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Lava flow growth inferred from morphometric parameters: a case study of Citlaltépetl volcano, Mexico

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Abstract – Recent (Quaternary) lava fields, such as those of Citlaltépetl (Pico de Orizaba) volcano in Mexico, are excellent places to obtain precise measurements of flow-field dimensions that can be used to estimate volume, eruption duration and effusion rates. The relationship between these parameters and the influence of some other interrelated features such as lava composition, superficial structures and lava type are important tools that can help to infer conditions when the lavas were active and thus improve understanding of how flow fields grow. The Holocene lavas of Citlaltépetl volcano are homogeneous in composition (dacites) and are generally blocky with well-developed levees. The eruption duration obtained for the Citlaltépetl lavas by a method proposed by C. Kilburn and R. Lopes presents a good correlation with the different lava types morphologically classified here. Results from that method compare favourably with the inferred effusion rates estimated by an empirical cooling method (Graetz). The lavas show different behaviour, mainly controlled by fluctuations in the effusion rate that promote changes from single- to multiple-flow style. The maximum distance achieved by a flow is directly proportional to the effusion rate in Citlaltépetl lavas, but it is always lower for multiple flows, independent of the volume of erupted lava. Observations of Citlaltépetl lavas can be used to understand how lava flow growth occurs on other volcanoes.

1. Introduction

Different empirical correlations between distinct flow-field characteristics have been proposed to understand flow-field growth. Relationships between conditions at the start of a flow and final flow dimensions have been established, for instance, flow-field length and mean extrusion rate (Walker, 1973; Wadge, 1978; Lopes & Guest, 1982; Kilburn & Lopes, 1991; Kilburn, 1993; Lopes & Kilburn, 1994), flow length and volume (Malin, 1980; Lopes & Guest, 1982), and surface area and mean effusion rate (Pieri & Baloga, 1986). Although not all of these correlations necessarily apply to any given set of lavas (Lopes & Guest, 1982), the overall growth of *aa* and blocky flow fields apparently follows some systematic patterns (Kilburn & Lopes, 1991) that can be used to infer eruptive conditions and possibly also to forecast final flow dimensions (Kilburn, 1995).

The main controls on lava flow morphology are: effusion rate (Walker, 1973), the lava's physical properties (density and rheology), and slope (Hulme, 1974). Of these factors, the influence of lava rheology is extremely difficult to quantify. Fortunately, simple relationships between flow-field dimensions, slope and eruption duration have been proposed, independent of terms involving lava rheology or gravity (Kilburn & Lopes, 1991). These relations are here applied to the morphological features of lavas recently erupted by the Citlaltépetl volcano (Pico de Orizaba) in Mexico, in order to investigate the conditions of eruption. The results are compared with those from an independent method based on the Graetz number (Hulme & Fielder, 1977), providing a more rigorous approach.

Holocene lavas of Citlaltépetl volcano, some emplaced in historic times, are fresh and still preserve their characteristic shape and surface features, so flow dimensions can be easily and precisely obtained and then used to interpret Citlaltépetl's recent flow-field development. An interpretation of the future behaviour of Citlaltépetl lavas based on such analysis can be useful in assessing the hazard from effusive eruptions. Moreover, discrimination of the morphologically different lava types from Citlaltépetl volcano, which are interpreted to be associated with distinct flow behaviour, may help to increase understanding of how lava flow fields grow on other volcanoes.

2. Summary of the eruptive history of Citlaltépetl volcano

Citlaltépetl or Pico de Orizaba, is an ice-capped, andesitic stratovolcano, which at 5675 m a.s.l. is Mexico's highest peak. It is the easternmost stratovolcano of the Trans-Mexican Volcanic Belt, a Plio-Quaternary province that crosses the central part of Mexico (Fig. 1). Like many other stratovolcanoes, Citlaltépetl shows a long and complex evolution, which includes repetitive phases of construction and destruction of the main volcanic edifice (Robin & Cantagrel, 1982; Höskuldsson, Robin & Cantagrel, 1990; A. Höskuldsson, unpub. Ph.D. thesis, Blaise Pascal Univ., France, 1992; G. Carrasco-Núñez, unpub. Ph.D. thesis, Michigan Tech. Univ., USA, 1993; Carrasco-Núñez & Ban, 1994).

Although Citlaltépetl is a Quaternary volcano with historic activity, it is at present in a dormant stage. The evolution of Citlaltépetl volcano has been divided into

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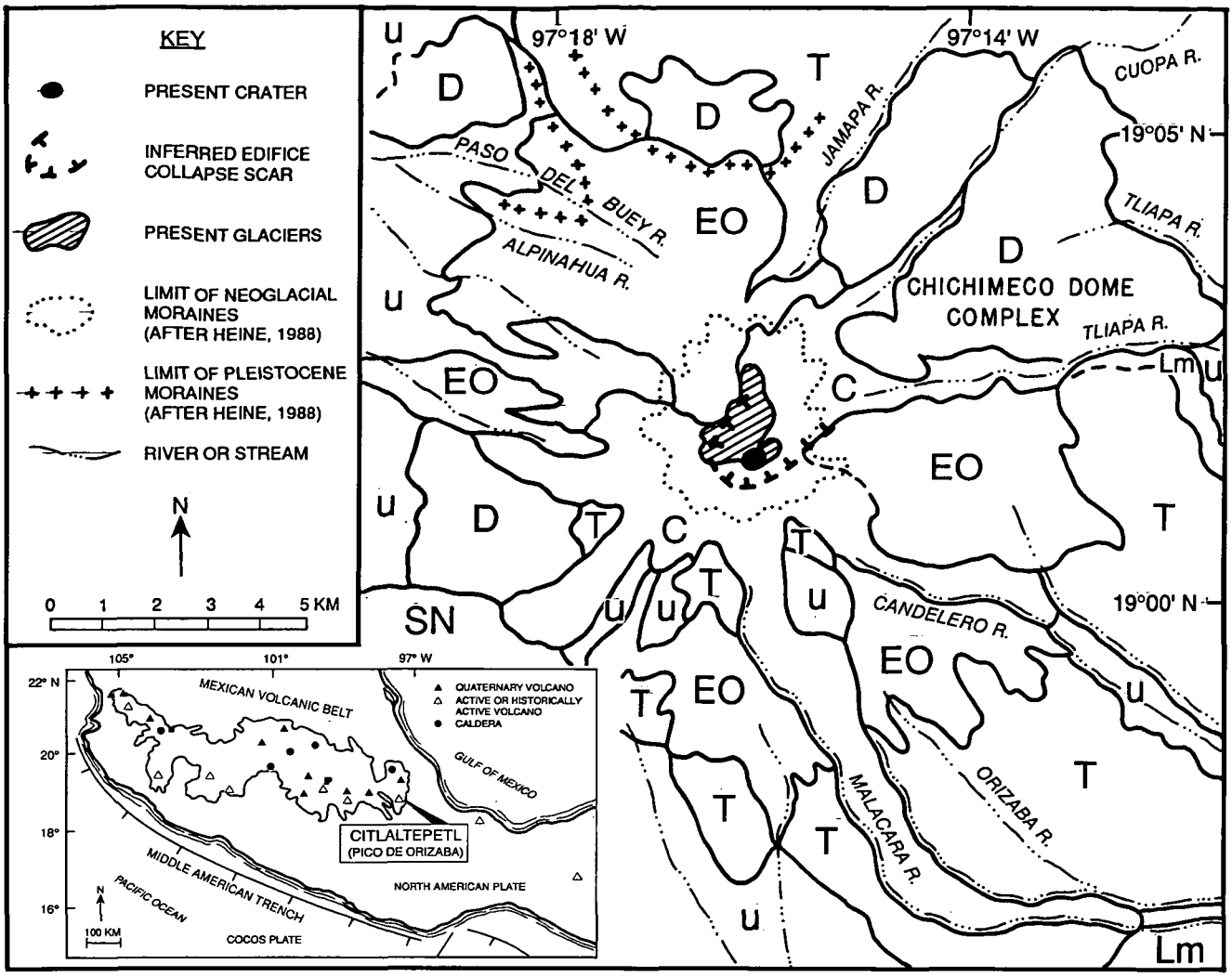


Figure 1. Location of Citlaltépetl volcano at the eastern end of the Trans-Mexican Volcanic Belt and geological sketch of Citlaltépetl summit crater. Labels represent evolutionary stages from the oldest to the youngest (G. Carrasco-Núñez, unpub. Ph.D. thesis, Michigan Tech. Univ., USA, 1993): T – Torrecillas volcano, EO – Espolón de Oro cone, D – dacite domes, and C – Citlaltépetl cone. Other symbols are: Lm – Cretaceous limestone, u – undifferentiated pyroclastic deposits, SN – Sierra Negra volcano. See text for explanation of Citlaltépetl's evolution.

three separate phases (Robin & Cantagrel, 1982; A. Höskuldsson, unpub. Ph.D. thesis, Blaise Pascal Univ., France, 1992), however, a new scheme based on a detailed study of the structure and stratigraphy of the summit crater area reveals four distinct stages, which correspond to the construction of three superimposed volcanoes and the emplacement of peripheral volcanism at different times during the formation of the central cones (G. Carrasco-Núñez, unpub. Ph.D. thesis, Michigan Tech. Univ., USA, 1993; Carrasco-Núñez & Ban, 1994). Figure 1 shows a geological sketch of the Citlaltépetl summit area, depicting major evolutionary stages (central cones from the oldest to the youngest: Torrecillas – T, Espolón de Oro – EO, and Citlaltépetl – C; dome activity – D, which occurred at different times). The main features of these eruptive stages are summarized in Table 1.

The first eruptive stage began about 0.5 Ma with the construction of a mostly effusive large stratovolcano (Torrecillas), whose activity began with the eruption of olivine basaltic andesites, followed by two-pyroxene andesites, breccias and amphibole dacites dated at 0.29 ± 0.05 Ma (Carrasco-Núñez & Ban, 1994) and ending with two-pyroxene andesites. Although Höskuldsson (unpub. Ph.D. thesis, 1992) proposed that Citlaltépetl activity started 0.9 ± 0.2 Ma ago, no rock has been found preserving a reversed palaeomagnetic field (Carrasco-Núñez, unpub. Ph.D. thesis, 1993). The collapse of the Torrecillas edifice occurred about 0.25 Ma. During the second stage, another cone (Espolón de Oro) was built on

Table 1. Summary of main stages of Citlaltépetl volcano

Eruptive stage	Age range (Ma)	Main lithology	Volume (km^3)
Citlaltépetl cone	< 0.01	Dacite	25
Silicic domes	Variable	Dacite–rhyolite	35
Espolón de Oro cone	0.21–0.02	Dacite, basaltic andesite	50
Torrecillas volcano	0.5–0.29	Andesite	270

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the remnants of Torrecillas volcano, erupting amphibole dacites, dated at 0.21 ± 0.04 Ma (Carrasco-Núñez & Ban, 1994), followed by two-pyroxene andesites and olivine basaltic andesites, which alternate with welded ignimbrites. This stage ended with the collapse of the Espolón de Oro edifice between 13 000 and 27 000 yr BP (Carrasco-Núñez, Vallance & Rose, 1993). The third stage includes the emplacement of several dacitic domes outside of the central crater and at different times. The most recent dome activity occurred about 4000 yr BP, associated with the emplacement of voluminous block-and-ash flow deposits. Numerous explosive eruptions producing tephra and ignimbrites were generated in the last 13 000 years. During the fourth stage, the present cone was built (Citlaltépetl) on the remnants of ancient craters erupting amphibole-pyroxene dacite, of which the most recent erupted in the sixteenth century. These lavas show very fresh morphology and hence are used in the present analysis.

3. Characteristics of Citlaltépetl's recent lavas

The stratigraphic relationships between the analysed Holocene lavas of Citlaltépetl volcano suggest their relative ages as shown in Figure 2, where lavas are grouped into zones north and south. Although those lavas were originally grouped into several rock units (Carrasco-Núñez & Ban, 1994), they compositionally correspond to three different groups. However, based on their distribution, morphology and stratigraphic relationships, the recent lava flows are interpreted to represent four main eruptive episodes, each starting with the eruption of single flows and followed by the emplacement of multiple flows. The timing between individual eruptions producing either single or multiple flows is unknown. Nevertheless, historical records (Crausaz, 1994) reveal the occurrence of four confirmed eruptions during the sixteenth and seventeenth centuries, whose flows were apparently channelled towards Citlaltépetl's southern flank, and which represent the two latest eruptive stages proposed here (see Fig. 2). Although the erupted lavas are not unequivocally identified in the field, the reports of the 1537, 1545 and 1566 eruptions possibly correspond to lavas *Sbl3, Mb3 and Mb2* (eruptive period III), and those of the 1613 eruption may possibly be represented by lavas *Sbl1, Sbl2* and/or *Mb1*, which represent the eruptive period IV.

3.a. Morphology and flow dimensions

Although the majority of recent Citlaltépetl lavas were emplaced from the summit vent, some lavas emanated from peripheral domes. Only 5 km northeast of the Citlaltépetl crater, five overlapping domes constitute the Chichimeco dome complex formed during Holocene time. They show a characteristic endogenous morphology with a rugged topography consisting of surface ridges and spine-like structures. These features can be compared

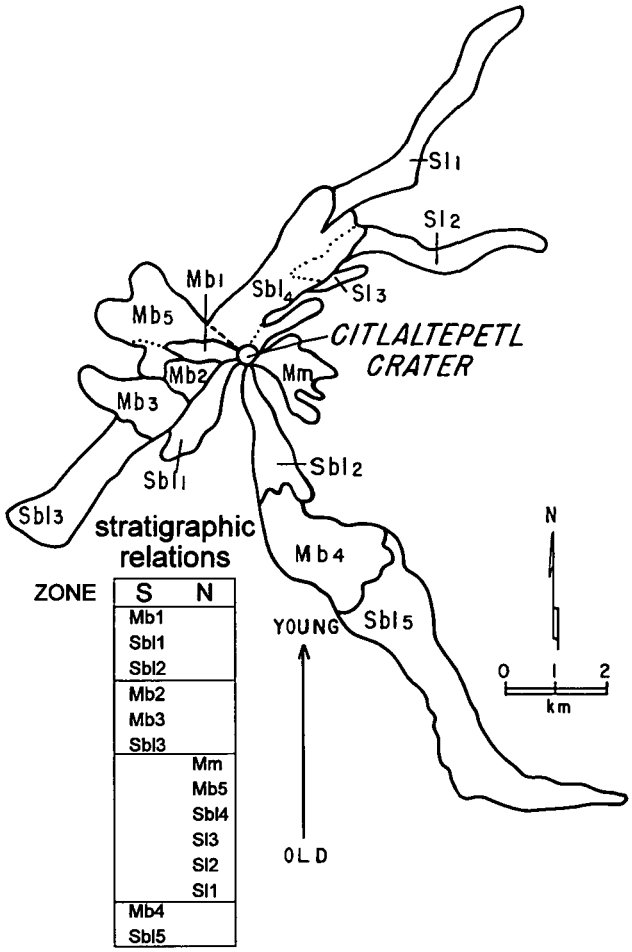


Figure 2. Distribution of the recent (Holocene) lava field of Citlaltépetl volcano, which is characterized by the successive emplacement of single and multiple blocky lavas. Stratigraphic relationships between lava flows for different zones are shown in inset table. Lines separate eruptive periods, from I (older) to IV (younger). Key for lavas: '*Sl*' – single flows with lateral levees, '*Sbl*' – single blocky flows with lateral levees, '*Mb*' – multiple, blocky flow fields, and '*Mm*' – multiple, massive flow field. Stratigraphic relationships are based on field data and interpretation of aerial photographs.

with those observed on the Santiaguito dome complex which originated in 1922 at the base of Santa María volcano in Guatemala (Rose, 1972). Only one dome, located between the main dome complex and the Citlaltépetl crater (Fig. 1), shows a gentle surface and characteristic layering, which suggests an exogenous origin. The composition of these domes is quite homogeneous, consisting of porphyritic dacites (64 wt% SiO_2) with phenocrysts of plagioclase, amphibole and minor amounts of clinopyroxene.

The central effusive activity of Citlaltépetl volcano, which is the focus of this paper, consists of episodic eruptions of generally blocky and levee-sided lava flows. The oldest lavas of this phase cover a widespread block-and-ash flow deposit dated at 4200 ± 80 yr BP (Carrasco-Núñez & Ban, 1994). The lavas form either single flows or multiple flow fields. Although most

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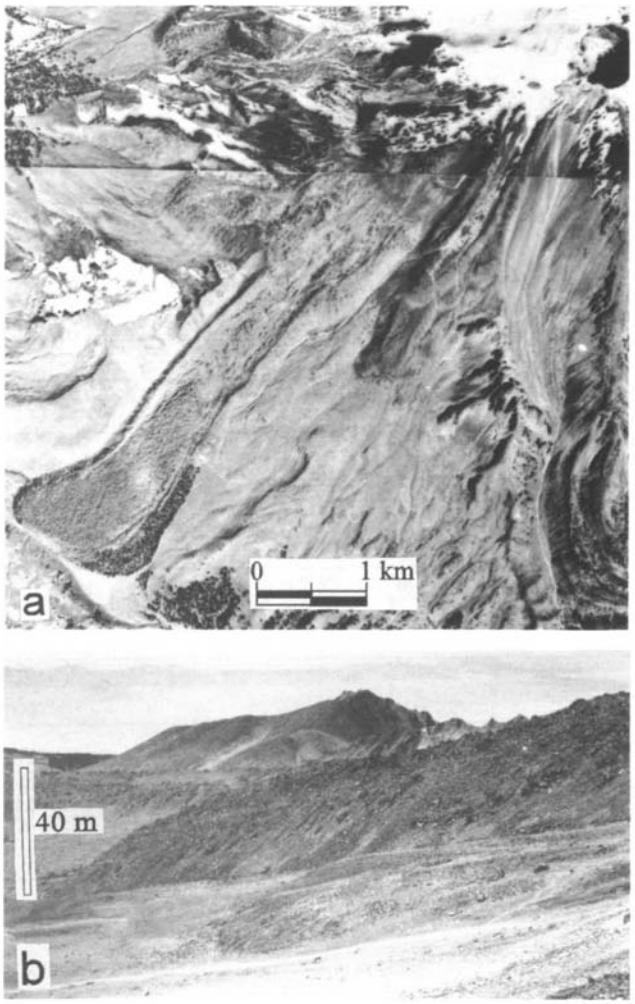


Figure 3. Photographs showing morphological features of Citlaltépetl's Holocene lavas. (a) Single and multiple flows at Citlaltépetl's western flank. *Sbl3* lava flow shows well-defined lateral levees, blocky surface and a flow front that widens after encountering a topographic barrier. (b) Typical profile of a lava flow (*Sbl1*) having a prominent blocky flow front and levee about 40 m thick (for location see Fig. 2).

individual flows show similarities in surface features, flow type and general composition, some have different shapes, flow dimensions and proportions of constituents that may reflect differences in eruptive conditions during which the lavas were formed. For instance, general observations on Citlaltépetl's recent lavas suggest that the earliest lavas were apparently less viscous than later ones, travelled longer distances, and were mostly channelled into lower ravines, indicating strong topographic control of the lavas during their emplacement; in contrast, the most recent lavas flowed without constraint and are preferentially restricted to the upper slopes of the volcano.

Based on their structure and shape, Citlaltépetl lavas can be grouped into four categories as proposed here: (a) single, mostly channelled flows with well-defined and conspicuous lateral levees (*Sl*), (b) single, blocky flows with lateral levees (*Sbl*), (c) multiple, mostly blocky flow fields, sometimes showing lateral levees (*Mb*), and (d)

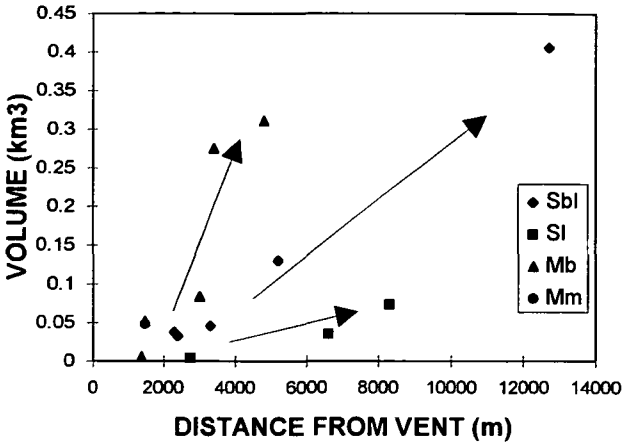


Figure 4. Plot of volume vs. maximum distance achieved for Citlaltépetl lavas. Arrows show suggested trends for the different lava types. Key as in Figure 2.

multiple, massive flow fields (*Mm*); where '*S*' stands for single and '*M*' for multiple flows, '*l*' for lateral levees, '*bl*' for blocky flows with levees, '*b*' for blocky, and '*m*' for massive. This classification does not follow any stratigraphic order, that is, the different lava types erupted during distinct eruptive episodes.

Lavas have a particular distribution pattern (Fig. 2). Type '*Sl*' flows are only found on the north face of the volcano and were directed along self-made channels into lower river valleys leaving only prominent lateral levees, about 25 m high, with almost empty channels in the middle part of the flow upstream, but with thick channel deposits downstream and at the flow front. Type '*Sbl*' flows were emplaced either to the south, where flows channelled into deeply-incised barrancas, or to the southwest where a lava flow shows characteristic levees with very rugged top surface and a wider flow front (Fig. 3). Type '*Mb*' flows are restricted to the proximal south and west areas around the crater and are partially covered by glacial ice (Fig. 3). Finally, type '*Mm*' flows were emplaced towards the east, forming a sequence of successive lavas that were apparently erupted in a single eruptive episode.

Flow-field dimensions such as maximum length, width and thickness were obtained from field data in conjunction with the examination of 1:30000-scale aerial photographs, and 1:50000-scale topographic maps (INEGI, 1984). With these data, volumes for each single flow or flow field were calculated. For multiple flows, the width of the larger individual flow composing the flow field was used, not the total width.

Although there is not an obvious correlation between the volume of the overall lavas and the maximum distance achieved by them, when lavas are grouped into the different flow types proposed here ('*Sl*', '*Sbl*', '*Mb*', and '*Mm*'), some rough tendencies are observed (Fig. 4), indicating that the travelled distance is proportional to the volume of erupted lavas, but that the correlation differs depending on the lava type. Trends are better defined for single, rather than for multiple flows. Type '*Sl*' flows are

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Table 2. Selected parameters of Citlaltépetl lavas

Lava flow unit	SiO_2 (wt %)	Phenocrysts vol. (%)	H_2O+ (wt %)	slope (°)
Sl1	60.15	11	0.60	14
Sl2	60.50	15	0.58	13
Sl3	62.40	19	0.50	17
Sbl1	63.02	28	0.52	25
Sbl2	63.15	40	0.46	25
Sbl3	63.37	47	0.44	11
Sbl4	62.82	42	0.20	19
Sbl5	63.03	39	0.66	13
Mb1	64.03	30	0.40	33
Mb2	65.54	31	0.45	22
Mb3	63.85	29	0.55	16
Mb4	64.97	36	0.39	18
Mb5	64.10	40	0.50	21
Mm	65.88	52	0.31	31

far less voluminous than type '*Sbl*' for the same travelled distance. In contrast, multiple flows ('*Mb*' type) for a short travelled distance show a dramatic increase in volume, however, this relationship is less well constrained than that of the other flow types.

3.b. Composition

Some parameters, such as chemical composition, crystal and water content, and slope, may play an important role in the mobility of lavas, so their possible effects on Citlaltépetl lavas are analysed further.

Composition is a principal factor controlling lava viscosity. Silica content is especially important because Si–O bonds promote high degrees of polymerization, and therefore viscosity, reducing lava mobility. A direct correlation between these parameters is not clear for Citlaltépetl's recent lavas, partly because they are relatively homogeneous in composition, so the range of variability of major elements is very restricted. Most of Citlaltépetl's recent lavas are mainly porphyritic dacites (types '*Sbl*', '*Mb*', and '*Mm*') with a minor proportion of aphanitic andesites ('*Sl*'). Chemical analyses of these rocks show a variation in silica content from 60 to 66 wt% silica (Table 2). It is clear that multiple flows, which are generally closer to the vent, have higher silica content than single flows; however, no substantial compositional differences are observed on Citlaltépetl's recent lavas, and apparently there is not a systematic correlation between the composition of lavas and their travelled distance (Fig. 5a).

The rheology of lavas may also be influenced by variations in both crystal and water content. Crystallinity may cause an increased bulk viscosity (Marsh, 1981); in contrast, the water content may contribute to reduction in the degree of polymerization of the melt by breaking Si–O–Si bridges. Citlaltépetl lavas are mostly composed of two pyroxenes, hornblende and oligoclase–andesine phenocrysts in a microlitic and sometimes glassy groundmass. The proportion of phenocrysts (considering crystal sizes greater than 1 mm in maximum length) within both single and multiple lava fields does not show a systematic

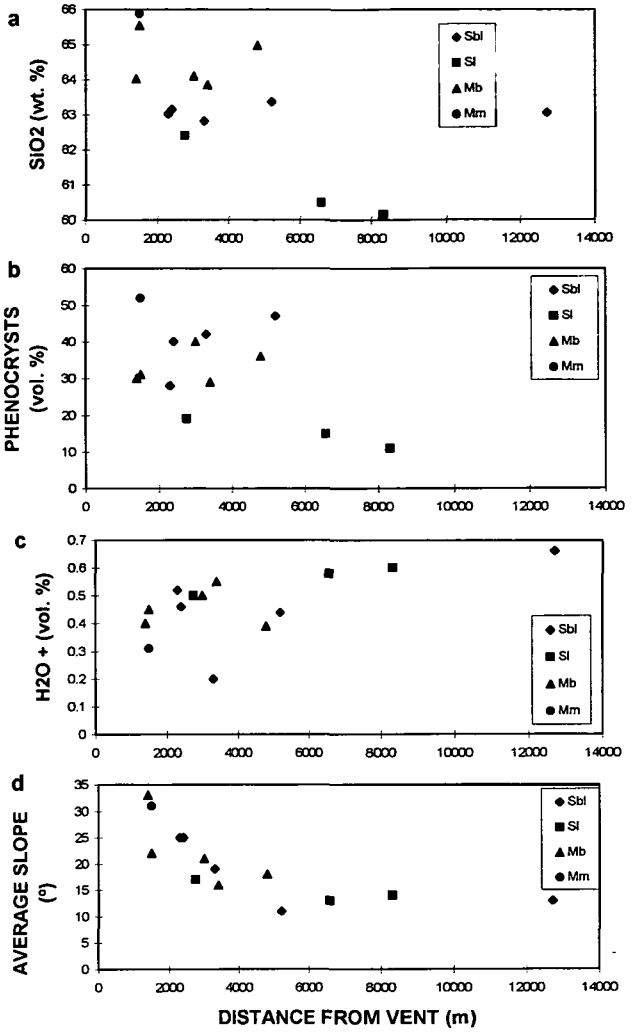


Figure 5. Plot of (a) silica, (b) phenocryst, (c) water content and (d) average slope vs. maximum distance from vent achieved by lavas of Citlaltépetl volcano. Key as in Figure 2.

variation with distance, however, phenocrysts are relatively more abundant in lavas closer to the vent, especially '*Sl*' lavas (Fig. 5b). On the other hand, the water contents of Citlaltépetl lavas, which were determined by gravity measurements at about 950 °C, show only a crude tendency towards an increase with distance, showing highly variable values within a 2.5 km radius of the vent (Fig. 5c). Therefore, the mobility of Citlaltépetl's recent lavas is apparently not affected by crystal or silica content, and little influenced by water content.

Length and width vary inversely with ground slope. The relationship between mean slope and distance from the vent for Citlaltépetl lavas is non-linear, with a dramatic change within the first 3.5 km (Fig. 5d). In fact, the data seems to follow a trend of the form: $L = B/\sin^2 \alpha$, where L is length, B is a constant, that in this case was empirically estimated to be 330, and α is the mean slope in degrees. This relation is somewhat similar to that proposed by Kilburn (1995) to forecast maximum lengths of *aa* flows, particularly in the case of flows from Mauna Loa. In this case, slopes are always steeper than 11° and

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for shorter flow distances tend to be around 13° or more. It could be expected that, if future flows follow the same trend, in places where the mean slope is higher than about 15°, the flows would probably not travel more than about 5 km, and longer distances are expected for slopes shallower than about 13°. Such information can be essential for long-term land management policies in areas that potentially could be affected by future effusive activity.

Most lavas are concentrated closer to the volcano even though the slopes are much steeper. This suggests that factors other than gravity were possibly more important in determining the final length of the lava flows; in fact, the main factor that limits the downslope flow of lavas is effusion rate, which is closely related to cooling (Pinkerton & Sparks, 1976; Hulme & Fielder, 1977), where heat is lost by radiation at the upper surface and by conduction to the ground.

4. Calculation of the effusion rate for Citlaltépetl lavas

It could be inferred that the morphological differences observed in Citlaltépetl lavas may reflect the different regimes in which they were formed. Relationships between different parameters may serve to describe basic growth patterns, considering that lava flow behaviour is systematic. Kilburn & Lopes (1991) proposed four ideal growth patterns for *aa* and blocky lavas that are emplaced as: (a) single flows or (b) single flows that evolved to multiple flow fields, in which new flows are generated by: (1) lengthening, (2) thickening or (3) widening. Under the simplest conditions a single flow is produced, but if effusion continues once the first flow has ceased, a multiple flow field may develop.

Effusion rate is used here as the flux of lava expressed as the volume of effused material (m^3) per unit of time (s). Two different methods were used in this study to estimate the effusion rate of Citlaltépetl lavas. The first method estimates eruption duration by applying the model proposed by Kilburn & Lopes (1991), which relates flow-field dimensions, underlying slope and eruption duration for *aa* and blocky lavas. The following equation shows the relation of those parameters:

$$(W_m/L_m)H^2 \sin \alpha = bkT$$

where W_m is the maximum continuous width of the flow field, L_m is the maximum length, H is the mean depth, α is the angle of underlying slope, b is a dimensionless constant, k is thermal diffusivity of the lava and T is the eruption duration.

The correlation of $(W_m/L_m)H^2 \sin \alpha$ with T is independent of both gravity and lava rheology because gravitational and viscous forces dominate both widening and lengthening, making the ratio of width to length insensitive to both forces.

Some important points should be discussed about the applicability of this method and its associated errors. The Kilburn & Lopes method considers the interaction between the lava's hot interior and the chilled outer crust to be important to flow-field evolution. To apply the method it should be considered that the mean rate of advance of a flow is controlled at the distal core of the flow, where it is assumed that the flow motion is steady (constant velocity with time) and uniform, somewhat approximate to a laminar flow because of the low apparent bulk deformation rates estimated for this zone. Other important assumptions outlined by Kilburn & Lopes (1991) are that: (a) shorter-term variations in discharge rate at the vent are either insignificant to flow advance or they are dissipated before the flow can reach the frontal zone; (b) flow-field dimensions are not governed by size and shape of the feeding vent; (c) arterial flows in a flow field have similar dimensions and emplacement times; (d) flow fields are either single or multiple (governed by widening) flows.

Kilburn & Lopes (1991) show that the variation of $(W_m/L_m)H^2 \sin \alpha$ with T on a logarithmic plot yields an approximate correlation for *aa* and blocky lavas of a wide compositional range from potassic phonolitic tephrite to dacite and, although the scatter is considerable, 80 % of the points lie within the accepted 82 % of the expected trend. The total associated errors give about 70 % on $(W_m/L_m)H^2 \sin \alpha$ and about 10 % on T, due to the uncertainties in measurement of some of the parameters, especially depth and slope. Nevertheless, the model has been successfully tested for single lavas from Mount Etna, as compared with an empirical cooling method proposed by Pinkerton & Sparks (1976), and for Hawaiian lavas, as compared with the empirical length-to-volume relation proposed by Malin (1980). Although multiple flows have not been tested, results are consistent with multiple flows formed by widening; in this case, the associated errors could be higher than those estimated for single flows.

Analysing the assumptions and conditions of the Kilburn & Lopes method, some important considerations should be revised. The method assumes that the arterial flows propagate from the upper reaches of a flow field and then travel alongside each other, but it does not consider flow superposition such as that observed for 1983 Etnean flows (Frazzetta & Romano, 1984), which may cause an overestimate of T (eruption duration) because the value of H for flow fields is greater than the H reached during emplacement.

Effusion rates typically peak soon after the beginning of an eruption and then diminish as the eruption proceeds (see, e.g. Wadge, 1981; Stasiuk, Jaupart & Sparks, 1993). Therefore, the main discharge of magma may have been effused very rapidly, in contrast with the last minor contribution of magma that erupted for a longer period of time. Eruption duration apparently includes periods of stasis, which may result also in an overestimation of the duration (de Silva *et al.* 1994). Although such conditions suggest that the eruption duration calculated by the Kilburn & Lopes method could be used as maximum estimates, other factors, such as the possible distal flow

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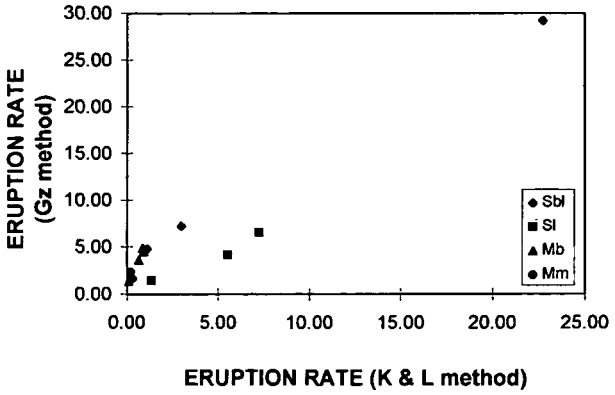


Figure 6. Comparison between the inferred eruption rate determined by both the Graetz and the Kilburn & Lopes methods. Key as in Figure 2.

generation or the hiatuses between emplacement of successive arterial flows, could lead to underestimating the eruption duration. Therefore, it is not absolutely clear whether this method gives maximum or minimum estimates of true duration; despite these difficulties, the method seems to provide a close approximation of maximum estimates of duration, then providing estimates close to the minimum values for effusion rates. The method has been applied in this way to the Chao dacite in the central Andes (de Silva *et al.* 1994).

Independent estimates of effusion rates were also obtained using the Graetz model, an empirical, conduction-limited cooling model (Pinkerton & Sparks, 1976; Hulme & Fielder, 1977; Guest *et al.* 1987), in which lava flow cooling is compared to a warm fluid moving through a cool pipe. The temperature distribution across the flow is described by the dimensionless Graetz (Gz) number, expressed as:

$$Gz = VH^2/kL$$

where V is the mean flow velocity, H is the flow thickness, k is the thermal diffusivity and L is the length. It has been empirically determined that lava flows come to rest before Gz falls to about 300. The effusion rate (F) is given by:

$$F = WHV$$

where W is the flow width, so the equation can be rewritten as:

$$Gz = (F/kL)(H/W)$$

and the effusion rate calculated using morphometric parameters. Because the Graetz number model does not consider variations in conduit diameter, effusion rate or local slope, and since it assumes a continuous, steady state eruption, the eruption duration generally tends to be underestimated.

Table 3. Volume, inferred eruption duration and inferred effusion rates for Citlaltépetl lavas

Lava flow unit	Volume (m^3) $\times 10^6$	Inferred eruption duration (days)*	Inferred effusion rates (m^3/s) *	†	Average effusion rate (m^3/s)
Sl1	73	116	7.25	6.54	6.89
Sl2	35	73	5.54	4.16	4.85
Sl3	4	34	1.36	1.38	1.37
Sbl1	38	1667	0.26	1.58	0.91
Sbl2	33	1210	0.32	1.66	0.99
Sbl3	130	504	2.38	7.21	4.79
Sbl4	46	483	1.10	4.75	2.92
Sbl5	406	206	22.71	29.20	25.95
Mb1	6	311	0.22	1.76	0.99
Mb2	52	6118	0.10	1.35	0.72
Mb3	275	4925	0.63	3.57	2.11
Mb4	319	4065	0.97	4.56	2.73
Mb5	84	1126	0.86	4.85	2.85
Mm	48	2746	0.20	2.36	1.28

* Kilburn & Lopes method.
† Method using the Graetz number (in Hulme & Fielder, 1977).

The two different methods used here to estimate the effusion rates of Citlaltépetl's recent lavas help to determine more precise estimates, assuming that each method allows the calculation of values close to the maximum and minimum estimates. This helps to reduce somewhat the large degree of uncertainty inherent in each method when applied independently. In fact, by comparing the results of both methods (Fig. 6), they both show an acceptable correlation with some discrepancies but following a general trend. Differences of up to an order of magnitude are more marked for multiple, rather than single flows, which suggests that the results for multiple flows are more conservative. Comparison of the two methods is valid because both assume that lava flows halt due to cooling. Therefore, it is possible to get a better approximation for the effusion rate of Citlaltépetl lavas by combining the estimates obtained by the two methods. In addition, it should be considered that lavas advance at different rates, implying that effusion rates of lavas vary during their emplacement.

Therefore, effusion rates tend to be maximum if calculated by the Graetz number approach, which are closer to the peak values, and minimum if using the Kilburn & Lopes model. Of course, the results are not absolute, so a mean effusion rate is calculated from those values to give a more representative number (Table 3).

5. Effusion rates and formation of Citlaltépetl lava types

To understand more fully the flow development of Citlaltépetl's lava field it is important to know how distinct lava flows formed and how effusion rate affects the growth of the flow field.

Average effusion rates for single flows are very variable, ranging from 0.92 to 25.95 m^3/s, but they are generally higher than for multiple flows, which range from 0.72 to 2.85 m^3/s. '*Sl*' flows have relatively higher

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effusion rates than '*Sbl*' and multiple flows for the same erupted volume. '*Sl*' flows show low differences between the calculated effusion rates as compared with the other flow types (Table 3).

5.a. '*Sl*' lavas

These lavas were emplaced during the second effusive episode and are characterized by prominent levee structures and no material filling the flow interior in the upper and medial reaches. Such channel drainage suggests that the lava was relatively fluid upon eruption, a feature consistent with the low silica content and crystal content values, and the absence of deposits within the active channel. During emplacement, marked irregularities apparently developed across the leading edge of the flow, creating near-static margins that concentrated the flow within a channel (Borgia & Linneman, 1990). Once the channel was formed, the active lava continued moving downslope, leaving behind its levees as the magma supply decreased or ceased. If effusion continued after the flow had achieved its maximum distance, another flow could have formed, following a different route if the original path were blocked (e.g. flows *Sl2* and *Sl3*, Fig. 2), which progressively decreased their output rate (from 6.89 to 1.37 m^3/s), volume (from 73 to 4×10^6 m^3), and travelled distance (from 8300 to 2750 m). Effusion rate estimates are very consistent using both methods. In this case, single flows always continued as individual arterial flows and did not evolve into multiple flow fields.

The levees observed in '*Sl*' lavas and in other flows are comparable with the initial levees formed by lavas of Mount Etna (Sparks, Pinkerton & Hulme, 1976), which are thought to be formed because of the yield strength of a lava that behaves as a bingham fluid, as suggested by Hulme (1974).

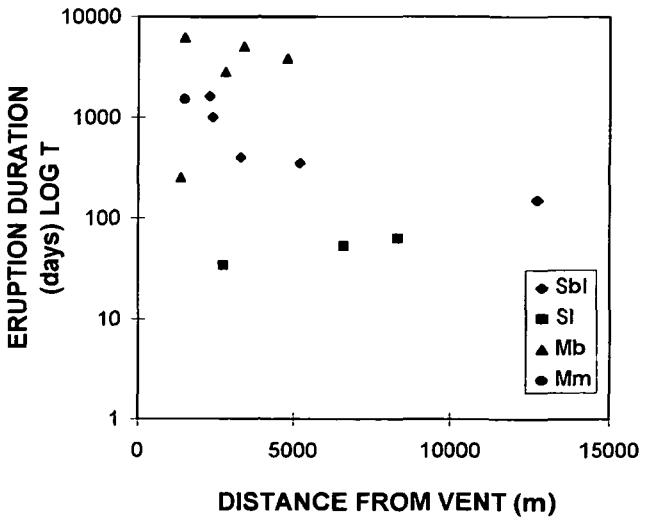


Figure 7. Plot of inferred eruption duration (T), using a logarithmic scale, and distance from vent for Citlaltépetl lavas. Key as in Figure 2.

5.b. '*Sbl*' and '*Mb*' lavas

Individual lavas of '*Sbl*' and '*Mb*' types behave very similarly. The main difference between them appears to be related to the continuity of magma supply and the eruption duration, which is always very large for multiple flows (except for one case, they range between 1126 to 6118 days). If effusion continues after the first flow has stopped advancing, the flow may grow by simple thickening, or a multiple flow field may be formed by widening, thickening or lengthening, as suggested by Kilburn & Lopes (1991).

Following the above considerations, it is possible to suggest that '*Sbl*' lavas did not evolve into multiple flows because the magma supply ended once the flow stopped advancing. That is the case of the *Sbl3* flow (Figs 2, 3), which widened laterally until the eruption ceased once the front reached a topographic obstacle. However, subsequent lavas continued to grow, forming multiple flows possibly owing to a sudden decrease in the effusion rate, as discussed in Section 6. For this particular case, the effusion rate was estimated using a maximum width (W_m) at the point where the flow starts to widen markedly, because the observed maximum width was artificially constrained. With the exception of this case ('*Sbl*'), all the other flows show a morphology that was apparently not artificially influenced by topographic barriers or other factors.

As inferred from their morphology and spatial distribution, most multiple flow fields ('*Mb*' type) grew mainly by widening. However, in some cases such as the *Mb2* flow (Fig. 2), they were apparently dominated by thickening through the superposition of discrete flows. This lava field consists of thick flows, related to long emplacement times (Table 3).

Individual flows are typically blocky and have well-defined levees and flow fronts. Apparently they ('*Sbl*' and '*Mb*' lavas, but especially the latter) were more viscous, having higher silica content than '*Sl*' lavas and having travelled shorter distances, with only one exception represented by a voluminous flow that has the highest apparent effusion rate of all Citlaltépetl lavas (*Sbl5* lava). Because the main factor that limits the downslope flow of lava is cooling (Pinkerton & Sparks, 1976), when lavas erupted at higher rates they could travel farther before cooling (by radiation and convection of the air at the upper surface and by conduction to the ground), lowering their viscosity and inhibiting movement. Thus the *Sbl5* lava flowed further simply because it erupted at a higher rate.

Some lavas have irregular surfaces with many hummocks, and most flow fronts of Citlaltépetl lavas have pronounced edges that suggest that the flow moved very slowly and the fronts rolled forward as entire units, overriding lava crust, which continually mixed into the active flow.

5.c. '*Mm*' lavas

These lavas are restricted to the eastern upper slopes in the crater area and travelled no more than 1.5 km. These are not blocky but massive lavas that do not show levees or flow fronts; they have higher values of

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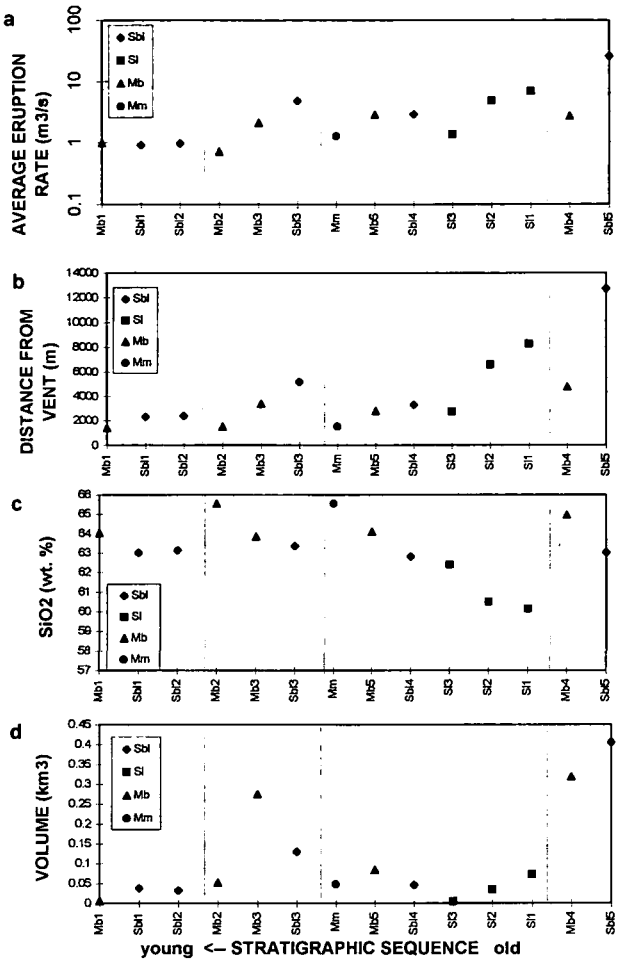


Figure 8. Relation between stratigraphic position and (a) averaged effusion rate, (b) distance from vent, (c) silica content and (d) volume for Citlaltépetl lavas. Key as in Figure 2. Dotted lines indicate boundaries between eruptive periods, varying from I (older) to the right, to IV (younger) to the left of the plot.

silica content and are more viscous, hence they did not flow as much.

It is suggested here that '*Mm*' lavas could be fed by a dome-like structure emplaced at the top of the crater, which was periodically injected with new batches of magma. These lavas flowed as sheets spreading in various directions to eventually form a fan-like shape. Accordingly, this multiple flow field seems to have grown mainly by thickening as new flows were superimposed on previously emplaced ones, forming a thick succession of comparatively low volume. This growth pattern is not characteristic of the emplacement regime observed for multiple flow fields of Citlaltépetl volcano, which is mostly dominated by widening, as mentioned earlier.

6. Discussion

The inferred eruption duration of the Citlaltépetl lavas, obtained by the Kilburn & Lopes method, are different for single and multiple flows, which is in agreement with the classification of different lava types proposed here. Figure 7 shows that multiple flows have, in general, a much higher eruption duration (greater than 1000 days) than single flows (lower than 1000 days) and all multiple flows are emplaced closer to the crater. Also, estimation of eruption duration for type '*Sl*' lavas show that this is markedly lower than for type '*Sbl*' flows. However, the distance travelled by a lava flow, in general, appears to be independent of eruption duration.

With the exception of the highest value of 26 m^3/s, the calculated average effusion rate of Citlaltépetl lavas ranges between 0.7 and 6.9 m^3/s. These values are relatively low in comparison to those of basaltic lava flows like those erupted several times during the period between 1851 and 1950 at Mauna Loa volcano with 100 m^3/s, or like the eruption of Laki volcano, Iceland in 1783 with 500 m^3/s, in both cases considered as single flows. Average effusion rates of historic andesitic and dacitic lavas are reported between 0.05 and 11.6 m^3/s (Newhall & Melson, 1983). However Swanson *et al.* (1987) estimated a variable effusion rate ranging from 2 to 26 m^3/s for the growth of the lava dome at Mount St Helens between 1981 and 1983. Also, the peak effusion rate for the Chao dacite (de Silva *et al.* 1994) was calculated at about 25 m^3/s. Therefore, effusion rates for Citlaltépetl lavas are within the range of lavas of comparable composition.

The value of 26 m^3/s, which is comparably higher, could be attributed to the combination of different conditions, such as voluminous discharge rate, relative higher water content, and average slope. This lava (*Sl5*) also represents the onset of the recent effusive activity.

The observed differences in flow dimensions, lava type and surface structures suggest distinct eruptive conditions during which Citlaltépetl lavas were formed, involving variations in erupted volume, eruption duration and effusion rate. The volcanic field studied here is characterized by alternating effusions of single and multiple flows reflecting varying unsteady conditions of magma supply as can be inferred from Figure 8a.

The average effusion rate for Citlaltépetl lavas is plotted against the stratigraphic position of the lava sequence

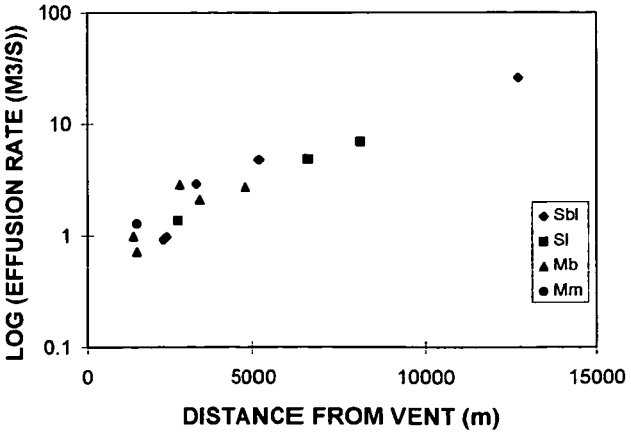


Figure 9. Relationship between log of averaged effusion rate and maximum distance from vent achieved by lavas from Citlaltépetl volcano. Key as in Figure 2.

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in Figure 8a. Although there is not a systematic variation of the effusion rate with the stratigraphic position, a general trend can be delineated indicating an apparent general decrease in the effusion rate of Citlaltépetl's recent lavas with time. Main discrete changes in effusion rate coincide approximately with the limits that separate the four eruptive stages that form the youngest effusive activity of Citlaltépetl volcano. In each of these eruptive stages, which start with the eruption of single flows and end with the formation of a multiple flow field, the average effusion rate decreases similarly to the general trend, even though there is a small increase for the single flows at the beginning of each eruptive stage. Similar correlation is observed for the relationship between travelled distance and time (Fig. 8b).

With the available data, one can observe an apparent systematic correlation between the variation in the silica content and the eruptive phases defined for Citlaltépetl's recent lavas (Fig. 8c). Although the differences in SiO_2 are not very large, an andesitic-to-dacitic compositional trend is observed for each eruptive episode; this trend is especially pronounced for the second and third episodes, the compositional changes being evident during the transition from single to multiple flow. Single flows always have lower than 63.5 % SiO_2 content, in contrast with multiple flows that are above that value. For some eruptive phases (second and third), the transition from single to multiple flows is marked by a significant increase in the erupted volume (Fig. 8d), but with corresponding different trends of the effusion rates (Fig. 8a). Although a general increase of erupted volume is observed when multiple flows are formed (Fig. 8d), these changes do not correlate with similar variations in effusion rate, suggesting that the magma supply was much slower when forming most of the multiple flows. With the exception of flow *Sbl5*, most single flows show higher output rate and smaller associated volume than multiple flows. Therefore, fluctuations of output rate and composition were important in determining the development of single versus multiple flows.

The emplacement conditions of Citlaltépetl lavas vary with time. The earliest lavas (*Sbl*) are voluminous dacitic single flows, which erupted at the highest rate and travelled further than the rest of the flows. Subsequent lavas were less voluminous, with higher silica content and lower effusion rate, forming multiple flows. The second eruptive phase started with the eruption of andesitic lavas (*Sl*), which show evidence of being emplaced with relative mobility (lower viscosity); they erupted at lower rates and therefore travelled shorter distances. These lavas (*Sl*) are far less voluminous than the '*Sbl*' lavas. A marked increase in eruption duration and a slight decrease in magma discharge rate may have induced a drastic deceleration of the flow front, promoting an increased solidification. These conditions may have favoured the development of multiple flows instead. However, sometimes (in the second and third eruptive phases) the erupted volume is higher for multiple flows, suggesting a tendency towards a balance between the rate of magma supply and lava solidification. For the same volume, multiple flows flowed smaller distances than single flows, as depicted in Figure 4.

The second and third effusive episodes produced single flows with similar or lower volumes than subsequent multiple-flow events, but erupted at slightly higher rates, suggesting a new injection of more basic magma in the system. Transition from single to multiple flow phase is again apparently associated with a notable increase in the erupted volume but a decrease in the effusion rate, and coincides with an increase in silica, exceeding the value of about 63.5 %. The last effusive stage including both single and multiple lavas erupted at much lower rates.

New flow developments are possibly due to changes in magma discharge rate. Multiple flows are associated with a decrease in effusion rate, and new effusive episodes, starting with single flows, show increased effusion rates. In fact, the distance travelled by Citlaltépetl lavas appears to be proportional to the effusion rate, as depicted in Figure 9. This relationship was first proposed by Walker (1973) who considered that effusion rate is the most important controlling factor on lava shape, especially on lava lengthening. In this case, the plotted samples, representing different lava types, are not grouped as in Figure 4, where distinctive paths are traced for each lava type. Multiple flows seem to be not very dependent on volume variations, because although they have relatively high volumes, their eruption durations are much higher, producing low effusion rates as compared with single flows. In contrast, single flows even with low erupted volumes, typically have much lower duration, and then effusion rates are relatively higher. As a result of the relative balance between volume and duration, the relation of effusion rate to distance is apparently independent of the lava type.

7. Conclusions

In this paper, a simple relation (independent of lava rheology and gravity) between flow-field dimensions, slope and eruption duration (Kilburn & Lopes, 1991) was used to infer the effusion rate of Citlaltépetl lavas. The results were compared to an independent method (Graetz model), and the combination of both methods allowed a better constrained estimation of approximate maximum and minimum effusion rates. Calculations for *Sl* flows give the least scattered estimates, compared with the other flow types. A good correlation was observed between inferred eruption duration and the types of lava classified here ('*Sl*', '*Sbl*', '*Mb*' and '*Mm*'). Although multiple flows have longer duration and smaller average output rate than single flows, the former are always thicker and have travelled shorter distances. Correlation between erupted volume and travelled distance for Citlaltépetl's recent lavas is only possible when these lavas are grouped into the different types as proposed in this paper, implying that multiple flows ('*Mb*' and '*Mm*')

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will always travel shorter distances regardless of the erupted volume of material involved. In contrast, small changes in erupted volume for '*Sl*' lavas are expected to cause significant variations in the travelled distance. The '*Sbl*' flows behave in a manner intermediate to these two end-member types. Effusion rate estimates for single flows are better constrained than for multiple flows, due to the assumptions and restrictions of the methods used.

Each of the morphologically distinct lavas from Citlaltépetl are associated with different eruptive conditions. Most lavas are dominated by single or flow-field widening regimes. Effusion rate appears to be the main controlling factor on the shape, flow structures, and type of lavas. However, the beginning of a new eruptive phase is marked with the injection of andesitic magma, which eventually evolves to a dacitic composition, promoting the transition from single to multiple flows. Because the composition of these lavas is quite homogeneous, compositional variations are not clearly correlated, but siliceous lavas above about 63.5 % SiO_2 may be more likely to be transformed from single to multiple flows. Accordingly, inferred fluctuations in discharge rate are responsible for changes in the flow-field development and eruptive style.

Effusion rates of Citlaltépetl lavas show a general tendency to decrease with time, but minor pulsating increments occurred when new single flows were emplaced, suggesting that if single and subsequent multiple flows are related, they may indicate the periodic replenishment of the magmatic reservoir. Each of the four eruptive stages show the same tendency, decreasing the effusion rate when the transition from single to multiple flows takes place even when the effusions are relatively more voluminous.

If flow-field growth follows a systematic pattern and effusion rates keep this present tendency to decrease with time, it is not likely that future lava flows could threaten nearby towns because they are located in safe places much further than 13 km from the vent, which is the maximum length achieved by a recent lava. That assumption is only valid if future lavas follow the same compositional tendency, considering that the youngest lavas tend to be more siliceous and viscous than lavas emplaced earlier. However, considering the long repose of Citlaltépetl volcano since its last eruption, replenishment of new magma could recur and the possibility of increased effusion rate may not be discounted. The apparent correlation between slope and travelled distance may be used to predict potential flow lengthening. Mean slopes higher than 15° would anticipate flows that would be restricted to the first 5 km from vent, while lava flows on slopes around 11–13° could reach distances about 10 km or more.

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