Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

TECTONIC CHARACTERISTICS OF THE GEOTHERMAL ZONE OF PATHÉ, MEXICO

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Key Words: exploration, tectonics, Pathé geothermal zone, geology, Mexico.

ABSTRACT

In the geothermal zone of Pathé, located in the central part of Mexico, the first geothermal power plant on the American Continent was installed in 1959. This plant, of 3500 kilowatts, had to be abandoned because the steam was not enough. However, an important geothermal resource could be at greater depths than reached by former wells. Some hot springs and extensive alteration zones outcrop in Pathé, with superficial temperatures higher than 35°C, while the temperatures in the old wells were in excess of 250°C. The outcropping rocks can be grouped in four units: Unit I, consisting of sedimentary and volcano-sedimentary rocks of Mesozoic to Early Tertiary ages; Unit II, composed by intrusive (granodiorite to diorite) rocks of Eocene-Oligocene ages; Unit III, made up volcanic and sedimentary (lacustrine) rocks, whose age is Late Miocene; and Unit IV, mainly composed of volcanic rocks of Plio-Quaternary age. At the geothermal zone, the most recent outcropping rocks are andesites and basalts dated at 6.2 million years (My). Thus, the zone is located out of the Mexican Volcanic Belt province. Four deformation phases were identified, mostly on rocks of Unit III. The oldest is a tensional phase producing normal faults with an almost E-W trend. The second was produced by compressive and tensional stresses, which formed some lateral faults with variable trends and some normal NE-SW faults. The third deformation event was of the distensive type, producing normal faults with a N-S to NNW-SSE trend, including the formation of the Graben of Pathé. The most recent phase was also tensional, with normal faults of an E-W direction, and took place between 6.2 and 4.2 million years ago. The Pathe geothermal zone is found at the eastern side of the Graben of Pathé, which is oriented N-S and is some 10 km wide, aged between 7 and 6.2 My. The hot springs and alteration zones are related to the intersection of the E-W (fourth phase) and N-S (third phase) faults. The probable deep geothermal system could be related to those structural intersections, and its fluids could be contained in the fractured rocks of units III and I.

1. INTRODUCTION

The geothermal zone of Pathé is located in the central part of Mexico (Fig. 1). It was the first geothermal zone explored in Mexico. Between 1950 and 1955 some geological studies were done by the former Geothermal Energy Commission (GEC), an official agency of the Mexican government, later integrated with the Comisión Federal de Electricidad (CFE).

In August 1955, drilling of the first exploration well started, which produced hot water and steam in January 1956. Between 1956 and 1960 the GEC drilled 24 wells, at depths from 195 to 1288 m (Maciel, 1982). Three of them were successful, and one geothermoelectric unit of 3.5 MW_e was installed in 1959 (Milán and Herrera, 1987).

This geothermal plant, the first on the American Continent, was in operation until 1972, at an annual average of 15-20% of its nominal capacity. Then, it was abandoned and dismantled. During this time, the unit used the dry steam produced by just one well, well 2-A, because the other two wells stopped production (Milán and Herrera, 1987).

From 1981 to 1984 new exploration studies were carried out in the zone by the CFE, including: geology (Herrera and Milán, 1981; Maciel, 1982), electrical soundings (López and Campos, 1982; Arroyo, 1982), gravimetry (Ballina, 1982, 1983), magnetometry(Campos, 1982, 1983), and geochemical analyses (Bigurra, 1984).

In 1994 the CFE decided to renew its exploration in Pathé. Drilling of a slimhole exploration well to 2000 m depth was programmed, but drilling had to stop at 429 m depth. Since then, no further studies have been conducted. However, the Pathé geothermal zone seems to present important tectonic and structural features that are favorable to the presence of a high temperature reservoir at the subsurface, whose main evidence is well 2-A. These tectonic and structural characteristics are presented in this paper.

2. LITHOLOGICAL UNITS

Around 17 lithological units outcrop in the Pathé geothermal zone and its surroundings. They were grouped into four main units, according to the tectonic and volcanic evolution of the region: Units I, II, III and IV (Fig. 2).

Unit I is the Mesozoic-Early Tertiary Basement. It consists of Mesozoic rocks belonging to the Sierra Madre Oriental Province and some volcano-sedimentary series of Paleocene-Eocene age. This unit outcrops in the northern and northeastern portion of the studied region (Fig. 2). Some rocks belonging to Unit I are also observed at the bottom of the Rio San Juan canyon, near the geothermal zone. Rocks of Unit I include massive limestones, epiclastic and volcanic rocks, the oldest of which were affected by the compressive stresses of the Laramide Orogeny (Early Tertiary). The youngest epiclastic rocks of this unit are erosive products of the mountains formed during the orogeny.

Unit II is composed of intrusive rocks outcropping in the eastern portion (Fig. 2). They are granodiorites to diorites and intrude to limestones of Late Cretaceous age. Similar rocks, that correlate to these ones, have been dated at 40-50 My (Pasquaré *et al.*, 1988). The rocks of Unit II are the product of a post tectonic magmatic event, whose emplacement could have been propitiated by a tensional stress following the Laramide Orogeny between Late Eocene and Early Oligocene.

Unit III includes several volcanic units and one extended sedimentary unit, composed of lacustrine and fluvial lacustrine sediments (Fig. 2). All of them are of Late Miocene age, from 9 to 6.2 million years ago. However, some outcroppings of andesites and rhyolites grouped in this Unit III are in the eastern part of the area (Fig. 2). These rocks lie over limestones or epiclastic rocks of Unit I, and could be correlated to similar rocks of the so-called Grupo Pachuca. In this case, their age could be Oligocene-Miocene.

Unit III presents the following sequence, as can be seen in the canyon of the Rio San Juan and other locations in the region: At the base, andesites, basalts and some rhyolites and pyroclastics aged between 9 and 7.5 My. Overlying these rocks are extensive deposits of lacustrine and fluvial lacustrine sediments, whose age is probably between 7.5 and 6 My. Finally, there are basaltic and andesitic lavas, extruded by spatter cones, dated at 6.4 to 6.2 My.

Volcanic rocks and some lacustrine deposits of Plio-Quaternary age were grouped in Unit IV. This unit outcrops in the southern portion of the studied region, and in some small, isolated locations (Fig. 2). Most of the outcrops shown in Figure 2 are ignimbrites (San Francisco Ignimbrite) related to the collapse of the Huichapan Caldera located further south, beyond the limits of Figure 2. Eruption of this ignimbrite occurred more than 4.3 million years ago. The only northern outcrop of Unit IV (Fig. 2) consists of basaltic andesites. Other rocks grouped in Unit IV include caldera and post- caldera products of the Huichapan Caldera, such as the Don Guiñó Ignimbrite, rhyolitic and dacitic domes and some andesitic lava flows. Lacustrine sediments, deposited between the eruption of both ignimbrites, and basaltic andesites are also grouped in Unit IV.

All the rocks of Unit IV belong to the Mexican Volcanic Belt (MVB) province, which is the main regional volcanic feature of Mexico. The MVB is composed of volcanoes and volcanic products of Plio-Quaternary age, and includes three of the five Mexican geothermal fields: Los Azufres, Los Humeros and La Primavera. It should be noted that the geothermal zone of Pathé is located outside the MVB.

3. TECTONIC AND STRUCTURAL FEATURES

Some field observations were conducted on the structural features of the limestones of Unit I, confirming the compressive stress related to the Laramide Orogeny. Particularly interesting is the ramp and flat tectonics affecting the Cretaceous limestones of the El Doctor Formation, which produced an important cortical shortening (Carrillo and Suter, 1982). Another interesting tectonic characteristic implied by Unit I is that the Laramide Orogeny seems to have finished with a strike-slip faulting that displaced all the previous reversed fault planes. However, the main field work was done on rocks of Unit III, in which the geothermal zone is located. Fourteen micro-structural stations were set up on rocks of this unit, the most representative of which are shown in Figure 3. Interpretation of these stations leads to the conclusion that four main deformation stages took place in the area.

The first deformation phase was of the distension type, with a maximum tensional stress oriented NE 20° SW, as shown in Figure 3. This tensional stress produced normal faults with several trends, but in general almost E-W. Faults of this phase were recognized in micro structural station number E-16, located on limestones of Unit I (Fig. 3). Data from station came from three major normal faults, whose dips are between 40 and 80°. The low angle dips, which are not common in normal faults, are explained by further movements (fourth deformation phase) of the whole block. Therefore, these fault planes are not in their original position.

The second phase of deformation seems to be more complex than the first. It started with a main compressive stress of a NE 60° SW direction (station E-15, Fig. 3), forming strike-slip faults. Right-lateral faults present strikes from N-S to N 40° E, and the left-lateral ones from N 40° W to N 80° W. This disposition of the lateral faults also implies a further tensional stress of NW 30° SE (stations E-1 and E-15, Fig. 3). These compressive and then tensional stresses have been recognized at other localities in Chapala, Jal., Cuitzeo and Tierra Caliente, Mich., and Querétaro (Pasquaré *et al.*, 1988). The second phase seems to finish with a new tensional stress, but now oriented NW 70° SE (stations E-10 and E-14), forming normal faults of a NE-SW trend.

The third deformation phase was also distensive, with its maximum stress oriented NE 60-80° SW (stations E-1 and E-7, Fig. 3). This stress produced normal faults with a N-S to NNW-SSE trends, including the Uxdehjé and Las Rosas faults that form the Pathé Graben where the geothermal zone is located. The so-called Pathé fault was also formed in this phase. At locations of the neighboring state of Querétaro, faults produced in this phase cut basaltic lavas dated at 7 My, so that the deformation is younger than it, but older than the fourth phase.

The fourth phase of deformation is the most evident. It is of the tensional type, and affects lacustrine sediments and some basalts of Unit III. These basalts are dated at 6.2 My. The main tensional stress varies from NE 20° SW to NW 30° SE, and produced normal faults with an E-W trend (stations E-3, E-5 and E-15, Fig. 3). Tensional stresses also caused some inclination on rocks and previous faults, specially the faults from the first deformation phase. Faults originated by this fourth phase have high angle dips (almost vertical), and cut the N-S and NW-SE faults from the third phase. None of the faults cut the ignimbrites of Unit IV, and thereafter the deformation had to occur between 6.2 and 4.2 million years ago.

Summarizing, besides the tectonic events that affected rocks of Unit I, from Late Miocene to Early Pliocene four distinct deformation phases occurred in the area. Therefore, all of the rocks have been affected by important stresses, most of them of tensional type. This means that subsurface rocks of the geothermal zone must present extensional fractures to contain the probable geothermal fluids, even though there is no evidence of fracturing more recent than 4.2 million years ago.

4. GEOTHERMAL FEATURES

There are some hot springs and former fumaroles with temperatures between 32 and 39°C located on the margins of the Río San Juan (Fig. 3). The geothermal well 2-A, which was supplying steam to the geothermal unit while it was in operation, has emitted until now some steam at 99°C. There are also three shallow wells, drilled for groundwater, with temperatures around 33°C; they are located south of Pathé and west of Tecozautla.

Extensive hydrothermal alteration zones have been identified in the area. In the surroundings of well 2-A one can see a wide alteration zone composed of clay minerals (kaolin) and silicic deposits (sinter), with isolated veinlets of hydrothermal gypsum. In the western part, far from Pathé, there is another extended deposit of kaolin.

Chemical analyses on water from hot springs conclude that they are bicarbonate-sodium (Herrera and Milán, 1981). The temperatures of these waters, calculated by geothermometry, are as follows: Na-K-Ca: 190°C, Na-K: 214°C, and SiO_2: 196°C (Maciel, 1982; Bigurra, 1984). There are no recent data from gas geothermometry, but the following gases have been identified: N_2, CO_2, H_2S, CH_4, and H_2.

Measured temperatures from wells are not reliable because of the methods with which they were recorded, but the available data are as follows (Maciel, 1982):

Well	Depth (m)	Max. Temp. (°C)
1	238	260
2-A	279	289
3	285	160
6	370	103
7	220	150
8	180	150
9	274	73
10	372	110
11	125	100
12	772	132
13	344	149

Some wells present reversions of temperature (wells number 3, 7 and 8). In some cases, wells near to one another show quite different temperatures (wells 8 and 10, 2-A and 13).

Petrographic and X-ray diffraction analyses on core samples from some wells and on superficial samples, indicate the following alteration minerals (Maciel, 1982): quartz, kaolin, montmorillonite, illite, chlorite (chamosite), anhydrite, calcite, epidote, magnetite, zeolites (analcite, stilbite) and other clay minerals. Except for epidote, the mineralogical associations are typical of low to medium temperature geothermal systems.

5. CONCLUSIONS

The geothermal zone of Pathé is located at the eastern border of a N-S graben, limited by the Uxdehjé and Las Rosas faults. This graben was formed during the third phase of deformation identified on the rocks of the area, between 7 and 6.2 million years ago.

The superficial geothermal manifestations are related to the intersection of structures of a N-S trend with structures of an E-W trend, the latter produced by the fourth deformation phase, between 6.2 and 4.2 million years ago. In fact, faults of the E-W trend seem to be deeper than the N-S trending faults, as suggested by their almost vertical dips.

Between 9 and 4.2 million years ago, the geothermal zone was affected by four distinct phases of deformation, most of them with a maximum stress of the tensional type. This suggests that subsurface rocks can be highly fractured, so presenting a good secondary porosity and permeability. Actually, there is no evidence for either volcanic or tectonic activity more recent than 4.2 My. However, the extension of the hydrothermal alteration zones, the subsurface temperatures and the fact that well 2-A produced steam over several years, at 289°C from less than 300 m depth, are very interesting conditions. It is probable that a geothermal reservoir could exist at depths of around 2000 m. This reservoir would be related to structures produced by the fourth deformation phase, and would be contained in volcanic rocks at the base of Unit III, and/or in limestones of Unit I. Therefore, drilling of a deep exploratory well to 2000 m is recommended.

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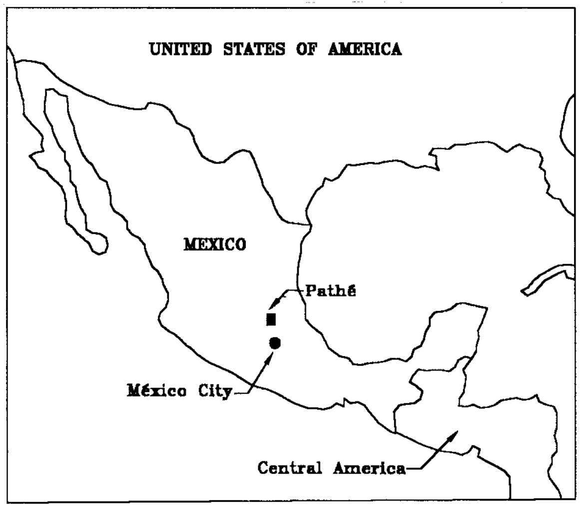

Figure 1. Location of the area.

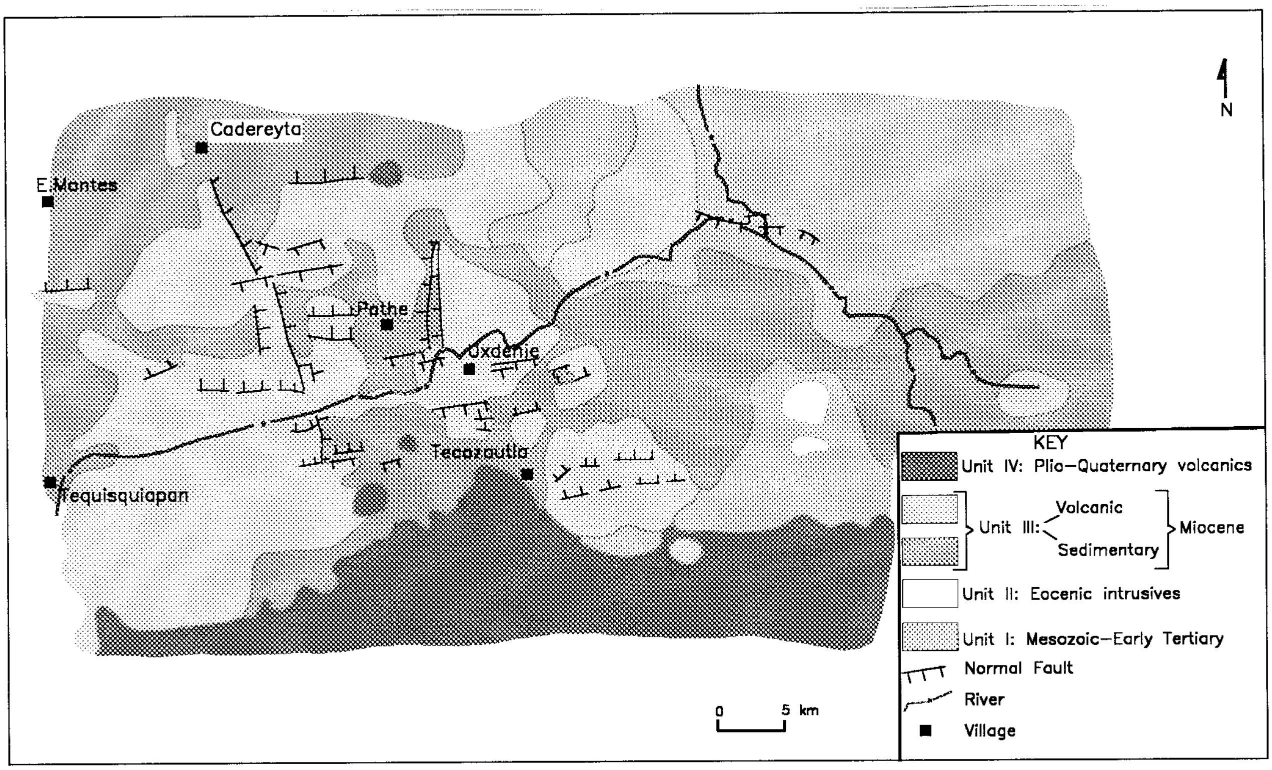

Figure 2. General geology of the area

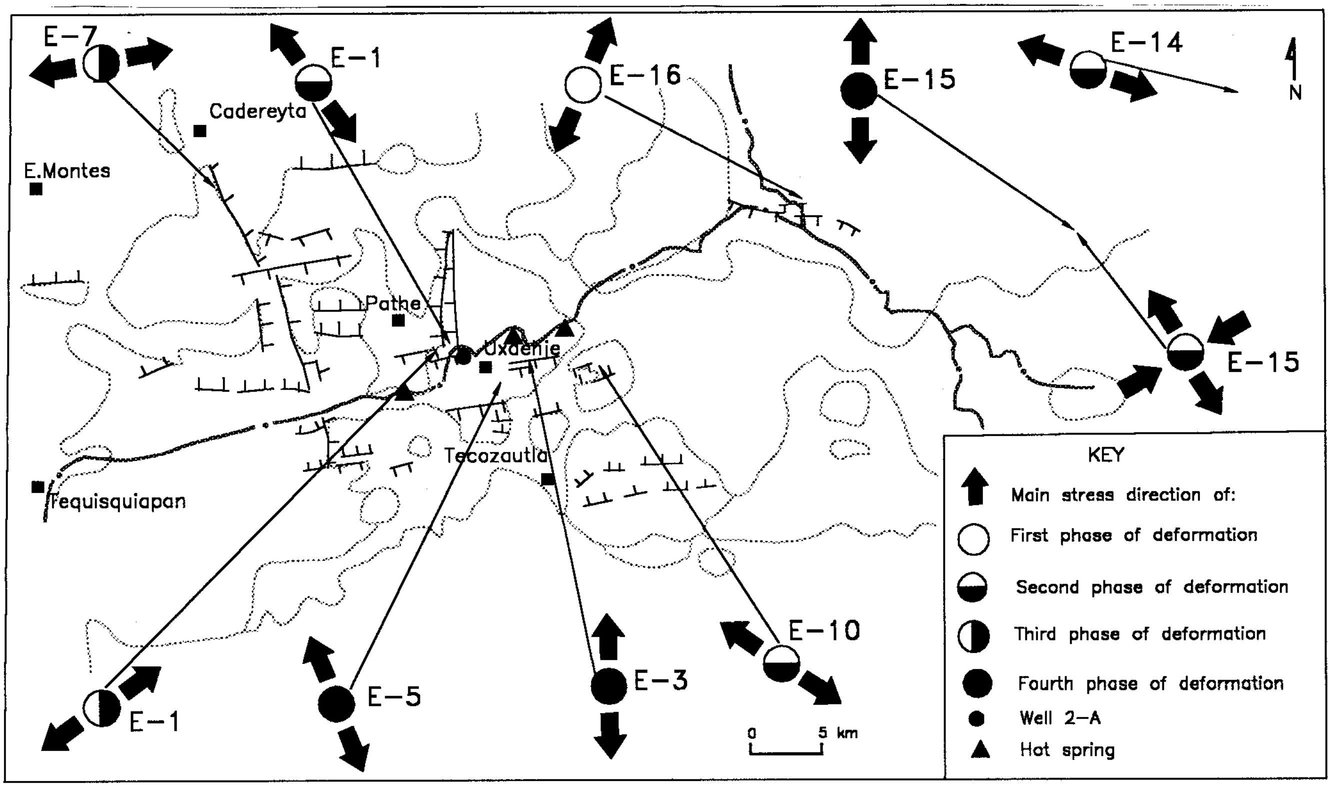

Figure 3. Micro structural stations in the area, and phases of deformation