Pattern and Mechanism of Volcanic Activity at the Santiaguito Volcanic Dome, Guatemala

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Abstract

Santiaguito volcano has shown a continuous slow extrusion of dacite lava since 1922. In the 50 years of activity there have been four periods of abnormally high extrusion rates, interspersed by periods of little magma production. The type of activity shown by the volcano has been varied and crudely cyclic. Dome extrusion periods are accompanied by pyroclastic activity and followed by lava flows. There are now 16 time stratigraphic units delineated on the dome. Activity since 1967 has been especially closely observed. Dome extrusion at the west end of the complex has been accompanied by pyroclastic eruptions and plug dome extrusion at the east end. The current extrusion rate has remained essentially constant since 1967 at about 5×10^6 m^3/yr, far below Santiaguito's 1922-71 average of 14×10^6 m^3/yr. The active vent at the east end of the volcano (Caliente vent) has been the principal vent of the volcano since the creation of the explosion crater in 1902. After its initial period of dome extrusion (1922-25), the Caliente vent has chiefly produced pyroclastic eruptions as well as at least 95 % of the dome's fumarolic activity, while lateral vents have continued to give rise to lavas. Lava flows at Santiaguito have effective viscosity values of about 10^{11} poises, while dome lavas are significantly more viscous. The differences in viscosity are in part related to volatile content of the lava when it reaches the surface. During dome extrusion, lavas lose their volatiles through pyroclastic activity before they reach the surface. Lava flows at Santiaguito occur when lava reaches the surface with higher volatile content. Obstruction of either the central (pyroclastic) vent or the lateral (dome extrusion) vent or both vents has an important influence on succeeding activity. In June 1972, at the time of this writing, the outbreak of new lava flows at both the Caliente and lateral El Brujo vents has just occurred, resulting from obstruction of pyroclastic activity by a large plug dome at the Caliente vent.

Previous Work

The activity of Santiaguito has been the subject of many published accounts, most recently STOIBER and ROSE (1969) and ROSE and others (1970). Older accounts are listed in these references and in Table 1.

A geologic map of Santiaguito, along with a discussion of the geologic setting and petrology of the volcanic rocks is found in ROSE (1972*b*).

Summary of Volcanic Activity, 1902-1971

Historic activity at Santa María commenced in October 1902, when one of the ten largest historic eruptions in the world blasted 5.5 km^3 of debris into the atmosphere (SAPPER, 1904). The eruption was concentrated in two days (see Table 1) and left an explosion crater 1000 × 700 m on the southwest flank of Santa María's composite cone. Details of this great eruption have been recently collected

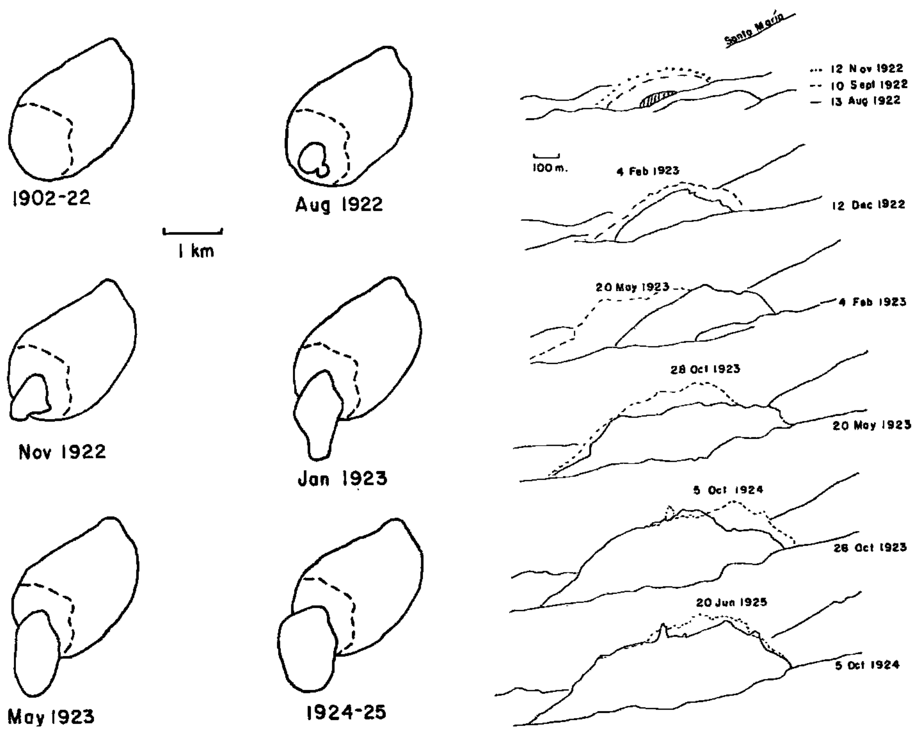

FIG. 1 - Growth of the Santiaguito volcanic dome, 1922-25 (after SAPPER, 1925). Line drawings to the left show the outline of the 1902 explosion crater and the approximate outlines of the dome at the dates listed (map view). To the right are line drawings constructed from a series of photographs of Santiaguito taken from a single observation spot, Merced Patzulin, 4 km SSE of the crater.

TABLE 1 - Summary of Major Reported Eruptive Events, Santa María and Santiaguito - 1902-1972.

Date	*Description*	*Source*
24-26 Oct. 1902	Initial and strongest phase of 1902 eruption-produced the bulk of 5.5 km^3 of pyroclastic debris	SAPPER, 1913
27 Oct. 1902	Large ash eruption; 4 PM	SAPPER, 1904
30 Oct. 1902	2 large ash eruptions, 11 AM, 2:30 PM	SAPPER, 1904
1 Nov. 1902	Large ash eruption, 11:30-12 AM	SAPPER, 1904
6-7 Nov. 1902	Large ash eruption	SAPPER, 1904
29 June 1922	Ash eruption 2-4 mm of ash fall to south and west of Santa María	SAPPER, 1926
1-4 July 1922	Small ash falls, Costa Cuca-Tapachula	Von TUERCKHEIM, 1923 (N. Y. TIMES, July 3, 1922) SAPPER, 1926
4-8 Sept. 1922	Spectacular flowing rock falls, S. Side	SAPPER, 1926
15 Oct. 1922	Ash fall at Las Majadas	SAPPER, 1926
16-22 Feb. 1923	Rumblings heard in Quezaltenango ash falls at San Felipe, Retalhuleu	SAPPER, 1926
March 1923	Frequent ash falls on coastal side	SAPPER, 1926
5-6 May 1923	Compact, steam clouds observed from Quezaltenango	SAPPER, 1926
10 May 1923	Compact, steam clouds observed from Quezaltenango	SAPPER, 1926
13 May 1923	Largest ash eruption since June 1922, 15 mm of ash at Xepach	SAPPER, 1926
23-25 May 1923	« Incredible rolling noises », hot muddy water in R. Tambor	SAPPER, 1926
15 July 1923	Small nuées ardentes	SAPPER, 1926
11-13 Aug. 1923	Small ash falls at coastal points more small nuées	SAPPER, 1926
2 Sept. 1923	Strong steam clouds observed from Quezaltenango	SAPPER, 1926
11 Sept. 1923	Strong steam clouds observed from Quezaltenango	SAPPER, 1926
15 Oct. 1923	1/2 mm ash fall at Santa María de Jesus	SAPPER, 1926
28 Oct. 1923	Small nuée ardente	SAPPER, 1926
22-24 Dec. 1923	« Renewed activity », tremors felt in Quezaltenango	SAPPER, 1926
16 Jan. 1924	Minor quakes and ash falls, strong sulfur smell at Quezaltenango	SAPPER, 1926
3 Feb. 1924	Ash falls E and SE of crater	SAPPER, 1926

Continued: TABLE 1 - Summary of Major Reported Eruptive Events, Santa María and Santiaguito - 1902-1972.

Date	*Description*	*Source*
6 Feb. 1924	Strong white eruption cloud above crater; observed from Quezaltenango	SAPPER, 1926
29-30 June 1924	Ash falls at many fincas along Boca Costa	ALVARADO, 1936
4 Aug. 1924	Bright incandescence at night; ash clouds	SAPPER, 1926
16 Nov. 1924	Glowing cloud	SAPPER, 1926
7-30 Dec. 1924	Fine white ash fall at Xepach thick steam clouds persist to height of Santa María	SAPPER, 1926
21 Dec. 1924	Small glowing cloud	SAPPER, 1926
14 May 1928	Large ash eruptions; 4-7 mm of ash fall in coastal slope	TERMER, 1929
20-28 Feb. 1929	Large ash eruptions; strong quakes. Ash falls as far as Tapachula, Mexico	DEGER, 1931 N. Y. TIMES, Feb. 22, 24, 27, 1929 ALVARADO, 1936
15 Mar. 1929	Ash eruption	KAISER, 1930
13 July 1929	Ash eruption, glowing cloud	SAPPER and TERMER, 1930*a*
27-29 Sept. 1929	Ash eruptions, strong glow of dome at night	SAPPER and TERMER, 1930*a*
2-5 Nov. 1929	Series of large, glowing clouds, many killed; ash eruptions accompany	SAPPER and TERMER, 1930*b* DEGER, 1931
10 Nov. 1929	Glowing cloud	N. Y. TIMES, Nov. 11, 1929
13 Nov. 1929	Ash eruptions	SAPPER and TERMER, 1930*b*
26 Nov. 1929	High cauliflower ash cloud; light quakes	SAPPER and TERMER, 1930*b*
28 Nov. 1929	Ash, tremors	N. Y. TIMES, Nov. 29, 1929
16 Dec. 1929	Large steam-ash cloud; glowing cloud, 5 PM; Large landslide, 10 AM	SAPPER and TERMER, 1930*b*
28 Aug. 1930	Ash eruption; ash fall as far as V. Tacaná; glowing cloud to Tambor Valley	TERMER, 1930
28 Mar. 1931	Glowing cloud follows series of tremors, 3:30 AM	SAPPER and TERMER, 1932
5 Oct. 1931	Glowing cloud to Río Tambor 7:45 AM	TERMER, 1934
17 Oct. 1931	Glowing cloud to Río Tambor Valley	TERMER, 1934
4 Nov. 1931	Steam and ash eruption	TERMER, 1934
22 May 1932	Strong activity (glowing cloud?) follows strong quake	TERMER, 1934

Continued: TABLE 1 - Summary of Major Reported Eruptive Events, Santa María and Santiaguito - 1902-1972.

Date	*Description*	*Source*
24-27 May 1932	Series of glowing clouds	TERMER, 1934
June 1932	Glowing cloud to Río Tambor	TERMER, 1934
Dec. 1932	Ash explosions	TERMER, 1934
5 Jan. 1933	Steam and ash eruption; blocks thrown to 100 M. height	TERMER, 1934
Oct. 1933	Glowing cloud to Río Concepcion	RECK and Von TUERCKHEIM, 1936
14 Dec. 1934	Ash eruption, 6:30 AM, ash fall at San Francisco Zapotitlán Quake follows eruption, 8:30 AM	EL IMPARCIAL, 14-15 Dec., 1934
24 Dec. 1934	Local tremor triggers large rock falls	RECK and Von TUERCKHEIM, 1934
26 Dec. 1934	Ash fall at San Francisco Zapotitlán	EL IMPARCIAL, 27 Dec. 1934
17-18 Mar. 1935	« Intensification of Activity » follows quake	Von TUERCKHEIM, 1935
Sept.-Oct. 1941	Period of prominent activity, including ash eruptions	J. VASSAUX P., pers. comm.
15-26 Nov. 1949	Small quakes, ash eruptions, extrusion on SW flank	J. VASSAUX P., pers. comm.
Feb.-July 1951	Continuous activity dense steam and ash clouds	J. VASSAUX P., pers. comm. MORRIS, 1963 HANTKE, 1955
14 Apr. 1956	Large ash eruption ash to Quezaltenango, El Palmar, San Felipe and W. El Salvador	MEYER-ABICH, 1956
Dec. 1956-57	Glowing rock falls on N and NW slopes, minor ash eruptions from Caliente vent	MORRIS, 1963 J. VASSAUX P., pers. comm. POUGH and MULFORD, 1957
Dec. 1960	Active lava flow SW of dome	TERMER, 1964
1963	Small nuées ardentes to south of El Brujo vent	BOHNENBERGER *et al.*, 1969
1963-66	Moving flow south of El Brujo vent, hot rock falls, very minor ash eruptions	D. EBERL, pers. comm.
April 1967	Minor ash eruptions from Caliente vent	STOIBER and ROSE, 1969
June-Nov. 1967	Small nuées ardentes on north side of El Brujo vent	STOIBER and ROSE, 1969
9-14 June 1968	Several large ash eruptions; ash fall and SO_2 odor at Llano del Pinal, 7 km NE	PRENSA LIBRE June 14. 1968
14 July 1968	Blocks as large as 20×20×40 cm are thrown a distance of 500 m laterally from the vent	ROSE, *et al.*, 1970

Continued: TABLE 1 - Summary of Major Reported Eruptive Events, Santa María and Santiaguito - 1902-1972.

Date	*Description*	*Source*
15 Aug. 1968	White ash fall at Quezaltenango, 12 km NE; 3:30 PM	ROSE, *et al.*, 1970
2 Sept. 1968	Tremors precede large black ash and bomb explosion. Noise heard in Quezaltengo. Bombs 40×40×40 cm as far as 1 km from vent; 9:50 AM	ROSE, *et al.*, 1970
12-19 Jan. 1969	Series of large ash eruptions ash falls at Quezaltenango on Jan. 19; 8 AM	PRENSA LIBRE (Guatemala) Jan. 20, 1969
26 Jan. 1969	Very strong SO_2 odor at Quezaltenango	ROSE, *et al.*, 1970
3 Feb. 1969	Very strong SO_2 odor at Quezaltenango 11:15 AM	ROSE, *et al.*, 1970
16 Feb. 1969	Very high ash cloud; strong SO_2 odor reaches Quezaltenango; 8:45 AM	ROSE, *et al.*, 1970
2 March 1969	SO_2 odor at Quezaltenango; 6:10 AM	ROSE, *et al.*, 1970
30 March 1969	Loud noise heard at Llano del Pinal; 4 AM	ROSE, *et al.*, 1970
11 July 1969	Loud explosion heard at Llano del Pinal; 11 PM bombs as large as 1×1×3 m thrown 500 m laterally from the vent	ROSE, *et al.*, 1970
26 July 1969	Ash and bombs erupted with strong, high black and white ash cloud. Tremors felt in Llano del Pinal; ash cloud visible in Quezaltenango; 8:30 AM	ROSE, *et al.*, 1970
25 Sept. 1969	Ash fall at Quezaltenango, SO_2 smell ash column visible 1:30 PM, bombs and tremors felt at Buena Vista	PRENSA LIBRE Sept. 26, 27, 1969
7 Nov. 1969	Strong eruption cloud observed and SO_2 smell noticed at Llano del Pinal	ROSE, 1970
19 June 1970	Loud noise heard at Llano del Pinal	Field notes
24 Dec. 1970	Large eruption of bombs and pumice	Field notes
15 April 1971	Ash eruption follows quake felt at El Palmar; 8 AM	Field notes
Dec. 1971 - July 1972	Small nuées ardentes from the El Brujo vent	Field notes

from diverse sources (ROSE, 1972*a*) and estimates of the energy of the eruption calculated. In terms of energy, this first 2-day event was at least twice as significant as all subsequent activity combined. If volume is considered, this dominance becomes even more impressive (Table 2).

After a twenty-year lapse, volcanic activity at Santa María resumed in 1922 (Fig. 1). The initial phase of dome extrusion, beginning

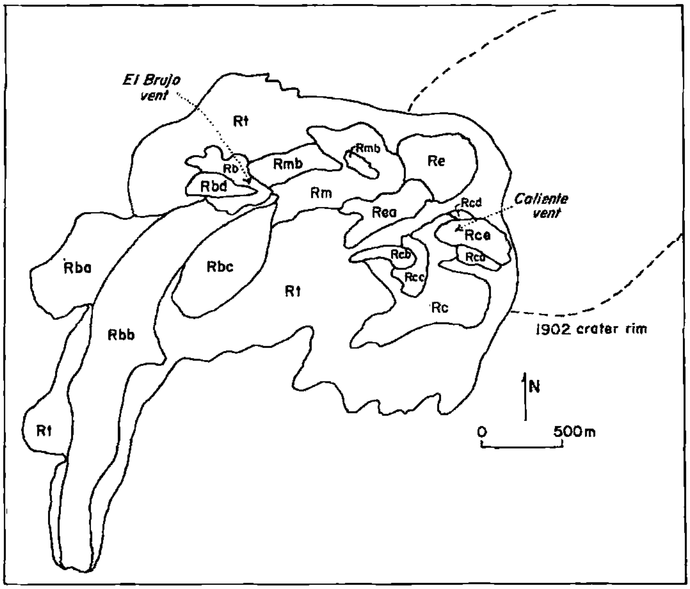

FIG. 2 - Sketch map showing historic units of the Santiaguito volcanic dome as of July 1972. For explanation of symbols see Table 3. For a more detailed map of the same zone, see ROSE (1972, fig. 2). Rt is talus derived from all the other recent units.

within the explosion crater, was reported in great detail, thanks chiefly to the efforts of Gottfried HURTER, whose complete observations were reported by SAPPER (1926). This dome extrusion was accompanied by impressive pyroclastic eruptions and nearly constant tseam cloud emission. The pattern of the initial phase of growth (1922-1925) of the Santiaguito dome can be constructed from HUNTER's descriptions and photographs in the form of line maps and sections (Fig. 2). This first phase of growth produced about 30 % of Santiaguito's present volume (Table 2) and the first of sixteen units of the dome (Table 3 and Fig. 2). The chronology of major reported eruptive events at Santa María and Santiaguito to the present is given in Table 1.

From 1925 through 1935, several viscous lava flows were extruded at Santiaguito (Table 3, Plates). Ash eruptions occurred during this period, but were overshadowed by frequent nuées ardentes. The largest nuée of Santiaguito's history occurred in November, 1929 (SAPPER and TERMER, 1930), devastating several villages and fincas and killing hundreds of people.

Since 1935, there have been four more periods of dome extrusion: 1939-42, 1949?-52, 1956-58, and 1967-71 (Table 3). These periods have been interspersed with extrusion of at least 8 lava flows, resulting in almost continuous activity. Between 1958 and 1965, large volumes of lava were extruded, forming three thick blocky flows. The volumes of these flows are more than an order of magnitude greater than other flows at Santiaguito, and the lava extrusion rate was far above average during the period. Recent activity has produced a new dome (El Brujo) at the west end of Santiaguito (STOIBER and ROSE, 1969) and pyroclastic activity as well as the extrusion of several plug domes from the Caliente vent (ROSE *et al.*, 1970), and finally new vesicular flow units at both the El Brujo and Caliente vents.

Details of the historical record are summarized by ROSE (1970), and will not be reiterated. Between the years of 1940 and 1955, information on Santiaguito's activity are relatively sparse, but aerial photo coverage of the mountain during these years has aided the reconstruction of events.

Volumes of Volcanic Rocks Produced by Various Kinds of Activity

The growth of the Santiaguito dome since 1922, is shown by Figure 3, and volume estimates on selected dates are given in Table 2. The total volume of extruded rock at Santiaguito far exceeds the volume erupted during the same time period produced by nuées ardentes or pyroclastic explosions. The volume of debris deposited by the nuée sequence of early November, 1929, was estimated at 3×10^6 m^3, or 0.003 km^3 (SAPPER and TERMER, 1930). This was the largest such eruption in Santiaguito's history; less than 10 others of even comparable magnitude have occurred. Thus, considering all large glowing cloud activity from 1922 to 1970, it is very unlikely that these eruptions produced more than 10 times this total or 0.03

km^3. Even this maximum is less than 5 % of the volume of the dome itself.

Pyroclastic products are probably somewhat more important volumetrically. The volume of a relatively large ash event in May, 1928, was determined above to be about 1×10^6 m^3 or 0.001 km^3.

TABLE 2 - Volume Estimates; Santiaguito Volcanic Dome 1925-69.

Date	*Approximate Total Volume of Dome Complex*
1925	0.2 km^3
1945	0.3 km^3
1954	0.5 km^3
1968	0.7 km^3

Volume of large ash flow-mud flow of November 1929: 3×10^6 m^3
SAPPER and TERMER, 1930, p. 86
Volume of 1902 eruption debris: 5.5 km^3
SAPPER, 1904, p. 67
Volume of Santa María cone = 20 km^3
Volume of 1902 explosion crater = 0.5 km^3

The eruptive history proves it unreasonable to suggest that there were more than 50 eruptions of similar magnitude, and none of the ash eruptions since 1922, was materially larger than this 1928 event. Thus, a maximum volume of ash produced from 1922-1971, is 0.05 km^3, or 7 % of the extrusive volume of the dome.

The material of the dome itself can be divided into two gross classes. The first, and most important, is extrusive dome material, which seems to make up about 2/3 of the volume of Santiaguito. Vesicular, thick, blocky lava flows make up the other third of the volume figure. Such lava flows have comprised the bulk of Santiaguito's volume growth in the last 15 years, representing a marked change from the earlier predominance of dome extrusion. These percentages are slightly uncertain, due to the existence of intermediate rock units and due to the great importance of talus slopes in computing the volume estimates.

Trends and Cycles of Activity

A chart comparing the four types of volcanic activity at Santiaguito was prepared (Figure 4). Unfortunately, the lack of good observational data during the period of 1940-1955 limits the usefulness of this chart, but a few generalities are evident. Dome extrusion periods tend to be preceded and accompanied by pyroclastic activity and followed by lava flows. An almost cyclic pattern emerges. Su-

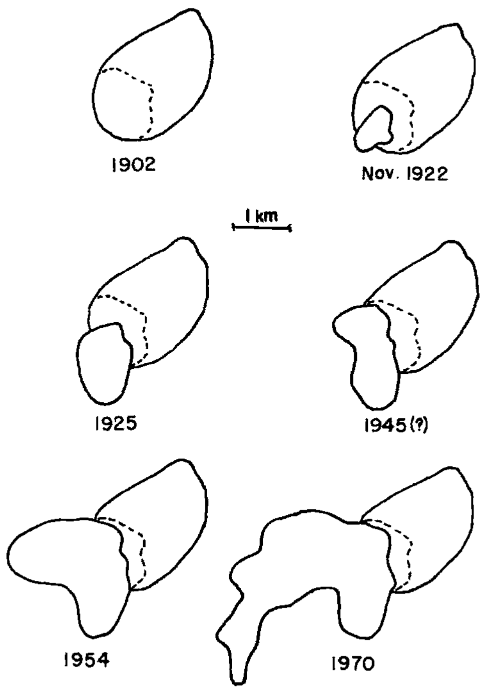

FIG. 3 - Growth of the Santiaguito volcanic dome, 1922-70. Line drawings, as in Fig. 1, showing growth of Santiaguito.

perimposed on this pattern is the occasional occurrence of glowing clouds. A list of the main extrusive events is given in Table 3. Obviously these events correspond with units on the sketch map (Figure 2).

The activity since 1967, has been closely observed. Volumes of extrusives produced at the two vents can be compared with each other and with the gross average extrusion rate at Santiaguito (Table 4). The 1969-71 extrusion rate is similar to the 1967-69 values and is also lower than the gross average. The onset of extrusion in large volumes at the Caliente vent in 1970, coincided with reduced extrusion at El Brujo. After the Caliente vent was capped by a large plug dome, vesicular, more fluid magma began rising to the surfgace at both the El Brujo and Caliente vents (see Figures 5 and 6).

Although examination of Table 4 also suggests that there may be a recent increase (from 4×10^6 to 6×10^6 m^3/yr) in the total

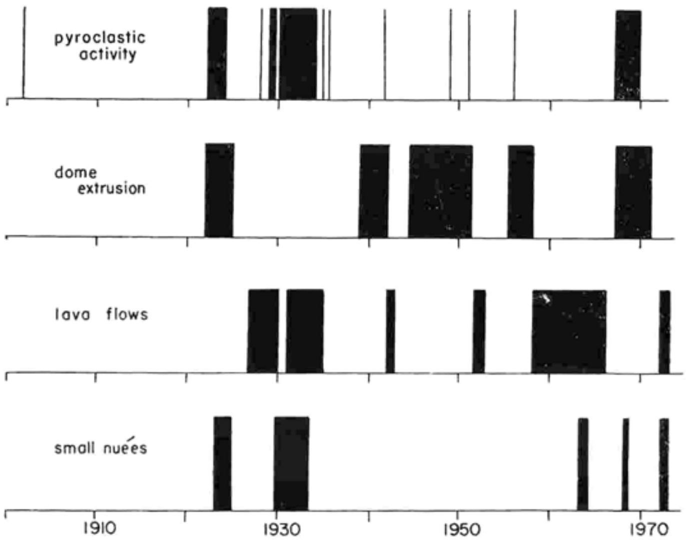

FIG. 4 - Schematic drawing showing times of various types of activity at Santa María and Santiaguito, 1900-1970.

extrusion rate for Santiaguito, the table does not attempt to estimate the volume of pyroclastic material being produced by the Caliente vent during 1968-69. On the basis of calculations like those applied above above to the May 1928 eruption, it seems likely that this intense pyroclastic eruption period produced volumes well in excess of 10^6 m^3. Thus, there has probably been no important increase in the rate of magma eruption at Santiaguito since 1967.

The use of a gross average extrusion rate is misleading unless we make some examination of the variability of extrusion through time. Figure 7 shows the results of such an attempt, based on knowledge of the age of the units of the dome complex. While the figure is very approximate, it is clear that there have been only four periods, usually only lasting a few years which have accounted for most of the volume of the dome. In other words, the dome has grown in « spurts ».

The Function of the Caliente Vent

From 1922 to 1970, all available photographs of the Caliente vent area have shown strong fumarolic activity. The first dome extrusion

TABLE 3 - Main Extrusive Events, Santiaguito Dome, 1922-72.

Date	*Description*	*Reference(s)*
June 1922-Feb. 1925	Extrusion of Caliente dome (Rc)	SAPPER, 1926
Jan. 1927-May 1929	Extrusion of vesicular mantle on west slope of Caliente dome (Rcd)	TERMER, 1927 KAISER, 1930
Nov. 1929-Dec. 1934	Extrusion of two blocky flows down the avalanche slope SW of Caliente vent (Rcc, Rcb)	SAPPER and TERMER, 1930
1932-Dec. 1934	Extrusion of blocky flow NE of Caliente vent, within the 1902 crater (Rca)	TERMER, 1934 Von TUERCKHEIM, 1934
1933-1938	Extrusive activity on NW slope of Caliente dome, few direct observations	RECK and Von TUERCKHEIM, 1936
1939(?)-1942(?)	Extrusion of La Mitad dome (Re)	E. G. ZIES (pers. comm.) * J. VASSAUX P. (pers. comm.)
194?	Extrusion of La Mitad flow (Rea)	* ROSE, 1970
194?-1952(?)	Extrusion of El Monje dome I (Rm)	* HANTKE, 1955
1952?	El Monje flow extruded (Rma)	* ROSE, 1970
1956-1958	El Monje dome II extruded (Rmb)	* MORRIS, 1963
1958	First El Brujo flow extruded (Rba)	* STOIBER and ROSE, 1969
1959-Mar. 1963	Second El Brujo flow extruded (Rbb)	* TERMER, 1964 STOIBER and ROSE, 1969 BOHNENBERGER, *et al.*, 1969
1963-1966	Third El Brujo flow extruded (Rbc)	STOIBER and ROSE, 1969
Feb. 1967-present	Extrusion of the El Brujo dome (Rb)	STOIBER and ROSE, 1969 ROSE, *et al.*, 1970
June 1968-Nov. 1969	Extrusion of a series of small plug domes at the Caliente vent	ROSE, *et al.*, 1970
May 1970-Jan. 1972(?)	Extrusion of a large plug dome in the Caliente vent (Rce)	This paper
Dec. 1971	Extrusion of flow at El Brujo vent (Rbd)	This paper
Jan. 1972(?)-present	Extrusion of flow from Caliente vent (Rce)	This paper

* Aerial photo coverage important in establishing the event.
NOTE: Details on many of these extrusive events may be found in ROSE (1970).

occurred from this vent. Even before the dome formed, observers noted that the strongest fumarolic emission and geyser activity was toward the eastern end of the explosion crater, coinciding with Caliente's location. Furthermore, no large pyroclastic eruption at Santiaguito has had a documented source other than the Caliente vent. In spite of the pattern of extrusion which has lead to growth westward, away from the Caliente vent, Caliente still shows very strong activity and must be considered the principal vent at Santia-

TABLE 4 - Volumes of Extrusive Lavas, Santiaguito Volcano, 1967-71.

	Volume, m^3
El Brujo Dome (March 1967-August 1969)	8.5×10^6
Caliente plug dome (June 1970-August 1971)	5×10^6
El Brujo Dome (March 1967-August 1971)	10×10^6
Extrusion Rates	*Rate, m^3/yr*
Gross Average (1922-1971)	14×10^6
El Brujo Rate, 1967-69	4×10^6
Caliente Rate, 1970-71	5×10^6
El Brujo Rate, 1970-71	1×10^6

guito. Its function in the dynamics of eruption will be discussed further below. The recent association of dramatic fumarolic and pyroclastic activity at the Caliente vent with dome extrusion at the El Brujo vent is of great significance. It shows that the central vent still represents the locus of the deep-seated magma conduit, while the location of surficial extrusion is evidently controlled by near-surface structures. This conclusion is not obvious from the geomorphology of the volcano, as might be the case for the principal vent at a composite cone or cinder cone.

Looking carefully at the current (1967-72) activity at the Caliente vent, we can observe that it has shown four distinct phases (Table 5) culminating with the extrusion of a large plug dome and finally a vesicular flow at the Caliente vent. Since the extrusion of the large plug dome began, pyroclastic activity at the Caliente vent has declined

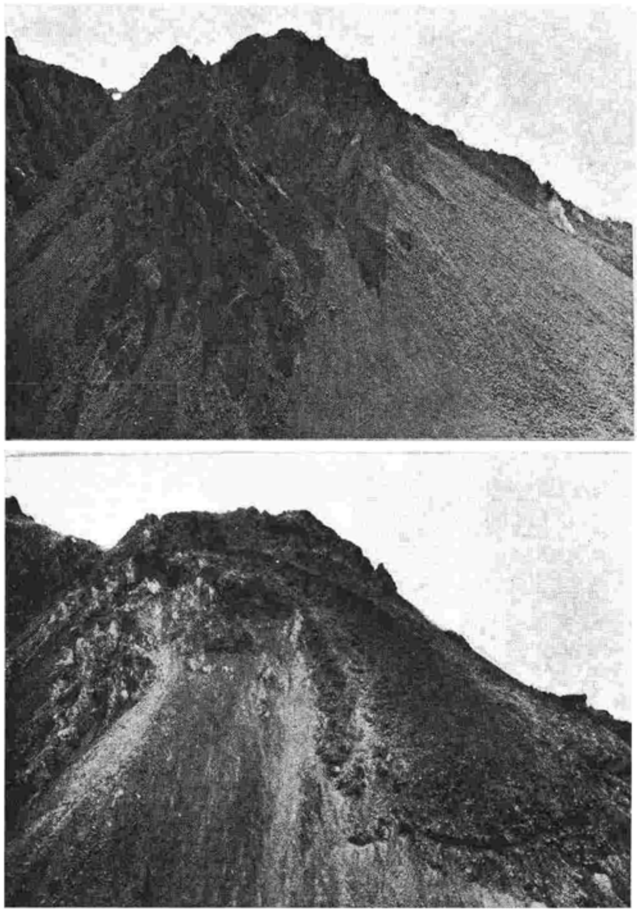

Fig. 5 - The El Brujo vent area as seen from the la loma trail below Magermanns Hotel (looking east). The view above taken in January 1970; below, July 1972. Distance from side to side in the photos is approximately 500 m. The lower photo shows a still active blocky flow.

in importance, consisting almost entirely of mild steam eruptions from the plug dome. In December 1971, as was the case following previous dome extrusion periods, vesicular, more fluid magma began to emerge both at the Caliente vent and at the lateral (El Brujo) vent (Table 3). If the Caliente vent is to retain its well established identity as the primary central vent — then a large explosive event is likely, although the timing of this event is uncertain.

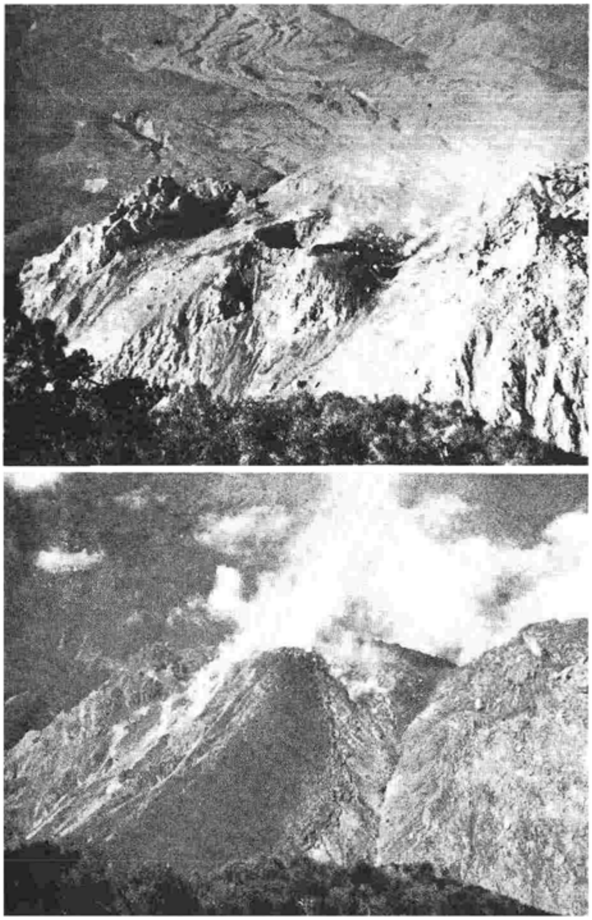

FIG. 6 - The Caliente vent area as seen from the summit of Santa María (looking southwest). The view above taken in January 1970; below, July 1972. The diameter of the open vent in the upper photograph is about 40 m. An active blocky flow can be seen in the lower photo.

Quantity of Volatile Release at Santiaguito

There is no straightforward method of measuring the quantity of volatiles released by Santiaguito. From regular observation during the middle 1960's, however, it was established that most of the gaseous discharge (probably more than 90 %) occurs at the Caliente vent (STOIBER and ROSE, 1969). This fact is true even in periods of no pyroclastic eruptions — the Caliente vent area has historically been the most important fumarolic area on the mountain.

Efforts to gain a crude estimate of the rate of fumarolic emission at Santiaguito have employed the degree of contamination of local rainwater by Santiaguito gas and the measurements of flow rates

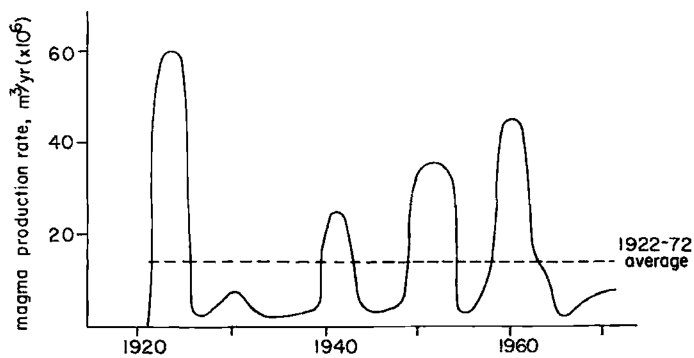

FIG. 7 - Estimate of the magma extrusion rate during the historic activity of Santiaguito, 1922-1972. The figure was constructed based on field observations of the various units of the dome and the data of Table 3.

at individual fumaroles with a velometer (ROSE, 1970). Both data suggest a minimum rate of fumarolic gas flow at Santiaguito of 10^3 g/sec, with the true value being perhaps as much as an order of magnitude higher. Thus, fumaroles at Santiaguito add 10^3 to 10^4 g/sec of gas to the atmosphere.

Certainly the total fumarolic emission rates at Santiaguito are infinitesimal compared to the gas output per second during pyroclastic activity. The values determined in Table 6 for recent Caliente vent eruptions are $1.0\text{-}2.7 \times 10^9$ g/sec. Thus, the entire yearly output of steady fumarolic degassing could be equalled by about 10 seconds to 10 minutes of pyroclastic activity. Clearly the gaseous output of the volcano during pyroclastic activity increases by several orders of magnitude.

The approximate nature of the figures above should be reemphasized. They were done to reach a comparative evaluation of fumarolic and eruptive gas outputs. Still unanswered is the question of meteoric or atmospheric contamination of the fumarolic or eruptive gas before it reaches the surface. Thus, an estimate for rates of magma degassing is made very uncertain. It does seem certain, however, that magma degassing is progressing at a dramatically faster rate during pyroclastic activity.

TABLE 5 - Recent Caliente Vent Volcanic Activity, Santiaguito Dome.

Phase I	
April 1967 - October 1968	At first small explosive ash eruptions, later the eruptions were larger. Multiple vents active. A small plug dome grows in the last few months, and is exploded away in a large eruption.
Phase II	
January 1969 - November 1969	Many violent pyroclastic eruptions. One central vent. Two more small plug domes grow in the throat of the vent and are dramatically blasted out. Steam eruptions common.
Phase III	
May 1970 - December 1971	Weak ash eruptions, many steam eruptions. Extrusion of large plug dome and accompanying constant steam emission through the plug dome.
Phase IV	
January 1972 - July 1972	Constant steam emission. Extrusion of vesicular lava flow down slope E of Caliente vent to the floor of the 1902 crater.

No estimate of degassing rates of Santiaguito lava flows has been attempted, since such flows have not occurred until the very end of the current observation period.

Viscosity of Lavas at Santiaguito

Employing the equation of NICHOLS (1939) and observational data on active lava flows at Santiaguito the effective viscosity of the flows can be calculated (Table 7). Table 7-A is based on the continual downslope movement of one large Santiaguito flow for a distance of about 2 km in 1.5 years (July 1959 - January 1961). As FRIEDMAN and others (1963) have suggested, such viscosity estimates are perhaps two orders of magnitude too high because of imperfections in the viscosity model. This difference is supported by the calculations in

Table 7-B, using data collected by von TUERCKHEIM in 1932-1933 (TERMER, 1934, p. 47).

The effective viscosity of dome extrusion at Santiaguito cannot be estimated without knowing more about the pressure causing

TABLE 6 - Calculations Involving Caliente Vent Activity, Santiaguito, 1968-69.

Symbols: ρ = density of lava, g cm^{-3}
g = gravitational constant = 980 cm sec^{-1}
r = distance of travel of bombs, cm
v_o = initial velocity of bombs, cm sec^{-1}
P = pressure, dynes cm^{-2}
X = volume rate of discharge, 1 sec^{-1}
Y = weight rate of discharge, g sec^{-1}
R = radius of vent, cm
A = area of vent, cm^2
T_1 = temperature of gas eruption, deg K = 1200
T_2 = ambient temperature, deg K = 300
P_1 = pressure of the eruption, atm = P
P_2 = surface pressure = 1 atm

Initial velocities of bombs:

	Dates	*Distance of bomb travel*
(1)	July 14, 1968 July 11, 1969	500 m
(2)	Sept. 2, 1968	1000 m

$v_o = \sqrt{rg}$ (MINAKAMI, 1939)
(1) $v_o = 71$ m sec^{-1}
(2) $v_o = 99$ m sec^{-1}

Pressure of the eruption:

$P = 1/2\ \rho\ v_o^2$ (YOKOYAMA, 1957, p. 87)
(1) $P = 0.6 \times 10^8 = 60$ atm
(2) $P = 1.2 \times 10^8 = 120$ atm

Discharge rates:

$X = Av_o$ where $A = \pi R^2$; $R = 20$ m, so $A = 1200\ m^2$
(1) $X = 8.5 \times 10^7$
(2) $X = 12. \times 10^7$

$Y = X\,(T_2/T_1)\ (P_1/P_2)$ (18 g $mole^{-1}$)/(22.4 1 $mole^{-1}$)
(1) $Y = 1.0 \times 10^9$ g sec^{-1}
(2) $Y = 2.7 \times 10^9$ g sec^{-1}

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extrusion. Judging from their lack of downslope flow, however, domes are undoubtedly significantly more viscous than flows.

Chemical analysis of lavas of the dome (ROSE, 1972*a*) reveal no

TABLE 7

A. Calculation of the viscosity of the Santiaguito lava flow of 1959-1961, based on the equation of NICHOLS (1939).
Symbols:

η_l = coefficient of viscosity, poises
v = velocity of flow, cm sec^{-1}
sin A = average slope or inclination
d = thickness of flow, cm
ρ = density of lava, g cm^{-3}
g = gravitational constant = 980 cm sec^{-2}

Equation:

$$\eta_l = \frac{g \sin A \, d^2 \rho}{3v}$$

When sin A = 0.2, d = 2500, $v = 5 \times 10^{-3}$ and ρ = 2.6
$\eta_l = 2.5 \times 10^{11}$ poises

B. Calculated viscosity of 1932-1933 lava flow, Santiaguito Volcano.
(1) $v = 2 \times 10^{-2}$ cm/sec velocity at the flow front
(2) $v = 4 \times 10^{-1}$ cm/sec velocity near the vent
(observational velocities from TERMER, 1934, p. 47).

Equation:

$$\eta_l = \frac{g \sin A \, d^2 \rho}{3v}$$

If sin A = 0.5, d = 2000 and ρ = 2.6
(1) $\eta_l = 9 \times 10^{10}$ poises viscosity at the front
(2) $\eta_l = 5 \times 10^{8}$ poises viscosity near the vent

major element differences between the dome lavas and flow lavas and petrographic examination shows a roughly similar phenocryst: groundmass ratio. Thus, neither compositional factors (except volatiles) nor suspended solids can account for the apparent viscosity contrast. Chemical analysis also showed both dome and flow rock to be nearly completely devoid of H_2O, even though flow rock has a much greater vesicularity. It is possible that the flow lavas are erupted with a higher volatile content, which is lost during surface cooling (forming vesicles) and so not reflected in the analysis. It is also possible that flow lava is erupted at a higher temperature. Both slightly higher (50-100° C. higher) temperature and slightly higher (from 0 to 0.5 %) volatile content have been shown to dramatically reduce the viscosity of rhyolite (FRIEDMAN and others, 1963). Both the greater vesicularity of the flows and large Fe^{+3}/Fe^{+2} variations in the lavas suggest that volatile content variations are at least partly responsible for the viscosity differences.

Summary

The association of pyroclastic activity with dome extrusion is thus clear — it represents the surface reflection of subsurface degassing and cooling of the magma prior to its extrusion as a dome. In the case of the 1967-71 dome extrusion, the magma lost volatiles and probably temperature by degassing through the Caliente vent before it was extruded at the El Brujo vent. Since mid-1971, however, volatile escape from Caliente vent has declined, and in December new lava flows began to emerge at both El Brujo and Caliente signalling an end to the dome extrusion. Since there are two active vents with contrasting characteristics, congestion or obstruction of either of both vents has different effects on activity. Obstruction of both vents simultaneously will result in a strong pyroclastic eruption which will clear the gas and ash vent. If pyroclastic activity continues and finally wanes at the cleared central vent, slow dome extrusion may begin at the congested subsidiary vent, resulting in very viscous non-vesicular lava. Continued viscous extrusion within the conduit of the central vent (as exemplified by plug-domes) finally may seal the waning volatile pressure from below, but at this stage passage for magma to the new subsidiary vent has been established and hotter, more volatile-enriched magma may emerge there as a lava flow as has just occurred at the El Brujo vent. Continued extrusion of lava flows from the subsidiary vent may finally cause it to be congested again and the cycle will start anew.

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