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GEOLOGY & GEOTHERMAL POTENTIAL OF THE TECUAMBURRO VOLCANO AREA OF GUATEMALA

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ABSTRACT

Radiometric ages indicate that Tecuamburro Volcano and 3 adjacent lava domes grew during the past 38,300 years, and that a 500-m-wide phreatic crater, Ixpaco, formed near the base of these domes about 2,900 years ago. Thus, the likelihood of a partly molten or solid-but-still-hot near-surface intrusion beneath the area seems great. Fumaroles and hot springs issue locally from Tecuamburro and adjacent domes and at and near Ixpaco crater. Analyses of samples from these and other nearby thermal manifestations yield chemical-geothermometer temperatures (Goff and others, this volume) of about 150°C to 300°C, with the highest temperatures at Ixpaco. The existence of a commercial-grade geothermal reservoir beneath the Ixpaco area seems likely.

INTRODUCTION

Tecuamburro Volcano, southeastern Guatemala, lies within the Central-American chain of active volcanoes that extends uninterrupted from southeastern Mexico across Guatemala and beyond (Fig. 1). Tecuamburro rises about 800 m above its surroundings, and may be considered a relatively small stratovolcano or a large dome of mixed endogenous and exogenous origin. Two pene-contemporaneous adjacent volcanic constructs, of about Tecuamburro size and apparently of similar growth history, and a third body, a 500-m-wide and 100-m-high dome, form a cluster of four vents (Fig. 2, TCB) and associated eruptive products herein informally called the Tecuamburro complex.

The Tecuamburro complex has no record of historic activity, but its nearly uneroded constructional form has suggested a Pleistocene age to geologists who studied the area (for example, Williams and others, 1964; Carr, 1984; Reynolds, 1987). A radiometric age, which was completed as part of our current studies, indicates that these rocks were emplaced since 38,300 ± 1,000 years ago. In addition, powerful phreatic explosions formed a 500-m-wide crater, Ixpaco, near the base of the Tecuamburro complex about 2,900 years ago. It thus seems likely that magma still resides within the crust beneath this area.

Ixpaco crater contains a lake with a pH of about 3. Fumaroles and boiling mud pots are present locally around the shore of the crater lake, and foci of vigorous upwelling are visible on the lake surface. There are many other hot springs and fumaroles within a few kilometers of Ixpaco and the Tecuamburro complex. Gas and hot-water geothermometry reported by Goff and others (this volume) suggests that subsurface temperatures range from about

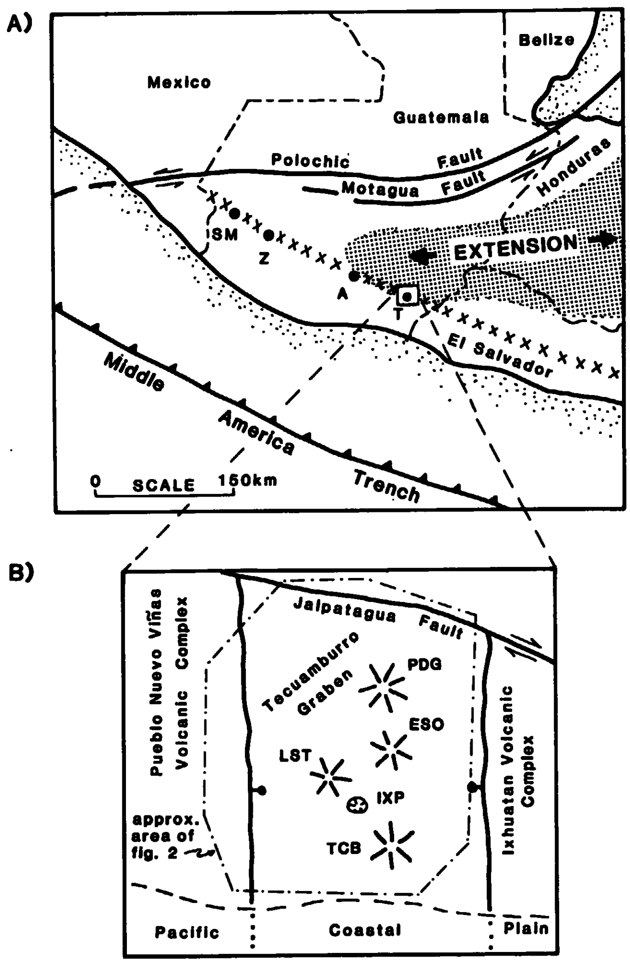


Figure 1. Index maps of the Guatemala and Tecuamburro Volcano regions. (A) Guatemala and adjacent areas, with lithospheric-plate-bounding structures. Polochic and Motagua Faults form a left-lateral transform boundary between the Caribbean and North American plates. The Middle America Trench is the surface expression of a subduction-zone boundary between the Caribbean and Cocos plates. Active volcanic chain generalized as xxxxxxxx. Principal geothermal fields of Guatemala: SM = San Marcos; Z = Zunil; A = Amatitlan; T = Tecuamburro. (B) Schematic structural map of the Tecuamburro area. The graben is about 20 km wide. Patterns of radiating lines mark principal vent areas of map units (see Fig. 2) within the graben. Closed depression (IXP) is Ixpaco tuff ring and enclosed phreatic crater.

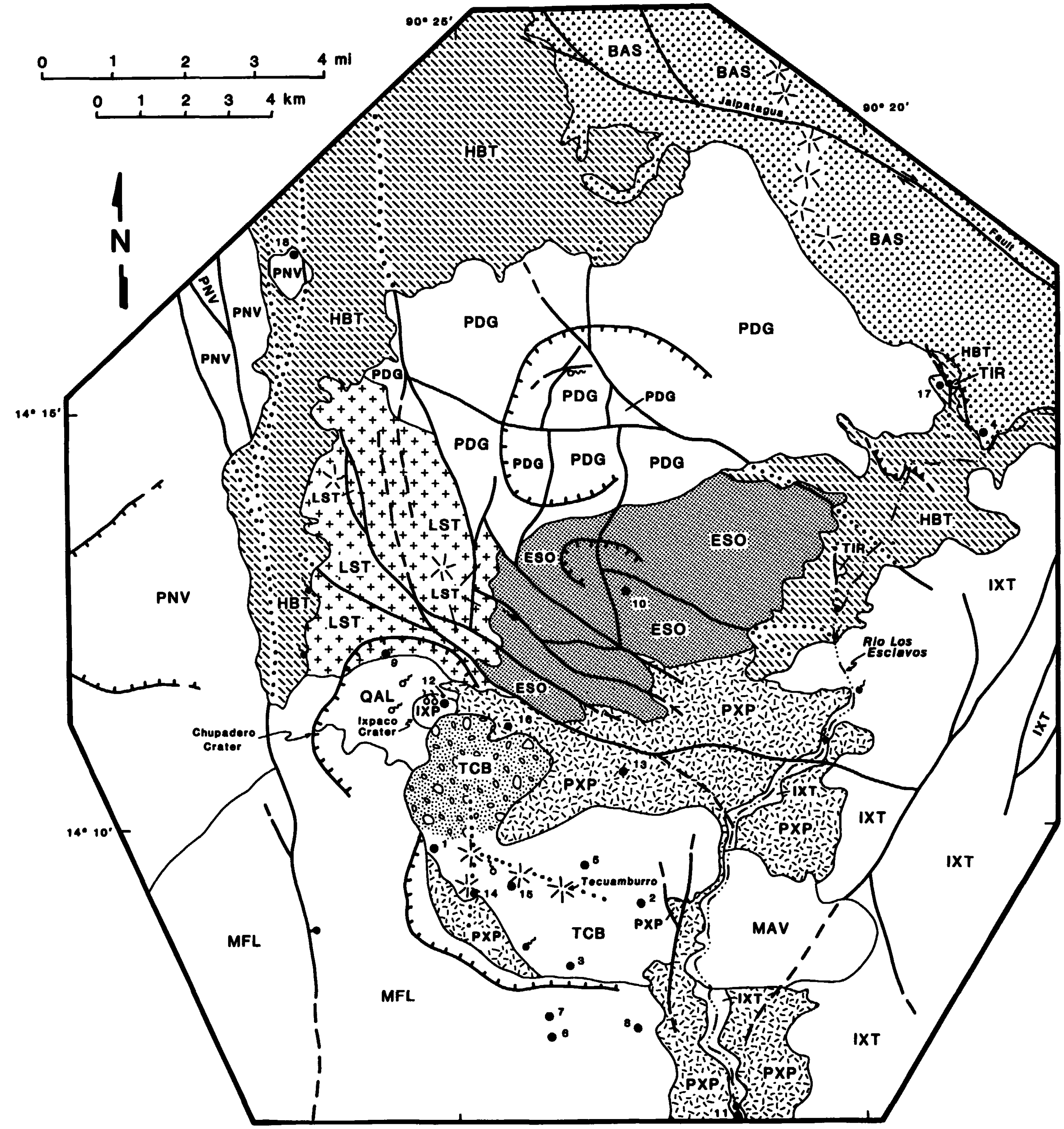
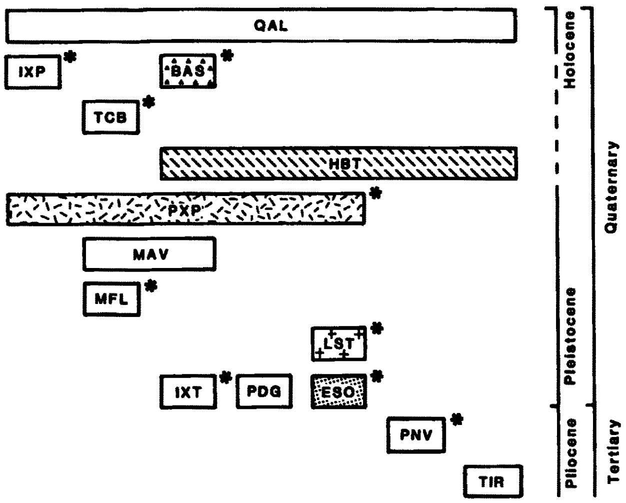


Figure 2. Geologic map of Tecuamburro Volcano and adjacent areas. Map compiled by Wendell A. Duffield. Mapping by Duffield, Grant Heiken, Kenneth Wohletz, Larry Maassen, Gabriel Dengo and Oscar Pinzon, during July 1988 and February 1989, supplemented by information from the Geologic Map of Guatemala, Cuilapa Sheet (1980).

CORRELATION OF MAP UNITS

Relative ages of units within a column are generally well established by field relations. Relative ages of units in different columns are uncertain but are implied by vertical positions in the chart. * denotes unit for which a radiometric age has been determined (see Table 1).



EXPLANATION OF SYMBOLS

Contact

Fault, sense of offset unknown. Dashed where uncertain and dotted where concealed

Normal fault, bar and ball on downthrown side

Reverse fault, teeth on upper side

Right-lateral strike-slip fault

Location of volcanic vent

Trace of topographic rim or escarpment that marks volcanic crater or headwall of debris flow

Location and number of sample used for radiometric age determination and/or chemical analysis (see Tables 1 & 2)

Fumarole

Hot spring

DESCRIPTIONS OF MAP UNITS

QAL	Quaternary alluvium
IXP	Ixpaco phreatic tuff ring and enclosed pH-3, water-filled crater
BAS	Scoria cones and associated lava flows of basaltic andesite
TCB	Four adjacent andesitic lava domes and associated avalanche deposits. The southeasternmost vent is that of Tecuamburro proper. Partial collapse of the northwesternmost dome produced a debris avalanche (patterned) that overlies part of the IXP tuff ring.
HBT	Hornblende- and biotite-bearing rhyodacitic ignimbrite
PXP	Fallout, flow and minor surge deposits of two-pyroxene-bearing andesite pumice
MAV	Debris avalanche formed by sector collapse of stratovolcano MFL
MFL	Andesite stratovolcano (Miraflores)
LST	Scoria cones and associated andesite lava flows
ESO	Andesite stratovolcano
PDG	Andesite stratovolcano
IXT	Andesitic volcanic complex (Ixhuatan)
PNV	Andesitic volcanic complex (Pueblo Nuevo Vinas)
TIR	Quartz-phyric Tertiary lavas

150^{o}C to 300^{o}C. These temperatures generally increase toward Ixpaco and the Tecuamburro complex, which is additional evidence that a heat source apparently is centered beneath this area.

Steeply dipping faults, some roughly north trending and others west-northwest trending, are common within the area. Some thermal manifestations are located on faults of these two sets, and others are inferred to be localized by fault permeability. Thermal fluids also rise along vents such as that of Ixpaco crater, and zones of subhorizontal permeability may be provided by rubbly top and bottom parts of lava flows.

We conclude that the Tecuamburro area holds promise of containing a commercial geothermal resource because of the high calculated reservoir temperatures and the apparently adequate permeability.

STRUCTURAL SETTING

Tecuamburro Volcano is within the west-tapering tail of the Caribbean lithospheric plate (Fig. 1). The southern boundary of the plate in this area is defined by the Middle America Trench and related subduction zone, above which is a chain of active volcanoes. The northern boundary is defined by the Polochic and Motagua system of left-lateral transform faults. This fault system and the trench apparently intersect offshore about 300 km west of the Mexico-Guatemala border.

Active structures in southern Guatemala include a system of roughly north-trending grabens (Burkhart and Self, 1985; Fig. 1, this paper). Such structures are readily identifiable at least as far east as the Honduran depression, which is a series of en echelon grabens that essentially bisects that country. The westernmost examples of the system of grabens likely are buried beneath volcanic rocks accumulating rapidly within western Guatemala. This regional east-west extension, expressed as grabens, presumably is a result of plate interactions, as the Caribbean plate moves east-northeast relative to adjacent parts of the North American and Cocos plates (Burkhart and Self, 1985). Alternatively, Carr and others (1982) proposed that graben formation, as reflected in segmentation of the volcanic chain along north-trending normal faults, is controlled by mirror-image segmentation of the underlying subducting Pacific-plate slab above which the grabens and volcanoes are growing; boundaries between the inferred subduction-slab segments are thought to propagate upward and form faults in the overlying lithosphere.

THE TECUAMBURRO GRABEN

Whatever the cause of graben formation, the Tecuamburro complex lies within a graben (Fig. 1B) that is about 20 km wide. It terminates to the north against a west-northwest-trending strike-slip fault, the Jalpatagua; and it is buried by Quaternary sediments to the south, where it merges with the Pacific coastal plane. Graben faults along the north and central parts of the west side of the structure separate the Pueblo Nuevo Viñas volcanic complex (Fig. 2, PNV) from a fault-zone valley partly filled with a younger ignimbrite (Fig. 2, HBT). To the south these faults offset, down to the east, part of the Miraflores stratovolcano (Fig. 2, MFL), which is ancestral to the Tecuamburro complex as judged by near colocation of vents. The cast boundary of the graben is expressed as a north-trending zone of faults that cuts across the Ixhuatan volcanic complex, just outside our map area (Fig. 1B). Part of this fault zone was seismically active in 1979-1980, when a swarm of earthquakes occurred along a north-trending, steeply west-dipping plane with first motions indicative of west side down (White and others, 1980).

Tecuamburro graben contains several volcanic craters, most of which are expressed as arcuate, asymmetric topographic rims and collapse features; other prominent structures include steeply dipping normal faults of roughly north and northwest trends, and gently dipping reverse faults about 5 km south of the Jalpatagua strike-slip fault in the northeast part of the map area (Fig. 2). All of the rocks in our study area are offset by faults of one or more of these sets. In addition, vents of the Tecuamburro complex are aligned in north- and west-northwest-trending arrays (Fig. 2) and thus may be localized along reactivated faults in underlying rocks.

RADIOMETRIC AGES, PETROLOGY AND CHEMISTRY

Stratigraphic succession as indicated by field relations is summarized in Figure 2. Some age assignments are equivocal, and some adjacent vent areas likely had overlapping periods of activity; but broadly speaking, vents and associated eruptive products within the graben are progressively younger toward the south. Volcanic centers that flank and partly occupy the graben to the east (Fig. 2, IXT) and west (Fig. 2, PNV) are interpreted to predate most if not all of the rocks that vented within the graben, although some overlap in ages is likely.

Radiometric ages are generally consistent with field-defined stratigraphy (Table 1 and Fig. 2). The four oldest ages, 2.6 ± 0.3 Ma, 1.16 ± 0.048 Ma, 1.18 ± 0.080 Ma and 0.800 ± 0.061 Ma were determined for rocks from the flanking PNV and IXT volcanic complexes, and the part of the graben north of Tecuamburro, respectively. In the south-central part of the graben, the stratovolcano that is ancestral to Tecuamburro (Fig. 2, MFL) is about 0.1 Ma. This volcano subsequently was modified by a large sector collapse, which was followed by the emplacement of two-pyroxene pyroclastic deposits (Fig. 2, PXP) at 38.3 ± 1.0 ka, in turn followed by the growth of the Tecuamburro complex within the crater formed by sector collapse. These Tecuamburro rocks are too young to yield accurate K-Ar ages, but their calculated ages and associated uncertainties (Table 1) are consistent with the less-than-38.3-ka constraint provided by the radiocarbon age of a log in the underlying PXP unit. Conservative interpretation suggests that all of the ≤ 0.1 Ma rocks within the south part of the graben were erupted from closely spaced vents, which implies equally long-lived residence of crustal magma beneath the area.

Monogenetic basaltic vents and associated lavas along the Jalpatagua fault zone at the north margin of the map (Fig. 2) are inferred to represent the youngest magmatic eruptions in the study area. These olivine-phyric rocks contain about 50% SiO_2, which is the most primitive composition of the analyzed samples (Table 2).

With the exception of local, small-volume deposits of alluvium and minor lacustrine beds, both of which are somewhat reworked volcanic rocks, most of the Tecuamburro area is underlain by two-pyroxene andesites. Complexly twinned and zoned plagioclase is a nearly ubiquitous

Table 1. Radiometric ages for samples from the Tecuamburro Volcano area. All K-Ar ages are on whole-rock samples of lava flows. See Figure 2 for sample locations.

POTASSIUM-ARGON

Sample	Map unit	% K_2O	^{40}Ar mole/gm	% Rad. ^{40}Ar	Age, Ma
1	TCB	1.085	3.0663×10^{-13}	0.16	.019±.056
2	TCB	0.528	7.5074×10^{-14}	0.50	.096±.105
3	TCB	0.576	-4.8337×10^{-14}	-0.3*	-.056±.098
4	BAS	0.765	4.0044×10^{-14}	0.29	.036±.064
5	TCB	0.671	-1.0465×10^{-13}	-0.9*	-.108±.130
6	MFL	0.769	1.1921×10^{-13}	6.85	.108±.045
7	MFL	0.910	1.2675×10^{-13}	0.14	.094±.263
8	MFL	0.936	1.8283×10^{-13}	5.39	.131±.039
9	LST	1.300	1.4977×10^{-12}	5.13	.800±.061
10	ESO	0.748	1.2758×10^{-12}	7.32	1.180±.080
11	IXT	1.257	2.1009×10^{-12}	10.60	1.160±.050
18	PNV				2.6 ±.3@

CARBON FOURTEEN

Sample	Map Unit	Material Dated	Age, Years
12	IXP	Sediment	2,910 ±70
13	PXP	Wood	38,300 ±1,000

* The negative ^{40}Ar and age are artifacts of the method of calculating radiogenic ^{40}Ar. The experiment shows that the sample contains too little radiogenic ^{40}Ar to be detectable, presumably an indication of a very young age.

@ Reported by Reynolds (1987, Table 2).

The carbon-14 age determinations were carried out by Steve Robinson and Debbie Trimble in the laboratories of the USGS, Menlo Park, CA. The K-Ar age determination of sample 5 was carried out at the laboratory of the Institute of Human Origins, Berkeley, CA. All others were done at the USGS, Menlo Park, CA. Samples were crushed, sieved to 60-100 mesh, washed in water, treated for 30 minutes in 14% HNO_3, and treated for 2 minutes in 5% HF. This procedure removes extraneous argon from whole-rock samples. Samples also were boiled in water for 12 hours before loading them into an ultra-high-vacuum fusion-extraction system for collection of argon. This procedure inhibits adsorption of atmospheric ^{40}Ar, hence it increases the proportion of radiogenic ^{40}Ar recovered from a sample. Potassium was analyzed by a lithium metaborate flux fusion-flame photometry technique, with the lithium serving as an internal standard (Ingamells, 1970). Argon was analyzed by isotope-dilution using a five-collector system for simultaneous measurement of argon ratios in a static mass spectrometer (Stacey and others, 1978) at the USGS, and by a 10-cm Reynolds-type gas-source spectrometer at Berkeley. The ± values represent analytical uncertainty at one standard deviation, as determined by experience with replicate analyses. Radioactive-decay constants and abundance of ^{40}Ar are from Steiger and Jager (1977).

Table 2. Major-element chemical analyses of selected rocks from the Tecuamburro Volcano area. The samples of map unit TCB comprise one each of lavas erupted from the four vents within this unit. See Figure 2 for sample locations. All analyses have been recalculated to total 100%. Neither H_2O content nor weight loss on ignition at high temperature was determined; thus, water and other volatiles may account for original totals that are as low as about 97.3% for samples 14, 16 and 17, and are greater than 99% for all other samples. Analyses by x-ray fluorescence at Los Alamos National Laboratory.

	(Sample number) MAP UNIT									
	(4) BAS	(2) TCB	(14) TCB	(8) MFL	(9) LST	(11) IXT	(15) TCB	(16) PXP	(1) TCB	(17) HBT
SiO_2	49.63	53.22	57.85	56.50	57.49	57.12	60.61	62.34	63.12	68.44
TiO_2	1.32	0.79	0.78	0.73	0.71	0.59	0.65	0.59	0.56	0.50
Al_2O_3	18.11	18.97	20.27	18.22	18.20	18.53	17.46	17.54	16.84	15.87
Fe_2O_3t	10.12	8.69	8.57	8.47	8.00	8.10	6.95	6.64	6.14	3.71
MnO	0.16	0.15	0.17	0.18	0.14	0.18	0.14	0.14	0.13	0.10
MgO	7.00	4.98	3.49	3.35	3.19	2.51	2.84	2.53	2.51	0.96
CaO	9.53	9.00	4.99	7.80	7.63	6.81	6.25	5.61	5.81	2.89
Na_2O	3.05	3.49	3.14	3.71	3.25	4.59	3.74	3.31	3.45	3.81
K_2O	0.78	0.56	0.65	0.85	1.27	1.27	1.23	1.24	1.33	3.63
P_2O_5	0.30	0.15	0.09	0.19	0.12	0.30	0.13	0.06	0.11	0.09

phenocryst; hornblende and olivine are minor constituents of some of the rocks. Andesite ranges from sparsely to moderately porphyritic and occurs as lava domes and flows, laharic breccias, ignimbrites, fallout and surge deposits. Silica contents in andesite range from about 53% to 63% (Table 2), and all analyzed rocks comprise a weakly calcic suite (Fig. 3).

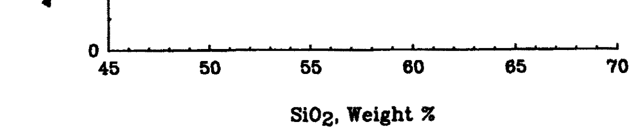


Figure 3. Silica versus CaO and $K_2O + Na_2O$ for rocks vented in Tecuamburro graben, plus ignimbrite (Fig. 2, HBT) that probably was erupted from Amatitlan Caldera (see text and Table 2). Curves are best-fit regressions for quadratic functions, and their intersection at about 63% SiO_2 indicates a calcic rock series in the classification scheme of Peacock (1931).

Silicic rocks are restricted to rhyodacitic ignimbrites that partly fill valleys along the east and west sides of the Tecuamburro graben (Fig. 2, HBT) and to inliers of similarly silicic quartz-phyric volcanic rocks that are interpreted to be Tertiary "basement" (Fig. 2, TIR). These latter rocks are exposed only in two small upfaulted blocks, and their subsurface extent is unknown but perhaps widespread. The ignimbrites contain phenocrysts of sanidine, plagioclase, biotite and hornblende, and these rocks are similar in age, petrography and chemical composition to part of the outflow sheet erupted from Amatitlan Caldera, which is located about 50 km to the northwest (Wunderman and Rose, 1984). This correlation is also suggested by the fact that the ignimbrites in the northwest part of our map area can be traced almost continuously back to Amatitlan Caldera; those along the valley of Rio Los Esclavos, in the eastern part of our map area, are interpreted to have flowed over an intervening drainage divide during emplacement, or alternatively, the ignimbrites followed a valley now buried by basaltic lavas that post-date them along the Jalpatagua fault zone. The only other nearby caldera young enough to be a potential source for the ignimbrites is Ayarza, about 50 km to the northeast of Tecuamburro Volcano (Reynolds, 1987); however, the Ayarza outflow sheet is more silicic than that from Amatitlan (>75%, our unpublished data; and about 70% to 74%, Wunderman and Rose, 1984, respectively).

Two nested craters are located near the northwest base of the Tecuamburro complex (Fig. 2). The larger and older of these craters, informally called Chupadero, is developed in rocks of about 0.8 Ma and 0.1 Ma (Fig. 2, LST and MFL), and in turn contains some of the 38.3 ± 1 ka pyroclastic deposits of map unit PXP and part of the Tecuamburro complex (Fig. 2). Chupadero crater may mark the vent of map unit PXP, whose pumiceous falls and flows once blanketed adjacent hills and filled the lower part of Rio Los Esclavos, respectively.

The younger crater, Ixpaco, has yielded a ^{14}C age of 2.91 ± 0.07 ka on an organic-rich zone within the tuff ring around the crater. Interestingly, a debris avalanche, whose source is the nearest of the Tecuamburro-complex domes, buries part of the Ixpaco tuff ring. Thus, dome growth may have been as recent as < 2.91 ka, although the avalanche could have been triggered by an event unrelated to, and younger than dome growth > 2.91 ka and < 38.3 ka.

GEOTHERMAL ASSESSMENT

We conservatively estimate that 50 km^3 of magma was erupted from several closely spaced vents within the south part of the graben during the past 100,000 years, and that several cubic kilometers of this amount, the Tecuamburro complex, was erupted during the past 38,300 years or less, all possibly from the same magma reservoir. Thus, according to the analysis of magma-related geothermal systems developed by Smith and Shaw (1979), this area is underlain either by a partly molten or a solid-but-hot intrusive complex within the uppermost 10 km of the crust. Moreover, the youngest of the Tecuamburro-complex vents fed the most silicic (Table 2, sample 1) eruptions of this group whereas the oldest fed the least silicic (Table 2, sample 2), which hints at a single crustal magma reservoir evolving through time.

Whatever the depth and temperature of a crustal heat source may be, chemical geothermometers (Goff and others, this volume) strongly suggest that the heat source is centered in the southern part of the graben and is sufficiently potent to produce geothermal fluids of 300°C. The highest calculated temperatures are for gases, which vent at Ixpaco and which presumably rise more or less vertically from a source reservoir. Calculated temperatures are lower for samples of thermal fluids collected at outlying springs and fumaroles, and this situation may reflect cooling during lateral outflow from a system centered beneath the Ixpaco area, from the existence of a second and cooler hydrothermal-convection system centered several kilometers from Ixpaco, and/or from subsurface mixing of reservoir fluids with cool meteoric water (Goff and others, this volume). Whatever scenario most accurately describes the subsurface geothermal regime, the character and age of volcanism, combined with the results of chemical geothermometry, suggest a high-priority target for further exploration in the immediate area of Ixpaco. A 600-m stratigraphic and thermal-gradient well may be drilled near Ixpaco during 1990.

REFERENCES

Burkhart, B., and Self, S., 1985, Extension and rotation of crustal blocks in northern Central America and effect on the volcanic arc: Geology, v. 13, p. 22-26

Carr, M. J., 1984, Symmetrical and segmented variation of physical and geochemical characteristics of the Central American volcanic front: Jour. Volcan. Geothermal Res., v. 20, p. 231-252

Carr, M. J., Rose, W. I., and Stoiber, R. E., 1982, Central America, in Thorpe, R. S., ed., Andesites: New York, John Wiley & Sons, p. 149-166

Goff, F., Truesdell, A., Janik, C., Adams, A., Rodan, A., and Meeker, K., this volume, Hydrogeochemical exploration of the Tecuamburro Volcano region, Guatemala:

Ingamells, C., 1970, Lithium metaborate flux in silicate analysis: Anal. Chimica Acta, v. 52, p. 323-334 Peacock, M. A., 1931, Classification of igneous rocks: Jour. Geology, v. 39, p. 54-67

Reynolds, J. H., 1987, Timing and sources of Neogene and Quaternary volcanism in south-central Guatemala: Jour. Volcan. Geothermal Res., v. 33, p. 9-22

Smith, R. L., and Shaw, H. R., 1979, Igneous-related geothermal systems, in Muffler, L. J. P., ed., Assessment of Geothermal Resources of the United States--1978: U. S. Geol. Survey Circular 790, p. 12-17

Stacey, J. S., Sherrill, N. D., Dalrymple, G. B., Lanphere, M. A., and Carpenter, N., 1978, A computer-controlled five -collector mass spectrometer for precision measurement of argon isotope ratios: U.S. Geol. Survey Open-file Report 78-701, 3 p

Steiger, R. H., and Jager, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmo-chronology: Earth Planet. Sci. Letters, v. 36, p. 359-362

White, R.A., Sanchez, E., Cifuentes, I. L., and Harlow, D. H., 1980, Preliminary report to the government of Guatemala on the on-going earthquake swarm in the Department of Santa Rosa, Guatemala: U. S. Geol. Survey Open-file Report 80-800, 17 p.

Williams, H., McBirney, A. R., and Dengo, G., 1964, Geologic reconnaissance of southeastern Guatemala: Univ. California Pubs. in Geological Sciences, v. 50, 62 p.

Wunderman, R. L., and Rose, W. I., 1984, Amatitlan, an actively resurging cauldron 10 km south of Guatemala City: Jour. Geophys. Res., v. 89, no. B10, p. 8525-8539

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