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The Escuintla and La Democracia debris avalanche deposits, Guatemala: Constraining their sources

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ABSTRACT

The Escuintla and La Democracia debris avalanches are the two largest debris avalanches so far identified in Guatemala, with respective volumes of 9–15 km^3 and 2.4–5 km^3. Based upon their geographic locations on the Guatemalan coastal plain, both deposits have several possible source volcanoes. The Escuintla debris avalanche could have originated at either the Fuego or Acatenango volcanic complexes, or Agua volcano. Farther to the west, the La Democracia debris avalanche could only have come from the Fuego or Acatenango volcanic complexes. An apparent collapse scar on the east face of the Meseta edifice (the northernmost vent of the Fuego volcanic complex) has been attributed to the formation of the Escuintla debris avalanche. A mostly obscured summit collapse scar on Acatenango and an erosional remnant of a debris avalanche deposit near the base of the cone have been linked to the La Democracia debris avalanche. Petrographic and geochemical analyses of lava blocks collected from the Escuintla debris avalanche suggest that a substantial volume of amphibole-bearing dacitic lavas were present at its source volcano. Examination of rocks from the possible source volcanoes indicate that no dacitic lavas or tephras are known to have erupted from the Fuego volcanic complex and that the rocks exposed in the Meseta scarp bear little resemblance to the Escuintla debris avalanche samples. A few dacitic lavas and tephras are known from the Agua volcano, and several dacitic tephras have erupted from Acatenango. Geochemical comparisons of lavas and tephras from these volcanoes with rocks from the Escuintla debris avalanche showed greater similarities than those from Fuego and Meseta. Even though Acatenango is not known to have erupted dacitic lavas, its geochemistry is the most consistent with that of the Escuintla debris avalanche. Lava blocks from the La Democracia debris avalanche are mostly basaltic, although one andesitic sample contains phenocrystic amphibole. Geochemical analyses of Fuego and Meseta lavas overlap with the La Democracia debris avalanche samples; however, no amphibole-bearing rocks are known from Meseta, and Fuego is presumed to be younger than the La Democracia debris avalanche. Compared to the Acatenango rocks, the geochemistry and mineralogy of the La Democracia debris avalanche are

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quite similar. Furthermore, rocks from the debris avalanche deposit on the flank of Acatenango are also consistent with the chemistry of the La Democracia debris avalanche. Thus, Acatenango produced at least one debris avalanche, the La Democracia debris avalanche, and possibly also generated the Escuintla debris avalanche.

Keywords: debris avalanche, geochemistry, Fuego, Acatenango, Agua.

INTRODUCTION

Since the eruption of Mount St. Helens in 1980, debris avalanches have been recognized as a common process at stratovolcanoes throughout the world. Many debris avalanche deposits are now easily identified by their conspicuous "hummocky" topography that spreads outward on the gentle lower slopes of their source volcanoes. An arcuate collapse scar, or sometimes a gaping amphitheater, is the best evidence that a volcano has undergone sector collapse and generated a debris avalanche (Siebert, 1984). With time, however, stratovolcanoes rebuild themselves, often obscuring the collapse scars (Clavero et al., 2002; Crandell, 1989) and burying the proximal portions of the deposits. Erosion or burial of the distal deposits can also mask evidence indicative of their source. In Guatemala, five debris avalanche deposits have been identified (Vallance et al., 1995; Duffield et al., 1989, Conway et al., 1992), and four others are inferred from source volcano evidence (Mercado and Rose, 1992; Reynolds, 1987; Siebert et al., 1994; Vallance et al., 1995). The source volcano for a few of these debris avalanche deposits is tentative at best. The two largest debris avalanche deposits in Guatemala, the Escuintla debris avalanche and the La Democracia debris avalanche, each have several possible sources (Fig. 1). The Escuintla debris avalanche lies on the coastal plain downslope from and midway between the Fuego volcanic complex and Agua volcano. The Acatenango volcanic complex, just to the north of the Fuego complex, is also a possible source for this deposit. Farther to the west, also on the coastal plain, the La Democracia debris avalanche could have originated at an edifice in either the Fuego or Acatenango volcanic complexes. This paper will review the physical evidence for the sources of these debris avalanche deposits and further constrain the source for each deposit using petrography and geochemistry.

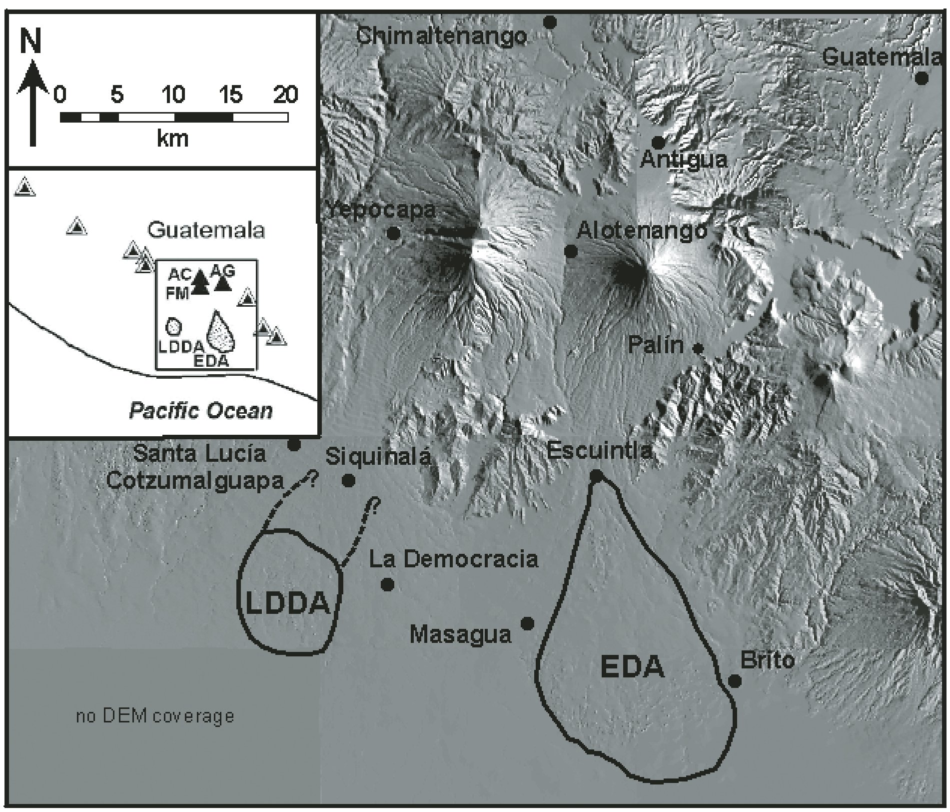

Figure 1. Digital elevation model showing the Escuintla (EDA) and La Democracia (LDDA) debris avalanche deposits and their possible source volcanoes, the Fuego (FM) and Acatenango (AC) volcanic complexes between the towns of Yepocapa and Alotenango, and the Agua Volcano (AG) to the east. Inset map shows the location of the study area.

DEBRIS AVALANCHE DEPOSITS

Escuintla Debris Avalanche

Analysis of Sky-Lab photographs of southern Guatemala led Rose et al. (1975) to suggest that a huge fan south of Escuintla might consist of volcaniclastic rocks derived from the stratovolcanoes upslope (Fig. 2). Subsequently, the Escuintla debris avalanche was mapped as Tertiary volcaniclastic and volcanic rocks by Hunter et al. (1984). Vallance et al. (1988, 1995) recognized it as a debris avalanche and described its characteristics within the modern context of debris avalanche deposits. It is 27 km long by 18 km wide, covers 300 km^2, and has an estimated volume of 9 km^3 (Vallance et al., 1995). Siebert et al. (1994) have inferred a 6 km^3 buried proximal portion, increasing the total volume to ~15 km^3. Four small outliers of the deposit have been isolated from the main body by fluvial processes. The northern apex of the exposed portion of the Escuintla debris avalanche outcrops just north of Escuintla and the deposit widens toward its southern terminus 45–50 km from its likely source volcanoes. It is bounded more-or-less to the east and west by the Michatoya and Guacalate Rivers, which have eroded small portions of the deposit. An apparent NNW-trending longitudinal axis could point toward its source or simply be an artifact of erosion or paleotopography. Individual hummocks range in height from 5 to 50 m, although most rise ~10 m above a gently sloping surface consisting of the deposit matrix (Figs. 3A and 3B). Their density and size is greatest in a proximal zone extending ~10 km south of Escuintla and in a 3-km-wide zone near the distal and lateral margins. At the terminal margin, the surface of the deposit drops abruptly 20 m to the coastal plain below. Vallance et al. (1995) interpret these hummock zones to represent emplacement of 2 sequential slide blocks from the same collapse event. Retrogressive flank failure would thus deposit lower flank rocks near the distal margin of the deposit and upper flank and summit rocks farther upslope. The relief at the distal end implies that the deposit is at least 20 m thick, and Vallance et al. (1995) have used a 30-m overall thickness as an estimate for their volume calculation. The Escuintla debris avalanche is geomorphologically the younger of the two avalanche deposits and has ~2–5 m of soil development according to Vallance et al. (1995). Because the Los Chocoyos tephra does not overlie the deposit, the Escuintla debris avalanche must be younger than 84 ka (Drexler et al., 1980).

The Puerto Quetzal Autopista transects the center of the deposit N-S from its proximal exposures to its distal end. Highway excavations and active quarries expose the interiors of several hummocks along the axis of the deposit. The interiors of the hummocks display many of the characteristics of debris avalanche deposits, such as large coherent lava blocks, multiple lava blocks of varying mineralogies and textures, “jigsaw” textured blocks (Fig. 3C), intact volcanic stratigraphy, and a multicolored matrix. A total of 26 lava block samples were collected from 16 different Escuintla debris avalanche hummocks during field seasons in 1999 and 2003 (Fig. 2).

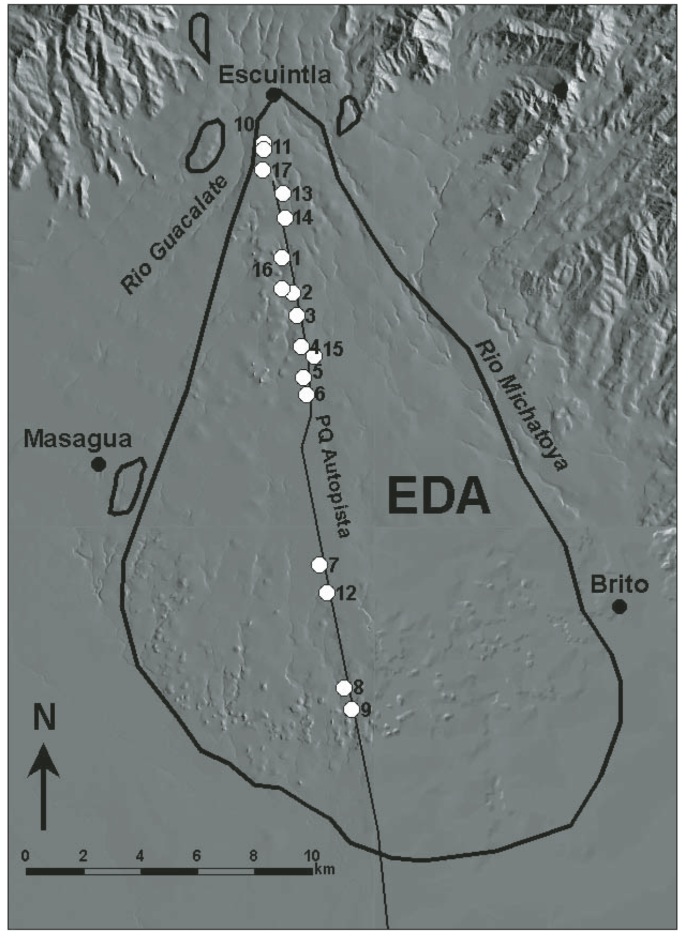

Figure 2. Digital elevation model showing the Escuintla debris avalanche deposit (EDA) and sample locations for this study. Note the four small outliers of EDA to the north and west of the main deposit and the northern and southern hummock concentration zones.

La Democracia Debris Avalanche

A portion of the La Democracia debris avalanche was also mapped by Hunter et al. (1984) as Tertiary volcanics, and the entire deposit was recognized and described as a debris avalanche by Vallance et al. (1988, 1995). It is 10 km wide by 15 km long, covers ~120 km^2, and has an estimated volume of 2.4 km^3 (Vallance et al., 1995). Incorporating an inferred buried proximal portion of the La Democracia debris avalanche, Siebert et al. (1994) estimated a total volume of ~5 km^3. Lying south of Siquinalá and Santa Lucía Cotzumalguapa and west of La Democracia, the northern half of the deposit is actively being buried by alluvial fan deposits of the Rio Panteleón drainage system. In this portion of the deposit, scattered hummocks barely protrude through the alluvium. Farther south, numerous hummocks up to

Figure 3. Hummocks from the northern hummock concentration zone of the Escuintla debris avalanche (A and B); fence-posts for scale. (C) A jigsaw block from the Escuintla debris avalanche; pocket-knife for scale in the center of the photograph.

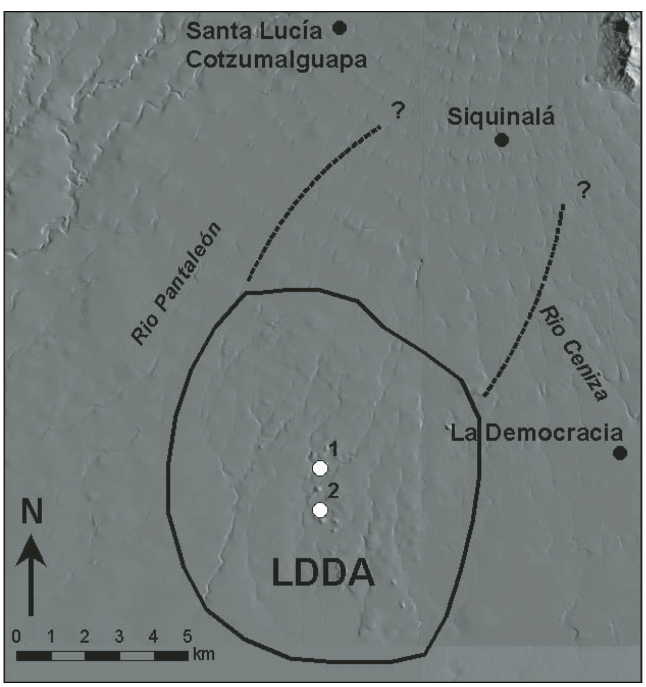

Figure 4. Digital elevation model showing the La Democracia debris avalanche (LDDA) and sample locations for this study.

40 m high are common (Fig. 4). The southern terminus of the deposit is ~40 km from its potential source volcanoes. The La Democracia debris avalanche is more deeply weathered than the Escuintla debris avalanche, with soil developed to a depth of six or more meters (Vallance et al., 1995). Absence of overlying Los Chocoyos tephra constrains its upper age limit to 84 ka also. The Finca El Balsamo road transects this deposit, but intersects few hummocks. Only 10 lava block samples were collected from two of the deeply eroded La Democracia debris avalanche hummocks in 1999 (Fig. 4).

POSSIBLE SOURCE VOLCANOES

Considering the locations and youthful geomorphologies of the Escuintla and La Democracia debris avalanches, the only possible source volcanoes are the Fuego volcanic complex, Acatenango volcanic complex, and Agua volcano. The Fuego complex consists of the historically active Fuego vent and the inactive prehistoric Meseta vent. These vents are aligned along a N-S trend with the Acatenango and Yepocapa vents of the Acatenango complex farther to the north (Fig. 5A). About 15 km to the east of these paired and aligned volcanoes lies the single vent edifice of Agua volcano (Fig. 5B).

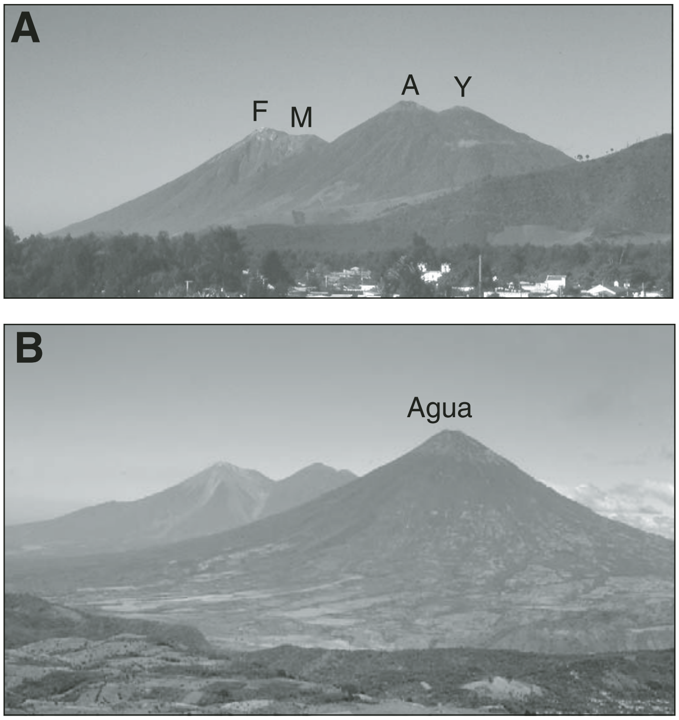

Figure 5. (A) View looking west of the Fuego and Acatenango volcanic complexes. Volcanoes from north to south are Y—Yepocapa, A—Acatenango, M—Meseta, and F—Fuego. (B) View looking west of Agua Volcano with the Fuego and Acatenango complexes in the background.

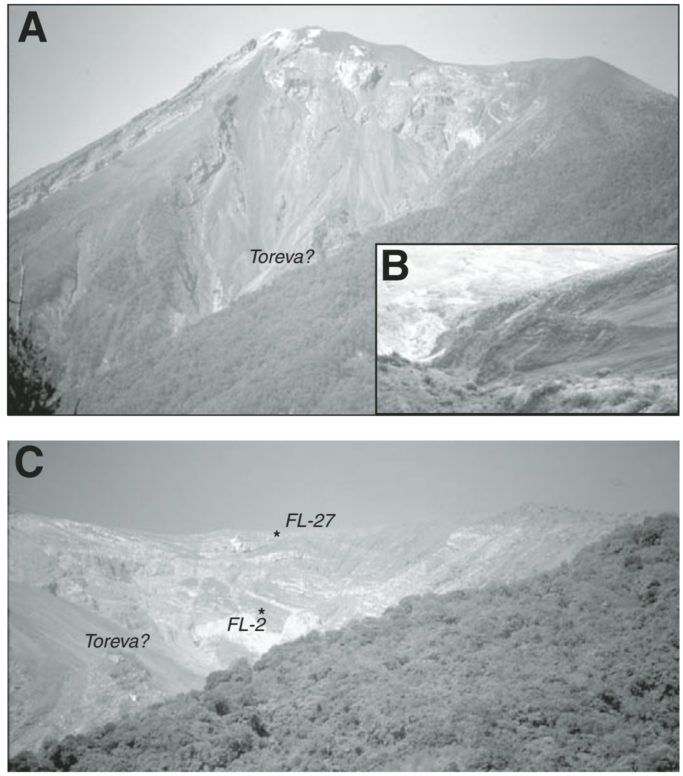

Figure 6. (A) View looking west of the Meseta scarp. The active Fuego vent is the hydrothermally altered summit, and the flat area is the inactive Meseta edifice. A possible toreva block is shown near the base of the scarp. (B) View looking down from Meseta at the possible toreva block in the center of the photograph. (C) Close-up view of sequential lava flows in the Meseta exposure. Lavas FL-2 and FL-27 were dated at 230 ka and 18 ka, respectively. The possible toreva block can also been seen in this view.

Meseta Volcano

Previous studies have postulated that the source of the Escuintla debris avalanche was Meseta volcano, the northernmost vent of the Fuego volcanic complex (Vallance et al., 1995; Siebert et al., 1994; Chesner and Halsor, 1997). A steep east-facing scarp on Meseta presumably formed by sector collapse, generating the Escuintla debris avalanche (Fig. 6A). The amphitheater shape of the scarp, an apparent displaced slide block (toreva) at the base of the exposure (Fig. 6B), and the absence of a significant portion of the cone all point to a major debris avalanche producing sector collapse. Vallance et al. (1995) also argued that the straightest path for the avalanche would have been from the Fuego and Acatenango complexes, not Agua. The scarp exposes a thick stratigraphic section of lavas and tephras that represents a significant portion of Meseta's eruptive history. A stratigraphic section of 27 consecutive lavas exposed in the upper 75% of the scarp has been characterized petrographically and geochemically by Chesner and Halsor (1997). Marvin Lanphere at the U.S. Geological Survey in Menlo Park has dated two lava block samples from the Meseta exposure by whole-rock $^{40}Ar/^{39}Ar$ dating (Vallance et al., 2001). Sample FL-27, located near the present summit of Meseta (Fig. 6C), yielded an integrated $^{40}Ar/^{39}Ar$ age of 18 ± 11 ka. Near the bottom of the sampled exposure, sample FL-2 yielded an age spectrum plateau of 234 ± 31 ka and an inverse isochron age of 232 ± 93 ka. Thus, if the Escuintla debris avalanche originated at Meseta, it is younger than 18 ka.

Fuego Volcano

The Fuego vent is the closest edifice to the La Democracia debris avalanche and is only 17 km from the nearest exposures of the Escuintla debris avalanche. However, there is no evidence of a sector collapse scar on the Fuego edifice. Martin and Rose (1981) estimated an age of 13 ka for the Fuego volcanic complex (Fuego and Meseta vents) using a time averaged overall eruption rate. Chesner and Rose (1984) have estimated that the Fuego volcanic complex has a minimum age of 17 ka and that the Fuego vent is ca. 8.5 ka based on projections of its historic eruption rates. Chesner and Halsor (1997) suggested that a shift in activity from the Meseta vent to the Fuego vent was initiated by collapse of the Meseta edifice. Therefore, the Fuego vent is presumed to be younger than both debris avalanches. If this evolutionary model is correct and the Escuintla debris avalanche originated at Meseta, the Escuintla debris avalanche's age is constrained between ca. 18 and 8.5 ka.

Agua Volcano

Based upon geographic location, the Agua volcano is equally as likely to be the source of the Escuintla debris avalanche as the Fuego vent. The summit of this large, symmetrical stratovolcano also lies ~17 km from the first exposures of the Escuintla debris avalanche. A small debris flow originating at a crater lake that once filled Agua's summit crater destroyed much of the original city of Antigua (the first capital of Guatemala) in 1541, but there is no evidence of a major sector collapse on the Agua cone. A "hump" on the west flank of Agua, possibly thought to represent a former crater wall, was investigated in the field and appears to be a flank vent. Oto Matias (2002, personal commun.) generated a global information system map of the lava flow–dominated cone and found nothing to suggest that Agua produced a debris avalanche. Considering the route from all possible source volcanoes that the Escuintla debris avalanche would have followed, the route from Agua is the most direct. However, an avalanche from Agua would be expected to have a north- or NNE-trending longitudinal axis due to deflection by the ridge of Tertiary volcanics between Escuintla and Palín (Fig. 1). It is impossible for the La Democracia debris avalanche to have originated at Agua because it is located west of the Fuego and Acatenango complexes.

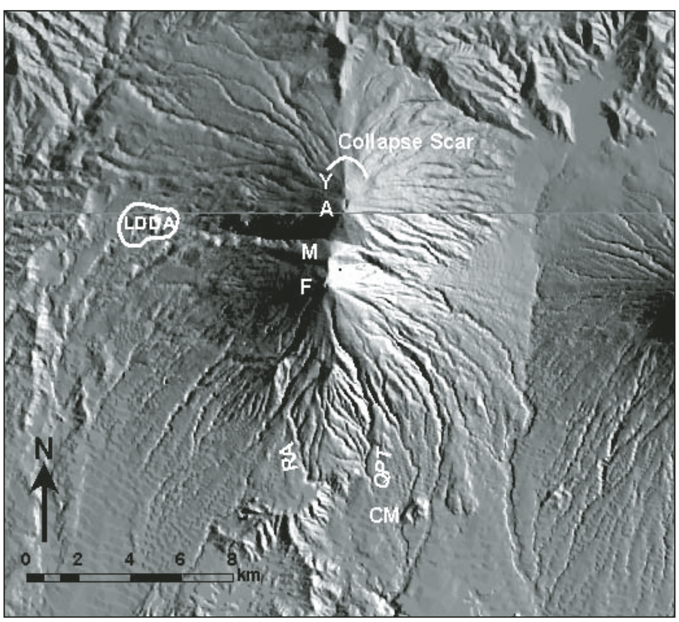

Figure 7. Digital elevation model of the Acatenango and Fuego volcanic complexes. Collapse scar and proximal La Democracia debris avalanche (LDDA) mapped by Basset (1996) are indicated. Yepocapa (Y), Acatenango (A), Meseta (M), and Fuego (F) vents are indicated. The Quebrada Playa Trinidad (QPT) Fuego rock suite and other amphibole bearing rock localities at Rio Achiguate (RA) and Cerro Mongoy (CM) are also shown.

Acatenango Volcano

Another possible source for the Escuintla debris avalanche and La Democracia debris avalanche is the Acatenango volcanic complex, which overlaps the Fuego volcanic complex to the north. Basset (1996) has demonstrated that at least one debris avalanche has originated from the Acatenango complex. The main evidence for this event is a proximal debris avalanche deposit on the west flank of Acatenango near Yepocapa (Fig. 7). Based upon proximal evidence of a debris avalanche and geochemical arguments, Basset (1996) concluded that the summit region of the ancient Acatenango edifice collapsed between 43 and 70 ka to form the La Democracia debris avalanche. In his evolutionary model, the Yepocapa cone was then built in the ancient Acatenango collapse crater from 43 to 20 ka. Activity then shifted to the modern Acatenango cone during the past 20 k.y.

PETROGRAPHIC SOURCE CONSTRAINTS

Approximately 75 thin sections from the Fuego and Meseta volcanoes have been examined by Chesner and Rose (1984) and Chesner and Halsor (1997). These samples are predominantly lavas; a few are blocks from block and ash flow deposits. Rocks exclusive to the Fuego vent were collected mostly from historical eruptions and lava flows or block and ash flow deposits outcropping in barrancas that drain the cone. In an effort to assure sampling of the older portion of the Fuego cone, Chesner and Rose (1984) collected 13 lava block samples from alluvial deposits in Quebrada Playa Trinidad, and in January 2006 lava blocks from several nearby drainages and outcrops from Cerro Mongoy were also sampled (Fig. 7). Rocks exclusive to the Meseta vent were collected from lava flows exposed high on the cone within the presumed avalanche scar. Petrographically, both the Fuego and Meseta rocks can be classified as basalts, basaltic andesites, and andesites. Their mineralogy consists of varying proportions of plagioclase, clinopyroxene, orthopyroxene, olivine, and magnetite phenocrysts (Fig. 8A). Amphibole phenocrysts occur in a small proportion of andesitic lava blocks from Quebrada Playa Trinidad and Rio Achiguate and some lavas exposed at Cerro Mongoy. No amphibole-bearing rocks are known at Meseta or in drainages originating in the east-facing Meseta exposure.

A suite of 18 lavas and one light-colored tephra sample (AG-8) were collected mostly from the summit region and the southwest sector of Agua volcano (Fig. 9). Petrographically, the lavas were basaltic andesites and andesites carrying varying proportions of plagioclase, clinopyroxene, orthopyroxene, olivine, and magnetite phenocrysts (Fig. 8B). None of the lavas examined in this study contain amphibole. The tephra sample can be characterized as a hornblende dacite and contains green amphibole phenocrysts.

Petrographic analyses of 48 Acatenango lavas by Basset (1996) indicated a suite of basaltic andesites and andesites. Only

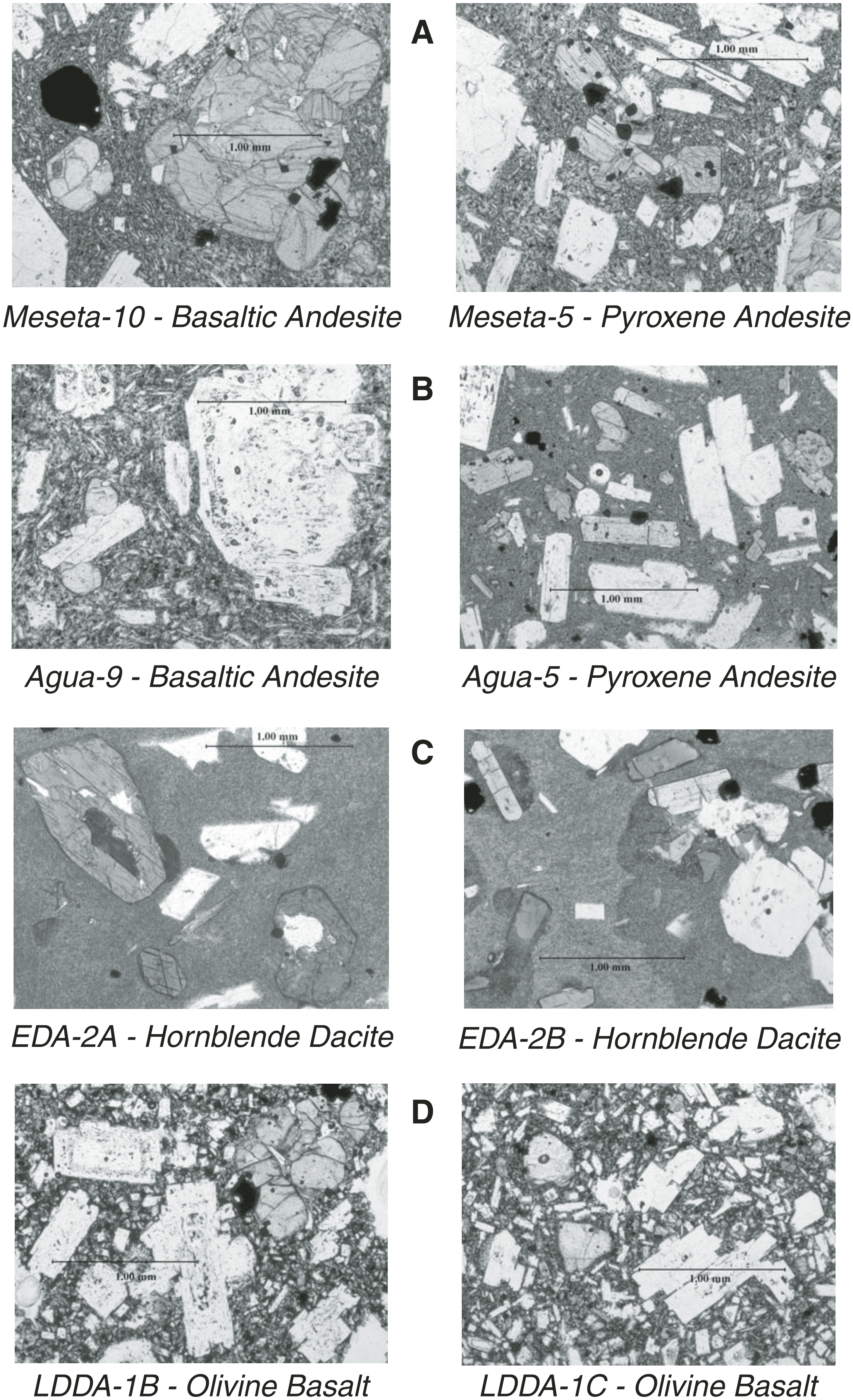

Figure 8. Photomicrographs of typical Meseta (A), Agua (B), Escuintla debris avalanche (C), and La Democracia debris avalanche (D) samples. All images were taken in plane-polarized light.

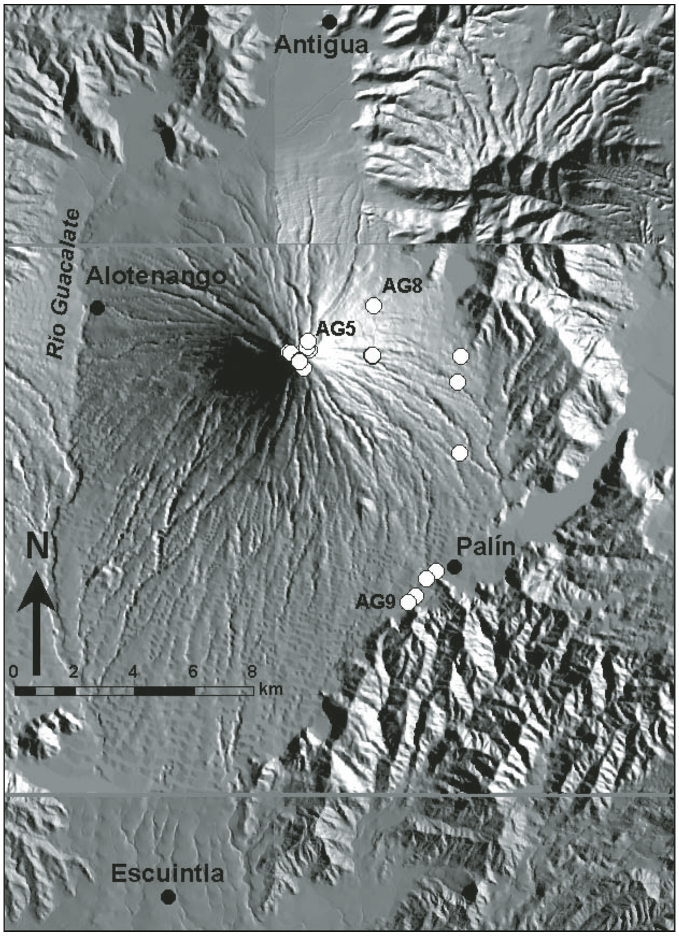

Figure 9. Digital elevation model of Agua volcano showing sample sites for petrographic analyses reported in this study. Lava flows were sampled at all sites except for AG-8, where the amphibole-bearing dacite tephra was collected.

five of these samples showed trace amounts of amphibole phenocrysts. Several andesitic and dacitic tephra samples in this study contained appreciable phenocrystic amphibole, some as high as 10% by volume.

The 26 Escuintla debris avalanche lava blocks that were collected from 16 separate hummocks are mineralogically distinct from the Meseta rocks. They are mostly basaltic andesites, andesites, and dacites. Olivine is less abundant in the Escuintla debris avalanche samples, but the most striking difference between the Escuintla debris avalanche and Meseta samples is that seven lava blocks from five different hummocks contained significant amounts of phenocrystic amphibole (Fig. 8C). The amphibole was distinctly green, except in two samples where it was highly oxidized. All but one of the amphibole-bearing hummocks are located in the northern hummock concentration zone (sites 2/16, 3, 4, and 14, Fig. 2). The other hummock that was found to contain amphibole (Site 7) was in the portion of the deposit between the hummock concentration zones. Highly oxidized amphibole occurred in the two most southern amphibole-bearing hummocks (Sites 4 and 7).

Thin sections of all 10 La Democracia debris avalanche lava blocks collected from two separate hummocks were also examined. These rocks are mostly basalts and basaltic andesites and are generally similar to lavas from the Meseta and Fuego volcanoes (Fig. 8D). One andesite sample, however, did contain abundant, highly oxidized amphibole phenocrysts. The La Democracia debris avalanche samples are not nearly as fresh as the Escuintla debris avalanche samples, often containing highly iddingsitized olivine. This observation is consistent with the greater observed soil development and more subdued topographic expression of the presumably older La Democracia debris avalanche deposit.

These petrographic assessments strongly suggest that the Escuintla debris avalanche source volcano contained a significant volume of amphibole-bearing dacitic lavas or lava domes. Our observations indicate that no such rocks are known to have erupted from the Meseta or Fuego volcanoes. Some debris avalanche deposits have been shown to incorporate significant amounts of underlying basement rocks (Wadge et al., 1995; Francis and Self, 1987). In these cases, the basement rocks tend to concentrate in the distal slide blocks, whereas the proximal slide blocks represent upper flank and summit rocks. Since the dacites in the Escuintla debris avalanche were all collected from the proximal slide block, we do not believe that they have been inherited from the basement. Although the vast majority of La Democracia debris avalanche samples are mineralogically compatible with the Meseta and Fuego vents, the one amphibole andesite precludes its origin from Meseta. Thus, petrographic constraints have reduced the possibility that the Escuintla debris avalanche or La Democracia debris avalanche originated at the Meseta vent as previously postulated.

GEOCHEMICAL SOURCE CONSTRAINTS

Comparing geochemical analyses of lava blocks from debris avalanche deposits with rocks collected from possible source volcanoes has been shown to help constrain debris avalanche sources, especially when physical evidence is absent or inconclusive (Siebert et al., 2004). Preliminary geochemical studies of eight Escuintla debris avalanche and seven La Democracia debris avalanche lava blocks by Vallance et al. (1995) indicated that the Escuintla debris avalanche's chemistry was consistent with the Meseta, Acatenango, and Agua volcanoes, but not Fuego. They also suggested that the La Democracia debris avalanche lava blocks were more consistent with Fuego than Acatenango or Meseta. However, since Fuego is presumed to be younger than the La Democracia debris avalanche, they invoked an eroded or buried cone as the La Democracia debris avalanche source.

New major and trace element X-ray fluorescence spectrometry (XRF) analyses of 24 Escuintla debris avalanche and 10 La Democracia debris avalanche samples were acquired at Michigan State University using the same laboratory and XRF spectrometer that was used for the Meseta suite (Table 1). These analyses were compared to the Meseta data set previously studied by Chesner and Halsor (1997), assuring internal analytical consistency.

TABLE 1. GEOCHEMICAL ANALYSES OF LAVA BLOCKS FROM THE ESCUINTLA AND LA DEMOCRACIA DEBRIS AVALANCHE DEPOSITS

Sample:	EDA-1A	EDA-1B	EDA-1C	EDA-2A	EDA-2B	EDA-3A	EDA-4A	EDA-4B	EDA-5A	EDA-5B	EDA-6	EDA-7
SiO_2	61.33	59.14	58.59	66.05	66.20	64.73	61.94	64.92	56.42	54.71	57.56	65.79
TiO_2	0.70	0.80	0.85	0.46	0.46	0.58	0.69	0.61	0.90	0.93	0.78	0.50
Al_2O_3	17.80	17.74	18.12	17.25	17.20	16.52	17.24	18.86	18.88	19.10	18.65	17.55
FeO	6.00	6.75	6.81	3.85	3.77	5.40	5.82	5.14	7.09	7.77	6.67	4.05
MnO	0.13	0.14	0.14	0.12	0.12	0.12	0.12	0.13	0.13	0.14	0.14	0.13
MgO	2.45	3.23	3.20	1.31	1.25	1.61	2.39	1.44	3.73	4.40	3.60	1.29
CaO	5.63	6.92	7.27	4.01	4.04	3.88	5.45	2.77	8.09	8.80	8.01	3.75
Na_2O	3.90	3.41	3.36	4.56	4.59	4.33	4.02	3.48	3.24	2.96	3.16	4.54
K_2O	1.88	1.66	1.46	2.19	2.17	2.64	2.14	2.49	1.24	0.95	1.22	2.21
P_2O_5	0.19	0.19	0.20	0.19	0.19	0.19	0.18	0.18	0.29	0.23	0.22	0.20
Cr	–	18	2	–	–	2589	–	–	27	36	17	–
Ni	2	12	11	5	2	214	14	11	24	31	16	6
Cu	43	50	94	23	15	33	44	36	71	62	49	21
Zn	79	88	88	75	68	70	75	73	89	87	82	71
Rb	25	35	26	43	40	75	51	57	25	15	28	41
Sr	461	459	532	449	452	402	454	361	624	618	601	453
Y	23	29	25	26	23	26	27	31	22	21	26	29
Zr	173	134	136	179	188	219	168	205	171	117	144	190
Nb	8	–	–	–	3	3	–	6	3	–	5	6
La	23	–	26	14	16	41	28	32	13	–	17	21
Ba	925	607	638	975	1070	915	753	1214	559	546	616	882

Sample:	EDA-8	EDA-9	EDA-10A	EDA-10B	EDA-10C	EDA-11	EDA-12A	EDA-12B	EDA-13	EDA-14A	EDA-14B
SiO_2	59.33	59.05	57.15	53.37	52.61	57.23	61.95	64.75	58.34	57.81	67.50
TiO_2	0.73	0.73	0.95	1.01	0.97	0.81	0.73	0.58	0.68	0.83	0.54
Al_2O_3	18.44	18.88	18.26	19.20	19.72	20.20	18.40	16.97	19.32	18.00	17.40
FeO	6.70	6.33	7.57	9.09	8.86	6.47	6.34	4.74	6.24	7.59	3.94
MnO	0.14	0.13	0.15	0.15	0.15	0.13	0.15	0.11	0.13	0.16	0.10
MgO	3.01	2.94	3.41	4.25	4.59	2.32	1.74	1.66	2.83	3.36	0.45
CaO	6.76	6.97	7.63	8.35	8.91	7.35	4.50	4.39	7.08	6.76	3.18
Na_2O	3.40	3.45	3.25	3.35	3.14	3.85	4.09	4.22	3.75	3.53	4.43
K_2O	1.31	1.32	1.42	1.03	0.86	1.39	1.86	2.39	1.40	1.75	2.24
P_2O_5	0.19	0.19	0.21	0.21	0.17	0.24	0.24	0.18	0.24	0.22	0.21
Cr	–	–	–	8	–	–	–	12	7	1745	–
Ni	9	11	12	12	13	6	9	10	9	139	6
Cu	38	48	70	118	81	71	44	42	68	74	30
Zn	77	82	90	94	86	83	83	75	82	84	72
Rb	24	19	32	27	25	43	52	73	45	55	59
Sr	560	608	576	622	633	604	494	440	612	510	408
Y	29	25	26	18	19	20	20	22	22	21	24
Zr	122	116	134	121	109	146	178	215	150	169	197
Nb	2	–	–	4	3	12	8	12	8	9	10
La	12	13	11	32	27	47	50	51	50	43	44
Ba	586	551	623	508	454	594	813	925	641	742	994

Sample:	EDA-15	LDA-1A	LDA-1B	LDA-1C	LDA-1D	LDA-1E	LDA-1F	LDA-1G	LDA-2A	LDA-2B	LDA-2C
SiO_2	54.72	52.04	51.96	51.66	52.28	52.03	51.48	52.07	61.62	50.05	54.36
TiO_2	0.97	0.95	0.93	1.01	0.96	0.96	1.02	0.99	0.58	1.01	0.90
Al_2O_3	20.68	18.91	19.34	19.72	18.78	18.94	18.47	18.81	18.88	19.12	18.84
FeO	7.20	9.49	9.62	8.95	8.97	9.38	9.77	9.49	6.45	10.33	8.81
MnO	0.11	0.15	0.16	0.14	0.14	0.15	0.14	0.15	0.16	0.15	0.15
MgO	2.55	5.49	4.88	5.18	5.05	5.54	5.87	5.49	1.56	6.12	4.26
CaO	9.66	9.05	8.86	9.34	9.90	9.06	9.57	9.14	5.17	9.84	8.21
Na_2O	3.09	2.94	3.04	2.99	2.98	2.94	2.83	2.93	3.84	2.68	3.32
K_2O	0.82	0.80	1.04	0.78	0.78	0.82	0.70	0.76	1.50	0.57	0.93
P_2O_5	0.20	0.17	0.18	0.23	0.17	0.16	0.15	0.17	0.24	0.14	0.21
Cr	–	70	36	45	74	51	76	74	–	63	17
Ni	3	38	23	26	40	36	42	40	5	36	17
Cu	82	99	58	73	56	65	46	92	26	62	44
Zn	85	108	83	88	81	86	92	91	98	79	91
Rb	16	26	21	7	11	10	5	11	31	–	7
Sr	629	607	572	624	605	609	601	585	582	594	583
Y	17	16	22	23	24	24	26	25	26	24	26
Zr	115	92	85	112	71	73	66	76	148	57	95
Nb	3	–	–	–	–	–	–	–	–	–	–
La	32	40	12	18	–	–	7	34	19	–	7
Ba	487	419	455	501	506	366	453	426	864	343	476

Note: Analyses normalized to 100% with all Fe as FeO. Major elements (SiO_2 through P_2O_5) given in wt%; trace elements (Cr through Ba) given in ppm.

Samples collected from the Escuintla debris avalanche have a wide compositional range (53–67.5 wt% SiO_2) and are predominantly andesites and dacites (Fig. 10). Nearly one-third (7 of 24) of the Escuintla debris avalanche lava blocks are dacites. These samples occur in six hummocks (sites 2, 3, 4, 7, 12, and 14, Fig. 2) spanning ~20 km along the N-S axis in the northern part of the deposit. This distribution suggests that dacites were a common rock type at the source volcano. Retrogressive flank failure, eventually capturing a dacitic lava dome complex, is consistent with such a distribution. The Meseta rock suite consists mostly of basaltic andesites with a few andesites and has a more restricted SiO_2 range (51–59 wt%) than the Escuintla debris avalanche (Fig. 11). On most geochemical plots, the Escuintla debris avalanche samples form a distinct group with wide linear trends, offset from the tight trends of the Meseta samples. A limited data set of older lavas from Fuego volcano is also plotted in Figure 11. Most of the Fuego rocks are basaltic andesites and andesites with SiO_2 contents ranging from 52 wt% to 61.5 wt%. Although the Fuego rocks overlap with Escuintla debris avalanche samples in some plots, in others they are quite distinct. Furthermore, like Meseta, none of the Fuego lavas are dacitic. This data strongly suggests that the Escuintla debris avalanche did not originate from the scarp on Meseta volcano as previously proposed, and its generation from Fuego is also unlikely.

The Escuintla debris avalanche was also compared to a data set consisting of 39 XRF analyses of lava flows collected from Agua volcano by Oto Matias (2002, personal commun.) and analyzed by Barry Cameron (Northern Illinois University). The Agua sample suite ranges from 52%–70% SiO_2, and the vast majority of the samples (37 of 39) are basaltic andesites and andesites containing <60 wt% SiO_2 (Fig. 12). Only two samples have SiO_2 contents between 60% and 70% and can be characterized as dacitic. Agua and Escuintla debris avalanche samples display overlapping trends on most geochemical plots. Although the Agua sample suite does not contain as many evolved rocks as the Escuintla debris avalanche, the Agua dacites plot along or close to the Escuintla debris avalanche trends. This data suggests that Agua volcano is a better candidate as an Escuintla debris avalanche source than the Meseta or Fuego volcanoes.

The Acatenango complex was also evaluated as a potential Escuintla debris avalanche and La Democracia debris avalanche source by utilizing an XRF data set consisting of 94 chemical analyses, 48 of which are lava flows (Basset, 1996). Lava flows from Acatenango are mostly basaltic andesites and andesites with SiO_2 contents ranging between 51% and 61.5% SiO_2 (Fig. 13). The vast majority of the lavas have SiO_2 contents above 55%, but there are no dacitic lavas in the suite. Of the numerous pyroclastic samples in this suite, several (~18) are dacitic tephras; they have been included in Figure 13. The Escuintla debris avalanche samples consistently lie along the Acatenango trends in virtually all chemical variation diagrams. Therefore, of all the data sets, the rocks from the Acatenango suite are the best chemical match to those from the Escuintla debris avalanche.

Samples from the much smaller La Democracia debris avalanche suite are mostly basaltic (50%–55% SiO_2) and include only one andesite sample containing ~61.5% SiO_2 (Figs. 11 and 13). The majority of La Democracia debris avalanche analyses overlap with those from Meseta and Fuego on most geochemical plots (Fig. 11). Thus, based on geochemical data, neither Fuego nor Meseta can be eliminated as a possible source of the La Democracia debris avalanche. There is considerable overlap of the Acatenango lava flow data and the La Democracia debris

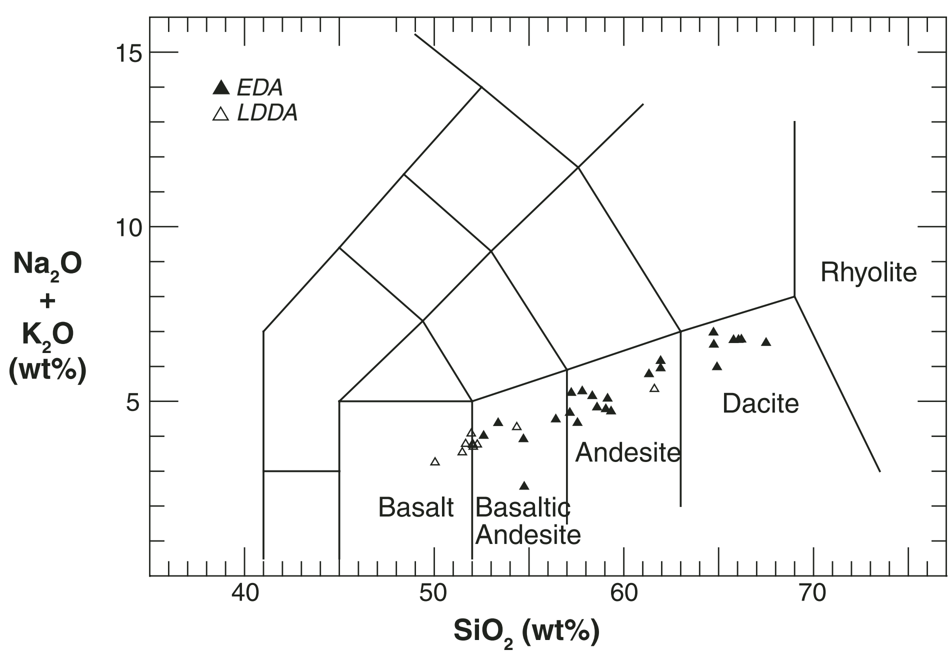

Figure 10. Volcanic rock classification diagram (LeBas et al., 1986) showing the Escuintla debris avalanche (EDA) and La Democracia debris avalanche (LDDA) samples.

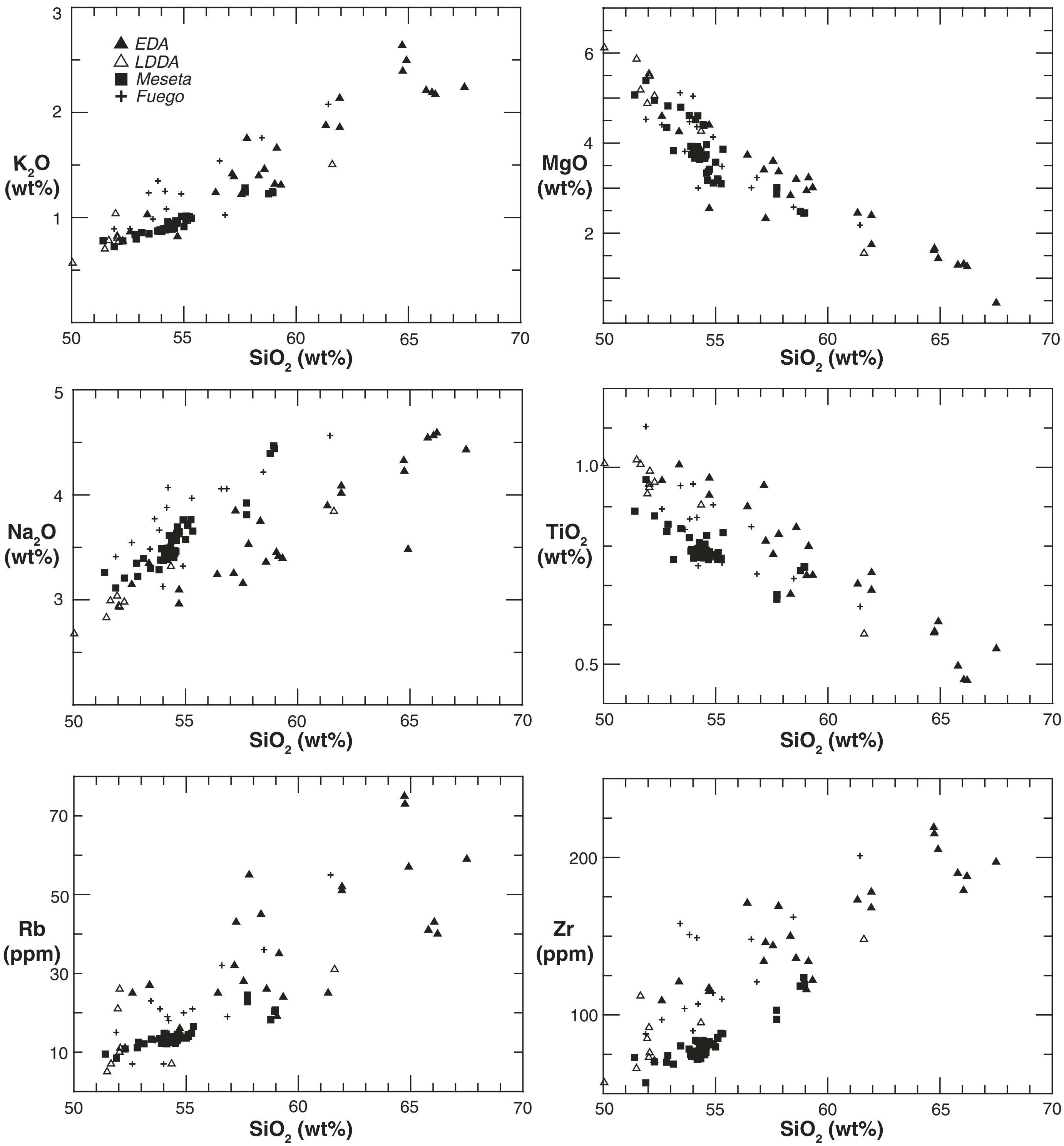

Figure 11. Variation diagrams showing Escuintla debris avalanche (EDA), La Democracia debris avalanche (LDDA), Meseta, and Fuego samples.

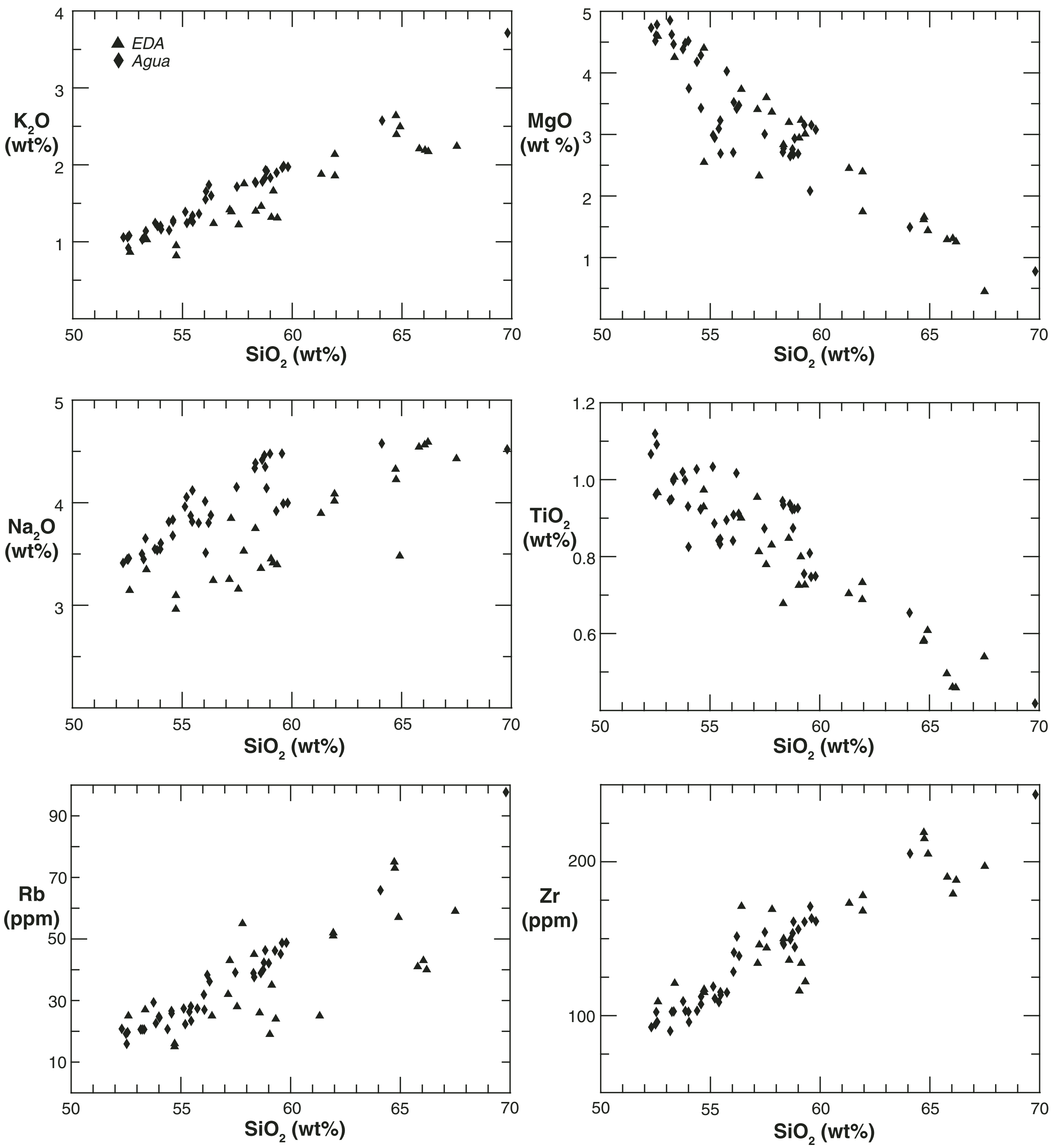

Figure 12. Variation diagrams showing samples from the Escuintla debris avalanche (EDA) and Agua volcano. Agua data is from Oto Matias (2002, personal commun.) and was analyzed by Barry Cameron (Northern Illinois University).

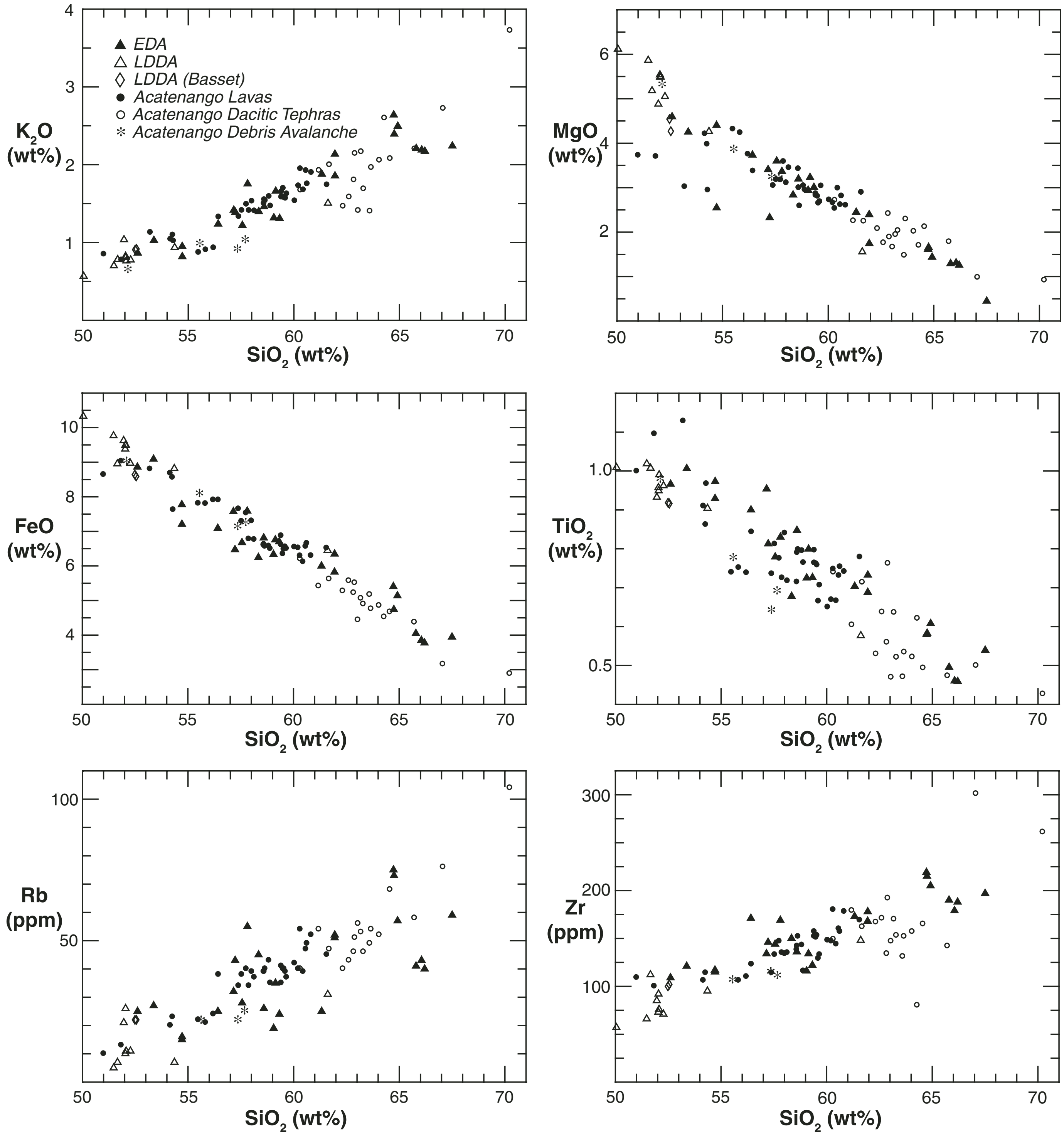

Figure 13. Variation diagrams showing Escuintla debris avalanche (EDA), La Democracia debris avalanche (LDDA), and Acatenango samples. All Acatenango analyses are from Basset (1996). Acatenango lava flows and dacitic tephras are shown with separate symbols. Three LDDA samples and four Acatenango debris avalanche samples analyzed by Basset are also shown.

avalanche analyses (Fig. 13). Two La Democracia debris avalanche lava blocks analyzed by Basset (1996) have also been included in Figure 13 and plot within the mafic cluster of La Democracia debris avalanche samples. Therefore, based on geochemical correlations, it is also possible that the ancient Acatenango edifice was the source of the La Democracia debris avalanche. Analyses of four lava blocks from the debris avalanche identified by Basset on the west flank of Acatenango were also plotted in Figure 13. Three of these samples lie along a trend between the mafic group of La Democracia debris avalanche rocks and the single andesite sample. Consequently, there is nothing in the geochemistry to refute Basset's suggestion that the debris avalanche on the west flank of Acatenango is a proximal remnant of the La Democracia debris avalanche.

DISCUSSION

Source Constraints of the Escuintla Debris Avalanche

Several lines of evidence suggest that the Fuego vent was not the source of the Escuintla debris avalanche. Fuego is the youngest and most active of the possible source volcanoes and is generally thought to be younger than the Escuintla debris avalanche. Furthermore, no collapse scars have been identified on the edifice. In terms of petrology, Fuego has erupted mostly basalts and basaltic andesites during its short history, while the Escuintla debris avalanche consists of a more evolved set of rocks containing appreciable dacitic material with SiO_2 contents up to 67.5 wt%. No dacitic lavas or tephras are known to have erupted from Fuego. The most silicic Fuego sample is a lava block collected in Quebrada Playa Trinidad containing ~61.5 wt% SiO_2. Consistent with this geochemistry, there are relatively more olivine-bearing rocks at Fuego than are found in the Escuintla debris avalanche. However, before Fuego can be eliminated as a potential Escuintla debris avalanche source, further investigation of the amphibole bearing rocks on its southern flank is necessary.

Physical evidence is strongly suggestive that the Meseta edifice was the source of the Escuintla debris avalanche. The steep east-facing exposure at Meseta is reminiscent of a sector collapse amphitheater. Additional evidence consists of a large toreva slide block located at the base of the Meseta exposure that appears to be a portion of the Meseta cone that did not travel far from its original position. According to Vallance et al. (1995), Meseta is also along the most direct path that the Escuintla debris avalanche would have traveled. Petrologic evidence, however, does not support the physical evidence of a Meseta source for the Escuintla debris avalanche. The most silicic rock known at Meseta contains ~59% SiO_2. Like Fuego, there are no known dacitic lavas or tephras at Meseta, and none of the Meseta rocks contain amphibole phenocrysts. Conceivably, the summit of Meseta may have consisted of a dacitic lava dome complex prior to a collapse event, but we deem this scenario highly unlikely because even the more mafic rocks at Meseta are somewhat chemically distinct from the Escuintla debris avalanche samples (Fig. 11). Minor variations between geochemical data sets collected at different laboratories might be expected to result in subtle distinctions between two data sets on chemical variation diagrams, such as those noted in the more mafic Escuintla debris avalanche and Meseta samples. However, the Escuintla debris avalanche and Meseta rock suites were both analyzed at Michigan State University by XRF. If the Escuintla debris avalanche did not originate from the Meseta scarp, then an alternate explanation of this exposure is required. Perhaps the exposure does represent a sector collapse and its debris avalanche deposit is buried beneath younger volcanics and volcaniclastics between Meseta and Agua volcanoes or under the alluvial apron to the south. Alternatively, perhaps the Meseta exposure is merely the result of incremental mass wasting, and a debris avalanche never took place.

Although there is no direct physical evidence for a substantial volume sector collapse at Agua volcano, indirect physical evidence and petrologic data do not exclude it as a possible source for the Escuintla debris avalanche. After examining the composite digital elevation model (DEM) image (Fig. 1), it is our opinion that the most direct path for the Escuintla debris avalanche would have been from Agua volcano. Orientation of the longitudinal axis of an Agua debris avalanche is likely to depend upon location of the collapsed sector. Geochemically, the Agua sample suite has greater similarity to the Escuintla debris avalanche than the Fuego and Meseta data sets. Petrographic examination of 18 lava samples collected from Agua did not result in definitive mineralogical consistencies between Agua and the Escuintla debris avalanche. The majority of the Agua samples were similar to the basaltic andesites and andesites of the Escuintla debris avalanche, but none of the Agua lava samples contained phenocrystic amphibole like the Escuintla debris avalanche dacites. Two of the 39 Agua lavas analyzed by Cameron at Northern Illinois University, however, are dacitic, containing ~64 wt% and 70 wt% SiO_2. These samples plot within the chemical trend of the Escuintla debris avalanche dacites (thin sections were not available for these samples). A 2-m-thick coarse dacitic tephra unit (AG-8) was collected from the northeast flank of Agua and does contain phenocrysts of amphibole. A charcoal sample from this unit has a ^{14}C age of 23,950 ± 270 yr B.P. (B. Rose, 2004, personal commun.). Thus, dacitic amphibole-bearing rocks are known to have erupted from Agua, and the requisite dacitic lava dome complex is not out of the question. If dacitic lavas and tephras were erupting from Agua ca. 24 ka, and Agua collapsed to generate the Escuintla debris avalanche, this age could represent an upper limit for such an event. If the Escuintla debris avalanche did originate from Agua, all physical evidence of a possible collapse and a dacitic lava dome complex are now obscured.

The Acatenango complex provides strong but inconclusive evidence for being the Escuintla debris avalanche source volcano. Basset (1996) identified and mapped the remnant of a former caldera or collapse scar on the northern part of Acatenango's upper cone. He attributed this south-facing feature to a sector collapse that took place between 43 and 70 ka generating the La Democracia debris avalanche. No other collapse scars have been identified on the Acatenango volcanic complex. Petrographic analyses also performed by Basset indicate that some Acatenango lavas contain trace amounts of amphibole. The only Acatenango samples reported to have substantial phenocrystic amphibole contents are dacitic tephras. Several amphibole-bearing tephras were erupted from the Yepocapa and modern Acatenango vents in the past 43 k.y. (Basset, 1996). Thus, amphibole-bearing dacitic tephras have been fairly common since 43 ka at the Acatenango complex. Geochemical analyses indicate that no Acatenango lava flows overlap with the dacites found in the Escuintla debris avalanche. The most silicic lava flow in the Acatenango data set has only 61 wt% SiO_2, less silicic than lavas at Agua and Fuego. Acatenango lavas do, however, have overlapping trends with the less silicic Escuintla debris avalanche rocks on variation diagrams. When the chemistry of the dacitic tephras is considered, the overall Acatenango data set is more similar to the Escuintla debris avalanche than that of Meseta, Fuego, or Agua. Determining which data set, Acatenango or Agua, better matched the Escuintla debris avalanche analyses was difficult. Subtle chemical differences between the three data sets, possibly inherited from their respective analytical laboratories, may be responsible for some chemical overlaps or distinctions. Regardless, our evaluations of the data indicated that the best agreement was between the Acatenango and Escuintla debris avalanche data sets. Because Acatenango has produced amphibole-bearing dacitic tephras, and geochemical trends consistently overlap with the Escuintla debris avalanche, Acatenango should be considered a strong candidate as the source of the Escuintla debris avalanche. In order for an Acatenango collapse event to generate the dacite-bearing Escuintla debris avalanche, it would need to have occurred since 43 ka, after eruption and accumulation of dacite from the Yepocapa and modern Acatenango cones. Even though Basset (1996) has attributed the collapse scar on Acatenango to the La Democracia debris avalanche, it is feasible that the scar could be the source of the Escuintla debris avalanche. Basset's calculations, however, suggest that the volume of missing cone associated with this collapse scar is only ~2.7 km^3, far too small to have generated the Escuintla debris avalanche.

Based upon the source volcano requirements of significant amounts of amphibole-bearing dacite, we believe that a Fuego-Meseta source of the Escuintla debris avalanche is highly unlikely. Instead, we have demonstrated that both Agua and the Acatenango complex were erupting dacitic magma ca. 24 ka and <43 ka, respectively. One collapse event has already been documented at the Acatenango complex, and several studies have shown that multiple collapses from the same volcano are common (Ponomareva et al., 1998; Tibaldi, 2001; Begét and Kienle, 1992). Furthermore, the N-S alignment of vents in the Acatenango complex and inferred dike-like configuration of the shallow magma chamber could make Acatenango more prone to edifice collapse than the symmetrical Agua cone. An Acatenango collapse from such structural factors would likely occur to the SE or SW, whereas an Agua collapse direction would be more strongly influenced by the regional slope of the basement toward the south (Vallance et al., 1995). Proximity and direct route arguments might favor an Agua source, but the NNW-trending axis of the Escuintla debris avalanche could also imply derivation from Acatenango. Final conclusions concerning the Escuintla debris avalanche source should await dating of the Escuintla debris avalanche dacites and comparison of its amphibole geochemistry with Fuego, Agua, and Acatenango, or discovery and study of proximal Escuintla debris avalanche exposures.

Source Constraints of the La Democracia Debris Avalanche

Far less mineralogical and geochemical data is available for use in determination of the La Democracia debris avalanche source volcano. Geographical location does, however, preclude its origin from Agua volcano; thus, only the Fuego and Acatenango volcanic complexes need to be considered as possible sources. We do not believe that the Fuego vent generated the La Democracia debris avalanche because the La Democracia debris avalanche is considered to be much older than the Escuintla debris avalanche, and the Fuego vent is presumed to be younger than the Escuintla debris avalanche. Although geochemistry of the La Democracia debris avalanche is quite similar to both Fuego and Meseta, one sample from the small La Democracia debris avalanche suite contained considerable phenocrystic amphibole, precluding its origin from Meseta.

Compelling physical evidence of an Acatenango source for the La Democracia debris avalanche has been presented by Basset (1996) and includes identification of a partial collapse scar on Acatenango's upper cone, a missing volume calculation of 2.7 km^3 that is similar to the volume of the La Democracia debris avalanche (2.4–5 km^3), and identification of a proximal debris avalanche on the west flank of the Acatenango cone. The age range suggested for this collapse event (40–73 ka) by Basset seems more appropriate for the age of the highly weathered La Democracia debris avalanche than for the less-weathered Escuintla debris avalanche. The majority of our limited suite of La Democracia debris avalanche samples consists of basalts and basaltic andesites, which is consistent with Basset's model of a mafic ancestral Acatenango cone. Our chemical analyses of the La Democracia debris avalanche overlap well with Basset's Acatenango data set. In addition, analyses of four lava blocks from the proximal debris avalanche identified on Acatenango are also consistent with our La Democracia debris avalanche analyses. Thus, we concur with Basset that the La Democracia debris avalanche originated from collapse of the ancestral Acatenango cone.

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The Escuintla and La Democracia debris avalanche deposits, Guatemala: Constraining their sources

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Notes