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QUATERNARY SILICIC PYROCLASTIC DEPOSITS OF ATITLÁN CALDERA, GUATEMALA

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Abstract

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Atitlán caldera has been the site of several silicic eruptions within the last 150,000 years, following a period of basalt/andesite volcanism. The silicic volcanism began with 5-10 km^3 of rhyodacites, erupted as plinian fall and pyroclastic flows, about 126,000 yr. B.P. At 85,000 yr. B.P. 270-280 km^3 of compositionally distinct rhyolite was erupted in the Los Chocoyos event which produced widely dispersed, plinian fall deposits and widespread, mobile pyroclastic flows. In the latter parts of this eruption rhyodacite and minor dacite were erupted which compositionally resembled the earliest silicic magmas of the Atitlán center. As a result of this major eruption, the modern Atitlán (III) caldera formed. Following this event, rhyodacites were again erupted in smaller (5-13 km^3) volumes, partly through the lake, and mafic volcanism resumed, forming three composite volcanoes within the caldera. The bimodal mafic-/silicic Atitlán volcanism is similar to that which has occurred elsewhere in the Guatemalan Highlands, but is significantly more voluminous. Mafic lavas are thought to originate in the mantle, but rise, intrude and underplate the lower crust and partly escape to the surface. Eventually, silicic melts form in the crust, possibly partly derived from underplated basaltic material, rise, crystallize and erupt. The renewed mafic volcanism could reflect either regional magmato-tectonic adjustment after the large silicic eruption or the onset of a new cycle.

Introduction

The Atitlán Caldera is the largest of the silicic volcanic centers in the volcanic front of Guatemala (Fig. 1). The center of this 300-km^2 caldera is located 5–10 km north of the front. Atwood (1933) concluded that the Atitlán basin formed by collapse of a great stratovolcano. Williams (1960) proposed that it resulted from gradual cauldron subsidence associated with the build-up of the three andesitic composite volcanoes, San Pedro, Tolimán and Atitlán, in the southern half of the caldera. Only after the great size of the 84,000 yr. B.P. Los Chocoyos eruption became known (Koch and McLean, 1975; Hahn et al., 1979, Rose et al., 1979; Drexler et al., 1980) was it evident that the caldera collapse was associated with a major eruption. The caldera is now partially filled by the three stratovolcanoes and contains the 300-m-deep Lake Atitlán.

Mapping by Newhall (1980) demonstrated

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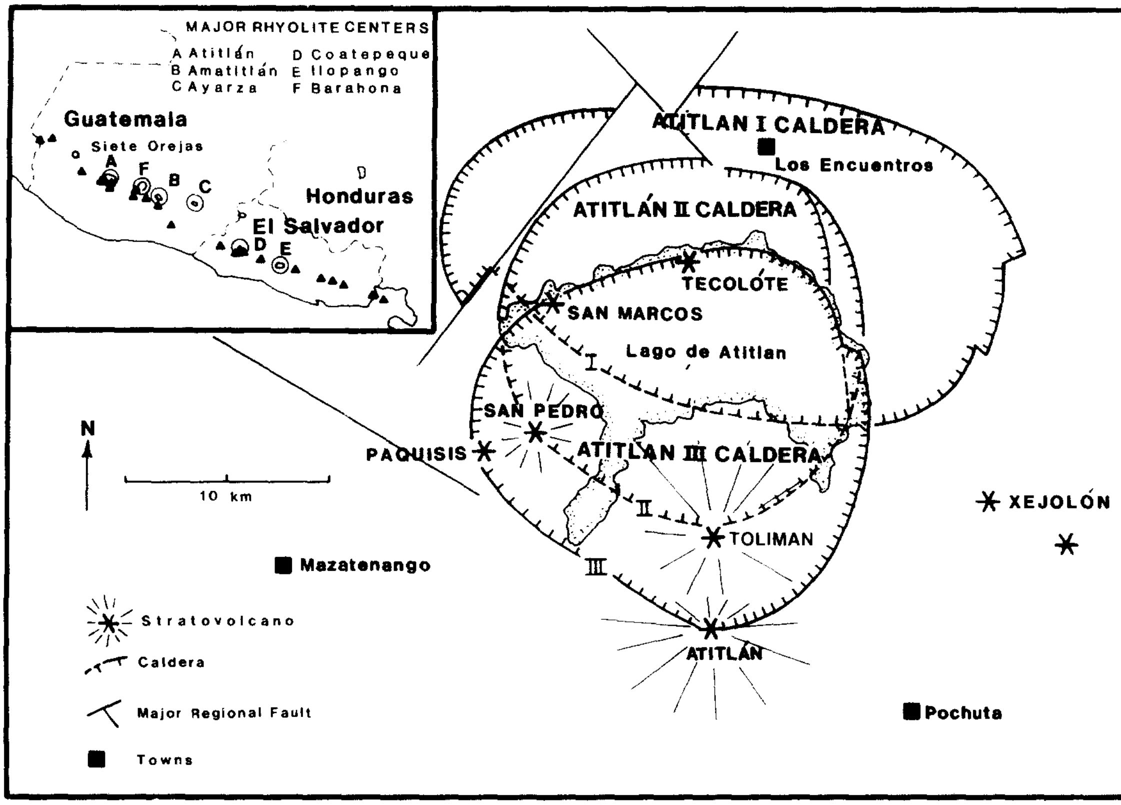

Fig. 1. Map of Atitlán area showing locations and features named in text. Inset: map of northern Central America, showing the location of Atitlán Caldera and other calderas (circles) relative to active composite volcanoes of the volcanic chain (triangles).

that three overlapping calderas have formed at Atitlán in the last 13 m.y. with a southerly migration of the locus of collapse (Fig. 1). The present-day caldera (Atitlán III) is the youngest; the other two are largely filled with sediments and volcanic deposits. This paper describes silicic pyroclastic deposits of Atitlán III (Fig. 1), discusses the eruptive history and presents data on the magma types present.

Stratigraphy

Figure 2 is a simplified composite section of the silicic pyroclastic deposits from Atitlán III caldera, which result from five eruptive periods in roughly the past 150,000 years. Descriptive terminology follows Wright et al. (1980). Most of these pyroclastic rocks have $SiO_2 = 70–77$ wt.%, locally admixed with minor amounts of basalt and basaltic andesite. This kind of admixture is more important in other, smaller volume, volcanic centers in Central America (Bornhorst and Rose, 1981).

Sampling and chemical analysis of silicic pyroclastic rocks

We have shown (Rose et al., 1979) that bulk analyses of samples of pyroclastic deposits do not give results which reflect magmatic compositions because they are subject to crystal concentration processes (Walker, 1972) and lithic and/or xenocrystic contamination. All of the samples analyzed in this study are ultrasonically cleaned pumices. Individual whole pumices were used when possible, but when the masses of individual pumices were less than a few grams we selected groups of individual small

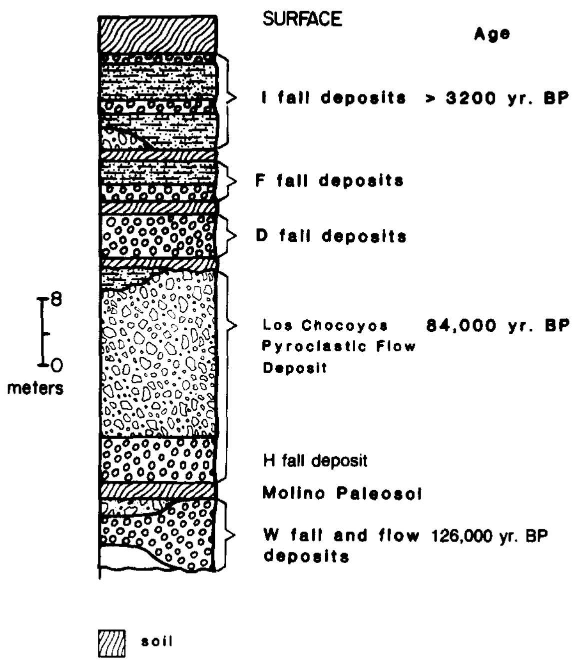

Fig. 2. Generalized composite cross section of the Atitlán rhyolitic deposits, with age dates.

pumices of similar hand-sample appearance. The individual large pumices are representative of magmatic composition, but the composite pumice samples could reflect a hybrid composition of two or more pumice (magma) types (see discussion).

The pumice was analyzed by X-ray fluorescence with an automated Phillips X-ray spectrometer system, and 35 international geochemical reference standards, using a modification of a method of Leake et al. (1970), which uses pressed rock powder pellets and a consistent ratio standard. The details of the procedure and quantitative estimates of precision and accuracy are given in Rose et al. (1986).

W fall deposit

The W pumice fall (McLean, 1970), is a crystal-rich biotite-bearing, rhyodacite to rhyolite plinian deposit, and it is the earliest recognized pyroclastic fall deposit from the Atitlán III center. Near Lake Atitlán, it has a basal basaltic andesite scoria-fall layer which grades upward over a few tens of cm through streaky to banded mixtures of basaltic andesite and rhyodacite/rhyolite pumice to more thoroughly mixed gray pumice, and then to the biotite-rich rhyodacite/rhyolite pumice which forms more than 95% of the unit. Both the silicic and mafic portions decrease in thickness and grain size away from Atitlán, suggesting a common vent area.

Distinctive features of the W fall include:

(1) The mafic base.

(2) The unusually high crystal content, up to 50 wt.% or more of the sub-4 mm fraction, compared to only 10–15 wt.% in the pumice. Phenocrysts are predominantly quartz, plagioclase and golden-brown biotite, with minor hypersthene, hornblende and magnetite. The basaltic andesite scoria contains up to 15 wt.% calcic plagioclase, pyroxene and olivine, which also appear in mixed samples alongside quartz and biotite of the rhyodacite/rhyolite.

(3) A coarse "granular" appearance, related in part to the high crystal content and in part to the generally small pumice sizes. Median pumices are typically 5 mm even where the deposit is 5 m thick.

(4) The presence, in exposures near Lake Atitlán, of elongate (up to 6–8 cm) tubular pumices, rare in silicic pyroclastic deposits, which may suggest that the W magma was more fluid than most rhyolitic melts.

(5) A pseudo-stratification marked by iron-stain bands; with rare exceptions these appear to reflect ground water leaching processes.

The W fall deposit has a maximum thickness of 9 m, and the thickness variation is shown in Fig. 3. Koch and McLean (1975) estimated an areal extent of 2700 km^2; newly recognized locations northwest and southeast of the lake extend the area within the 1-cm isopach to about 10,000 km^2. Using data from McLean (1970), Koch and McLean (1975), Eggert and Lea (1978) and the present study, the volume is at least 3 km^3 dense rock equivalent (DRE) and, if the area/thickness trends are extrapolated, it

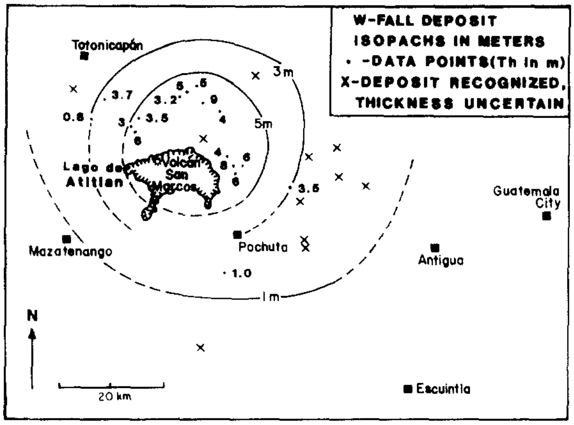

Fig. 3. Map of measured thickness of the W fall deposit, Guatemala.

may be as much as 8 km^3 DRE. A crystal enrichment factor (Walker, 1972) of up to 7.3 suggests that much fine, vitric dust was widely dispersed in the eruption cloud (c.f. Walker, 1980). The rhyolite has a volume at least 25–30 times greater than the basaltic andesite.

McLean (1970) described localities near Paticizia where the W fall deposit was interfingered with ashes (S, X, Y, etc.) which were erupted from the Barahona caldera near Antigua (Bornhorst and Rose, 1982). Because the Barahona deposits continue to the Guatemala City basin, they also provided a link with the Amatitlán stratigraphy and their dates. Unfortunately, these exposures are now so modified by weathering and slumpage that we cannot find W. Although we have verified with major- and minor-element geochemistry nearly all of the Koch and McLean exposures and many new ones, we cannot verify the interfingering of W with the Barahona units without new roadcuts.

W pyroclastic flow deposits

Two pyroclastic flow deposits found southeast (and possibly southwest) of Lake Atitlán were also produced by the W eruption. They bracket the fall deposit. The lower one is very poorly sorted and consists of approximately 90 wt.% ash and 10 wt.% pumice lapilli. The pumice contains 5% biotite and 5% quartz by volume. The deposit is nonwelded where it is thickest, but is incipiently welded over several km^2 south and east of Pochuta (Gardner and von Eschen, 1980). A highly weathered, quartz-rich pyroclastic flow deposit exposed southeast of Mazatenango on the coastal plain, some 40–50 km from Atitlán, probably correlates with the lower W flow and other parts of the coastal area south of Atitlán were at one time possibly covered by up to 5 m of this deposit.

The upper flow deposit is a block-and-ash flow, with abundant (25–50%) round, cobble-size clasts of slightly vesicular biotite-quartz rhyolite, in a poorly consolidated matrix of fine ash. There is little or no lapilli-size pumice, and 1% of lithics. Although the deposit resembles a lahar the presence of only one lithology and the fact that the fine-grained ash matrix has the same mineralogy suggests that it is a pyroclastic flow deposit. The large clasts have a distinctive "crystalline" appearance but are slightly vesicular and are predominantly phenocryst-rich glass. They probably represent large blebs of magma which vesiculated only slightly before being cooled and carried off in the pyroclastic flows.

The W pyroclastic flow deposits cover at least 200 km^2 and have an average combined thickness of 15 m yielding a volume of ca. 2 km^3 (DRE). The total volume of W is therefore 5–10 km^3 (DRE), similar in volume to the 1902 Santa María eruption (Williams and Self, 1983), but the fall deposit is not nearly as widely dispersed, suggesting that it resulted from a much lower eruption column. The exact source is unknown, but the distribution of the coarsest pumice and lithic clasts suggest that the vent area was within the Lake Atitlán basin.

Geochemistry of the W rhyolite

Chemical analyses of pumice from W fall and flow deposits are presented in Table 1. The ba-

TABLE 1

Chemical analyses of W fall and flow pumices (XRF, recalculated H_2O-free)

Unit:		1 Lower W flow	2 W fall scoria	3 W fall	4 W fall	5 W fall	6 W fall	7 Upper W flow	8 Upper W flow
Wt.%:	SiO_2	72.97	52.76	70.54	72.79	75.84	75.62	75.31	74.87
	Al_2O_3	15.38	22.56	17.40	17.18	14.31	14.07	13.57	13.94
	Fe_2O_3*	2.23	10.21	2.54	2.35	1.96	1.45	1.62	1.54
	MgO	0.44	3.08	0.55	0.47	0.38	0.33	0.35	0.32
	CaO	1.89	7.07	2.13	1.98	2.18	1.65	1.17	1.33
	Na_2O	3.51	2.33	3.43	2.93	2.87	2.76	2.89	3.71
	K_2O	3.29	0.99	3.07	2.03	2.28	3.90	4.84	4.08
	TiO_2	0.28	0.87	0.31	0.27	0.17	0.18	0.20	0.21
	P_2O_5	0.02	0.14	0.03	0.02	0.02	0.05	0.04	0.02
ppm:	Rb	129	41	134	122	116	126	145	141
	Sr	282	619	298	302	335	331	148	189
	Y	12	13	16	6	3	8	9	15
	Zr	137	89	121	104	118	112	111	105
	Ba	810	631	874	1200	810	888	866	828
	La	27	14	28	8	19	18	22	33

*Total Fe as Fe_2O_3

Sample descriptions:

No.	Location	Sample type
1. 2540a	Near Pochuta	Pumice block
2.81T60B	Godinez	Composite of basaltic tephra
3. 2540b	Near Pochuta	Composite of pumices
4. 2712	Jct. of CA1 and Solola rd	Composite of pumices
5. LC/SOL-2	Godinez	Composite of pumices
6. 2711	Near Nahuala	Composite of pumices
7. 726	Godinez	Composite of pumices
8. 2100	S of Pochuta	Pumice block

saltic andesite magma (analysis 2) was restricted to the earliest part of the W fall and is of minor volume. Its composition contrasts sharply with the rhyodacite and rhyolite (analyses 1, 3–8) but it is quite similar to basaltic andesite lavas of pre-W age stratovolcanoes in the area (Newhall, 1980).

Bulk compositions of W are quite variable and include rhyodacite and rhyolite ranging from 70 to 75 wt.% SiO_2. Stratigraphic compositional trends are slight with a tendency toward an upward increasing SiO_2 among the rhyolites (Table 1). Pumice from the lower flow deposit has a lower Si and K content than pumice from the upper flow deposit, and the plinian pumice generally falls between these two limits.

The Los Chocoyos Ash

The next youngest silicic pyroclastic deposit is the Los Chocoyos Ash (Koch and McLean, 1975; Hahn et al., 1979), which occurs above a distinct paleosol (the Molino paleosol of Koch and McLean), representing an hiatus in large-scale explosive activity (Fig. 2). The Los Chocoyos Ash can be divided into three depositional members: fall, flow and surge. The fall deposit is referred to as H.

H pumice fall member

The H pumice fall is well sorted, consists of a uniform type of white pumice, and is often doubly graded from sandy ash at the base to 1–10 cm lapilli in the bulk of the deposit to coarse ash-sized pumice at the top. Blade-shaped lapilli are common. Pumice lapilli and blocks do not contain tubular vesicles, unlike those of the succeeding pyroclastic flows. The pumice is a crystal-poor (1–5%), biotite-bearing rhyolite which varies only slightly in its bulk chemistry. There is a slight tendency toward a more silicic composition upward (Table 2). Overall, it is more silicic and has a higher K_2O content than any of the Atitlán units. We use the term high-K rhyolite to distinguish it.

H is the largest plinian fall deposit known in Central America. Its maximum observed thickness is only 3.6 m, but it thins very gradually away from Atitlán and is preserved over the entire Guatemalan Highlands (Fig. 4). One of the most significant aspects of the Los Chocoyos eruption is very wide dispersal. Drexler et al. (1980) demonstrated that ash from this eruption was dispersed from the Straits of Florida to the Panama Basin. The dispersal pattern seems to have two directions, one to the north and one to the south. One question is whether the deep sea ashes are mostly derived from the early plinian (H) phase. If so, the total volume of the fall deposit would be 150–160 km^3 (DRE) and the dispersal index D (Walker, 1973) would be 100,000 km^2. However, it is possible that some or all of the deep-sea ash is of coignimbrite type, dispersed from the pyroclastic flow members. We note that:

(1) The composition of the pyroclastic flow is much more variable than the H fall because it includes a rhyodacite component.

(2) Both the D (Pacific) and YB (Gulf of Mexico) ash layers are mostly like the biotite-bearing high-K pumice, which makes up all of the H fall and most of the pyroclastic flow.

(3) The glass in Pacific (D) ash is more variable than the Gulf of Mexico ash (Taylor et al., 1981) and the Pacific ash has more variable trace-element concentrations (Drexler et al., 1980).

(4) The morphology of the Pacific ash, from SEM imagery, is also more complex than the Gulf materials.

We suggest, tentatively, that the Pacific ashes are at least partly of coignimbrite origin while the Gulf ashes may be entirely derived from the H plinian phase.

TABLE 2

Bulk composition of selected samples of H fall deposits (XRF, recalculated to 100% H_2O-free)

		1	2	3	4	5
Wt%:	SiO_2	74.93	75.89	77.47	77.22	74.8-77.5
	Al_2O_3	15.96	15.04	13.38	13.42	13.0-16.1
	Fe_2O_3*	1.02	0.96	0.72	0.76	0.72-1.30
	MgO	0.16	0.16	0.14	0.17	0.10-0.32
	CaO	0.72	0.78	0.70	0.70	0.70-1.10
	Na_2O	3.03	2.87	3.07	3.23	2.18-3.58
	K_2O	4.00	4.12	4.38	4.34	3.74-4.82
	TiO_2O	0.16	0.16	0.13	0.13	0.12-0.18
	P_2O_5	0.02	0.02	0.02	0.02	0.01-0.03
ppm:	Rb	129	125	134	132	116-139
	Sr	116	123	110	108	108-188
	Y	16	16	14	15	11-81
	Zr	74	77	67	65	59-81
	Ba	915	898	829	824	830-990

*Total Fe as Fe_2O_3.
1-4 = Composite pumice samples from consecutive stratigraphic levels of the H fall deposit at Godinez. 1 = stratigraphically lowest, 4 = stratigraphically highest (2566).
5 = Range of 21 composite pumice samples collected all over Guatemala (see sample map in Hahn et al., 1979, fig. 10).

Los Chocoyos pyroclastic flow member

Most of the valleys of western Guatemala are filled with up to 200 m of non-welded Los Chocoyos pyroclastic flow deposits (Koch and McLean, 1975; Hahn et al., 1979). Similar deposits up to 50 m thick (reworked in places) are found along the Pacific coastal plain as far

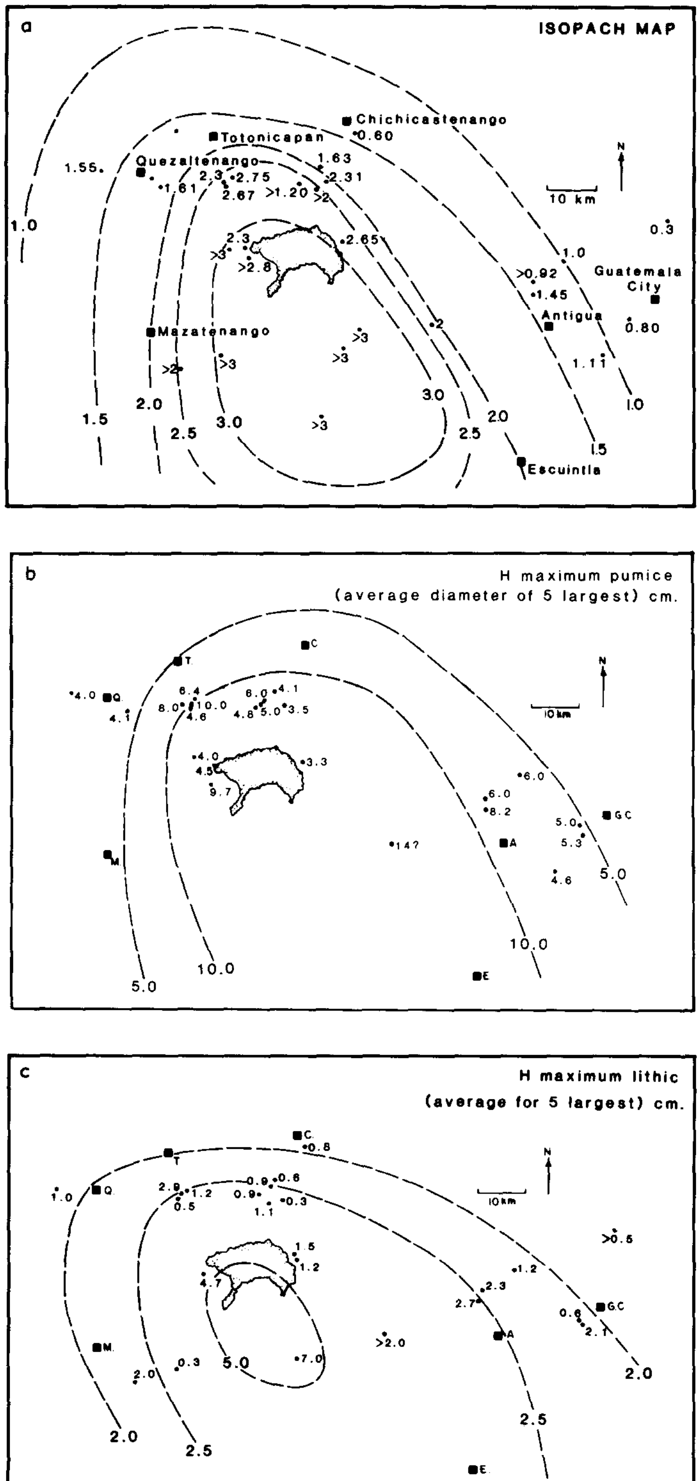

Fig. 4. Maps showing the measured thickness in meters (4a) and maximum clast sizes [pumice (4b) and lithic (4c)] in the H fall deposit of the Los Chocoyos Ash, Guatemala.

east as Escuintla and at least as far west as Mazatenango (Fig. 5). It has not been identified within the present (Atitlán III) caldera, although it is not known whether the approximately 300 m of low-velocity material on the floor of the lake includes any primary flow deposit (Newhall et al., 1987, this issue).

Hahn et al. (1979) estimated the volume of the ash flow deposits to be 100 km^3 DRE. If coastal plain deposits are included and if they covered 2000 km^2 to an average thickness of 20 m, the total volume may be about 120 km^3 DRE.

Los Chocoyos ignimbrite in the Atitlán area is a poorly sorted, non-welded deposit consisting of pumice, crystals, ash and lithic fragments. Average component analyses are 80–90 wt.% ash, 10–20 wt.% lapilli and block size pumice and 0–5 wt.% lithics. Most pumice clasts are 1–20 cm diameter, but a few are as large as 1 m. Pumice has 5–15 vol.% phenocrysts, with biotite and amphibole (both hornblende and cummingtonite) as the principal mafic phases, and plagioclase and quartz as the principal felsic phases. Pumice usually contain either biotite or hornblende, suggesting that two magma types are represented: high-K, crystal-poor biotite rhyolite, and low-K hornblende rhyodacite (Rose et al., 1979). Both magma types are less porphyritic than other silicic units of the Guatemalan Highlands. Another distinctive aspect of the Los Chocoyos pumice is tubular vesicles, which suggest that vesiculation was occurring deep in the conduit and/or in hot ductile magma. At the top a salmon-pink coloration commonly occurs. Koch and McLean (1975) concluded this resulted from oxidation of iron as the flow cooled.

Lithic fragments are common and are predominantly andesite with lesser amounts of friable granitic to dioritic rocks. No other Quaternary ash flow of the highlands is known to have incorporated such an abundance of "plutonic lithics" (Koch and McLean, 1975). A lithic-rich layer several meters thick, with 20–30 wt.% lithics, is locally present about 1 m above the base of a lower flow unit.

Distal exposures show evidence of multiple flow units. At Totonicapán in the Quezalten-

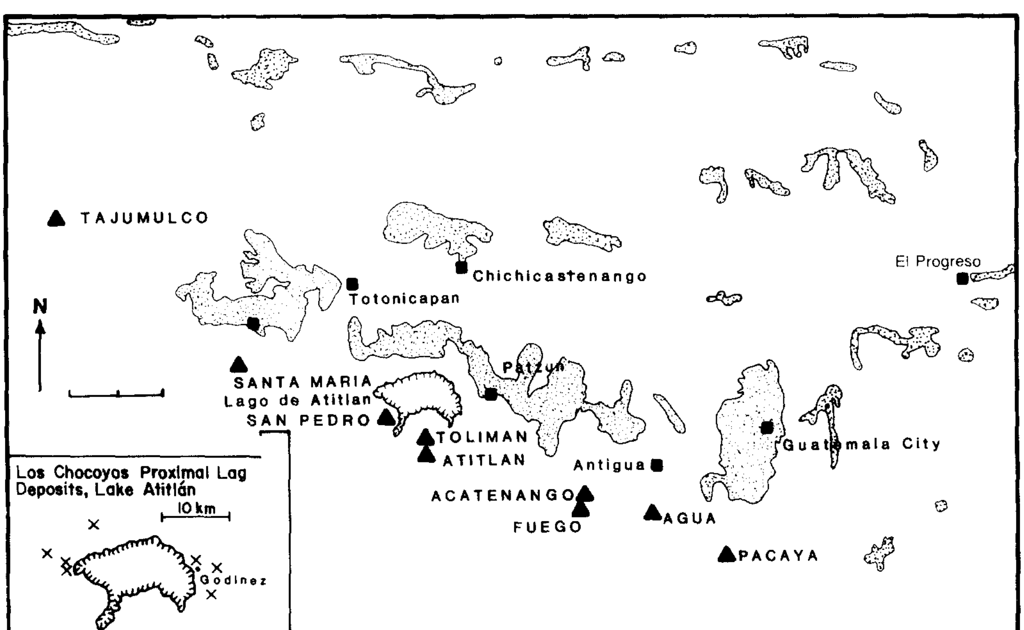

Fig. 5. Map of distribution of Los Chocoyos ignimbrites (after Hahn et al., 1979). Inset shows the distribution of proximal lag deposits of the Los Chocoyos pyroclastic flows. Scale bar is 20 km.

ango Valley, two flow units are observed, while in the Guatemala City area, three flow units occur, divided by zones of rafted pumices. The pink top is preserved even in very thin (0.5 m) exposures, at extreme distal locations (such as El Progreso, Fig. 5) or where the flow is an ignimbrite veneer deposit, on ridges between valley fills, such as near Los Encuentros.

The ignimbrite is never welded, in spite of the fact that single flow units sometimes exceed 100 m in thickness. Many valleys filled by pyroclastic flows were located on the opposite side of topographic barriers of several hundreds of meters. The great mobility of the Los Chocoyos flows and the total lack of welding are consistent with an eruption in which a very high column collapsed. This would have caused the pyroclastic flows to overrun topographic barriers and the large amount of atmospheric admixture in the column would have cooled the particles to temperatures too low to weld after deposition.

Wright and Walker (1977) described co-ignimbrite lithic lag fall deposits which form near ignimbrite vents from the coarsest and densest fraction of a collapsing eruption column. Druitt and Sparks (1982) have also described proximal lithic lag breccias at Santorini. At Atitlán, deposits similar to lag fall deposits and proximal lag breccias form crudely stratified units containing 25–80% lithics (pebbles to boulders) and 5–30% fibrous pumice (like that of the ash-flow but generally in smaller, broken pieces), and a small amount of finer matrix. These deposits exceed 20 m in thickness between Godinez and Los Robles just east of the caldera but are typically 3–5 m thick (Fig. 5, inset). They are interpreted to be proximal lithic breccias as they occur within 6 km of the caldera rim, or 10–13 km from the center of the caldera. Their significance is that they are strong evidence that the Los Chocoyos eruption was from the present-day Atitlán caldera.

Los Chocoyos surge deposits

Spectacular surge deposits from a late stage of the Los Chocoyos eruption are exposed northwest of Lake Atitlán near Novillero, northeast of Lake Atitlán and north of Godinez, and in barrancos cutting pumiceous valley fill near Patzun. They mostly show "sand wave" bedding (Wohletz and Sheridan, 1979), have discontinuous and often cross-bedded lapilli and ash horizons, and locally show U-shaped channels similar to those described by Fisher (1977). Most grains are sand-size ash to coarse lapilli, but some layers contain coarse pumice (up to 45 cm diameter). Individual beds are typically well-sorted, but a few are poorly sorted and resemble the Los Chocoyos ignimbrite. Surge beds may contain up to 5–10%, and rarely up to 30%, of lithics (the same suite as in the ignimbrite). Distal surge deposits near Patzun tend more toward the "planar" facies of Wohletz and Sheridan (1979), but still exhibit fine-scale lensing of individual beds and occasional cross-bedding. The volume of the surge deposits is only 1 km^3 DRE. They may have resulted from phreatomagmatic explosions in the newly-formed caldera after the climactic eruption.

Geochemistry of the Los Chocoyos (H) deposits

Chemical analyses of a stratigraphic sampling of pumice clasts from the H fall member are given in Table 2 and Fig. 6. They show a slight change upwards from rhyolite to high-silica rhyolite, that may reflect a slight but real inverse compositional gradation at the top of the magma body.

The Los Chocoyos pyroclastic flow deposit contains two distinct pumice types (Table 3): a high-K biotite rhyolite which is compositionally identical with the upper part of the (H) pumice fall and a low-K hornblende rhyodacite which chemically resembles the earlier W pumice (see also Rose et al., 1979). The composition of the rhyodacite is more variable than the rhyolite (Fig. 6). Rose et al. (1979) have shown that the ignimbrite in the Quezaltenango Valley is a mixture of about 60% rhyolite and 40% rhyodacite. Pumice blocks of the two magmas commonly occur together in any part of the

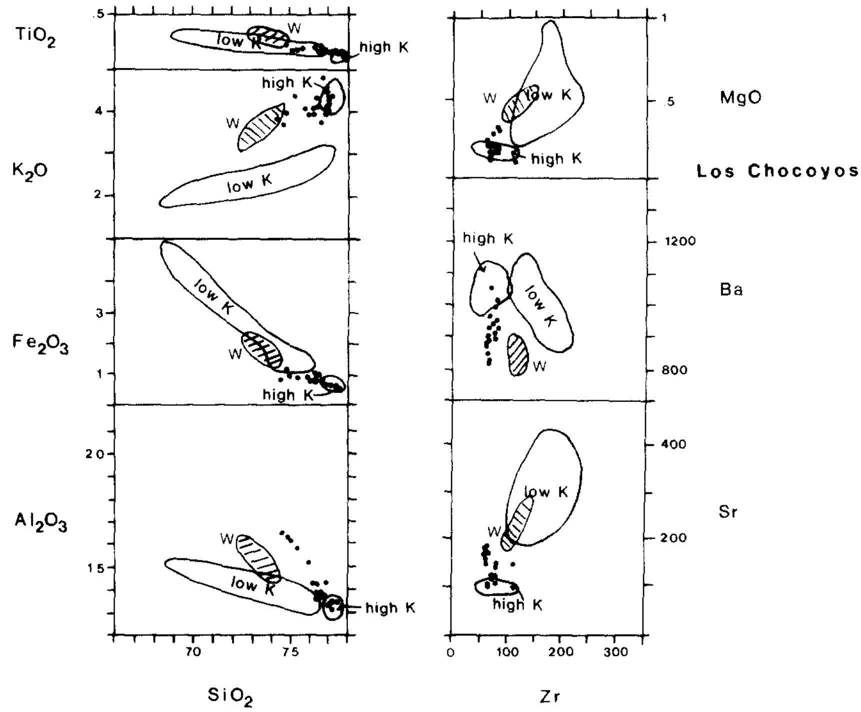

Fig. 6. Variation plots for pumices of the Los Chocoyos rhyolitic deposits with H-fall samples plotted as individual points and the fields of high- and low-K rhyolite pumices of the pyroclastic flows outlined (see Tables 2 and 3). Composition of W pumices are shown for comparison.

ignimbrite, but the relative proportion of rhyodacite increases upward (see Rose et al., 1979, fig. 7), thus a transition from high-K biotite-rhyolite fall deposit to low-K hornblende rhyodacite is reflected in the flow deposit as an upward increase in the proportion of hornblende pumice. There is a distinct compositional gap between the two pumice compositions, and the trends of variation shown are different (Fig. 6). In a few outcrops of the ignimbrite hornblende-rich basaltic andesite pumice occurs in intimate, streaky mixtures with rhyolite (784A, Table 3). Pumice in the Los Chocoyos surges is lower in SiO_2 (65–68%) than even the most mafic "hornblende-rhyodacite" samples (e.g. OL-5, Table 3).

Source of the Los Chocoyos Ash

Evidence that the Los Chocoyos Ash was erupted from and caused the formation of the youngest (Atitlán III) caldera includes:

(1) isopach maps of the H fall member and isopleth maps of maximum pumice and lithic sizes in the deposit show that the deposit is thickest and coarsest near the caldera (Figs. 6a and b);

(2) proximal lithic lag deposits are restricted to a narrow belt around the rim of the caldera (Fig. 5, inset);

(3) surge deposits are recognized only within a 25-km radius of Lake Atitlán;

(4) the largest pumice and lithic clasts in the ignimbrite occur near Atitlán;

(5) no H or pre-H deposits of any kind have been found within the caldera, implying that the caldera did not exist until the Los Chocoyos eruption; and

(6) the estimated DRE volume of the Los Chocoyos Ash (270–280 km^3) matches that of the Atitlán III caldera (ca. 260 km^3; Newhall, 1980).

TABLE 3

Bulk geochemistry of selected individual pumices from Los Chocoyos pyroclastic flow deposits

		SC7	OL4	OL5	Range (31 samples)[a]	784A
Wt.%:	SiO_2	77.61	74.34	68.24	(68.24-77.61)	54.53
	Al_2O_3	12.69	13.47	14.85	(12.69-14.85)	18.81
	Fe_2O_3*	0.65	2.02	5.47	(0.64-5.47)	8.48
	MgO	0.17	0.61	0.98	(0.17-0.98)	4.39
	CaO	0.77	2.05	3.51	(0.77-3.51)	8.35
	Na_2O	3.26	4.21	4.35	(3.26-4.95)	3.28
	K_2O	4.57	2.80	1.87	(1.87-4.68)	1.05
	TiO_2	0.10	0.28	0.46	(0.10-0.46)	1.00
	P_2O_5	0.02	0.26	0.11	(0.02-0.10)	0.12
ppm:	Rb	177	85	56	(56-117)	12
	Sr	97	238	423	(78-423)	707
	Zr	109	166	164	(55-207)	129
	Ba	1050	1050	990	(890-1140)	400
	La	20.4	22.2	33.3	(20.4-33.3)	11

*Total Fe as Fe_2O_3

SC7 = high-K rhyolite pumice block from San Cristobal Totonicapan.

Ol4 = low-K rhyolite pumice block from Olintepeque.

OL5 = low-K rhyolite pumice block from Olintepeque.

784A = hornblende andesite blebs in Los Chocoyos pyroclastic flow at Xajaxac.

[a]31 individual pumices collected in the Quezaltenango Valley and near Los Chocoyos form the basis of the range quoted. See also Rose et al., 1979, especially pp. 91-94, for discussion of this unit.

D and F fall deposits

Pumice deposits from at least five post-Los Chocoyos silicic eruptions and two to three periods of basaltic and andesitic eruptions are represented in the tephra layers around the caldera rim and at a few locations near lake level within the caldera (Fig. 7). The maximum thickness is about 60 m; no single section contains all units, much less all units at their maximum thickness. Typically, the thickness near the lake is 5–10 m. Arbitrary letter designations not already used by Koch and McLean (1975) or Hahn et al. (1979) are assigned here to newly recognized units.

The first air-fall tephra ("D1") is hornblende-plagioclase andesite with 3–5 vol.% hornblende and minor biotite. It is thickest and coarsest at the western end of the caldera (Fig. 7). Just north of San Juan La Laguna, grey and pink oxidized pumice clasts reach 25 cm diameter and the total thickness reaches 10 m. Up to 5 wt.% lithics, including granite, diorite, and dacite are included. A 1-m-thick layer of weathered ash separates this unit from the underlying Los Chocoyos lithic lag deposits.

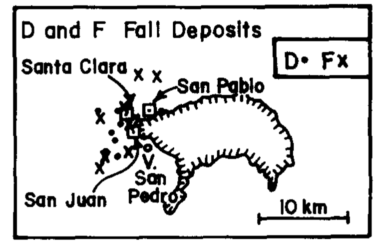

Fig. 7. Map showing the sites where D and F fall deposits are found.

The next youngest unit ("D2"), consists of 1 m of airfall pumice lapilli (maximum pumice diameters = 6 cm) between two 1-m-thick grey ashes. Both ashes contain sandy beds and occasional pumice lapilli; the lower ash is fine-grained, white and contains accretionary lapilli in several outcrops at the west end of the lake. A thin paleosol and/or some minor water-reworked or surge deposits separate it from the underlying "D1" tephra. The top of the upper ash is fine-grained and pinkish-grey. The thickness, maximum pumice and lithic size, and the presence of accretionary lapilli in western outcrops all suggest that D2 was erupted from near the vent for the D1 tephra. However, its rhyodacite composition is very different from D1, and similar to W and the low-K Los Chocoyos magmas (Table 4). The thickness of both of the D units decreases to the west, consistent with a local source.

The mafic composition of D1, and its stratigraphic proximity to the terminal Los Chocoyos pyroclastics which contain mafic blebs (784A, Table 4) shows that mafic magmas erupted at Atitlán, even at the time of the largest rhyolitic eruptions.

Overlying D2 is a sequence of 5 andesitic ashes, separated by thin (several cm) paleosols. The maximum combined thickness is 4 m, they are thickest and coarsest near San Pedro

TABLE 4

Chemical compositions of selected samples of D fall deposits (XRF, recalculated to 100% H_2O-free)

		1	2
Wt.%:	SiO_2	58.51	70.68
	Al_2O_3	18.38	17.25
	Fe_2O_3*	7.25	2.71
	MgO	3.46	0.65
	CaO	6.27	2.09
	Na_2O	3.47	3.44
	K_2O	1.78	2.80
	TiO_2	0.76	0.33
	P_2O_5	0.13	0.04
ppm:	Rb	53	96
	Sr	631	282
	Y	19	6
	Zr	163	145
	Ba	658	1157
	La	11	14

*Total Fe as Fe_2O_3
1 = D1 fall deposit (1429c), near Santa Clara La Laguna, Composite pumice.
2 = D2 fall deposit (1193j), San Juan La Laguna, Composite pumice.

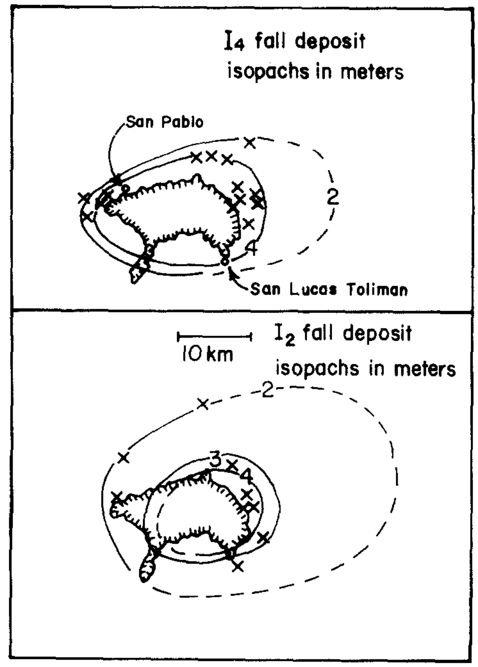

Fig. 8. Isopach maps of the I2 and I4 fall deposits, Lake Atitlán area.

volcano, and it is likely that they mark early andesitic eruptions of San Pedro. No letter designation has been assigned.

At several exposures on the western side of Lake Atitlán, a 2-m-thick sequence of silicic lapilli and ash fall deposits (F) overlie the 5 andesitic ashes. We do not know enough about the distribution of F to tell if they have a local source. They are hornblende-bearing rhyodacites like the D and I deposits (Table 4), but because they might be unrelated to Atitlán, we do not consider them in subsequent discussion.

I pyroclastic deposits

The I pyroclastic deposits are phreatomagmatic, including alternating ash-fall and pumice-lapilli fall layers, surge deposits, and a small pumice and ash flow deposit. Three or more I eruptions produced texturally and chemically similar deposits separated by 2–10 cm paleosols. Deposits from the first eruptions (I1) are mostly surge beds overlain by a thick, fine grey ash. The surge deposits are best exposed on the southeastern caldera rim, and the fall deposit is thickest to the northeast (Fig. 8). Accretionary lapilli are common in the thicker proximal portions of I1. Both ash and lapilli in I1 contain small amounts of plagioclase, quartz, biotite and hornblende.

A 75-cm-thick layer of andesitic or basaltic lapilli overlies I1 at San Pablo La Laguna; elsewhere a thin paleosol separates I1 and I2. I2 eruptions began with surges and a small ashflow. A 60-m-thick, non-welded ignimbrite in I2 underlies surge deposits southwest of the lake. Most of the surge ash is sparsely porphyritic, but some beds contain up to 20–30% of plagioclase, quartz, biotite and hornblende. Locally, as near San Lucas Tolimán, the surge deposits are pink.

A thin paleosol separates I2 from I3 northwest and northeast of Lake Atitlán. The base of I3 is a fine white ashfall with accretionary lapilli and locally abundant plant fossils. As much as 30 cm of basal ash is overlain by as

TABLE 5

Chemical composition of selected samples of I fall deposits (XRF, H_2O-free)

		1	2	3	Total range (18 samples)
Wt.%:	SiO_2	71.20	72.49	68.15	67.5-73.4
	Al_2O_3	15.81	15.07	19.41	14.4-20.4
	Fe_2O_3*	2.61	2.41	2.83	1.42-3.65
	MgO	0.69	0.84	0.45	0.38-1.01
	CaO	2.24	1.74	2.74	1.61-3.52
	Na_2O	4.04	3.25	3.50	2.34-4.20
	K_2O	3.00	3.80	2.52	2.57-3.80
	TiO_2	0.35	0.34	0.37	0.22-0.47
	P_2O_5	0.05	0.05	0.03	0.03-0.08
	Total	100.0	100.0	100.0	
ppm:	Rb	90	118	83	75-118
	Sr	312	239	440	257-451
	Y	6	8	5	3-13
	Zr	154	148	176	129-200
	Ba	1054	1095	1112	879-1170
	La	18	24	20	14-26

*Total Fe as Fe_2O_3
1 = I_1 fall deposit (1193f), San Pablo La Laguna, Composite pumice.
2 = I_2 fall deposit (758d), near Godinez, Composite pumice.
3 = I_4 fall deposit (3114), near Nahuala, Composite pumice.

much as 5 m of pumice lapilli with plagioclase, quartz, 3–4% biotite and subordinate hornblende and hypersthene. Some I (I3?) tephra fell on the flanks of the San Pedro, where it overlies the A4.0 lava flow of Rose et al. (1980).

I4 rests on I3 without an intervening paleosol. The base of I4 is usually a surge deposit. It is overlain by a thick layer of fine grey accretionary lapilli-bearing ash.

I4 is overlain by up to 0.9 m of a white plinian pumice lapilli fall (I5). There is no obvious paleosol on I4 but a local unconformity is present north of Godinez. I5 is thickest on the northwest side of Lake Atitlán. It is not graded; pumices average about 1 mm in diameter, and attain a maximum diameter of 2 cm. Ash-size mafic lithics are abundant. Pumice has minor amounts of hornblende and scarce biotite. I5 fall is overlain by about 1.5 m of brown soil.

The I sequence includes base surge to phreatoplinian (and plinian) deposits and probably resulted from eruptions through Lake Atitlán. Self and Sparks (1978) infer that the ash was finely comminuted by explosive interaction of the magma and lake and/or groundwater, and when moistened by steam formed accretionary lapilli. The surge deposits are also phreatomagmatic (cf. Moore, 1967; Fisher and Waters, 1971). The plinian pumice reflect a time when the magma was isolated from the lake water, by construction of a cone above lake level (cf. Surtsey, 1963–1964), or by a temporary reduction in lake level. There is no pyroclastic cone visible now or revealed by seismic profiles of the upper 200 m of Atitlán's lake sediments, so any such cone was either destroyed by later eruptions or is buried and lacks enough contrast with lake sediments to be seen in seismic profiles (Newhall et al., 1987, this issue).

The volumes of I1–I5 are estimated to be 2.1, 1.4, 0.2, 1.7 and 0.1 km^3 DRE, respectively, with large uncertainties. The bulk chemical compositions are all similar, and there is no consistent chemical or mineralogical change with stratigraphic position (Table 5 and Fig. 9), nor any apparent relation between the volume of individual I deposits and their chemical composition. The average composition is rhyodacitic, and is similar to the W, D and Los Chocoyos rhyodacites (Fig. 9). The variation trends are similar to the whole rock and glass trends described by Rose et al. (1979, p. 95) for the low-K Los Chocoyos magma.

Dates of Atitlán silicic eruptions

Dating of eruptions in Guatemala has presented problems. Many of the rocks are too young to be dated accurately by K-Ar methods and too old to be dated by ^{14}C analysis of incorporated charcoal. Major contributions to establishing a chronology for these eruptions were made by Koch and McLean (1975), who made the first stratigraphic synthesis, and by Drexler et al. (1980) who correlated the Los Chocoyos deposits to dated deep sea cores. Figure 10 summarizes the stratigraphic relationships, together

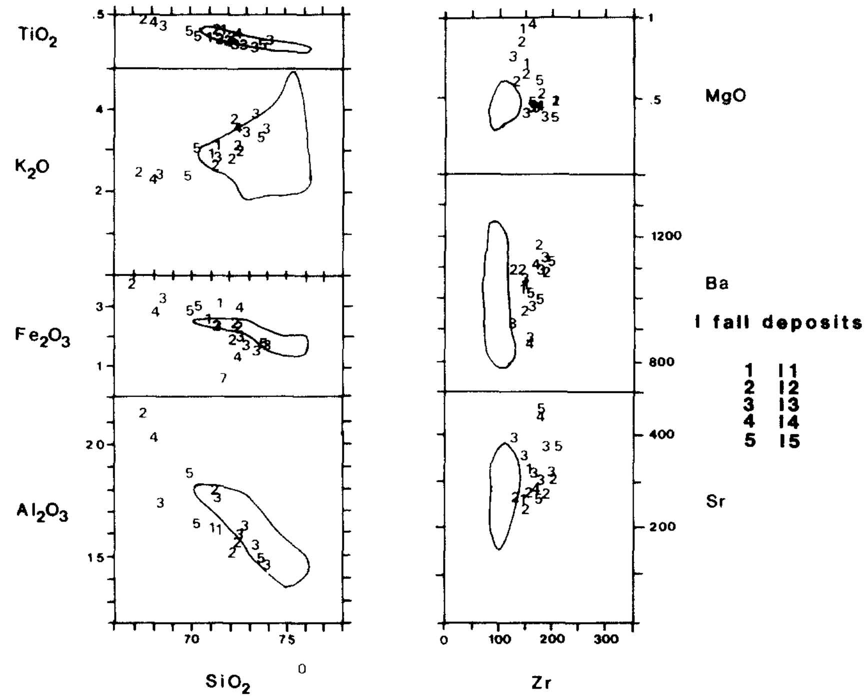

Fig. 9. Variation plots (as Fig. 6), for pumices of the I fall deposits. For reference, the field of W deposits is outlined.

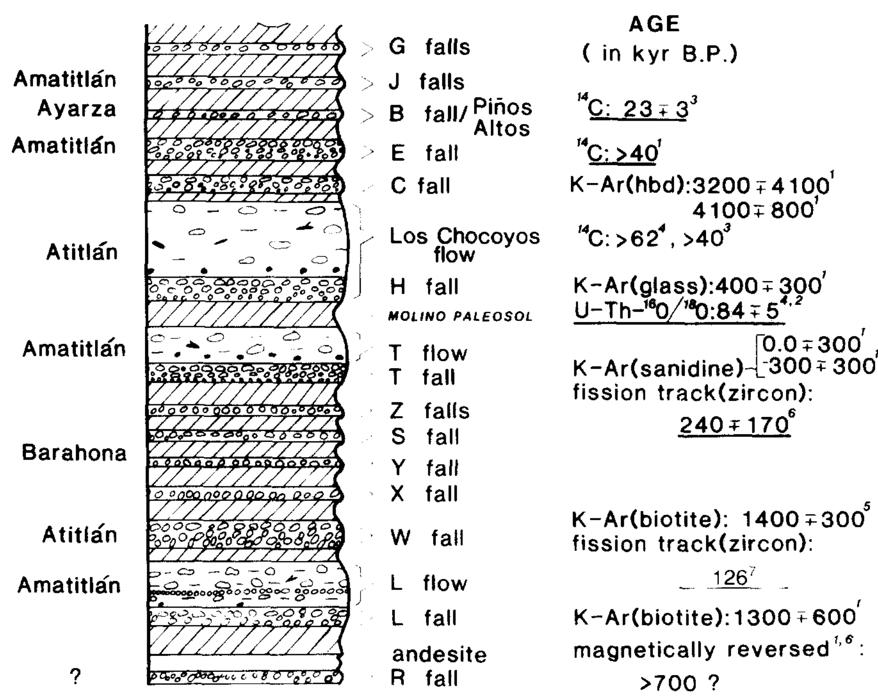

Fig. 10. Composite cross section of Quaternary pyroclastic units of the Guatemalan Highlands, showing stratigraphic relationships, age dates and caldera sources. Modified from Koch and McLean (1975). Where more than one age is given, the preferred age is underlined. Sources (denoted by superscripts in AGE column): 1 = Koch and McLean, 1975; 2 = Hahn et al., 1979; 3 = Peterson and Rose, 1985; 4 = Drexler et al., 1980; 5 = McLean, 1970; 6 = Wunderman and Rose, 1984; 6 = Table 6.

TABLE 6

Results of fission-track age determinations of sample GU/LA 2703a, W pyroclastic fall deposit, near Godinez (C.A. Chesner)

Grain no.	Natural tracks	Detector tracks	Grain age (kyr.)	Cumulative age (kyr.)
9-1	3	760	113	113
9-2	1	473	61	93
9-3	0	208	-	79
9-4	1	493	58	74
7-1	3	949	91	80
7-2	11	1031	306	140
7-3	4	729	157	142
7-4	3	666	129	140
7-5	1	610	47	130
7-6	5	1371	105	126
Summary	32	7290		126 ± 22

with present information on ages. One K-Ar sanidine age of T fall deposit from Amatitlán is consistent with a fission track zircon age of the same unit. Usually K-Ar dates on hornblende, glass and biotite give ages that are older than the fission track ages. The K-Ar ages for some units (e.g., C) are clearly unreasonable. In the case of the W biotite date, we believe that the occurrence of biotite of xenolithic origin may have affected the result, because in most biotite separates we have observed a significant proportion of altered, optically different biotite. A discussion of the problems of dating such rocks and the advantages of the fission track method was given by Chesner (1984). For Atitlán, our preferred ages of major eruption units are: W fall and flow, 0.126 m.y.; Los Chocoyos ash, 0.084 ± 0.005 m.y. A summary of fission track data on W is given in Table 6, and Drexler et al. (1980) discuss the age of the Los Chocoyos deposits.

Zircon in the I3 fall yielded no fission tracks, but this indicates only that it is younger than about 75,000 yr. B.P. The I5 fall must be older than 3,200 years, because an early Mayan tomb of that age is excavated into paleosol developed on that ash. From the available chronology, Atitlán must be considered to be active and could be the site of a future silicic eruption.

The stratigraphic relationships of pyroclastic units are the most direct and reliable constraints on the timing of these eruptions, because dating young rocks can be so problematic. Silicic pyroclastic deposits tend to be widely distributed and may thus interfinger with deposits from widely separated vents. Near the Atitlán caldera we find mainly thick deposits

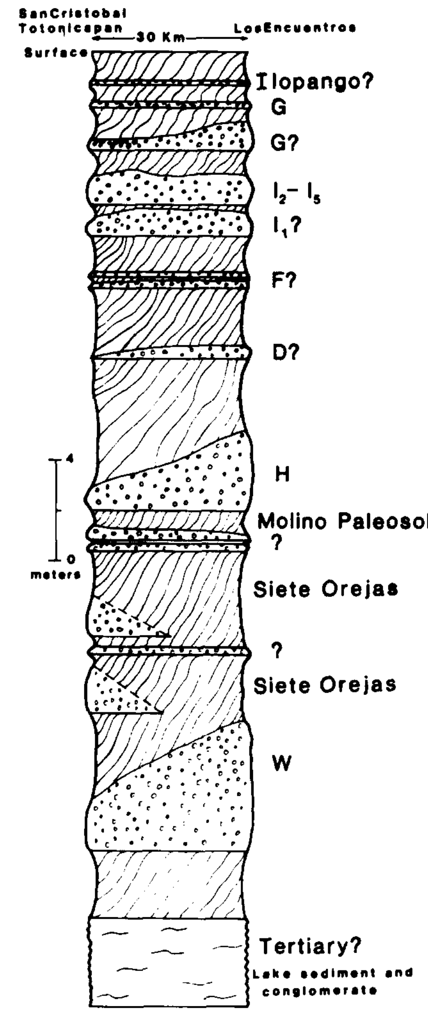

Fig. 11. Composite cross section compiled from a 30-km-long series of road cut exposures of fall deposits along CA1 from Los Encuentros to San Cristobal Totonicapán (approximately E-W across Fig. 1). A total of 42 samples were collected and approximately 80 thickness measurements are integrated. Correlations were checked with composite pumice XRF analyses. Queried deposit designations indicate equivocable correlations.

originating from Atitlán itself. To the east Koch and McLean (1975) were able to work out the relationship between some Atitlán deposits and those originating from the calderas of Ayarza (Peterson and Rose, 1985), Amatitlán (Wunderman and Rose, 1984) (Fig. 1) and Barahona (Bornhorst and Rose, 1982). Figure 11 is a synthesis of the stratigraphy of Atitlán deposits and others originating from the west. This is based on many stratigraphic sections along Highway CA-1 for 20 km on either side of Nahaulá. The deposits in this section were correlated by geochemistry with characterized deposits from near vent. The climactic eruptions of Siete Orejas (located on Fig. 1 inset) occurred between about 126,000 (W-eruptions) and 85,000 years ago (Los Chocoyos). The sequence of all major Quaternary silicic deposits in Guatemala is now known (see also Rose et al., 1981, Fig. 3, p. 202; Peterson and Rose, 1985), although the interfingering of W with the Barahona units (see section on W-fall deposit, above) is not clearly established.

Mineralogy and geochemistry of silicic pyroclastic rocks

Table 7 summarizes the mineralogy of the stratigraphic units. Most rocks contain 80–95% glass and all contain plagioclase (oligoclase). Quartz is usually present in lesser amounts and sanidine is absent. Biotite or hornblende is the dominant mafic mineral. This allows division of the units into hornblende rhyolites and biotite rhyolites. Zircon, apatite and Fe-Ti oxides are nearly always present in trace amounts, while cummingtonite, clinopyroxene, orthopyroxene, and allanite are sometimes present.

There is alternation of eruption of mainly hornblende-bearing rhyodacite and biotite rhyolites, and the Los Chocoyos pyroclastic flow is a mixture of both types (Rose et al., 1979). The Fe-Ti oxide geothermometer gives an equilibration temperature for the rhyodacites 100°C higher than for the biotite rhyolites (Tables 7 and 8). The Kudo-Weill plagioclase geothermometer allows crude H_2O estimates for the same magmas (Table 9), showing that the Los Chocoyos rhyodacites have lower pH_2O.

Average bulk chemical analyses are given in Table 10. Excluding a very small volume of rocks which are basaltic or clearly hybrids of silicic and mafic magma (not shown on Table 10), the range of SiO_2 is from 70 to 77 wt.%. The rhyodacites and rhyolites are similar to others from orogenic continental margins and would be termed transitional calc-alkalic or high-K by Ewart (1979).

Trace element average abundances for Atitlán units are distinct from silicic rocks from other calderas in northern Central America (Fig. 12). Units erupted from the same caldera plot in distinct fields on variation plots, particularly for trace elements. It is this chemical identity of sources and particular units which has made chemical fingerprinting so successful

TABLE 7

Mineralogy of Atitlán silicic pyroclastic deposits

Magma type	Unit	Felsic minerals	Mafic minerals	Accessories
Low K	I5 fall	plag > qtz	hbd > opx	mag, ilm, apt, biot, zirc
Low K	I3 fall	plag > qtz	bio > hbd > cpx = opx	mag, ilm, apt, zirc
Low K	L.C.-low K	plag > qtz	hbd > cumm > cpx	mag, ilm, all, zirc
High K	L.C.-high K	plag > qutz	biot ≫ cumm	mag, ilm, zirc
High K	H fall	plag > qtz	biot ≫ cumm	mag, ilm, zirc
Low K	W fall	plag > qtz	biot ≫ cpx	mag, ilm, apat, zirc

Plag = plagioclase, qtz = quartz, biot = biotite, hbd = hornblende, mag = magnetite, ilm = ilmenite, apat = apatite, zirc = zircon, cumm = cummingtonite, opx = orthopyroxene, cpx = clinopyroxene, all = allanite.

TABLE 8

Fe-Ti oxide analyses - Atitlán tephra

Unit	Sample no.	USP	ILM	T (°C)	$\log f_{O_2}$	Magma type
Hornblende rhyodacites/rhyolites						
I5 fall	81T78	0.169	0.727	(865±53)	(−10.6±0.5)	Low K
I3 fall	81T75	0.126	0.729	(811±26)	−11.2±0.2	Low K
LCPF, Low K	TOT 7	0.132	0.672	(848±24)	(−10.5±0.2)	Low K
LCPF, Low K	OL 5	0.145	0.662	(873±50)	(−9.9±0.2)	Low K
LCPF, Low K	OL 4	0.147	0.645	(885±50)	(−10.1±0.2)	Low K
Biotite rhyolites/rhyodacites						
LCPF, High K	SC 7	0.089	0.729	(774±17)	(−11.7±0.2)	High K
LC, H-fall	SJO-4	0.097	0.766	(769±21)	(−12.0±0.2)	High K
W-fall	81T60D	0.063	0.764	(737±37)	(−12.5±0.6)	Low K
W-fall	79-4B	0.082	0.743	(763±18)	(−11.9±0.2)	Low K
W-fall	79-4A	0.081	0.744	(762±18)	(−12.0±0.2)	Low K
Biotite/hornblende rhyolite						
I3 fall	I_3-30	0.146	0.814	784±17	−12.3±0.2	Low K (?)

T and f_{O_2} calculated from USP and ILM data based on model of Spencer and Lindsley (1981). Data in () are estimated since they fall outside experimental calibration.
USP and ILM calculation using method of Anderson (1968) after analysis of 6±2 grains of ilmenite and magnetite in each sample.

in Central America (Hahn et al., 1979; Drexler et al., 1980; Rose et al., 1981; Peterson, 1980).

Atitlán silicic rocks group in two distinct fields on a plot of Zr vs Sr (Fig. 13). One group includes W and I, and the rhyodacite of the Los Chocoyos flow deposits. The second group consists of H and the rhyolite of the Los Chocoyos ignimbrite. There is a composition gap between the two groups, and they show some different variation trends (Figs. 6 and 13). We refer to the two groups as the high-K and low-K groups, recognizing that the "low-K" group is low in potassium relative only to the high-K group, and not to a worldwide population of volcanic rocks. The high-K group corresponds to a high-silica rhyolite, the low-K to a composition that is transitional between rhyodacite (or quartz latite) and rhyolite. Note that the high-K and low-K chemical groupings do not coincide with the mineralogical groupings in Tables 7 and 8. Low-K rhyolites may be either biotite-bearing with equilibration temperatures of 740–780°C or hornblende-bearing with equilibration temperatures of 810–890°C. High-K rhyolites generally carry biotite and have low equilibration

TABLE 9

p_{H_2O} estimates, Atitlán magmas

Unit	Sample no.	p_{H_2O}, kbar
I5 fall	81T78	3.1
I3 fall	81T75	3.1
LCPF, low K	OL-5	1.7
LCPF, low K	OL-4	0.6
LCPF, high K	SC-7	2.0
W fall	81T6D	3.6

Results based on Kudo/Weill plagioclase-glass geothermometer, assuming Fe-Ti oxide temperatures and using plagioclase core compositions and whole rock compositions. Plagioclases show very little compositional contrast from core to rim, and the rocks have a low crystallinity (2–20% crystals).

TABLE 10

Chemical composition of silicic pumices from Atitlán

	Unit (no. of samples):	I fall (18)	Los Chocoyos			W-flow (2)	W-fall (6)
			Pyroclast. Fl. low K (16)	Pyrocl. Fl. high K (15)	H-fall (26)		
Wt.%:	SiO_2	71.6	75.7	77.4	76.6	73.8	72.8
	Al_2O_3	15.9	13.2	12.4	13.6	14.6	16.0
	Fe_2O_3*	2.47	1.71	0.86	0.86	1.90	2.20
	MgO	0.58	0.41	0.20	0.22	0.41	0.46
	CaO	2.06	1.95	0.80	0.92	1.56	1.90
	Na_2O	3.72	4.00	3.60	3.58	3.50	2.80
	K_2O	3.31	2.80	4.40	4.11	3.84	3.55
	TiO_2	0.33	0.22	0.10	0.14	0.25	0.24
	P_2O_5	0.05	0.06	0.02	0.03	0.03	0.04
ppm:	Sc	4	3.9	2.8	2	3	5
	Mn	961	520	616	579	-	740
	Rb	96	76	124	128	135	117
	Sr	319	269	109	146	236	310
	Y	8	-	-	13	14	9
	Zr	165	147	59	67	121	109
	Ba	1042	970	1135	910	819	876
	La	21	22	20	20	30	23

*Total Fe as Fe_2O_3.
- Not determined.

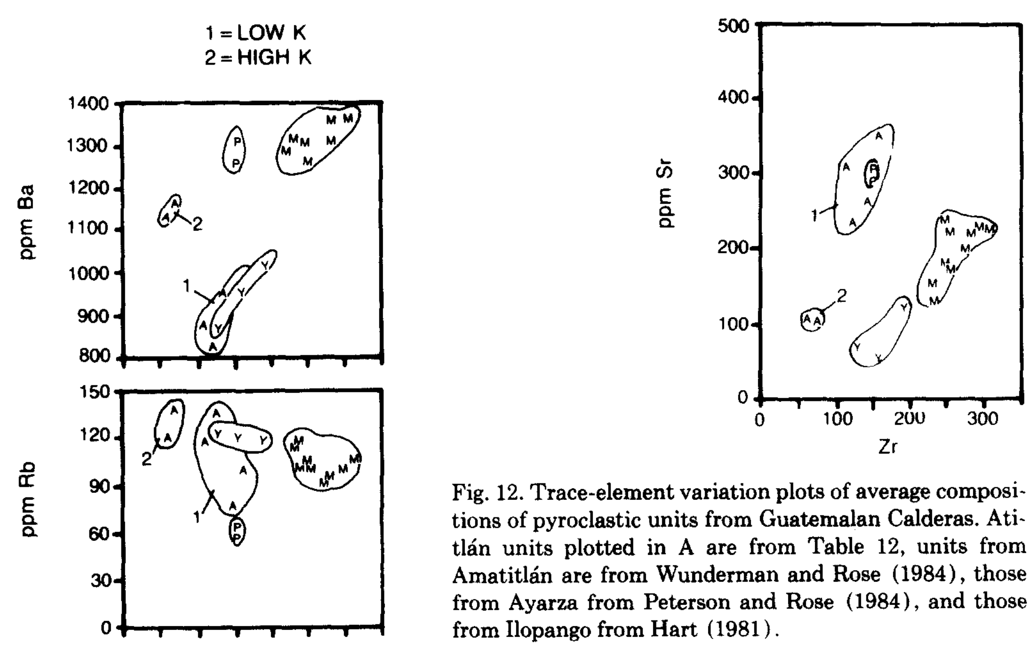

Fig. 12. Trace-element variation plots of average compositions of pyroclastic units from Guatemalan Calderas. Atitlán units plotted in A are from Table 12, units from Amatitlán are from Wunderman and Rose (1984), those from Ayarza from Peterson and Rose (1984), and those from Ilopango from Hart (1981).

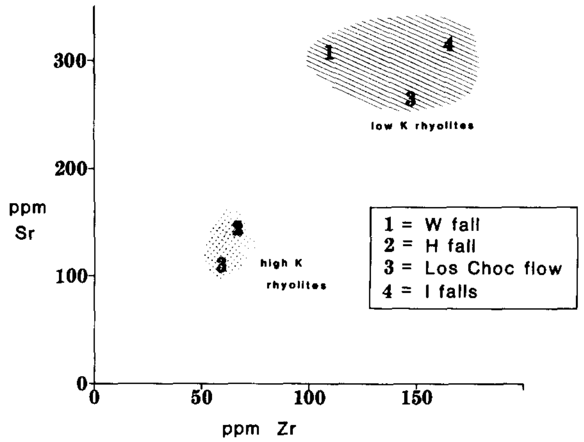

Fig. 13. Sr-Zr plot showing average compositions of the major Atitlán pyroclastic deposits from 1 to 4, in order of their eruption. The two Los Chocoyos flow compositions are each plotted with a "3". Shaded fields are drawn to encompass the high-K and low-K rhyolites. Data are from Table 12.

temperatures. We suggest that the formation of crystals in the Atitlán rhyolites took place late, after the chemical character of the rhyolites were already established. Some of the low-K rhyolite crystallized biotite at low temperatures and higher p_{H_2O} (W) and some crystallized hornblende at higher temperatures (LCPF, low-K; I3, I5). Thus, the observed phenocrysts appear to be unrelated to the major chemical variations among the rhyolites.

Discussion

Rose et al. (1979) showed that the two magma types in the Los Chocoyos ignimbrite could be related by a plausible crystal-liquid fractionation involving observed phenocryst phases in the low-K magma. Such a relationship is also consistent with the common Sr isotopic ratios of the two rhyolites. They suggested that the Los Chocoyos magma body would be a zoned pluton with a homogeneous cooler, volatile-rich top (high-K biotite rhyolite) and a hotter, drier (low-K, hornblende rhyolite to rhyodacite) and more variable lower portion. The gap between the two compositions could reflect a boundary layer segregation of high-K liquid from the crystallizing edges of the low-K magma (after McBirney et al., 1985; Baker and McBirney, 1985) to form a silicic cap on the magma body. In this paper we have the added perspective of data on other Atitlán rhyolites and more comprehensive field observations, and attempt to develop a more detailed model.

Important facts about these groups are evident from Tables 10–12 and from Figs. 6, 9 and 13:

(1) There is no simple compositional trend through time. Rather, the W pumices are largely low-K rhyolite and rhyodacite, with a small volume of dacite that is demonstrably a rhyolite-/basaltic andesite hybrid. W pumice was followed by a high-K rhyolite, then both high- and low-K erupted together, then low-K rhyodacite and dacite, and finally a succession of dacites and low-K rhyodacite.

TABLE 11

Chemical types of Atitlán silicic magmas

	Low K	High K
Critical elements		
K_2O	<3.5%	>3.5%
Sr	>200 ppm	<200 ppm
Zr	>100 ppm	<100 ppm
TiO_2	>0.2%	<0.2%
Fe_2O_3	>1.0%	<1.0%
K_2O/Na_2O	<1	>1
Stratigraphic units	W fall	
	W flow	H fall
	L.C. Low K	L.C. High K
	D_2 fall	
	I falls	Some late falls?
Mafic mineralogy	first: biotite-minor hbd.-(W) later: hbd-dom. (LCLK) last: both hbd and biot. (I)	biotite throughout little or no hbd
Interpretation	Undersaturated with saturated "top", which partially regenerates	volatile-saturated
Temperature	750 to 870°C	770°C

TABLE 12

Estimated volumes of silicic magma erupted from Lake Atitlán. Listed by magma type

	Volume, km^3 (DRE)	
Magma type:	Low K	High K
I falls	6	-
L.C.P.F. surge	1	-
L.C.P.F. flow	50?	70?
L.C. H-fall	-	150-160
W flow	2	-
W fall	3-8	-
Totals	65	230

(2) The most voluminous products, by far, are high-K rhyolite, followed by low-K rhyolite. Dacite is at least an order of magnitude less voluminous still.

(3) There is a compositional gap between low- and high-K rhyolite of the Los Chocoyos eruption (Fig. 6). Even though the compositional gap is not clear for all elements, the high- and low-K groups define different trends (e.g., in plots of K_2O and Al_2O_3 vs. SiO_2, or Ba and Sr vs Zr, Fig. 6). The high-K magma had a higher H_2O content and was 100°C cooler than the low-K magma.

(4) Some eruptions exhibit time/composition trends which suggest that a gradual zonation of the magma body existed before eruption. The H and W eruptions showed weak trends toward more silicic compositions while the low-K pumice of the Los Chocoyos eruption shows a stronger trend toward more mafic compositions. The I magma shows no clear time/stratigraphic trend.

(5) In the W eruption two radically different magmas were erupted. Most of the volume was relatively crystal-rich, biotite-bearing low-K rhyodacite to rhyolite, beginning with a pyroclastic flow of that composition followed by a plinian fall phase which was initially marked by a tiny amount of basaltic andesite and subsequently reverted to low-K pumice. We do not know how these two distinct magmas came to participate in the same eruption or whether the eruption was triggered by the intrusion of one magma into the other. The hybrid W eruption and the occurrence of hybrid rocks in the Los Chocoyos low-K rhyolite and the existence of both mafic and silicic magmas in D demonstrates that some mafic magmas were involved in volcanism throughout the period studied. Hybrid eruptions have also been documented in the youngest andesitic Atitlán volcanoes by Halsor et al. (1983, 1985). We conclude that basaltic and rhyolitic magmas have generally coexisted at Atitlán. Three mafic stratovolcanoes were active at Atitlán before the W eruptions (Newhall, 1980) and the mafic cones of Atitlán, Tolimán and San Pedro became active after the Los Chocoyos eruption (Rose et al., 1980). Thus, there is a consistent bimodal association of volcanic rocks in the area and mafic magmatism changes to predominantly rhyolitic during the caldera-formation phase and then reverts to mostly mafic volcanism afterward. The mafic-silicic-mafic sequence at Atitlán is similar to that of other nearby centers, such as Pacaya-Amatitlán (Wunderman and Rose, 1984) and the Almolonga Volcano (Johns, 1975).

(6) The low-K magma erupted in W, Los Chocoyos and I eruptions is similar in bulk composition, but differs in mineralogy, being biotite-bearing in W, hornblende-bearing in the Los Chocoyos and containing either or both biotite and hornblende in I. From this we conclude that the phenocrysts in these magmas grew after emplacement, responding to temperature and pressure conditions and are unlikely to have been responsible for the crystal-liquid fractionation discussed in Rose et al. (1979).

(7) Several lines of evidence suggest that the rhyolites and rhyodacites of Atitlán partly originated from moderate to deep crustal levels (c.f. the Fish Canyon Tuff; Whitney and Stormer, 1985); these rhyolites have steep REE patterns (Fig. 14) with depleted middle and heavy rare earth elements (Rose et al., 1979). This is consistent with a sufficient depth of origin to sta-

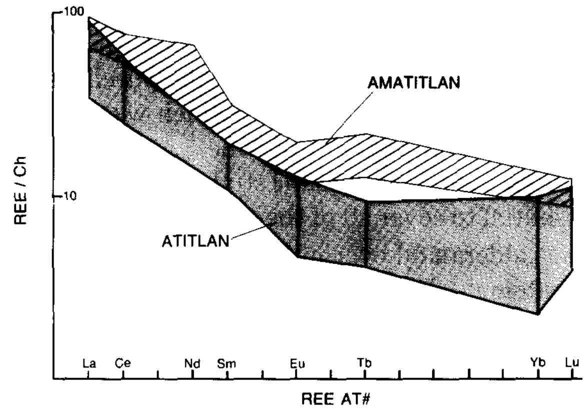

Fig. 14. Chondrite-normalized REE abundance plot showing field of Atitlán and Amatitlán rhyolites. Data from Rose et al. (1979), Wunderman and Rose (1984) and unpublished data.

bilize garnet in the source region. Second, the pH_2O levels indicated by some of the rhyolites (Table 9) is consistent with depths of 10 km or more and the high total Al content (1.9 per formula unit) of hornblendes in the low-K rhyolite of the Los Chocoyos magma (Rose et al., 1979) is also consistent with a high pressure (Hammarstrom and Zen, 1983). Third, the independence of phenocryst mineralogy and bulk chemistry suggests that observed phenocrysts form under variable conditions which is consistent with a considerable range of residence depths for magma bodies. The low crystallinity and absence of two feldspars precludes the more elaborate tests used by Stormer and Whitney (1985) for the Fish Canyon Tuff. The magmas may have come from deep in the crust and then resided at a variety of depths before eruption.

(8) As shown in Table 12, the volume of high-K rhyolite (230 km^3) erupted from Atitlán is much greater than the volume of low-K rhyolite/rhyodacite (65 km^3). The high-K magma was erupted following the low-K W eruptions and was also followed by low-K eruptions. Thus, the silicic magma sequence is rhyodacite-rhyolite-rhyodacite. The most silicic and most voluminous magma of the Los Chocoyos eruption was preceded and followed by smaller volumes of more mafic silicic magmas.

We infer the following sequence of events during the evolution of Atitlán III:

(1) Growth of the andesitic stratovolcanoes San Marcos, Tecolote and Paquisis (Newhall, 1987, this issue).

(2) Development of at least 5–10 km^3 of low-K rhyolite magma below the area destined to become the Atitlán III caldera, with a stabilization and partial crystallization taking place to form biotite rhyodacite at a depth of about 10 km.

(3) Eruption of W low-K rhyodacite possibly triggered by encounter of basaltic magma with the rhyodacite in a mixed eruption similar to those of many mature stratovolcanoes.

(4) Development of a large (250 km^3) volume of rhyolitic magma consisting of 2 parts: A dominant, homogeneous low-temperature high-K rhyolite and a much smaller heterogeneous higher-temperature low-K rhyodacite which is compositionally similar to the W rhyodacite. The genetic relationship of the two magmas could result from either (1) different degrees of anatexis from the same crustal source and subsequent emplacement or (2) crystal/liquid fractionation of low-K rhyodacite to develop a high-K top.

(5) Los Chocoyos eruption of high-K rhyolite in the opening plinian phase, followed by simultaneous eruption of high-K and low-K magmas in pyroclastic flows. The proportion of high-K magma decreased with time and in the final phases a tiny amount of mafic andesitic magma was admixed into the rhyolite.

(6) Near or at the end of the Los Chocoyos eruption the Atitlán III caldera formed.

(7) Very small (D,F?) eruptions of andesite to rhyolite from vents along the west end of the caldera ring fracture, following by a sequence of larger low-K rhyolitic eruptions (I series) which show mineralogical variability implying crystallization under variable conditions, erupted through Lake Atitlán.

(8) Growth of andesitic stratovolcanoes San Pedro, Atitlán and Tolimán, which begins during Stage 7 (above). The location of these volcanoes is generally south of those in Stage 1,

reflecting southerly movement of the volcanic front.

The Atitlán system is a bimodal assemblage of mafic and silicic magmas which alternate in a general way but both silicic and mafic magmas are repeatedly generated. Even in the biggest rhyolitic eruption some mafic magma was present and even in the modern period with predominantly andesites and basalts there is evidence of rhyolite admixture.

Quaternary volcanism at Atitlán began with mafic stratovolcanoes about 0.5 m.y. ago. Silicic volcanism began possibly 350,000–400,000 years later. The first silicic eruptions were small and of rhyodacite but were followed by very large and more silicic magma of the caldera-forming event at 85,000 yr. B.P. Subsequently more mafic silicic magmas were erupted in lesser volumes. Finally basaltic andesite volcanism resumed and composite cones formed again.

The mafic lavas are modified mantle materials, affected by evolution in magma ponds at or near the base of the crust (Grant et al., 1984) as well as at shallower levels. We suggest that the rhyolites may originate by partial melting of the lower crust, and evolve and crystallize to some degree at different levels generating variable mineralogy. They probably depend on heat from the mafic magma ponds to form and thus they are most prevalent at or following the peak of mafic magma generation.

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