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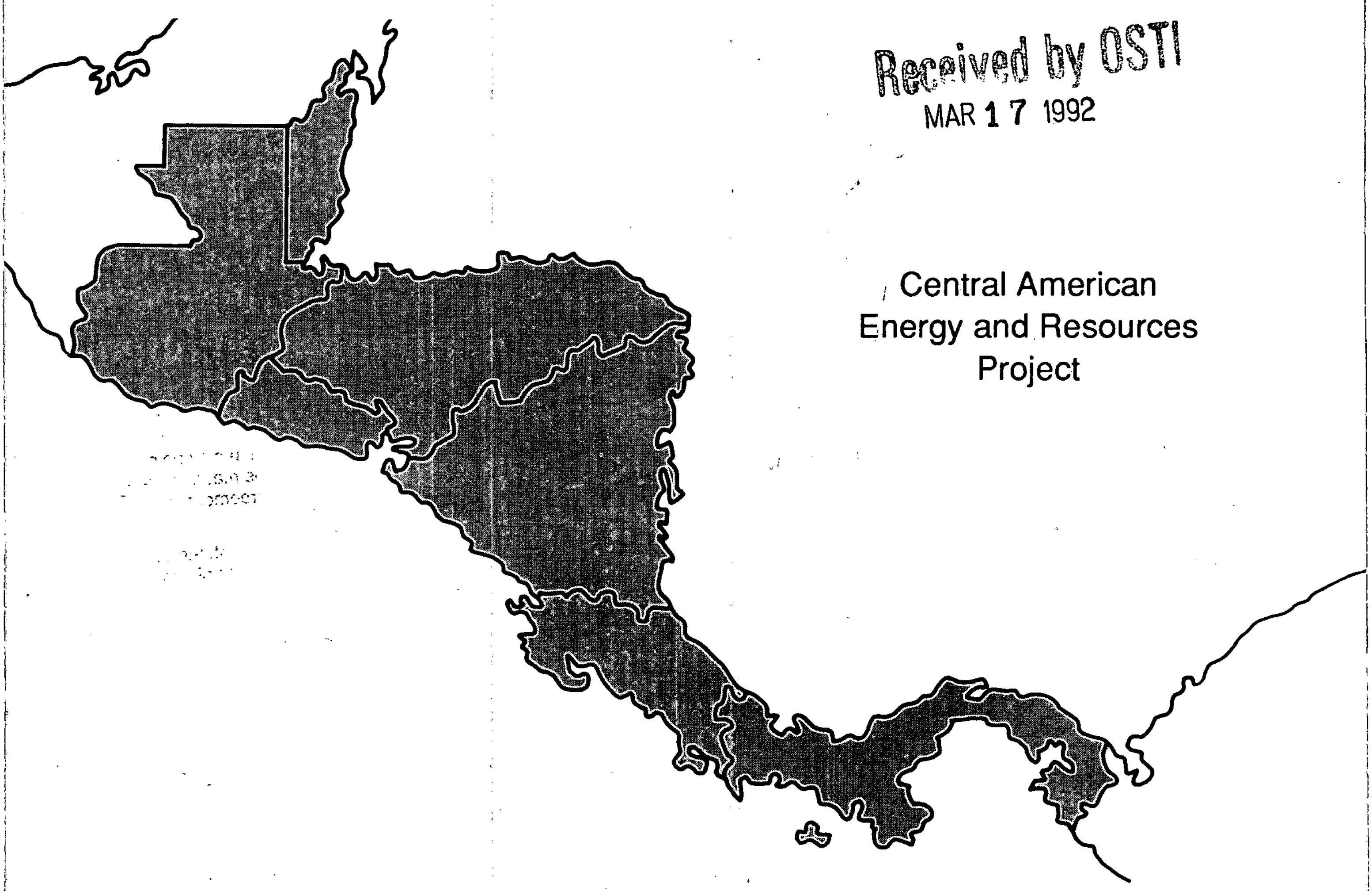

Central American Energy and Resources Project

Results of Geothermal Gradient Core Hole TCB-1 Tecuamburro Volcano Geothermal Site Guatemala, Central America

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Results of Geothermal Gradient Core Hole TCB-1 Tecuamburro Volcano Geothermal Site Guatemala, Central America

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EXECUTIVE SUMMARY

The Los Alamos National Laboratory (Los Alamos)/U.S. Geological Survey (USGS)/Instituto Nacional de Electrificacíon (INDE) prefeasibility assessment of the Tecuamburro volcano geothermal site is now complete. The results of geological, volcanological, hydrogeochemical and geophysical field studies conducted in 1988 and 1989 (Duffield *et al.*, 1989; Goff *et al.*, 1989; Heiken and Duffield, eds., 1990), indicated that there is a substantial shallow (<10 km) heat source beneath the area of youngest volcanism and that this area contains acid-sulfate springs and fumaroles emitting gases which yield maximum indicated reservoir temperatures of 250 to 300°C. To obtain subsurface data needed for verification of conclusions drawn from exploration efforts, a geothermal gradient core hole (TCB-1) was located low on the northern flank of the Tecuamburro volcano complex on the Finca de las Nubes, between Laguna Ixpaco and the Tecuamburro summit within the inferred Chupadero crater (Fig. 1).

The gradient drilling/coring/testing phase of the assessment of the Tecuamburro volcano geothermal area was initiated on February 7, 1990. The primary objectives of this borehole were to determine a temperature gradient and to core as deeply as possible within the constraints of the funding. Quantitative information on the temperature distribution as a function of depth was needed to verify that a high-temperature resource exists. Other objectives were to obtain continuous core (75% or better) for studies of stratigraphy, rock alterations and fluid inclusions, and to obtain fluid samples for hydrogeochemical studies. All objectives were met, and the results are presented here in the following chapters: I. Drilling and related testing and sampling; II. Stratigraphy; III. Thermal gradients; IV. Fluid geochemistry; and V. Fluid inclusions.

TCB-1, now the deepest core hole in Guatemala, was drilled to a total depth of 808.35 m during the period from February to May 1990 with an average rate of advance of 21 m per day. The hole is cased to 674 m and below 674 m the hole is open to 772 m. A broken stem of drill rods was left in the hole from 772 m to the bottom (TD). On June 6 the geochemistry team was successful in its attempt to unload the borehole of fluids associated with the drilling operations, but the hole was unable to sustain flow. Between June 6 and June 11 downhole samples were taken with a Klyen sampler but these samples are of uncertain quality because the hole was filled only with steam. No significant fluid entries exist in the open-hole section of the borehole below 674 m.

The TCB-1 site is located on a lobe of interbedded tuffs and avalanche deposits from the Tecuamburro complex; the borehole penetrates Tecuamburro, Peña Blanca, and pre-Peña Blanca avalanche breccias and tuffs to 144.6 m (Fig. 2). It appears that the thin edge of the Ixpaco phreatic tuff ring was

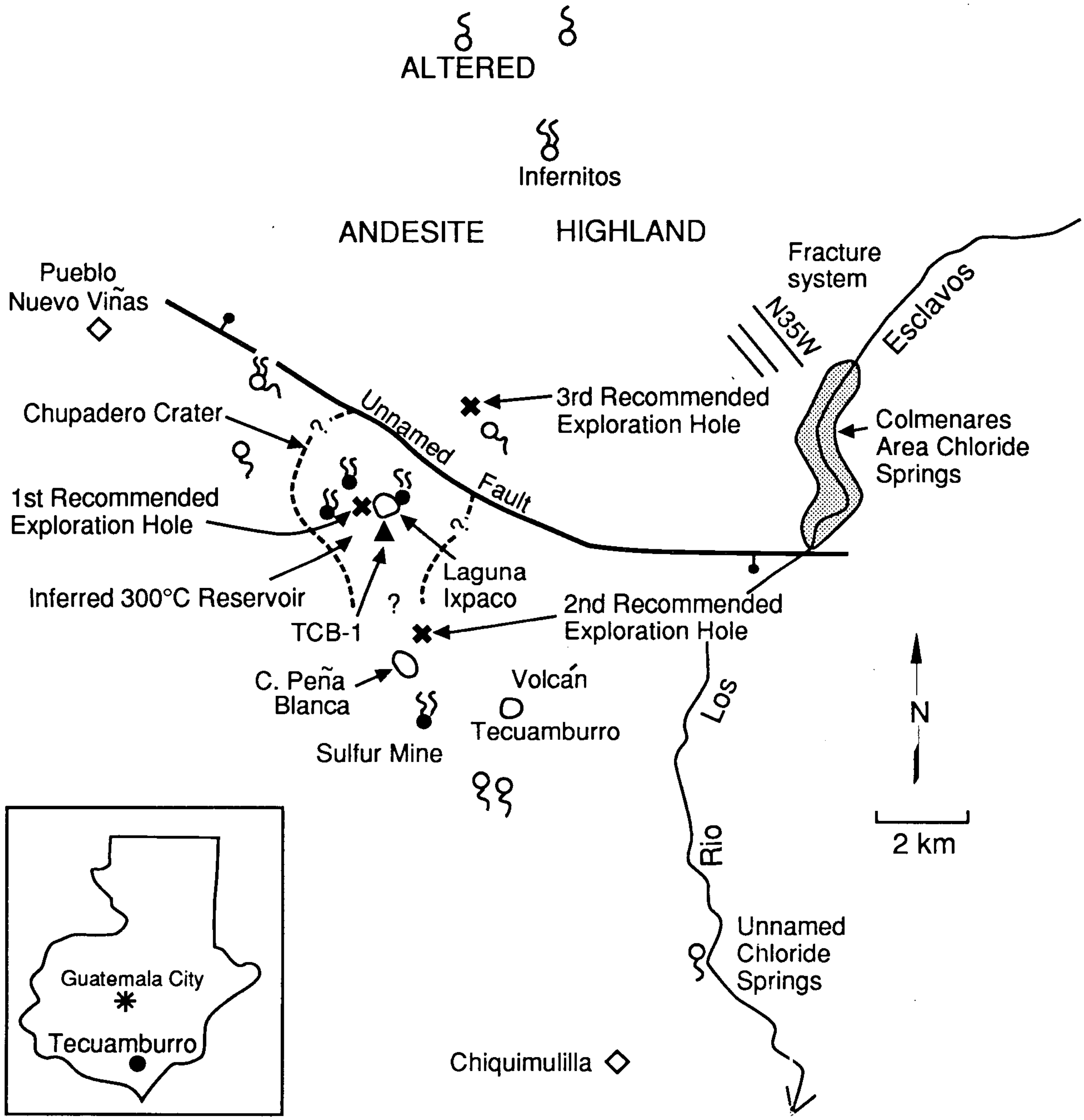

Fig. 1. Location map, Tecuamburro volcano geothermal area, Guatemala.

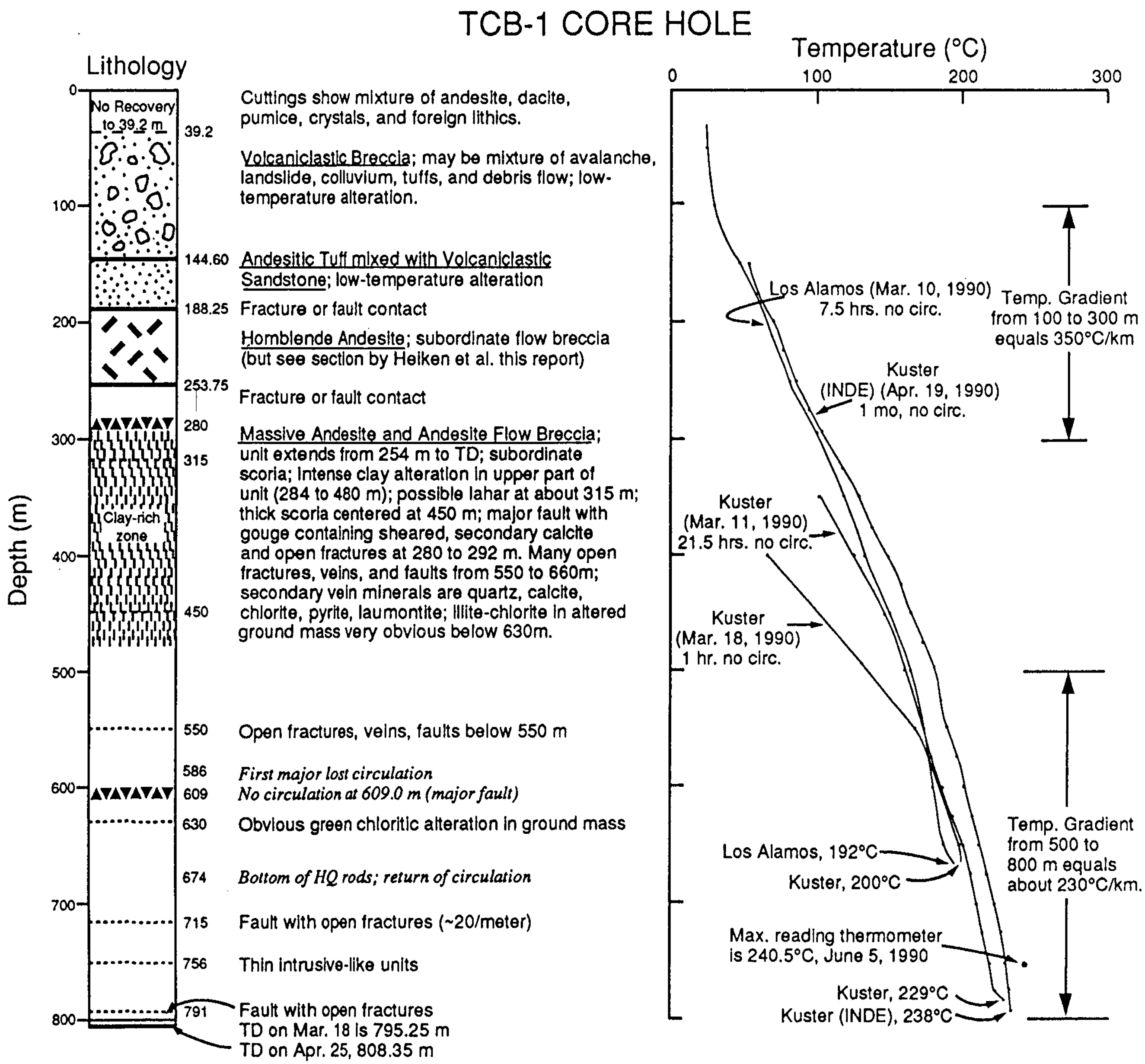

Fig. 2. Lithology and temperature logs, TCB-1 core hole.

reached at a depth of 65 m. The consensus of opinion is that between 144.6 m and 253.75 m the borehole penetrates a mixed pyroclastic and volcanoclastic rock and an andesite flow. Below the fracture or fault contact at 253.75 m are interbedded andesitic lavas, scoria, thin tuff beds, and laharic breccias of the Miraflores composite cone. This andesitic sequence, mostly lavas, is intensely chloritized, with very low permeability; nearly all pore spaces are filled with hydrothermal minerals. There are some zones of open fractures at 280 m, 550 m, 714 m, and 791 m, and a major fault at 609 m (where we lost circulation).

The best temperature log of TCB-1 was obtained by INDE using a Kuster tool on April 19 after the borehole had been shut in for 3 weeks (Fig. 2). Measured bottom hole temperature at 795 m was 238°C. The temperature versus depth curve does not show isothermal conditions. Using the calculated temperature gradient from 500 to 800 m of 230°C/km and the gas geothermometer temperatures indicated by fumarole samples from the nearby Ixpaco area, we would expect to encounter a 275-300°C reservoir at about 1000-1200 m.

Thermal conductivity and physical property measurements were made on six samples of core taken from 160 to 745 m depth. Using the conductivity values for five samples and the linear temperature gradients from two zones, heat flow values of roughly 370 mW/m^2 or nearly 9 HFU (heat flow units) were obtained.

Over 120 fluid inclusions, both primary and secondary, in calcite and quartz from several veins were studied. In general, homogenization temperatures are very close to those measured during the April 19 temperature log. The tightest cluster of homogenization temperatures for samples from 791 m averages about 237°C, which is essentially identical to the bottom hole temperature (of 238°C) measured with the Kuster tool. Many of the temperatures of homogenization are lower than present measured temperatures. The data could indicate that the rock has heated up since vein formation. Freezing point depressions are very small which suggests that the fluid salinity is low (<1.2 wt% NaCl) and/or that CO_2 content is relatively high, up to 4.3 wt %.

The chemistry of the fluids obtained from the open hole section below 674 m verifies the results of the fluid inclusion study. Swab, weirbox and *in situ* samples consist of a mixture of condensed steam and a small amount of formation fluid and have high B/Cl, HCO_3/Cl, and NH_4/Cl ratios. The best estimate of chloride content in the formation fluid is 300 mg/kg. Fluids from TCB-1 may originate from a vapor-rich horizon that is dominantly $NaHCO_3$ in chemistry, which is similar to fluids from the Zunil I geothermal site.

Integration of results from TCB-1 with results from previous studies is intended to provide the Guatemalan government with information for planning the next phase of the geothermal assessment of the

Tecuamburro area. In summary, the Tecuamburro area holds great promise as a commercial geothermal resource. A very young volcanic heat source is evidenced by young andesitic and dacitic domes at the summit of the complex, the 2,900 year old Ixpaco phreatic crater, and the 38,000 year old pyroclastic flows from an inferred crater (Chupadero). There is a shallow resistivity low in the Ixpaco region. The projected thermal gradient of 230°C/km in the lower part of the borehole suggests that temperatures of about 300°C (indicated by gas geothermometry on samples from acid springs at the nearby Laguna Ixpaco phreatic crater) may exist at a depth of 1000 to 1200 m. With the exception of differences in H_2 contents there is close similarity in gas compositions between steam discharged from fumaroles at Laguna Ixpaco and at the summit of Tecuamburro. The predicted 300°C reservoir was not encountered, but the temperature continued to increase with depth in TCB-1. It is therefore recommended that a borehole be drilled to at least 1200 m at a location near TCB-1 or slightly closer to the volcano. The well should be designed with a diameter large enough to be used as a production well if the reservoir is encountered.

It is also proposed that at least three more exploration holes be drilled to learn more about the Tecuamburro geothermal system (Fig. 1). One exploration hole should be located about 700 m west of the center of Laguna Ixpaco, about half-way between the phreatic crater and a group of fumaroles. This is near the center of the inferred Chupadero crater along an extension of a proposed buried fault. Another exploration hole should be located closer to the Tecuamburro Summit, south-southeast of TCB-1. The relation of neutral-chloride geothermal waters located along the Rio Los Esclavos to the overall Tecuamburro geothermal system is still not resolved. A third exploration hole should be located northeast of Laguna Ixpaco on the north side of an east-west trending fault in order to test whether or not there are more than one geothermal system.

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The authors wish to thank Ed VanEeckhout, Steve Booth, and Anne Tellier (Los Alamos), Mario Funes, Regional Office, Central American Project (USAID), and Andrés Caicedo (INDE) for their organizational work that made this project possible. We also thank Anthony Garcia for illustration work and Barbara Hahn and Julie Romero for typing this report.

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RESULTS OF GEOTHERMAL GRADIENT CORE HOLE TCB-1
TECUAMBURRO VOLCANO GEOTHERMAL SITE
GUATEMALA, CENTRAL AMERICA

Compiled by

Sue Goff

ABSTRACT

Results of geological, volcanological, hydrogeochemical, and geophysical field studies conducted in 1988 and 1989 at the Tecuamburro volcano geothermal site in Guatemala indicated that there is a substantial shallow heat source beneath the area of youngest volcanism. To obtain information on subsurface temperatures and temperature gradients, stratigraphy, hydrothermal alteration, fracturing, and possible inflows of hydrothermal fluids, a geothermal gradient core hole (TCB-1) was drilled to 808 m low on the northern flank of the Tecuamburro volcano Complex, 300 km south of a 300-m-diameter phreatic crater, Laguna Ixpaco, dated at 2,910 years. Gases from acid-sulfate springs near Laguna Ixpaco consistently yield maximum estimated subsurface temperatures of 250-300°C. The temperature versus depth curve from TCB-1 does not show isothermal conditions and the calculated thermal gradient from 500-800 m is 230°C/km. Bottom hole temperature is 238°C. Calculated heat flow values are nearly 9 heat flow units (HFU). The integration of results from the TCB-1 gradient core hole with results from field studies provides strong evidence that the Tecuamburro area holds great promise for containing a commercial geothermal resource.

I. EXPLORATION GRADIENT CORE HOLE DRILLING, LOGGING, AND TESTING OPERATIONS

Sue Goff, Fraser Goff, Grant Heiken, Wendell Duffield, Jamie Gardner, Luciano Martinelli, Oscar Castañeda, Sergio Aycinena, Cathy Janik, A. W. Laughlin, Andrew I. Adams, and Lynne Fahlquist

A. INTRODUCTION

The drilling/coring/testing phase of the assessment of the Tecuamburro volcano geothermal area was initiated on February 7, 1990 on the Finca de las Nubes. The site for exploration core hole TCB-1 is located within the inferred Chupadero crater and between Laguna Ixpaco and the Tecuamburro summit, 300 m south and 55 m above the level of Laguna Ixpaco. Initial plans called for a 700 m deep core hole.

The objective of this borehole was to core drill as deeply as possible to obtain quantitative information on the temperature profile as a function of depth. Other objectives were to obtain continuous core (75% or better) for studies of stratigraphy, alteration, and fluid inclusions, and to obtain hydrogeochemical data from fluid samples.

Swissboring Overseas Corporation, Ltd., Guatemala Branch, mobilized a Longyear 44 drill rig during the week of January 29, 1990. This rig was equipped with a 30 ft mast and was powered by a GM 4-53 diesel engine.

B. SUMMARY OF CORING OPERATIONS

The actual (as completed) borehole configuration is shown in Fig. I-1. The core hole TCB-1 was spudded on February 7, 1990 and a 6-5/8 in. x 6-1/4 in. conductor casing was set to 38.2 m. PQ (approx. 3 5/16") diameter core[1] was recovered to 84.55 m and PW (5 1/2" x 5") casing was installed and cemented to this depth. Drilling mud circulation was lost between 83 and 84.55 m. The annular cementing job required more than 40 bags of cement. A 4-in.-annular type blowout preventer and a 4-in.-gate valve were set to the PW anchor casing. Coring continued with PQ (4 5/8" x 4 1/6") size drill rods to 87.45 m where circulation was again lost. HW (4 1/2" x 4") casing was hung from the well head to 87.45 m. The lost circulation at this depth was in a zone of avalanche breccia. Vuggy fractures, up to 8 cm long, and chloritic alteration were present. Drilling continued with HQ (3 1/2" x 3 1/16") rods from 87.45 m to 666.9 m.

At 388.4 m the decision was made to pull the rods to grease them and change the bit to improve the penetration rate. The first Kuster log was obtained on February 27 inside the HQ rods right after circulation was discontinued (Fig. I-2).

Coring operations to 598.8 m were uneventful, obtaining over 95% core recovery, with a core production of over 20 m per day. Between 598.8 m and 606.6 m core recovery decreased considerably. The bit was changed at 605.95 m after drilling 222 m and drilling was continued between 606.6 m and 611.1 m, but no core was recovered. Circulation was lost below 609.65 m. At 612.05 m, a core sample was obtained that resembled a pile of cement rubble. The string was pulled in order to retrieve a stuck core barrel. The matrix of the bit had been completely consumed and the inner tube bent out of shape as drilling was essentially being done with the core catcher. In addition the pin in the overshot and the lifting fork failed. At this depth, drilling mud composition was changed to a mix of high temperature stable polymers and soda ash. Bottom hole temperature measured with two maximum reading thermometers after 15 hours without mud circulation was 210°C at 612.05 m. A smell of H_2S accompanied the retrieved thermometers.

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[1]Drill rods and casing used in the diamond coring industry are referred to by letters (PQ, HW, NW, etc.) that designate diameter and wall thickness. Dimensions are also shown on Fig. I-1.

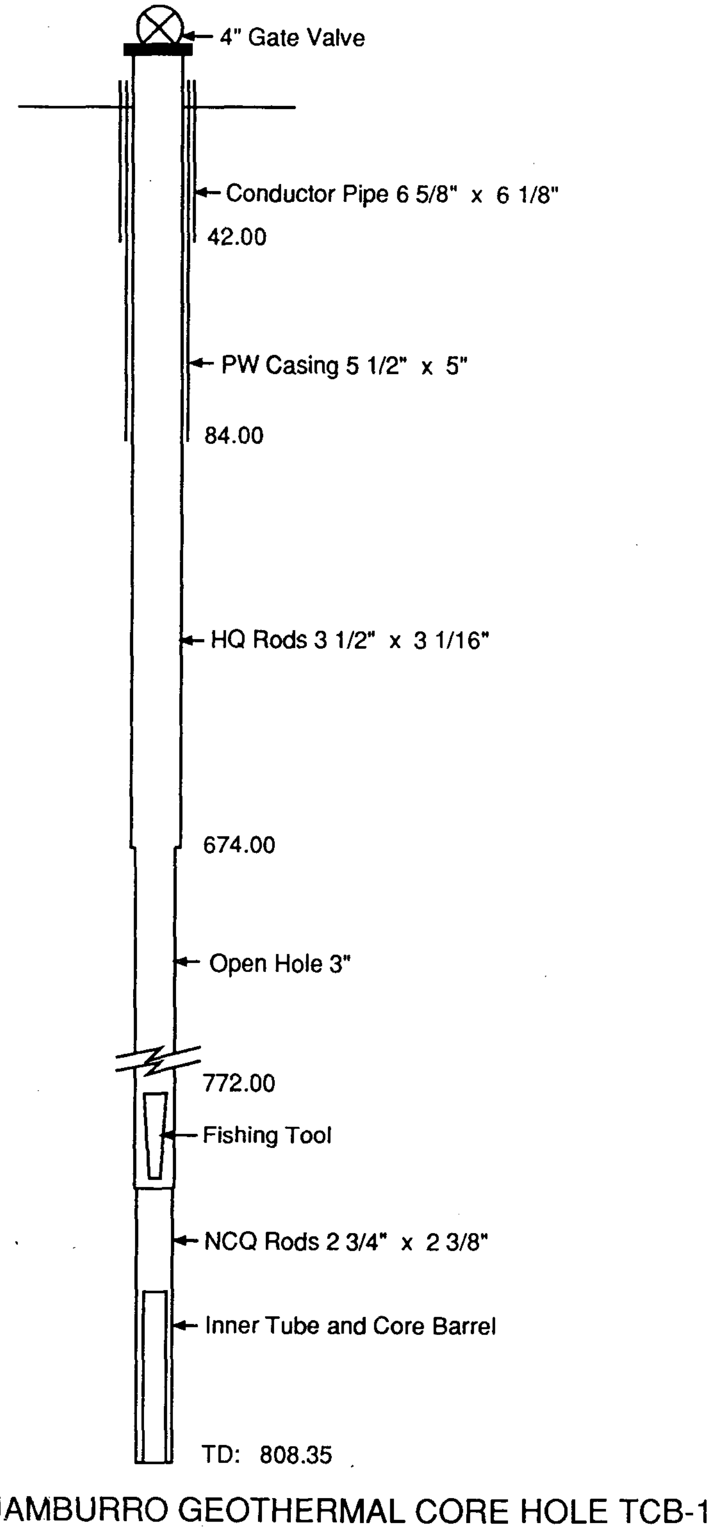

Fig. I-1. Actual (as completed) borehole configuration, TCB-1.

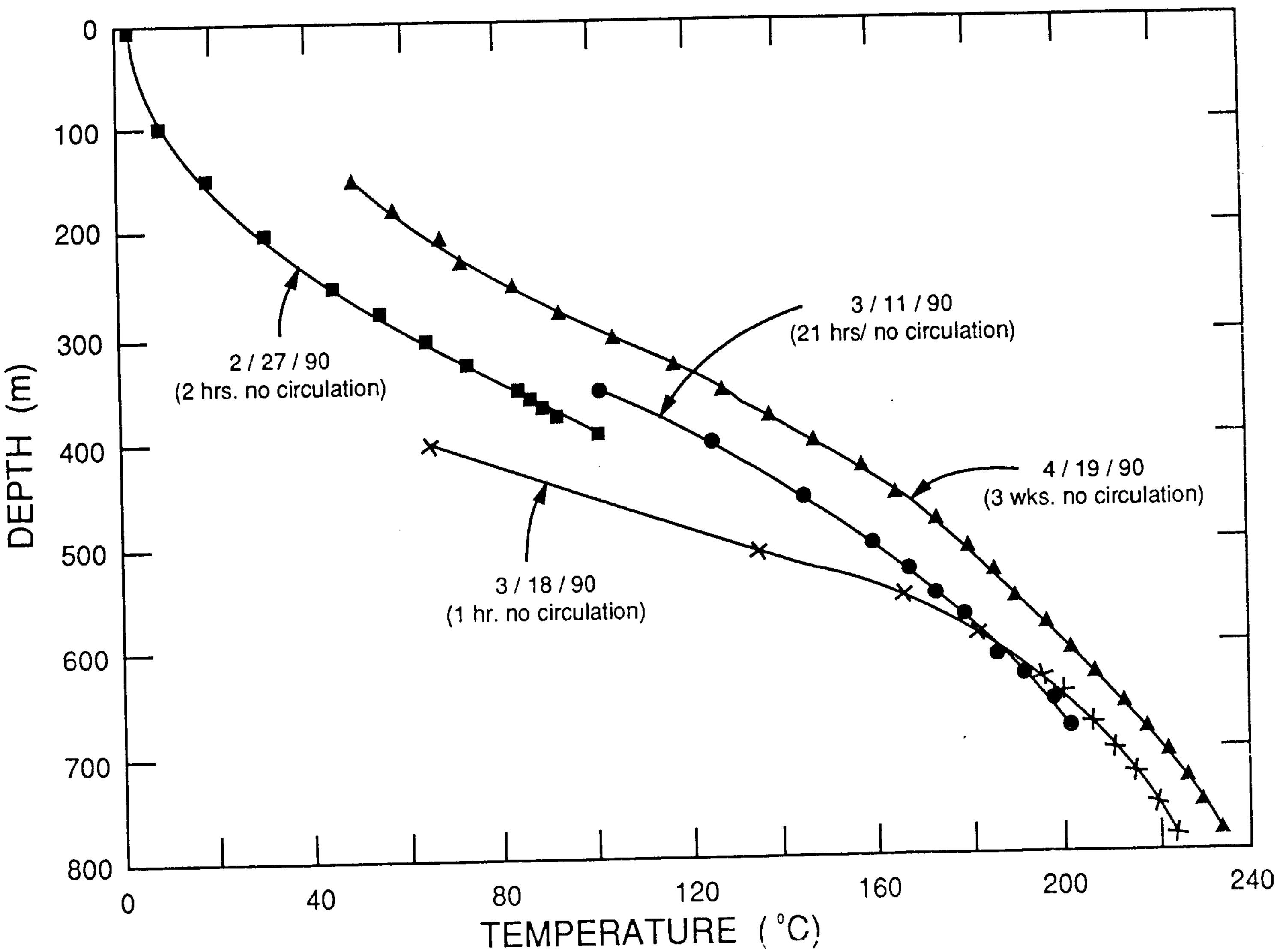

Fig. I-2. Kuster tool temperature logs, TCB-1.

At 633.4 m two pins on the overshot failed as it was going in to retrieve the core barrel. On March 10 the decision was made to stop drilling in HQ at 666.9 m, hang the HQ rods in the hole, and continue with NQ (2 3/4" x 2 3/8") to lost circulation. It was hoped that at least 100 m of open hole could be drilled below 666.9 m. The Los Alamos logging crew arrived on site and obtained a temperature log in the hole 8 hours after circulation was discontinued. The Kuster tool was run in the hole on Sunday March 11 after 21 hours without circulation (Fig. I-2). There was a very strong smell of H_2S several meters away from the rig. A hand held field monitor measured 135.8 ppm H_2S near the mud return. Water had been pumped down the rods to clean out all of the chemicals and it was from the mud that the strong H_2S smell emanated.

The HQ rods were then cemented in. Drilling continued in NQ to 676 m. The HQ casing separated somewhere around 300 m but the crew managed to fish and and rescrew the HQ rods together. At 703.65 m the same problem with the HQ string occurred. Apparently the casing shoe advanced the HQ rods (from 340 m down) and drilled 7 m into the rock. The HQ rods were successfully joined again and stood in the hole which prevented them from becoming unscrewed.

The high temperature continued to cause problems. Twenty-five gallons of Torq Trim were added to the mud because of too much torque on the rods. Core springs were changed 4-6 times. Polymers started to turn rubbery below 748 m where a maximum reading thermometer measured 212°C.

On March 16 the core barrel "twisted off" from the bottom rod at 769.9 m while pulling the rods to change the bit. The inner barrel was successfully fished later on the 16th but the core barrel plus the bit was not retrieved. In the early morning of the 17th, Swissboring successfully fished the core barrel with a system using the overshot, 6 NQ rods for weight, and an on-site designed fishing tool. Although problems with core springs continued, the hole was drilled to 795.25 m when the inner tube got stuck. Operations were suspended on March 18. A Kuster log was done shortly after stopping circulation (Fig. I-2).

Upon pulling the rods to prepare for borehole stimulation attempts, it was discovered that most of the core barrel plus the inner tube had "twisted off" and remained in the open hole. By late afternoon on March 19, the inner tube was successfully retrieved but the outer core barrel remained in the hole. The decision was made to attempt to stimulate the borehole with the core barrel in the hole. Temperature measured with a maximum reading thermometer after 2 days without circulation was 230°C at 788 m.

C. WELL STIMULATION AND SAMPLING OPERATIONS OF MARCH 20-22, 1990

At 9 A.M. on March 20 the NQ fishing string was removed from the hole, but the NQ core barrel was apparently "loose" at the bottom of the hole. The wellhead was removed at 9:10 A.M. and the water level was measured at 28 m depth. This level is considered to be much higher than "static" water level because formation permeability is minimal in the open hole section below 674 m. An elevated water level was easily maintained during the fishing operations described above.

The rest of March 20 was spent constructing a flow line in preparation for stimulation of the well. The design of the flow line is identical to the one constructed for flow tests of the PLTG-1 and PLTG-3 boreholes at Platanares, Honduras (S. Goff *et al.*, 1988). The only design modification for TCB-1 was an elbow that raises the inflow side of the line about 1.5 m due to the elevated height of the TCB-1 wellhead gate valve.

At 8 A.M. on March 21 an attempt was made to stimulate the well using compressed air and an on-site compressor rated at 125 psig and 600 cfm. Twenty 6 m lengths of NQ rods with a check valve screwed on the bottom were run into the hole by 9:10 A.M. and rigged up such that compressed air was delivered through the rods. No water came out of the well, so the water level had dropped to below 120 m in one day. Another five 6 m lengths were added and the compressed air turned on by 9:30 A.M. but very little water was blown out of the borehole. Because a 10 m column of water is equivalent to 1 bar or 14.5 psi of pressure and because we had to lift the water 150 m, it was obvious that the compressor was inadequate to blow the water out of the borehole.

At 10 A.M. the NQ rods with a check valve were run all the way to the bottom of the borehole (790 m) to displace water and aid well stimulation. By 3 P.M., at reaching this depth, 1210 liters of drilling mud were displaced from the hole. Calculations based on water levels, casing diameters, and rod diameters indicated that about 2390 liters of mud should have been displaced. Therefore, the open hole section of the hole was accepting some of the fluid. By 6:30 P.M., after removing the rods, the water level was measured at about 265 m depth with a temperature of 85°C. These conditions indicated that the "displacement" method of stimulation was not successful.

The wellhead was next configured so that the on-site compressor could be left on all night applying 125 psig to the top of the water column in an attempt to push the water level down. At 8 A.M. on March 22, the pressure was suddenly released on the wellhead in hopes that the water column would boil and begin to lift. Although much noise was heard from the wellbore, as the pressure was released, the fluid would not flow.

At 11:30 A.M. on March 22 a truck arrived from Guatemala City with 50 kg of dry ice. The rig crew began smashing the dry ice into pieces and stuffing them down the wellhead (Fig. I-3). It was hoped that rapid effervescence from the dry ice at the top of the hot water column would cause the core hole to unload and turn on. After about 25 kg of dry ice were successfully dropped down the wellbore, the

Fig. I-3. Photograph of dry ice going into borehole.

borehole began to rumble and a thick cloud of CO_2 and water vapor was generated at the muffler/weirbox end of the flow line. However, the next 25 kg of dry ice began to stick in the gate valve due to moisture freezing into the dry ice. Within minutes the gate valve was choked and became so cold the moisture in the air began to freeze on the exterior of the valve. At this point stimulation operations ceased.

D. DRILLING AND LOGGING OPERATIONS, MARCH 24 - MAY 9, 1990

Many of our drilling objectives had been achieved by mid-March. An outstanding temperature gradient of 23O°C per km had been determined that showed no temperature reversals. A temperature of 238°C was measured at 795 m. Core recovery was excellent with almost 100 m more than originally planned. Almost 130 m of open hole had been drilled, but no lost-circulation zone with temperatures of interest had been encountered. On March 24 the core barrel was successfully retrieved and the hole was clear and ready to continue in NQ-size. The decision was made to continue drilling the hole until a major lost-circulation zone was encountered or 1000 m (the practical limits of the capability of the rig) was reached. Because of twisting-off problems with the NQ core barrel, the heavier duty, Longyear system CDH 76 core barrels, bits, shells, etc. would be used to continue drilling. The rig was put on long-term standby status until April 24.

On April 19 the INDE logging crew did a Kuster log after 3 weeks with no circulation (Fig. I-4). As was to be expected, the upper and middle part of the borehole had heated up 20-40°C. Bottom hole temperature was 238°C. The temperature gradient was 230°C per km between 500 and 800 m and the log did not show isothermal conditions. If the gradient remains constant, a reservoir of between 275°C and 300°C could be expected at about 1000 to 1200 m.

Drilling resumed on April 24 with NQ size core to 797.5 m when the water pressure shot up and the decision was made to pull the rods. Metal (perhaps from the retrieved NQ core barrel) was found with the core sample and the bit had been etched out. On April 25th at a depth of 808.35 m rod failure occurred. The coring string broke and 6 pieces of NQ rods plus the CHD core barrel and the inner tube were left in the hole. Because of the desire to hit a major lost circulation zone, the success of the borehole so far, and the outstanding fishing record of Swissboring, it was decided that it was worth the effort, time, and cost to fish.

Swissboring personnel designed a tool out of BQ (2 3/16" x 11 13/16") rods that went into the broken rods but could not pull the rods out. Another attempt with the BQ rods penetrated around the NQ rods and actually recovered 20 cm of core. This indicated that there is quite an enlargement in the borehole around the broken end of the NQ rods at 759 m.

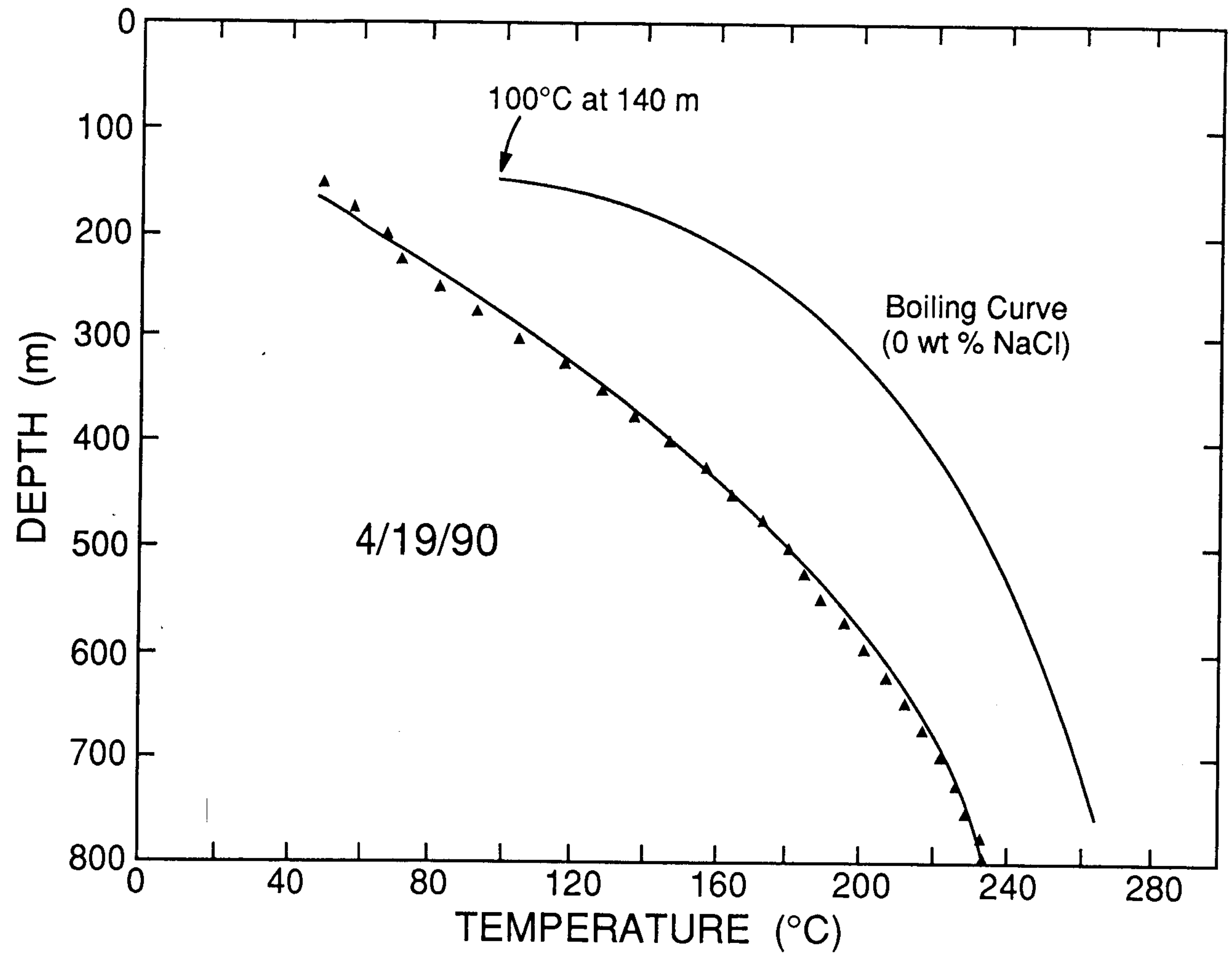

Fig. I-4. INDE Kuster tool temperature log, April 19, 1990.

Attempts were made repeatedly to enter the broken stem of the NQ rods. A special tool prepared at the Swissboring workshop in El Salvador did enter the broken string but did not have big enough tungsten grippers to pull the rods out. It was decided to continue attempts to fish until 7 A.M., May 4. The plan was to go in with NQ rods and ream 6 in. of the broken stem, then go in with a rod cutter and try to cut out some of the broken stem. If the cut worked, the NQ rods would be lowered to sit on top of the remaining rods stuck in the hole. The BQ rods with the overshot welded at the end would then be sent into the hole. However, the cut was not successful, the fishing tool did not go in, the N rods did not line up, and fishing and further drilling were terminated on May 4.

On May 5 preparations began for another stimulation attempt. The hole was cleaned out and the flow line re-installed. As per the operations in March, an attempt was made to displace as much water from the hole as possible. The goal was to lower the static water level to below the boiling point in the hole (approximately to 350-400 m). The borehole would then be allowed to heat up for a month to assist the stimulation attempt. Initially the water level was at 131 m. It was displaced to 180 m. Bailing was started and on May 8 the water level was lowered to 264 m after 34 bails. Bailing continued on May 9 to 400 m. The borehole was shut in and the rig put on long-term standby.

E. WELL STIMULATION AND SAMPLING OPERATIONS OF JUNE 1990

On June 5, the TCB-1 core hole was rigged up with flow line as per the operations described in March. The water level had risen to 140 m depth after nearly 1 month of static conditions. This is the best estimate of "static" water level for TCB-1 although the data indicate that the formation slowly produced water from below 400 m. At 6 P.M. two maximum temperature thermometers were run into the hole on the overshot and recorded a temperature of 240.5 ± 1°C at 750 m depth.

On June 6 a new 1/4-in. cable was threaded onto the wireline core retrieval drum which was modified to take the heavier cable. A double cup knuckle joint swabbing unit obtained from Oil States Industries in Houston, Texas was rigged onto the 1/4 in. cable and standard rubber sand cups were placed on the swab (Fig. I-5). At 10 A.M. the swab was run to 170 m depth and a 30 m column of water was pulled easily out of the hole. Five more runs were made with the swabbing unit which progressively lowered the water level to a depth of roughly 450 m (Fig. I-6). The 6th "pull" brought up water at temperatures above 80°C that effervesced. Swabbing efforts were stopped while a pressure lock was fabricated to prevent the well from unloading vertically onto the rig floor and burning the rig crew.

At 1:40 P.M. the pressure lock was completed and flow was diverted to the flow line. The 7th pull with the swabbing unit lowered the water level to about 510 m depth. On the 8th pull, the well suddenly

Fig. I-5. Photograph of knuckle-joint swab.

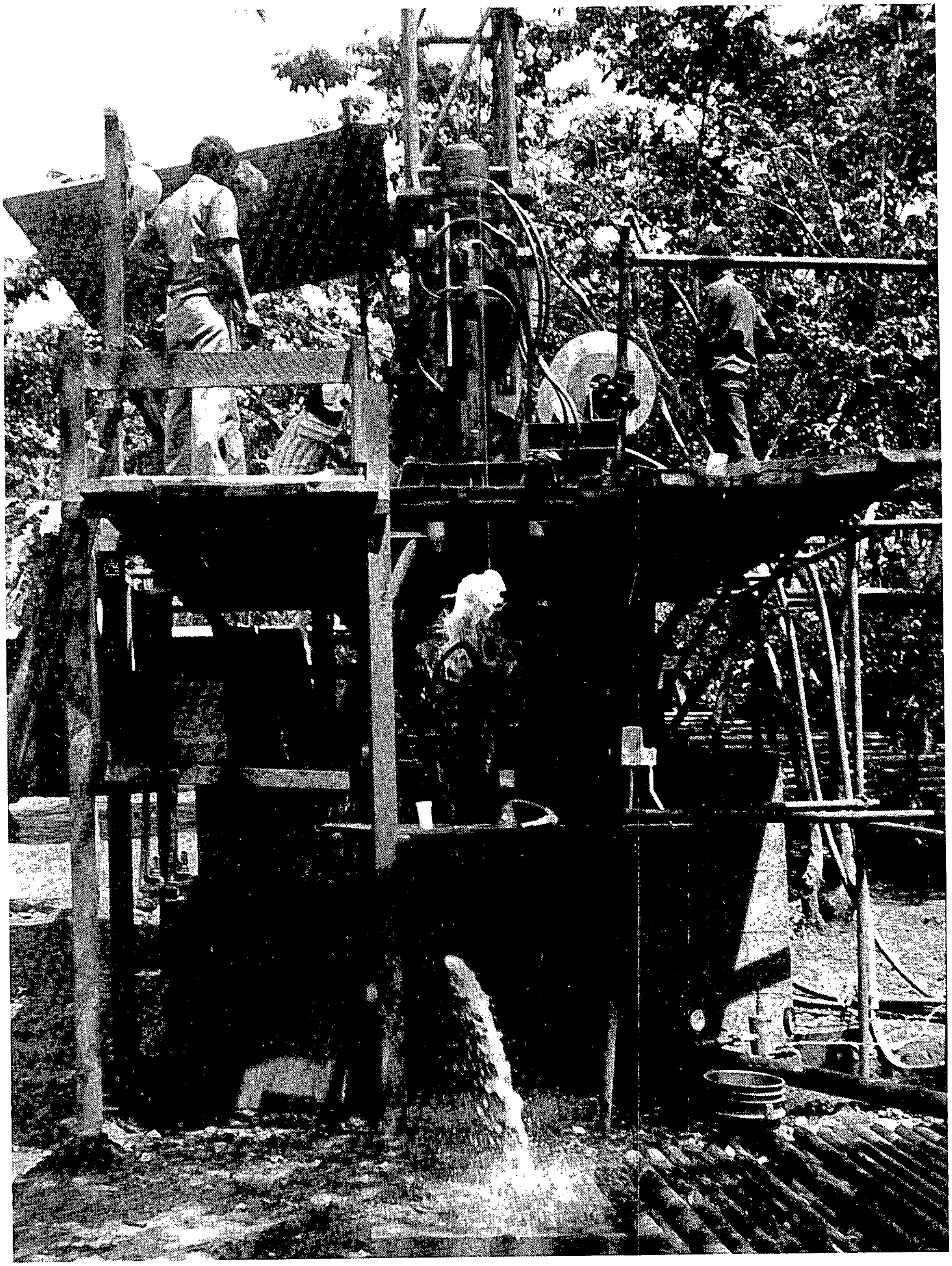

Fig. I-6. Photograph of water being swabbed.

began to unload and flow rapidly, creating clouds of steam at the muffler/weirbox (Fig. I-7). At 3:15 P.M. the hydrogeochemistry team began sampling gas and water but by 4:43 P.M. the well had purged itself of the mixture of drilling fluid and formation fluid and the flow rapidly diminished. Clearly no fluid entries exist in the open-hole section below 674 m that can sustain flow and a decision was made to shut the well in.

At 8 A.M. on June 7 the shut-in pressure of TCB-1 was about 35 psia. The team began assembly of a Klyen downhole sampler purchased from New Zealand. This tool has a design temperature limit of 350°C and a sampling volume of about 700 ml. (For a complete description of the Klyen downhole sampler inquire from Forgan Jones, Co., Ltd., Auckland, New Zealand. For a complete description of general downhole sampling methods consult F. Goff *et al.* (1987); Grigsby *et al.* (1989); and F. Goff *et al.* (1990)).

An attempt was then made to take a series of downhole samples. At 11 A.M. the sampler was rigged up and run into the hole through a loading chamber above the wellhead (Fig. I-8). While running into the core hole, the brake was accidentally released from the cable drum, the entire cable unreeled, and the tool was lost in the hole. Because of the "fish" in the hole, the tool stopped at a depth of about 762 m. By 4 P.M. the tool and cable were fished out of the hole and procedures for fluid extraction began (see Section V of this report).

On June 8 two more runs were made with the rebuilt *in situ* sampler to depths of 750 m without problems. These runs as well as the one from the previous day each retrieved only about 100 ml of water and field tests indicated that this water was very dilute. Thus, it appeared that the borehole was filled to a depth below 750 m with steam that condensed inside the sampler. A decision was made to put the rig on standby time for three days in hopes that formation fluid would slowly fill the borehole to depths above 750 m.

Downhole sampling resumed on June 11. Starting at 8 A.M. two more runs were made to a depth of 750 m. However small sample volumes in the fluid chamber and dilute chemistry still indicated that the borehole was filled primarily with steam or that the water level (and resulting hydrostatic pressure) was too low to fill the tool. At this point, fluid sampling operations ceased and a decision was made at 2:30 P.M. to release the rig. All data from these downhole sampling runs are discussed in Section V of this report.

F. SUMMARY AND CONCLUSIONS

TCB-1, now the deepest cored hole in Guatemala, was drilled to a depth of 808.35 m during the period from February to May 1990. The borehole was completed to 795.25 m on day 40 of rig operations,

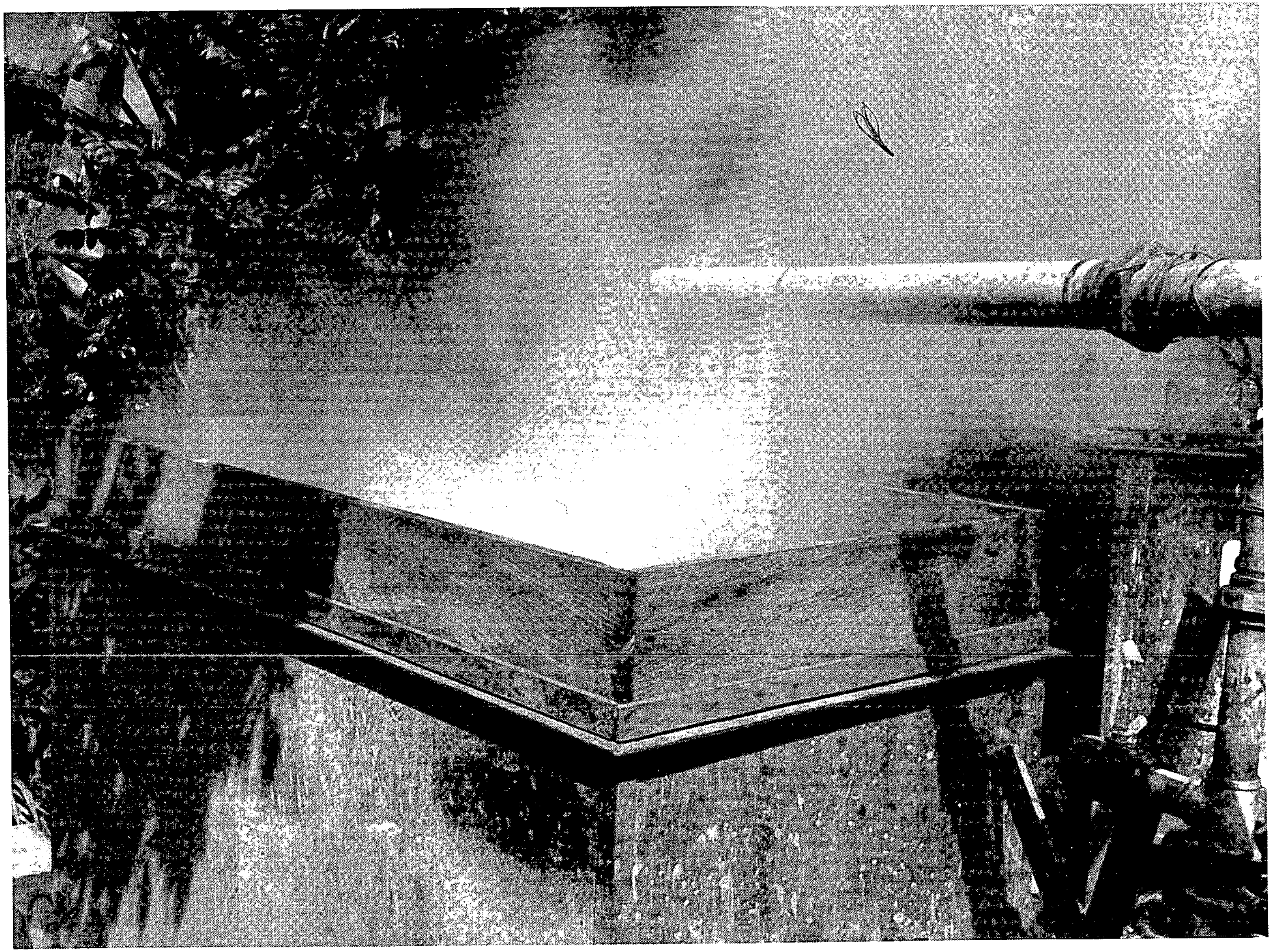

Fig. I-7. Photograph of steam over weirbox.

Fig. I-8. Photograph of Klyen downhole sampler before going into the borehole.

with an average advance rate of 21 m per day. We consider this to be quite an outstanding rate of advance, compared to other similar projects in Guatemala. Fig. I-9 presents a summary of the coring operations history. Drilling, coring, sampling, and testing operations accounted for 57.7% of total rig time (Fig. I-10). This compares with 57.0%, 53.3%, and 56.4% for similar gradient core holes drilled in Honduras (S. Goff *et al.*, 1988). Core recovery exceeded 90%.

Fig.s I-1 and I-11 present the final borehole configuration and wellhead stack respectively. HQ rods remain in the hole as casing to 674 m. Below 674 m, the hole is open (NQ size 3") to 772 m. Several twist-offs occurred and from 772 m to TD is a broken stem of rods that includes: drillpipe, a fishing tool, the inner tube, and core barrel. Swissboring had chosen to use NCQ rods (same dimensions as NQ) in place of NQ rods as they are lighter and had hoped that these rods would be more appropriate for the targeted depth. Rod failure occurred both at the joints and in the middle of the rods.

Success was achieved in spite of the difficult drilling conditions and operating near the limits of the drill rig. Over 100 m more depth was reached than originally planned, a high bottom hole temperature (238°C) and high gradient (230°C/km) were measured, greater than 90% of the core was recovered, and hydrogeochemical data were obtained from fluid samples and fluid inclusions.

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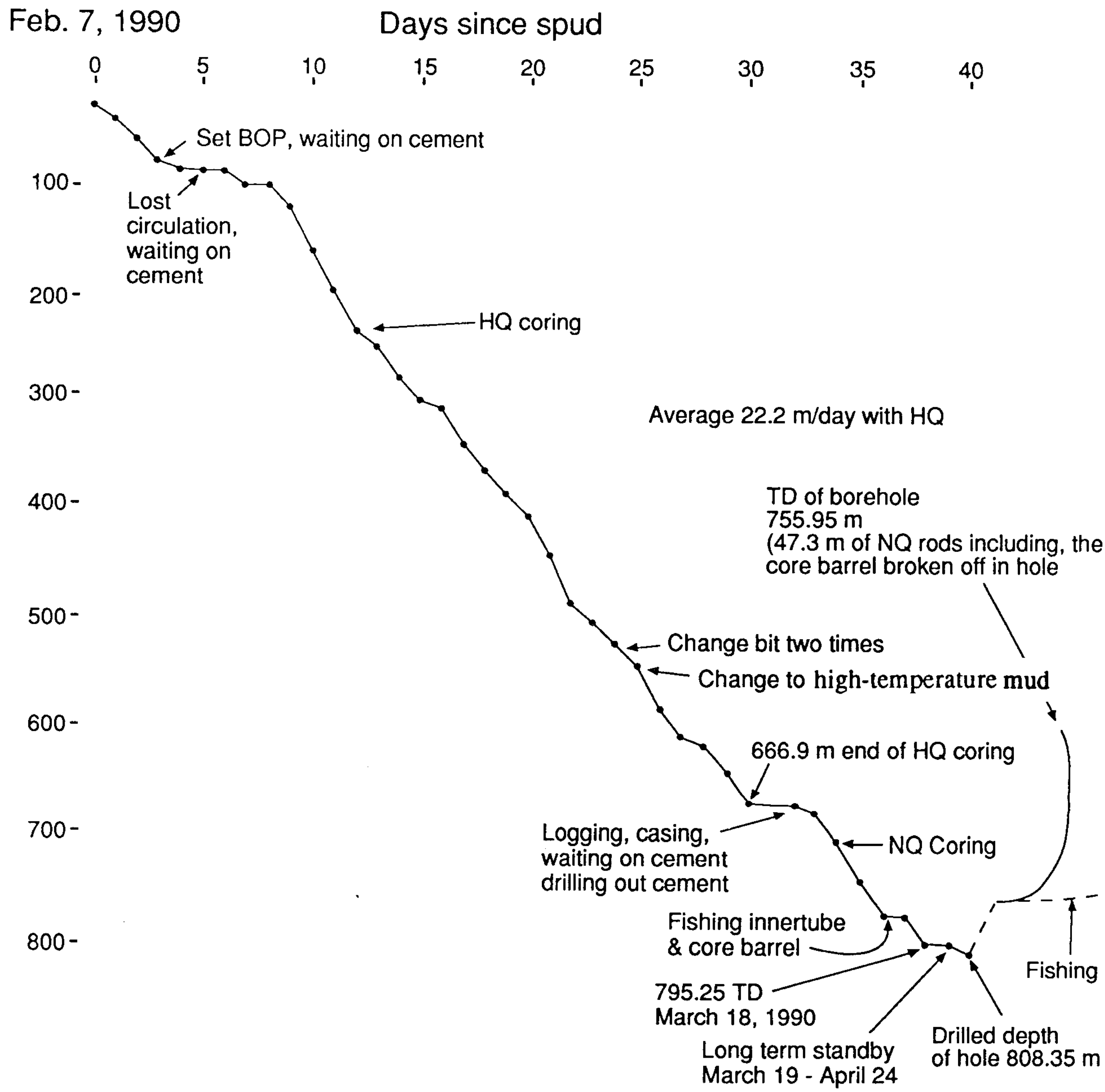

Fig. I-9. Coring operations history of TCB-1.

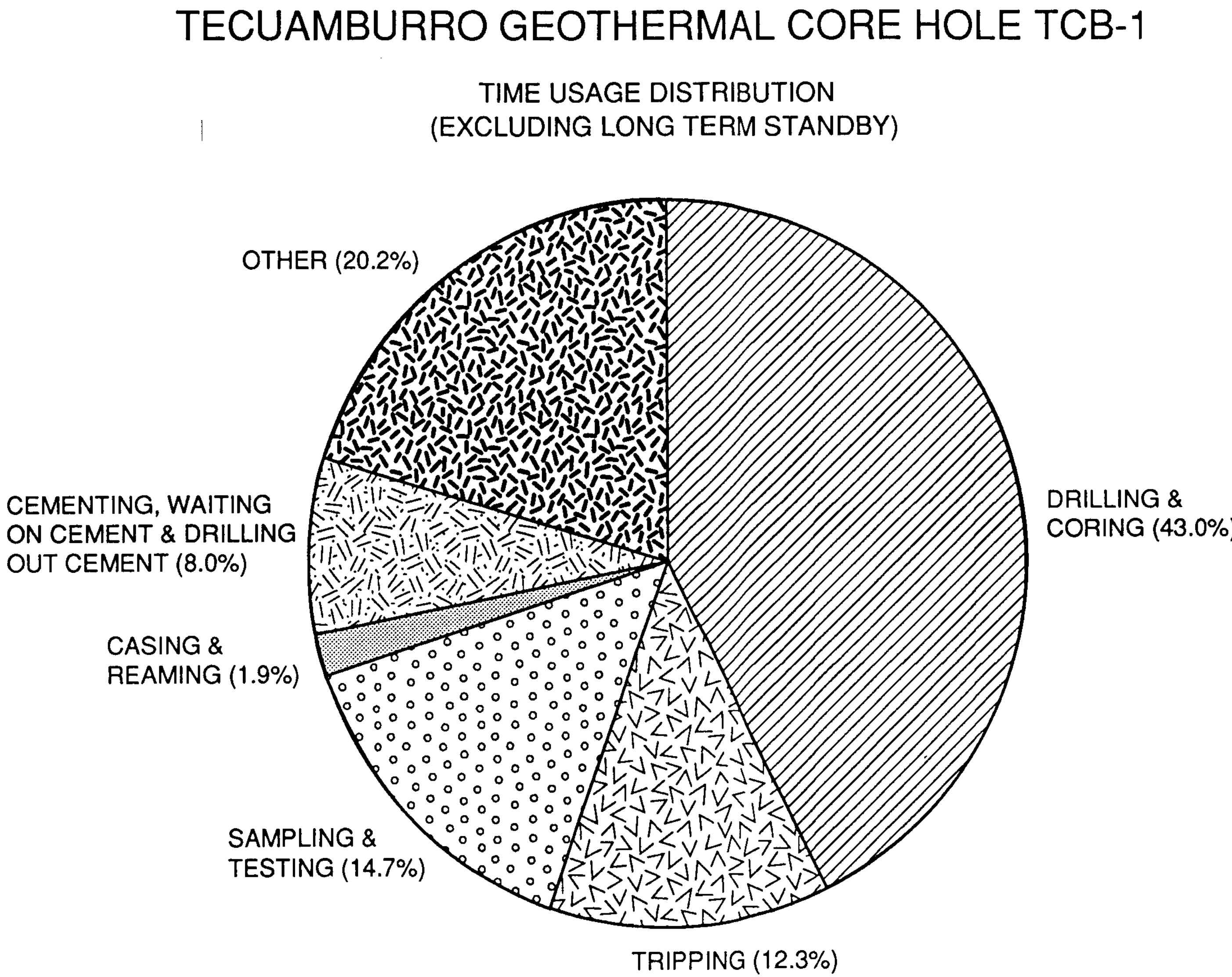

Fig. I-10. Activities by percentage of total rig time - TCB-1.

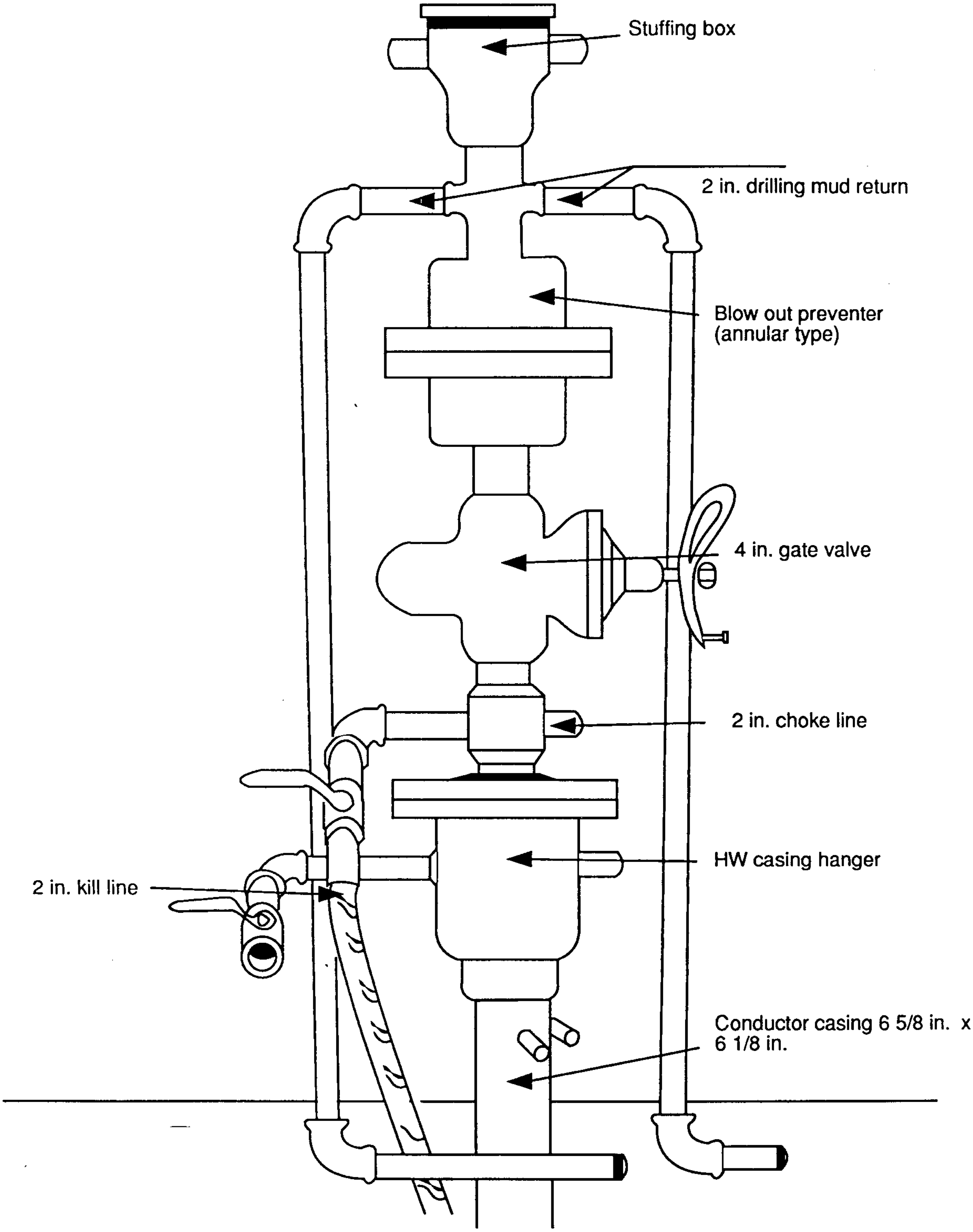

Fig. I-11. Wellhead, TCB-1.

II. TECUAMBURRO GEOTHERMAL GRADIENT WELL TCB-1 STRATIGRAPHIC DESCRIPTION

Grant Heiken, Wendell Duffield, Oscar Castañeda, Sue Goff, Fraser Goff, Jamie Gardner, John Musgrave, and Steve Chipera

A. INTRODUCTION

The geothermal gradient corehole TCB-1 was drilled to a depth of 808 m during February-March and May, 1990. The corehole is located low on the northern flanks of the Tecuamburro volcanic complex, and 300 m south and 55 m above the Laguna Ixpaco phreatic crater. (See Fig. 1, Executive Summary).

The location of TCB-1 was determined on the basis of geological, geophysical, and hydrogeochemical studies of the Tecuamburro volcanic complex (Duffield *et al.*, 1989; Goff *et al.*, 1989; and Heiken and Duffield (eds), 1990). A possible 4-km-diameter crater (Chupadero crater) encloses the Laguna Ixpaco phreatic crater and three clusters of fumaroles. This crater is crossed by NW-SE-trending faults (Duffield *et al.*, 1989).

The inferred Chupadero crater may be the vent for a widespread pyroxene pumice deposit, which consists of a pumice fall deposit overlain by ignimbrite deposits, and is thickest in the valley of Rio Los Esclavos (Heiken and Duffield, 1990). If this is the vent for these pyroclastic deposits, which have a ^{14}C date of 38,000 years, it is possible that there are shallow intrusions, which serve as a heat source for the thermal springs and fumaroles. Gases from acid sulfate springs near Laguna Ixpaco, consistently yield estimated subsurface temperatures of 300°C (Goff *et al.*, 1989). The tuff ring around Laguna Ixpaco has been dated at 2,910 ^{14}C years.

Immediately south of TCB-1 is the Tecuamburro volcanic complex. This volcanic complex grew within the crater of the ~100,000-year-old composite cone of Miraflores volcano. The Miraflores crater may have formed by sector collapse; a hummocky deposit extending from the base of the volcano, east to the lower slopes of the Ixhuatn volcano has been interpreted as a sector collapse deposit (Duffield *et al.*, 1989).

Andesitic and dacitic domes that have grown within the Miraflores crater have also collapsed several times, leaving avalanche debris deposits on the northern slopes of Miraflores/Tecuamburro. There are at least four avalanche deposits. The youngest avalanche deposits are from the Peña Blanca dacite dome and overlap the Ixpaco tuff ring, dated at 2,900 years. An older avalanche deposit penetrated by TCB-1 may have come from a north-facing open crater, which encloses the Mina Azufre and the San Francisco and Peña Blanca domes.

The chemical characteristics of gases and waters in the Ixpaco area also match those of the Mina Azufre, a fumarolic area near the summit of Tecuamburro volcano. This leads to the hypothesis that the fluids and gases of the Ixpaco area are emitted from a subsurface reservoir beneath the entire Ixpaco-Tecuamburro area. The original location of TCB-1 was chosen by investigators to be 700 m northwest of the center of Laguna Ixpaco, halfway between the phreatic crater and a group of fumaroles, near the center of the Chupadero crater. This location is also located along the extension of a proposed buried fault. The goal was to be located near the center of the proposed heat source of Chupadero crater, and in a zone of fracture permeability, along the fault trend and close to the Ixpaco phreatic crater, where there may be zones of hydrothermal fracturing. However, the site was not available at the time when exploration drilling was to begin.

A second site (site B), located south of Laguna Ixpaco (Fig. 1, Executive Summary), on available land and close to a source of water was chosen for drilling TCB-1. It is located 300 m south of Laguna Ixpaco, at the base of one of the lobes of one of the Pea Blanca avalanche deposits. This location serves to test the hypothesis that Chupadero Crater is the source for a major late-stage eruption of pyroclastic rocks and thus a major heat source, and also the hypothesis that the hydrothermal reservoir may extend toward Tecuamburro proper.

The TCB-1 site is located on a lobe of interbedded tuffs and avalanche deposits from the Tecuamburro complex. The drill site surface consists of soils developed on a massive boulder-bearing breccia. The location is at UTM Grid YF779698 (Cuilapa 1:50,000 topographic sheet; 2158 IV).

No core was collected in the uppermost 39 m of section. However, several cuttings samples were collected. The stratigraphy reported here is "top down," with depths in meters below the drill rig floor. Table II-1 presents quantitative XRF results.

B. DESCRIPTION OF CORE AND CUTTINGS FROM TCB-1

0-39 m (thickness=39 m); Massive avalanche deposit and colluvium?

The cuttings from 13 to 16 m depth consist of ~40% porphyritic pumice (~10% phenocrysts, with plagioclase>>clinopyroxene>orthopyroxene; ~40% vesicles, which are 10 μm-50 μm long and spherical to ovoid). The pumice fragments are unaltered. They may be correlative with the pyroxene pumice (Qai) and have been washed in from adjacent hillsides that are covered with this unit. The remaining cuttings consist of fragments of consolidated, altered tuff, scoria; clasts of porphyritic two-pyroxene andesite; and mineral clasts (plagioclase>>clinopyroxene>orthopyroxene>Fe-Ti oxides).

Samples collected at depths of 22 m and 32 m consist of fragmented poorly-sorted volcaniclastic rock; angular to subrounded clasts of two-pyroxene andesite, andesitic lithic tuff, and mineral clasts in a yellow-brown clayey matrix. This may be part of the unit described from a depth of 39 to 46.5 m.

39-46.5 m (thickness=7.5 m, or if extended to the surface, 46.5 m); Massive andesitic avalanche deposit.

Massive, dark yellowish-brown (10YR 6/6; Munsell color system) breccia, composed of andesitic lava pebbles, cobbles and boulders (up to 140 cm in diameter) in a coarse arkosic matrix. The andesitic lava clasts are porphyritic, with plagioclase>>orthopyroxene>clinopyroxene>Fe-Ti oxides; many phenocrysts are bound up in glomeroporphyritic clots. Although the upper 39 m was not sampled, these deposits are similar in appearance to those at the surface and exposed along the nearby stream.

46.5-53 m (thickness=6.5 m); Lithic-vitric tuff.

Massive pumice- and dacite- and andesite-clast-bearing vitric tuff. Dark greenish-grey (5G 2/1 to 5G 4/1) ignimbrite. Lithic and pumice clasts range from <1 mm to 4 cm long. Pumice swarms occur throughout the ignimbrite. There is a thin soil at the top of the unit. The rock has been weathered, but relict forms of pumice, shards, and lithic clast textures are still visible.

53-58.7 m (thickness=5.7 m); Lithic tuff.

The unit appears to be mostly massive nonwelded ignimbrites. Most of the unit has been altered to a clayey soil. Interbedded with the ignimbrites are 0.5-1.0-cm-thick fine ash beds, which are now plastically deformed.

58.7-65 m (thickness=6.3 m); Massive tuff-breccia.

Dacitic and andesitic lava clasts, up to 60 cm in diameter, make up about 50% of this deposit. The dacite clasts are porphyritic dacitic pumice bombs; 60% phenocrysts, with plagioclase>>hornblende>sanidine>Fe-Ti oxides. The matrix is lithic ash, consisting of mostly 1-3-mm-long andesite clasts, small pumice clasts, and shards (?) in fine-grained alteration products. The matrix is dusky yellow-green (10GY 3/2).

65-66.5 m (thickness=1.5 m); Lithic tuff; possible edge of the Ixpaco tuff ring.

Subangular to subrounded andesitic lava and dacitic pumice clasts (60%) in a pale yellowish-brown (10YR 6/2) clayey matrix. Most of the clasts are <10 cm in diameter. Many of the clasts appear to be silicified, with a pink hue. Most of the pumice clasts have been altered to kaolinite (?), although unaltered pumice clasts are present. This unit has been interpreted as the edge of the tuff ring that surrounds Laguna Ixpaco; the surface of the crater lake is 55 m below the surface at the drill site, not too far above this level.

66.5-108 m (thickness=41.5 m); Tuff breccias; possible avalanche breccias or clast-rich ignimbrites from Cerro la Soledad and pre-Pea Blanca domes of the Tecuamburro volcanic complex.

This unit is composed of several massive to graded subunits of tuff-breccia, with one interbed of bedded lithic ash. Most of the units consist of ~60% clasts of pumiceous hornblende dacite (20% phenocrysts; plagioclase>hornblende>orthopyroxene>clinopyroxene>quartz>Fe-Ti oxides) and andesitic lava (~25% phenocrysts; plagioclase>hornblende>Fe-Ti oxides, in a trachytic groundmass; this is a unique and distinctive lava type in this area) in a medium- to fine-grained volcaniclastic matrix. Many of the pumice clasts appear to be bombs, supporting the interpretation that these are lithic-rich ignimbrites.

Clast populations range in size from <100 m to 1 m in diameter for the dacite pumice and from <100 m to 2.2 m for andesitic lavas. Distribution of these clast populations can be interpreted as grading. Contacts, however, are not distinct enough to say much other than there are concentrations of lithic clasts (see original lithologic logs, which are attached to this report).

The breccia matrices are similar, consisting of angular 0.15 mm diameter clasts of porphyritic andesitic lava with aphanitic to trachytic groundmass, porphyritic dacite, and porphyritic dacitic pumice, and broken mineral clasts (plagioclase>hornblende>orthopyroxene).

Much of this unit is hydrothermally altered and perhaps hydrothermally fractured. Most of the zones of fracturing, alteration, and lost circulation are associated with large andesitic clasts (cobble- to boulder-size). These alteration zones are listed below:

68-69 m. Fractures within an andesitic clast; fractures filled with hematite and surrounded by limonite staining.

70-70.4 m. Matrix vugs, filled with limonite; alteration of dacitic pumice clasts to clay.

72.8 m. Fractures associated with limonite staining.

82.9-84.6 m. Two major lost circulation zones. These are in an andesite boulder, which is heavily fractured. The andesite appears to be silicified and brittle and is crossed by vuggy fractures. The porphyritic lava groundmass has been replaced by spherulites of a silica phase. Small vugs are filled with hematite.

85.6 m. Abundant fractures with hematite staining.

86.4 m. Criss-crossed by abundant fractures with silicification and iron staining of the rock. Fractures are partly filled with hematite and silica.

87.2-88.4 m. Abundant fractures with hematite coatings. Matrix altered to dark greenish gray.

88-101 m. Numerous vuggy fractures, which are mostly dipping at <45. The tuff matrix and many of the clasts have been altered to clays and silica minerals and only faint relict textures remain. Boulder- and cobble-size andesitic clasts are rimmed by authigenic silica. Limonitic and hematitic staining. Lost circulation zone at a depth of 99.6 m.

105-107 m. Vertical and steeply-dipping fractures in an andesite boulder are partly filled with limonite and hematite.

108-130.2 m (thickness=22.2 m); Scoria-bearing tuff breccia.

The upper contact of this unit is not clear, as the change (scoria clasts) occurs at a fracture. This tuff breccia consists of <1-cm- to >10-cm-diameter pumice (~15%), andesitic lithic clasts (25%), and scoria (10-20%) in lithic ash matrix (40-50%). The andesitic clasts are porphyritic, with plagioclase>>hornblende>orthopyroxene>Fe-Ti oxides. Pumice clasts consist of rare phenocrysts of plagioclase>>hornblende>Fe-Ti oxides in a vesicular glassy groundmass; ovoid vesicles make up ~20% by volume. Most of the matrix clasts also include broken minerals similar to phenocrysts in the lithic clasts, but these are mostly altered to clays.

This subdivision appears to be a sequence of two scoria-bearing tuff breccias, each with scoria clasts concentrated within upper portions of the subunits. Scoria clasts are black, vesicular, with rugose shapes. Most appear to be lapilli and bombs.

Scattered throughout, but concentrated mostly at depths of 121.5124 m, are low-angle fractures; fracture surfaces are coated with silica and limonite. Once again, most fractures are concentrated in an andesite boulder.

130.2-138 m (thickness=7.8 m); Homogeneous clast-supported "puzzle" (?) breccia.

This is a clast-supported breccia consisting of 80% angular to subangular, <1 cm- to 20-cm-diameter clasts of andesite or dacite (relict textures). The larger clasts have bleached rims 1-3 cm thick. The rock is dark-yellow orange (10YR 6/6). The clasts appear to be one rock type, with similar textures occurring in adjacent clasts.

The space between clasts is filled with limonite, hematite, clays and silica minerals. Surficially there is intense limonitic alteration. Matrix materials that have survived alteration include broken phenocrysts.

This may be either a deposit of lithic tuff-breccia with one rock type or a hydrothermal "puzzle" breccia. In favor of the latter hypothesis is the similarity of adjacent clasts and the intense alteration. There is also very little matrix material.

138-141 m (thickness=3 m); Bedded lithic tuff.

This tuff unit consists of 10 cm of bedded deposits (with evidence of soft-sediment deformation), grading up into 2.9 m of massive lithic tuff breccia. Most clasts appear to have been <1-cm- to 5-cm-diameter pumices. The unit is dusky blue (5PB 3/2) and fine-grained pyrite is disseminated throughout.

141-144.6 m (thickness=3.6 m); Massive tuff-breccia.

This tuff-breccia consists of ~40% subangular to subrounded andesite and hornblende dacite clasts, and small pumice clasts in ~60% matrix. The unit is heavily stained by hematite and limonite; fractures are filled with hematite.

144.6-188.5 m (thickness=43.90 m); Massive pyroxene tuff.

With the exception of post-depositional fractures and variations in the concentration of lithic clasts, this unit is exceptionally uniform over its entire thickness. Textures are easy to interpret within this rock unit. This tuff is dark greenish-gray (5/G 4/1), reflecting the slight chloritic alteration. There are about 25% large (2-20 cm) pumice clasts and 5-10% andesitic lava clasts in 50-70% coarse ash and lapilli matrix. The larger pumices have been altered and are now vuggy.

The barely pumiceous (<10% vesicularity) glassy clasts are equant, subrounded to subangular, consisting of 0.1-0.5 mm long phenocrysts of plagioclase>orthopyroxene>clinopyroxene (~20-40% by volume) in hyalo-crystalline groundmass. Vesicles are mostly ovoids and are <60 m long.

Lithic clasts are mostly andesitic lavas and consist of 25-50% phenocrysts (plagioclase>>orthopyroxene and clinopyroxene>Fe-Ti oxides>rare hornblende) in a hyalocrystalline groundmass with well-developed flow texture. These clasts have about 15% irregular vesicles. Lithic clasts are most common (~volume=5-10%) in the uppermost 44 m of this deposit and appear again near the bottom, at a depth of 247 m. In the most compacted and altered rocks of this sequence, the lithic clasts are the most obvious field indicator that these are clastic rocks.

188.5–about 244 m (thickness=55 m); Massive andesite.

Massive two-pyroxene andesite with a trace of small, oxidized hornblendes makes up a very uniform unit. The unit may be an andesitic lava, with alteration along flow banding or vesicles, or a welded andesitic tuff (the majority of analysts favor the former hypothesis).

From depths of ~185 m to 244 m, elongate lenticular masses cross the rock unit; these have been interpreted as bands of alteration and as pumice clasts that have been compacted into lenticular, porphyritic fiamme. The best developed of these lenticular forms are visible at depths of 239 to 244 m and are dipping at angles of 20 to 45. This orientation is also visible in thin sections.

The massive andesite is cut by faults with slickensides and gouge. The upper contact is adjacent to a low-angle fault with slickensides. Zones of intense fracturing occur at depths of 172-174 m, and from 205.5-238.5 m (the latter zone coincides with what has been interpreted here as a massive lava or densely welded and altered zone within a massive tuff). Fractures in the deeper, more extensive zone have dips ranging from 40 to 80 and many show slickensides; fractures are filled or partly filled with calcite, ovuidal calcite, limonite, and a finely-crystalline, apple-green mineral, most likely chlorite.

About 244-253.8 m (thickness=9.8 m); Andesitic tuff.

Within this sequence of tuffs (250.2-251 m) is a reversely-graded, nonwelded pumice bed. It grades from coarse ash and 0.5 to 4-cm-long pumice lapilli at the base, upward into tuff containing pumice blocks up to 10 cm long. Although altered, the pumices appear to be pyroxene-bearing; matrix is now mostly clay, but contains angular, broken plagioclase and pyroxene clasts.

The base of the tuff unit is a low-angle fault with slickensides.

253.8-457.2 m (thickness=203.4 m); Andesitic scoria and interbedded lavas and lithic tuffs; buried cinder cone?

This stratigraphic division is based on the thick sections of massive, poorly bedded, clast-supported, coarse-grained scoria. The type of scoria beds and associated lithic tuffs and thin lava flows are similar in many ways to sequences typical of scoria cones (Houghton and Schmincke, 1989).

This 203-m-thick section is composed of 73% scoria (13- to 59-m-thick subunits), 16% lithic ash (2- to 17-m-thick subunits), and 11% lava (9- to 12-m-thick subunits). Most of the deposits have been altered to smectite clays, but excellent relict textures have been preserved.

The scoria deposits are composed of black scoria clasts, ranging in size from <1 mm to 6 cm in diameter; overall color of the deposits is greenish-black (5G 2/1). There are some small vugs lined with secondary minerals. Equant to subequant scoria clasts appear to be andesitic, with relict zoned plagioclase phenocrysts >> relict pyroxene phenocrysts in what was a tachylitic groundmass. The deposit appears to have originally been clast supported, but the open space between clasts has been filled with smectite clays, calcite, hematite, and a trace of a silica phase.

Interbedded with the scoria deposits are andesitic lithic lapilli-ash beds. These are massive, matrix-supported tuffs, which have distinct contacts with lavas, but both sharp and gradational contacts with scoria deposits. What appear to be pumice lapilli in hand sample appear to be mostly altered scoria clasts in thin section. The lithic ashes consist of mostly equant to subequant clasts of porphyritic andesite and some scoria clasts in a matrix composed of smaller lithic clasts, mineral clasts, and shards (?). The matrix has been replaced by orangish-brown smectite, rare kaolinite, and hematite.

Two thin lavas are interbedded with the scoria near the top of the sequence. They are massive, greenish-black (5G 2/1) lavas, consisting of ~30-40% <1 mm- to 6 mm-long oscillatory-zoned plagioclase>>clinopyroxene> orthopyroxene (there are relict forms and traces of unaltered phenocryst phases) in what appears to have been a hyalocrystalline groundmass.

The sequence can be interpreted as a near-vent section through the rim or high on the slopes of a scoria cone. The coarse grain size of the scoria and massive bedding is supporting evidence for this interpretation, because more distal portions of scoria deposits (fallout beyond the base of the cone) are much finer grained (Heiken and Wohletz, 1985). The interbedded, matrix-supported andesitic lithic ashes can be interpreted as being Vulcanian, i.e., with a phreatomagmatic component (e.g., similar sections were mapped in the well-exposed Rothenberg scoria cone, Germany; Houghton and Schmincke, 1989). The intermixing of Strombolian and Vulcanian activity is common behavior at scoria cones and can be seen today at the nearby active cone of Pacaya. Thin lava flows near the top of the section can be interpreted as spill-over from a lava lake in a crater or as rootless lava flows, formed during rapid extrusion of large scoria bombs; the textures of this lava support the first interpretation. A scoria cone ~200 m thick is not unusual, because cones range in height from <50 m to >300 m.

The consolidated, well-cemented scoria deposits, lithic tuffs, and lavas are all criss-crossed by thin veins filled with calcite, silica minerals, hematite, and smectite clays. Some of the fractures have slickensided surfaces. There are zones with numerous fractures and intense alteration at depths of 263 m, 279 m, and 370 m. Most of the section appears to have low permeability.

457.2-474.5 m (thickness=17.3 m); Andesitic lava flow.

Porphyritic andesitic lava, consisting of 30% phenocrysts of zoned plagioclase>>pyroxene (the latter mineral has been replaced by clays and a trace of chlorite) in an undecipherable groundmass.

Near-vertical fractures cut the lavas. The fractures have been sealed with chalcedony, authigenic quartz, calcite, and chlorite.

474.5-480 m; "Breccia" (thickness=5.5 m)

This massive clastic rock consists of andesitic lithic clasts and pumice (?) in a highly altered matrix. Vertical fractures are filled with calcite, hematite and chlorite (?). Possible fault.

480-611 m; (thickness =131 m); Andesitic lava flow(s).

Andesitic lava(s), broken only by faults and fractures could be interpreted as one massive, ponded lava or as multiple, perhaps as many as four lava flows; textural variations in the lavas can be interpreted either way. Because of the fracturing and alteration, it is not possible to draw conclusions regarding the subdivision of these lavas. There are no interbedded tuffs, scoria beds, or soil horizons.

From a depth of ~480 to 525 m, the lavas are porphyritic, with 20-50% phenocrysts of zoned plagioclase>>orthopyroxene(?) in an indeterminate groundmass (completely altered; 75% smectite, 3% quartz, 4% calcite, 2% hematite, and 1% pyrite).

A unique porphyritic lava is present from ~525 to ~535 m, a zone of difficult drilling and poor recovery. It consists of 25% phenocrysts of zoned plagioclase (200 μm to 2 mm long), orthopyroxene (in glomeroporphyritic clots), clinopyroxene, and Fe-Ti oxides in a finely crystalline, trachytic groundmass. Only the clinopyroxene has been severely altered. Small vugs are filled with calcite and chalcedony. This could be a separate flow or the chilled base of the overlying flow.

From ~535 to ~573 m, the lavas are uniform in appearance, consisting of 50% phenocrysts of zoned plagioclase (200 μm to >1.5 mm long) and a ferromagnesian mineral, most likely clinopyroxene (altered) in a relatively coarse intergranular texture. Nearly all of the groundmass minerals have been replaced by hematite, magnetite, calcite, and chalcedony.

A lava similar in appearance to the lava with trachytic groundmass (525-535 m) appears at depths of ~573 to 581 m. It could be a separate flow, but also may be the chilled base of the overlying flow with a coarse intergranular groundmass. This zone is fractured.

The lavas from depths of 581 to 611 m are porphyritic, consisting of 35-50% phenocrysts of zoned plagioclase>>clinopyroxene>orthopyroxene in an intergranular groundmass (with scattered poikilitic patches of clinopyroxene). There is some flow structure visible in the groundmass of these lavas. Vugs are filled with hematite linings, overlain by radial growths of calcite and chalcedony.

Nearly all fractures are filled with hydrothermal minerals. Most are lined with sparry calcite, scaly calcite, authigenic quartz and chalcedony, hematite, smectite clays, and dolomite (?). Thin veins pervade most of the lavas, but larger fractures occur at depths of 490 m, 506 m (with fault gouge), 512 m (with fault gouge), 530 m, 548 m, 562 m, 573-580 m, and 599-612 m (major lost circulation zone).

611-633.5 m; (thickness=22.5 m); Andesitic lava flow (?).

The core was described in the field as a greenish-black (5G 2/1), altered tuff. The thin section is of an andesitic lava, consisting of ~35% phenocrysts in a relatively coarse intergranular groundmass. The phenocrysts consist of plagioclase>>clinopyroxene>orthopyroxene, as individuals or in glomeroporphyritic clots; rounded clinopyroxenes are up to 1.5 mm in diameter.

This could either be a clast-rich tuff and the sample happened to be of a clast, or the unit could be a lava flow with few fractures.

633.5-639.6 m; (thickness=6.1 m); Scoria bed.

Massive scoria bed, composed of scoria and andesitic lithic clasts from ash size to bombs and blocks up to 15 cm in diameter. The well-cemented scoria bed is cut by fractures filled with veins of coarsely crystalline sparry calcite and dolomite.

639.6-662 m; (thickness=22.4 m); Andesite flow.

Massive pyroxene andesite flow. The lava is cut by high-angle veins filled with calcite, hematite, chlorite, and a sulfide mineral. A brecciated section at 651.5 m depth may be a tectonic or hydrothermal breccia; there are open vugs containing quartz. The flow rock has been altered to smectite (50 ± 23%), chlorite (8 ± 2%), quartz (19 ± 4%), and calcite (13 ± 3%).

662-806 m; (thickness=144 m+); Interbedded andesite flows, andesitic breccias, and scoriaceous lithic tuff.

Because of the degree of hydrothermal alteration, this sequence of andesitic volcanic rocks has been particularly difficult to interpret. Much of the rock is dark greenish-grey, having been altered to a mixture of smectite (70 ± 36%), chlorite (24 ± 7%, calcite (3 ± 2%), and pyrite (2 ± 1%). Sixty percent of the smectite consists of allevardite.

The section consists of 42.2% massive, monolithologic, andesitic breccia (beds are 0.5-19.5 m thick), 23.8% andesitic lava flows (4.3 to 10.5 m thick), one matrix-supported andesitic breccia, 43.3 m thick, with a variety of clast types (23.8%), and a 7-m-thick section of scoria (3.5%). Regardless of the interpretations of the breccia types, the section represents the rock types found on the slopes of composite cones and is likely part of the Miraflores volcano.

662-673 m.

Andesitic breccia, with clasts up to 0.5 m long. The matrix of this breccia consists of ~20% rounded, andesitic scoria clasts (200 m-3 mm long) and ~60% angular to subangular finely crystalline, porphyritic lava clasts, in a completely altered mass of clay and chlorite. Vesicles in the scoria are now filled with chlorite and calcite. From 662-662.6 m are fault gouge and veins of calcite and smectite.

673-683.5 m.

Andesitic lava flow, consisting of 30% phenocrysts (zoned plagioclase>>clinopyroxene>Fe-Ti oxides. Most of the texture is relict, with most phenocrysts and groundmass altered to smectite and chlorite. At 675 m is a 30-cm-thick zone of high-angle fractures now filled with clay and chlorite. At 681 m is what may be a hydrothermal breccia with open vugs partly filled with quartz, calcite, a sulfide mineral, and laumontite.

683.5-703 m.

Andesitic breccia, with clasts up to 60 cm long. At 689.1 m is a zone of fractures, filled with calcite, laumontite, and a sulfide mineral.

703-708 m.

Massive andesitic pyroxene andesite flow, which grades into a breccia at 708 m. Veins at 707.2 m are filled with calcite and chlorite.

708-713 m.

Massive andesite breccia.

713-717 m.

Andesite lava flow. Much of the flow is fractured (20 fractures/m depth). Nearly horizontal fractures, filled with secondary minerals, are cut by open high-angle fractures with slickensided surfaces.

717-724.8 m.

Andesitic breccia. At a depth of 718.5 m, there appears to be intermittent solution porosity, which continues to the bottom of the core hole.

724.8-728.5 m.

Andesite lava flow.

728.5-729 m.

Rubble, composed of andesitic lava clasts; possibly caused by drilling.

729-733.3 m.

Massive, hydrothermally altered andesitic lava flow, or a large clast within a breccia.

733.3-735.5 m.

Andesitic breccia.

735.5-742.4 m.

Andesitic lava flow.

742.4-785.7 m.

Massive andesitic breccia, with a variety of lithic clasts. The matrix of the rock is an andesitic lithic tuff, consisting of a variety of subangular to subrounded andesitic lava lithic clasts ranging in size from <100 m to 3.5 cm long. All of the clasts are porphyritic, with plagioclase being the major phenocryst mineral. The finer-grained matrix and pore space are replaced and filled with smectites and finely-crystalline calcite. Veins are filled with sparry calcite and dolomite (?). Lava clasts consist of several types: (1) ~30% feldspar phenocrysts in what was an intergranular groundmass, and (2) ~25% phenocrysts (plagioclase>>pyroxene) in a finely crystalline groundmass. All of these descriptions are based upon relict textures. Vugs in the lava clasts are filled with clays, chlorite, calcite, and chalcedony, and authigenic quartz. The rock is silicified from 752-755 m.

From 756.7-776.5 m are what have been interpreted as 0.1-0.6 m thick andesitic or dioritic dikes. This is supported by field observations. However, in thin section, these are andesitic lavas, no different than the clasts or lava flows of the overlying and underlying rocks. An alternate interpretation is that these are large clasts in a matrix-supported debris flow. Any interpretation is clouded by the degree of brecciation and hydrothermal alteration of this section.

At 781 m is an open fracture, with fracture surfaces coated with calcite and pyrite.

785.7-789.3 m.

Massive andesitic breccia. The matrix consists of 80% 100-m- to 1-cm-long, subrounded to subangular vuggy porphyritic andesite clasts and 20% porphyritic scoria. Much of the rock has been replaced by clays, chlorite, and calcite.

789.3-795 m.

Andesitic breccia, which has been strongly altered. There was poor core recovery in this section. Lava clasts and matrix have been replaced by clays, calcite, chlorite, and pyrite. At 791 m is a 0.3-m-thick zone of cataclastic breccia; open fractures are coated with quartz, calcite, pyrite, and chlorite.

795-806 m.

Interbedded scoria and thin andesitic lava. Lava clasts are reasonably fresh and consist of 30% phenocrysts (200 m- to 3-mm-long) of zoned plagioclase and plagioclase clots>>pyroxene (pyroxene has been altered to chlorite); the trachytic groundmass has been altered to smectite clays. Fracture fillings consist of quartz, sparry calcite, dolomite, and clays.

C. REFERENCES

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Table II-1. Quantitative XRD results for G. Heiken's TCB samples.

SAMPLE		I/E	SMECTITE	KAOLINIT	CHLORITE	QUARTZ	CRISTOB	FELDSPAR	CALCITE	HEMATITE	PYRITE	% Collapsed Layers in the I/S Clay
TCB-1-20	134m	I	23 +- 7	16 +- 4	--	3 +- 1	18 +- 1	32 +- 4	1 +- 1	--	--	<5%
TCB-1	188.25m	E	62 +-31	1 +- 1	--	1 +- 1	8 +- 3	27 +- 8	--	2 +- 1	--	<5%
TCB-1	285.0m	E	87 +-49	1 +- 1	TR	TR	--	--	11 +- 4	1 +- 1	--	<5%
TCB-1	292.3m	E	96 +-57	3 +- 2	--	--	--	1 +- 1	--	1 +- 1	--	<5%
TCB-1-46	346M	I	86 +-26	TR	--	--	--	11 +- 1	2 +- 1	2 +- 1	--	<5%
TCB-1-60	481m	I	75 +-23	TR	--	3 +- 1	--	18 +- 2	4 +- 1	2 +- 1	1 +- 1	<5%
TCB-1	651.5m	E	50 +-23	--	8 +- 2	19 +- 4	--	8 +- 2	13 +- 3	--	TR	Allevardite ~60%
TCB-1	756.0m	E	70 +-36	--	24 +- 7	1 +- 1	--	--	3 +- 2	--	2 +- 1	Allevardite ~60%

TECUAMBURRO GEOTHERMAL GRADIENT WELL TCB-1

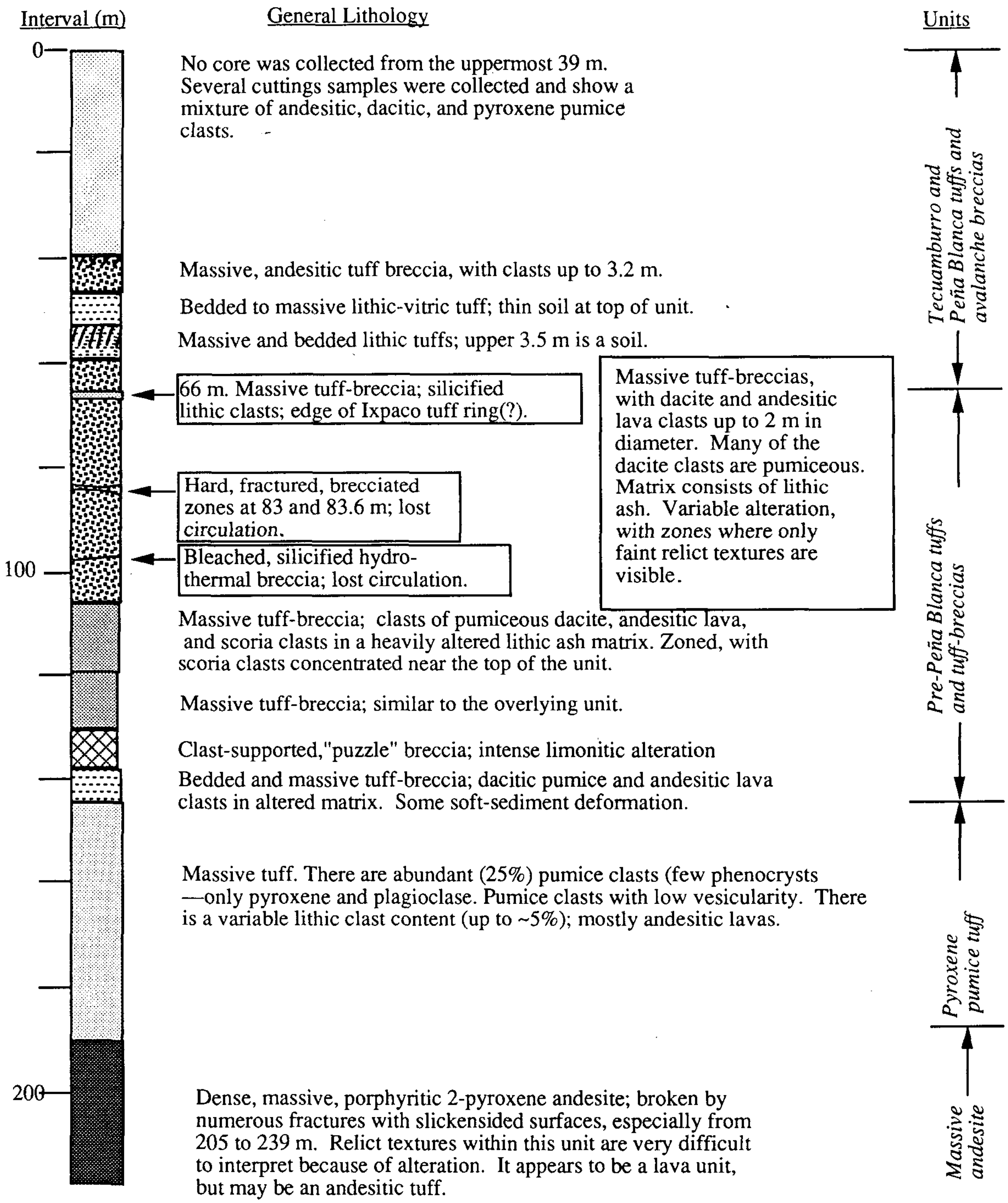


Fig. II-1. Tecuamburro geothermal gradient well TCB-1.

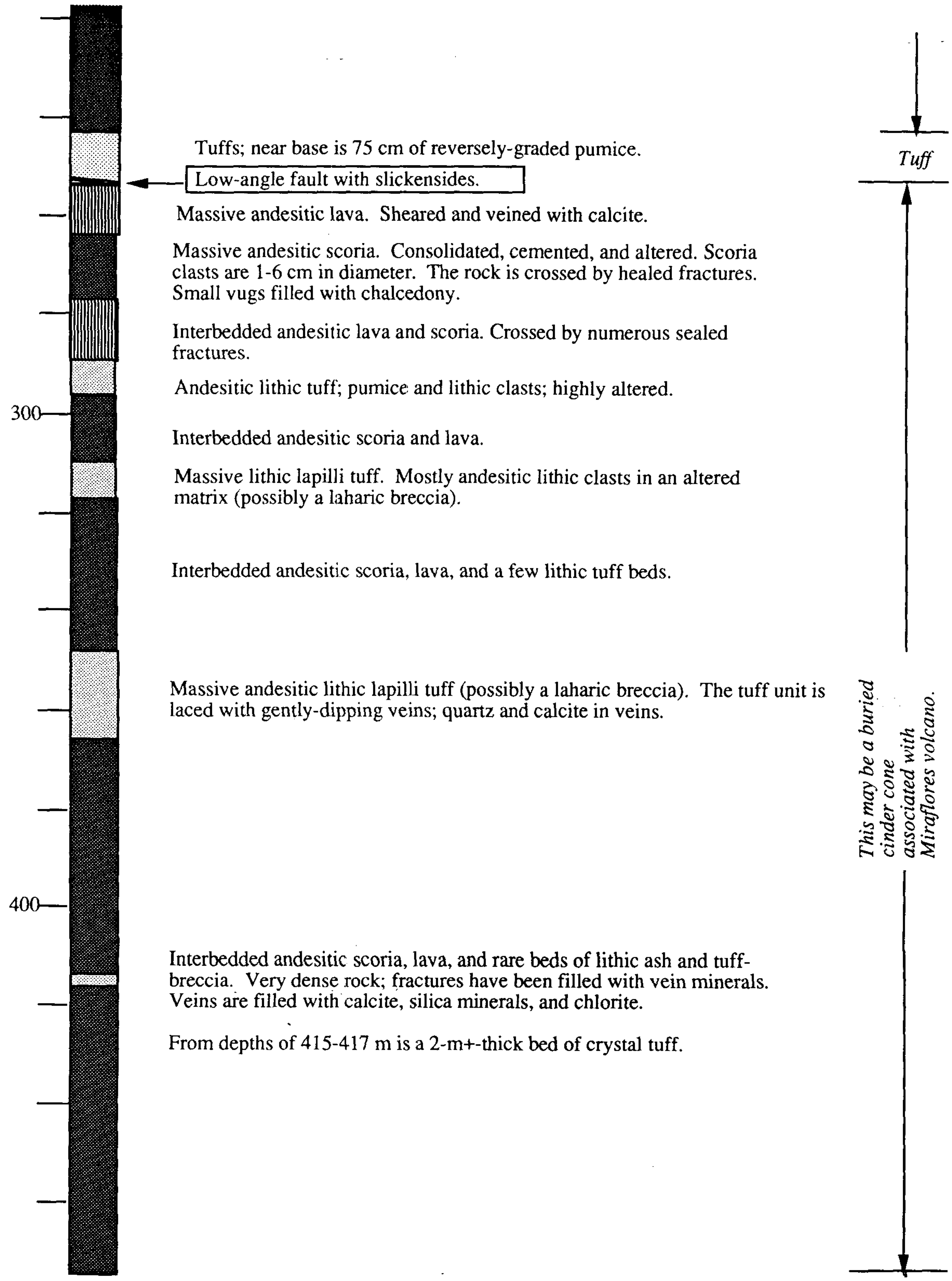


Fig. II-1 (continued)

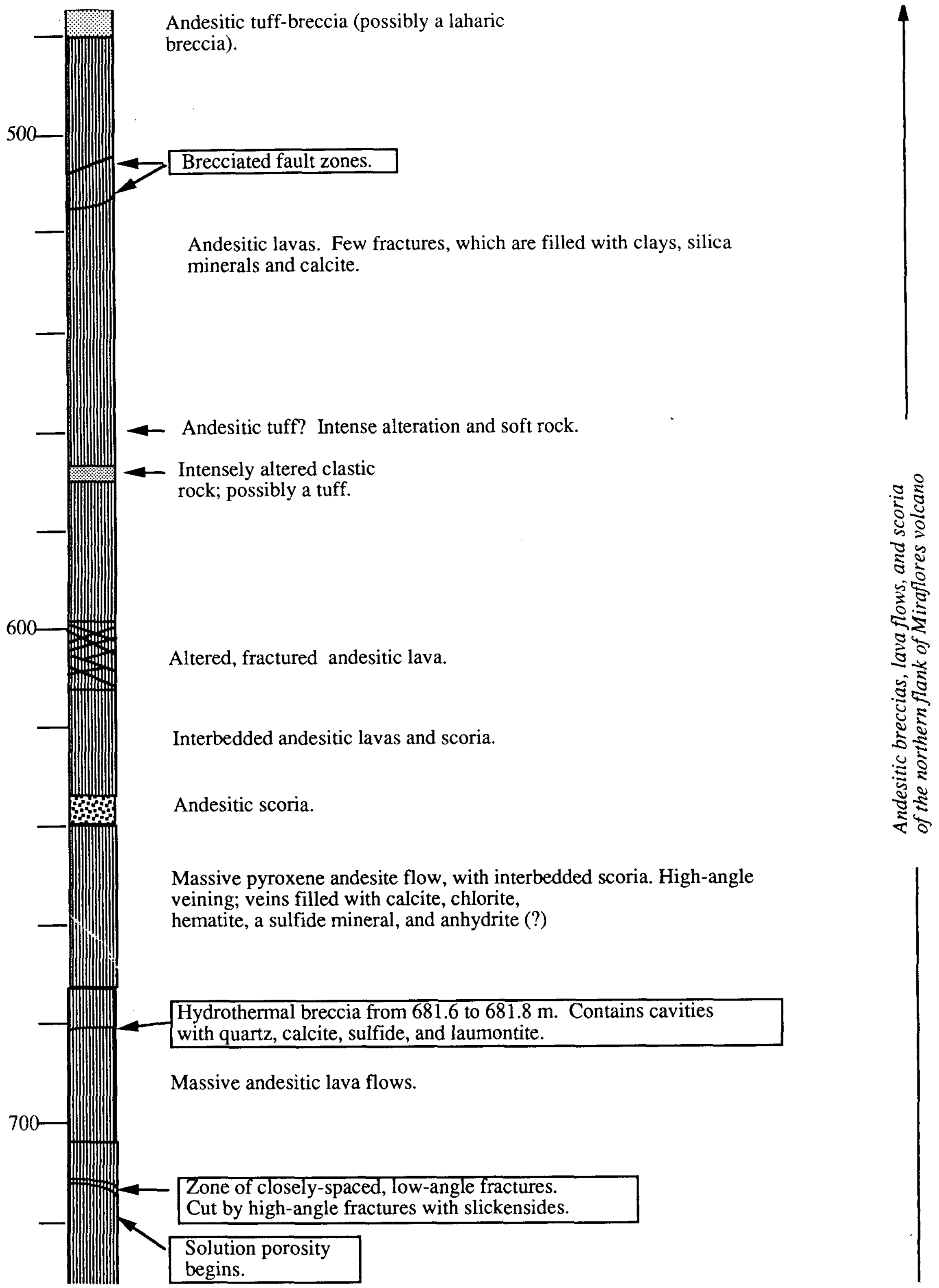
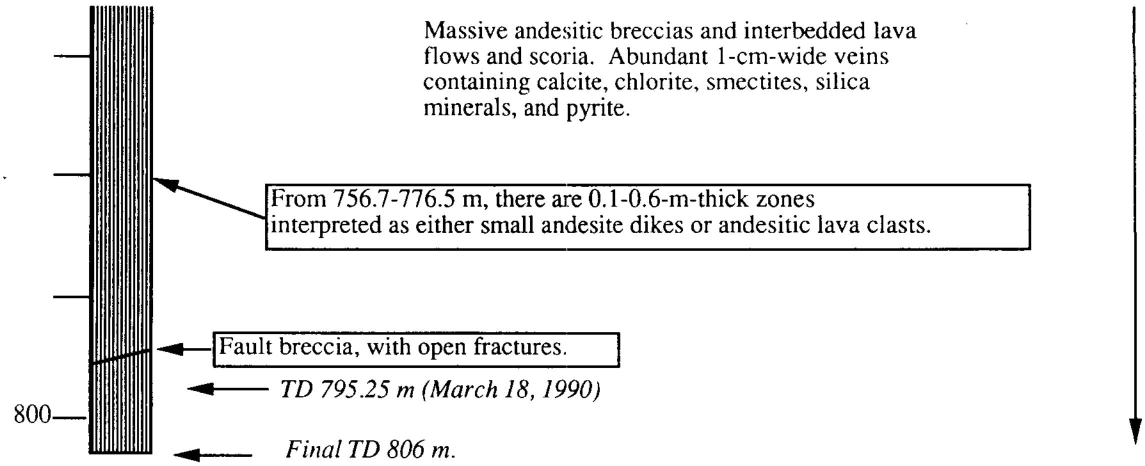


Fig. II-1 (continued)



The well was logged during February and March, 1990 by G. Heiken, W. Duffield, O. Castañeda, S. Goff, J. Gardner, and F. Goff.

Fig. II-1 (continued)

III. THERMAL GRADIENT ANALYSIS AND HEAT FLOW CALCULATION

Fraser Goff

A. GRADIENTS

Thermal gradient logs were obtained several times during coring operations at TCB-1 and these logs were augmented with measurements made by maximum reading thermometers run down hole on the overshot (S. Goff *et al.*, this report). A series of figures showing these logs in relation to the boiling point to depth curve appear earlier. Fig. 2 of the Executive Summary shows the last temperature logs compared with the lithology of the hole. In this figure it should be noted that the curves are smooth representations of a series of widely spaced temperature-depth measurements. Much information on lost circulation zones is probably not represented because the usual depth interval between temperature measurements was 25 m.

The logs show general agreement in their shape and slope. Logs obtained after longer intervals of no circulation are usually shifted to higher temperatures. An exception to this rule is provided by the data from the Los Alamos log of March 10, 1990 and the Kuster log of March 11, 1990. No drilling was performed between these logging events, yet the upper part of the Kuster log indicates cooler temperatures than the Los Alamos log for reasons unknown.

The upper 100 m of TCB-1 displays a smooth, nearly vertical gradient indicating that rainfall in this region of Guatemala is significant enough to erase any near-surface thermal anomaly in the immediate vicinity of the well. The rocks of this interval are relatively permeable volcaniclastic breccias displaying low-temperature alteration.

The gradient suddenly jumps to higher values once the andesitic tuffs and associated sedimentary rocks are encountered. It is impossible for us to say conclusively that the change in gradient occurs at the contact between units at 144.6 m depth because we do not have enough measurements. However, the lower of the two units is less chaotic and contains considerably more beds with moderately-to-well-sorted, sand-sized grains, suggesting less permeability and porosity than the overlying breccias. Thermal gradient changes very little from the second into the third major unit (contact at about 188 m), a hornblende andesite flow with subordinate flow-breccia. In fact the second and third units may be closely related genetically because many of the tuff fragments are composed of a similar hornblende andesite. Alteration in units two and three is low-temperature and not very pervasive.

A gradual change in thermal gradient to lower values occurs in the fourth major stratigraphic unit, a complex sequence of porphyritic andesite flows and flow breccias that persists from about 254 m to T.D. Alteration intensity is extreme in this unit. A very pervasive clay-rich zone occurs near the top of the unit (predominantly smectite; see Heiken *et al.*, this report). Below depths of 630 m, the rock changes progressively in color from grey to green as chlorite becomes more abundant. Although the temperature gradient decreases, density and thermal conductivity increase as discussed below.

Many open fractures and faults with vein minerals occur between depths of 550 to 660 m. An extremely large fault encountered at about 609 m caused complete lost circulation during drilling. However, these features are not obvious in the logs due to the 25 m spacing between successive temperature measurements.

By and large the curves appear relatively smooth. Temperatures increase steadily in TCB-1 with no apparent large isothermal zones other than at the top of the borehole. The data suggest that the rocks are relatively impermeable and that temperatures will continue to increase until the reservoir or outflow zone of the reservoir is intercepted at greater depth.

B. PHYSICAL PROPERTY AND THERMAL CONDUCTIVITY MEASUREMENTS

Six specimens of TCB-1 core about 12 cm in length were sent to a contract laboratory for physical property and thermal conductivity measurements. Specimens were chosen to represent different lithologies and states of alteration and were not chosen at regular depth intervals. Because the core specimens were not preserved in any systematic fashion during the period between core retrieval and shipment to the lab, measurements of moisture saturation and air void content may be subject to large error. All measurements are listed in Table III-1.

In general, the as-received and dry bulk densities of the six samples increase with depth due in part to the greater intensity of hydrothermal alteration with depth. An exception is the sample at 299.0 m from the clay-rich zone in the upper part of the lower andesite unit. This rock has been so thoroughly reconstituted into smectite that most physical properties behave anomalously compared to other samples. In addition this specimen is so brittle and easily fractured that thermal conductivity could not be measured. Moisture content and porosity of the samples generally decrease with depth.

Thermal conductivities were determined over a range of temperatures and confining (lithostatic) pressures determined from the log of April 19, 1990 and by depth. Although somewhat imprecise, these attempts to simulate *in situ* conditions improve the resulting measurements of thermal conductivity. In general, thermal conductivities increase with depth due to the increase in hydrothermal alteration, the decrease in porosity, and the somewhat denser nature of the original host rock for this particular sample suite. The slight decrease in thermal conductivity of the bottom-most sample may be a reflection of its greater content of air-filled voids.

Table III-1. Physical property and thermal conductivity data obtained from core samples of TCB-1, Tecuamburro, Guatemala (TerraTek Inc., Salt Lake City, Utah).

Depth (m)	Rock Type[a]	Density[b] As Received (g/cm^3)	Density[b] Dry Bulk (g/cm^3)	Density[b] Grain (g/cm^3)	Moisture[c] Content (%)	Porosity[d] (%)	Saturation[e] (%)	Air filled[f] Voids (%)	Thermal Conductivity[g] Confining Temperature (°C)	Thermal Conductivity[g] Pressure (bars)	Thermal Conductivity[g] Conductivity (watts/m-°K)
159.6	Lithic Tuff	2.042	1.831	2.731	10.3	33.0	64.1	11.8	25	35.2	0.87
188.4	Hornblende Andesite	2.012	1.821	2.650	9.5	31.3	61.2	12.2	30	41.0	1.02
255.8	Andesite	2.219	1.994	2.814	10.1	29.1	77.3	6.6	50	55.5	1.23
299.0	Altered Scoriaceous Andesite	1.992	1.596	2.823	19.9	45.4	87.4	5.7	--	--	--
618.5	Altered Andesite	2.712	2.664	2.881	1.8	7.5	63.8	2.7	185	134.5	1.71
744.7	Altered Andesite Breccia	2.323	2.278	2.769	1.9	17.7	25.4	13.2	220	161.7	1.58

[a] Lithologic descriptions listed are by F. Goff; see more detailed log of Heiken et al., 1991 to assess lithologic variations in major units.

[b] As received densities by water immersion technique; grain densities by a water pycnometer technique.

[c] Moisture content, $w = (\rho_s - \rho_d)/\rho_s x100$ where ρ_s = as received density and ρd = dry bulk density.

[d] Porosity, $\phi = 1 - (\rho_d/\rho_g) \times 100$ where ρ_g = grain density.

[e] Saturation, $s = (\rho_s - \rho_d)/\phi \times 100$.

[f] Air void content, $v = \phi(1-s) \times 100$.

[g] Thermal conductivities were determined by the transient line heat source ("needle probe") method.

C. HEAT FLOW

Two zones of TCB-1 have relatively constant thermal gradient: the zone from 100 to 300 m and the zone from 500 to 800 m. Calculated gradients in these zones are about 350°C/km and 230°C/km, respectively. Thermal conductivity data were averaged within the two zones. For the upper zone three measurements yield an average of 1.04 ± 0.2 watt/m-°K whereas two measurements from the lower zone yield an average of 1.65 ± 0.1 watt/m-°K (equivalent to watt/m-°C). To obtain heat flow, the gradient and thermal conductivity from each zone are multiplied to obtain products of 364 and 380 mwatt/m^2 (about 8.9 HFU). These are very consistent values. Such high values of heat flow can only be caused by a hydrothermal system or some portion of a hydrothermal system beneath TCB-1.

IV. HYDROGEOCHEMISTRY OF THE TCB-1 CORE HOLE AND BRIEF COMPARISON WITH SELECTED HOT SPRINGS IN THE TECUAMBURRO REGION

Fraser Goff, Cathy Janik, Andrew I. Adams, Lynne Fahlquist, Alfredo Roldan, Mario Revolorio, P.E. Trujillo, Jr., and Dale Counce

A. INTRODUCTION

A variety of swab, weirbox, miniseparator, and *in situ* samples were collected from the TCB-1 core hole in June, 1990 in an attempt to characterize the formation chemistry of the fluid in the open-hole interval below 674 m depth. Because the hole did not sustain continuous flow after "unloading," it is probable that make-up water and drilling fluids were not completely purged from the well and that the quality of the fluid is highly variable due to nonstable conditions. For this reason, all data and conclusions drawn from chemical data on TCB-1 well fluids should be viewed with skepticism.

A limited suite of thermal waters in the Tecuamburro region were collected during the same time period to compare with samples collected in previous years and to provide a measure of quality control on the TCB-1 samples. An interpretation of hydrogeochemical relations among thermal and nonthermal waters of the Tecuamburro region has been previously provided by Goff *et al.* (1989), Goff and Janik (1989), and Janik *et al.* (1990). The new regional data do not change in any way our previous thoughts about the Tecuamburro geothermal "system." In addition, because the chemistry of the latest set of regional samples shows little differences with respect to earlier samples, it is our opinion that the chemical and isotopic values reported for the TCB-1 samples are valid even though the quality of the samples is less than desirable.

B. TCB-1 CORE HOLE

A general description of events during stimulation and flow-test operations of TCB-1 is recounted in Section I. Field data for hydrogeochemical samples are listed in Table IV-1. Although the hole did not sustain flow, many attempts were made to obtain samples that might give indications regarding the character of thermal fluids residing in the open-hole section of the well below 674 m. However, the chemical data of Table IV-2 show many problems with the TCB-1 sample suite. Swab samples, collected while the hole was being stimulated, are variably contaminated with cold make-up water from the stream adjacent to the coring site. This water was added to the hole one month previous to swabbing operations to flush as much drilling mud out of the well as possible. The make-up water then sat in the well during the intervening one month period and was presumably mixed with small quantities of formation fluid while the entire water column was heating up.

Samples collected from the miniseparator on the flow line are of dubious quality because the flow from the well would not stabilize and the miniseparator could not be continuously adjusted to accommodate rapidly changing conditions. The single weirbox sample was collected immediately after TCB-1 unloaded. Unfortunately this sample is a complex mixture of flushed wellbore fluid, rainwater in the weirbox, and small quantities of water from other drilling-related operations. TCB-1 would not flow long enough to purge this mixture from the weirbox.

In situ samples are not considered representative of formation fluid because the downhole sampler was run into a well that had been emptied after rapid unloading. The relatively primitive logging techniques used at this time were not capable of providing good information on water levels and interface temperature after unloading and during well recovery. It was believed that during *in situ* sampling operations, only condensed steam was entering the sample chamber due to the low mass of sample recovered. Although the chamber can hold up to 700 ml of fluid (about 700 g assuming the density of fluid is 1.0 g/cm^3), less than 250 g were recovered. If condensed steam did not enter the sample chamber, the sampler was retrieving fluid from the top of an unstable water column whose pressure was not large enough to push fluid past the spring-loaded inlet check valve.

Chemistry: TCB-1 samples show considerable scatter when viewed on a B vs. Cl plot (Fig. IV-1). No general trends are found in the data set although a possible trend is defined by *in situ* samples #2 through #5 as B/Cl ratios increase. In general TCB-1 samples have B/Cl ratios that plot between steam-heated and neutral-chloride waters of the Tecuamburro region (Fig. IV-2). The erratic character of the data does not positively indicate a genetic relation to neutral-chloride of fluids previously sampled in the region. When compared to other fluids, there is a slight suggestion that the swab sample from 400 m may be

Table IV-1. Field data for hydrogeochemical samples from TCB-1 core hole and selected hot springs, Tecuamburro Region, Guatemala.

Field No.	Description[a]	Date	Location, UTM Grid Coordinates		Temp (°C)	Field pH	Flow Rate (l/min)	Mass of Fluid (g)
TCB-1 CORE HOLE, TECUAMBURRO VOLCANO								
TCB1-90-1	Make-up water from creek that is large inflow to Lago Ixpaco (equivalent to to GT-88-8 and GT-89-55)	90/06/06	1569.98	777.80	22.1	7.82	~200	–
TCB1-90-2	Swab water from 200 m depth collected during second pull	90/06/06	1569.98	777.80	>32.5	6.50	--	–
TCB1-90-3	Swab water from 400 m depth collected during fifth pull	90/06/06	1569.98	777.80	>61.2	5.98	--	–
TCB1-90-4a	Weirbox sample collected soon after TCB-1 unloaded after eighth pull	90/06/06	1569.98	777.80	96	7.75	~30	
TCB1-90-4b	Miniseparator sample from water side with full bleed	90/06/06	1569.98	777.80	105	--	--	–
TCB1-90-4c	Miniseparator sample, total flow	90/06/06	1569.98	777.80	105	–	--	–
TCB1-90-5	In situ sample #1 from 762 m depth; temp. of removal 22.3°C	90/06/07	1569.98	777.80	~240	8.47	--	95.6
TCB1-90-6	In situ sample #2 from 750 m depth; temp. of removal 29.4°C	90/06/08	1569.98	777.80	~240	9.14	--	142.9
TCB1-90-6a	In situ sample #2 from 750 m depth; nose-cone water	90/06/08	1569.98	777.80	~240	--	--	–
TCB1-90-7	In situ sample #3 from 747 m depth; temp. of removal 28.3°C	90/06/08	1569.98	777.80	~240	6.09	--	74.3
TCB1-90-7a	In situ sample #3 from 747 m depth; nose-cone water	90/06/08	1569.98	777.80	~240	--	--	–
TCB1-90-8a	Miniseparator sample with TCB-1 essentially "shut in"; gas only from steam side	90/06/11	1569.98	777.80	24.6	--	--	–
TCB1-90-8b	Miniseparator sample as above; gas only from water side	90/06/11	1569.98	777.80	24.6	–	--	–
TCB1-90-9	In situ sample #4 from 747 m depth; temp. of removal 31.0°C	90/06/11	1569.98	777.80	~240	5.60	--	248.3
TCB-1-90-10	In situ sample #5 from 747 m depth; temp. of removal 28.6°C	90/06/11	1569.98	777.80	~240	6.70	--	96.3

Table IV-1. (Continued)

Field No.	Description[a]	Date	Location UTM Grid Coordinates		Temp (°C)	Field pH	Flow Rate (l/min)	Mass of Fluid (g)
SELECTED HOT SPRINGS, TECUAMBURRO REGION								
GT-90-103	Gas sample from sulphur mine, Tecuamburro Volcano (equivalent to GT-88-21 and GT-89-80)	90/06/07	1565.95	778.90	94.3	--	--	--
GT-90-104	Gas sample from frying pan spring on north shore of Laguna Ixpaco (equivalent to GT-88-6)	90/06/08	1570.45	778.05	94.7	3.0	seep	--
GT-90-105	Gas sample from bubbling pool on northeast shore of Laguna Ixpaco (equivalent to GT-88-5 and GT-89-53)	90/06/08	1570.40	778.20	91.4	3.0	seep	--
GT-90-106	Gas from fumarole at Infernitos (equivalent to GT-88-42 and GT-89-101)	90/06/09	1577.80	781.15	98.0	6.5	seep	--
GT-90-107	Spring at Finca Bonanza (equivalent to GT-88-37 and GT-89-92)	90/06/09	1580.95	779.60	35.5	4.0	14	--
GT-90-108	Spring at Finca Esperanza (equivalent to GT-88-26 and GT-89-90)	90/06/09	1580.95	781.65	38.4	5.2	30	--
GT-90-109	Gas from fumarole at Las Playitas (equivalent to GT-88-24 and GT-89-70)	90/06/11	1570.40	776.95	32.8	4.3	seep	--
GT-90-110	Spring at Finca San Lorenzo behind gazebo pool (equivalent to GT-88-34 and GT-89-68)	90/06/11	1572.98	775.30	41.4	5.0	3	--
GT-90-111	Spring at Finca Silencia (equivalent to GT-88-29 and GT-89-77)	90/06/12	1564.65	780.10	57.8	5.8	320	--
GT-90-112	"Coldest" spring in Colmenares group (equivalent to GT-88-10 and GT-89-84)	90/06/12	1571.95	786.75	57.8	6.8	60	--
GT-90-113	"Hottest" spring in Colmenares group (equivalent to GT-88-12 and GT-89-85)	90/06/12	1571.95	786.75	94.9	6.8	30	--
GT-90-114	Fuente Limon (equivalent to GT-88-19 and GT-89-88)	90/06/12	1573.85	787.60	46.0	6.8	12	--
GT-90-115	Spring on west shore of Rio Los Esclavos (equivalent to GT-88-45 and GT-89-71)	90/06/13	1572.60	787.00	98.5	7.5	60	--
GT-90-116	Spring on west shore of Rio Los Esclavos (equivalent to GT-88-46 and GT-89-72)	90/06/13	1572.55	786.95	89.8	6.8	35	--
GT-90-117	Spring at Finca El Chorro (equivalent to GT-88-38 and GT-89-81)	90/06/13	1572.79	779.20	53.3	5.1	60	--

[a] Additional field numbers are listed and discussed in Janik et al., 1990.

Table IV-2. Major element analyses from TCB-1 core hole and selected hot springs, Tecuamburro region, Guatemala.[a]

Sample No.	Description	Date	Temp., °C	pH-L	Li	Na	K	Mg	Ca	Cl	F	HCO_3	CO_3	SO_4	B	SiO_2
TCB-1 CORE HOLE, TECUAMBURRO VOLCANO																
TCB1-90-1	Make-up water	90/06/06	22.1	7.64	<0.01	16.3	2.2	6.86	24.0	1.87	0.05	124	0	12.8	0.15	74
TCB1-90-2	Swab water, 200 m, second pull	90/06/06	>32.5	7.44	0.01	100	12.6	0.23	12.9	67.8	0.25	131	0	55.1	1.02	46
TCB1-90-3	Swab water, 400 m, fifth pull	90/06/06	>61.2	7.34	0.04	238	27.3	0.25	12.4	183	0.32	256	0	115	4.64	268
TCB1-90-4a	Weirbox	90/06/06	96	6.97	0.03	98.7	11.4	0.32	4.6	62.8	0.28	115	0	54.2	2.75	112
TCB1-90-4b	Minisep., water	90/06/06	105	7.41	<0.01	3.5	1.3	–	13.3	1.61	0.20	259	0	4.0	0.01	–
TCB1-90-4c	Minisep., total flow	90/06/06	105	7.37	0.02	9.9	3.3	0.57	28.8	3.80	0.10	140	0	6.0	0.43	23
TCB1-90-5	In situ #1, 762 m	90/06/07	~240	7.33	0.09	45.6	12.4	–	9.1	37.7	1.25	102	0	16.7	0.18	–
TCB1-90-6	In situ #2, 750 m	90/06/08	~240	7.90	0.20	34.2	3.8	0.14	9.7	18.2	0.49	83.4	0	17.8	0.37	86
TCB1-90-6a	In situ #2, 750 m, nose cone	90/06/08	~240	–	–	93.2	5.6	–	2.1	42.0	0.68	–	–	51.5	2.01	–
TCB1-90-7	In situ #3, 747 m	90/06/08	~240	7.49	0.27	36.4	4.2	–	26.7	17.3	0.55	162	0	27.3	0.55	–
TCB1-90-7a	In situ #3, 747 m, nose cone	90/06/08	~240	–	–	143	8.2	–	5.1	69.7	7.57	–	–	85.8	3.12	–
TCB1-90-9	In situ #4, 747 m	90/06/11	~240	6.97	0.28	79	6.7	0.19	20.8	37.0	0.50	176	0	35.9	1.30	154
TCB1-90-10	In situ #5, 747 m	90/06/11	~240	6.70	2.91	127	7.4	0.20	10.2	62.1	3.80	–	0	67.1	2.17	220
SELECTED HOT SPRINGS, TECUAMBURRO REGION																
GT-90-107	Finca Bonanza	90/06/09	35.5	3.53	<0.01	9.3	4.3	6.65	27.5	1.66	0.18	0	0	147	0.01	78
GT-89-92	Finca Bonanza	89/03/07	35.5	3.65	0.01	9.5	4.3	6.60	27.5	1.7	0.19	0	0	149	<0.05	79
GT-88-37	Finca Bonanza	88/07/13	34.8	3.33	<0.01	8.9	4.3	6.1	27.6	1.2	0.24	0	0	149	<0.02	75
GT-90-108	Finca Esperanza	90/06/09	38.4	6.46	<0.01	11.9	3.5	4.93	15.7	0.46	0.23	26.8	0	71.7	0.01	64
GT-89-90	Finca Esperanza	89/03/07	37.9	5.82	0.01	11.9	3.5	5.0	16.2	0.6	0.24	29	0	72	<0.05	67
GT-88-26	Finca Esperanza	88/07/11	37.4	5.75	<0.01	11.8	3.5	4.8	15.8	0.5	0.08	44	0	69	<0.02	63
GT-90-110	Finca San Lorenzo	90/06/11	41.4	6.91	<0.01	41	7.2	10.3	47.4	2.07	0.16	183	0	103	0.01	59
GT-89-68	Finca San Lorenzo	89/02/25	40.8	6.45	<0.01	38.2	7.4	10.2	46.5	2.0	0.15	183	0	104	<0.05	58
GT-88-34	Finca San Lorenzo	88/07/12	42.0	6.19	0.01	39.0	7.2	8.7	43.1	1.3	<0.05	186	0	109	0.02	55
GT-90-111	Finca Silencia	90/06/12	57.8	7.00	0.03	67	9.6	32.0	119	5.70	<0.02	212	0	410	0.01	196
GT-89-77	Finca Silencia	89/03/03	58.0	6.40	0.01	56.0	8.1	28.8	104	3.90	<0.05	206	0	324	<0.05	184

Table IV-2. (Continued)

Sample No.	Description	Date	Temp., °C	pH-L	Li	Na	K	Mg	Ca	Cl	F	HCO_3	CO_3	SO_4	B	SiO_2
GT-88-29	Finca Silencia	88/07/11	58.1	6.42	0.02	62.0	9.1	31.8	115	4.10	0.07	195	0	376	0.09	200
GT-90-112	Colmenares, "coldest" spring	90/06/12	57.8	7.59	0.97	346	20	6.76	56.1	460	1.07	172	0	144	9.6	89
GT-89-84	Colmenares, "coldest" spring	89/03/04	65.4	7.30	1.07	339	14.6	4.66	47.2	423	1.37	165	0	138	9.6	92
GT-88-10	Colmenares, "coldest" spring	88/07/08	60.0	7.25	1.04	334	13.8	2.73	35.9	377	1.77	239	0	124	8.9	90
GT-90-113	Colmenares, "hottest" spring	90/06/12	94.9	7.81	1.74	587	27	1.22	60.3	794	2.20	71.9	28.8	275	18.1	94
GT-89-85	Colmenares, "hottest" spring	89/03/04	95.8	7.78	1.99	612	23.0	1.28	61.2	810	2.50	74	27.6	270	18.1	95
GT-88-12	Colmenares, "hottest" spring	88/07/08	94.3	7.22	1.99	610	24.0	1.10	66.1	811	2.58	147	0	259	17.5	90
GT-90-114	Fuente Limon	90/06/12	46.0	7.63	0.02	20.8	6.8	5.17	30.5	6.07	0.05	154	0	7.4	0.01	113
GT-89-88	Fuente Limon	89/03/04	42.0	7.59	0.02	22.5	7.1	5.3	31.1	6.1	0.05	162	0	7	<0.05	123
GT-88-19	Fuente Limon	88/07/08	40.2	6.92	0.02	22.0	6.9	4.8	30.3	4.0	<0.05	168	0	4	<0.02	115
GT-90-115	Rio Los Esclavos (TM-2)	90/06/13	98.5	7.83	1.88	619	28	1.03	61.3	813	2.49	73.2	30.0	280	17.8	99
GT-89-71	Rio Los Esclavos (TM-2)	89/02/25	96.5	7.63	2.02	671	25.4	1.46	67.2	815	2.69	131	0	275	18.7	107
GT-88-45	Rio Los Esclavos (TM-2)	88/07/16	96.2	7.35	1.86	604	25.2	1.18	69.0	817	2.46	144	0	280	17.6	95
GT-90-116	Rio Los Esclavos (TM-3)	90/06/13	89.8	7.80	1.72	555	26	1.39	57.5	740	2.09	80.6	31.2	258	16.6	93
GT-89-72	Rio Los Esclavos (TM-3)	89/02/25	87.4	7.66	1.83	587	23.4	1.62	60.9	730	2.47	145	0	246	16.7	102
GT-88-46	Rio Los Esclavos (TM-3)	88/07/16	88.8	7.29	1.55	504	22.4	1.25	56.1	709	2.32	159	0	235	16.4	99
GT-90-117	Finca El Chorro	90/06/13	53.3	4.84	0.01	23.1	8.6	5.93	22.4	1.40	0.16	20.7	0	161	0.01	87
GT-89-81	Finca El Chorro	89/03/04	52.4	4.85	0.06	23.9	8.8	6.0	22.4	1.1	0.07	21	0	162	<0.05	88
GT-88-38	Finca El Chorro	88/07/14	51.6	4.96	<0.01	25.0	9.0	5.7	22.8	1.1	0.19	30	0	165	0.03	85

[a] Analyses by P. E. Trujillo, Jr. and Dale Counce, Los Alamos National Laboratory; all values in mg/kg except where noted.

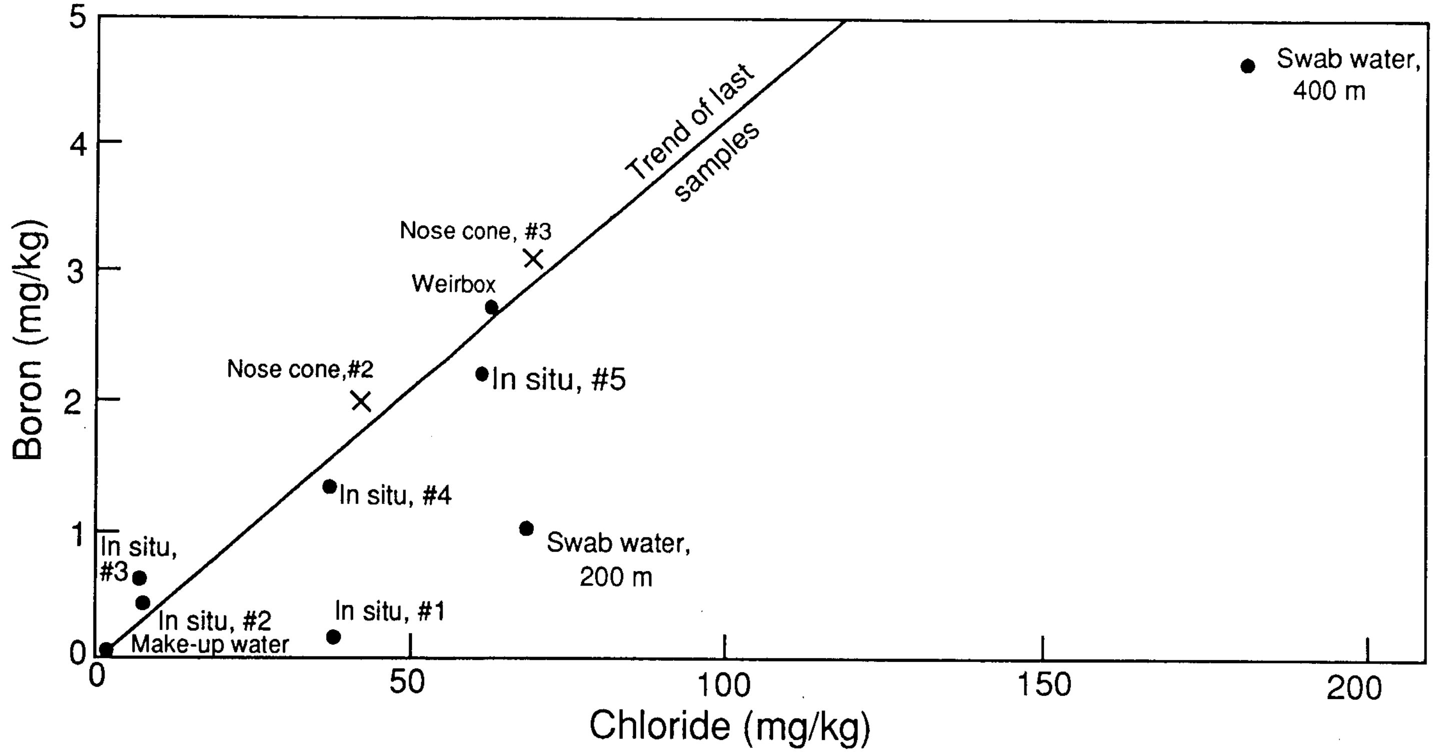


Fig. IV-1. Plot of boron versus chloride for TCB-1 core hole fluids, Tecuamburro, Guatemala. The values are scattered indicating the samples are nonhomogeneous and unequilibrated. A possible trend is indicated but should be viewed with caution.

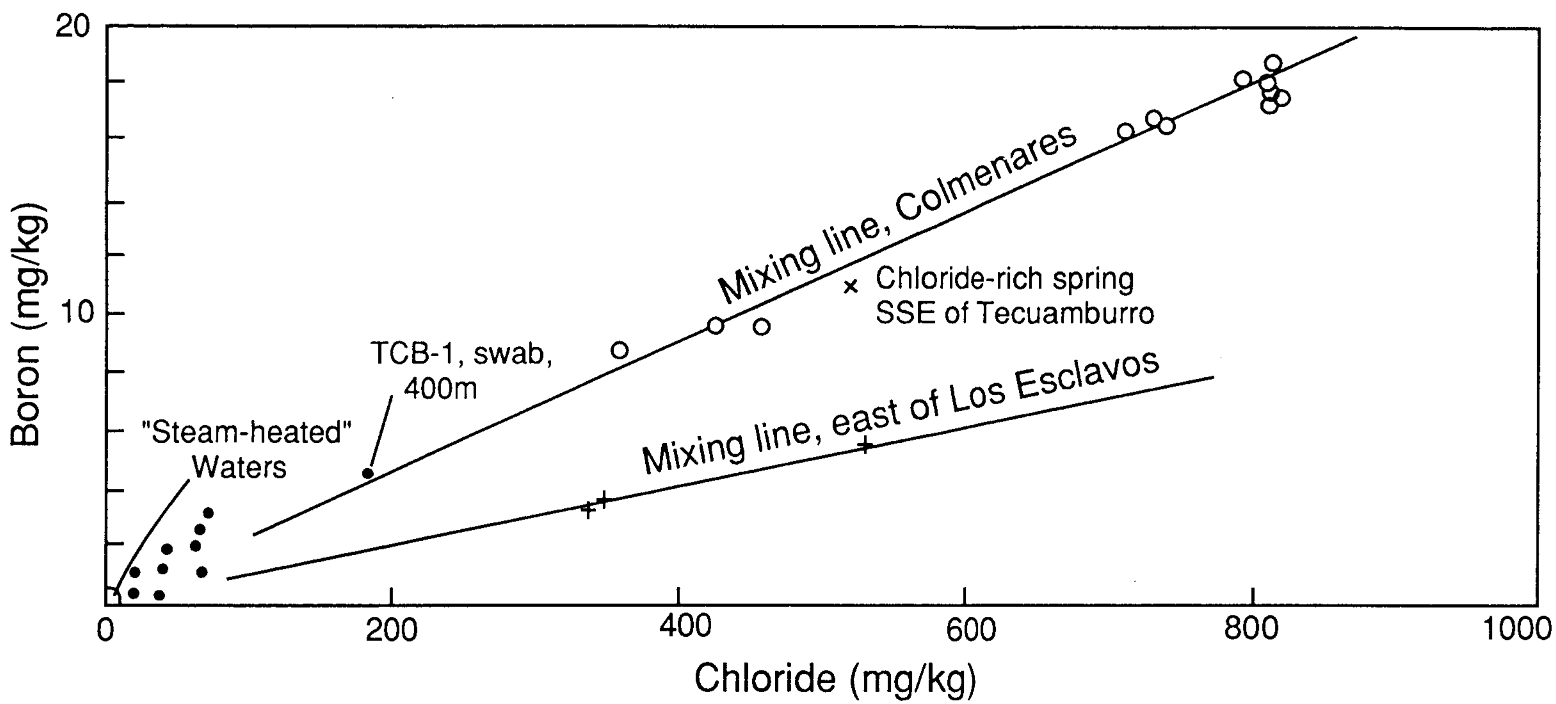


Fig. IV-2. Plot of boron versus chloride comparing TCB-1 samples (dots) to other thermal waters in the Tecuamburro region. The data do not allow unambiguous characterization of TCB-1 fluids.

related to fluids from the Colmenares area or from the source feeding the warm spring south-southeast of Tecuamburro (see Goff *et al.*, 1989 or Janik *et al.*, 1990 for discussion of these springs). However such an association between a swab sample and deep thermal waters is tentative at best.

TCB-1 samples appear to have high HCO_3/Cl and NH_4/Cl ratios as well as high B/Cl ratios (Tables IV-2, IV-3, Fig. IV-3). If the samples can be considered semireliable, high contents of volatile components relative to chloride would suggest that the fluids originate from a vapor cap above a deeper neutral-chloride reservoir. However, anomalous concentrations of NH_4 could also be produced by thermal breakdown of the organic polymers used in the high-temperature drilling muds. Thus, the NH_4 values may be relatively high for nonnatural causes.

Trace element analyses do not yield additional insights. The elements As, Br, Li, Cs, Rb, I, and F tend to be relatively high in neutral-chloride waters of this region but they are not high in TCB-1 samples. Thus, there is scant evidence for mixing of a small component of deep reservoir water with the make-up water.

Stable Isotopes of Water: A plot of δD versus $\delta^{18}O$ (Fig. IV-4) shows that all TCB-1 samples are related to the make-up water (used for drilling and cleaning of the hole) by processes of boiling. Samples enriched in deuterium and oxygen-18 relative to make-up water have lost steam by boiling at temperatures somewhat higher than 100°C. On the other hand, samples that are isotopically depleted are primarily condensed steam from boiling make-up water. Theoretically, the chemistry of the samples that are boiled should be concentrated relative to make-up water due to steam loss. Unfortunately, there is no systematic relation between δD or $\delta^{18}O$ and Cl; thus, once again, the samples do not provide reliable evidence about their origin.

Particularly confusing is the difference between *in situ* samples #4 and #5 collected on the same day under the same sampling conditions. Sample #4 had the highest mass of all *in situ* samples and, from stable isotope relations, appears to be a residual of boiled make-up water. Yet sample #4 had less chloride and boron than sample #5 which had considerably less mass and lighter stable isotope values suggesting that sample #5 is predominantly condensed steam. We can only conclude that the wellbore fluid was so unstable during this period that all *in situ* samples are dubious in quality. We can also conclude that TCB-1 samples are not isotopically similar to other neutral-chloride thermal waters in the Tecuamburro region (see also Goff and Janik, 1989).

Tritium: Tritium relations can be examined in Fig. IV-5. Few tritium samples were taken during the stimulation and flow test operations because of the relatively large sample required (500 ml), the non-stable

Table IV-3. Trace element and other analyses from TCB-1 core hole and selected hot springs, Tecuamburro region, Guatemala.

Sample No.	Description	Date	Temp °C	pH (L)	Ag mg/kg	Al[b] mg/k	As mg/k	Ba mg/k	Br mg/k	Cd mg/kg	Co mg/kg	Cr mg/kg	Cs mg/kg	Cu mg/kg	Fe mg/kg
TCB-1 CORE HOLE, TECUAMBURRO VOLCANO															
TCB1-90-1	TCB1, make-up water	06/06/90	22.1	7.64	<0.002	<0.1	<0.05	0.02	<0.05	<0.002	0.004	<0.002	<0.005	<0.002	0.03
TCB1-90-2	TCB1, swab water 200 m	06/06/90	>32.5	7.44	<0.002	<0.1	<0.05	0.08	0.14	<0.002	0.006	<0.002	0.009	0.004	0.08
TCB1-90-3	TCB1, swab water 400 m	06/06/90	>61.2	7.34	<0.002	<0.1	<0.05	0.12	0.33	<0.002	0.004	<0.002	0.013	<0.002	2.64
TCB1-90-4a	TCB1, weirbox	06/06/90	96	6.97	<0.002	<0.1	<0.05	0.02	<0.05	<0.002	<0.002	<0.002	<0.005	0.009	--
TCB1-90-4b	TCB1, minisep., water	06/06/90	105	7.41	<0.002	<0.1	<0.05	0.09	<0.05	<0.002	<0.002	<0.002	<0.005	<0.002	--
TCB1-90-4c	TCB1, minisep., total flow	06/06/90	105	7.37	--	<0.1	<0.05	0.19	<0.05	--	--	--	--	--	<0.01
TCB1-90-5	TCB1, in situ #1, 762 m	06/07/90	~240	7.33	--	--	--	--	0.11	--	--	--	--	--	--
TCB1-90-6	TCB1, in situ #2, 750 m	06/08/90	~240	7.90	<0.002	1.16	<0.05	0.04	<0.05	<0.002	<0.002	<0.002	0.006	0.053	0.14
TCB1-90-6a	TCB1, in situ #2, 750 m, nose cone	06/08/90	~240	--	--	--	--	--	<0.05	--	--	--	--	--	--
TCB1-90-7	TCB1, in situ #3, 747 m	06/08/90	~240	7.49	--	--	--	--	<0.05	--	--	--	--	--	--
TCB1-90-7a	TCB1, in situ #3, 747 m, nose cone	06/08/90	~240	--	--	--	--	--	<0.05	--	--	--	--	--	--
TCB1-90-9	TCB1, in situ #4, 747 m	06/11/90	~240	6.97	<0.002	<0.1	<0.05	0.13	<0.05	<0.002	0.006	0.003	0.008	0.004	1.92
TCB1-90-10	TCB1, in situ #5, 747 m	06/11/90	~240	4.26	<0.002	1.33	<0.05	0.04	<0.05	<0.002	<0.002	0.006	0.015	0.13	0.20
SELECTED HOT SPRINGS, TECUAMBURRO REGION[d]															
GT-90-107	Finca Bonanza (TM-15)	06/09/90	35.5	3.53	<0.002	2.1	<0.05	0.04	<0.05	<0.002	0.005	<0.002	<0.005	0.012	1.56
GT-89-92	Finca Bonanza (TM-15)	03/07/89	35.5	3.65	<0.001	2.33	<0.05	0.04	<0.05	<0.001	0.004	<0.002	<0.005	<0.002	1.41
GT-90-108	Finca Esperanza (TM-17)	06/09/90	38.4	6.46	<0.002	<0.1	<0.05	0.07	<0.05	<0.002	<0.002	<0.002	<0.005	<0.002	0.13
GT-89-90	Finca Esperanza (TM-17)	03/07/89	37.9	5.82	<0.001	0.08	<0.05	0.07	<0.05	<0.001	<0.002	<0.002	<0.005	<0.002	0.07
GT-90-110	Finca San Lorenzo (TM-14a)	06/11/90	41.4	6.91	<0.002	<0.1	<0.05	0.06	<0.05	<0.002	<0.002	<0.002	0.008	<0.002	0.24
GT-89-68	Finca San Lorenzo (TM-14a)	02/25/89	40.8	6.45	<0.001	0.05	<0.05	0.07	<0.05	<0.001	<0.002	<0.002	<0.005	<0.002	0.05
GT-90-111	Finca Silencia (TM-12)	06/12/90	57.8	7.00	<0.002	<0.1	<0.05	0.05	<0.05	<0.002	<0.002	<0.002	0.007	<0.002	0.07
GT-89-77	Finca Silencia (TM-12)	03/03/89	58.0	6.40	<0.001	<0.1	<0.1	0.04	<0.05	<0.001	<0.002	<0.002	<0.005	0.003	<0.02
GT-90-112	Colmenares, "coldest" spring	06/12/90	57.8	7.59	<0.002	<0.1	1.07	0.04	1.48	<0.002	<0.002	<0.002	0.071	<0.002	0.01
GT-89-84	Colmenares, "coldest" spring	03/04/89	65.4	7.30	<0.001	<0.1	1.1	0.03	1.14	<0.001	<0.002	<0.002	0.06	<0.002	0.06
GT-90-113	Colmenares, "hottest" spring	06/12/90	94.9	7.81	<0.002	<0.1	1.81	0.01	2.66	<0.002	<0.002	<0.002	0.11	<0.002	<0.01
GT-89-85	Colmenares, "hottest" spring	03/04/89	95.8	7.5	<0.001	<0.1	2.0	<0.02	1.74	<0.001	<0.002	<0.002	0.12	0.002	0.04
GT-90-114	Fuente Limon (TM-19)	06/12/90	46.0	7.63	<0.002	<0.1	<0.05	0.06	<0.05	<0.002	0.003	<0.002	0.010	0.005	<0.01
GT-89-88	Fuente Limon (TM-19)	03/04/89	42.0	7.59	<0.001	0.05	0.05	0.07	<0.05	<0.001	<0.002	<0.002	0.011	<0.002	<0.01
GT-90-115	Rio Los Esclavos (TM-2)	06/13/90	98.5	7.83	<0.002	<0.1	2.18	0.02	2.61	<0.002	<0.002	<0.002	0.085	<0.002	0.02
GT-89-71	Rio Los Esclavos (TM-2)	02/25/89	96.5	7.63	<0.001	0.1	2.0	0.02	1.85	<0.001	<0.002	<0.002	0.14	<0.002	0.08
GT-90-116	Rio Los Esclavos (TM-3)	06/13/90	89.8	7.80	<0.002	<0.1	1.79	0.01	2.39	<0.002	<0.002	<0.002	0.094	<0.002	0.03
GT-89-72	Rio Los Esclavos (TM-3)	02/25/89	87.4	7.66	<0.001	<0.1	1.8	<0.02	1.61	<0.001	<0.002	<0.002	0.11	<0.002	<0.02
GT-90-117	Finca El Chorro (TM-33)	06/13/90	53.3	4.84	<0.002	<0.1	<0.05	0.02	<0.05	<0.002	<0.002	<0.002	<0.005	<0.002	13.8
GT-89-81	Finca El Chorro (TM-33)	03/04/89	52.4	4.85	<0.001	0.08	0.12	0.02	<0.05	<0.001	<0.002	<0.002	<0.005	<0.002	15.7

[a] Analyses by P. E. Trujillo, Jr. and Dale Counce, Los Alamos National Laboratory.
[b] Total aluminum.
[c] Parameters calculated for both Tables 2 and 3.
[d] Trace element data for last two years reported, only; see Janik et al., 1990 for all data.

Table IV-3. (Continued)

Sample No.	Description	Date	Hg mg/k	I mg/k	Mn mg/k	Mo mg/k	NH_4 mg/k	Ni mg/k	NO_3 mg/k	Pb mg/kg	PO_4 mg/kg	Rb mg/kg	Sb mg/k	Se mg/kg	Si mg/k	S_2O_3 mg/kg
TCB-1 CORE HOLE, TECUAMBURRO VOLCANO																
TCB1-90-1	TCB1, make-up water	06/06/90	<0.1	<0.01	0.02	0.008	0.12	<0.002	9.8	<0.002	<0.1	0.012	<0.1	<0.1	34.8	<0.1
TCB1-90-2	TCB1, swab water 200 m	06/06/90	<0.1	0.05	0.03	0.030	3.17	0.013	4.04	<0.002	<0.1	0.036	<0.1	<0.1	21.3	0.05
TCB1-90-3	TCB1, swab water 400 m	06/06/90	<0.1	0.16	0.32	0.13	6.93	0.019	0.33	<0.002	<0.1	0.048	<0.1	<0.1	125	0.03
TCB1-90-4a	TCB1, weirbox	06/06/90	<0.1	0.01	0.04	0.10	1.87	0.011	<0.05	<0.002	<0.1	0.023	<0.1	<0.1	52.4	<0.01
TCB1-90-4b	TCB1, minisep., water	06/06/90	<0.1	--	--	0.034	69.3	0.033	0.52	<0.002	0.59	0.007	--	<0.1	--	--
TCB1-90-4c	TCB1, minisep., total flow	06/06/90	<0.1	<0.01	0.35	--	6.4	--	0.36	--	<0.1	--	<0.1	<0.1	10.8	<0.01
TCB1-90-5	TCB1, in situ #1, 762 m	06/07/90	--	--	--	--	2.50	--	0.26	--	<0.1	--	--	<0.1	--	--
TCB1-90-6	TCB1, in situ #2, 750 m	06/08/90	<0.1	<0.01	0.04	0.039	1.53	0.009	0.09	0.033	<0.1	0.010	<0.1	<0.1	40.3	<0.01
TCB1-90-6a	TCB1, in situ #2, 750 m, nose cone	06/08/90	--	--	--	--	--	--	1.09	--	<0.1	--	--	--	--	--
TCB1-90-7	TCB1, in situ #3, 747 m	06/08/90	--	--	--	--	2.40	--	0.23	--	<0.1	--	--	--	--	--
TCB1-90-7a	TCB1, in situ #3, 747 m, nose cone	06/08/90	--	--	--	--	--	--	<0.05	--	<0.1	--	--	--	--	--
TCB1-90-9	TCB1, in situ #4, 747 m	06/11/90	<0.1	0.01	0.43	0.061	2.14	0.048	0.07	0.003	<0.1	0.017	<0.1	<0.1	72.0	<0.01
TCB1-90-10	TCB1, in situ #5, 747 m	06/11/90	<0.1	0.01	0.18	0.25	6.13	0.026	<0.05	0.08	<0.1	0.019	<0.1	<0.1	103	0.19
SELECTED HOT SPRINGS, TECUAMBURRO REGION[d]																
GT-90-107	Finca Bonanza (TM-15)	06/09/90	<0.1	<0.01	0.37	0.025	0.06	0.006	<0.05	0.005	<0.1	0.014	<0.1	<0.1	36.4	<0.01
GT-89-92	Finca Bonanza (TM-15)	03/07/89	<0.1	<0.05	0.32	<0.002	<0.05	0.003	<0.05	<0.002	<0.05	0.014	<0.05	<0.1	37.1	<0.05
GT-90-108	Finca Esperanza (TM-17)	06/09/90	<0.1	<0.01	0.08	0.015	0.34	<0.002	<0.05	<0.002	<0.1	0.013	<0.1	<0.1	29.8	<0.01
GT-89-90	Finca Esperanza (TM-17)	03/07/89	<0.1	<0.05	0.06	<0.002	0.07	<0.002	<0.05	<0.002	<0.05	0.015	<0.05	<0.1	31.1	<0.05
GT-90-110	Finca San Lorenzo (TM-14a)	06/11/90	<0.1	<0.01	0.23	0.011	0.19	0.004	<0.05	<0.002	<0.1	0.022	<0.1	<0.1	27.6	<0.01
GT-89-68	Finca San Lorenzo (TM-14a)	02/25/89	<0.1	<0.05	0.19	<0.002	0.19	<0.002	<0.05	<0.002	<0.05	0.025	<0.05	<0.1	27.1	<0.05
GT-90-111	Finca Silencia (TM-12)	06/12/90	<0.1	<0.01	1.25	0.010	0.38	<0.002	<0.05	<0.002	0.48	0.044	<0.1	<0.1	91.6	<0.01
GT-89-77	Finca Silencia (TM-12)	03/03/89	0.2	<0.05	0.92	<0.002	0.11	<0.002	<0.05	<0.002	0.55	0.038	<0.1	<0.2	86	<0.05
GT-90-112	Colmenares, "coldest" spring	06/12/90	<0.1	0.61	0.10	0.012	<0.05	<0.002	<0.05	<0.002	<0.1	0.080	<0.1	<0.1	41.6	<0.01
GT-89-84	Colmenares, "coldest" spring	03/04/89	<0.2	0.57	0.06	0.002	0.06	<0.002	<0.1	<0.002	<0.1	0.08	<0.1	<0.2	43.2	<0.05
GT-90-113	Colmenares, "hottest" spring	06/12/90	<0.1	1.08	0.08	0.013	0.11	<0.002	<0.05	<0.002	<0.1	0.097	<0.1	<0.1	44.1	0.17
GT-89-85	Colmenares, "hottest" spring	03/04/89	<0.2	1.05	0.07	<0.002	0.11	<0.002	<0.1	<0.002	<0.05	<0.005	<0.1	<0.2	44.6	<0.05
GT-90-114	Fuente Limon (TM-19)	06/12/90	<0.1	<0.01	0.02	0.007	<0.05	<0.002	11.0	<0.002	<.1	0.026	<0.1	<0.1	52.9	<0.01
GT-89-88	Fuente Limon (TM-19)	03/04/89	<0.1	<0.05	<0.01	<0.002	<0.05	<0.002	14.8	<0.002	<0.05	0.032	<0.05	<0.1	57.7	<0.05
GT-90-115	Rio Los Esclavos (TM-2)	06/13/90	<0.1	1.10	0.08	0.013	0.12	<0.002	<0.05	<0.002	<0.1	0.11	<0.1	<0.1	46.2	0.05
GT-89-71	Rio Los Esclavos (TM-2)	02/25/89	<0.2	1.12	0.04	0.007	0.41	0.007	<0.1	<0.002	<0.1	0.13	<0.1	<0.2	50.0	<0.05
GT-90-116	Rio Los Esclavos (TM-3)	06/13/90	<0.1	1.00	0.09	0.013	0.10	<0.002	<0.05	<0.002	<0.1	0.11	<0.1	<0.1	43.6	0.09
GT-89-72	Rio Los Esclavos (TM-3)	02/25/89	<0.2	1.01	0.04	0.011	0.15	<0.002	<0.1	0.002	<0.1	0.12	<0.1	<0.2	47.6	<0.05
GT-90-117	Finca El Chorro (TM-33)	06/13/90	<0.1	<0.01	0.26	0.006	0.10	<0.002	0.12	<0.002	<0.1	0.046	<0.1	<0.1	40.5	<0.01
GT-89-81	Finca El Chorro (TM-33)	03/04/89	<0.1	<0.05	0.23	<0.002	0.09	<0.002	<0.05	<0.002	<0.05	0.043	<0.1	<0.1	41.0	<0.05

Table IV-3. (Continued)

Sample No.	Description	Date	Sr mg/k	U mg/k	Zn mg/k	TDS[c] mg/kg	Cation[c] Sum	Anion[c] Sum	Balance[c]
TCB-1 CORE HOLE, TECUAMBURRO VOLCANO									
TCB1-90-1	TCB1, make-up water	06/06/90	0.11	<0.1	0.08	274.0	2.541	2.545	-0.0015
TCB1-90-2	TCB1, swab water 200 m	06/06/90	0.11	<0.1	0.13	435.0	5.523	5.353	0.0314
TCB1-90-3	TCB1, swab water 400 m	06/06/90	0.15	<0.1	2.40	1118.6	12.298	11.988	0.0255
TCB1-90-4a	TCB1, weirbox	06/06/90	0.03	<0.1	0.24	465.1	4.957	4.945	0.0024
TCB1-90-4b	TCB1, minisep., water	06/06/90	0.04	<0.1	0.25	--	--	--	--
TCB1-90-4c	TCB1, minisep., total flow	06/06/90	0.18	<0.1	0.23	--	--	--	--
TCB1-90-5	TCB1, in situ #1, 762 m	06/07/90	--	--	--	--	--	--	--
TCB1-90-6	TCB1, in situ #2, 750 m	06/08/90	0.08	<0.1	0.72	259.0	2.356	2.318	0.0163
TCB1-90-6a	TCB1, in situ #2, 750 m, nose cone	06/08/90	--	--	--	--	--	--	--
TCB1-90-7	TCB1, in situ #3, 747 m	06/08/90	--	--	--	--	--	--	--
TCB1-90-7a	TCB1, in situ #3, 747 m, nose cone	06/08/90	--	--	--	--	--	--	--
TCB1-90-9	TCB1, in situ #4, 747 m	06/11/90	0.12	<0.1	0.20	517.4	4.948	4.784	0.0336
TCB1-90-10	TCB1, in situ #5, 747 m	06/11/90	0.07	<0.1	1.85	514.3	7.219	3.472	0.7008
SELECTED HOT SPRINGS, TECUAMBURRO REGION[d]									
GT-90-107	Finca Bonanza (TM-15)	06/09/90	0.08	<0.1	0.24	279.5	3.072	3.165	-0.0296
GT-89-92	Finca Bonanza (TM-15)	03/07/89	0.11	<0.1	0.06	282.5	2.793	3.186	-0.1315
GT-90-108	Finca Esperanza (TM-17)	06/09/90	0.05	<0.1	0.29	200.0	1.836	1.973	-0.0721
GT-89-90	Finca Esperanza (TM-17)	03/07/89	0.06	<0.1	0.10	205.9	1.851	2.024	-0.0892
GT-90-110	Finca San Lorenzo (TM-14a)	06/11/90	0.14	<0.1	0.02	454.2	5.215	5.231	-0.0031
GT-89-68	Finca San Lorenzo (TM-14a)	02/25/89	0.17	<0.1	<0.01	450.2	5.040	5.247	-0.0403
GT-90-111	Finca Silencia (TM-12)	06/12/90	0.62	0.1	0.01	1054.4	11.810	12.253	-0.0369
GT-89-77	Finca Silencia (TM-12)	03/03/89	0.50	<0.2	0.02	917.0	10.248	10.299	-0.0049
GT-90-112	Colmenares, "coldest" spring	06/12/90	0.91	<0.1	0.01	1310.4	19.061	19.286	-0.0118
GT-89-84	Colmenares, "coldest" spring	03/04/89	0.72	<0.2	<0.02	1239.8	18.018	18.001	0.0009
GT-90-113	Colmenares, "hottest" spring	06/12/90	1.18	<0.1	0.01	1969.5	29.566	31.164	-0.0526
GT-89-85	Colmenares, "hottest" spring	03/04/89	1.12	<0.2	<0.02	2004.0	30.634	31.495	-0.0277
GT-90-114	Fuente Limon (TM-19)	06/12/90	0.25	<0.1	0.01	355.8	3.036	3.046	-0.0032
GT-89-88	Fuente Limon (TM-19)	03/04/89	0.29	<0.1	0.02	380.0	3.165	3.217	-0.0161
GT-90-115	Rio Los Esclavos (TM-2)	06/13/90	1.25	<0.1	0.76	2035.5	31.059	31.872	-0.0258
GT-89-71	Rio Los Esclavos (TM-2)	02/25/89	1.18	<0.2	0.32	2123.9	33.611	31.789	0.0557
GT-90-116	Rio Los Esclavos (TM-3)	06/13/90	1.13	<0.1	0.01	1870.8	28.026	29.442	-0.0493
GT-89-72	Rio Los Esclavos (TM-3)	02/25/89	1.10	<0.2	0.02	1922.8	29.550	28.926	0.0213
GT-90-117	Finca El Chorro (TM-33)	06/13/90	0.03	<0.1	0.07	344.8	3.591	3.786	-0.0530
GT-89-81	Finca El Chorro (TM-33)	03/04/89	0.05	<0.1	0.06	349.1	3.750	3.779	-0.0079

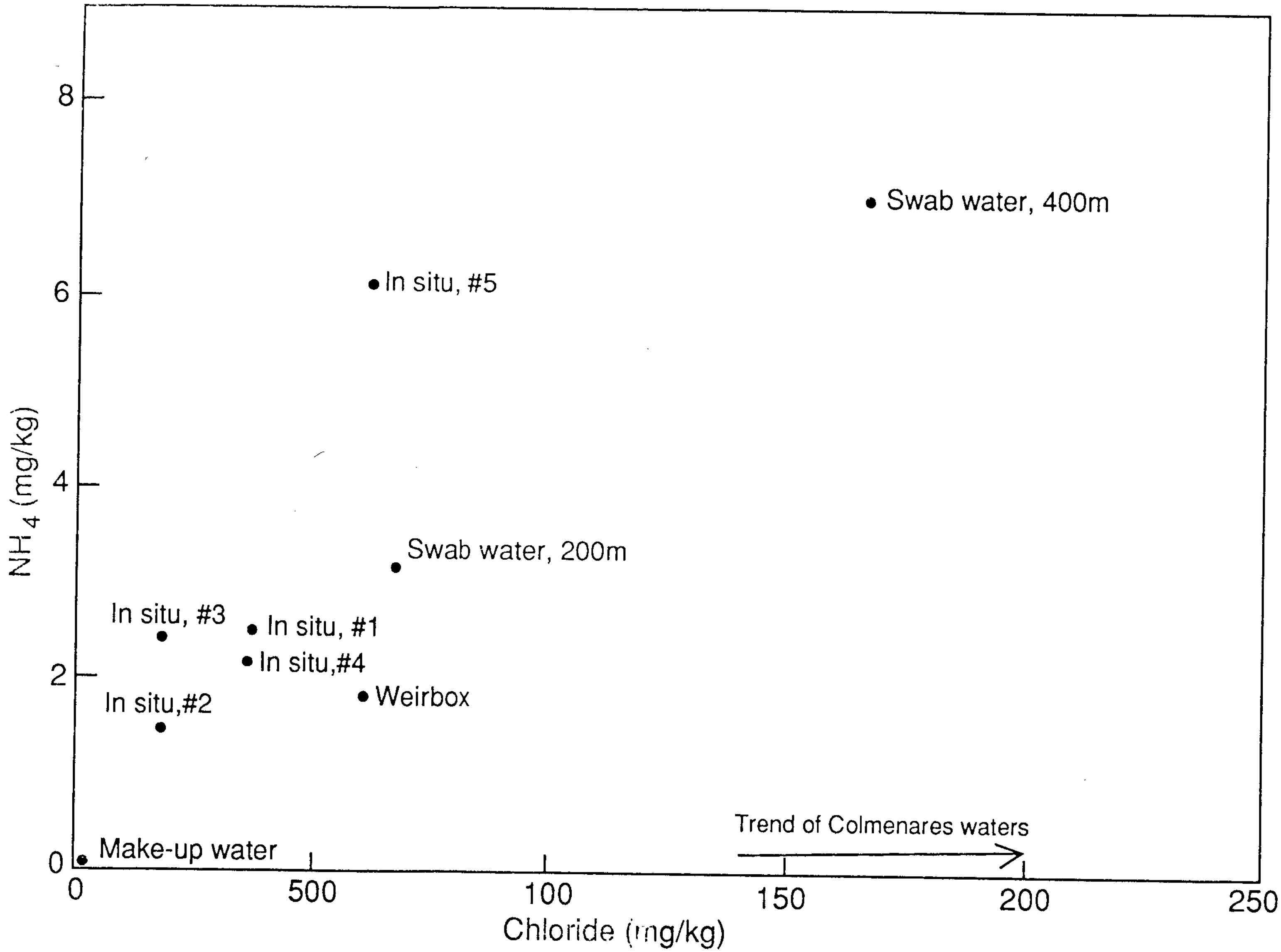


Fig. IV-3. Plot of ammonium versus chloride for TCB-1 core hole fluids. Although the data are scattered they indicate very enriched NH_4 compared to neutral-chloride springs in the region (trend shown).

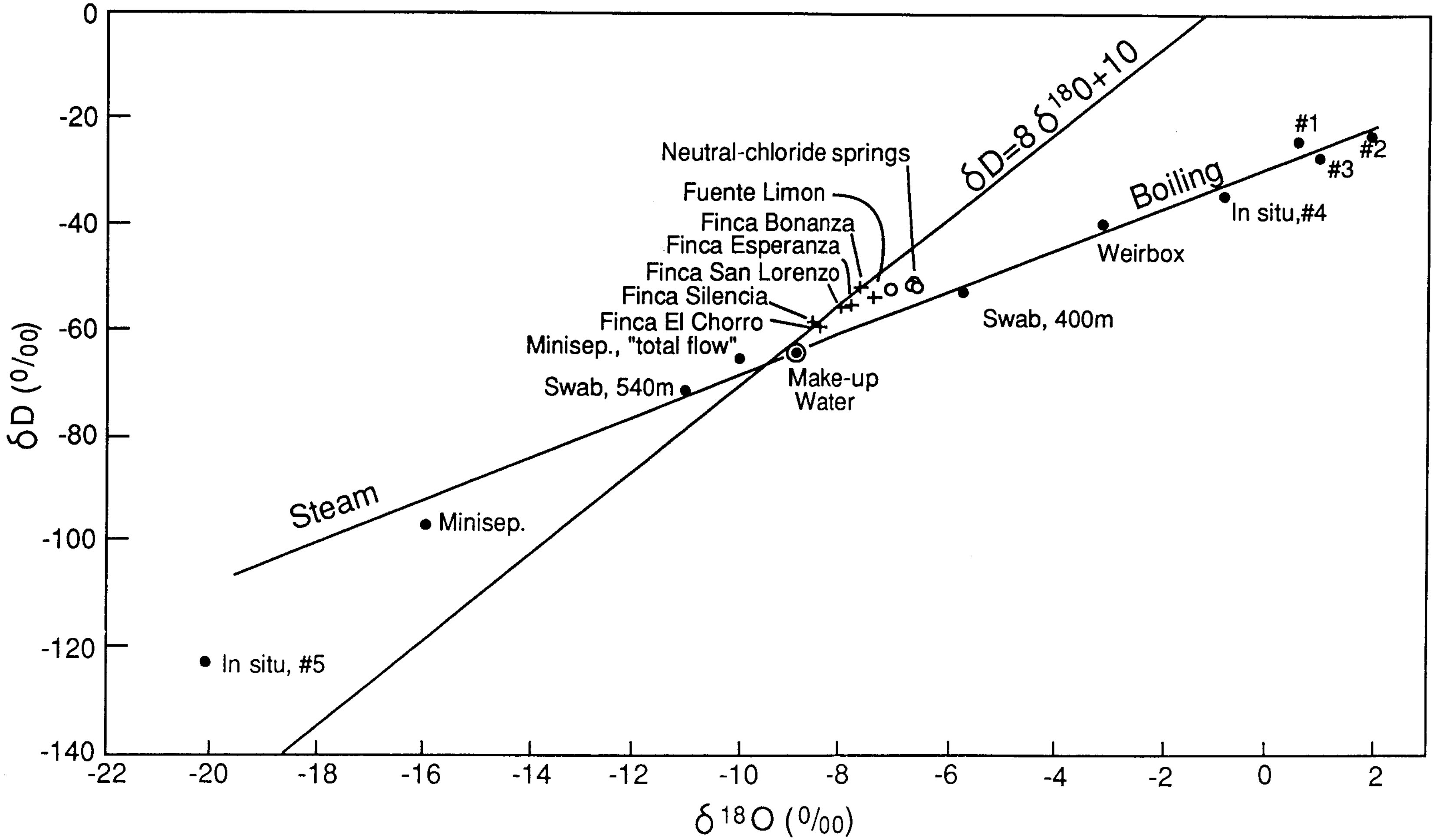


Fig. IV-4. Plot of δD versus $\delta^{18}O$ for TCB-1 core hole fluids and selected thermal spring samples (values averaged from Table IV-4) in the Tecuamburro region. All TCB-1 samples are derived from make-up water through processes of boiling (see text). The springs show no relation to the core hole fluids.

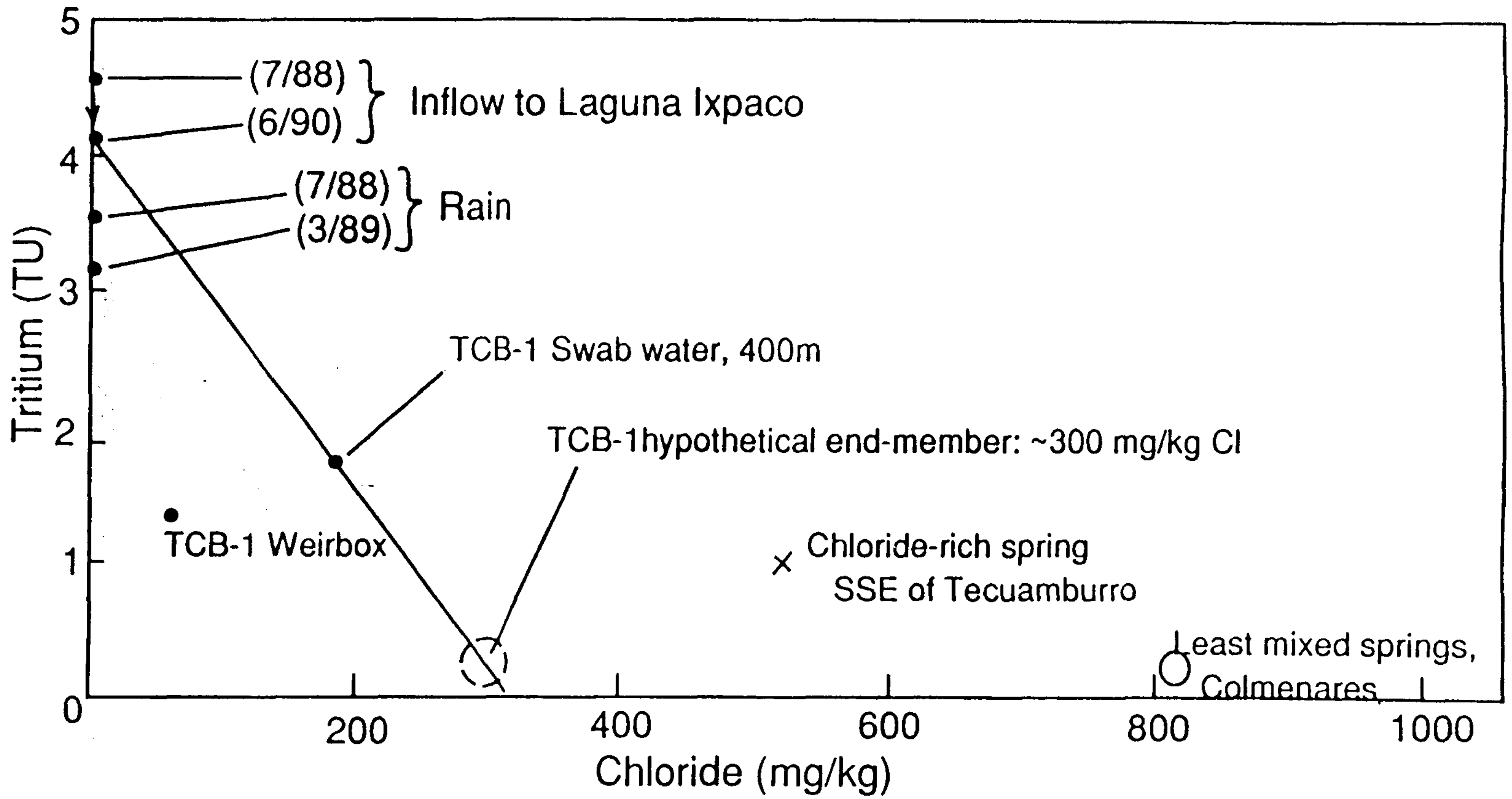


Fig. IV-5. Plot of tritium versus chloride for TCB-1 core hole fluids and selected thermal waters in the Tecuamburro region. A rough estimate of the chloride content of fluids in the open hole section of the TCB-1 well can be made by extrapolation to low tritium values. The estimated valued of 300 mg/kg is low compared to most high-temperature geothermal fluids although this estimate should be viewed with caution.

behavior of the well, and the small volume of the *in situ* samples. Tritium values of typical thermal waters in the Tecuamburro region can be compared to TCB-1 fluids in Table IV-4. The high tritium content of the make-up water (labeled as "inflow to Laguna Ixpaco, 6/90") is typical for cold meteoric waters in Central America (Goff *et al.*, 1987). The tritium contents of both the weirbox and swab samples are lower, presumably due to some mixing of formation water with the make-up water. Assuming that the swab water from 400 m is most representative of formation water (a very liberal assumption), the chloride content of "uncontaminated" formation water can be estimated by extrapolation of the line between make-up water and swab water to very low tritium contents. Low tritium contents (<1 T.U.) typify geothermal reservoir waters (for example, see Goff *et al.*, 1987) and the value of 0.25 T.U. from the least mixed thermal waters in the Colmenares area is normal. A value of about 300 mg/kg Cl is estimated for hypothetical end-member TCB-1 fluid by this method. This would be a very dilute reservoir fluid compared to most geothermal fluids associated with Quaternary volcanism and these results again suggest that TCB-1 has merely tapped a vapor-rich cap above an underlying neutral-chloride reservoir.

Carbon-13: $\delta^{13}C\text{-}HCO_3$ and $\delta^{13}C\text{-}CO_2$ data for selected Tecuamburro samples appear in Tables IV-4 and IV-5, respectively. No samples for $\delta^{13}C\text{-}HCO_3$ were collected from the TCB-1 core hole. However, four gas samples collected for $\delta^{13}C\text{-}CO_2$ during the flow test operations after stimulation have values of -2.6 to -2.9‰ which are very similar to the values of -2.7 to -3.4‰ obtained from seven fumarole samples collected in thermal areas at Laguna Ixpaco and near the summit of Tecuamburro. These values suggest that CO_2 within the immediate Tecuamburro area originates from a similar source. On the other hand the $^{13}C\text{-}CO_2$ values are somewhat heavier than the usual values associated with volcanic/mantle sources. Either the $^{13}C\text{-}CO_2$ signature has become heavier due to fractionation processes within the postulated deep reservoir or a source of heavier carbon such as Mesozoic limestone may underlie the region at great depths. The latter possibility has already been proposed (Goff *et al.*, 1989; Goff and Janik, 1989; Janik *et al.*, 1990) due to the presence of isolated Mesozoic limestone masses to the north and east of the Tecuamburro site.

The $^{13}C\text{-}CO_2$ values in the Tecuamburro-Ixpaco area are also similar to the values of fumarole CO_2 emitted from the Infernitos area to the north. Possibly a widespread but isotopically uniform source of deep CO_2 is being released throughout a broad area.

Only two hot springs with nonacid characteristics release collectable quantities of CO_2 (Finca San Lorenzo and spring TM-2 in the Colmenares area). The $^{13}C\text{-}CO_2$ values of these springs (-4.6 to -6.5‰) are more depleted than values at the fumarole areas suggesting that near surface fractionation or dissolution processes are at work. In general $^{13}C\text{-}HCO_3$ values from springs are considerably more depleted than the $^{13}C\text{-}CO_2$ indicating that high temperature (>150°C) reaction of CO_2 in steam occurs with

Table IV-4. Isotopic analyses from TCB-1 core hole and selected hot springs, Tecuamburro region, Guatemala.[a]

Sample No.	Description	Date	Temp. (°C)	^3H (T.U.)	δD (‰)	$\delta^{18}O$ (‰)	$\delta^{13}C-HCO_3$ (‰)	$\delta^{18}O-SO_4$ (‰)
TCB-1 CORE HOLE, TECUAMBURRO VOLCANO								
TCB1-90-1	Make-up water	90/06/06	22.1	4.09	-63.5	-8.95	--	--
TCB1-90-2	Swab water, 200 m	90/06/06	>32.5	--	--	--	--	--
TCB1-90-3	Swab water, 400 m	90/06/06	>61.5	1.70	-51.2	-5.73	--	--
TCB1-90-4	Swab water, 540 m	90/06/06	--	--	-70.6	-11.10	--	--
TCB1-90-4a	Weirbox	90/06/06	96	1.28	-39.6	-3.54	--	--
TCB1-90-4b	Minisep., water	90/06/06	105	--	-96.0	-16.00	--	--
TCB1-90-4c	Minisep., total flow	90/06/06	105	--	-64.5	-10.07	--	--
TCB1-90-5	In situ #1, 762 m	90/06/07	~240	--	-23.8	+0.56	--	--
TCB1-90-6	In situ #2, 750 m	90/06/08	~240	--	-22.1	+1.50	--	--
TCB1-90-6a	In situ #2, 750 m, nose cone	90/06/08	~240	--	--	--	--	--
TCB1-90-7	In situ #3, 747 m	90/06/08	~240	--	-25.5	+0.78	--	--
TCB1-90-9	In situ #4, 747 m	90/06/11	~240	--	-33.2	-1.16	--	--
TCB1-90-10	In situ #5, 747 m	90/06/11	~240	--	-122.4	-20.17	--	--
SELECTED HOT SPRINGS, TECUAMBURRO REGION								
GT90-107	Finca Bonanza	90/06/09	35.5	--	-52.1	-7.2	--	--
GT89-92	Finca Bonanza	89/03/07	35.5	--	-49.2	-7.68	--	2.81
GT88-37	Finca Bonanza	88/07/13	34.8	3.37	-53.6	-7.81	--	3.20
GT90-108	Finca Esperanza	90/06/09	38.4	--	-53.0	-7.75	-12.9	--
GT89-90	Finca Esperanza	89/03/07	37.9	0.26	-55.5	-7.95	--	10.45
GT88-26	Finca Esperanza	88/07/11	37.4	0.20	-54.6	-7.92	-12.5	10.92
GT90-110	Finca San Lorenzo	90/06/11	41.4	--	-55.3	-7.98	-3.9	7.81
GT89-68	Finca San Lorenzo	89/02/25	40.8	0.20	-53.6	-8.15	-4.3	--
GT88-34	Finca San Lorenzo	88/07/12	42.0	0.18	-55.7	-8.26	-4.3	7.24
GT90-111	Finca Silencia	90/06/12	57.8	--	-56.7	-8.63	-6.0	--
GT89-77	Finca Silencia	89/03/03	58.0	--	-56.7	-8.56	-5.6	3.42
GT88-29	Finca Silencia	88/07/11	58.1	4.85	-58.0	-8.58	-5.1	4.11
GT90-112	Colmenares, "coldest" spring	90/06/12	57.8	--	-51.6	-7.18	-13.0	--
GT89-84	Colmenares, "coldest" spring	89/03/04	65.4	3.04	-51.1	-7.11	--	--
GT88-10	Colmenares, "coldest" spring	88/07/08	60.0	1.90	-51.7	-7.15	-15.2	3.12
GT90-113	Colmenares, "hottest" spring	90/06/12	94.9	--	-48.4	-6.63	-6.3	2.95
GT89-85	Colmenares, "hottest" spring	89/03/04	95.8	0.51	-50.0	-6.74	-5.6	2.77
GT88-12	Colmenares, "hottest" spring	88/07/08	94.3	--	-49.4	-6.56	-5.4	3.66
GT90-114	Fuente Limon	90/06/12	46.0	--	-51.0	-7.33	-15.2	--
GT89-88	Fuente Limon	89/03/04	42.0	--	-54.1	-7.43	--	--
GT88-19	Fuente Limon	88/07/08	40.2	5.24	-53.6	-7.49	--	--
GT90-115	Rio Los Esclavos (TM-2)	90/06/13	98.5	--	-49.6	-6.70	-6.4	2.89
GT89-71	Rio Los Esclavos (TM-2)	89/02/25	96.5	--	-48.1	-6.68	-6.2	2.96
GT88-45	Rio Los Esclavos (TM-2)	88/07/16	96.2	0.65	-53.9	-6.72	-5.4	3.64
GT90-116	Rio Los Esclavos (TM-3)	90/06/13	89.8	--	-49.6	-6.65	-8.0	3.04
GT89-72	Rio Los Esclavos (TM-3)	89/02/25	87.4	2.74	-49.9	-6.70	-8.0	2.93
GT88-46	Rio Los Esclavos (TM-3)	88/07/16	88.8	--	-48.0	-6.52	--	--
GT90-117	Finca El Chorro	90/06/13	53.3	--	-57.6	-8.48	-17.1	--
GT89-81	Finca El Chorro	89/03/04	52.4	1.01	-60.2	-8.53	--	5.74
GT88-38	Finca El Chorro	88/07/14	51.6	0.14	-56.6	-8.40	-17.3	6.41

[a] Tritium analyses by H. Göte Ostlund, Tritium Laboratory, University of Miami; stable isotope analyses on water by M. Colucci, Stable Isotope Laboratory, Southern Methodist University or by C. J. Janik and D. G. White, U.S. Geological Survey, Menlo Park, Calif., all other analyses by C. J. Janik and L. Fahlquist, U.S.Geological Survey, Menlo Park, Calif.

Table IV-5. Gas data from TCB-1 core hole fluids and from selected hot springs and fumaroles in the region of Tecuamburro volcano.

Sample No.	Description	Date	Temp., (°C)	CO_2	H_2S	H_2	CH_4	NH_3	N_2	O_2	Ar	He	$\delta^{13}C$	T-DP[b]
TCB1 CORE HOLE														
TCB1-90-4(1)	Miniseparator; flowline valve to weirbox fully open	90/06/06	105.0	85.44	0.270	0.854	0.340	0.439	10.87	1.815	0.094	0.00097	-2.7	215
TCB1-90-4(2)	Miniseparator; flowline valve to weirbox closed	90/06/06	101.4	90.58	0.105	0.453	0.665	0.039	8.10	0.004	0.016	0.00067	-2.7	182
TCB1-90-8(1)	Wellhead buildup; steam side of miniseparator	90/06/11	24.6	75.29	0.006	2.469	1.089	0.005	19.13	1.907	0.099	0.00084	-2.6	190
TCB1-90-8(2)	Wellhead buildup; water side of miniseparator	90/06/11	24.6	82.35	0.008	2.744	1.186	0.004	13.29	0.045	0.021	0.00091	-2.9	192
SELECTED HOT SPRINGS AND FUMAROLES, TECUAMBURRO REGION														
GT90-103	Sulfur mine, fumarole	90/06/07	94.3	89.25	7.76	0.00063	<0.0014	0.0005	2.968	0.001	0.0032	0.00020	-3.1	(190)
GT89-80	Sulfur mine, fumarole	89/03/03	95.0	85.35	11.58	0.00196	0.0051	ND	3.036	0.001	0.0169	0.00036	-2.7	212
GT88-21	Sulfur mine, fumarole	88/07/09	94.9	86.22	10.65	0.00145	0.0086	0.0018	3.076	ND	0.0129	0.00035	-3.0	199
GT90-104	Ixpaco, frying pan at North Shore	09/06/08	94.7	89.61	7.28	0.0752	0.0047	ND	3.015	ND	0.0056	0.00022	-3.3	230
GT88-6	Ixpaco, frying pan at North Shore	88/07/07	71.5	88.06	8.84	0.111	0.0086	ND	2.924	0.002	0.0150	0.00035	-3.4	238
GT90-105	Ixpaco, mud pot at NE Shore	90/06/08	91.4	89.94	6.52	0.370	0.0051	ND	3.154	0.002	0.0070	0.00015	-3.9?	274
GT89-53	Ixpaco, mud pot at NE Shore	89/02/21	93.5	87.59	9.13	0.657	0.0092	0.0014	2.582	ND	0.0079	0.00022	-3.1	293
GT88-5	Ixpaco, mud pot at NE Shore	88/07/07	85.0	87.12	9.38	0.616	0.0087	ND	2.836	ND	0.0116	0.00021	-3.0	292
GT90-106	Infernitos, TM-32	90/06/09	98.0	95.46	0.069	0.0534	0.0430	0.0011	4.234	0.086	0.0364	0.00096	-2.8	152
GT89-101	Infernitos, TM-32	89/03/08	97.0	95.36	0.149	0.0548	0.0406	0.0034	4.223	0.143	0.0388	0.00182	-2.9	160
GT88-42	Infernitos, TM-32	88/07/15	98.6	95.37	0.212	0.0550	0.0464	0.0221	4.230	0.028	0.0330	0.00102	-2.6	163
GT90-109	Las Playitas	90/06/11	32.8	88.79	7.925	0.00048	0.0263	ND	3.253	0.001	0.0047	0.00032	-4.1	164
GT89-70	Las Playitas	89/02/25	20.1	88.26	8.18	0.00040	0.0323	ND	3.515	0.001	0.0059	0.00039	-4.8	159
GT88-24	Las Playitas	88/07/09	33.0	89.60	7.22	0.00196	0.0288	0.0021	3.133	ND	0.0069	0.00034	-3.0	192
GT90-110	Finca San Lorenzo	90/06/11	41.4	80.34	0.213	<0.00085	1.068	ND	18.19	ND	0.213	0.00133	-4.8	(121)
GT89-68	Finca San Lorenzo	89/02/25	40.8	83.10	0.251	0.00132	0.956	ND	15.49	0.005	0.188	0.00130	-4.6	130
GT88-34	Finca San Lorenzo	88/07/12	42.0	78.41	1.721	0.00084	0.976	0.0031	18.73	ND	0.223	0.00188	-4.9	140
GT90-115	Rio Esclavos, TM-2	90/06/13	98.5	26.33	0.051	<0.005	0.271	ND	70.83	1.715	1.097	0.0318	-6.5	(82)
GT89-71	Rio Esclavos, TM-2	89/03/06	96.9	27.57	0.076	0.0146	0.261	ND	69.67	1.485	1.036	0.0445	-6.5	100

[a] Analyses by C. J. Janik and L. Fahlquist; concentrations in mole percent and permil PDB.

[b] T-DP empirical gas geothermometer temperature (D'Amore and Panichi; 1980) in degrees C; values in parentheses were calculated using a concentration of a gas at the limit of detection in gas chromatographic analyses.

rock to produce ^{13}C-depleted dissolved bicarbonate or that organic carbon is entering the flow systems of some springs.

Gas Chemistry: The composition of gases from TCB-1 can be compared to other Tecuamburro samples in Table IV-5. The quality of the TCB-1 gas samples is questionable for several reasons:

1. The make-up water contains dissolved air;
2. H_2S is apparently consumed by reaction with iron casing;
3. Excess H_2 is produced by reaction of high-temperature water with the iron casing. In addition, CH_4 and NH_3 contents in TCB-1 samples are much higher than values in nearby fumaroles possibly due to high-temperature breakdown of the organic polymers used in the drilling muds.

For these reasons it is impossible to make a valid comparison. The analyses indicate the gases originate from a source of elevated temperature but the H_2S concentrations are much lower than those usually found in very high-temperature geothermal fields.

Analyses obtained from duplicate samples of other thermal features show few changes from previous years. The Laguna Ixpaco-Tecuamburro area continues to have gas compositions most indicative of a deep, high-temperature source.

Chemical Geothermometry: Although samples from the TCB-1 well are not considered to be representative of uncontaminated formation fluids, subsurface reservoir temperatures were estimated using a standard suite of chemical geothermometers (Table IV-6). The geothermometers are very hard to interpret due to obvious effects of dilution. A liberal interpretation would indicate temperatures in the 200 to 250°C range. Temperature estimated from gas compositions using the D'Amore-Panichi equation (D'Amore and Panichi, 1980) are near 200°C. However, the well is known to have a bottom hole temperature of 240°C so the geothermometers add little to our knowledge of the system.

Geochemical geothermometers are also listed for four neutral-chloride springs from the general Colmenares area. As discussed previously (Goff *et al.*, 1989; Janik *et al.*, 1990), these springs indicate reservoir temperatures that are considerably less than temperatures indicated by gas compositions at the Ixpaco fumaroles. The bottom hole temperature of 240°C at TCB-1 strongly suggests that if the Colmenares springs are related to the apparent reservoir beneath the Ixpaco-Tecuamburro area then they have undergone considerable cooling and chemical reequilibration during lateral outflow.

C. CONCLUSIONS

Samples collected from TCB-1 during swabbing, flow test, and *in situ* sampling operations in June 1990 are generally of poor quality. The well was unable to sustain stable flow and fluid samples show

Table IV-6. Chemical geothermometry from the TCB-1 core hole and selected neutral-chloride hot springs, Tecuamburro Region, Guatemala.[a]

Sample No.	Description	Date	Temp., °C	TQC	TCH	TNK-WE	TNK-F	T13	TNaLi	TKMg	TSO_4 Cond.
TCB-1 CORE HOLE, TECUAMBURRO VOLCANO											
TCB1-90-2	Swab water, 200 m	90/06/06	>32.5	98	67	214	238	188	0	124	--
TCB1-90-3	Swab water, 400 m	90/06/06	<61.2	201	183	203	229	199	2	148	--
TCB1-90-4a	Weirbox	90/06/06	96	144	117	204	230	192	23	116	--
TCB1-90-5	In situ #1, 762 m	90/06/07	~240	--		328	321	222	117	--	--
TCB1-90-6	In situ #2, 750 m	90/06/08	~240	129	101	199	226	164	205	96	--
TCB1-90-7	In situ #3, 747 m	90/06/08	~240			203	230	159	230	--	--
TCB1-90-9	In situ #4, 747 m	90/06/11	~240	163	139	170	203	159	160	108	--
TCB1-90-10	In situ #5, 747 m	90/06/11	~240	187	166	136	175	154	394	110	--
SELECTED HOT SPRINGS, TECUAMBURRO REGION											
GT-90-112	Colmenares, "coldest" spring	90/06/12	57.8	131	103	135	174	156	141	89	--
GT-90-113	Colmenares, "hottest" spring	90/06/12	94.9	134	107	117	158	153	145	122	185
GT-90-115	Rio Esclavos (TM-2)	90/06/13	98.5	137	109	115	157	153	148	125	185
GT-90-116	Rio Esclavos (TM-3)	90/06/13	89.8	133	106	118	160	153	149	1181	184

[a] TQC= quartz conductive temperature; TCH=chalcedony temperature; TNK-F=sodium-potassium temperature of Fournier; TNK-WE=sodium-potassium temperature of White and Ellis as reported by Truesdell; T^{13}=sodium-potassium-calcium (β=1/3) temperature (see Fournier 1981 for equations); TNaLi=sodium-lithium temperature of Fouillac and Michard (1981); TKMg=potassium-magnesium temperature of Giggenbach (1986); TSO_4=conductive sulfate isotope geothermometer of McKenzie and Truesdell (1977).

obvious contamination with make-up water. Nonetheless, the core hole fluids do contain elevated concentrations of some elements indicative of high-temperature conditions. A rough estimate of the chloride content of the formation fluid below 674 m depth is about 300 mg/kg. The fluids have B/Cl, HCO_3/Cl, and NH_4/Cl ratios that suggest the well is completed in a vapor-rich cap above a deeper high-temperature reservoir. Values of ^{13}C-CO_2 in gases collected from the well are similar to values obtained for CO_2 from the acid fumaroles at Laguna Ixpaco and near the summit of Tecuamburro. Stable isotope analyses of water and chemical geothermometers do not provide any useful information about the well fluids. The limited hydrogeochemical data do not change previous interpretations regarding the thermal regime of the area. Because of high temperatures in the well (240°C) and a temperature gradient that indicates increasing temperature with depth, it is likely that a high temperature neutral-chloride reservoir or outflow of a reservoir underlies the vapor-rich cap tapped by TCB-1.

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V. CHEMICAL AND THERMAL HISTORY OF FLUIDS FROM THE TECUAMBURRO GEOTHERMAL SITE

John A. Musgrave and Joe N. Moore

A. INTRODUCTION

Fluid inclusions provide an independent means of obtaining chemical information on the composition of a geothermal reservoir fluid and on the processes occurring within it. In wells or regions of the reservoir that cannot be directly sampled, fluid inclusion studies frequently represent the only means of characterizing the composition and temperatures of geothermal waters.

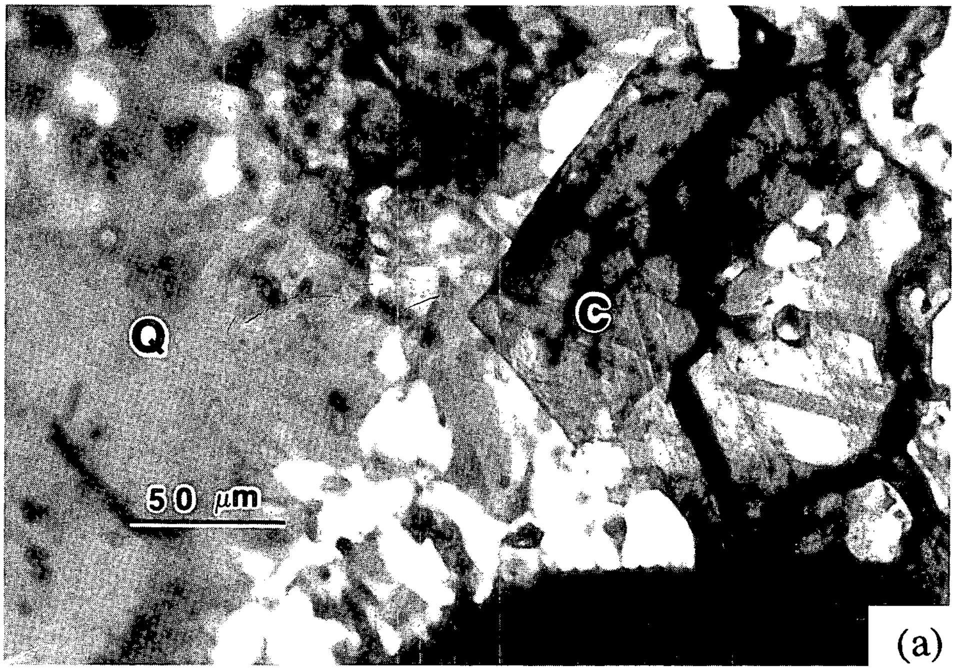
This paper describes the initial results of fluid inclusion studies from four depths in the lower half of an 808 m gradient well drilled at Tecuamburro, Guatemala. The samples were studied as part of an overall program to characterize this previously untested geothermal system.

B. GEOLOGY AND HYDROTHERMAL ALTERATION

The Tecuamburro geothermal field is one of several thermal systems associated with volcanic activity in southeastern Guatemala. The geologic setting of this field and the chemical characteristics of the fumaroles and springs have been described by Duffield *et al.* (1989); Heiken and Duffield (eds.) (1990); Goff *et al.* (1989). Several features bear directly on the interpretation of the fluid inclusion measurements presented in this paper. The geologic features of the area and the distribution of thermal features are shown in Fig. 1 of the Executive Summary.

TCB-1 was drilled within 0.5 km of Laguna Ixpaco, a large phreatic explosion crater that formed 2,900 years ago. According to Goff *et al.* (1989) all of the thermal features in the immediate vicinity of TCB-1 result from boiling of the thermal fluids and include springs that discharge acid-sulfate or steam-heated water, mud pots, and fumaroles. Springs that discharge sodium chloride waters are found along the Rio Los Esclavos to the east. These springs are relatively dilute, with chloride contents of less than 850 mg/kg and high concentrations of Ca and Mg. The composition of these springs is thought to result from dilution with cool groundwaters. These chloride waters, if trapped in fluid inclusions, would yield ice-melting temperatures of approximately - 0.1°C.

Fluid inclusions were studied in vein quartz and calcite from depths of 578, 641, 657, and 791 m. The veins are mineralogically simple and consist of quartz and calcite. Fig. V-1 illustrates the vein textures from a depth of 657 m. Calcite and quartz are intergrown, suggesting that both minerals were precipitated from a boiling fluid. As discussed below, planes of vapor-rich inclusions in the quartz provide



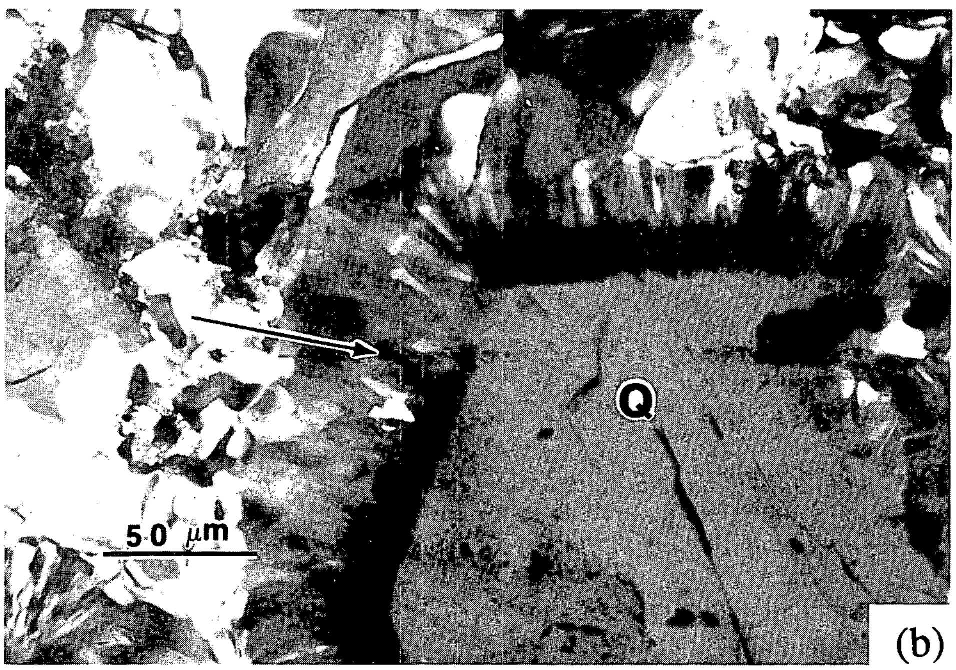


Fig. V-1. Photomicrographs taken under crossed nicols of a quartz-calcite vein from a depth of 657 m. (a) Intergrowth of calcite (C) and quartz (Q). (b) Coarse-grained quartz (Q) rimmed by finer-grained quartz (arrow) that may have been precipitated as chalcedony.

further evidence of boiling during its deposition. The quartz is present in two different habits. Most of the quartz forms euhedral to subhedral crystals. These crystals are rimmed by finer-grained quartz with radiating to irregular extinction patterns. The habit of the finer-grained quartz suggests that it was originally precipitated as chalcedony. No fluid inclusions were measured in the fine-grained quartz. However, homogenization temperatures of secondary fluid inclusions in the early formed quartz and the associated calcite (Table V-1) are consistent with the deposition of chalcedony as a primary silica mineral (Fournier, 1985).

C. FLUID INCLUSION TYPES

Three types of aqueous two-phase fluid inclusions were observed in the samples studied from TCB-1 (Fig. V-2). Liquid-rich inclusions are the most common. They can be grouped into two types on the basis of their compositions and behavior during freezing. In type 1a inclusions, ice was the final solid phase to melt. In type 1b inclusions, the final solid phase to dissociate was CO_2 clathrate. These CO_2-rich inclusions are characterized by the persistence of a solid phase at temperatures above 0.0°C and a pronounced phase change at approximately -30°C. This low temperature phase change is interpreted as being due to the formation of CO_2 clathrate.

Most liquid-rich inclusions could be easily classified as either type 1a or 1b. However, a few inclusions with negative final melting temperatures displayed features during freezing that were more typical of type 1b inclusions. The final solid phase in these inclusions could have been either ice or CO_2 clathrate. Because the invariant point in the system CO_2-H_2O is at a temperature of -1.48°C, CO_2 clathrate may exist in an ice-free inclusion at temperatures below 0.0°C (Hedenquist and Henley, 1985). For the purpose of the calculations discussed below, the inclusions that displayed this behavior were classified as type 1a inclusions.

The majority of type 1a and all of the type 1b liquid-rich inclusions studied were secondary or pseudosecondary in origin. These inclusions occur in short planar arrays that represent healed fractures within the crystals. Most of the secondary and pseudosecondary inclusions are small, with maximum dimensions ranging from 3 to 10 microns. A few larger, isolated inclusions up to 20 microns across were also found in some of the samples. These inclusions may be primary in origin.

Planes of vapor-rich inclusions that define healed fractures were observed in samples from 657 and 791 m. The vapor-rich inclusions are typically small, less than 10 μm, and display either irregular outlines or negative crystal shapes. Even though it was not possible to observe any phase changes in the vapor-rich

TABLE V-1. Characteristics of the fluid inclusions from the TCB-1 core hole, Tecuamburro, Guatemala.[a]

Depth (m)	Th	Tm-ice	NaCl (wt %)	Tm-clath	CO_2 (wt %)	Prin. (p) or Sec. (s)	Mineral
578	184			0.1	4.3	s	Cc
578	182			0.1	4.3	s	Cc
578	194					s	Cc
578	181			0.1	4.3	s	Cc
578	180					s	Cc
578	181	-0.4	0.6			s	Cc
578	183					s	Cc
578	180	-0.4	0.7			s	Cc
578	184					s	Cc
578	182	-0.2	0.4			s	Cc
578	184					s	Cc
578	184					s	Cc
641	173			1.0	4.6	s	Cc
641	160			1.5	4.7	s	Cc
641	164			0.9	4.5	s	Cc
641	169			1.4	4.7	s	Cc
641	168			1.2	4.6	s	Cc
641	157			1.0	4.5	s	Cc
641	152			1.2	4.6	s	Cc
641				1.1		s	Cc
641	166			1.4	4.7	s	Cc
641	188			0.7	4.5	s	Cc
641	176			1.4	4.7	s	Cc
641	189			0.9	4.6	s	Cc
641	157			1.2	4.6	s	Cc
641	166			0.7	4.5	s	Cc
641	162			1.4	4.7	s	Cc
641	169			0.9	4.5	s	Cc
641	158			1.4	4.7	s	Cc
641	200			1.3	4.8	s	Cc
641	162			1.4	4.7	s	Cc
657	202			0.5	4.5	s	Qtz
657	208			1.4	4.9	s	Cc
657	209			1.4	4.9	s	Cc
657	186					s	Cc
657	217	0.0	0.0			s	Qtz
657	178					s	Cc
657	209					s	Cc
657	208					s	Cc
657	207					s	Cc
657	207					s	Cc
657	191					s	Cc

TABLE V-1 (continued)

Depth (m)	Th	Tm-ice	NaCl (wt %)	Tm-clath	CO_2 (wt %)	Prin. (p) or Sec. (s)	Mineral
657	170			1.5	4.8	s	Cc
657	218	-0.1	0.2			s	Qtz
657	185			1.4	4.8	s	Cc
657	186	0.0	0.0			s	Qtz
657	231			0.7	4.7	s	Cc
657	210			0.6	4.5	s	Qtz
657	186			1.4	4.8	s	Cc
657	216			0.5	4.5	s	Qtz
657				1.4		s	Cc
657				0.5		s	Cc
657	208			1.8	5.0	s	Cc
657	229			0.7	4.7	s	Cc
657	193			1.8	5.0	s	Cc
657	209					s	Cc
657	207			1.5	4.9	s	Cc
657	218	-0.1	0.2			s	Qtz
657	208			1.4	4.9	s	Cc
657	182	0.0	0.0			s	Qtz
657	215			0.5	4.5	s	Qtz
657				0.5		s	Cc
657	212			1.4	4.9	s	Cc
657	209					s	Cc
657	209			1.4	4.9	s	Cc
657	180			0.3	4.4	s	Qtz
657	208			1.4	4.9	s	Cc
657				0.5		s	Cc
657	215			0.6	4.6	s	Qtz
657	207					s	Cc
657	217	0.0	0.0			s	Qtz
791		-0.1	0.2			s	Cc
791				0.1	4.5	p	Cc
791	221			0.1		p	Cc
791	243	-0.1	0.2			s	Cc
791	238			0.1	4.5	p	Cc
791		-0.3	0.5			s	Cc
791	239	-0.2	0.4			p	Cc
791	234	-0.1	0.2			s	Cc
791	213			0.4	4.5	p	Cc
791		-0.2	0.4			s	Cc
791	231					p	Cc
791	248	-0.5	0.9			s	Qtz
791	236			0.3	4.6	s	Cc

TABLE V-1 (continued)

Depth (m)	Th	Tm-ice	NaCl (wt %)	Tm-clath	CO_2 (wt %)	Prin. (p) or Sec. (s)	Mineral
791	258	-0.1	0.2			s	Cc
791	237			1.1	4.9	p	Cc
791		0.0	0.0			s	Cc
791	240					s	Cc
791	237	-0.1	0.2			s	Cc
791	236					s	Cc
791	245					s	Cc
791	236					s	Cc
791		0.0	0.0			s	Qtz
791	237					s	Cc
791	201	0.0	0.0			s	Qtz
791	248					ps	Cc
791	249	-0.2	0.4			s	Cc
791	243					p	Cc
791	246	0.0	0.0			s	Cc
791	238					p	Cc
791	241	-0.1	0.2			s	Cc
791	240					ps	Cc
791		-0.7	1.2			s	Cc
791	238					p	Cc
791	236	-0.1	0.2			s	Qtz
791	225					p	Cc
791	202	0.0	0.0			s	Qtz
791	235					p	Cc
791	236	-0.1	0.2			s	Cc
791	229					p	Cc
791	245	-0.3	0.5			s	Cc
791	237					p	Cc
791		0.0	0.0			s	Qtz
791	231					p	Cc
791		-0.1	0.2			s	Cc
791	246	0.0	0.0			s	Cc
791		-0.1	0.2			s	Cc
791	236					p	Cc
791	234					p	Cc

[a] Abbreviations = **Th** = homogenization temperature; **Tm-ice** = ice-melting temperature; **NaCl wt %** = salinity as equivalent weight percent NaCl; **Tm-clath** = CO_2-clathrate dissociation temperature; **CO_2 wt %** = CO_2 content in weight percent calculated from the Tm-clath; **prim. (p) or sec. (s)** = primary or secondary fluid inclusions, and pseudosecondary inclusions are denoted by **ps**; **Cc** = calcite; **Qtz** = quartz.

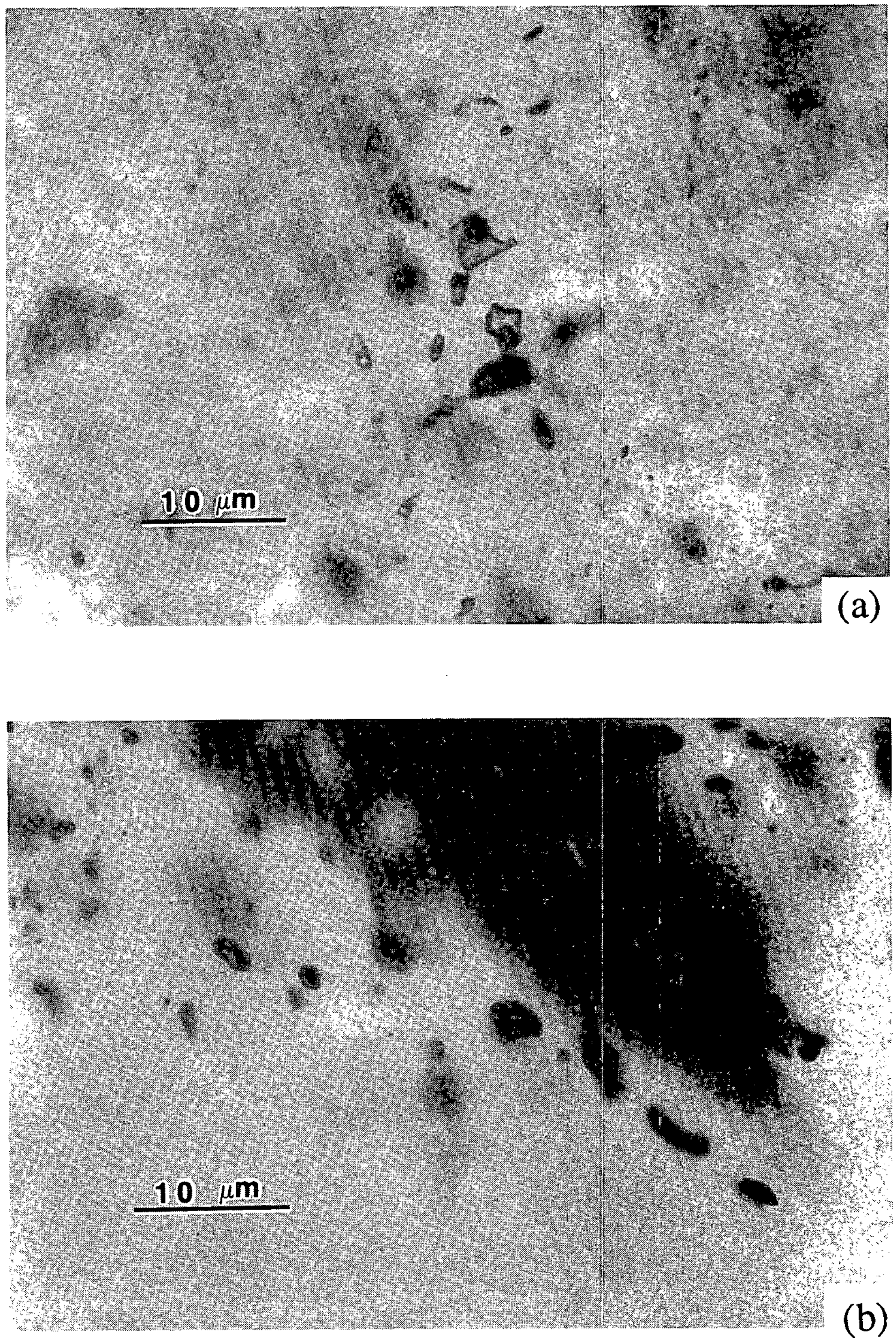


Fig. V-2. Photomicrographs of fluid inclusion types. (a) Type 1b liquid-rich inclusions in quartz from a depth of 657 m. The inclusions are secondary in origin. (b) A plane of secondary vapor-rich inclusions in quartz from a depth of 791 m.

inclusions during cooling, and thus better characterize their composition, the presence of vapor-rich inclusions provides unequivocal evidence of boiling within the reservoir.

D. METHODS

The microthermometric measurements discussed in this paper were made on either an SGE or a Fluid Inc. heating/freezing system. The SGE stage was calibrated with organic and inorganic compounds with known melting points. Synthetic fluid inclusions were used to calibrate the Fluid Inc system. All measurements were made in duplicate. Replicate measurements were within +0.2°C on heating runs whereas ice-melting temperatures were within +0.1°C. Determination of the CO_2-clathrate dissociation temperatures was more difficult. Type 1b inclusions frequently required repeated freezing runs under apparently identical conditions to nucleate the CO_2 clathrate. However, once the clathrate nucleus was established, the dissociation temperatures could generally be reproduced within ±0.3°C.

E. ESTIMATION OF SALINITIES AND GAS CONTENTS

Thermal and compositional data were obtained on approximately 130 liquid-rich fluid inclusions. The data are listed in Table V-1 and summarized graphically in Figs. V-3, V-4, and V-5. The homogenization temperatures of these inclusions range from 152° to 258°C. Fig. V-3 shows that the majority of inclusions from the lower two intervals, 657 and 791 m, are consistent with the downhole measured temperatures but that inclusions from shallower depths are typically up to several tens of degrees cooler than present-day conditions. The correspondence between the present and measured temperatures near the bottom of the hole implies that the fluid inclusions are related to the present thermal system. However, as discussed below, the CO_2 contents of the inclusions are much higher than would be expected from the ice-melting temperatures of the type 1a inclusions.

Type 1a inclusions had ice-melting temperatures that ranged from 0.0° to -0.7°C. A histogram of the ice-melting temperatures of these inclusions is shown in Fig. V-6. The data are skewed toward higher values, with the maximum occurring at -0.1°C. This distribution suggests that the average reservoir composition would correspond to an apparent salinity of 0.18 equivalent weight percent NaCl. For comparison, this ice-melting temperature is similar to the values calculated for the NaCl springs that discharge to the east of the field. Thus, the composition of the shallow reservoir may be similar to the spring compositions. Interpreting the range of ice-melting temperatures strictly in terms of differing salinities would imply salt contents ranging from less than 0.18 to 1.2 equivalent weight percent NaCl

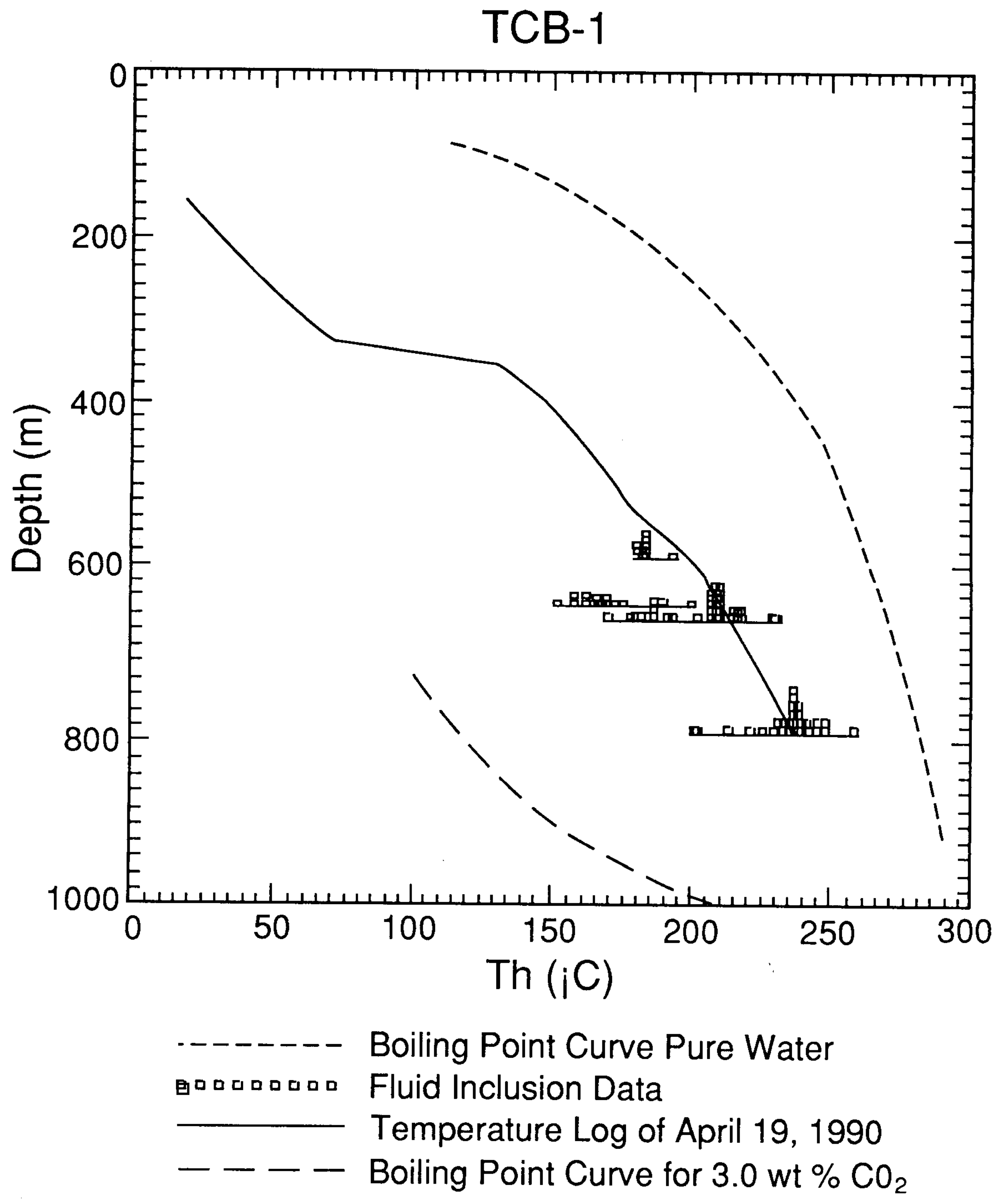


Fig. V-3. Distribution of homogenization (Th) temperatures from the four intervals studied. The downhole measured temperatures are shown as the solid line. Boiling point curves for pure water and for water with 3 weight percent CO_2 are shown for reference.

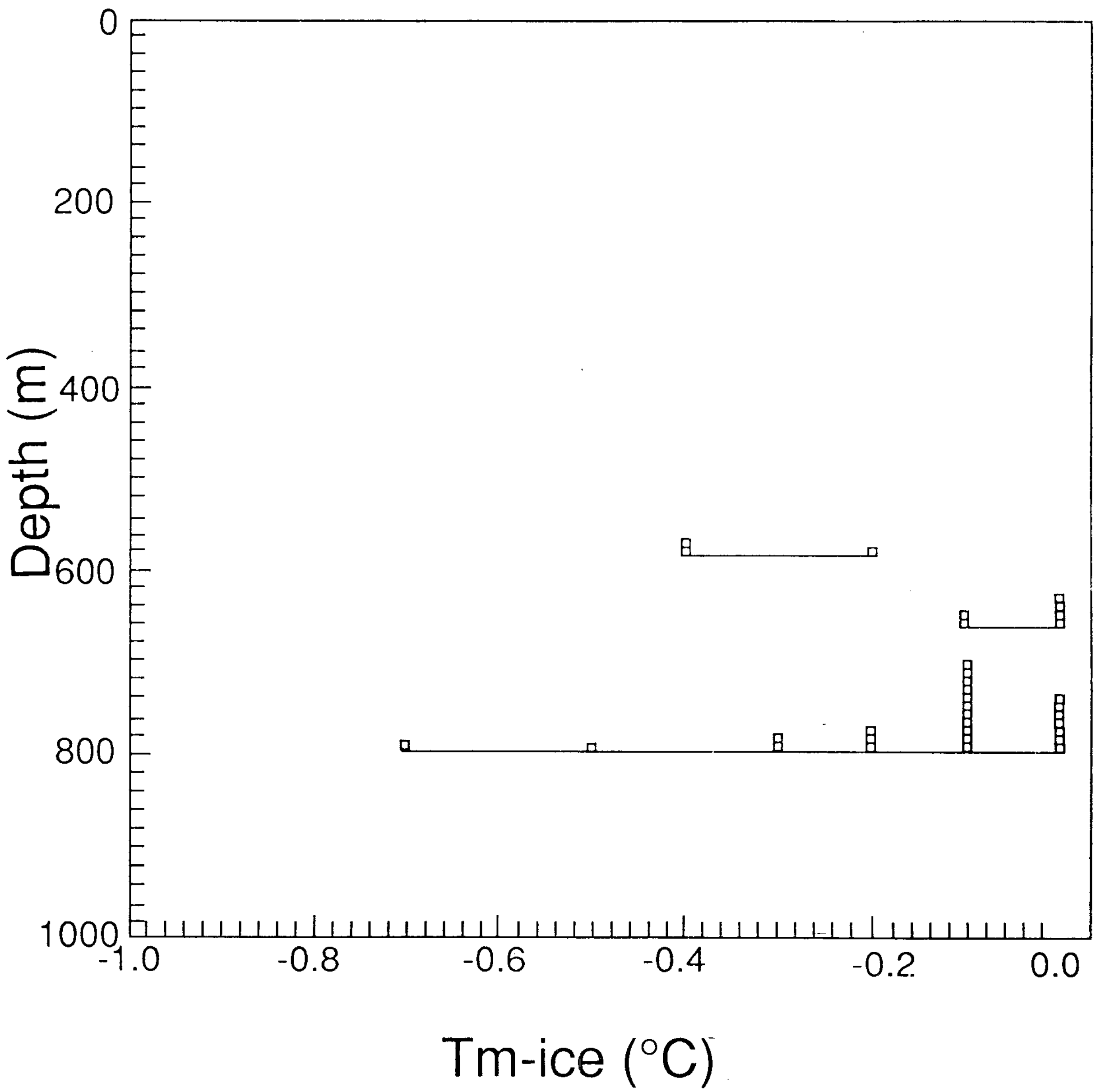


Fig. V-4. Ice-melting (Tm-ice) temperatures versus depth.

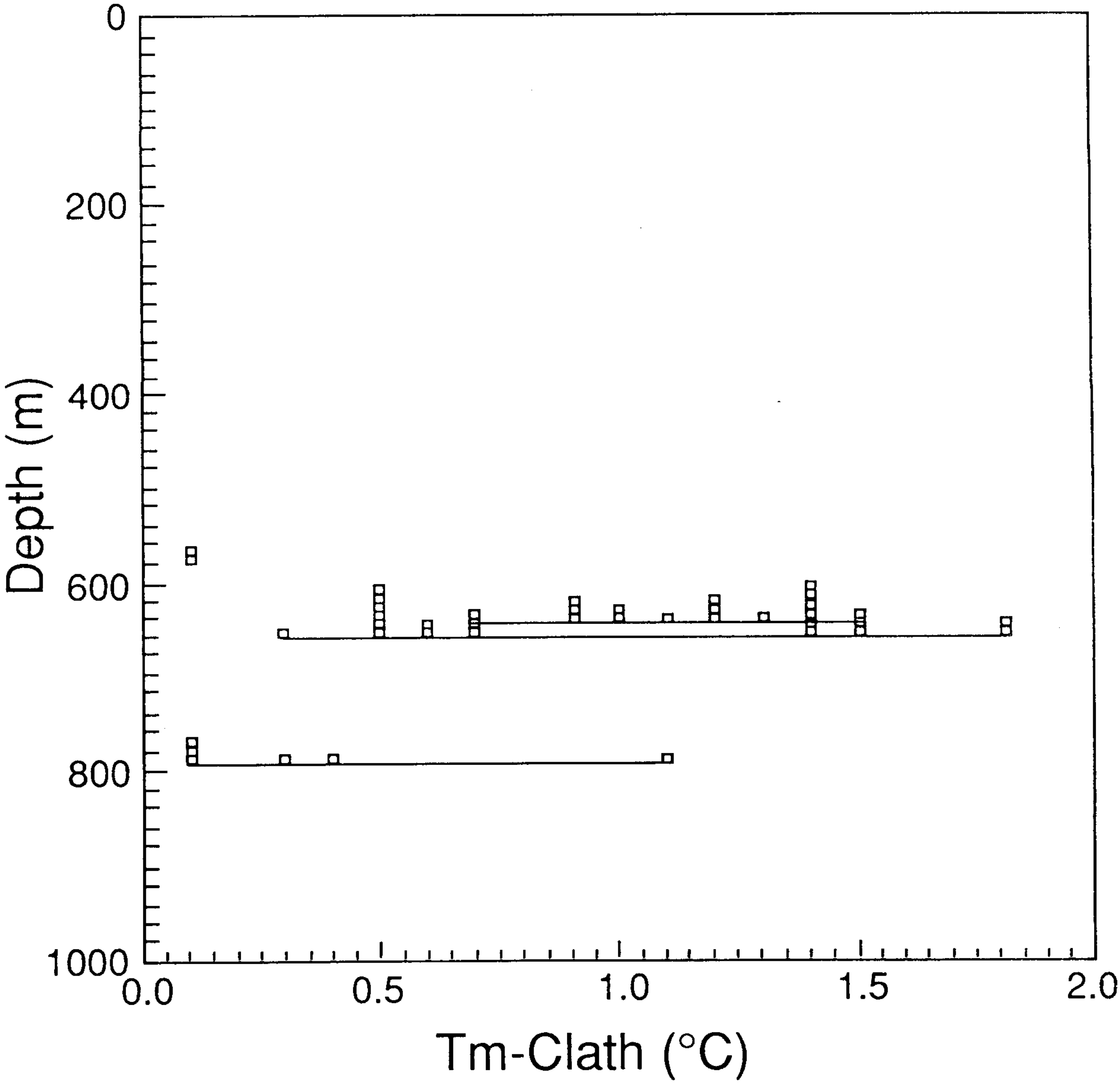


Fig. V-5. CO_2-clathrate dissociation (Tm-clath) temperatures versus depth.

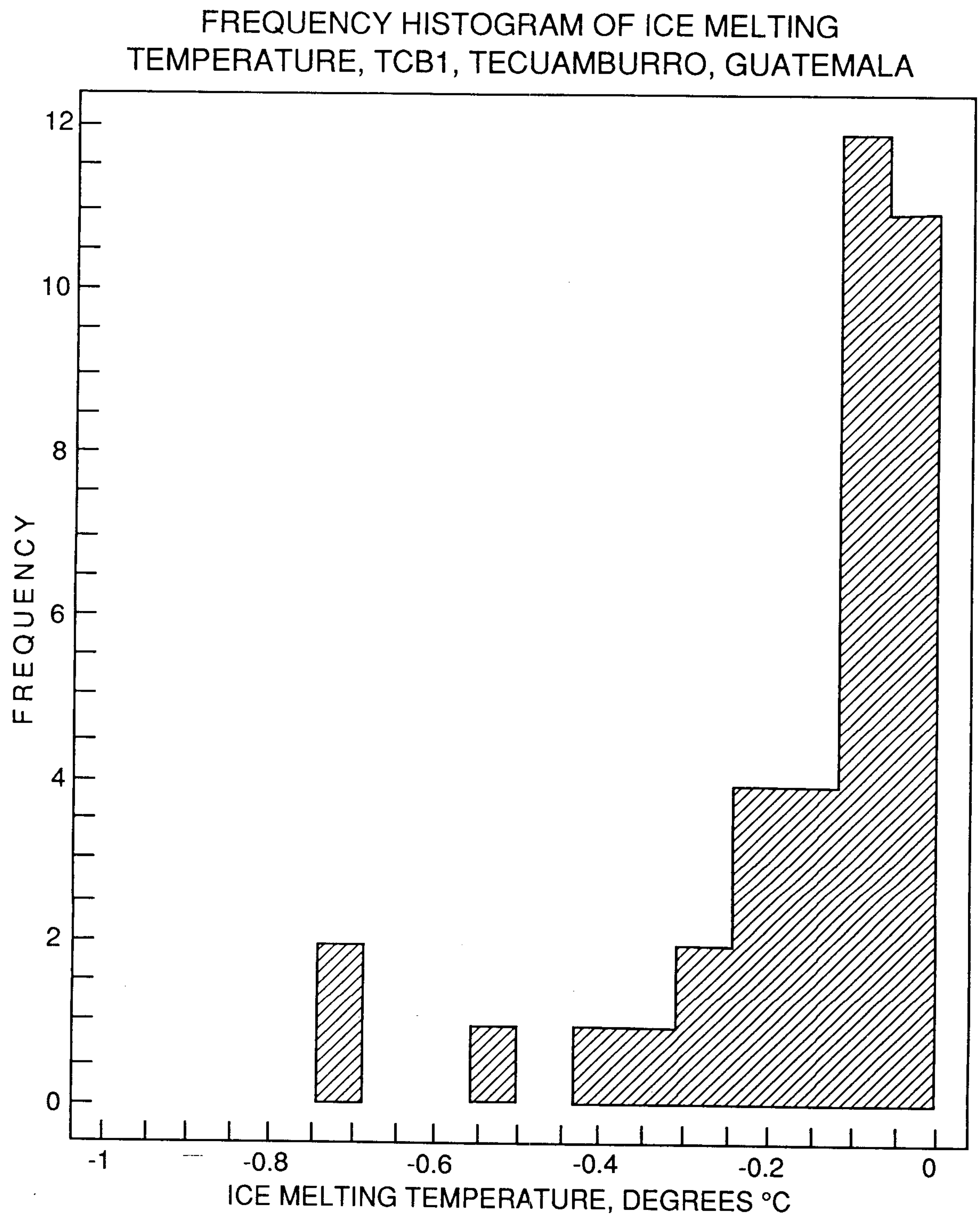


Fig. V-6. Histogram of ice-melting temperatures of type 1a inclusions.

(Potter *et al.*, 1978). Fig. V-7 shows that despite the relatively large range in ice-melting temperatures, there is little variation in the homogenization temperatures of these inclusions. Such variations are not likely to be caused by either mixing fluids with different salt contents or by increasing the salinity of the fluids as a result of boiling. Mixing would require the existence of two chemically distinct fluids at the same temperature. Although the composition of the reservoir fluids is not known, data from other geothermal systems associated with active volcanism suggest that fluids with such vastly different salinities but similar temperatures are unlikely to occur. Boiling will have only a relatively small effect on the salinity of the fluid. For example, boiling over a temperature range from 300° to 100°C would only increase the salt content by a factor of 1.7.

Alternatively, variations in the ice-melting temperatures of low-salinity inclusions can result from differences in their gas contents because dissolved gases will also affect the freezing- point depression (Hedenquist and Henley, 1985). The CO_2 contents of the type 1a fluid inclusions can be determined by combining the molar freezing-point depression of CO_2 with the homogenization temperature of the inclusions, Henry's Law coefficients (Harned and Davis, 1943; Drummond, 1981) and an estimate of the salinity of the degassed fluid (Hedenquist and Henley, 1985; Sasada, 1985; M. Adams, unpublished algorithms).

In calculating the CO_2 contents of the type 1a inclusions, we have assumed that the salinity of the degassed reservoir fluid is 0.18 equivalent weight percent NaCl, which corresponds to an ice-melting temperature of -0.1°C. The minimum ice-melting temperature of the type 1a inclusions is 0.7°C. Using this value yields a maximum CO_2 content of 1.6 weight percent. The presence of small amounts of CO_2 in the reservoir fluid would not greatly affect these calculations. For example, even if the entire freezing-point depression of inclusions with an ice-melting temperature of -0.1°C was caused by the presence of dissolved gas, the maximum CO_2 content of fluids trapped at 240°C would only be 0.27 weight percent. Similarly low salinities and comparable gas contents have been documented from other well-characterized systems in Guatemala and Mexico by Moore *et al.* (1990).

Type 1a fluid inclusions with ice-melting temperatures of 0.0°C are common in many geothermal systems (Moore *et al.*, 1990). These melting temperatures indicate salinities that are lower than would be expected for geothermal fluids with temperatures near 200°C. The high homogenization temperatures of these inclusions suggest that they represent condensed steam or steam that has mixed with small quantities of reservoir fluid.

The salinities of the type 1b inclusions cannot be determined from the homogenization and freezing data obtained on these inclusions. However, because of the inferred low salinities of the inclusion fluids,

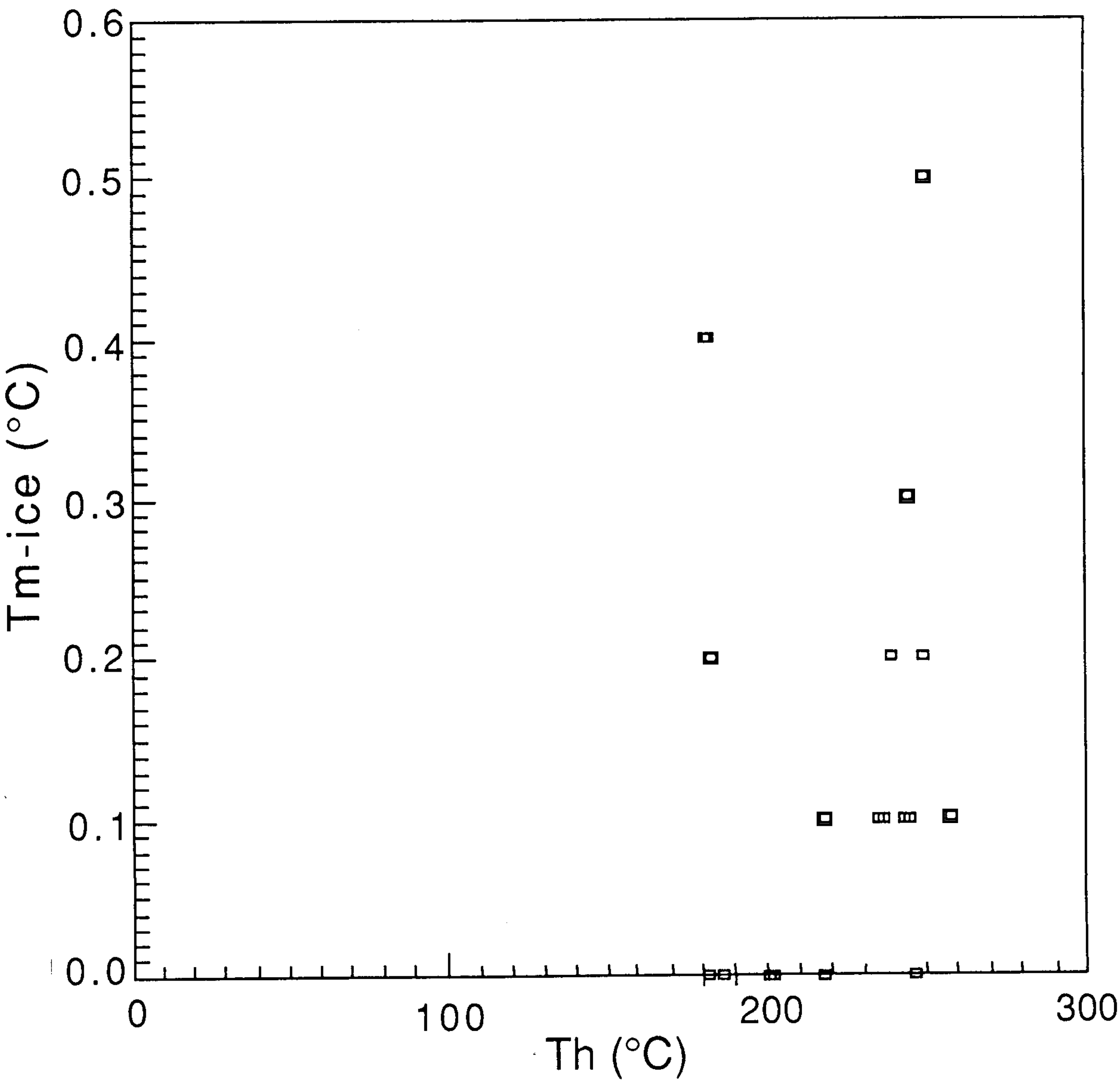


Fig. V-7. Plot of ice-melting (Tm-ice) vs. homogenization (Th) temperatures for type 1a inclusions.

their CO_2 contents can be estimated from the clathrate stability data of Bozzo *et al.* (1975) for pure water-CO_2 mixtures, combined with Henry's Law coefficients, the clathrate-dissociation temperatures, and the homogenization temperatures of the inclusions (M. Adams; unpublished algorithms). These calculations yield CO_2 concentrations ranging from 4.3 to 5.0 weight percent (Table V-1). For reference, the CO_2 content required to produce clathrate that dissociates at 0.1°C in a fluid inclusion that has trapped only water and CO_2 at 150°C is approximately 4.2 weight percent.

F. DISCUSSION

Origin of the CO_2-enriched inclusions

The temperatures and pressures in active geothermal systems typically follow hydrostatic boiling point to depth curves adjusted for their CO_2 contents (Henley *et al.*, 1985). Fig. V-3 shows the relationship between the fluid inclusion and downhole temperatures and the boiling-point to depth curves for pure water and for water containing 3 weight percent CO_2. CO_2 contents of 4 to 5 weight percent, which are more typical of the type 1b inclusions, will depress the top of the boiling-point curve to depths in excess of 1000 m (Sasada, 1985).

It is apparent from Fig. V-3 that the type 1b fluid inclusions have CO_2 contents greatly exceeding the values predicted from their homogenization temperatures. While this disparity implies conditions that are not presently observed in TCB-1, consistent homogenization temperatures among all of the inclusions and with the measured downhole temperatures imply that both type 1a and 1b fluid inclusions formed under the same temperature-depth regimes. Thus, the type 1b inclusions must have formed under pressures that were greater than hydrostatic.

Fluid inclusions with sufficient CO_2 to form clathrate have recently been described from several other geothermal systems associated with active volcanism. In addition to the data discussed in this paper, positive dissociation temperatures (up to several degrees centigrade) suggesting the presence of high CO_2 contents have been reported from the geothermal systems at Broadlands-Ohaaki and Kawerau, New Zealand (Henley and Hedenquist, 1985), Los Azufres, Mexico (Gonzales *et al.*, 1989; Combredet and Guilhaumou, 1987; Moore *et al.*, 1990), Momotombo, Nicaragua (Combredet *et al.*, 1987), and Zunil, Guatemala (Moore *et al.*, 1990). Our own experience indicates that CO_2 clathrate is difficult to nucleate at the low gas concentrations found in fluid inclusions from geothermal systems. This is particularly true if the cooling rates during the microthermometric measurements are relatively fast. Because evidence for CO_2 enrichments may go undetected, the presence of CO_2-enriched fluid inclusions may be more common than the literature suggests.

Moore *et al.* (1990) showed that the type 1b inclusions at Zunil and Los Azufres are concentrated in the upper and marginal parts of the geothermal systems where they define umbrella-shaped caps that thicken outward from the upwelling centers. Evidence for boiling, including vapor-rich inclusions, hydrothermal breccias, and quartz-calcite veins is abundant in both systems. Based on these relationships, and the similarities in trapping temperatures between type 1a and 1b inclusions, they concluded that the distribution of the type 1b inclusions resulted from boiling of steam-heated waters developed on the periphery of the thermal systems. The pressures required to trap liquid-rich inclusions with CO_2 contents exceeding 4 weight percent may reflect elevated pore pressures induced by tectonic activity.

<u>Temperature-Depth Relationships</u>

The mineralogic relationships, vapor-rich inclusions and the abundance of active fumaroles demonstrate that boiling has been an important process in controlling mineralization and temperatures at Tecuamburro. The downhole temperature measurements shown in Fig. V-3 suggest that boiling could first begin at a depth of approximately 350 m where a gradual change in temperature gradient occurs. This change may indicate that the geothermal reservoir is overlain by nonthermal groundwaters. Boiling under such conditions implies that the fracture zones which discharge steam and gas are effectively sealed from the incursion of cooler groundwaters.

The fluid inclusion data yield similar conclusions. If the majority of the inclusion homogenization temperatures from the lower two samples were close to the boiling point of the reservoir fluids and the inclusions with ice-melting temperatures of -0.1°C represent the degassed reservoir fluid as discussed above, then the top of the boiling water table could have been no shallower than approximately 450 m below the surface when the inclusions formed.

The homogenization temperatures of the fluid inclusions from the upper two sample intervals may reflect conditions during the early development of the geothermal system. The occurrence of type 1b inclusions from these intervals indicate that boiling has occurred. Although we have no established chronology among the inclusions, the distribution of homogenization temperatures from these depths suggests that the rocks are undergoing heating. Thus, the highest homogenization temperatures may be the most recent.

G. SUMMARY AND CONCLUSIONS

Fluid inclusions in veins from TCB-1 were used to characterize the composition of the shallow portions of the Tecuamburro reservoir and the process responsible for mineralization. Heating and freezing measurements were made on inclusions in secondary quartz and calcite crystals from 4 depths in the lower 300 m of the well. These data indicate that the shallow reservoir fluids are characterized by apparent salinities of approximately 0.18 equivalent weight percent NaCl and relatively low gas contents.

The majority of fluid inclusions from the lowermost two samples, which were collected from depths of 657 and 791 m, have homogenization temperatures that correspond closely to present downhole measurements. In contrast fluid inclusions from depths of 548 and 641 m were trapped at temperatures that were up to several tens of degrees below the measured downhole temperatures. These data indicate that portions of the reservoir are being heated, perhaps in response to recent fracturing and renewed fluid circulation. Significantly, we have found no evidence indicating that temperatures were generally higher in the past.

Many of the inclusions have CO_2 contents that exceed 4 weight percent. The high gas concentrations of these inclusions, combined with variations in the gas contents of inclusions with lower CO_2 contents indicate that the mineralization studied in the lower 300 m of the well occurred in response to boiling. The top of the boiling reservoir during vein deposition may have been as deep as 450 m.

Similar vein and fluid inclusion relationships have recently been described from Los Azufres, Mexico and Zunil, Guatemala, which are also associated with active volcanism and intense fumarolic activity (Moore *et al.*, 1990). Detailed studies on samples from numerous drill holes have shown that these features characterize umbrella-shaped regions surrounding the high permeability portions of the geothermal reservoirs.

H. ACKNOWLEDGMENTS

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