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GEOLOGY AND GEOTHERMAL POTENTIAL OF THE TECUAMBURRO VOLCANO AREA, GUATEMALA

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Abstract—Tecuamburro, an andesitic stratovolcano in southeastern Guatemala, is within the chain of active volcanoes of Central America. Though Tecuamburro has no record of historic eruptions, radiocarbon ages indicate that eruption of this and three other adjacent volcanoes occurred within the past 38,300 years. The youngest eruption produced a dacite dome. Moreover, powerful steam explosions formed a 250 m wide crater about 2900 years ago near the base of this dome.

The phreatic crater contains a pH-3 thermal lake. Fumaroles are common along the lake shore, and several other fumaroles are located nearby. Neutral-chloride hot springs are at lower elevations a few kilometers away. All thermal manifestations are within an area of about 400 km^2 roughly centered on Tecuamburro Volcano.

Thermal implications of the volume, age, and composition of the post-38.3 ka volcanic rocks suggest that magma, or recently solidified hot plutons, or both are in the crust beneath these lavas. Chemical geothermometry carried out by other workers suggests that a hydrothermal-convection system is centered over this crustal heat source. Maximum temperatures of about 300°C are calculated for samples collected in the area of youngest volcanism, whereas samples from outlying thermal manifestations yield calculated temperatures $\leq$165°C.

An 808 m deep drill hole completed in 1990 to partly test the geothermal model developed from surface studies attained a maximum temperature of almost 240°C. Thus, the possibility of a commercial-grade hydrothermal resource in the area seems high.

INTRODUCTION

Tecuamburro, an 800 m tall stratovolcano, is in southeastern Guatemala, within the Central American chain of active volcanoes (Fig. 1). This volcano has no record of historic activity, but its virtually noneroded edifice suggested a Pleistocene age to earlier workers (e.g., Williams *et al.*, 1964; Carr, 1984; Reynolds, 1987). Radiometric ages obtained as part of our study indicate that Tecuamburro Volcano is younger than about 38 ka and that powerful phreatic explosions produced a 250 m wide crater, called Ixpaco crater, along the northwest part of the base of the volcano at about 2.9 ka. It thus seems likely that magma, hot plutonic rocks, or both still reside within the crust beneath the Tecuamburro Volcano area.

Thermal manifestations are widespread within an area of about 400 km^2, roughly centered on Tecuamburro Volcano. For example, hot springs and fumaroles are present locally along the shore of Laguna Ixpaco, a pH-3 lake in Ixpaco crater; foci of vigorous upwelling are apparent on the lake surface. Other fumaroles lie 1–2 km west of Ixpaco crater, and many neutral-chloride hot springs issue from the banks of the Río Los Esclavos several kilometers to the east, near the base of the volcano; fumaroles and hot springs also are found on the flanks of Tecuamburro Volcano itself (Figs 2 and 3).

The combination of geologically young volcanism and widespread, vigorously-active thermal manifestations has been viewed by many as a promising indication of developable geothermal energy in the Tecuamburro area (OLADE, 1982; Giggenbach, 1988). In 1985, the United States Agency for International Development in cooperation with the government of Guatemala initiated a multidisciplinary evaluation of this potential resource.

As the geological component of this evaluation, the objectives of our study are (1) to document the volcanic history of Tecuamburro Volcano and surrounding area, and (2) to map structures that are related to volcanism and associated thermal manifestations. Companion studies emphasize the chemistry of thermal fluids (Janik *et al.*, 1990; also this issue) and electrical geophysical mapping (Hoover and Pierce, 1990), which are important components of the overall geothermal-energy assessment. Finally, a model of the geothermal system, developed by integrating the results of all surface studies, was partly tested by drilling a 808 m deep hole (Goff *et al.*, this issue). A maximum down-hole temperature of nearly 240°C indicates considerable promise for a commercial-grade hydrothermal-convection system beneath the area.

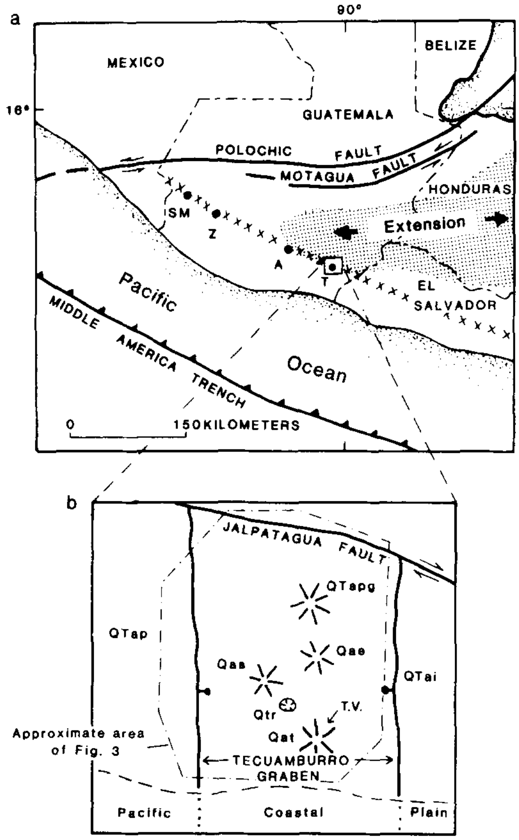
GEOLOGIC SETTING

Tecuamburro Volcano is within the west-tapering tail of the Caribbean lithospheric plate (Fig. 1). This plate in Guatemala is bounded on the south by the Middle America Trench and related northeast-dipping subduction zone, whose magma feeds the chain of active volcanoes within which Tecuamburro lies. The Polochic and Motagua system of left-lateral transform faults bound the north side of the Caribbean plate across central Guatemala.

Active tectonism in southern Guatemala includes formation of a system of roughly north-trending grabens and horsts that results in a crudely corrugated fabric to the landscape, readily identifiable from southeast Guatemala to central Honduras (Burkhart and Self, 1985). This style of tectonism is inferred to also affect western Guatemala, but landscape expression of the graben and horst structure appears to be buried beneath volcanic rocks rapidly accumulating there. Regional east-west crustal extension presumably is the result of interactions among the Caribbean and adjacent parts of the North American and Cocos lithospheric plates (Burkhart and Self, 1985). Alternatively, Carr and others (1982) proposed that faults between grabens and horsts are boundaries of segments of the chain of active volcanoes, offset slightly at right angles to the chain, and that these faults form by upward propagation of faults bounding a similarly segmented underlying subducting slab.

The position of Tecuamburro Volcano within this regional tectonic setting is illustrated by a Space-Shuttle radar image (Fig. 2). The most eye-catching feature in this image is a zone of essentially linear west–northwest-trending valleys that marks the trace of the Jalpatagua strike–slip fault system. Although the bounding faults are less apparent in the image, Tecuamburro Volcano lies within the south-central part of a roughly 20 km wide graben that terminates northward against the Jalpatagua fault system. Also visible on the Space-Shuttle image is the abrupt topographic rim of a 6 km-wide collapse crater (Miraflores crater) within which Tecuamburro Volcano is located. The Río Los Esclavos, the principal drainage for this region, flows southward, across the east central part of the graben.

We apply the informal name, Tecuamburro graben, to the 20 km wide, north-trending graben within which Tecuamburro Volcano is located (Fig. 1). Whereas this graben apparently terminates abruptly to the north against the Jalpatagua strike–slip fault, as noted above, the lateral faults that define the graben disappear southward beneath Quaternary sedimentary rocks of the Pacific coastal plain. Faults along the north and central parts of the west side of the graben offset a sequence of Pliocene and Pleistocene andesite lavas down to the east to form a valley



EXPLANATION

Normal fault - dotted where concealed; ball and bar on downthrown side

Strike-slip fault - dashed where inferred; arrows indicate relative horizontal movement

Thrust fault - sawteeth on upper plate

xxxx Active volcanic chain

Qas Vent area for map unit shown (see Description of Map Units for explanation of unit symbols)

Qtr Tuff ring and enclosed pH 3 Laguna Ixpaco

Approximate landward boundary of Pacific coastal plain

Fig. 1. Index maps of the Guatemala region and the Tecuamburro Volcano area. (a) Lithospheric plate boundaries and zone of east-west crustal extension (stippled) in Honduras, Guatemala, and El Salvador. Dots mark principal geothermal fields of Guatemala, which are San Marcos (SM); Zunil (Z); Amatitlán (A); Tecuamburro (T). (b) Schematic structural map of the Tecuamburro graben, which is about 20 km wide. T.V. = Tecuamburro Volcano.

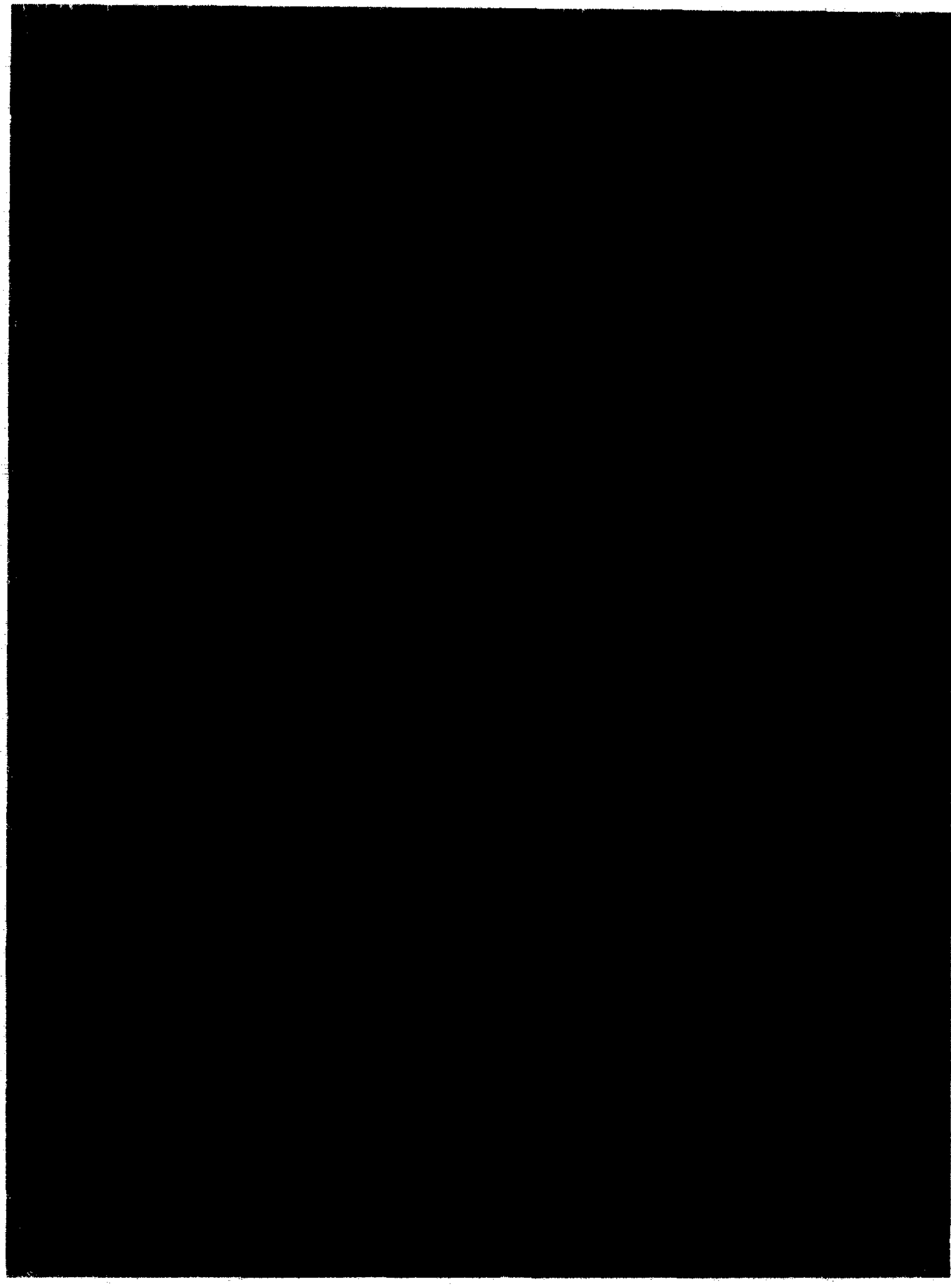


Fig. 2. (a) Synthetic-aperture-radar image of southeastern Guatemala, taken from Space Shuttle. Principal structural features are discussed in the text. Image provided by Ron Blom, NASA-Jet Propulsion Laboratory, Pasadena, California.

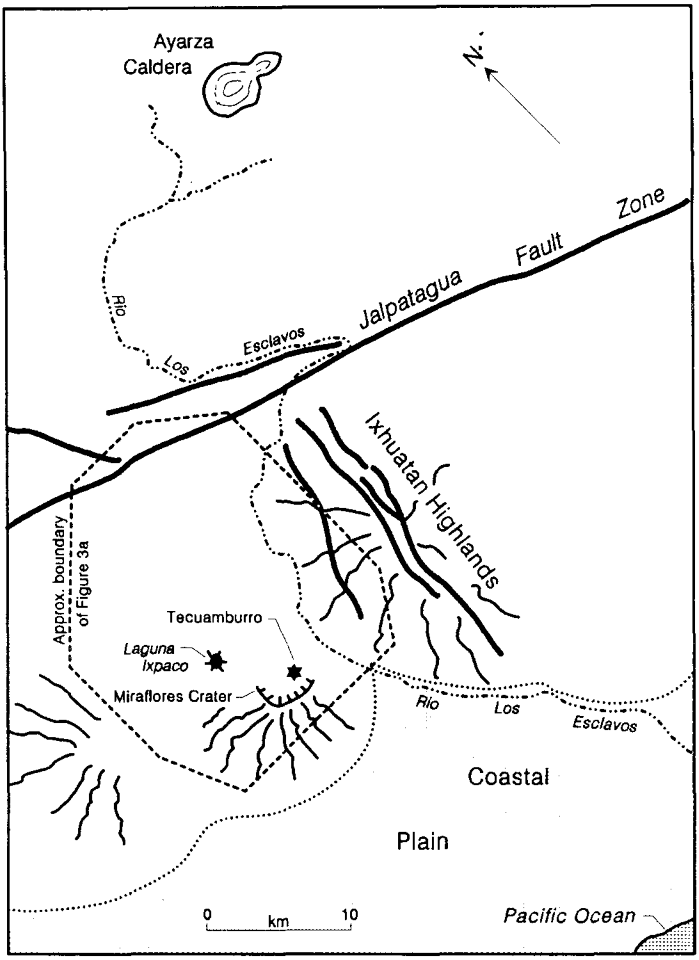


Fig. 2. (b) Sketch map of principal structural features visible on image shown in (a). The north-trending zone of faults across the Ixhuatán highlands is the locus of a swarm of earthquakes that occurred during 1979–1980.

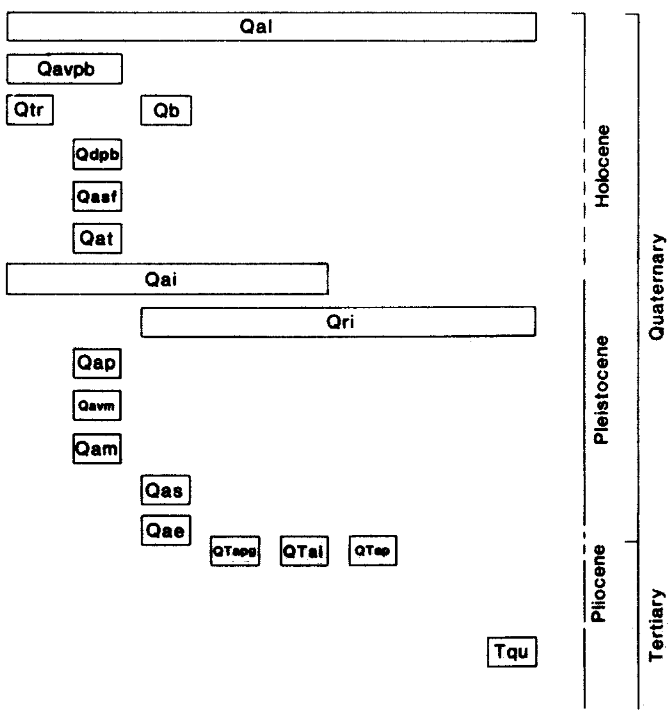
that is partly filled with Pleistocene silicic ignimbrite (Fig. 3, map units QTap and Qri, respectively). Further south these faults offset, down to the east, a sequence of andesite lavas that have ages of about 0.1 Ma (Table 1, samples 6, 7, 8; Fig. 3, map unit Qam).

The eastern boundary of the Tecuamburro graben is a north-trending zone of faults that cuts a sequence of andesitic lavas (Fig. 2b; just outside the map area of Fig. 3). This zone was the epicentral locus of many crustal earthquakes in 1979 and 1980. Determination of first-motions associated with these earthquakes indicates downthrow to the west along steeply west-dipping, north-trending planes (White *et al.*, 1980). The Tecuamburro graben apparently continues to grow.

The Jalpatagua fault zone bifurcates into three west–northwest-trending strands in the north-central part of the map area (Fig. 3). All three strands are traceable for several kilometers northwestward as topographic features on aerial photographs, until they become buried by late Pleistocene pyroclastic deposits erupted from Amatitlán Caldera (Wunderman and Rose, 1984). Within and southeast of the map area, the fault zone is well defined by steep escarpments, deep linear valleys, and sag ponds. Lavas and tuffs within the fault zone have been sheared into cataclastic breccias; locally, porphyritic nonwelded tuffs have been reduced to rock flour.

- Contact
- Fault - Sense of offset unknown. Dashed where approximately located. Dotted where concealed
- Normal fault - Dashed where approximately located. Bar and ball on downthrown side
- Reverse fault - Dashed where approximately located. Saw teeth on upper plate
- Right-lateral strike-slip fault - Dashed where approximately located
- Structural trend defined by aligned vents
- Topographic rim or escarpment - Marks volcanic crater or headwall of debris avalanche; hachures point toward inferred crater center or direction of avalanche movement
- Scoria cone
- 21 Collection locality of sample listed in Table 1 or 2
- 97 Fumarole
- 85 Hot spring

Correlation of Map Units



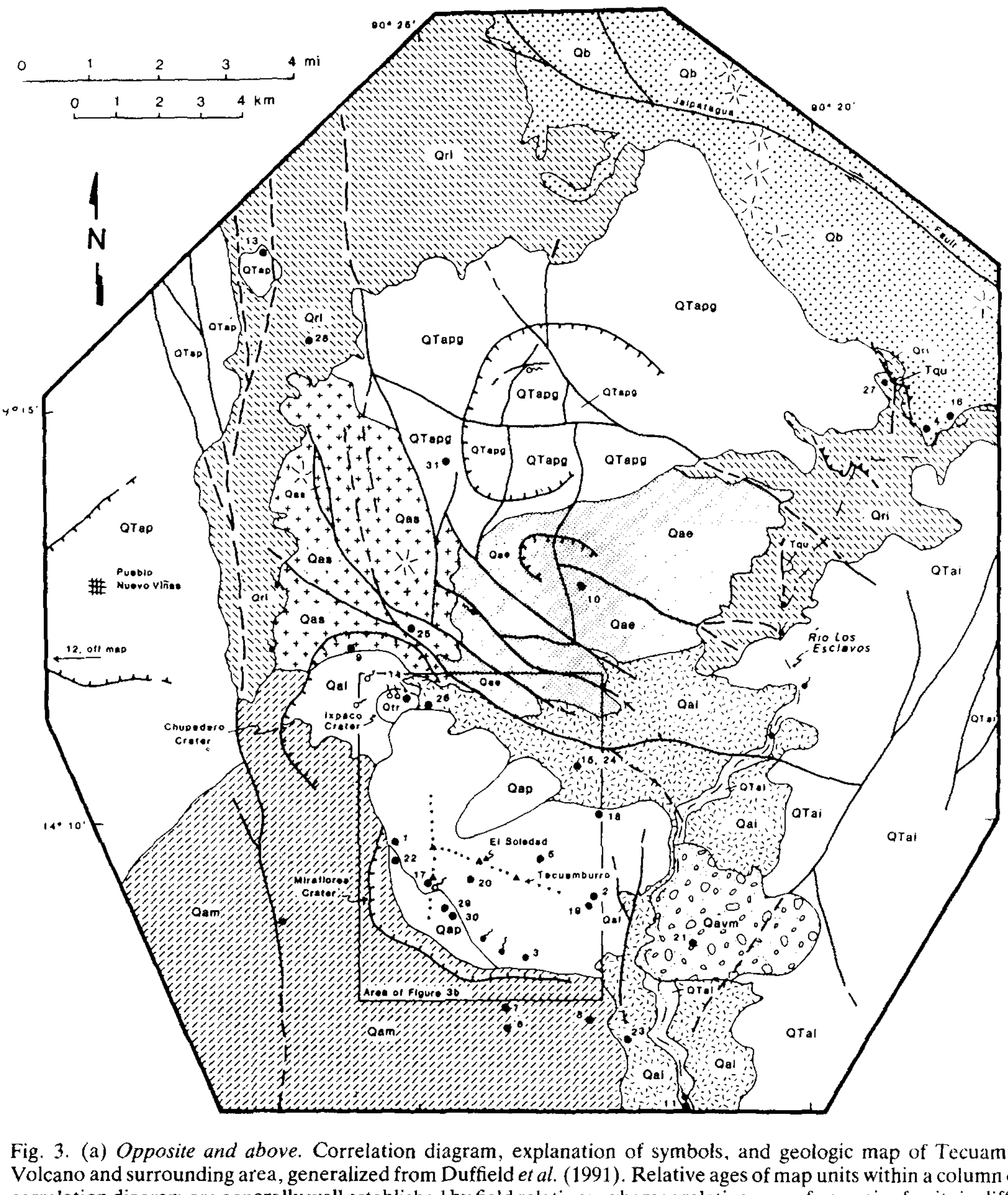


Fig. 3. (a) *Opposite and above.* Correlation diagram, explanation of symbols, and geologic map of Tecuamburro Volcano and surrounding area, generalized from Duffield *et al.* (1991). Relative ages of map units within a column of the correlation diagram are generally well established by field relations, whereas relative ages of any pair of units in different columns is uncertain but is implied by vertical position in the diagram. Numbers on the map mark sample locations for samples of Tables 1 and 2. Note that samples 21, 22, and 25 of pyroclastic unit Qai are from the fallout component that blankets older rocks (e.g. Qavm, Qas, Qap) and is not depicted separately in Fig. 3. Also note that Tecuamburro Volcano and adjacent lava domes are not subdivided. (*Continued*)

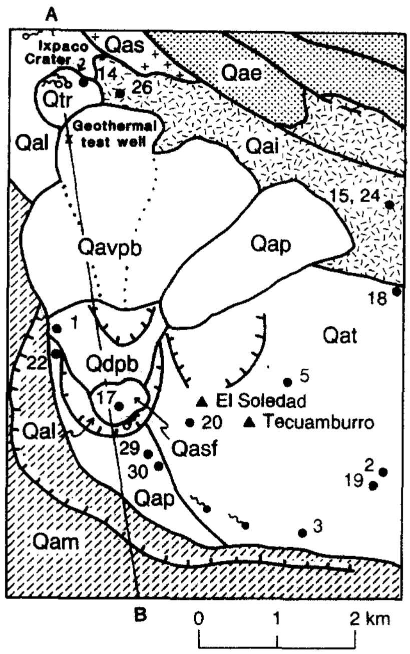


Fig. 3. (b) Enlargement of the part of the geologic map that includes Tecuamburro Volcano (Qat), adjacent unnamed (Qasf) and Peña Blanca lava domes (Qdpb), and the phreatic crater (Qtr) that contains Laguna Ixpaco, all <38.3 ka. A ------ B marks approximate line of section on Fig. 7.

A long quasi-linear trace across a variety of rugged terrains suggests that the Jalpatagua faults are vertical and that the sense of movement is predominantly strike slip; steep escarpments suggest the possibility of a component of vertical offset locally. Carr (1976) described the Jalpatagua as right lateral, because of apparent offsets in Tertiary volcanic terrains along the fault southeast of our map area. A right-lateral step in the course of the Río Los Esclavos where it crosses the fault zone (Fig. 2b) also suggests a right-lateral fault system. However, we note that two lines of Quaternary basaltic cinder cones in the north-central part of our map area (Fig. 3) suggest about 1 km of left-lateral offset. We tentatively conclude that the Jalpatagua fault is right-lateral, but we recognize that some local geologic evidence is contrary to this conclusion. Right-lateral movement is consistent with a model of eastward motion of the Caribbean plate in Guatemala suggested by Newhall (1987).

Moderately- to gently-dipping reverse faults are present within the Tecuamburro graben, about 3–5 km south of the trace of the Jalpatagua fault zone (Fig. 3). The more southerly of these faults is well exposed in a road cut where Quaternary silicic ignimbrite (Fig. 3, map unit Qri) is thrust over late Pleistocene (?) terrace gravels of the Río Los Esclavos (Fig. 4). These faults may be secondary structures related to the stress field associated with the nearby Jalpatagua strike–slip system. If so, their sense of convergence with the Jalpatagua would provide independent information about the character of the strike–slip stress field; unfortunately, this convergence is obscure and cannot be determined unequivocally.

Other faults to the south within the Tecuamburro graben form a complex pattern that presumably reflects a similarly complex stress field. The central part of the graben is broken by

Table 1. Radiometric ages for samples from the Tecuamburro Volcano area. All K–Ar ages are on whole-rock samples of lava flows and a dike (crosscuts unit QTap). Sample numbers are on Fig. 3 at collection localities

		POTASSIUM–ARGON			
Sample #	Map unit	% K_2O	^{40}Ar mol/g	% Rad. ^{40}Ar	Age, Ma
1	Qdpb	1.085	3.066×10^{-13}	0.16	0.019 ± 0.056
2	Qat	0.528	7.507×10^{-14}	0.50	0.096 ± 0.105
3	Qat	0.576	-4.834×10^{-14}	−0.3*	−0.056 ± 0.098
4	Qb	0.765	4.004×10^{-14}	0.29	0.036 ± 0.064
5	Qat	0.671	-1.047×10^{-13}	−0.9*	−0.108 ± 0.130
6	Qam	0.769	1.192×10^{-13}	6.85	0.108 ± 0.045
7	Qam	0.910	1.268×10^{-13}	0.14	0.094 ± 0.263
8	Qam	0.936	1.828×10^{-13}	5.39	0.131 ± 0.039
9	Qas	1.300	1.498×10^{-12}	5.13	0.800 ± 0.061
10	Qac	0.748	1.276×10^{-12}	7.32	1.180 ± 0.080
11	QTai	1.257	2.101×10^{-12}	10.60	1.160 ± 0.050
12	QTap (dike)	0.869	1.028×10^{-12}	5.40	0.821 ± 0.118
13	QTap				2.6 ± 0.3@

		CARBON FOURTEEN	
Sample #	Map unit	Material dated	Age, yr B.P.
14	Qtr	Sediment	2910 ± 70
15	Qai	Wood	38300 ± 1000

*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. QTap(dike) is outside map area. @ Reported by Reynolds (1987, Table 2).

The ^{14}C 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 min in 14% HNO_3, and treated for 2 min in 5% HF. This procedure removes extraneous argon from whole-rock samples. Samples also were boiled in water for 12 h before loading them into an ultra-high-vacuum fusion-extraction system for collection of argon. This procedure inhibits adsorption of atmospheric ^{40}Ar, and hence 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 *et al.*, 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 analysis. Radioactive-decay constants and abundance of ^{40}Ar are from Steiger and Jager (1977).

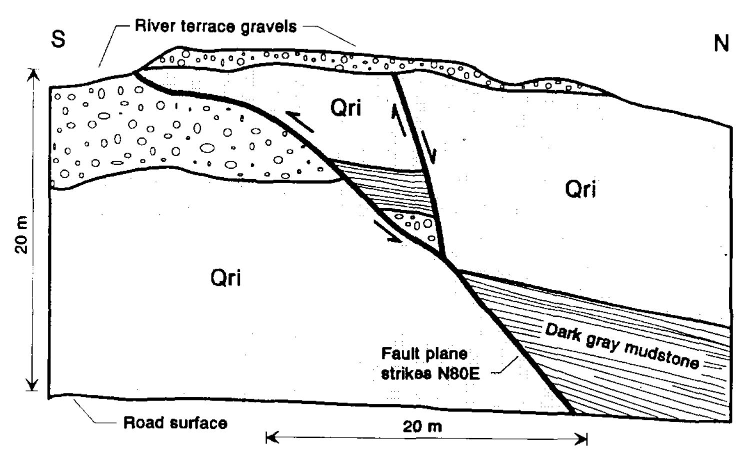


Fig. 4. Sketch of road cut showing reverse fault across Quaternary ignimbrite (map unit Qri), which is thrust over younger terrace gravels of the Río Los Esclavos. Horizontal and vertical scales are equal.

many faults that exhibit strikes of northwest, north–south, and northeast. Most of these are interpreted to be steeply dipping normal faults; strike varies only little along traces that cross rugged terrain. Actual field exposures of fault planes are rare.

Lines of warm mud volcanoes located 1 km west of Ixpaco crater, fissures from which hot springs issue along the banks of the Río Los Esclavos, and the alignment of some volcanic vents including those of Tecuamburro Volcano and two adjacent domes, all follow the northwest fault trend. Moreover, a northwest-oriented resistivity anomaly suggests that a fault of this trend passes through Ixpaco crater (Hoover and Pierce, 1990), and a northwest-trending fault that passes about 2 km north of Ixpaco crater may act as an aquaclude between two hydrothermal-convection systems (Janik *et al.*, 1990). Thus, consideration of northwest-trending faults is judged to be very important in assessing the geothermal potential of the area.

The Tecuamburro graben contains several volcanic craters of various sizes and origins, most of which are expressed as arcuate to circular, asymmetric topographic ridges steep to the concave side. The apparently oldest of these structures, in the north–central part of the map area (Fig. 3, map units QTapg and Qae), are greatly modified by faulting and erosion. These arcuate ridges are interpreted to focus on central-vent areas, although the present escarpments likely are not constructional vent features.

A several kilometer wide crater, developed in map unit Qam and informally called Miraflores, formed in response to collapse of the northeast sector of a nearly 2 km high stratovolcano. Upward projection of the dip of lava flows on the remaining volcano flanks suggests that the pre-collapse summit was approximately centered over the area that collapsed. The cause of collapse is uncertain; we recognize no juvenile magmatic products associated with the collapse deposit. Strong earthquake shaking and weakening of the edifice through hydrothermal alteration, both of which are common in active volcanic regions, might have contributed to collapse.

The distribution of the debris-flow deposit (Fig. 3a, unit Qavm) indicates that collapse material flowed eastward across the valley of the Río Los Esclavos, and that the leading edge of the debris lobe rode at least 4 km up onto the west-dipping flank of the adjacent Ixhuatán volcanic complex (Fig. 3, unit QTai). After temporary blockage of unknown duration, the Río Los Esclavos subsequently reestablished a channel through the collapse debris, and the generally noncohesive material thus exposed in steep river-valley walls has given rise to many landslides, some active during the 20th century (written communication, Randall White, U.S. Geological Survey).

An approximately 5 km wide and 150 m deep quasi-circular depression, informally called Chupadero, is a morphologic feature whose origin is uncertain. We tentatively suggest that it formed by collapse in response to eruption of a cubic kilometer or two of pyroclastic materials depicted as map unit Qai (Fig. 3). The distribution of erosional remnants of the fallout component of this unit roughly focuses on Chupadero crater, and these deposits are thickest and coarsest grained on hillsides adjacent to the crater.

Ixpaco crater is the product of phreatic eruptions, and a tuff ring built around the crater consists of hydrothermally altered fragmental debris that is tentatively identified as reworked pyroclasts of the eruption that led to the formation of Chupadero crater. The position of the tuff ring in the east–central part of Chupadero crater along a northwest-trending electrical anomaly (Hoover and Pierce, 1990) suggests the possibility of serial eruptions through a single vent or fissure-controlled vent system that first carried magma and later carried steam.

The youngest volcanic craters in the Tecuamburro graben are associated with Tecuamburro Volcano and onlapping lava domes, all of which grew within Miraflores crater. These include a constructional closed depression 300 m wide that marks the vent of Tecuamburro Volcano and escarpments of similar size that apparently mark the headwalls of local collapse structures originating on the flanks of the onlapping domes (Fig. 3; Duffield *et al.*, 1991).

RADIOMETRIC AGES

Stratigraphic succession indicated by field relations is summarized in Fig. 3. Some age assignments are equivocal, and some adjacent vent areas may have had overlapping periods of activity; but broadly speaking, vents and associated eruptive products within the Tecuamburro graben are progressively younger toward the south. Andesitic complexes that flank and partly occupy the graben to the east (Fig. 3, unit QTai) and west (Fig. 3, unit QTap) 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 (Table 1) are generally consistent with field-defined stratigraphy. The five oldest ages, 2.6 ± 0.3 Ma, 1.16 ± 0.050 Ma, 1.18 ± 0.080 Ma, 0.821 ± 118 Ma and 0.800 ± 0.061 Ma, were determined for rocks from the graben-flanking units QTai and QTap, and from the part of the graben north of Tecuamburro Volcano (units Qas and Qae). In the south-central part of the graben, the age of a stratovolcano (unit Qam) that is considered to be ancestral to Tecuamburro, on the basis of colocation of vents, is about 0.1 Ma. As described above, this volcano was modified by sector collapse, and this event was followed by the emplacement of pyroclastic deposits (unit Qai) at 38.3 ± 1.0 ka, in turn followed by the growth of Tecuamburro Volcano and onlapping domes within the crater formed by sector collapse. Tecuamburro Volcano and onlapping domes are too young to yield accurate K–Ar ages, but their calculated ages (Table 1) are consistent (within associated uncertainties) with the ^{14}C age of 38.3 ka for a charcoal log collected from the underlying pyroclastic deposits.

Monogenetic basaltic vents and genetically associated lava flows along the Jalpatagua fault zone within the north and northeast parts of the map are inferred to represent the youngest magmatic eruptions in the study area. These lavas overlie all rocks with which they are in contact and have yielded a K–Ar age of 0.036±0.064 Ma. The Jalpatagua fault offsets some of these young rocks.

Perhaps the youngest eruptions in the area, though phreatic rather than magmatic, were those that formed Ixpaco crater. This phreatic activity produced a 25 m high tuff ring whose topographic rim delineates a 1 km diameter circle. An organic-rich layer a few centimeters thick within the tuff ring has yielded a ^{14}C age of 2.91 ± 0.07 ka (Table 1), and the presence of this layer indicates a hiatus in tuff-ring growth long enough for vegetation to become established. Interestingly, a debris avalanche, whose source is one of the lava domes (Fig. 3b, unit Qdpb) of <38.3 ka, buries the southern part of the Ixpaco tuff ring. Thus, dome growth and daughter avalanche both could be younger than 2.91 ka; alternatively, the avalanche might have been triggered by an event (earthquake?) unrelated to the growth of the dome, in which case the age of the dome is greater than 2.91 ka and less than 38.3 ka.

PETROLOGY AND FIELD RELATIONS

With the exception of local, small-volume deposits of alluvium and lacustrine beds, most of the Tecuamburro area is underlain by varieties of pyroxene-bearing andesite. Complexly twinned and zoned plagioclase is a nearly ubiquitous 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. SiO_2 concentration for all rocks within the study area ranges from about 50 to 72% (Table 2) and represents a weakly calcic suite (Fig. 5) according to the classification of Peacock (1931).

Silicic rocks are restricted to rhyodacitic ignimbrites that partly fill valleys along the west side of the Tecuamburro graben and along the course of the Río Los Esclavos. Small fault-bounded inliers of quartz-phyric rocks also crop out near the river.

Table 2. Whole-rock chemical analyses of unaltered volcanic rocks from the Tecuamburro Volcano area. Analyses are recalculated to 100% on a volatile-free basis. Sample numbers are printed on Fig. 3 at collection localities

	Map unit/sample number							
	Qb/4	Qb/16	Qdpb/1	Qasf/17	Qat/18	Qat/19	Qat/2	Qat/20
SiO_2	49.63	56.00	63.71	57.86	52.76	53.62	53.41	60.61
TiO_2	1.32	1.09	0.54	0.78	0.90	0.80	0.78	0.65
Al_2O_3	18.11	17.27	16.50	20.27	19.48	18.45	18.93	17.46
Fe_2O_3	10.12	8.77	5.98	8.56	10.31	8.90	8.61	6.95
MnO	0.16	0.13	0.15	0.17	0.18	0.16	0.15	0.14
MgO	7.00	3.79	2.35	3.49	4.55	5.15	4.95	2.83
CaO	9.53	8.98	5.70	4.99	8.35	8.97	9.02	6.25
Na_2O	3.05	2.99	3.63	3.14	2.86	3.22	3.43	3.74
K_2O	0.78	0.75	1.33	0.65	0.45	0.56	0.56	1.23
P_2O_5	0.30	0.24	0.10	0.09	0.14	0.16	0.16	0.13
LOI			*0.16					
Total	100.01	98.23	99.98	97.25	98.57	98.78	99.63	99.10

	Qai/21	Qai/22	Qai/23	Qai/24	Qai/25	Qai/26	Qri/27	Qri/28
SiO_2	56.52	59.76	60.03	60.41	62.07	62.32	68.44	71.70
TiO_2	0.81	0.66	0.68	0.61	0.58	0.59	0.49	0.33
Al_2O_3	18.65	19.74	18.65	17.80	17.56	17.54	15.87	15.18
Fe_2O_3	8.37	7.54	7.56	6.84	6.38	6.64	3.71	2.50
MnO	0.17	0.14	0.13	0.14	0.12	0.14	0.10	0.08
MgO	3.31	2.88	3.32	2.72	2.77	2.53	0.96	0.50
CaO	7.54	5.27	5.85	6.78	5.89	5.61	2.89	1.84
Na_2O	3.69	2.91	2.90	3.48	3.28	3.31	3.81	3.88
K_2O	0.74	0.99	0.73	1.08	1.22	1.24	3.63	3.90
P_2O_5	0.20	0.10	0.13	0.13	0.12	0.06	0.09	0.07
LOI				*1.97				*3.49
Total	99.08	96.84	99.25	98.32	97.38	97.53	97.20	95.54

	Qap/29	Qap/30	Qam/8	Qas/9	QTapg/31	QTai/11	n.a./32
SiO_2	60.52	61.99	56.49	57.48	65.01	57.12	75.00
TiO_2	0.60	0.61	0.73	0.71	0.52	0.59	0.13
Al_2O_3	18.66	18.01	18.22	18.20	17.06	18.53	14.70
Fe_2O_3	6.91	6.36	8.47	8.00	15.51	8.10	1.32
MnO	0.14	0.13	0.18	0.14	0.11	0.18	—
MgO	3.27	2.88	3.35	3.19	1.72	2.51	0.10
CaO	5.32	5.34	7.80	7.63	4.48	6.81	0.82
Na_2O	3.43	3.40	3.71	3.25	3.18	4.59	4.20
K_2O	1.04	1.16	0.85	1.27	2.29	1.27	3.70
P_2O_5	0.10	0.11	0.19	0.12	0.11	0.30	0.03
LOI							
Total	99.06	98.75	99.92	99.29	97.60	100.14	

Notes: Analyses by X-ray fluorescence, at U.S. Geological Survey, Menlo Park, CA (*), or at Los Alamos National Laboratory. Total is original analytical total, without volatiles. LOI is loss on ignition at 900°C. Sample n.a./32 was collected from the Tapalapa ash flow of Ayarza Caldera (see Peterson and Rose, 1985, Table 5). Samples Qai/21, 22 and 25 are from the fallout component of this unit, which is not mapped separately in Fig. 3. — = no data.

Pliocene

Map unit Tqu. Quartz-bearing volcanic rocks form two small outcrops in the northeast part of the map area (Fig. 3). These outcrops are partly bounded by normal and reverse faults and are stratigraphically overlain by basalt lava flows (unit Qb) and rhyodacitic ignimbrite (unit Qri). Age relations with other rocks in the study area are unknown, but we infer that these outcrops are upfaulted blocks of a Tertiary basement complex possibly correlative with the Miocene Padre Miguel Group of Williams and McBirney (1969).

The mineralogy of these quartz-bearing rocks in the Tecuamburro graben and a pervasive hydrothermal alteration and silicification that affects them are distinct from features of the younger rocks of the area. Rock types include felsic porphyry and rhyolitic ignimbrite. A particularly coarse-grained porphyry superficially resembles granite and was mapped as such by earlier investigators (Beaty *et al.*, 1980). This rock consists of $\approx$10% euhedral to anhedral quartz ($\leq$2 mm), $\approx$25% euhedral plagioclase and K-feldspar ($\leq$2 mm), and $\approx$5% hornblende and biotite phenocrysts. The feldspars and groundmass are completely altered to clays.

Rhyolitic ignimbrite contains $\approx$15% rounded and embayed quartz phenocrysts up to 3 mm long, lesser amounts of broken and altered feldspar phenocrysts, and a few percent hornblende. Devitrified groundmass exhibits relict compacted shard texture. These rocks may be part of a widespread sequence of Tertiary silicic volcanics commonly found behind the active volcanic arc in Guatemala (Carr, 1984). Thus, these rocks may be representative of the Tertiary basement underlying the younger andesitic sequence of the Tecuamburro region.

Pliocene and Pleistocene

Map unit QTap. Rocks of this unit are thought to represent lavas erupted from two neighboring central vents, both located immediately west of the Tecuamburro graben and most of whose products lie west of the map area (Fig. 3). A K–Ar age of 2.6 ± 0.3 Ma (Table 1) for a lava flow in the northern part of this map unit is interpreted to be the age of some of the oldest rocks. Rocks adjacent to the southwest form a reasonably well preserved stratocone shape and are probably Pleistocene in age. A dike that cuts this younger-looking sequence has yielded a K–Ar age of 0.821 ± 0.118 Ma (Table 1, sample 12).

The relatively youthful-looking stratocone is more than 10 km wide at its base and has in part been downfaulted and buried beneath younger ignimbrite along the west edge of the Tecuamburro graben. The summit area has been modified by collapse that produced an amphitheater-shaped crater open to the east. The village of Pueblo Nuevo Viñas is built on hummocky terrain of collapse breccia within the amphitheater.

Lavas are of two main phenocryst types: (1) oxyhornblende-bearing andesite and dacite, and (2) two-pyroxene andesite. Each type contains $\approx$20% plagioclase phenocrysts. Dacite typically contains $\approx$20% quartz, 5% oxyhornblende, and 1% hypersthene phenocrysts.

Map unit QTai. Rocks of this unit are part of a 15 km wide and 1 km high shield-shaped highland that is centered a few kilometers east of the map area. Beaty and others (1980) named this group of rocks the Ixhuatán complex. The summit area of this highland is cut by many north-trending, west-dipping normal faults that mark the east side of the Tecuamburro graben. Fault scarps only little eroded and tens of meters high are common. These are within the epicentral area of 1979–1980 crustal earthquakes mentioned earlier.

The southwesternmost exposures of this map unit, along the Río Los Esclavos, are massive gray porphyritic andesite lavas (Tables 1 and 2, sample 11). These lavas contain $\approx$35% of the phenocrysts plagioclase, pigeonite and Fe–Ti oxides, in descending order of abundance. Upstream, roughly east of Tecuamburro Volcano, laharic breccias and some silicic pyroclastic rocks are interbedded with andesitic lavas. Outcrops within the highlands, just outside the map area, consist mostly of mafic lava flows, scoria cones, and breccia. These rocks contain hopper-shaped plagioclase phenocrysts and as such are petrographically unique within the study area.

The K–Ar age of an andesite lava flow along the Río Los Esclavos is 1.16 ± 0.050 Ma (Table 1, sample 11). We suggest that the entire Ixhuatán complex is of similar early Pliocene or late Pleistocene age. Most outcrops in the highlands are deeply weathered. A tuff with relict outlines of plagioclase, hornblende, and biotite phenocrysts is exposed locally there; this tuff is petrographically similar to the rhyodacite ignimbrite in the map area (unit Qri) but is much more deeply weathered.

Map unit QTapg. Rocks of this unit occupy the north-central part of the Tecuamburro graben. Though highly eroded and faulted, this map unit is interpreted to be a sequence fed from a single central vent area, now marked by arcuate escarpments (Fig. 3). The unmodified volcanic edifice apparently was at least 7 km wide at the base and rose a km or so above its surroundings.

Much of the rock sequence is hydrothermally altered, most extensively in the western half of the map-unit area. Analyses by X-ray diffraction techniques indicate that alteration products include smectite, opal CT, tridymite, cristobalite, and pyrite. A single fumarole in this area may represent a waning-stage vestige of a hydrothermal-convection system responsible for the alteration.

We found no rocks fresh enough for radiometric-age determination, but some of the lavas apparently interfinger with rocks to the south (unit Qae) that are about 1.2 Ma. Most of unit QTapg is believed to be somewhat older than this. All other onlapping rocks are ≤0.8 Ma.

The most common rock types are two-pyroxene andesite lavas and derivative laharic breccias; welded dacitic tuff and dacite lavas also crop out locally. The welded tuff contains ≈14% plagioclase (≤3 mm), 7% oxidized hornblende (≤3 mm), 4% sanidine (≤0.4 mm), 2% Fe–Ti oxides, and a trace of orthopyroxene as phenocrysts.

Pleistocene

Map unit Qae. Similar to adjacent unit QTapg, this unit is interpreted to be a faulted and eroded volcanic edifice that was fed from a central vent area now marked by arcuate escarpments (Fig. 3). A mafic lava flow has yielded a K–Ar age of 1.180 ± 0.080 Ma (Table 1, sample 10). Onlapping rocks to the west, south and east are all ≤0.8 Ma.

The rocks of this map unit are basaltic andesite lava flows and derivative laharic breccia. Most contain ≈30% plagioclase (≤3 mm long), 2–8% hypersthene (≤1 mm), and 1% pigeonite (≤1.5 mm) phenocrysts. Hyalopilitic groundmass is common and is partly devitrified; clinopyroxene and plagioclase microlites locally exhibit trachytic texture. A few of the lavas contain as much as 2.5% olivine, and some others contain ≈4% hornblende phenocrysts.

Map unit Qas. Rocks of this unit consist of two slightly faulted and moderately eroded scoria cones built around vents that produced a field of surrounding interfingering lava flows. These rocks are andesites of uniform 57–58 wt% SiO_2, and they generally contain ≈25% plagioclase (≤2 mm), 1–2% clinopyroxene (≤0.5 mm), 1% Fe–Ti oxides, and a trace of olivine; groundmass is commonly pilotaxitic.

The north part of Chupadero crater is formed in these rocks. Several meters of fallout pumice of map unit Qai covers most of the crater rim in this area. A sample collected from an outcrop protruding through this cover has yielded a K–Ar age of 0.800 ± 0.061 Ma (Table 1, sample 9).

Map unit Qam. Rocks of this unit represent a wide stratovolcano, or two closely spaced overlapping stratovolcanoes, whose summit area was lost when the northeast sector of the edifice collapsed. The basal diameter of this edifice is about 14 km, and the original summit probably rose at least 2 km above adjacent terrain. Upward projection of lava flows on the upper flanks of the present edifice suggests that the uppermost 400 m was lost during collapse, which resulted in the formation of a 5–6 km wide amphitheater open to the eastnortheast. The rim at the headwall of this collapse structure, informally called Miraflores crater, is a topographically-high, little-eroded landform; the amphitheater has been subsequently almost filled with lava domes and flows that include Tecuamburro Volcano. The vents for these post-collapse rocks and that of the pre-collapse stratovolcano all lie within a circular area of about 1 km radius.

This map unit apparently consists entirely of andesite. Lava flows predominate on the steep upper flanks, and derivative laharic breccia predominate below elevations of about 700–800 m, where a distinct break in slope locates a change to gently inclined lower flanks. The lavas contain $\approx$45% phenocrysts, which are mostly plagioclase accompanied by subordinate hypersthene and Fe–Ti oxides. Three samples of lava flows have yielded K–Ar ages of 0.108 ± 0.045 Ma, 0.094 ± 0.263 Ma, and 0.131 ± 0.039 Ma (Table 1, samples 6, 7, 8).

Map unit Qavm. Rocks of this unit form the debris avalanche that originated from the collapse of the northeast sector of the stratovolcano represented by unit Qam. The avalanche deposit lies directly east of its source area, and is expressed as an eastward tapering lobe of hummocky-surfaced ground. It flowed across the canyon of the Río Los Esclavos and advanced at least 4 km up the west dipping flank of the Ixhuatán volcanic complex.

The avalanche deposit is about 3 km at its widest and 250 m at its thickest, both dimensions exposed along the east bank of the Río Los Esclavos. A significant part of the deposit has been eroded since emplacement; the apparent size and shape of the source region suggest that as much as 5 km^3 of the volcano was removed during collapse, although this volume is quite uncertain because the original shape of the amphitheater is obscured by Tecuamburro Volcano and adjacent domes. The present volume of the debris avalanche is about 2 km^3.

The age of the avalanche is constrained by the age of the source stratovolcano, about 0.1 Ma, and the age of overlying pyroclastic rocks, about 38 ka. Furthermore, enough time had to elapse between emplacement of the debris avalanche and that of the overlying pyroclastics for the Río Los Esclavos to erode a deep canyon through the avalanche deposit. The pyroclastic rocks include both pumice-fallout and ignimbrite components; fallout mantles the surface of the debris avalanche whereas ignimbrite was channelled southward by the river canyon where it crosses the avalanche and then spilled laterally over river terraces downstream of the avalanche.

As mentioned earlier, the relatively non-cohesive avalanche deposit, where deeply incised by the river, is the source of a system of historically active landslides that slip downward toward the river. The headwalls of the landslides provide the best views into the debris avalanche, although most of these exposures are inaccessible by foot because they are tens of meters high and nearly vertical. Accessible outcrops are mostly sequences of andesite lava flows and interlayered andesite breccia. Locally such sequences are about horizontal and essentially intact over distances of tens of meters, as though only minor jostling occurred during avalanche emplacement. Elsewhere, randomly tilted blocks tens of meters long reflect considerable disruption during emplacement.

Examples of sector collapse of stratovolcanoes are common in the geologic record. A thoroughly documented historic event of this sort occurred at Mount St. Helens, WA, in 1980 (Voight *et al.*, 1981; Siebert, 1984), and a prehistoric example at Mount Shasta, CA, was described by Crandell and others (1984). Sector collapse may result from (1) deformation and oversteepening of volcano slopes by magma intrusion, (2) structural weakening of a volcanic edifice by hydrothermal alteration, (3) earthquake shaking, or a combination of these factors.

A hummocky surface is characteristic of sector-collapse deposits. Hummocky terrain is common along the inland part of the Pacific coastal plain of Guatemala and is likely a reflection of many collapse events originating from the line of active stratovolcanoes that forms the adjacent Guatemalan volcanic chain. The avalanche from stratovolcano Qam did not reach the nearby coastal plain, apparently because it was directed eastward instead of southward.

Map unit Qap. Rocks of this unit crop out only within Miraflores crater. Although comprising a distinctive constructional volcanic landform with quaquaversal dip radiating from the same vent area as that of some other lava domes in Miraflores crater, outcrops are few because of almost complete burial by the fallout component of map unit Qai. Available outcrops are andesitic lava flows that contain ≈40% phenocrysts of plagioclase and subordinate orthopyroxene. These lavas apparently were the first products of eruptions within Miraflores crater following sector collapse and crater formation.

Map unit Qri. North-trending valleys that flank the volcanic centers within the Tecuamburro graben are partly filled by rhyodacitic ignimbrites and subordinate fallout of the same lithology. Emplacement units of ignimbrite are from a few to several meters thick; all are nonwelded. Pyroclasts are pumice lapilli in an ash matrix, and sparse xenoliths are andesite, basalt and siltstone.

Vesicles of the pumice lapilli characteristically are tube shaped. Thus, shards of the ash matrix tend to be needle shaped. In descending order of abundance, phenocrysts are plagioclase, sanidine, biotite, Fe–Ti oxides, and hornblende. Total phenocryst content ranges from ≈2% to 10%.

Mean pumice size (≈15 cm) is greatest in the western part of the area, which is consistent with the interpretation that these pyroclastic deposits are products of caldera-forming eruptions at Amatitlán, ≈50 km to the northwest. Moreover, outcrops of this map unit can be traced almost continuously from the northwest part of the Tecuamburro graben back to

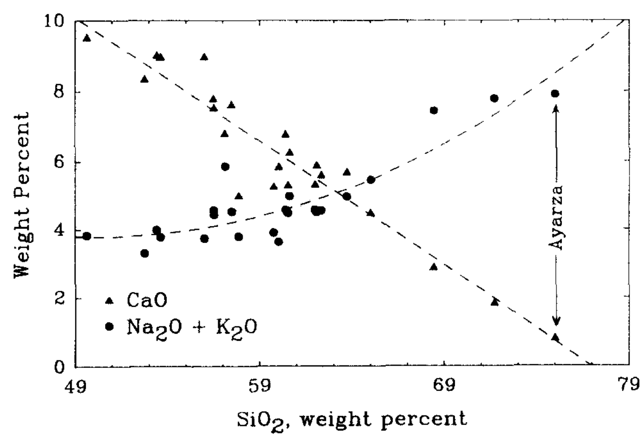


Fig. 5. Silica versus CaO and versus $K_2O + Na_2O$ for analyses of Table 2. Curves are best-fit regressions for quadratic functions, and their intersection at about 63% SiO_2 indicates a calcic rock series in the classification of Peacock (1931).

Amatitlán Caldera. The deposits along the valley of the Río Los Esclavos, in the east part of the Tecuamburro graben, are interpreted to have been emplaced by flow southeastward from Amatitlán over an intervening drainage divide, or alternatively by flow along a valley now filled by basaltic lavas that post-date the ignimbrite. Petrographically and chemically, the unit Qri material is similar to several caldera-related Amatitlán deposits described by Wunderman and Rose (1984). The only other possible source area in the Tecuamburro region is Ayarza Caldera (Fig. 2), but Ayarza outflow is distinctly more silicic than the pumice of unit Qri (Fig. 5).

Ignimbrite of map unit Qri is overlain by 38.3 ka pyroclastic deposits of unit Qai. At the only known exposure of the contact, the two are separated by a well developed soil about 2 m thick. Rocks of youngest known age that underlie unit Qri are 0.1 Ma (Fig. 3, unit Qam). These age constraints are consistent with a source for unit Qai from Amatitlán Caldera (Wunderman and Rose, 1984), and inconsistent with a source from the 27 to 23 ka Ayarza Caldera (Peterson and Rose, 1985).

Map unit Qai. All rocks of this unit are pyroclastic, and they include components emplaced by surge, fall, and flow mechanisms. Surge deposits are volumetrically minor. Estimations of the erupted volumes of fall and flow deposits are highly uncertain, mostly due to uncertainties about what volumes have been eroded. Nonetheless, present outcrops suggest roughly comparable volumes were emplaced by fall and flow, and that the two account for at least 1 km^3 ($\approx$0.5 km^3, dense rock equivalent). This is a rather large volume if associated with an eruptive cycle that culminates in the growth of a lava dome the size of those present in the Tecuamburro area (Heiken and Wohletz, 1987). However, the volume is reasonable for the associated formation of a collapse crater the size of Chupadero (Fig. 3).

Erosional remnants of the fallout component are widely distributed within a 12 km wide, roughly circular area, which is centered on the area of Chupadero crater and Tecuamburro Volcano. The thickest fallout sections are $\approx$4 m and are located on hills that form the north and south inward-facing slopes of Chupadero crater. The distribution of fallout permits the possibility of a source vent now buried beneath Tecuamburro Volcano and onlapping lava domes. While this possibility violates no known stratigraphic and geographic constraints, we tentatively conclude that Chupadero crater marks the vent for and in fact formed as a result of the eruption of this material.

In addition to some uncertainty about the location of the vent for this map unit, there is also uncertainty about the period of time represented by the deposits. We infer that very little time is represented, because no soil horizons, stream channelling and the like have been observed within the unit. Moreover, at most outcrops with substantial amounts of both fallout and flow deposits, the fallout is the initial phase, as though a single eruption went through a fall-to-flow evolution. A few centimeters of fallout also is present locally between pyroclastic flows.

The fallout component of this map unit is the only widespread stratigraphic marker bed in the study area and as such is the key to establishing many stratigraphic relations. Moreover, the ^{14}C age of 38.3 ka for a log recovered from this map unit provides the only numerical age constraint to several over- and underlying rock units. Magmatic eruptions known to postdate this map unit are those of Tecuamburro Volcano and adjacent onlapping lava domes.

Pyroclastic flows are distributed from near Laguna Ixpaco, eastward to the course of the Río Los Esclavos, and southward along the river valley to the Pacific coastal plain. They are thickest, as much as 150 m, where exposed in the walls of the river valley, presumably because they were channelled by and ponded in this valley during emplacement.

Vesicularity is $\approx$65% for pumice of the fallout deposits and $\approx$35% for the flow deposits.

Vesicles are spherical to ovoid. In descending order of abundance, phenocrysts include plagioclase, orthopyroxene, clinopyroxene, and Fe–Ti oxides (all ≤ 2 mm), and phenocrysts amount to about 20 volume percent. Whole-rock silica ranges from about 57 to 62 weight percent (Table 2). As much as a percent or two of andesite-lava lithic clasts are present locally.

Map unit Qat. Rocks of this unit are the eruptive products of two vents that form northwest-aligned prominences about 1 km apart (Fig. 3b). One of these vents, Tecuamburro Volcano, attains an elevation of 1680 m and is indented by a 40 m deep and 300 m wide constructional crater at the summit. Cerro El Soledad, the other vent, has an elevation of 1845 m, lacks a summit depression, and exhibits a partly covered north-facing escarpment that reflects partial collapse of the summit area immediately before the youngest eruptions there built the present peak. Though evidence from field exposures is equivocal, apparent age relations revealed in aerial photographs suggest that the vent of Tecuamburro Volcano was the more recently active of the two.

The upper elevations of this map unit are mostly andesitic lava flows whereas laharic breccia, scoria, and subordinate lithic tuff with accretionary lapilli crop out at lower elevations. Though our samples may not be representative of the entire compositional range of products from the two vents, they suggest that lavas erupted from El Soledad vent are a bit more mafic than those from Tecuamburro, $\approx 53\%$ versus $\approx 60\%$ SiO_2, respectively. All of the lavas contain $\approx 45\%$ phenocrysts (≤ 3 mm), mostly plagioclase and lesser amounts of clinopyroxene, and orthopyroxene, $\pm$minor olivine. These rocks overlay the pyroclastics (unit Qai) whose ^{14}C age is 38.3 ka.

Map unit Qasf. Rocks of this unit form a 400 m wide and 100 m high lava dome partly surrounded by a tuff ring, which apparently represents an initial pyroclastic phase of the dome-building eruption. This dome partly fills a somewhat older 1 km wide crater developed in map units Qap and Qat (Fig. 3). The floor of this crater southeast of the dome is the site of weak fumaroles depositing sublimates, which were once mined for sulfur.

The dome lava is vesicular, flow-banded, porphyritic andesite that contains as much as 45% phenocrysts of plagioclase, clinopyroxene, orthopyroxene, and Fe–Ti oxides, in descending order of abundance. Traces of hornblende are apparent in some thin sections, and groundmass exhibits a glassy diktytaxitic texture.

Map unit Qdpb. Rocks of this unit are a 1.5 km wide dacite lava dome, informally called Peña Blanca, that rises about 300 m above its surroundings. This dome partly covers that of map unit Qasf and partly fills the crater in which the vents for both domes are located.

The dome lava is massive, light gray dacite containing $\approx 50\%$ phenocrysts of plagioclase, hypersthene, and hornblende in a glassy matrix. The hornblende occurs as glomeroporphyritic clots with plagioclase and hypersthene and is pleochroic in shades of deep red, unique for studied rocks of the area. At about 64 weight percent SiO_2, this rock is the most evolved of the post-38.3 ka cluster of lavas within Miraflores crater.

Repeated partial collapse of the north face of Peña Blanca dome produced at least two debris avalanches (Fig. 3b, unit Qavpb). Evidence of this history is seen in a 1 km wide north-facing headwall escarpment and avalanche deposits of lobate outline that extend about 2–3 km from the source area. Steep, sharply defined margins and hummocky surfaces indicate that these deposits are geologically young. As discussed in an earlier section, ^{14}C age constraints indicate that at least one is ≤ 2.9 ka. Feeble, yet sulfur-depositing fumaroles are located at the base of the headwall escarpment, which is nearly vertical.

Map unit Qtr. Deposits of this unit form a phreatic tuff ring whose enclosed depression is partly filled by Laguna Ixpaco and whose southern sector is buried by a debris avalanche from Peña Blanca lava dome. Though few outcrops are available for examination, a change from inward to outward dip of tuff beds occurs at about the present topographic rim of the tuff ring where exposed locally in road cuts.

Man-made exposures also reveal two sequences of tuff beds, separated by an organic-rich zone a few centimeters thick. The organic material has yielded a ^{14}C age of 2.9 ka (Table 1, sample 14). Both the upper and lower tuff sequences are thoroughly hydrothermally altered. Alteration minerals include smectite kaolinite, halloysite, jarosite, alunite, pyrite, and cristobalite. Many fumaroles along the shore of Laguna Ixpaco are evidence that alteration continues.

Lapilli and larger clasts were collected from the tuff beds to examine relict textures. Enhanced images by scanning electron microscopy reveal many pumice pyroclasts with $\approx$45% vesicles of round to ovoid shapes; subordinate amounts of porphyritic (andesitic?) lithic clasts and relict plagioclase(?) and pyroxene(?) phenocrysts also were identified. These features are compatible with our interpretation that the tuff beds represent principally pumice of map unit Qai, reworked by phreatic explosions and subsequent alteration in a fumarolic acid environment.

Map Unit Qb. Rocks of this unit include several scoria cones that mark vents and a field of interfingering basalt lava flows fed from the vents. These rocks are all within or adjacent to the Jalpatagua fault zone, a relation that extends northwest and southeast outside the map area.

The basalt lavas overlie all rocks with which they are in contact. A single K–Ar age is 0.036 $\pm$ 0.064 (Table 1, sample 4). The scoria cones are only little-eroded, and minimal soil has developed on the surfaces of the cones and flows. We speculate that all of this basalt is Holocene.

The lava flows appear fairly uniform in the field. They contain about 10–34% phenocrysts of plagioclase, clinopyroxene, olivine, and Fe–Ti oxides in a trachytic to diktytaxitic groundmass.

Unit Qb locally includes inliers of Tertiary andesite (Duffield *et al.*, 1991), which are not depicted separately here (Fig. 3).

DISCUSSION

A principal aim of our study was to try to identify high-temperature geothermal resources capable of being developed to generate electricity. Thus, a controlling premise is that the heat source probably is a magma body in the crust. Basalt that crops out along the Jalpatagua fault zone apparently is the youngest volcanic rock in the study area, but this zone is not considered very promising for high-enthalpy geothermal energy. Basalt along the Jalpatagua fault zone is volumetrically minor and intrusions, as indicated by vent locations, are not geographically focused, which is unlike the situations in Iceland and Hawaii, where high-temperature geothermal systems are supported by frequent intrusions and eruptions of basaltic magma that are structurally focused within rift zones. Moreover, such derivative evolved lavas as dacites and rhyolites have not been erupted in the Jalpatagua fault zone, which suggests a lack of crustal magma reservoirs as heat sources; the basaltic magma probably rose quickly from a mantle source to sites of eruption, undergoing little or no interaction with the crust. In addition, the few thermal manifestations here are feeble and indicate only relatively low subsurface temperatures (Janik *et al.*, 1990).

In contrast, relations among age, composition, and volume suggest that the crust beneath Tecuamburro Volcano and Chupadero crater likely contains a reservoir of magma. Conservative interpretation suggests that all of the volcanic rocks $\leq$0.1 Ma within the south part of the Tecuamburro graben were erupted from closely spaced vents. Vents for units Qam, Qap, Qat, Qasf, and Qdpb lie within a 2 km wide circle, and that for unit Qai is only about 3 km away, if our interpretation that Chupadero crater is the vent for unit Qai is correct. This close spacing of vents active during such a geologically brief period of time implies continuous residence of a body of magma within the crust beneath the vent area.

Independent evidence for this implied magma body is suggested by changes in magma composition with time (Fig. 6). For rocks in the south part of the Tecuamburro graben that are $\leq$0.1 Ma, SiO_2 and K_2O vary in cyclic fashion and attain their maximums of 63.7 wt% and 1.3 wt% in rocks in the Peña Blanca dome, the youngest magmatic eruption of the area and the only rock with much hornblende as phenocrysts. Compositional ranges within individual eruptive units could represent zonation of the magma reservoir at the time of eruption. Longer-term variation, during a period of about 100,000 years, could reflect a secular trend caused by fractionation within a single magma reservoir, with or without periodic input of relatively primitive mantle-derived magma into the base of the reservoir. The crustal thermal regime implied by volume and age relations of the volcanic history also suggests the possibility that a single reservoir has existed beneath the Tecuamburro area during that past 0.1 Ma or so.

Smith and Shaw (1979) calculated cooling times for bodies of magma in the crust as functions of their initial temperatures and volumes. They also summarized evidence for a model of crustal magma reservoirs whose ratio of intrusive to extrusive volumes is about 10:1. We conservatively estimate that 50 km^3 of magma was erupted in the Tecuamburro area during the past 0.1 Ma, and that several cubic kilometers of this was erupted since about 38 ka. Through the evaluation procedures suggested by Smith and Shaw (1979), these volumes and ages are consistent with the presence of hot plutons, if not magma, in the crust beneath the area today. This situation is illustrated in cross section (Fig. 7). The mutually offsetting thermal effects of quasi-periodic input of magma into the base of a crustal reservoir and of quasi-continuous hydrothermal convection within the upper part of the reservoir and surrounding country rocks cannot be quantitatively evaluated. Nonetheless, independent evidence from vapor and hot-water geothermometry (Janik *et al.*, 1990; also this volume) indicates a crustal heat source which supports

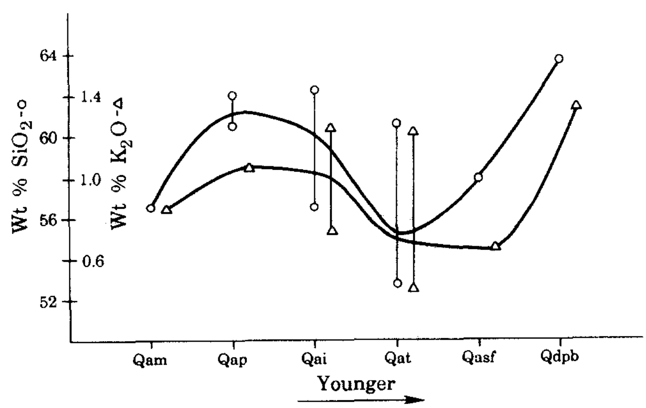


Fig. 6. SiO_2 and K_2O versus time for the six youngest magmatic map units of the Tecuamburro area. Chemical data from Table 2. Vertical lines show ranges within map units, and curves are visual best fits that pass through means. Map units are arbitrarily spaced equally in time, for lack of better numerical age constraint. Total time represented is about 100,000 years.

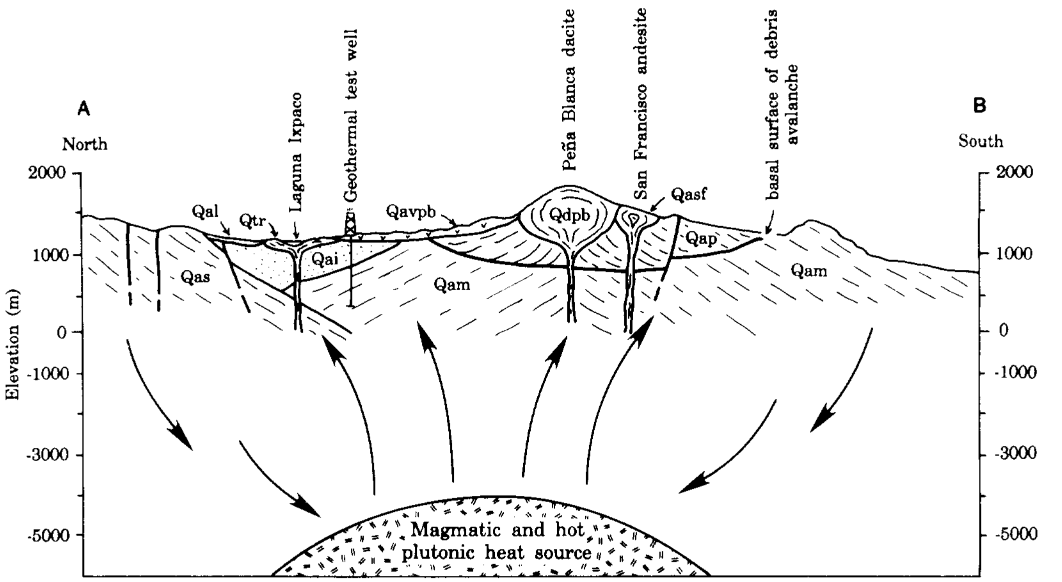


Fig. 7. Cross section through area of youngest volcanism and highest chemical-geothermometer temperatures (see Fig. 3b for approximate location, and Duffield *et al.*, 1991, for exact location). Quaternary alluvium (Qal) south of the lava dome of map unit Qasf not shown on section. Magmatic heat source and overlying hydrothermal-convection system shown schematically. Note change in vertical scale at sea level; above sea level, horizontal and vertical scales are equal. For a more detailed view of possible configuration of hydrothermal system, see Janik *et al.* (1990).

a hydrothermal–convection system, of at least 300°C, centered beneath the Ixpaco-Tecuamburro Volcano area. Similarly, the temperature of nearly 240°C encountered in an 808 m deep drill hole near Ixpaco (Goff *et al.*, this issue) confirms that a considerable thermal anomaly exists within the shallow crust beneath the area.

CONCLUSIONS

Our geologic studies suggest that a magmatic heat source(s?) exists within the crust beneath the area of Tecuamburro Volcano and Chupadero crater. Chemical geothermometry indicates a high-temperature hydrothermal–convection system centered beneath this area (Janik *et al.*, 1990; also this issue). The highest temperatures, about 300°C, are calculated from gas samples collected from fumaroles which vent at Laguna Ixpaco and whose gases presumably rise more or less vertically from an underlying hydrothermal–convection system. Calculated temperatures are ≤165°C for samples of thermal fluids collected at outlying fumaroles and neutral-chloride springs, a situation that could reflect cooling during lateral outflow from a 300°C system centered beneath Laguna Ixpaco, the existence of a second cooler system centered several kilometers from Ixpaco, or the subsurface mixing of 300°C reservoir fluids with cool shallow groundwater (Janik *et al.*, 1990; also this issue).

Whatever scenario most accurately describes the subsurface geothermal regime, all evidence points toward a high priority target for further exploration beneath the Laguna Ixpaco area. An 808 m deep well drilled about 1 km south of this lake in 1990 encountered a maximum temperature of nearly 240°C (Goff *et al.*, this issue). This initial drilling experience bodes favorably, but additional wells and flow tests are needed to verify the presence of a commercial-quality hydrothermal reservoir.

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