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ABSTRACT

The Santiaguito volcanic dome in southwestern Guatemala is a multiple extrusive dome that has shown constant volcanic activity since its birth in 1922. Fourteen extrusive units are mapped. Five of these are volcanic domes; the remaining nine are lava flows which generally cling to the sides of the domes. The volume of material extruded at Santiaguito since 1922 (0.7 km³) is a small fraction of the volume of pyroclastic debris from the 1902 eruption of Santa María (5.5 km³), Santiaguito's parent composite cone. Extrusion of the dome began in the center of the explosion crater created by Santa María's 1902 activity. This crater was volumetrically much smaller (0.5 km³) than the amount of material erupted during the 1902 event, and local slumping near the crater has occurred and is continuing along a series of east-trending faults. The general westward growth of the dome complex and many of the structural features on Santiaguito are controlled by these near-vertical faults. The domes are studded with Pelean spines. Twenty-five new chemical analyses are presented, showing Santiaguito's eruptive products to be soda-rich dacite of the calc-alkaline suite. The dome lava has differentiated quite significantly from the overwhelmingly abundant pyroxene andesite magma which makes up Santa María and the older volcanic rocks in the area. Trace element analyses of the lavas, along with major element data suggest a differentiation by fractional crystallization under constant or increasing PO_2. Sr isotope determinations could not detect contamination of the lavas by radiogenic crustal material; the Sr^{87}/Sr^{86} ratio in Santiaguito rock averages .7043. The Santiaguito lavas are tridymite-bearing hypersthene dacites, characterized by strongly zoned plagioclase phenocrysts and oxyhornblende. Compositional and petrographic comparisons are made with other modern volcanic domes and other Central American lavas.

INTRODUCTION AND GEOLOGIC SETTING

The Santiaguito Dome is located in southwestern Guatemala (14°44′30″ N. lat, 91°34′ W. long), on the active volcanic chain of Central America. Williams (1960) and Bonis (1965) have discussed the regional setting; the local setting is described by Stoiber and Rose (1969). Santiaguito is a multiple extrusive dome which began forming in 1922 inside the large explosion crater created in 1902 on the southwestern slope of Santa María Volcano (Fig. 1).

A comparison of the historic activities of Central American volcanoes (Table 1) shows that Santa María–Santiaguito is one of five most active volcanoes in the last 150 yrs, and if only the last 50 yrs are considered, it is the most active.

Many active volcanoes in Guatemala lie on linear fractures transverse to the dominant west-northwest volcanic trend. Santiaguito, Santa María, and Cerro Quemado lie along such a northeast-trending structure. This trend is parallel to fault scarps on the southeast side of Cerro Quemado and along the bottom and sides of the Río Samalá Canyon (Williams, 1960, p. 39). The largest fault in the canyon, the Zuñil fault, has been traced inland 25 km to Totonicapán. Alignment of Chicaval and Siete Orejas volcanoes, northwest of Santiaguito, is also northeast. From Lake Atitlán eastward, fractures transverse to the volcanic belt are more nearly north trending. Dollfus and de Montserrat (1868) first called attention to these transverse trends, observing that the most seaward volcanic vent showed the most prolific recent activity. Table 1 shows that this generality is still true. Other volcano pairs that lie along apparent transverse trends are Atitlán and Tolimán, Fuego and Acatenango, and Izalco and Santa Ana. Central American north-trending transverse structures are discussed in more detail by Dengo and others (1970).

Central American volcanoes lie north and inland of an offshore trench, and the volcanic

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Figure 1. Santa María (right) and Santiaguito from the south: January 1970.

chain has long been recognized as an island arc. Recent compilation of earthquake data and earthquake mechanism studies (Molnar and Sykes, 1969) indicate a Benioff zone dipping from the trench under the volcanic chain. The depth from the surface to the seismic zone under Santiaguito is about 100 to 120 km, a depth typical for volcanoes producing high alumina suites (Kuno, 1966). The Benioff zone under Guatemala and eastern Mexico has a much greater seismicity than the same zone farther east or west. This fact helped Molnar and Sykes (1969, p. 1666–1667) to conclude that underthrusting rates were greater in this area.

PREVIOUS WORK

A summary of previous work at Santiaguito has already been published (Stoiber and Rose, 1969, p. 479). Recently works dealing with the chemistry of fumarolic activity at Santiaguito have appeared (Stoiber and Eberl, 1969; Stoiber and Rose, 1970). The 1902 eruption of Santa María is discussed in a separate article (Rose, 1972). The present paper formed part of the author's doctoral thesis (Rose, 1970).

VOLCANIC UNITS

Descriptions of volcanic units of the Santiaguito area (Fig. 2) are below. In most cases chemical analyses of these units appear in Table 2.

Tertiary(?) Andesite Flows

The oldest rocks of the Santiaguito area are flat-lying basaltic andesite flows lying to the north and northwest of the dome. These rocks form the basement for the Santa María cone but their age is not established. They are deeply denuded and are interpreted as being of Tertiary age, based on proximity to rocks mapped as Tertiary in the valley of the Río Ocosito (Bonis, 1965), and along Zuñil ridge (Williams, 1960, p. 26), and based upon the convention (Bonis, 1965, p. 62) of assigning Tertiary age when erosional and destructional forms are dominant (in contrast to units showing original depositional and constructional forms, which are interpreted as Quaternary).

The flows are rarely interbedded with laharic and ash-flow materials and have a thickness of more than 500 m. They are undeformed, except by faults. Directly north of Santiaguito the volcanic rocks of Santa María's cone cover the Tertiary rocks; to the south the rocks are covered by laharic and fluvial deposits of the coastal slope.

The Tertiary flows near Santiaguito are olivine-bearing pyroxene andesites (no. 1118 in Table 2). Phenocrysts of twinned labradorite

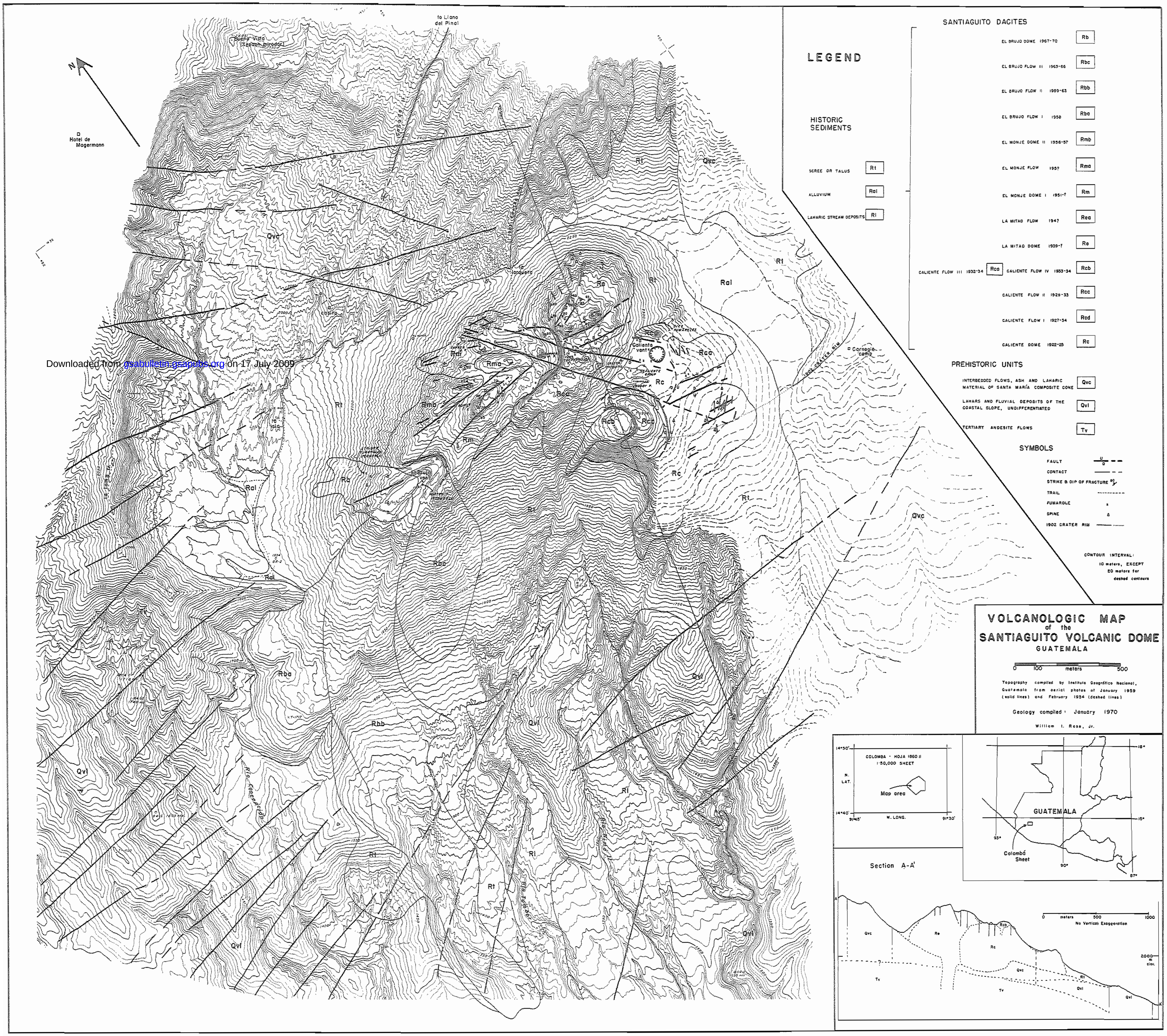

Figure 2. Volcanologic map of Santiaguito, Guatemala.

TABLE 1. RELATIVE "ACTIVITY" OF CENTRAL AMERICAN VOLCANOES, BASED ON DATA FROM CATALOGUE OF ACTIVE VOLCANOES (MOOSER AND OTHERS, 1958) AND SUPPLEMENTED BY RECENT OBSERVATIONS

Volcano	No. of decades since 1820 in which eruptions were reported (Max = 15)	No. of semi-decades since 1920 in which eruptions were reported (Max = 10)
Tacaná	2	0
Tajumulco	1	0
Santa María-Santiaguito	6	10
Atitlán	3	0
Acatenango	1	2
Fuego	8	9
Pacaya	2	2
Santa Ana	2	1
Izalco	15	9
San Salvador	1	0
Islas Quemadas	1	0
San Miguel	9	7
Conchaguita	1	0
Coseguina	1	0
Telica	1	1
Cerro Negro	7	6
Las Pilas	1	1
Momotombo	5	0
Masaya	5	4
Mombacho	1	0
Concepción	5	4
Rincón de la Vieja	2	1
Arenal	1	1
Poás	5	2
Irazú	3	2
Turrialba	1	0

(An_{50-55}), corroded olivine, and smaller twinned and zoned augite occur in a crystalline groundmass of andesine, augite and ore.

Laharic-Fluvial Materials of Volcanic Origin on the Coastal Slope

Unsorted, thick, irregular units of volcanic boulders in a volcanic ash-silt matrix locally form much of the Pacific slope. These units were characterized by Bonis (1965, p. 75) as "laid down by torrential floods and mudflows." They have been eroded everywhere by fast-flowing intermittent streams, but support dense vegetation except where affected by heat from recent activity of Santiaguito. These units are nearly always unindurated south of Santiaguito; however, a well indurated laharic unit is exposed in the Río Tambor valley. This laharic unit has a fossil soil on top and is covered by 40 ft or more of the more typical bouldery unindurated, unstratified material. This latter unit is overlain by the 1902 ejecta of Santa María.

Interbedded Flows, Pyroclastic Deposits and Laharic Materials of Santa María

Flows, pyroclastic debris, and laharic materials directly associated with the Santa María composite cone occur on three sides of the dome. The surface of the cone north and south of the 1902 crater is thickly mantled with the 1902 eruption debris, but in places erosion has exposed andesite flows and laharic units. A laharic unit fills most of the valley floor north of the isla and casita (Fig. 2); it is up to 50 m thick and has a well developed soil layer on top, in which the fossil 1902 forest was rooted. East of the casita, andesite flows underlie the 1902 debris.

The interior of the composite cone of Santa María is irregularly exposed in the steep walls of the 1902 explosion crater (Fig. 3). On the west wall 26 lava flows are exposed, 4 to 20 ft thick, interbedded with unconsolidated layers 6 to 25 ft thick, consisting of pyroclastic, laharic, and ash-flow materials. On the east side 32 such flows are visible, with similar interbedding. All of these materials are prehistoric, but spectacular activity of Santa María is clearly documented in Cakchiquel Indian legend (Recinos and Goetz, 1953, p. 69–70). The total volume of the Santa María cone is about 20 km^3.

Santa Maria's lava flows are pyroxene andesite (Bergerat, 1894, p. 143; Sapper, 1913, p. 9; Fricke, 1926, p. 34; Williams, 1960, p. 36) usually with olivine. Two chemical analyses were made (Table 2, nos. 14, and 560). Zoned plagioclase feldspar (An_{45-70}), augite, and olivine phenocrysts occur in a crystalline groundmass of plagioclase, augite, and opaque minerals. Hypersthene may occur as both phenocrysts and in the groundmass. Some pyroxenes are hypersthenes rimmed with augite. The Santa María flows are similar to the Tertiary andesite described above. As such, if a "parent" magma is present on the surface in this area, it must be pyroxene andesite of the composition shown in Table 2, nos. 14, 560, and 1118.

In general, Quaternary cones in Guatemala are composed of pyroxene andesite (Williams, 1960). Indeed, andesite is the dominant magma produced at the surface in most island arcs (Dickinson and Hatherton, 1967; Hamilton, 1964) and though this is not compelling evidence, the idea of generation of andesitic parent magma from 100 km or greater depths (Green

TABLE 2. CHEMICAL ANALYSES OF VOLCANIC ROCKS OF THE SANTIAGUITO AREA

No.	1118	14	560	1401	1120	1115	1105	1125	1003	1103	1004	1104
Map Unit	Tv	Qvc	Qvc				Rc	Rc	Rcd	Rcc	Rca	Rcb
Chemical Analyses (weight percent)												
SiO_2	54.9	53.5	54.2	55.8	59.0	65.7	62.8	64.3	64.0	62.5	64.8	65.0
TiO_2	0.97	0.98	0.93	0.90	0.84	0.35	0.55	0.36	0.40	0.51	0.39	0.41
Al_2O_3	17.4	17.3	17.8	15.9	18.0	16.7	16.7	16.8	17.1	16.7	16.7	16.4
Fe_2O_3	3.0	2.9	3.4	3.1	3.4	1.4	2.7	1.6	1.7	2.1	2.0	2.4
FeO	5.1	5.2	5.4	5.6	3.6	2.5	2.9	2.4	2.5	2.9	2.2	2.3
MgO	5.58	5.59	4.88	4.70	3.00	1.35	1.93	1.48	1.57	1.85	1.58	1.62
CaO	7.7	8.3	8.5	7.6	7.0	4.0	5.7	4.5	4.6	5.3	4.2	4.4
Na_2O	3.7	3.7	4.0	3.5	4.4	5.1	4.9	4.9	5.0	4.7	5.1	5.0
K_2O	1.14	1.12	1.02	2.02	1.28	1.76	1.58	1.70	1.63	1.58	1.66	1.70
P_2O_5	0.14	0.16	0.20	0.28	0.21	n.d.	0.18	0.17	0.20	0.16	0.14	0.15
H_2O+	0.10	0.18	0.12	0.55	0.15	0.22	0.14	0.22	0.11	0.16	0.11	<0.05
H_2O^-	0.4	0.4	0.2	0.2	0.1	0.5	0.2	0.2	0.2	0.2	0.3	0.3
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
TOTAL	100.13	99.33	100.65	100.15	100.98	99.58	100.28	98.63	99.01	98.66	99.18	99.68
ppmRb	19	21	16	60	24	32	30	31	32	29	33	32
ppmSr	560	589	580	350	529	447	492	495	492	507	475	475

n.d. = not determined

1118 Pyroxene andesite flow, from la loma trail near Hotel de Magermann (Tv)
14 Pyroxene andesite flow from Santa María, collected along cañada trail above the casita (Qvc)
560 Pyroxene andesite flow from Santa María collected on the floor of the 1902 explosion crater (Qvc)
1401 Quartz diorite basement fragment ejected by 1902 eruption of Santa María, sample taken along cañada trail
1120 Andesite hypabyssal cognate inclusion in El Brujo dome rock, Santiaguito
1115 White dacite pumice from 1902 eruption of Santa María, collected at Xepach army camp, 2 km. NNE of Santiaguito
1105 Dacite, from Santiaguito, the Caliente dome (Rc), 150 meters west of Caliente vent, near Godoy fumarole
1125 Dacite, from Santiaguito, the Caliente dome (Rc), 400 meters south of the Caliente vent
1003 Dacite, from Santiaguito, the Caliente flow I (Rcd), near the Zies fumaroles
1103 Dacite, from Santiaguito, the Caliente flow II (Rcc)
1004 Dacite, from Santiaguito, the Caliente flow III (Rca)
1104 Dacite, from Santiaguito, the Caliente flow IV (Rcb)

and Ringwood, 1966) seems tenable for Guatemala and Central America.

1902 Eruption Debris

Dome extrusion at Santiaguito was preceded by a gigantic two-day explosive eruption in October 1902 (Rose, 1972) which produced large volumes (5.5 km^3) of white pumice. This material does not show as a separate unit on the volcanologic map, though it does cover, where it has not been eroded, all the pre-dome map units with thicknesses up to 20 m. This material was mostly clear glass with a refractive index of 1.496. It contains a few crystal fragments of plagioclase and green hornblende. The green hornblende is in contrast to the oxyhornblende of Santiaguito's lavas—indicating a probably greater pH_2O value and thus a greater depth of crystallization for the 1902 pumice. Following the experimental data of Boyd (1956) and the conclusions of Turner and Verhoogen (1960, p. 140), this depth may be 2 km or more.

A chemical analysis of the white pumice is included in Table 2 (no. 1115); it does not differ greatly from the subsequent dome lavas. Analysis of a dioritic xenolith erupted with the 1902 pumice is also found in Table 2 (no. 1401). It represents the commonest type of basement xenolith observed (Rose, 1972).

Santiaguito Dome

The rocks of the dome complex are uniform, gray-brown porphyritic dacite and andesite, usually with oxyhornblende phenocrysts as well as plagioclase. Thus, boundaries between mapped units (Fig. 2) have been determined using photographs of known dates, historical descriptions, field mapping of geomorphic features, and air photo interpretation. Chemical analyses of the units of the dome are given in Table 2, keyed to the map by symbols. The dates of extrusion of the fourteen individual units are shown in the legend of Figure 2. Two types of units are shown on Santiaguito: domes and flows.

Dome units are generally more grayish in color than the flows, are less vesicular, have more inclusions, and show little or no evidence of flow in response to gravity after extrusion.

TABLE 2. CHEMICAL ANALYSES OF VOLCANIC ROCKS OF THE SANTIAGUITO AREA (CONTINUED)

No.	1000	2003	1023	1005	802	1101*	800	1102	550	1106	1229*	1511	1669
Map Unit	Re	Re	Rea	Rm	Rma	Rb	Rba	Rbb	Rbc				Rb
Chemical Analyses (weight percent)													
SiO_2	56.1	64.5	61.8	63.8	64.3	63.92	64.1	63.6	64.4	64.0	63.86	63.5	64.3
TiO_2	0.82	0.45	0.53	0.53	0.42	0.43	0.48	0.46	0.45	0.42	0.43	0.49	0.48
Al_2O_3	17.9	16.6	17.2	16.9	17.0	17.54	16.9	16.8	17.0	16.5	17.50	17.0	16.7
Fe_2O_3	2.5	2.8	3.3	2.4	1.8	1.97	2.8	1.9	3.3	1.7	1.81	2.3	2.0
FeO	5.1	1.8	2.0	2.8	2.5	2.46	2.0	2.5	1.5	2.8	2.65	2.6	2.7
MgO	4.26	1.73	1.97	2.03	1.56	1.62	1.70	1.61	1.67	1.88	1.65	1.97	1.83
CaO	7.6	4.7	5.4	5.3	4.6	4.80	4.7	4.8	4.9	4.8	4.99	5.2	5.1
Na_2O	4.1	5.2	4.8	4.8	5.0	4.99	5.1	5.1	5.1	4.8	4.89	5.0	4.8
K_2O	1.14	1.67	1.48	1.53	1.64	1.68	1.59	1.70	1.64	1.60	1.59	1.58	1.62
P_2O_5	n.d.	0.24	0.20	n.d.	0.23	0.19	0.24	0.16	0.25	0.17	0.19	0.24	n.d.
H_2O+	0.05	<0.05	<0.05	0.05	<0.05	0.10	0.14	0.05	0.06	0.05	0.10	0.30	0.18
H_2O^-	0.1	0.2	0.2	0.2	0.2	0.05	0.2	0.2	0.2	0.2	0.06	0.5	0.2
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	0.14	n.d.	n.d.	n.d.	n.d.	0.14	n.d.	n.d.
TOTAL	99.62	99.89	98.88	100.34	99.25	99.79	99.95	98.88	100.47	98.92	99.76	100.68	99.91
ppmRb	21	33	27	31	34	31	32	31	30	29	32	30	33
ppmSr	568	463	516	507	484	488	489	488	502	489	482	503	482

n.d. = not determined

**Eugene Jarosewich, Washington D. C., analyst*

1000 Andesite, from Santiaguito, on the NE slope of the La Mitad dome (Re)
2003 Dacite, from Santiaguito, the La Mitad dome (Re), near von Tuerckheim fumarole
1023 Dacite, from Santiaguito, the base of La Mitad flow (Rea), west of Sapper fumarole
1005 Dacite, from Santiaguito, the El Monje dome (Rm) near El Monje spine
802 Dacite, from Santiaguito, the El Monje flow (Rma)
1101 Dacite, from Santiaguito, El Brujo dome (Rb), from north talus slope near la isla, collected 1967
800 Dacite, from Santiaguito, at the base of El Brujo flow I (Rba)
1102 Dacite, from Santiaguito, near the head of El Brujo flow II (Rbb)
550 Dacite, from Santiaguito, at head of El Brujo flow III (Rbc)
1106 Dacite ash, erupted from Caliente vent May 14, 1967, collected 150 meters north of the vent
1229 Dacite pyroclastic block, erupted 1967 from Caliente vent, Santiaguito
1511 Dacite pumicious bomb, erupted from Caliente vent, Santiaguito, September 1968
1669 Dacite from Santiaguito, El Brujo dome (Rb), extruded 1968

They comprise a much larger volume than the flow units. Spines and slabs stud the summits. The largest spine now preserved is on the La Mitad Dome; it is 200 m long and 70 m high. The shape of the dome units is sometimes circular, as in the case of the La Mitad and the El Brujo units, suggesting a simple central extrusive vent (Fig. 4). The Caliente and El Monje domes are not as simple. The Caliente unit was extruded from two or more vents and the El Monje dome can be subdivided into two elongate units on the basis of aerial photography control at various dates. Extrusive vents for the El Monje domes were apparently along fissures striking eastward.

Flow units at Santiaguito are generally darker and more brownish than the domes, are much more vesicular, and show clear evidence of downslope movement. Still they are substantially more viscous than most basaltic flows and many flow units solidified on the sides of domes (Fig. 5). The movement of these flows is characteristically by rockfalling of oversteepened flow fronts. Most flows are rather small in volume (Fig. 2), but the three most recent ones are significantly larger, the largest extending more than 2 km. The thickness of these larger flows is commonly greater than 50 m but is variable. Where exposed, the flows have a vesicular top as much as 10 m thick. Vesicles as large as 20 cm are common. Some flows seem to exhibit little evidence of downslope movement. This may be due to the lack of slope at the point of extrusion, or to the tendency for flows to become more sluggish in their waning stages, "stacking up" above their vents.

Recent Laharic-Stream Deposits

In 1929 to 1935 the valleys of the Río Tambor and Río Nimá Segunda were the paths for large *nuées ardentes*, and today, remnants of these deposits are found in the beds of both rivers, along with fluvially deposited volcanic materials, also derived chiefly from the dome. The *nuée* material moved in the riverbeds as a lahar or hot mudflow. Recent laharic material is barely distinguishable from the older units of the coastal slope.

Figure 3. The rim of the 1902 explosion crater of Santa María as seen from Santiaguito. Interbedding of lava flows and pyroclastic layers can be clearly seen. Photo taken by Dr. A. Mackenney in 1963.

Recent Alluvium

Recent volcanic-lacustrine deposits occur in the floor of the 1902 explosion crater and southwest of la isla camp, caused when the Santiaguito's activity dammed the Río Tambor.

Scree or Talus

Scree slopes are found almost all around Santiaguito, and also on the steep Santa María face within the 1902 crater. The Santiaguito scree has a complex origin: most of it is from rockfalling of fragments from the fracture of newly extruded cooling slabs or spines near the top of the dome; part of its volume is contributed by small *nuées ardentes* and by scree associated with the lava flows resulting from fracture of the flow during its slow movement. Some boulders on the slopes may exceed 10 m in diameter and many have broken along serrated fracture surfaces, similar to those described by Perret (1937) at Mont Pelée and shown to develop after rockfalling, as the hot boulders cooled (Fig. 6).

Figure 4. The growing El Brujo dome as seen from la loma trail in January 1970. To the left, the El Monje dome can be seen.

STRUCTURAL GEOLOGY

Recent Faulting Around and on the Dome Complex

More than 30 near-vertical faults have been mapped around the Santiaguito dome complex (*see* map). Their dominant trend is eastward,

Figure 5. Looking southwest from the south rim of the 1902 explosion crater of Santa María, near the old Carnegie Camp (*see* Fig. 2). In the foreground is deeply eroded 1902 eruption debris; in the background is the slope of Santiaguito with the Caliente Flow III clinging to it. The far (northwest) rim of the Santa María crater can be seen in the distance at right. Photo taken by O. G. von Tuerckheim in 1933.

although they range from northeast to northwest. There is a fan-shaped or radial pattern with the apex in the 1902 crater. Displacement on faults does not exceed a few feet. Movement along many of them has occurred during the recent observation period, triggering landslides down the cross-faulted ridge below the La Loma trail. Similar faults were described by Anderson (1941, p. 378–438) on the Medicine Lake Highland in California, and were interpreted as being due to "a small settling and adjustment . . . following the withdrawal of lava. . . ." Such an explanation is tenable for Santiaguito as well. The volume of 1902 eruption debris is eleven times the volume of the 1902 explosion crater (5.5 km^3 versus 0.5 km^3), and readjustment of the surface near the crater seems quite reasonable.

The faults at Medicine Lake served as loci of subsequent lava vents, and the same happened at Santiaguito. The eastward trend of the La Mitad–El Monje–El Brujo domes can be projected to one or more of the east-trending faults which can be seen to the west of the dome complex. The northwest trend of the grabenlike structure which extends from the Caliente dome to the Sapper A fumarole and beyond is clearly influenced by faulting to the north. Nearly all of the fault features on the dome are in sympathy with the pattern of faulting around the dome.

Arcuate faults occur in five places on the dome complex. They are concave around formerly active lava vents, and are the result of collapse. "Crescentic cracks" on the Fouque Kameni dome at Santorini observed by Washington (Williams, 1932) were caused by sinking of the dome, triggered by lava welling out below. In contrast, the linear faults on Santiaguito are accented mostly by differential upward movement during dome building, associated with extrusion of slablike spines. Although the presence of the grabenlike structures mentioned above is most simply attributed to extrusion of linear arrays of spines along parallel faults, the repeated occurrence of these structures striking into the convex side of the arcuate faults suggests that they may represent surface readjustment which reflects subsurface magma flow.

Internal and External Structure of the Dome

The internal structure of the Santiaguito dome complex has little apparent pattern or regularity; the same generalization has been reached for similar domes at Lassen Peak (Williams, 1929, p. 323–329), Mt. Pelée (Lacroix, 1904), and Mt. Lamington (Taylor, 1958). Poorly developed flow banding is rarely observed. No pattern to the flow structures could be established except that on the dome units they are generally near vertical, on the flows, horizontal. Joints and fractures on the dome most often follow the fault trends (*see* above); the exceptions usually dip steeply toward the center of the dome. Fractures do not always coincide with spine faces (Fig. 7). Polygonal cooling cracks are found on some spine faces.

The spines themselves have been a consistent feature of dome extrusion at Santiaguito, though none has attained the stature of the famous Pelean spine (over 300 m). Many of the spines are long slabs, others are pointed, with triangular or square bases. As can be readily observed at the El Brujo vent today, large massive hot extruded masses tend to cool and break up after extrusion. Most of the spines of Santiaguito are residual features, their shapes determined by breaking away of surrounding cooling material. Some spines, however, are definitely primary extrusive features (Fig. 8).

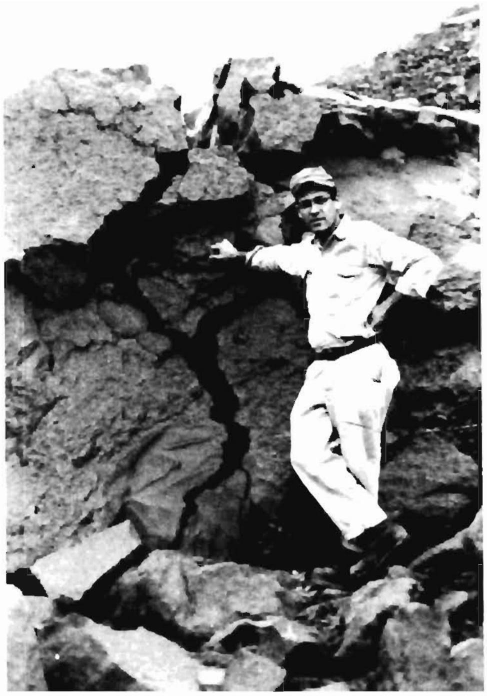

Figure 6. Characteristic serrated fracturing of large boulders produced from hot rockfalls. Fracturing takes place as the boulders cool, often hours or days after they fall. Photo taken in July 1967, at the foot of the El Brujo talus slope.

PETROLOGY AND CHEMISTRY OF THE SOLID PRODUCTS OF VOLCANISM

A few analyses of Santiaguito's 1924 through 1929 eruptive products have been published (Termer, 1929; Deger, 1931; Alvarado, 1936). Unfortunately these are of ash sampled at great distance (>10 km) from the volcano and are not representative of the lava. Previous petrographic descriptions of Santiaguito lavas (Sapper and Termer, 1930, p. 99; Termer, 1939, p. 768; Williams, 1960, p. 37; Adams, 1948, p. 42–43), conclude that the rock is andesite, usually containing zoned plagioclase, hypersthene, amphibole, abundant glass, and tightly held inclusions of "lamprophyric texture."

Figure 7. Spine on the north flank of Santiaguito, showing a set of joints dipping left toward the center of the dome.

Nineteen chemical analyses of Santiaguito eruptive products were made in this study (Table 2), representing all units of the dome. A

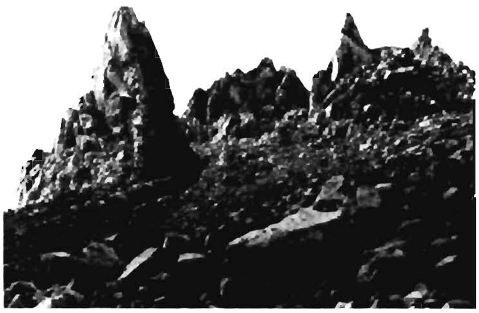

Figure 8. Spines on the northeast slope of the La Mitad dome, inside the 1902 crater. This view was taken looking up the talus slope. The large spine in the left foreground has steep, nearly planar sides which parallel fracture surfaces; it is probably of primary extrusive origin. Spines in the background have irregular or conchoidal outlines; they are probably residual features, remnants of the fracturing induced by cooling of much larger extrusions.

TABLE 3. AVERAGE COMPOSITION OF DOME ROCK AT SANTIAGUITO (INCLUDING FLOWS)

Oxide	Percent	C.I.P.W. Norm	Percent
SiO_2	63.45	QU	15.73
TiO_2	0.47	OR	9.40
Al_2O_3	16.94	AB	41.50
Fe_2O_3	2.27	AN	19.46
FeO	2.56	CADI	1.69
MgO	1.87	MGDI	1.06
CaO	5.03	FEDI	0.52
Na_2O	4.91	EN	3.61
K_2O	1.59	FS	1.77
H_2O+	0.08	AP	0.52
H_2O-	0.21	IL	0.90
P_2O_5	0.22	MT	3.29
MnO	0.14	REST	0.29
TOTAL	99.74	TOTAL	99.74
		DI	2.87
		HY	5.52
Mean Modal Analyses			
Plagioclase	*26*	*Olivine*	*0*
Hypersthene	*2*	*Ore*	*2*
Oxyhornblende	*1*	*Tridymite*	*+*
Augite	*+*	*Groundmass*	*69*

mean of these 19 analyses is given in Table 3, along with computed C.I.P.W. norm, and a mean modal analysis. Except for one of the La Mitad samples (no. 1000), none of the samples analyzed differs very greatly from the mean. Using the classification of Williams and others (1955), the mean describes a porphyritic hypersthene dacite, containing plagioclase, hypersthene, oxyhornblende, augite, tridymite, and opaque minerals, as well as a hypocrystalline groundmass. Table 4 compares the petrographic features of Santiaguito lavas to those of other historically active volcanic domes.

Plagioclase is by far the most abundant mineral in the Santiaguito rocks. Oscillatory zoned (An_{30-75}) phenocrysts of plagioclase (up to 2 mm size) account for more than 25 percent of the rock, and plagioclase is also the most important constituent of the groundmass. Glass blebs are commonly found in the phenocrysts, many of them following more sodic zonal bands. McDonald and Katsura (1965, p. 478) have described similar glass blebs in Mt. Lassen lavas, stating that they have the composition of sodic plagioclase, but the composition of the glass blebs in the Santiaguito plagioclase has not been determined. Some, or nearly all, of the cores of oscillatory-zoned phenocrysts have been remelted. The outer rims of the plagioclases are usually unaltered and apparently contemporaneous with small (0.5 mm) unzoned or normally zoned twinned phenocrysts of more sodic composition (An_{30-40}). Plagioclases in the groundmass are cryptocrystalline microlites of undetermined composition, but the normative feldspar of the groundmass appears to be in the range An_{20-25}.

The diffusion-supersaturation mechanism of Hills (1936, p. 52) has been endorsed to explain the oscillatory zoning of calc-alkaline plagioclases before (Larsen and others, 1937; Baker, 1949; Vance, 1962), and has recently received important experimental support from Bottinga and others (1966). Other mechanisms to explain oscillatory zoning require postulating repeated drastic reversals of temperature, pressure, or bulk composition (Vance, 1962, p. 751). Further, the other features of the Santiaguito feldspar can best be explained by starting with the Hills mechanism. Vance (1962, p. 752–757) shows that the diffusion-supersaturation process may not be effective after a melt is saturated with volatiles and has developed a volatile phase. In this case normal zoning would be expected. Such an interpretation could explain the small phenocrysts and the outer rims of Santiaguito plagioclase. An ascending magma would tend toward saturation as pressure decreased. Furthermore, resorbed cores of the feldspar would result,

TABLE 4. SUMMARY OF THE PETROGRAPHY OF SOME HISTORIC VOLCANIC DOMES*

Name, Location	Age	Rock Name	Plag. Comp.	Px	Silica	Amph.	Ol.
Pelée, WI	1902, 1929	a, d	and-an	h, a	q, t	ox	+
Bezymianny, K	1956	a, d	..	h, a	..	h	..
Sheveluch, K	1854-1950	a	and-lab	h, a	..	ox	+
Catarman, P	1871-1875	a	oli-lab	h, a	..	h	+
Galunggung, I	1918	a	..	h, a	..	..	..
Merapi, I	1883-1940	a	..	h, a	..	h	..
Lewotobi, I	1932-1933	a	..	+	..	..	..
Banua Wuhu, I	1835-1889	a	..	h, a	..	h	..
Syowa, J	1934	d	and-byt	h, a	t, c	..	..
Showa-shinzan, J	1944-1945	d	..	h	q, c	..	..
Tarumai, J	1909	a	and-byt	h, a	c, t	..	+
Lamington, M	1951-1956	a	lab	+	..	ox	+
Bagana, M	1948-1953	b, a	byt	d	..	+	..
Lassen, USA	1914-1917	d	oli-lab	h, a	q	ox	+

*Source: *Catalogue of Active Volcanoes of the World, including Solfatara Fields*, 21 vols.

Symbols

Rock Name: a = andesite d = dacite b = basalt
Location: WI = West Indies, J = Japan, M = Melanesia, P = Philippines, I = Indonesia, K = Kamchatka
Plagioclase composition: oli = oligoclase, and = andesine, lab = labradorite, byt = bytownite, an = anorthite
Pyroxene: h = hypersthene, a = augite, d = diopside
Silica: q = quartz, t = tridymite, c = cristobalite
Amphibole: ox = oxyhornblende, h = hornblende
+ = present, .. = absent or not given

since in water-deficient plagioclase systems the liquidus temperature is lowered with falling pressure. The crystallization of groundmass crystallites, still more sodic in composition, is then probably associated with volatile release during eruption and after saturation.

Hypersthene is always present in the Santiaguito rocks. It is euhedral and strongly pleochroic, and occurs as phenocrysts, usually of small (1 mm) size. Occasionally it shows minor alteration along the edges and cleavages, where the pleochroism is enhanced and a rusty color produced.

Oxyhornblende is nearly always present in the Santiaguito suite, as equidimensional phenocrysts larger than 3 mm in diameter, or as long narrow phenocrysts. The rims are invariably altered to pyroxene (usually augite), plagioclase, and opaque minerals; in some cases small phenocrysts have been completely altered. The oxyhornblende itself has strong red-brown pleochroism.

Barnes (1930) has shown that oxyhornblende can be synthesized from green hornblendes by heating to about 800° C. He demonstrated by chemical analyses that the Fe_2O_3 content of the amphibole increases and FeO and H_2O^+ contents decrease with the reaction. MacGregor (1938, p. 70) suggested that oxyhornblende at Montserrat was the result of conversion of green hornblende during slow cooling of the lava under dry conditions. A similar conclusion is indicated for Santiaguito, since green hornblende occurs in the 1902 pumice, an evidently gas-charged magma which ascended rapidly, while the amphibole in the sluggish Santiaguito lavas is oxyhornblende.

The essential features of the chemistry of oxyhornblendes are high Fe_2O_3/FeO ratios (2:5) and low H_2O contents (0.19 to 0.84 percent: Deer and others, 1963, p. 316). Amphiboles entirely devoid of OH apparently do not exist. The loss of the final portion of OH from the amphibole is associated with structural disintegration and conversion to phases which may include pyroxene, cristobalite, hematite, magnetite, olivine, plagioclase, water, and glass (Wittels, 1952). Such breakdown occurs when amphiboles are heated to between 900° and 1,125° C.

Breakdown of oxyhornblende was also described by MacGregor (1938, p. 54–55) in the Montserrat lavas. MacGregor interpreted his findings as indicating that the amphibole will completely break down near the surface unless the magma is rapidly chilled. At Santiaguito it is obvious that the extruded material is not chilled rapidly, and breakdown of the oxyhornblende probably occurs during extrusion at or just below the surface, coincident with crystallization of the groundmass.

All but a few of the Santiaguito lavas examined contain augite, but it is always less plentiful than hypersthene. It usually occurs as small phenocrysts and is commonly twinned. Hourglass structure is rare. The augite is usually unaltered, though a few crystals exhibit a rusty color along the edges.

Tridymite is found in nearly all Santiaguito samples. It occurs in tiny clots of faintly pinkish overlapping crystals, and is probably also disseminated in the groundmass. It was identified by its low index of refraction (<1.484), low birefringence, positive sign, small 2V and rare wedge-shaped twinning. Zies (1951, p. 325) reported finding cristobalite in one rock sample from the northeast portion of the dome, but this mineral was not positively identified in the suite examined here.

Opaque minerals, mostly magnetite with some ilmenite, occur as disseminated grains throughout the groundmass of Santiaguito lavas. It also occurs as the alteration product of oxyhornblende, as described above.

The groundmass of the Santiaguito lavas makes up about 70 percent of the rock. It is hypocrystalline, with small crystals of plagioclase, pyroxene(?), tridymite, and ore. The normative groundmass, if it were all crystalline, would contain about 20 percent tridymite or other silica phase, 55 to 65 percent plagioclase (An_{20}), about 10 percent pyroxene, about 5 percent ore, and 5 to 10 percent potash feldspar.

Xenoliths are very common in all the Santiaguito rocks, and range from a few millimeters to more than 20 cm in diameter. A very common type is a hypabyssal andesite. Both major and trace element data (Table 2, no. 1120) suggest that these hypabyssal xenoliths are cognate, though more basic than the dome rocks. The data also strengthen the suggestion of Williams (1960, p. 37) that they represent "fragments torn from the walls of the feeding fissures" underneath the volcano. Less common are xenoliths of intrusive igneous rock or schist, like those which appeared as ejecta in the 1902 pumice. Zies (1951, p. 325) observed granodiorite xenoliths on the south slope of the dome in 1939–1940. Xenoliths of intrusive rocks were also observed in August 1969 on the north slope below the active El Brujo vent (Rose and others, 1970).

One rock sample from the La Mitad dome (no. 1000, Table 2) is substantially more basic than the Santiaguito average. It is only slightly more silicious than Santa María andesite. Santiaguito rock of this composition was also observed by Zies (Adams, 1948, p. 43). Compared to the Santiaguito average, this rock has a higher percentage of hypersthene and augite, and contains badly corroded olivine and no tridymite. The rock is texturally similar to the other dome lavas. A sample from the La Mitad flow (no. 1023), extruded just subsequent to the La Mitad dome, is also significantly more basic than the Santiaguito mean values, while another sample from the La Mitad dome (no. 2003) is near the Santiaguito average. Both samples with anomalously basic compositions are closely associated in time. The simplest explanation seems to be local remelting of Santa María andesite, and extrusion of the resulting lava, partially mixed with the Santiaguito lava, during the growth of the La Mitad dome. Such a hypothesis explains the occurrence of compositionally distinct andesite (no. 1000) and dacite (no. 2003) in the same extrusive unit. Such an interpretation is also supported by trace element data (*see* below). Remelting of Santa María rock, if it did occur, was not a common feature of Santiaguito history—the portion of the dome strongly affected was restricted to the northwest side of La Mitad dome unit. Furthermore, even if the hypothesis of remelting is accepted, it does not explain why such a process should operate only at one stage in the history of the dome.

Analysis Procedure

Rocks were dissolved by the $LiBO_2$–HNO_3 solution method (Surr and Ingamells, 1966), and values were obtained for Na, Mg, Si and Al using atomic absorption spectrophotometry according to the procedure of Medlin and others (1969) and Yule and Swanson (1969). Total Fe, Ca and Ti was determined by x-ray fluorescence using La_2O_3 as a heavy absorber to eliminate mass absorption corrections (Rose and others, 1962). K was determined with flame photometry, using a Li internal standard and Na buffer (Cooper, 1963). Ferrous iron was determined by titration with $K_2Cr_2O_7$ and $Fe(NH_4)_2(SO_4)_2$ using sodium diphenylamine sulfonate as an indicator (Reichen and Fahey, 1962). All of the above references give the results of analysis of standards. P_2O_5 was determined by the gravimetric phosphamolybdate method at the Institute of Mineral Research, Houghton, Michigan.

H_2O^- was determined by weight loss after 10 hrs at 110° C. H_2O^+ was determined by the weight gain of a $CaCl_2$ absorption tube due to H_2O expelled from a weighed sample heated to fusion for 20 min. Dried air is passed over the sample during heating. The apparatus is similar to that shown by Maxwell (1968, p. 436) for carbon analysis.

Sr isotope analyses were done on a triple filament solid source mass spectrometer at the University of Arizona Geochemistry Laboratory. Sr was chemically separated by means of ion exchange columns. All values of Sr^{87}/Sr^{86} have been normalized for mass fractionation and scale factor. The Eimer and Amend $SrCO_3$ standard gives Sr^{88}/Sr^{86} of 8.375 and Sr^{87}/Sr^{86} of .7080, using the appropriate scale factors and normalization procedure (Damon, 1968, p. 19). The standard deviation indicated by three replicate mass spectrometer runs on each sample was slightly greater than ±.0001.

Rubidium and strontium determinations were done by x-ray fluorescence using Mo-Compton scattering peak to estimate sample mass absorption coefficient (Reynolds, 1963). Analytical precision was about ±3 percent for Rb and ±1 percent for Sr.

Santiaguito and Other Volcanic Domes: Chemistry

Suites from Santiaguito and seven other recently active domes are compared on a normative quartz-plagioclase–K-feldspar diagram (Fig. 9). The lavas of Showashinzan (Kuno, 1962, p. 293), Pelée (Robson and Tomblin, 1966, p. 36), Bezymianny (Vlodavetz and Piip, 1959, p. 74) and Lassen (Coombs and Howard, 1960, p. 44) have been described as dacites while Merapi (van Pandang, 1951, p. 125), Lamington (Taylor, 1958, p. 72) and Sheveluch (Vlodavetz and Piip, 1959, p. 88) have been called andesites. The most useful classification scheme for common volcanic rocks is probably that of Williams and others (1955), because of its simplicity. Applying this classification, the Santiaguito dome rocks are dacites, while the Santa María and Tertiary

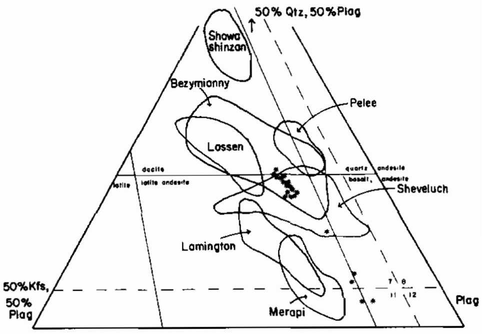

Figure 9. The lower righthand quarter of an APK diagram with fields of rocks of various labeled dome suites superimposed along with the Santiaguito–Santa María suite (asterisks). Solid lines and labeled fields show the Streckeisen (1967) classification, and dashed lines and numbered fields show Johannson's (1932) divisions.

volcanics are andesites. For the dome suites in Figure 9, the Showashinzan, Pelée, Lassen, and Bezymianny rocks would classify as dacite, the Merapi suite as andesite and the Lamington and Sheveluch groups as transitional. Like the rock suites shown in Figure 9, most recently active domes listed in the Catalogue of Active Volcanoes are andesites and dacites (Table 4).

Major Element Variations

The Santiaguito-Santa María rock suite belongs to the calcalkaline–high alumina volcanic series as defined by Peacock's alkali-lime index (Barth, 1962, p. 171) and by the high alumina magma series boundaries of Kuno (1965; Fig. 10). Data for other Central American volcanics from all available sources is compiled in Figure 11; with very similar results. On an AFM diagram (Fig. 12), the Santiaguito suite follows the calcalkaline trend described by Osborn (1959) as a function of constant or increasing pO_2 during crystallization and differentiation. Figure 13 plots experimental results of analyses of liquid fractions of the chemical system $MgO–FeO–Fe_2O_3–CaAl_2Si_2O_8–SiO_2$, differentiating at certain constant pO_2 conditions. Also plotted are analyses for rocks of the Cascades and Skaergaard (all data from Hamilton and Anderson, 1967), as well as of Santa María and Santiaguito. The latter points parallel the Cascade trend and again suggest constant or increasing pO_2. Nothing about the variation diagrams shown suggests that the Santiaguito–Santa María suite represents anything but a smooth compositional trend toward

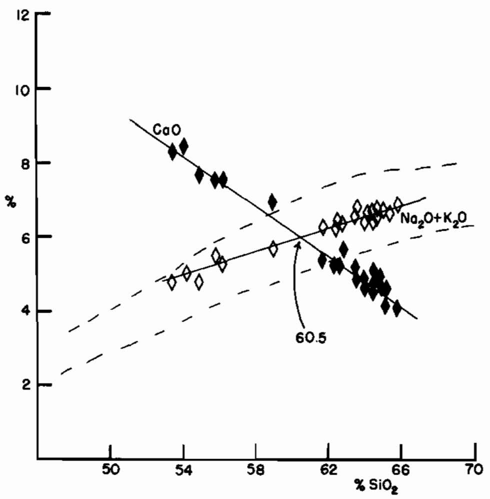

Figure 10. Variation of lime (solid points) and alkalis (hollow points) with silica in rocks from Santiaguito and Santa María (data from Table 2). Lines show best linear fits of data points. Dashed lines enclose the high-alumina field of Kuno (1965) for $Na_2O + K_2O$ data. Peacock's alkali-lime index is 60.5.

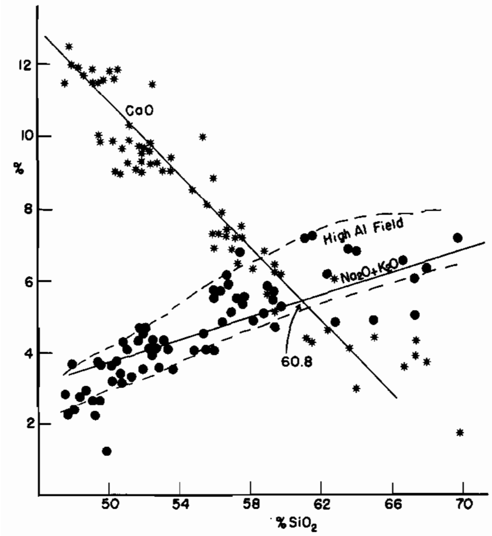

Figure 11. Covariation of lime and alkalis with silica for Central American volcanics. Data from Mooser and others (1958), McBirney and Williams (1965), Krushensky and Escalante (1967), and Stoiber and Rose (1970).

increasing SiO_2 and toward the AF side of the AFM diagram, as would be expected if the magma were differentiating by fractional crystallization in a subjacent magma chamber.

Using an AFM plot to compare the Santiaguito–Santa María suite with that of the entire Central American volcanic chain (Fig. 12), the latter data is seen to lie closer to the F corner. Following Osborn's (1959) ideas, this difference can be explained by relatively high pO_2 environment of differentiation for the Santiaguito suite. Figure 14 points up another important peculiarity of the Santiaguito suite—it is more sodic and less potassic than Central American rocks in general.

FeO–Fe_2O_3 Relations

Results of ferrous-ferric iron determinations for the Santiaguito suite show a marked variability, even though the samples are otherwise chemically similar (Table 2). Flow units may tend toward greater oxidation. The variability shown by analyses corresponds to Fe^{+3}/Total Fe values of 0.30 to 0.75.

Kennedy (1948) and Fudali (1965) have attempted to devise a method for estimating the fO_2 of basaltic and andesitic magmas from their Fe_2O_3 and FeO contents and from an experimentally derived equilibrium constant for such reactions as shown.

$$2Fe_2O_3 \rightarrow 4FeO + O_2$$

$$fO_2/K = \frac{(\text{mole \% } Fe_2O_3)^2}{(\text{mole \% } FeO)^4}$$

(1) Kennedy (1948, p. 531)

$$4FeO_{1.5} \rightarrow 4FeO + O_2$$

$$fO_2/K = \frac{(\text{mole \% } FeO_{1.5})^4}{(\text{mole \% } FeO)^4}$$

(2) Flood (Fudali, 1965, p. 1071)

While this method of determining absolute fO_2 is not considered reliable (Hamilton and Anderson, 1967, p. 468), it does appear capable of determining a "rough approximation" of changing pO_2 at a given T and composition. Using the Kennedy equation, the oxidized members of the Santiaguito suite show fO_2/K values about 1.5 orders of magnitude higher than the more reduced members. The difference is greater (2.5 orders of magnitude) if Flood's equation is used. If all the dome rocks are considered to have been extruded at the same temperature, then (since K will be constant) a relation between any two calculated fO_2/K values gives the magnitude of fO_2 differences between the oxidized and reduced members of the suite. From Kennedy's (1948, p. 538) work, we can see that a difference of 2 orders of magnitude in fO_2/K could be explained if the fO_2 were held constant and the temperature (and K) were to vary about 100° C, assuming that the temperature range of interest is about 800° to 900° C.

The fO_2/K differences can also be explained by fH_2O variations in the lavas. Considering the reaction

$$2H_2O(g) \rightarrow 2H_2(g) + O_2(g)$$

$$K' = \frac{(fH_2)^2(fO_2)}{(fH_2O)^2}$$

we see that at a given temperature a variation of one order of magnitude in fH_2O could cause differences of 2 orders of magnitude in fO_2, if fH_2 remained constant. The constancy of fH_2 is likely, since the rapid diffusion of H_2 would prohibit its rise. Thus, the more oxidized lavas could be the result of higher H_2O content at the same temperature. The oxidation differences described above are not explicable by auto-oxidation of flow surfaces, for although such oxidation was observed in vesicular tops of flows, it was avoided in sampling.

H_2O^+ Content of Santiaguito Rocks

The H_2O^+ content of Santiaguito lavas is very low (Table 2), averaging less than 0.1 percent. Other recently active volcanic domes including Sheveluch, Bezymianny (Vlodavetz and Piip, 1959, p. 89–90), Merapi (van Pandang, 1951, p. 126), Lamington (Taylor, 1958, p. 82), and Pelée (Robson and Tomblin, 1966, p. 37) have produced dome lavas in historic time with H_2O^+ contents always less than 0.3 percent, often less than 0.1 percent. Low water content undoubtedly is of great functional significance to volcanic domes, important in causing high viscosity. Pyroclastic ejecta, particularly pumice, tend to have substantially higher H_2O^+ content at most of the domes listed above, and the pumicious bombs from recent Caliente activity (no. 1511 in Table 2) are definitely water enriched.

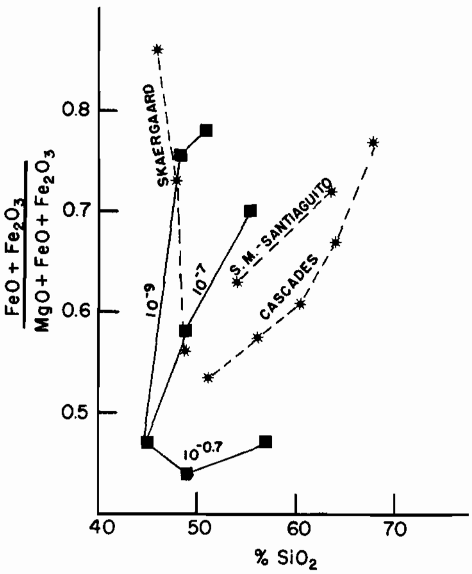

Figure 13. Variation diagrams comparing data from experimental melts in the system (FeO–Fe_2O_3–MgO–SiO_2–$CaAl_2Si_2O_8$) at controlled oxygen pressures (solid lines, as labeled) with data from rock suites (dashed lines, as labeled). Figure is after Hamilton and Anderson (1967, p. 464, 476).

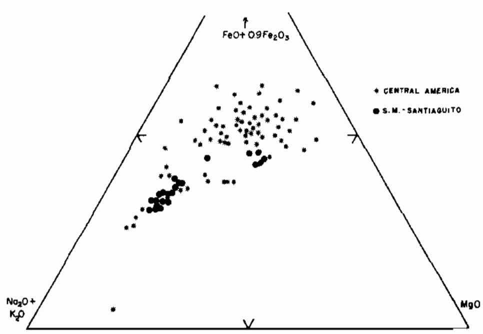

Figure 12. AFM diagram of Santa María–Santiaguito suite and other Central American volcanics. Source of data same as Figures 10 and 11.

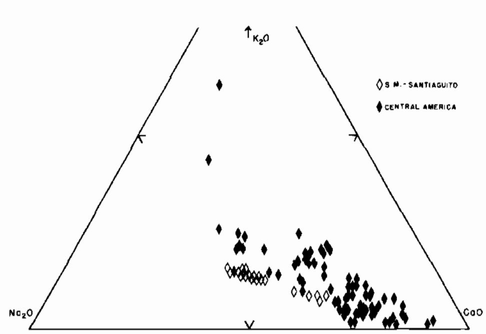

Figure 14. K_2O–Na_2O–CaO variation diagram for rocks of Central America and Santa María–Santiaguito. Source of Central American data same as Figure 11.

K/Rb, Rb/Sr and Sr^{87}/Sr^{86} Ratios

K/Rb ratios for the volcanic rocks in this study range from 401 to 531 (Fig. 15). For the Santiaguito dome products alone the range is much smaller, 401 to 459 with a mean of 435. The prehistoric andesites have a mean K/Rb ratio of 497; thus the series shown suggest K/Rb is decreasing with increasing K content. Taubeneck (1965, p. 476) and Philpotts and Schnetzler (1970) have shown that K/Rb frequently decreases during differentiation. All of the Santiaguito results are offset from Shaw's (1968) "main trend" of igneous rock K/Rb ratios obtained by covariance analysis (Fig. 15). They are higher than the range quoted by Prinz (1967, p. 308) as average for world basalts (250 to 414), and far higher than values quoted by Nockolds and Allen (1953, p. 137) for other calcalkaline differentiation suites (130 to 360). Bary (1965, unpub. thesis, p. 19) has determined K/Rb data for 22 volcanic rocks from 10 Central American volcanoes, finding a range of 189 to 529, with a mean of 298, again lower than the Santiaguito values.

Rb and Sr data for Santiaguito's rocks are shown in Figure 16. Data from Bary (1965, unpub. thesis, p. 19) for andesites and basalts from other Central American volcanoes are included for comparison. Again the volcanic rocks of Table 2 form a tightly grouped trend, and the dacites of the dome are generally separated from the older andesites. The trend of Santiaguito data in Figure 16 is similar but slightly less steep than a trend shown by Ewart and Stipp (1968, p. 716–717) for basalts and andesites of North Island, New Zealand, although the New Zealand rocks have much lower Sr content (200 to 350 ppm). It is also slightly flatter in slope than the trend of Bary's

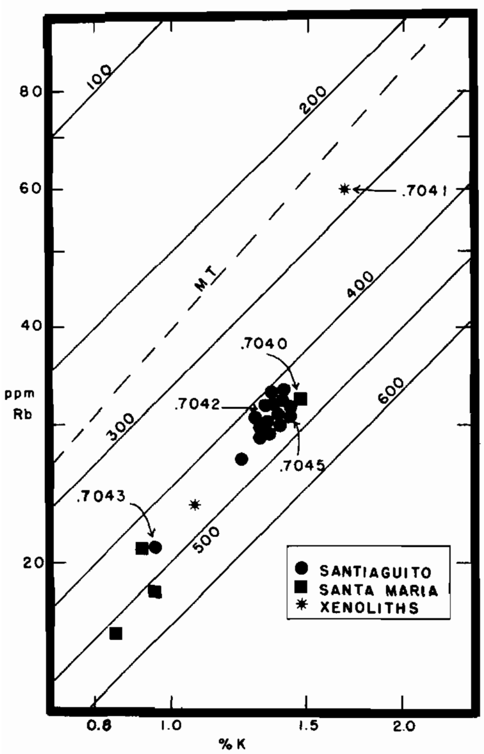

Figure 15. Rb and K data from Table 2 plotted along with labeled K/Rb ratio lines and Shaw's (1968) main trend (MT) [log (Rb, ppm) = 1.115 log (%K) + 1.597]. Sr isotope ratios are shown for those samples determined. Santa María points include the older andesite (Tv) sample (no. 1118).

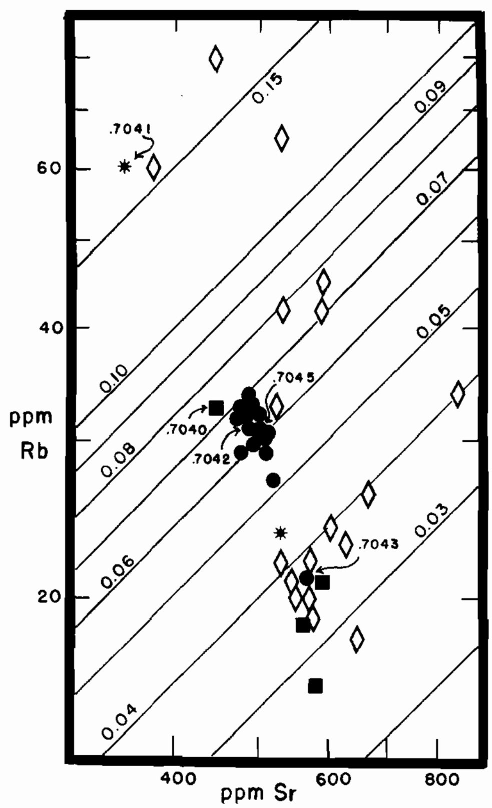

Figure 16. Rb and Sr data from Table 2 plotted along with labeled constant Rb/Sr lines for reference. Sr^{87}/Sr^{86} data are included for appropriate points. Symbols same as Figure 15, except diamonds represent data from Bary (1965, unpub. M.A. thesis).

Central American data (Fig. 16). Ewart and Stipp have attributed their observed trend to plagioclase crystallization in andesitic lavas, which depletes the residual liquid in Sr while Rb is enriched.

The difference in slope of trends from Santiaguito's andesite-dacite suite and the two basalt-andesite suites cited is probably explained by the increasing uptake of Sr by plagioclases associated with more silicious melts, which Ewart and Stipp (1968, p. 716) verified by finding higher Sr contents in plagioclases of rhyolitic lavas than in plagioclases of andesitic members of the same suite. Their rocks, like those of Santiaguito, are potash-poor and sanidine is nearly always absent. The slope of Rb-Sr variation for Santa María and Santiaguito shown on Figure 16 is thus probably controlled by Sr uptake of crystallizing feldspars in the andesite-dacite compositional range. It could also be related to fractional crystallization of other phases, such as pyroxene or amphibole, which were not investigated by Ewart and Stipp.

Figure 17 shows another Rb/Sr plot; in this case the present data have been supplemented by that published by Pushkar (1968, p. 2706–2707) for a variety of Central American volcanics and basement rocks. The intermediate to basic volcanic trend of Rb/Sr data is again visible in the right-hand side of the diagram. To the left, granite and phyllite basement rocks show marked deviation from the volcanic trend. Only samples for which Sr isotope data are available are plotted.

Although Figures 15 and 16 suggest that the dome rocks could be explained by mixture of basement quartz diorite sample no. 1401 with Santa Maria andesite, major element analyses (Table 2) show conclusively that such mixing cannot produce the correct composition by itself, since both the basement rock and the andesites are significantly more basic than the dacites of the dome. Thus the diorite basement sample is not chemically related to the Santa María and Santiaguito extrusives, while the hypabyssal sample (no. 1120) does appear related.

Sr isotope data obtained by Pushkar (1968) for Central American volcanics shows a mean Sr^{87}/Sr^{86} of .7039 ± .0005, which is intermediate with respect to values (.7034 to .7043) reported for island arc areas (Pushkar, 1968; Peterman and others, 1970a, 1970b; Ewart and Stipp, 1968). All of these values are

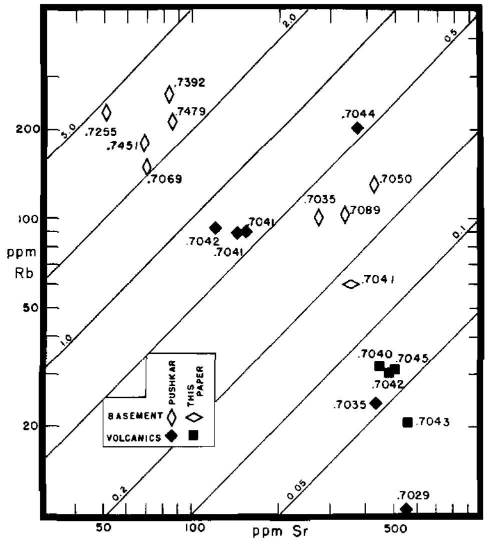

Figure 17. Plot comparing Rb/Sr data with Sr isotope determinations for Central American samples where both are available. Constant Rb/Sr lines are labeled appropriately. All isotope data are normalized to .7080 for the Eimer and Amend $SrCO_3$. Symbols as shown. Data from Pushkar (1968) are included.

significantly higher than values quoted for ocean floor tholeiites (.7022 to .7026, all values normalized to .7080 for E & A $SrCO_3$) by Peterman and others (1970b, p. 314). Even so, the authors quoted agree that their findings indicate a source area in the lower crust or upper mantle for island arc volcanic suites. An upper mantle source would be consistent with the 100 km depth to the Benioff zone dipping beneath Santiaguito.

When Pushkar's Central American volcanic data are compared to the new strontium isotope data of Santiaguito volcanics (Fig. 18), the Santiaguito suite is found to be slightly more radiogenic than Central American volcanic rocks as a whole, but still within the range of Pushkar's results. The mean value for Sr^{87}/Sr^{86} in the Santiaguito volcanic suite is inside the 1 sigma range of Pushkar's suite. Although the difference shown is not statistically significant, it does reaffirm the presence of a finite spread (.7029 to .7047) of Sr^{87}/Sr^{86} values within the Central American non-ignimbrite volcanic suite. The cause of this spread of values within Central America may either be due to local inhomogeneities in the source area, or to variable but more or less general and barely detectable contamination

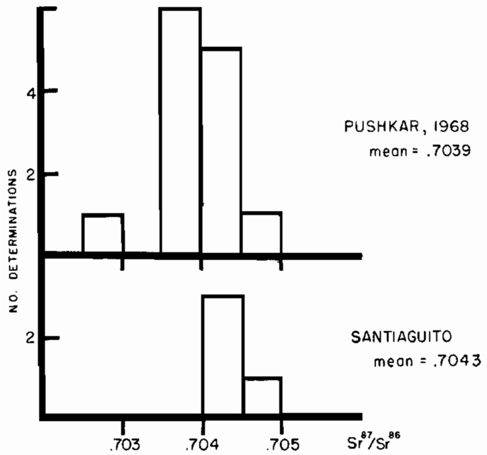

Figure 18. Sr^{87}/Sr^{86} ratios determined for Central American nonignimbrite volcanic rocks (above) and for the Santiaguito suite (below). All values have been normalized to .7080 for the Eimer and Amend $SrCO_3$.

by continental material. As Pushkar (1967, p. 58) has shown, contamination of andesite parent magma (such as is most abundant in much of Central America) by enough (up to about 25 percent) basement material (granite or phyllite) to raise the isotopic ratio from .704 to .706 is possible.

Santiaguito's magmas, like other Central American non-ignimbrite volcanic magmas, are not significantly contaminated with radiogenic basement rocks such as those shown to the left in Figure 17. Pushkar has shown (1967) that some Central American ignimbrites probably are contaminated with radiogenic granites or phyllites.

In summary, K/Rb, Rb/Sr, and Sr^{87}/Sr^{86} data for dacites and andesites from the Santiaguito dome complex and its parent volcano Santa María show trends which are best explained by differentiation due to feldspar crystallization. The source of the lava is the lower crust or mantle.

SUMMARY AND CONCLUSIONS

The Santiaguito Dome lies on the coastal side of the volcanic trend in Guatemala. To the north are the lava flows and pyroclastic deposits of the composite cone of Santa María; to the south are the laharic and fluvial deposits of the coastal slope. The volume of Santa María is about 20 km³. Flat lying Tertiary flows and lahars underlie both the composite cone and the Quaternary laharic fluvial deposits. Over all of these predome units in the map area is a variable (2 to 20 m) thickness of pumice, ash, and xenolithic debris from Santa María's 1902 eruption.

Since 1902 Santa María and Santiaguito have collectively been the most constantly active volcanic vent in Central America. During the first two days of activity, more than 85 percent of the volume of eruptive material produced in the entire 68 yr eruptive history was erupted (5.5 km³). Dome extrusion and accompanying lava flows have produced about 0.7 km³ in 48 yrs, from 1922 to 1970. Lava flows have been much more important in the recent activity; in all they make up about one third of the total Santiaguito volume, while dome units account for the remaining two thirds.

The Santiaguito dome complex has at least 14 distinguishable units, based on age. Of these, 9 are blocky flow units that generally cling to the sides of the more massive dome units. These flows are recognized by more vesicular character, more brownish color, occasional horizontal flow structure, and evidence of gravity flow downslope. Dome units are grayish and less vesicular, forming large slab-like surfaces and pelean spines, and everywhere showing conchoidal or serrated fracturing characteristic of cooling glassy rock. Dome units usually have more inclusions than flows. Some units are transitional, having characteristics of both flows and domes.

The sequence of extrusion has followed a general westward trend throughout most of Santiaguito's history. Talus slopes almost completely encircle the dome complex. Below the dome on the coastal side two of the rivers are choked with laharic and fluvial debris from the activity of Santiaguito.

More than 30 high-angle, mostly east-trending faults are found within the map area. They have minor and sometimes indeterminate displacement, but are still active. They are probably surface reflections of readjustment subsequent to the 1902 eruption, which produced more than 5 km³ of eruptive material. Some of the faults are clearly older structures along which renewed recent movement has occurred. These small faults control the pattern of extrusion at Santiaguito. All extrusion since 1938 has occurred along an east-west lineation. Furthermore, large spines or slabs and graben-like structures on the dome also follow trends of the areal faulting. In fact, nearly all major structures observed on the dome are probably a reflection of these areal fractures.

Arcuate faults are observed around many extrusive vents on the dome, caused by collapse after withdrawal of underlying material. Other than the structural features aligned with areal faulting, there is a lack of structural pattern on the domes. Measured fracture surfaces are usually steeply dipping, and flow structure, only rarely observed, is also steep, often vertical on the dome units. Spines on the dome have a dual origin; some are truly extruded monoliths, others are remnants of the fracturing of a much larger extrusive body.

The "parent magma" of the Santiaguito area is probably pyroxene andesite. Rock of this composition makes up the Tertiary flows of the area and the entire composite cone of Santa María, together accounting for the overwhelming bulk of igneous rock there. The magma of Santiaguito has a probable source in the upper mantle, consistent with the 100 to 120 km depth below the volcano of the center of the seismic zone. Evidence indicates that before 1902 the pyroxene andesite magma differentiated to dacite by fractional crystallization in a subjacent magma chamber where pO_2 was constant or increasing at a depth of about 2 km or more below the surface. The pH_2O of the system was greater than a few hundred atmospheres, and green hornblende was a stable phase. During differentiation, no detectable contamination by old granite or phyllite basement rock occurred. In 1902, with the large eruption and explosion of the crater, the volatile pressure was released from the chamber, and several cubic kilometers of gas-charged magma suddenly ascended and were erupted, forming pumice. A wide variety of xenolithic material from the newly-formed volcanic throat was also thrown out. Subsequent to the great eruption, a residual of volatile-impoverished magma remained, which began to produce oscillatory zoning of the plagioclase phenocrysts, and to alter the green hornblendes to oxyhornblendes. Slow ascent of the magma toward the surface caused remelting of some of the sodic portions of the plagioclase with lowering of pressure. Xenoliths of plutonic basement rock and hypabyssal andesite were incorporated in the magma. Near the surface the sluggish dome magma again became volatile-saturated, though this time the magma needed far less dissolved H_2O to saturate. The feldspars began to be zoned normally and vesicles began to form in the magma. Minor remelting of andesite wallrock may have occurred. With the release of volatile pressure to the surface, the extrusion of the dome began. Tridymite and crystals of plagioclase and augite in the groundmass were formed, and the oxyhornblende phenocrysts were partly altered to pyroxene, magnetite, and ore before the magma finally cooled.

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