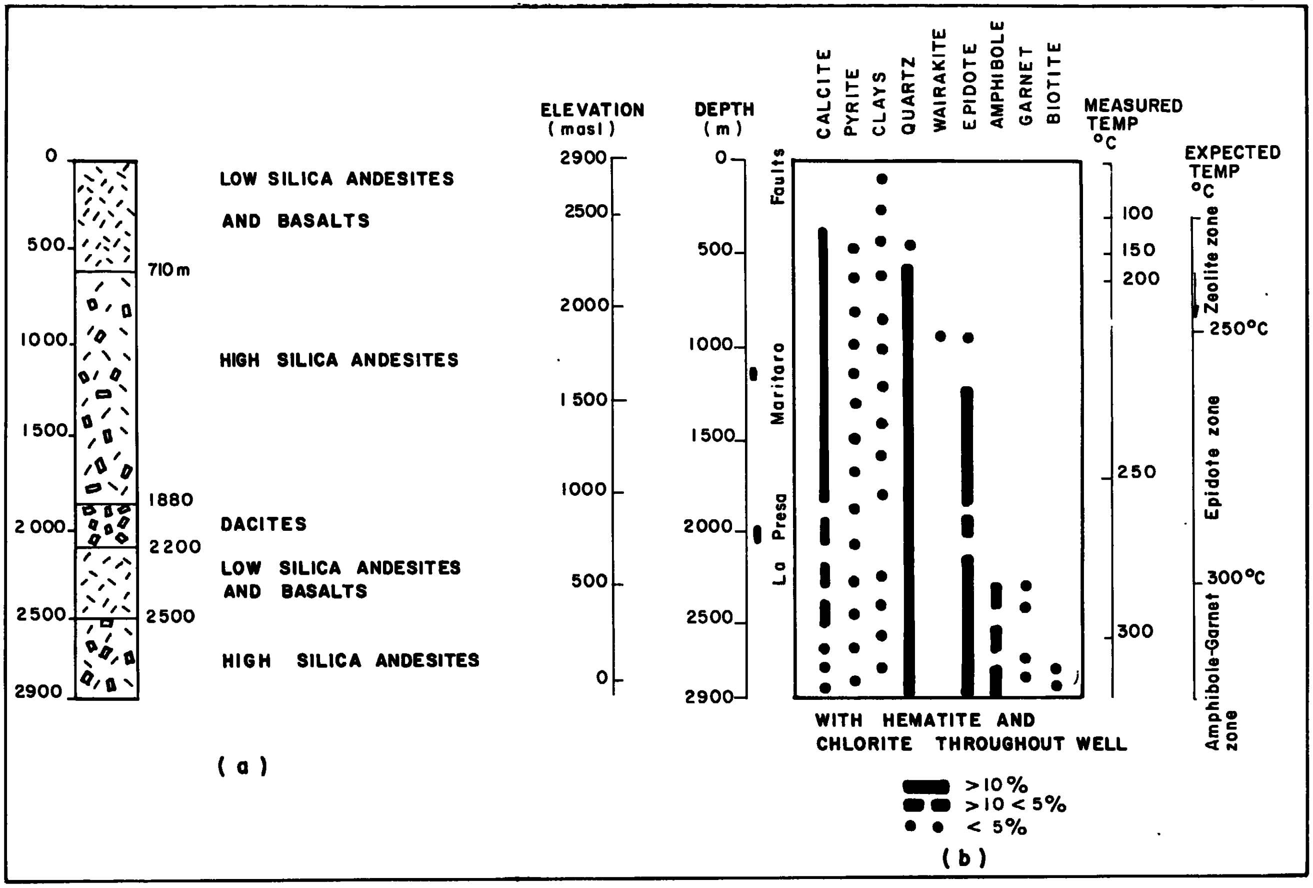

Figure 2 - Lithological column and hydrothermal mineralogy at the well A-29
(a) Primary petrology. (b) Hydrothermal Mineralization with respect to depth, measured temperatures and expected temperature according to hydrothermal zones. This figure was modifield from Viggiano, 1983.

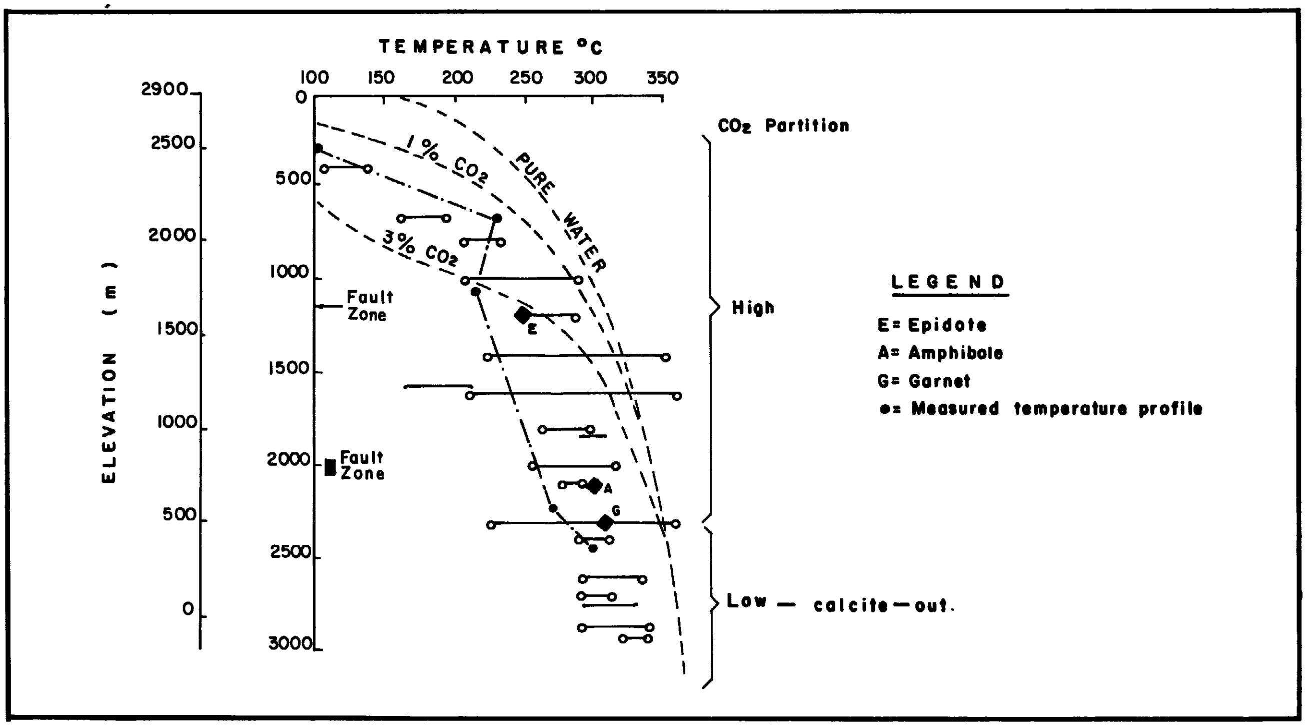

Figure 3 - Comparison of temperature at the well A-29
The homogenization temperature profile (minimum and maximum for every depth) is compared with measured temperature profile and with the expected temperature as the first occurrences of calc-silicates. The boiling point curves were taken from Lemieux et al. (1989).

| WELL | PRODUCING ZONE | MEASURED TEMPERATURE | NaCl | m $CO_2$ |
|---|---|---|---|---|
| A-13 | 1200 m | 280°C | 0.34 Eq. wt. % | 0.0013 |
| A-43 | 1700-1800 m | 281°C | 0.38 Eq. wt. % | - |
| A-29 | No | Epidote zone: >250°C<br>Amph.-garnet zone: > 300°C | Epidote zone: >0.5>3.0<br>Amph.-garnet zone: >0.5<4.0 | Epidote zone: 0.01-1.0<br>Amph.-garnet zone: <0.1 |

Table 1 - Some characteristics of the wells A-13 and A-43, compared with the well A-29