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GEOLOGIC AND PRELIMINARY RESERVOIR DATA ON THE LOS HUMEROS GEOTHERMAL SYSTEM, PUEBLA, MEXICO.

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ABSTRACT

Exploratory drilling has confirmed the existence of a geothermal system in the Los Humeros volcanic center, located 180 km east of Mexico City. Volcanic activity in the area began with the eruption of andesites, followed by two major caldera-forming pyroclastic eruptions. The younger Los Potreros caldera is nested inside the older Los Humeros caldera. At later stages, basaltic andesite, dacite, and olivine basalt lavas erupted along the ring-fracture zones of both calderas.

Geologic interpretation of structural, geophysical, and drilling data suggests that: (1) The water-dominated geothermal reservoir is hosted by the earliest andesitic volcanic pile, is bounded by the ring-fracture zone of the Los Potreros caldera, and is capped by the products of the oldest caldera-forming eruption. (2) Permeability within the andesitic pile is provided by faults and fractures related to intracaldera uplift. (3) The geothermal system has potential for a large influx of meteoric water through portions of the ring-fracture zones of both calderas. (4) Volcanic centers with similar magmatic and structural conditions can be found in the eastern Cascades, U.S.A.

INTRODUCTION

The Los Humeros volcanic center (LHVC) is located in the eastern end of the Mexican Neovolcanic Belt, 20 km northwest of Perote, Veracruz. Mild fumarolic activity sparked interest in the geothermal potential of the area in the mid-1960's. Preliminary geological and geophysical reconaissance surveys (Mooser, 1964; Pérez, 1978; Alvarez, 1978) led Mexico's Comisión Federal de Electricidad to undertake an extensive exploration program that included regional geologic mapping (Yáñez and Casique, 1980), detailed geologic mapping of the volcanic center (Ferriz and Yáñez, 1981), resistivity, self-potential, and aeromagnetic surveys (Palacios and Garcia, 1981), geochemical surveys (Molina, 1979), and exploration drilling (Rivera, 1982; López, 1982a; Gutiérrez, 1982).

This paper integrates some of the information collected during the exploration program, under the framework of detailed geologic mapping, to provide preliminary data on the characteristics of the geothermal reservoir.

REGIONAL GEOLOGY AND LOCAL "BASEMENT"

The Quaternary Mexican Neovolcanic Belt is an irregular belt of large andesitic stratovolcanoes, cinder-cone fields, and a few silicic centers, which bisects central Mexico in an east-west direction. Molnar and Sykes (1969) suggested that magmatism along this belt is related to the subduction of the Cocos Plate below Mexico along the Middle America Trench. LHVC is one of several silicic centers located in the "back-arc" portion of the belt. Two other of these silicic centers, Los Azufres and La Primavera (Mahood, 1980), also host significant geothermal systems.

The local basement of LHVC is formed by a Mesozoic sedimentary sequence and Tertiary intrusions and andesites. The Mesozoic rocks (Viniegra, 1965; Yáñez and Casique, 1980) can be divided in a Triassic to Middle Jurassic clastic sequence, and a Middle Jurassic to Upper Cretaceous sequence of marls and limestones of inferred low permeability.

GEOLOGIC HISTORY

The oldest exposed rocks at Los Humeros are dense porphyritic to sparsely porphyritic andesite and basalt flows of the Teziutlán Formation. K-Ar age determinations on these flows range from 3.5 ± 0.3 to 1.6 ± 0.07 Ma. These flows crop out in the northern portion of LHVC, but similar rock types have been found during drilling in its central and southern portions. Similar rock fragments are common in all the younger pyroclastic units. Thus, these andesite and basalts seem to have covered most of the area now occupied by LHVC. Mapping of flow directions, breccia pipes, and fossil hydrothermal alteration zones indicates that the vents for these flows were located in the area now occupied by LHVC. This inference is reinforced by an increase in the thickness of the Teziutlán Formation from 60 m in the northern outcrops to more than 1000 m in a borehole drilled in the central portion of LHVC (H-4 in Figure 1). It is in these dense and brittle rocks that fluid production has been found during exploration drilling.

The onset of silicic volcanism is marked by the intrusion of two high-silica rhyolite domes, one of which has been K-Ar dated at 0.5 ± 0.03 Ma. Later eruption of the 180 km^3 rhyolitic (76% SiO_2) to rhyodacitic (71% SiO_2) Xáltipan Ignimbrite led to the collapse of the Los Humeros caldera (LHC in Figure 1). The rim of this 21 by 15 km caldera is covered by younger volcanic rocks, so its configuration has been determined by the location of ring-fracture volcanism, as well as by topographic expression. Given the volume of magma equivalent to the Xáltipan Ignimbrite (≈90 km^3) and the area of the caldera, one can estimate the average amount of collapse as 350 m. Nowhere is the Xáltipan Ignimbrite exposed inside the Los Humeros caldera, but a 200 m-thick moderately welded ignimbrite found at 965 m depth in the H-1 borehole could be its intracaldera equivalent.

After collapse, several high-silica rhyolite domes were emplaced along the northwestern, northern, and southern (?) portions of the inferred ring-fracture zone. Their emplacement was followed by the eruption of more than 2 km^3 of rhyodacitic (72-69% SiO_2) air-fall tuffs.

The eruption of the 20 km^3 rhyodacitic (70% SiO_2) to andesitic (59% SiO_2) Zaragoza Ignimbrite resulted in the formation of the 10-km-diameter Los Potreros caldera (LPC in Figure 1), nested within the older Los Humeros caldera. Its eastern and western topographic walls can still be recognized in the field, but the northern and southern portions of the caldera rim have been obliterated by younger ring-fracture volcanism. A minimum of 200 m of collapse has been estimated from reconstruction of precaldera topography. Outflow sheets of the Zaragoza Ignimbrite tilted up to 12°, and postcaldera lavas that flowed radially away from Los Potreros caldera, indicate doming of the caldera and its surroundings shortly after collapse.

Although stratigraphic relations are unclear, it seems that after collapse a small basaltic and andesitic volcanic edifice occupied the central portion of the Los Potreros caldera. This edifice was later intruded by a biotite rhyodacite dome.

After the emplacement of the Zaragoza Ignimbrite an arc of basaltic andesite scoria cones developed along the southern ring-fracture zone of the Los Humeros caldera (Figure 1). The cinder cones fed approximately 4 km^3 of basaltic andesite (56-59% SiO_2) lava that flowed south of LHVC. Similar lavas erupted from two small shield volcanoes located between the eastern and northeastern rims of the two nested calderas. The lavas from these volcanoes, which flowed radially away from the Los Potreros caldera, have a total volume of ≈2 km^3.

Activity continued with the eruption of 10 km^3 of dacitic (68-69% SiO_2) flows from centers located along the northern, eastern, and southern portions of the ring-fracture zone of the Los Potreros caldera. The simultaneous venting of dacitic and andesitic tephra, approximately coeval with the eruption of the earliest dacite flows, led to the collapse of the 1.7-km-diameter El Xalapazco caldera along the south-southeastern ring-fracture zone of the Los Potreros caldera. This eruption was followed by minor fault-bounded uplift of the southeastern quadrant of the Los Potreros caldera, perhaps due to upward movement of magma.

The final stage of volcanic activity at LHVC is represented by the eruption of olivine basalts (49% SiO_2) on the floor of the Los Potreros and El Xalapazco calderas, and along the southwestern ring-fracture zone of the Los Humeros caldera. The total volume represented by these basalts is ≈0.25 km^3.

The apparent erratic composition of the products of LHVC appears to represent tapping of different levels of a magma chamber that was zoned from rhyolite to basaltic andesite in composition, and probably underplated by olivine basalts. This tapping of different levels would be possible only because of the existence of two nested collapse structures of significantly different size, the ring-fracture zone of the larger structure tapping deeper levels of the magma chamber than that of the smaller structure. Perhaps more relevant for the development of the geothermal system is that: (1) the mere existence of the collapse structures suggests that the magma chamber was lodged at a shallow depth, (2) the volume of the eruptive products indicates that the magma chamber was a voluminous one, (3) the long magmatic history implies a prolongued period of heating of the rocks that hosted the magma chamber, (4) the ring-fracture zones of both calderas have persisted as zones of structural weakness or discontinuity for an extended period of time, thus providing favourable structural conditions for the development of a hydrothermal system.

GEOPHYSICAL DATA

Aeromagnetic surveys of the area (Flores et al.,1978; J. Ruiz in Palacios and García,1981) show a change in polarity along the southern ring-fracture zone of the Los Humeros caldera, and a major bipolar anomaly on the northeastern quadrant of the Los Potreros caldera. The center of this bipolar anomaly corresponds with a small gravity high (Mena and González,1978) and, from what is known about the geology of LHVC, could correspond to a swarm of basaltic dikes, to the thick central portion of the eruptive center(s) that fed the Teziutlán andesites, or to an intracaldera intrusion.

Figure 1. Simplified geologic map of the Los Humeros volcanic center. LHC, Los Humeros caldera rim; LPC, Los Potreros caldera rim; caldera rims discontinuous where inferred, dotted where buried. Heavy lines, faults. Triangles, boreholes. Sandstone pattern, Xáltipan Ignimbrite; boulder pattern, Zaragoza Ignimbrite; dashes and "v" patterns, rhyolite and dacite domes; breccia pattern, scoria cones; dash-arrow pattern, basaltic andesites; dash-dot and cross patterns, dacites; arrow pattern, olivine basalts; blank, tuffs younger than the Zaragoza Ignimbrite.

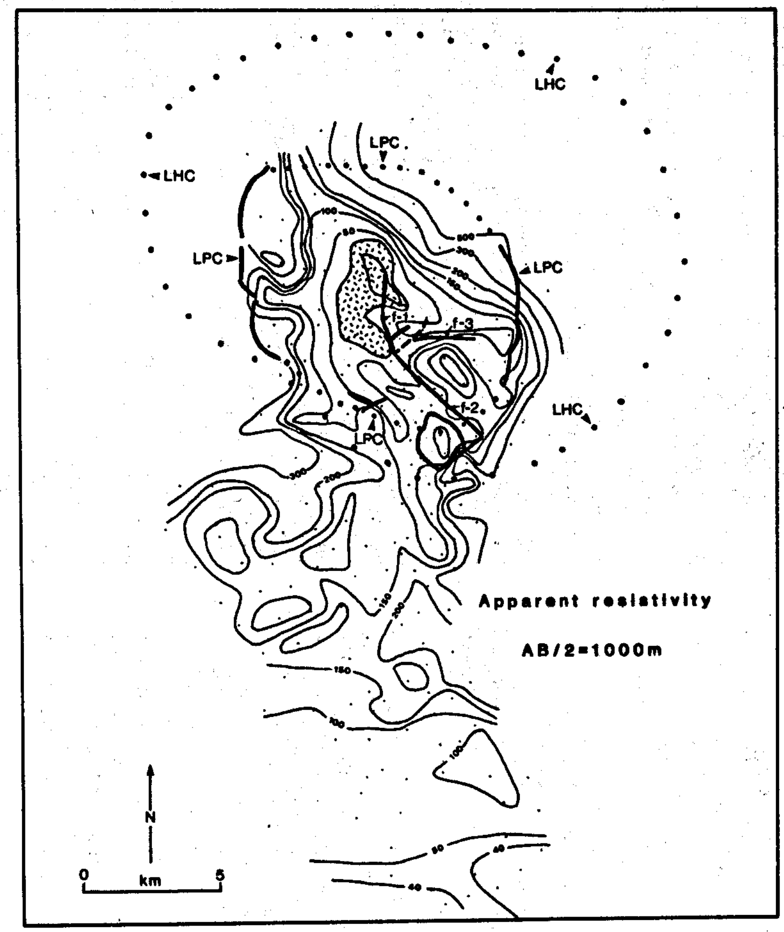

Figure 2. Apparent resistivity isopleth map for AB/2 = 1 km. Resistivities in ohm-m. LHC, Los Humeros caldera; LPC, Los Potreros caldera. Heavy lines, faults. Dash pattern, area enclosed by the 20 ohm-m apparent resistivity contour. Light dots, center of sounding. Modified from Palacios and García, 1981).

The LHVC corresponds with a broad negative low in the residual anomaly gravity map of Mena and González (1978), which they modelled as a ≤ 1-km-thick accumulation of material with an average density of 2.35 g/cm^3 and a density contrast of 0.32 g/cm^3 with respect to the surrounding rocks. An average thickness of 1 km for low-density intracaldera deposits is not unreasonable in the light of the results of boreholes H-1 and H-4 (Figure 1), in which the dense Teziutlán andesites were cut at depths of 1155 m and 874 m respectively. Other negative anomalies around LHVC are attributed to thick accumulations of the outflow sheets of the Xáltipan Ignimbrite.

Palacios and García (1981) reported the results of 184 Schlumberger vertical electric soundings with maximum electrode spacings (AB/2) of 2 km, and 32 soundings with maximum spacings of 4 km. Their results have been used to construct the simplified isopleth map of apparent resistivities, for an AB/2 spacing of 1 km, shown in Figure 2; the major structural features defined by geologic mapping are also shown as heavy lines and dots. A zone of low resistivity, delineated by the 20 ohm-m contour, occupies the central portion of the Los Potreros caldera; the general shape of the low seems to be controlled by fault f-1 and by the northwestward projection of fault f-2. Fault control in the central portion of the Los Potreros caldera seems to be better expressed by the 50 ohm-m contour, spurs of which are aligned along faults f-2 and f-3; however, the major southern spur of this contour does not correspond to any mappable fault or fracture zone. Apparent resistivities increase abruptly toward the rim of the Los Potreros caldera, except at the southern caldera rim and along a narrow "channel" through the northwestern rim. Thus, the Los Potreros ring-fracture zone seems to constitute an impermeable barrier that partially bounds the geothermal system, except for the southward and northwestern "openings", which, as discussed below, may represent zones of meteoric water influx into the system. Structural control by intracaldera faults can still be recognized in apparent resistivity maps with AB/2 of 1.5 and 2 km (Palacios and García, 1981) but, in addition, the southern ring-fracture zone of the Los Potreros caldera seems to become a major controlling structure.

BOREHOLE DATA

Three boreholes have been completed in the area (Figure 1). The data obtained during drilling have been reported by Gutiérrez (1982), López (1982a, 1982b), and Rivera (1982a).

The first exploratory borehole, H-1 in Figure 1, was sited near the intersection of faults f-1 and f-2. In its 1458 m it cut 700 m of intracaldera lavas and tuffs, 265 m of lithic tuff that may correlate with the upper Zaragoza Ignimbrite, 190 m of Xáltipan Ignimbrite, and 303 m of Teziutlán andesites. Two permeable zones, found at 1250 m and 1400 m depth, probably represent the down-hole intersections of faults f-1 and f-2. Maximum temperatures of 270° to 276° C were measured at the depth of the lower permeable zone during initial production tests in September, 1981 (López, 1982a).

The H-1 well is currently producing a 200 tonne/hr steam-water mixture at a wellhead pressure of 14 kg/cm^2 and with an enthalpy of 300 kcal/kg. One analysis of brine collected at atmospheric pressure (López, 1982a) shows, in ppm, Na(I)=265, K(I)=31, Li(I)=5, Ca(II)=1.9, Mg(II)=0.2, B=195, NH_4=7, F(I)=0.4, Cl(I)=100, HCO_3(I)=270, CO_3(II)=120, SO_4(II)=115, SiO_2=480, and pH=8.5. Incondensable gases collected at the wellhead form 0.5% by volume of the steam phase; their analysis (López, 1982a) shows, in mole %, CO_2=87.1, H_2S=0.03, H_2=0.03, and CH_4=0.4.

Borehole H-2 is located near, but on the outside, of the inferred rim of the Los Potreros caldera. According to Gutiérrez (1982), in its 2301 m it cut 495 m of postcaldera lavas and tuffs, 245 m of ignimbrite, 400 m of Teziutlan andesites, and 1161 m of Mesozoic marls. Although bottom temperatures as high as 280° C were recorded no permeable zones were found in this borehole.

Borehole H-4 is located near the northern end of fault f-1, on the down-thrown side of the fault. According to Rivera (1982b), in its 1880 m the borehole cut 108 m of postcaldera tuffs, 766 m of ignimbrite (which may represent the aggregate thickness of the Xáltipan and Zaragoza ignimbrites), and 1006 m of Teziutlán andesites. Because several intervals of circulation loss were found at depths greater than 1000 m, production casing was installed between 1100 m and 1880 m depth. A bottom temperature of 299° C was recorded prior to the start of production tests. The well began producing dry steam at a pressure of 116 kg/cm^2 by September, 1982; pressure soon stabilized at 17 kg/cm^2 and the dry steam flow rate stabilized at 160 tonne/hr. After a short period, however, pressure and flow rate began declining again and, by mid-November, 1982, had values of 4.6 kg/cm^2 and 47 tonne/hr respectively (López, 1982b). The field operators have attributed this decline to plugging of the well during production tests.

Incondensable gases, analyzed during the stage of stable pressure, formed 2.9% by volume of the steam. Their analysis (López, 1982b) shows, in mole %, CO_2=78.5, H_2S=9.4, H_2=11.9, CH_4=0.04, and N_2=0.15.

DISCUSSION

The preliminary geophysical and drilling data can be interpreted in light of the detailed geologic study (Ferriz and Mahood, in prep.) to estimate some of the parameters needed in reservoir engineering, namely the boundaries of the system; the location, nature, and extent of the major permeability controls; and the potential water influx into the system. These parameters will support and complement those obtained through transient pressure analyses once more boreholes are drilled. In the meantime they may prove useful in siting exploration boreholes.

It has already been suggested that the system is bounded laterally by the ring-fracture zone of the Los Potreros caldera. Of the major units found inside the caldera only the Xáltipan and Zaragoza ignimbrites could be expected to have significant primary permeabilities. However, production zones in wells H-1 and H-4 are within the very dense Teziutlán andesites, suggesting that the hot-water aquifer is confined to steeply dipping zones of secondary permeability such as fault f-1. Although mapped faults cut both andesites and ignimbrites, open fractures would be more likely to persist in the brittle andesites than in the moderately consolidated overlying ignimbrites. In addition, hydrothermal alteration will tend to reduce the primary permeability of the ignimbrites, which would then operate as a semi-impermeable cap for the reservoir. The restriction of mild fumarolic activity to the trace of fault f-1 implies the existence of such a cap. In summary, the geothermal system seems to be hosted by the essentially *homogeneous* Teziutlán andesites, and capped by impermeable intracaldera ignimbrite, within the Los Potreros caldera.

The resistivity surveys (Figure 2), and the results obtained from wells H-1 and H-4, suggest that permeable zones are controlled by the faults that bound the uplifted southeastern quadrant of the Los Potreros caldera (faults f-1, f-2, and f-3). If this uplift is indeed the result of magma intrusion, its boundary faults would not be expected to propagate beyond the inferred rim of the Los Potreros caldera, as has been confirmed by geologic mapping. The location of at least a group of permeable zones seems thus to be well constrained. However, spurs in the contours of the apparent resistivity maps (Figure 2 and Palacios and García, 1981) suggest fracture control in areas within the Los Potreros caldera in which no evidence of such fracture zones can be found in the surface. To confirm the existence of such zones, and to characterize them, is one of the tasks faced by the field operator. These inferred fractures are perhaps related to the regional doming experienced by the Los Potreros caldera shortly after its collapse, and thus would have been formed much earlier than the faults associated with the uplift of the southeastern quadrant of the caldera. Tensional faulting and fracturing related to somewhat similar doming has been documented in other caldera systems (Smith and Bailey, 1968); the faults thus formed are commonly parallel and do not extend beyond the boundaries of the caldera.

The apparent resistivity isopleths of Figure 2 suggest that there could be flow of fluid into or outwards from the geothermal system through the northwestern rim of the Los Potreros caldera; the idea that flow is into the system is favoured due to the lack of thermal indicators in the northern portion of LHVC. Peculiar regional topographic conditions cause precipitation in the northern portion of LHVC to be more intense than in the southern portion; an average of 1200 and 600 mm/yr respectively (Reyes, 1979). Precipitation infiltrates quickly through the permeable unconsolidated and unaltered pyroclastic deposits, but not so through the unfractured domes and lava flows. Taking into account the distribution of impermeable lavas shown in Figure 1, and the difference in precipitation intensity, a larger infiltration rate would be expected in the northwestern portion of LHVC. Assuming 50% evapotranspiration a potential water influx of 10^7 m^3/yr might be expected from the area enclosed by the northwest ring-fracture zones of both calderas into the Los Potreros caldera.

Another potential source of water influx is groundwater from the closed basin that extends south of LHVC, which forms its northern boundary. The basin has an area of approximately 5250 km, and an average annual precipitation of 620 mm; 40% of the precipitation infiltrates to later move outwards from the basin to the north (Reyes, 1979), where the groundwaters could be intercepted by the plumbing system of the volcanic center. Water influx would explain the "opening" in the resistivity contours south of the Los Potreros caldera (Figure 2). Alternatively, such "opening" could indicate migration of fluids from the geothermal system into the hydrologic system of the closed basin.

CONCLUSIONS

I currently see the geothermal reservoir as a water-dominated system bounded by the Los Potreros caldera, hosted by the Teziutlán andesites, and capped by the Xáltipan Ignimbrite and younger volcanic units. Permeable zones are controlled by the fault zones that bound an intracaldera uplift. Additional permeable zones are perhaps provided by fractures related to post-collapse doming of the caldera area; these fractures are not expected to propagate beyond the rim of the Los Potreros caldera. The heat that is now being tapped by the geothermal fluid was probably derived from a compositionally zoned magma chamber that developed in a shallow level of the crust within the last 0.5 Ma. A potentially large influx of water into the system may be structurally controlled by portions of the ring-fracture zones of the Los Humeros and Los Potreros calderas.

The conclusions obtained through geologic, geophysic, and hydrologic studies of this center, coupled with the development of the reservoir, shall be of interest for the exploration and development of reservoirs hosted by volcanic centers in the eastern Cascades. Centers such as the Newberry and Medicine Lake volcanoes have many similarities with Los Humeros, such as similar tectonic environment, complex magmatic histories, the potential for nested collapse structures and post-collapse doming and fracturing, and potentially high influx of cold water into the systems.

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