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THE ZUNIL-II GEOTHERMAL FIELD, GUATEMALA, CENTRAL AMERICA

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ABSTRACT

The geoscientific studies indicate a possible shallow magma chamber beneath the Paxmux lavas and a magma pocket beneath Zunil Volcano which are believed to be the major heat sources for the geothermal activity in Zunil-II. This and Zunil-I area lie at opposite sides of Samala River, east and west sides respectively. In the whole geothermal area of Zunil NE-SW and E-W trending faults are considered to be the major structural features for the transport of fluids. The Geochemical studies indicated a Cl-rich hot water reservoir located around the confluence of the Samala and Pachamiya rivers and another around Azufrales, Fuentes Georginas and Aguas Amargas (hereafter Azufrales-Fuentes Georginas). From the geothermometry of the neutral chloride type hot springs, the temperature of subsurface fluids near the confluence of Samala and Pachamiya rivers was estimated in 210ºC but the gas-geothermometry of Fumarola Negra rendered a temperature above 300ºC. On the other hand, the gas geothermometry applied to fumarolic gases sampled at Azufrales and Fuentes Georginas revealed temperatures in the range of 230º to 290ºC. Emanometry of Hg and Rn are also conclusive in the presence of fracture zones for the migration of geothermal fluids. Gravimetry and CSAMT resistivity studies detected structural feature agreeing to interpretations of surface geology. 2.5-D gravity modeling interpreted a dense basement shallower in Zunil-II than that in the Zunil-I. The interpreted gravity basement east of Samala River shows features such as horst and grabens that consolidated to the interpreted resistivity values indicate structural features appropriate to host a geothermal reservoir. The Zunil-II area is divided into two systems, one around the Paxmux area and other around the Azufrales–Fuentes Georginas area. Three slim holes were drilled. All three tapped a steam reservoir located in the fractured zones of Quaternary lava flows and in the granitic basement. The steam reservoir is considered overlying a hot water reservoir of neutral Cl waters. The geothermal potential resulted in 25 MW for the Paxmux system and from 16 to 23 MW for the Azufrales-Fuentes Georginas system.

INTRODUCTION

The Instituto Nacional de Electrificación, INDE studied in detail the Zunil area including the drilling of several production wells. Steam in enough quantities to drive a power plant was tapped in Zunil-I and in 1992 a Power Purchase Agreement was entered with the firm ORZUNIL to build-operate and own power facilities of 27MW installed capacity. The Zunil area is located at the north-west side of the country, close to Quetzaltenango city, the second largest city in Guatemala (Fig. 1). The Zunil geothermal zone is located close to the southern margin of the Quetzaltenango caldera. Within this caldera other zones of positive geothermal indications are also found, namely; Llano del Pinal, Cantel, Almolonga and the area currently known as Zunil-II (Fig. 1). INDE, with financial assistance of the Inter American Development Bank, entrusted the Consortium formed by West-JEC (Japan) - Telectro, S.A. (Guatemala) to carry out studies to evaluate the geothermal importance of these zones and to select the most promising one among them. Following, the Consortium proceeded to carry out pre-feasibility studies in the selected area. This paper concerns the description of the main characteristics of Zunil-II, the selected promising area, as disclosed by the pre-feasibility study (CyM-MKF, 1989, West JEC-Telectro, 1991 and 1995).

1. GEOLOGY

1.1 Regional Framework, Structural Setting and Volcanology

Quetzaltenango is located close to the boundary between the Cocos and the Caribbean Plates, where rotational effects resulted in an extensional faulting that originated several lithospheric segments. The boundary zone between two of these lithospheric segments passing near Quetzaltenango, is represented by a left-lateral strike slip fault zone trending NE. Here, many domes had emerged with a history of explosive volcanic activity that persists today. The Quetzaltenango caldera, one of these expressions of volcanic activity, lies within an extensional stress field resulting from the intersection of at least two major regional trends, NW-SE and NE-SW. An additional trend with E-W direction formed under this stress field.

The NE-SW faults, generally dipping to the NW, are related to the Zunil fault zone. The Zunil fault zone is not a single fault zone but rather a family of fault of as much as 10km in width (Fig. 2). These faults are concentrated along the Samala River. The system is visible at surface and is larger in scale compared to the NE-SW and E-W systems.

At a shorter scale, there are many circular and curved faults in the Zunil-I and Zunil-II areas, possibly derived from volcanic craters or small caldera collapses and/or large landslides. Particularly, these kind of circular structures and curved faults are well developed east of the Samala River.

In Zunil-II, the fault distribution is hardly visible because pyroclastic rocks widely cover the area. A horseshoe-shape semicircular structure of approximately 4 km in diameter and centered at Aguas Amargas (Fig. 2) was disclosed. Although the conforming curved faults are clear at its north and northeast portions and even the inside area of the structure is obviously depressed, the semicircular structure was not regarded as a caldera collapse.

The NW-SE faults are more visible in Zunil-I, but obscure and of small scale in Zunil-II. However, some faults trending in this direction could be mapped at the southwestern margin of the semi-circular structure while several lineaments trending NW-

SE could be inferred by the direction of quartz and calcite veins found in the altered zones of Paxmux. The E-W trending faults important for defining the geothermal system of Zunil-II are visible from areas in Zunil-I to areas along the Pachamiya River. In addition, a group concentric and/or radial lineament was mapped at Zunil-II. However its mechanism of formation is not well understood. Possibly they were formed by a diapiritic uplift of an intrusive body of low-density.

The Quetzaltenango caldera was formed 1.8 to 1.0 Ma during the Pleistocene. Its formation resulted in the deposition of huge volumes of silicic materials. Contemporarily to this caldera, dome-shaped volcanoes, volcanic cones and circular structures like maars and erosion calderas were formed. Along NE-trending faults parallel to the Samala River, dacitic and rhyolitic rocks called Paxmux lava were extruded 0.3 to 0.2 Ma and formed small lava domes. At the same time, the semicircular structure was formed.

During late Pleistocene (0.20 to 0.10 Ma), silicic volcanism was activated near the southeastern rim of the semicircular structure. Inside this structure, the volcanic activity of Zunil Volcano extruded mainly glassy lava flows, composed of biotite bearing rhyolite and dacite. Subsequently a dacitic volcanism occurred at the southeastern edge of the semicircular structure forming a lava dome at the Zunil Volcano. During this volcanism, a small caldera of 1.5 km in diameter was formed.

Chemical characteristics of rocks suggest that a shallow magma pocket formed from differentiated products with periodical refilling must exist beneath the Zunil Volcano. This magma pocket developed an acid magma cap at its top derived from partial melting of the overlying granitic rocks.

Accordingly, the heat source for the geothermal activity in Zunil-II is represented by the Paxmux domes and the magma pocket beneath Zunil Volcano.

2. GEOCHEMISTRY

2.1 Fluids Geochemistry

The geochemistry of Zunil-I and Zunil-II revealed the presence of two systems of neutral Cl-rich waters sharing the same origin but heated in different places. A mixing model established using stable isotopes and chloride ion concentrations, revealed that both flows may share their origin in the Quetzaltenango-Cantel. In their migration towards the south, they separate into two flow patterns, one passing through Llano del Pinal, bordering Cerro Quemado to finally migrate towards the NE in Zunil-I along the Samala River. The other flow infiltrates at Cantel along the NE-SW fault system, traveling south to meet the other flow from Zunil-I in the Paxmux–Fumarola Negra area. The two underground flows seem to be mixing at a relatively shallow level around the confluence of Samala and Pachamiya rivers. (Fig. 2). This conclusion was reached consolidating the results of enthalpy and chloride relationship, Cl/F and Cl/B ratios, Tritium content, concentrations correlation matrix and considerations on water mixing.

Three slim holes were drilled in the Zunil-II (Z-19, Z-20 and Z-21A, see section 4). These wells tapped only a steam zone but not the expected underlying deep Cl type geothermal reservoir.

In Zunil-II, the geochemistry indicates the presence of two Cl type hot water systems; Paxmux–Fumarola Negra system and the other system located around the Azufrales–Fuentes Georginas area.

The geothermometry of hot springs indicates that the temperature of the Cl type system ranges between 270ºC to 280ºC in the Zunil-I. The temperature of the Cl waters at Fumarola Negra is over 300ºC according to the gas geothermometry, while the temperature of the hot fluids in Paxmux area, according the fluid geothermometry, is around 210ºC (a maximum temperature of 207ºC was recorded in well Z-20 at 364m). The temperatures of the reservoir rocks near the heat source of Zunil-I production area and near Fumarola Negra may be from 360º to 400ºC according to the carbon isotope geothermometry (Fig.3).

In and around Azufrales-Fuentes Georginas, where there are several hot springs (Aguas Amargas and Fuentes Georginas) and fumaroles (Fuentes Georginas, Azufrales etc.) the geothermal fluids may be derived from the same source at depth. The heat source for this system and that for the systems in Paxmux and Zunil-I seems to be different according to the results of chemical analysis and isotopic data of fumarole gases (Fig. 3). The geochemistry of fluids revealed the presence of a SO_4 shallow reservoir in the area of Azufrales-Fuentes Georginas. According to the geothermometry of hot spring waters and oxygen isotope of fumarole gases, these acid waters are heated by geothermal steam but reaching only relatively low temperatures. According to the chemical and isotopic compositions of fumarole gases and the chemical characteristics of steam and water sampled from wells, it is suggested that the steam does not derive directly from a magmatic source but it is rather derived from a deep hot-water parent reservoir. Gas geothermometry of fumarole gases at Azufrales-Fuentes Georginas revealed temperatures in the range of 230º to 290ºC for the parent fluids forming the steam cap. However since the available data is not conclusive, still there are two possibilities for the origin for this steam; high temperature deep water or a shallow magma body. If this neutral Cl type deep parent reservoir exists around Azufrales-Fuentes Georginas, its temperature is expected to be higher than that estimated by gas geothermometry. The recharge zone of these fluids might be located in the Zunil Volcano area according to the isotopic data (Fig. 3). From the carbon isotope geothermometer, the temperature of deep rocks near the heat source is probably about 320º to 380ºC. The slim holes Z-19 and Z-21A tapped a saturated steam zone (small amount of water was produced by well Z-21A).

2.2 Emanometry

Mercury in soil and soil-gas and Radon in soil-gas were measured from Fumarola Negra -Paxmux area to Fuentes Georginas areas, to detect possible highly permeable zones.

Extremely high Hg concentrations around Fumarola Negra and a belt of high concentration of Hg in soil-gas and Hg in soil trending in a ENE-WSW direction from slim hole Z-4 to slim hole Z-1 along Pachamiya were disclosed (Fig. 4). The direction in which Hg anomalies distribute roughly coincides to those of Rn (total-Rn, ^{222}-Rn and ^{220}-Rn (Tn)) and to the low resistivity zone detected by the CSAMT survey (see Section 3). Another Hg in soil and soil-gas (Figs. 4) anomalies were also found trending in NE-SW direction along Samala River. These anomalies and those trending in ENE-WSW direction along Pachamiya River intersect at the confluence of both rivers. Except for the zone around the slim hole Z-4 and Fumarola

Negra, the Hg anomalies detected at Zunil-I do not extend to the east of Samala River.

Although the content of Hg in soil and soil-gas detected in and around Azufrales-Fuentes Georginas is relatively low compared to those in Paxmux and Zunil-I, Hg anomalies were observed in a zone extending in a E-W direction around Chuitziquiná.

In spite of shallow granitic basement (refer to section 3), Radon (total-Rn, ^{222}-Rn and ^{220}-Rn (Tn)) contents in soil-gas are relatively low. This is probably due to a relatively low permeability of these rocks and/or to the difficulty for deep geothermal fluid to reach the surface through faults clogged or sealed by clay alteration.

Radon concentration in soil-gas near fumaroles is high and were found showing similar distribution patterns as those of the Hg-anomalies. Zones where the Rn/Tn ratio is high, indicating fractured zones extending to deep levels, were found in a narrow belt trending ENE-WSW along Pachamiya River and trending NE-SW along Samala River. Other zone of high Rn/Tn ratio was found around Chuitziquiná trending roughly in E-W direction. Nevertheless, there is a possibility that the relatively high Tn content in soil-gas could be caused by the presence of ground water flowing towards the west from an eastern area where granitic rocks are encountered at shallow levels and where the ground water may be in contact with these rocks. The band of very low contents of Rn and Tn in the area around Chuitziquina between the Samala River and Chuimucubal may indicate depressions of the granitic basement or fracturing clogged by alteration.

3.0 GEOPHYSICS

3.1 CSAMT

A Controlled Source Audio Frequency Magneto Telluric study was carried out along eight survey lines with stations intervals of 200m and covering almost the entire Zunil-II area.

1-D inversions using the least squares method were applied to delineate the electrical discontinuities and surrounding low resistivity anomalies. The distribution of the low resistivity zones and the electrical discontinuities derived from the spatial position of the electrical basement, show two major low resistivity anomalies (Fig. 4.). One around the confluence of Samala and Pachamiya rivers, and the other, detected by the eight survey lines, trending E-W passing through Chuitziquina. These two low anomalies are considered to be reflecting hydrothermally altered zones and the electrical discontinuities near these resistive lows may indicate faults.

Since, the actual resistivity structure in the area is three dimensional, the depth of the electrical basement could be better approached from 2-D analysis The general tendency of the depth of the electrical basement is shallower at the east and deeper at the west of Zunil-II. From the drilling results of wells Z-19, Z-20 and Z-21A, the granitic basement was confirmed at depths of 569.4m, 312.8m and 385.0m respectively. Comparing the 2-D results and the actual basement depths, for stations, located near well Z-19 the calculated basement depths are between 300m and 600m; for stations located near well Z-20 is between 300m and 400m and for stations located near well Z-21A is around 500m. The depths of the geological basement almost correspond with those obtained from the CSAMT survey, meaning that the electrical basement distribution is well correlated to the geological basement except some points where hydrothermal alteration, even within the granitic basement, is intensive.

Both 1-D and 2-D results show clear electrical discontinuities trending in a E-W direction, especially in the Chuitziquina area which might reflect important faults. Other interesting resistive feature in the area is that a clear depression zone, running E-W starting around Chuimucubal towards the west, could be detected from 2-D sections (refer to section 2.2).

As a conclusion, the area can be divided into two low resistivity zones which trend mainly E-W as belt zones. One of these, near Paxmux (showing an additional trend in N-S direction along Samala River) and the other, also trending E-W centered at Chuitziquina. The electrical discontinuities along these low zones can be correlated to faults while the resistive lows above them might correspond to hydrothermal alteration zones. Around the low resistivity zone in the Paxmux area, electrical discontinuities trending NNE-SSW (F1), ENE-WSW (F2) and NW-SE (F6,F7) can be delineated (Fig. 4).

3.2 Gravity

Four groups of gravity data were merged and reinterpreted. The first group was a set of 511 stations spread over an area of 195 km^2 and measured by INDE during the regional studies carried in 1980. The second group is a set of stations lying on several traverse lines surveyed by INDE for detailing the gravity structure of Zunil-I and Zunil-II. The third group was a set of 135 stations surveyed by INDE in 1989 for detailed studies in Zunil-I and a fourth group a set of 180 surveyed by INDE for detailed studies in Zunil-II. The Zunil-II area lies almost at the center of the area covered by the whole set of stations. Latitude, Free Air, Bouguer and topographic corrections were applied. The topography maps of the whole study area was digitized and a discrete topographical model was constructed to do terrain corrections. A third order polynomial regional anomaly was extracted and the data was subject to spatial filtering to select the cutoff frequency. Twelve profiling lines were selected so as to cover both Zunil-I and Zunil-II, including the CSAMT survey lines and all the wells in the area with all available geological information (Fig. 2).The twelve profiles were subject to a 2.5 D modeling process. The results are summarized as follows.

1) Profiles 1, 2, 3 and 10 disclosed an elevation of the dense basement at the eastern edge of the Zunil-II area at Chuimucubal). However, it seems to be highly altered.

2) A horst structure was identified separating Zunil-I from Zunil-II. This horst is limited to the area along Samala River, between profiles 2 and 10.

4) Between profiles 2 and 10 and profiles 6 and 8 there is a ESE-WNW graben-like structure deepening towards the SW (west of Chuitziquina) and end at the horst structure separating Zunil-I and Zunil-II.

5) There is an ENE-WSW trending horst centered at Chuitziquina between profiles 1, 7, 9 and 11. The graben mentioned above is located at the north of this horst. At the south of this horst another graben-like feature was interpreted. The horst structure seems to separate two zones in Zunil-II, The northern zone corresponding to the confluence or Samala and Pachamiya Rivers and a southern zone to the areas of Azufrales- Fuentes

Georginas.

6) In addition, in Zunil-II an echelon type faulting dropping towards Samala River was interpreted.

4. SLIM HOLES

The three slim holes drilled in the Zunil-II area (Fig.2), wells Z-19, Z-20 and Z-21A encountered the following lithologic succession: granitic basement, gabbro, pyroclastic rocks, andesite, rhyolite, ash flow, tuff and alluvium, in ascending order.

Four zones of alterations were found at depths in the three wells; montmorillonite zone, chlorite-montmorillonite zone, chlorite zone and a kaolinite zone. The montmorillonite was found at relatively shallow levels (around 59m) with thickness ranging from 50 to 150m in all three wells. The chlorite/montmorillonite zone was found by the three wells immediately below the montmorillonite zone. In well Z-20, the chlorite/montmorillonite zone is thin layer and almost matches the 150ºC line between wells. In wells Z-19 and Z-21A, this zone has a thickness of 100 to 150m also matching the temperature lines of 150ºC to 200ºC. The chlorite zone followed down below in all the three wells. The boundary between the chlorite and chlorite/montmorillonite zones was found at elevations of 1800m to 1900m, suggesting similar temperature conditions at these depths in the three wells. The kaolinite zone is found at 170m depth only in well Z-19. In spite of the fluids over 200ºC encountered by wells Z-20 and Z-21A, the alteration in Zunil-II is not intensive. Particularly, alunite and the kaolinite zones playing the role of cap rock in many active geothermal fields, are less developed in Zunil-II. This is probably because the shallow vapor reservoir present here. However, well Z-20, drilled about 400m east of Fumarola Negra encountered a silicified zone from the 320m depth to the bottom, probably corresponding to the steam cap derived from a water dominated reservoir.

Pressure/Temperature borehole surveys were carried out in all three wells. The maximum temperature recorded in well Z-19 was 205ºC at 496m. The static P-T surveys indicate liquid conditions in the tapped reservoir. In well Z-20, the maximum temperature was 207ºC at 364m. The static P-T surveys indicate a reservoir of saturated or slightly superheated steam. In well Z-21A a maximum temperature of 244ºC was recorded at 685 m. The static P-T surveys indicate geothermal fluid at saturation condition.

5. GEOTHERMAL MODEL

5.1 Heat Source

a. The probable heat source for the Azufrales-Fuentes Georginas geothermal activity might be the magma pocket beneath Zunil Volcano and that for the activity found at Paxmux might be a shallow magma pocket existing beneath the Paxmux Dome.

b. The estimated temperature at the top of these magma pockets from zircon morphology is about 700ºC.

5.2 Reservoir Structure

a. Faults trending NE-SW and E-W form fractured zones in both the Quaternary volcanic lavas and granitic basement. The three slim holes drilled for the prefeasibility studies tapped geothermal fluids in these fracture zones.

b. The Zunil-II geothermal zone can be divided into two major systems; The northern system developed along the Pachamiya River and the southern system developed around Azufrales-Fuentes Georginas. The former is controlled by NE-SW trending faults along Samala River and E-W trending faults along Pachamiya River. The latter, is probably controlled by E-W trending faults, identified by the geophysical studies

5.3 Geothermal Systems

a. The steam cap tapped by the exploratory drilling suggests a deeper Cl-rich water dominated reservoir.

b. The fluid temperature for the northern system is around 210ºC according to the geothermometry of neutral chloride hot springs, or higher than 300ºC, as estimated by the gas-geothermometry of Fumarola Negra.

c. In Azufrales-Fuentes Georgina area, there is a shallow SO_4 type aquifer heated by steam. Its presence only at shallow levels was confirmed by the slim holes Z-19 and Z-21A. There are two possible explanations to the origin of this steam; a deep liquid reservoir of high temperature or directly derived from magma. Chemistry and gas geothermometry of chemical components of fumarolic gases of Azufrales-Fuentes Georginas permitted to interpret the temperature of the possible parent reservoir in 230º to 290ºC.

d. The probable deep Cl-type hot water reservoir around the confluence of Samala and Pachamiya rivers is partially connected at shallow level and mixing with the waters of the Zunil-I reservoir. The reservoir in the confluence of both rivers is recharged by groundwater infiltrating from the Quetzaltenango-Cantel area. The water of this reservoir is probably heated by a magmatic heat source different from those of Zunil-I and Azufrales-Fuentes Georginas.

6. GEOTHERMAL POTENTIAL

The stored heat method was applied to estimate the geothermal potential in the two systems of the Zunil-II geothermal area. For the northern system the result was 25 to 30 MW and that for the southern system was 16 to 23MW.

7. CONCLUSIONS

The Zunil-II geothermal area seems to be promising to the light of the results of the pre-feasibility studies. Additional work and deep drilling are required to detail its potential and the feasibility of its commercial exploitation.

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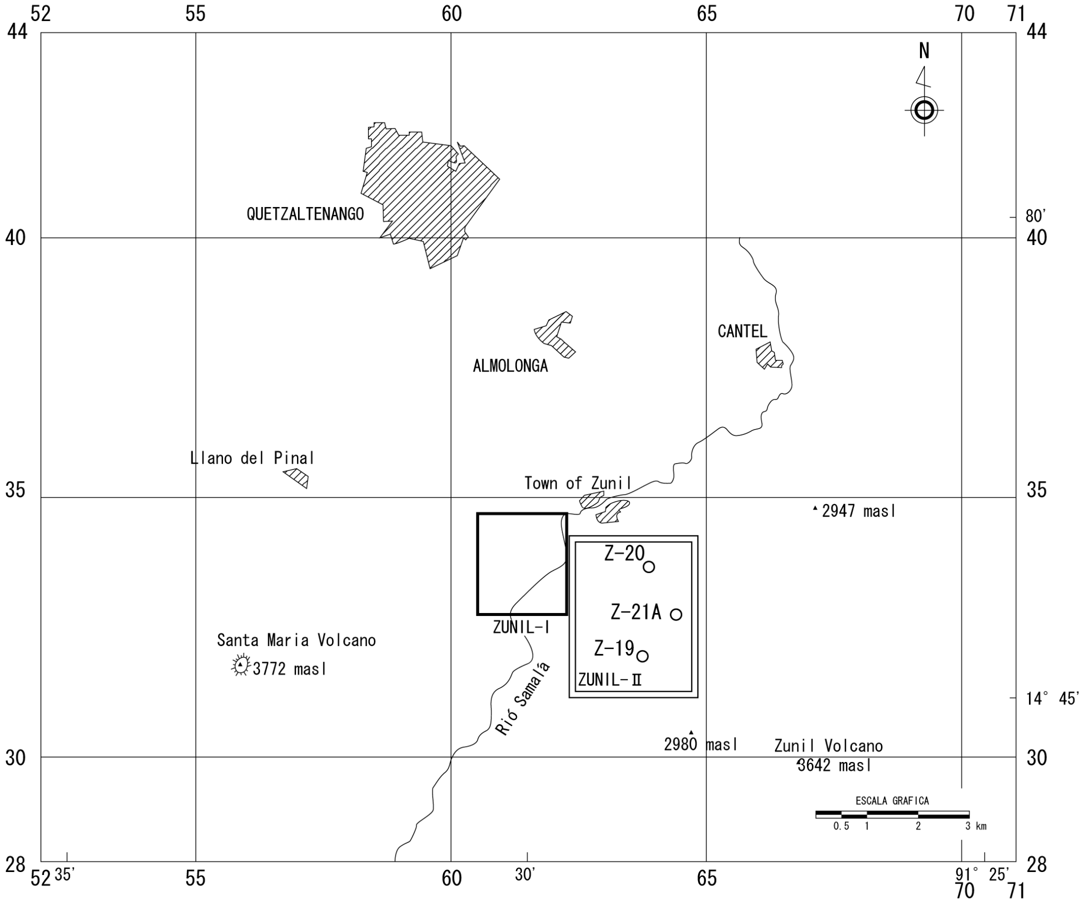

Figure 1 Location of the Zunil Geothermal Area

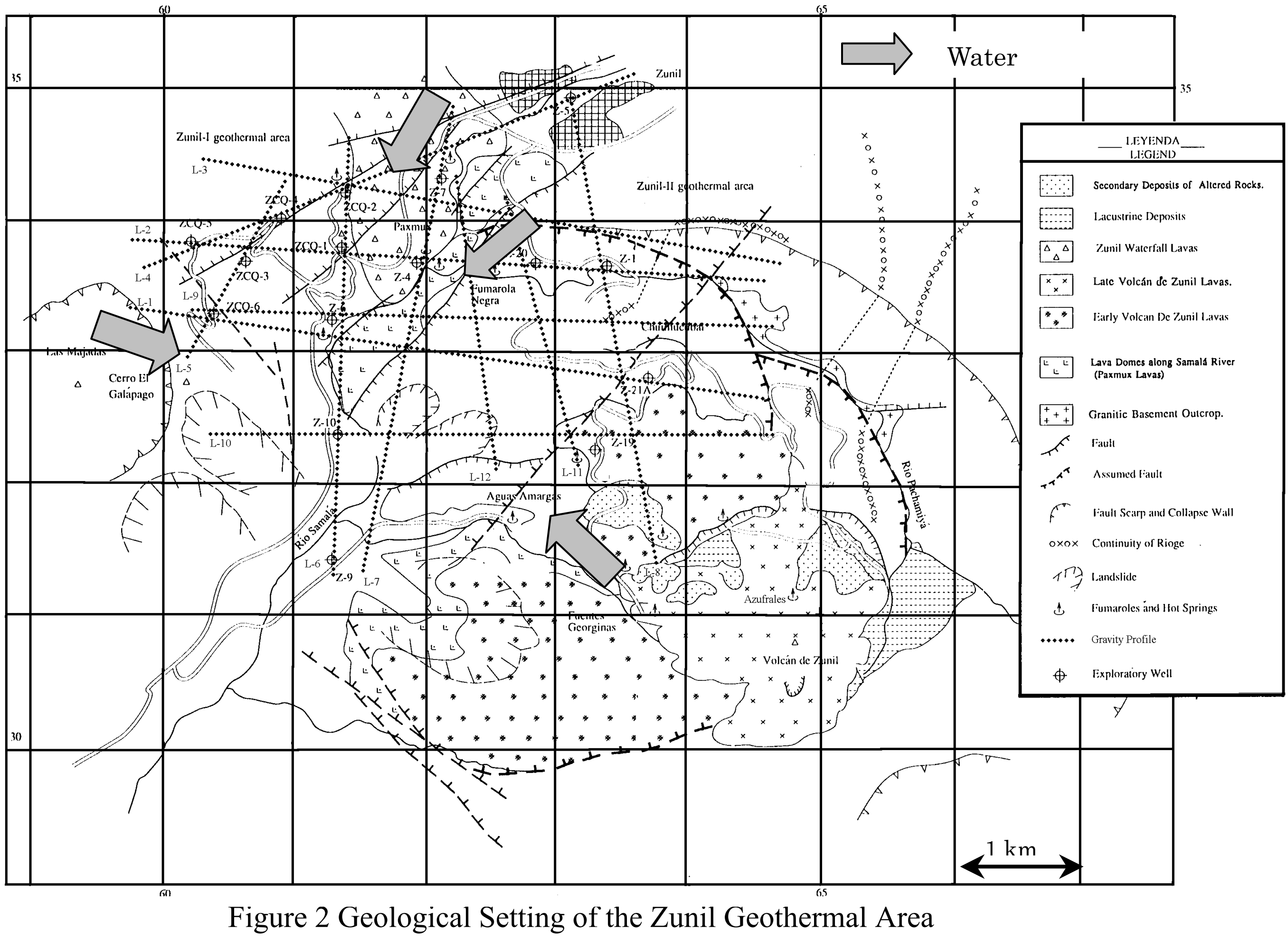

Figure 2 Geological Setting of the Zunil Geothermal Area

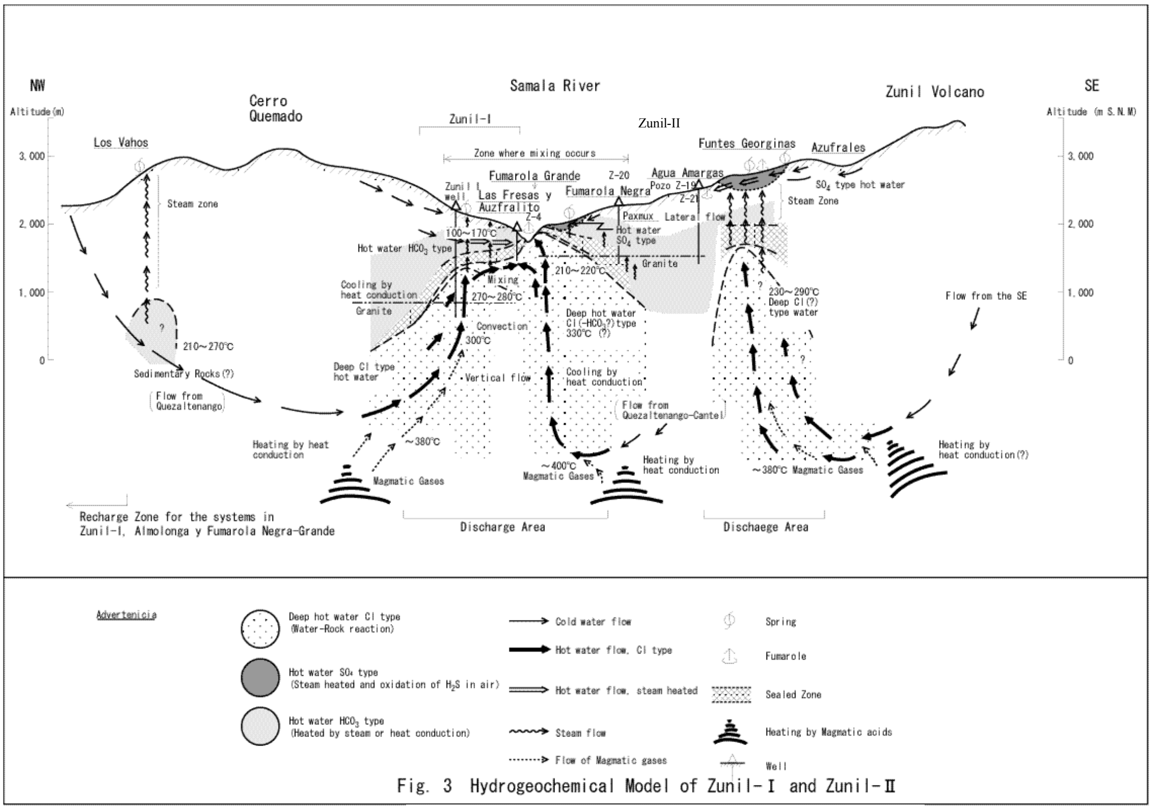

Figure 3 Hydrological Model of Zunil-I and Zunil-II

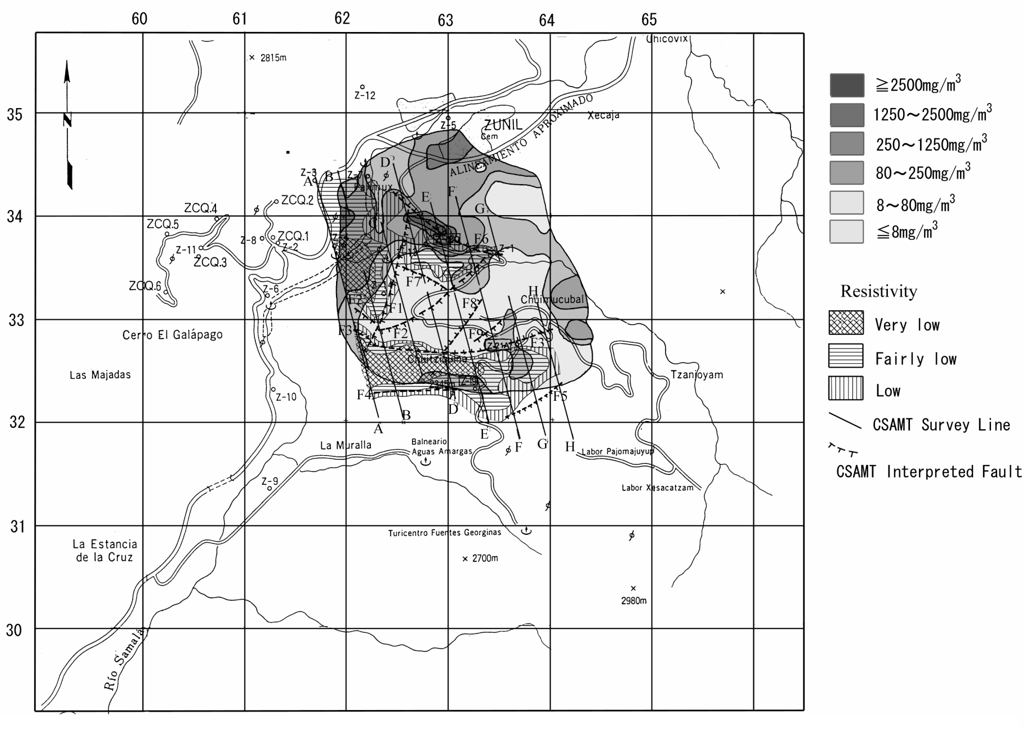

Figure 4 Smoothed Contours of Hg Iso-concentrations and CSAMT Detected Faulting