Journal of Volcanology and Geothermal Research, 25 (1985) 105—124
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

THE CINDER CONES OF MICHOACÁN—GUANAJUATO, CENTRAL MEXICO: THEIR AGE, VOLUME AND DISTRIBUTION, AND MAGMA DISCHARGE RATE

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(Received February 15, 1984; revised and accepted August 16, 1984)

ABSTRACT

Hasenaka, T. and Carmichael, I.S.E., 1985. The cinder cones of Michoacán—Guanajuato, central Mexico: their age, volume and distribution, and magma discharge rate. *J. Volcanol. Geotherm. Res.*, 25: 104—124.

The Michoacán—Guanajuato Volcanic Field (MGVF) in central Mexico contains over 1000 late Quaternary volcanic centers, of which approximately 90% are cinder cones. This area is distinct from other parts of the Mexican Volcanic Belt (MVB), where composite volcanoes predominate. Other volcanic forms in this field include lava cones, lava domes, maars, tuff rings, small shield volcanoes, and coneless lava flows. Most of the shield volcanoes are eroded and predate the currently observable cinder cones.

Within the MGVF, cinder cones are situated between 200 km and 440 km from the Middle America Trench. Nearly 75% of the volcanoes are distributed between 200 km and 300 km from the trench, and cone density is highest at 250 km. Overall cone density is 2.5 cones/100 km^2, and median separation distance is 2 km. The median cinder cone has a height of 90 m, a basal diameter of 800 m, a crater diameter of 230 m, and a volume of 0.021 km^3. The cinder cones typically erupted olivine-basalt or basaltic andesite; these rock types are less silicic than those of composite volcanoes in the MVB. In general, samples from the MGVF show higher MgO, Cr, and Ni and lower K_2O, P_2O_5, and Zr than those farther from the trench.

Cinder cones show various stages of degradation, from which relative ages can be estimated; radiocarbon dates of seven cinder cones were obtained for calibration. Of several morphological indices of age, gully density and surface morphology of associated lava flows are the most sensitive. The morphological classification, based on gully density and lava flow surface features, revealed that 78 volcanoes are younger than 40,000 years. All of them are situated in the south, and some have a rough NE alignment, parallel to the relative motion vector between the Cocos and North America plates. Such NE alignments are also found locally for older cones, although in general cones are randomly spaced. Local cinder cone alignments are E—W in the northern part of the volcanic field, where E—W normal faults also occur.

Despite the large number of scattered cinder cones and other small volcanoes in the MGVF, total erupted volume suggests a low magma supply rate. The estimated total volume of lava flows, ash, and cones erupted during the last 40,000 years for an area of 15,000 km^2 is 31 km^3. The calculated magma eruption rate of 0.8 km^3/1000 years is small in comparison to a single composite volcano in the MVB.

0377-0273/85/$03.30

INTRODUCTION

The Mexican Volcanic Belt (MVB) (Mooser, 1969, 1972) is defined by an E—W-trending belt of composite volcanoes, rhyolitic complexes, and smaller vents (Fig. 1). Like other active continental volcanic arcs, the MVB shows a sub-parallel distribution of Quaternary volcanism, earthquake foci, and an oceanic trench (Drummond, 1981; Nixon, 1982). However, the MVB does not parallel the Middle America Trench (MAT), but rather makes an angle of approximately 15° to it (Fig. 1) and deep earthquakes (>150 km) have not been observed under the active volcanoes (Molnar and Sykes, 1969; Hanus and Venek, 1978; Nixon, 1982). Within the MVB in central Mexico is a large concentration of cinder cones, lava cones, and central volcanoes. About

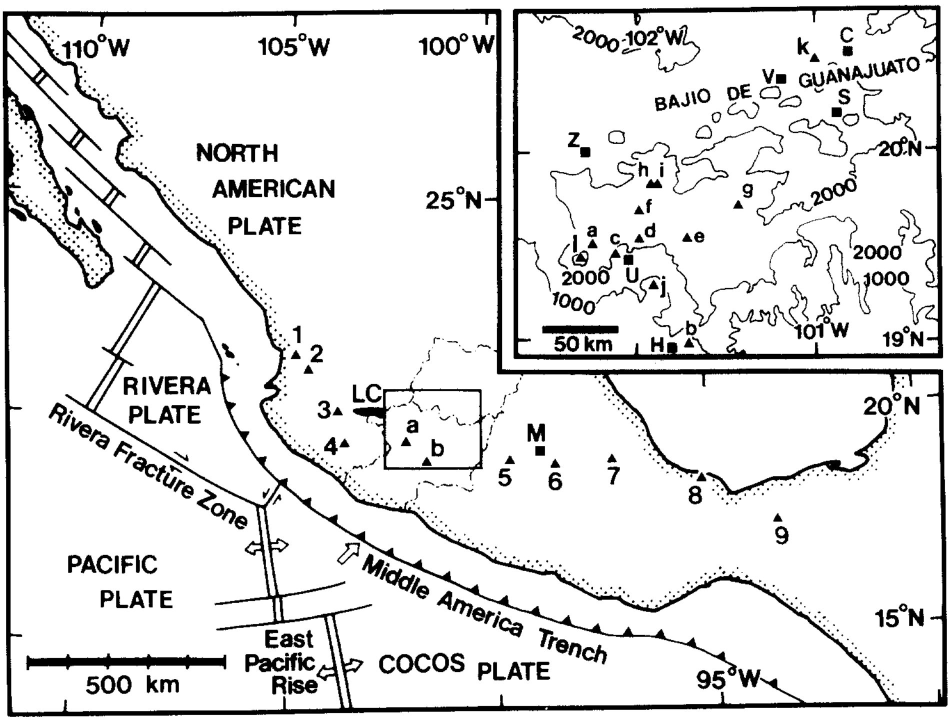

Fig. 1. Index map of the Michoacán—Guanajuato Volcanic Field. The location of the MGVF is shown as a rectangle. The inset enlarges the rectangle area. Contours of 1000 m and 2000 m show general topography of the area. Mexican Volcanic Belt (MVB) is shown as the chain of volcanoes. Plate boundaries are drawn after Drummond (1981).
Volcanoes: *1* = Sanganguey; *2* = Ceboruco; *3* = Sierra La Primavera; *4* = Nevado de Colima; *5* = Nevado de Tolúca; *6* = Popocatépetl; *7* = Pico de Orizaba; *8* = San Andrés Tuxtla; *9* = El Chichón.
a = Paricutin; *b* = El Jorullo; *c* = El Jabali; *d* = El Metate; *e* = La Taza; *f* = El Huanillo; *g* = La Mina; *h* = El Pueblito; *i* = Las Cabras; *j* = La Pilita; *k* = Santa Teresa; *l* = Tancitaro.
Places: *Z* = Zamora; *V* = Valle de Santiago; *S* = Salvatierra; *C* = Celaya; *U* = Uruapan; *H* = La Huacana; *M* = Mexico City; *LC* = Lake Chapala.

1000 eruptive vents, mostly cinder cones, are found in the northern half of the state of Michoacán and in the southern part of the state of Guanajuato. The youngest of these, Volcán Paricutin, erupted in 1943—1952; the second youngest, Volcán El Jorullo, in 1759—1774. This region, the Michoacán—Guanajuato Volcanic Field (MGVF) has an area of 40,000 km^2 and forms a unique part of the MVB, since it lacks the young large composite volcanoes dominant in other parts of the MVB.

This volcanic field was formerly referred to as: (1) the Michoacán volcanic province (Foshag and Gonzalez, 1956); (2) the Paricutin region (Williams, 1950); and (3) the Zamora volcanic field (Simkin et al., 1981) depending on the perspectives of researchers. As the volcanoes described in this paper are distributed in both Michoacán and Guanajuato, we suggest the broader label of the Michoacán—Guanajuato Volcanic Field (Fig. 1).

In general, cinder and lava cones are active for only a short period of time, perhaps a few months to twenty years, and rarely become active again. In contrast, central volcanoes are fed by a single conduit or a row of closely spaced conduits which repeatedly deliver magma to the surface; they may be either composite or shield. Cinder and lava cones either occur near a large central volcano (e.g., Porter, 1972; Downie and Wilkinson, 1972; McGetchin et al., 1974; Luhr and Carmichael, 1981; Nelson and Carmichael, 1984), or cluster to form a volcanic field lacking composite volcanoes (e.g., Colton, 1937; Singleton and Joyce, 1969; Scott and Trask, 1971; Bloomfield, 1975; Moore et al., 1976; Walker, 1981; Martin del Pozzo, 1983), but are sometimes accompanied by tuff rings, maars, and small shield volcanoes.

The purpose of this study of the MGVF are: (1) to describe the spacing, size, and morphology of cinder cones and their associated lavas; (2) to develop morphological age indices for cinder cones; (3) to calibrate these using radiometric ages; and (4) to estimate the eruption rate of magma in the region.

THE MICHOACÁN—GUANAJUATO VOLCANIC FIELD

Most of the volcanic centers of the MGVF occur on the E—W-trending plateau which corresponds to the axis of the MVB (Cordillera Neovolcanica) (Fig. 1); some extend to the north in the Bajio de Guanajuato, and a few to the south in the lowlands (Fig. 1).

The limited exposure of the basement rocks underlying the volcanic field consists mainly of felsic intrusive rocks (Williams, 1950). Granites, quartz monzonites, and quartz diorites crop out in the southern part of the volcanic field, south of Uruapan and north of La Huacana (Fig. 1). Clark et al. (1982) reported an Early Oligocene age of the La Huacana batholith. These basement rocks occur as partially fused inclusions in scoriae of Paricutin (Wilcox, 1954) and other cinder cones in the southern part of the volcanic field.

Basalt or andesite lavas of the Eocene to Miocene (?) Zumpinito Formation (Williams, 1950) underly the MVB and outcrop as eroded hills. Late

Miocene (?) ignimbrites, probably of the Sierra Madre Occidental province, form elongated ridges and mesas to the north and east of the volcanic field. They are also observed to the west of Lake Cuitzeo (Fig. 8), and near Salvatierra, Guanajuato (Demant, 1978). Shield volcanoes generally are older than the cinder cone eruptions. They range from 4 to 13 km in diameter, with a slope angle of 5° to 15°. Approximately 120 shields are distributed throughout the volcanic field, the largest being Cerro Tancitaro (3845 m) in the area SW of Volcán Paricutin (Fig. 1).

DISTRIBUTION OF VENTS

A total of 1040 volcanic vents in the MGVF were identified from topographic maps and air photographs (published by DETENAL, Mexico City, scale 1:50,000) in conjunction with field observations. This total includes 901 cones, 43 domes, 13 young shield volcanoes with surmounting cones, 22 maars or tuff rings, and 61 lava flows with hidden vents. (A table of the locations of these volcanoes with their dimensions and morphological parameters is available from the authors upon request.) Old, highly dissected shield volcanoes and eroded hills, the nature of which is not easy to discern from topography, are excluded from this compilation.

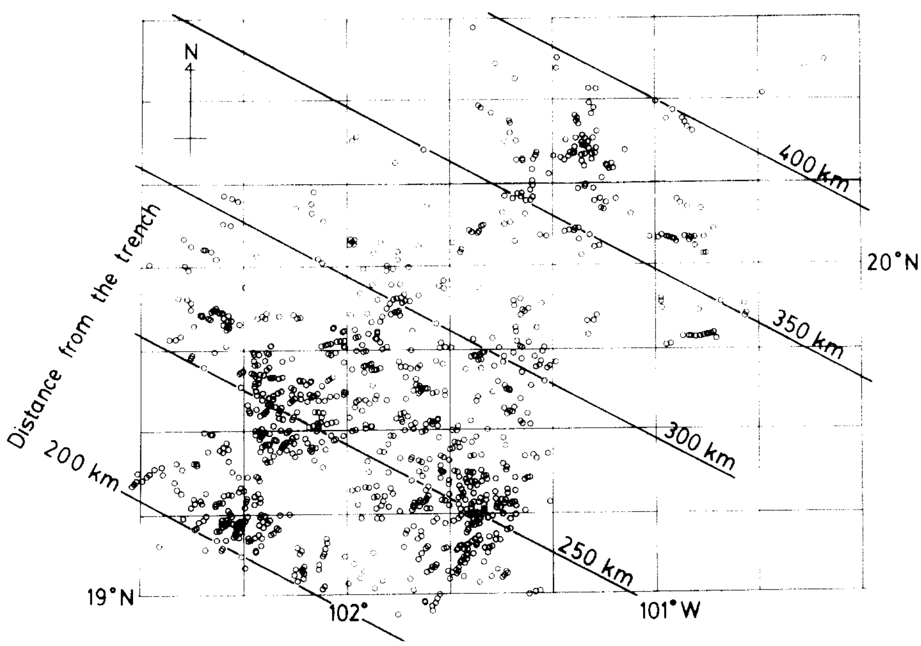

Fig. 2. Distribution of volcanoes in the Michoacán–Guanajuato Volcanic Field. The area is the same as the inset of Fig. 1. Circles indicate all volcanic centers: cinder cones, lava domes, maars, tuff rings, shield volcanoes with a summit cone, or lava flows which are not associated with cones. The position of estimated vents are used for locating the lava flows.

Few volcanoes occur closer than 200 km to the Middle America Trench (Fig. 2). The concentration of volcanoes is greatest about 250 km from the trench, and approximately 75% of the volcanoes are found between 200 km and 300 km. Farther than 300 km, the number of volcanoes decreases; the most distant cinder cone is 440 km from the trench. A local concentration of volcanoes at 380 km corresponds to the maar cluster of Valle de Santiago (Figs. 1 and 2).

In general, the cinder cones are randomly spaced and indicate no preferred orientation (Figs. 2 and 3). A small number of closely associated cinder cones, however, show local alignments; these trend E—W in the northern part of the volcanic field, ENE in the middle part, and NE in the southern part near the volcanic front (Fig. 2). In any given area, cinder cones are restricted to relatively low elevations as most cones formed either on alluvial plains or low on the flanks of eroded shield volcanoes (Fig. 3).

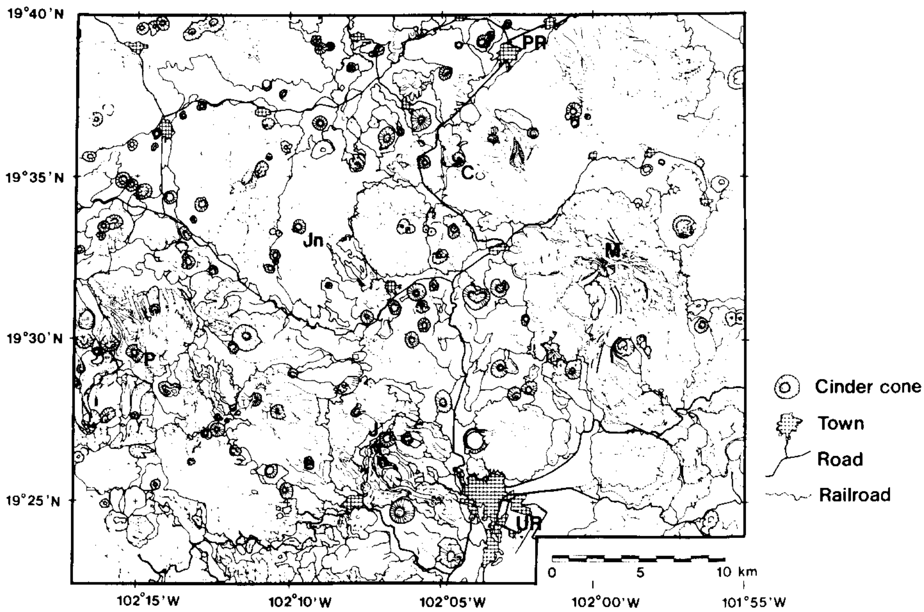

Fig. 3. Map of the volcanoes and associated lava flows in the Paricutin region constructed from air photographs. *UR* = Uruapan; *PR* = Paracho; *P* = Volcán Paricutin; *J* = Cerro El Jabali; *M* = Cerro El Metate; *Jn* = Cerro Janamo; *C* = Cerro Capatacuiro.

The overall density of volcanoes in the MGVF is 2.5 volcanoes/100 km^2 (1040 vents/40,000 km^2). The highest density of 11/100 km^2 is calculated for the Paricutin region (141 vents/1250 km^2 in Fig. 3). Cone separation distance, the distance from one cinder cone to its nearest neighbor, has a Poisson distribution (thus, mode < median < mean). A representative median value is 2 km for 100 selected cinder cones from the entire field, and 1.15 km for the Paricutin region (Fig. 3). If cone separation distance is calculated assuming equal cone density throughout the Paricutin region, the mean distance increases to 3.2 km, a reflection of the tendency for cones to cluster or form pairs.

Samples representative of the diversity of the 1040 cinder and lava cones include olivine basalt and basaltic-andesite (usually containing phenocrysts of olivine) and pyroxene or hornblende andesites, all calc-alkaline, and alkali olivine-basalt and basanite. There is a progressive change in composition with distance from the trench. For the same silica content, incompatible elements such as K, P, and Zr generally increase with distance from the trench. MgO, Cr, and Ni are richest in samples near the trench and poorest in the more alkaline volcanics farthest from it (Table 1) (Hasenaka, 1981). However, exceptions to this general trend are found; one example is of an older (ca. 0.2 Ma) cone next to Volcán El Jorullo, one of the closest cones to the trench and yet has 2.8% K_2O and 49.2% SiO_2 (Luhr and Carmichael, in press). The main rock types of the region, calc-alkaline basalt and basaltic andesite, are generally less silicic than those of the composite volcanoes in the MVB (Williams, 1950; Gunn and Mooser, 1971; Pal et al., 1978; Nelson, 1980; Luhr and Carmichael, 1980; Robin and Cantagrel, 1982).

TABLE 1

Representative chemical analyses of scoria and lava

Sample:	663	416A	432B	571T	555A
SiO_2	53.06	53.06	52.82	54.12	52.48
TiO_2	0.89	0.98	1.79	1.79	1.69
Al_2O_3	17.00	17.84	16.97	17.12	16.98
FeOt	6.85	7.04	8.70	8.33	8.10
MnO	0.13	0.12	0.14	0.14	0.13
MgO	7.96	6.61	4.86	3.75	4.47
CaO	7.75	8.61	7.38	6.54	7.86
Na_2O	3.74	3.83	3.86	4.21	3.94
K_2O	0.91	0.96	1.46	1.96	2.17
P_2O_5	0.18	0.21	0.39	0.59	0.74
Cr	364	142	100	47	n.d.
V	169	139	204	182	223
Ni	212	142	43	45	44
Sr	530	723	549	569	1419
Zr	117	99	207	243	240
Ba	267	297	399	574	850
DFT	201	249	305	345	401

Major element oxides in wt.%.
Trace elmenets in ppm.
FeOt = total iron as ferrous.
n.d. = not detected.
Analyses by X-ray fluorescence.
DFT = distance of the cone from the Middle America Trench in km.

CINDER CONE SIZE

Morphometric parameters of cinder cones and their associated lava flows were obtained from 1:50,000 topographic maps. These parameters include cone height (H), cone basal diameter or width (W_{co}), and crater diameter or width (W_{cr}) (Fig. 4). Most of the cinder cones show a symmetrical truncated cone shape, but cones that erupted on an inclined basement surface are often breached or elongated. To allow for this, W_{co} and W_{cr} are defined as the arithmetic means of the maximum and minimum values of cone and crater widths. H is the elevation difference between the summit of the cinder cone and its base. The basal elevation is the mean of the highest and the lowest basal values. The circumferences of crater rims and cone bases were determined where the generally equidistant topographic contours abruptly widen. Where the crater is not visible on the topographic maps, the diameter of a somewhat flatter summit was taken as the crater diameter value. From these values, the volume of a symmetrical truncated cone was calculated.

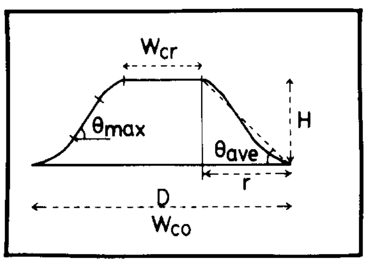

Fig. 4. Schematic diagram illustrating the parameters used to estimate cinder cone size.

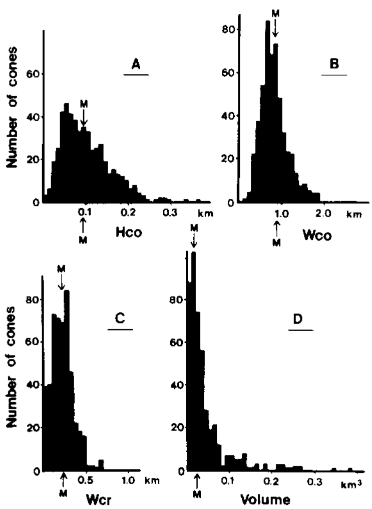

Fig. 5. Frequency distribution of cinder cone size in the MGVF. (A) cone height, (B) cone basal diameter, (C) cone crater diameter, (D) cone volume calculated as a symmetrical truncated cone shape. M indicates the median value.

TABLE 2

Dimensions and age of cinder cones

	Cinder cone	Latitude (N)	Longitude (W)	W_{co}	W_{cr}	H	Volume	Age	Sample method
a	Volcán Parícutin	19° 29′33″	102° 15′04″	0.95	0.25	0.220	0.069	1943—1952 AD	Historical record
b	Volcán El Jorullo	18° 58′19″	101° 43′03″	1.45	0.42	0.290	0.219	1759—1774 AD	Historical record
c	Cerro El Jabali	19° 26′56″	102° 06′46″	0.93	0.38	0.160	0.057	3,830 ± 150 y.B.P.	737C charcoal ^{14}C
d	Cerro El Metate	19° 32′20″	101° 59′33″	0.88	0.20	0.150	0.039	4,700 ± 200 y.B.P.	761C charcoal ^{14}C
e	Cerro La Taza	19° 31′33″	101° 43′28″	0.70	0.18	0.170	0.029	8,430 ± 330 y.B.P.	759C charcoal ^{14}C
f	Hoya El Huanillo	19° 41′01″	101° 59′04″	0.95	0.35	0.190	0.068	9,180 ± 250 y.B.P.	411C3 charcoal ^{14}C
								9,410 ± 230 y.B.P.	411C2 charcoal ^{14}C
g	Volcán La Mina	19° 42′45″	101° 26′02″	1.15	0.35	0.190	0.092	17,170 ± 430 y.B.P.	622C charcoal ^{14}C
h	El Pueblito	19° 49′29″	101° 55′24″	1.00	0.38	0.185	0.075	29,000 ± 3,300 y.B.P.	435C charcoal ^{14}C
i	Cerro Las Cabras	19° 49′34″	101° 53′37″	1.18	0.55	0.195	0.120	>40,000 y. B.P.	674C charcoal ^{14}C
j	Cerro Pelon	19° 17′52″	101° 54′47″	0.68	0.18	0.085	0.014	0.37 ± 05 Ma	426L lava K-Ar
k	Santa Teresa	20° 29′50″	100° 59′53″	0.63	0.15	0.030	0.004	2.78 ± 07 Ma	555A scoria K-Ar

Symbols (a—k) are the same as in Fig. 1.
W_{co} = basal diameter, W_{cr} = crater diameter, H = cone height (in km).
Volume of cinder cone (in km^3) is calculated as a symmetrical truncated cone, i.e.:

$$\text{Volume} = \frac{\pi H}{12} \cdot (W_{cr}^2 + W_{cr}W_{co} + W_{co}^2)$$

Cone size is measured using 1:50,000 topographic maps (DETENAL, Mexico City).
^{14}C ages are obtained from the charcoal in the soil under the ash and lappili layers (analyst: Teledyne Isotopes).
Charcoal samples were collected at two different sites for Hoya El Huanillo.
K-Ar ages are obtained from the whole rock samples of lava or scoria (analyst: G. Mahood).

For cones with discernable crater rims, frequency histograms for H, W_{co}, W_{cr}, and cinder cone volume are shown in Fig. 5. Median values are 90 m for the height, 800 m for the basal diameter, 230 m for the crater diameter, and 0.021 km^3 for the volume. Mean values are 100 m, 830 m, 240 m, and 0.038 km^3, respectively.

Younger cinder cones dated by ^{14}C are larger than the median (Table 2). Older cinder cones are often partly buried by later lava flows, and aeolian and alluvial deposits as well as erosional processes can diminish the dimensions of relatively old cinder cones. Large cinder cones are more frequent in the southwestern part of the MGVF where cones erupted on the lowlands (Fig. 1), indicating that there may be some elevation (crustal thickness) influence on cinder cone size (Vogt, 1974; Ben-Avraham and Nur, 1980).

LAVA FLOW VOLUME

Volumes of lava flows whose margins were clearly observable on the air photographs (scale 1:50,000) were estimated by tracing flow margins onto topographic maps and then calculating their thickness from the countour intervals (either 20 m or 10 m). The thickness estimates were made at equal intervals along the margins of a flow, and then averaged. When the thickness was smaller than the contour interval, an arbitrary value of one-half the contour interval was assumed. Lava flow area was measured with a planimeter. The volume of each flow unit was then calculated from its average thickness and area. Note that the volume of lava flows hidden under later flows was not estimated and that the thickness of a lava flow may be underestimated because of the accumulation of colluvium at the foot of the flow margins and later alluvial deposition surrounding the lava flows. Therefore, the calculated volumes represent minimum values. The thickness, length, and volume of the lava flows are compiled in Table 3.

TABLE 3

Dimensions and volumes of lava flows

	Mean	Median	Minimum	Maximum
Thickness[a] (m)	40	30	2–3	120
Length[a] (km)	3.5	3.0	0.7	15
Volume[b] (km^3)	0.23	0.20	0.01	4.8

[a]Calculated for 279 lava flows.
[b]Volume calculated as total lava erupted for a single cone.

Plots of lava flow volumes against the volumes of associated cinder cones for the MGVF show scatter of up to 2 orders of magnitude. The data, however, fall on the least-squares line defined by cinder cones with greater size ranges (Fig. 6), from which Wood (1980a) concluded that in general cone volume becomes a greater portion of the total eruption as the eruption volume increases. The ratio of cone to lava volume is a function of explosivity possibly reflecting the volatile content or viscosity of magma. On the average in the MGVF, the volume of a cinder cone is roughly 1/10 that of its associated lava flow, which is the same ratio observed at Paricutin, where more precise measurements exist (Fries, 1953).

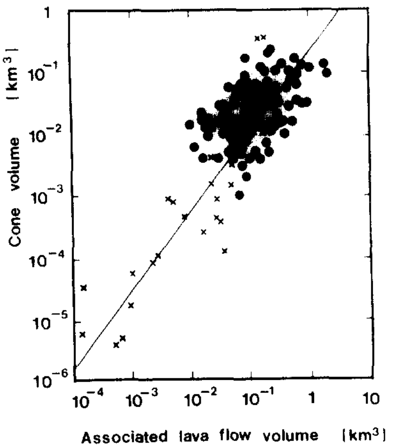

Fig. 6. The relationship between volume of cinder cones and associated lava flows in the MGVF (dots), combined with Wood's (1980a) data from San Francisco volcanic field, Etna, Reunion, Tolbachic, and Eldfelt (crosses). The line indicates the least-square fit derived by Wood (1980a).

GEOMORPHOLOGICAL PARAMETERS OF CINDER CONE AGE

One of the earliest studies of cinder cones was Colton's (1937) work in the San Francisco Mountain volcanic field of Arizona, in which he classified the stages of erosion of cones and their associated lava flows. Other semi-quantitative indicators of cinder cone age include: the maximum cone slope angle (Scott and Trask, 1971), the ratio of cone height to cone basal diameter (Scott and Trask, 1971; Wood, 1980b), the tangent of the cone slope (Bloomfield, 1975), and the change of surface features of lava flows associated with cinder cones (Bloomfield, 1975).

Cinder cones in the MGVF also show various stages of degradation, from which the relative ages of the cinder cones can be estimated. The youngest cones, like Paricutin, have a perfect cone shape with slope angles of 34°, the angle of repose of cinder. Their craters, whose rims are sharp and little modified by erosion, have little infilling of ash or scoriae. A large number of rills and shallow gullies have developed on the slopes of the youngest cones. The largest number of radial lineaments on the slope of Paricutin observed in air photographs, however, are not gullies but alternating bands of scoriae and lapilli. Vegetation is sparse on Paricutin where soil is absent, but most of the surface of Volcán El Jorullo is already covered with trees only 200 years after its eruption. Under the tropical to temperate climate of the MGVF, vegetatative recovery after eruption is rapid compared with the age span of cinder cones. The total annual precipitation in the MGVF is between 500 mm and 1800 mm/year, and the mean annual temperature is between 16° C and 29° C (total annual precipitation and mean annual temperature maps, published by DETENAL, Mexico City). The area on the plateau has a relatively cool and wet climate; in contrast, the lowland south has a relatively hot and dry climate, resulting in different erosional conditions.

Older, degraded cinder cones have lower slope angles, a smaller number of gullies (which are larger and deeper), greater soil development, and more weathered and oxidized ejecta than the youngest cones. Craters of the older cones are filled by ash from other volcanoes and by debris eroded from the higher slopes of the craters themselves. Some of the oldest cones may be almost completely buried and have very shallow slope angles. The oldest group includes cones with flattened and rounded shapes and deeply dissected cones with breached craters.

Lava flow morphology also changes with age. Holocene lava flows display well preserved original surface features, such as flow margins, boundaries of individual flow units, pressure ridges, and levees. Lava flows lose these characteristics with time and become covered with soils which may be cultivated. In a densely populated area where almost all the useful land is cultivated, lava surfaces covered with trees and shrubs indicate the absence of arable soils and hence relative youth. The lava flows of Paricutin and El Jorullo are exceptional; they only have sparse vegetation.

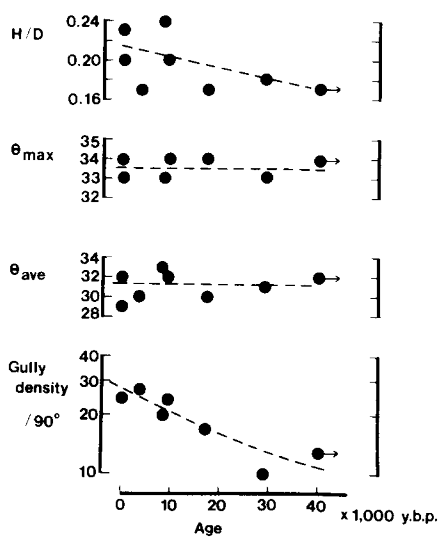

Fig. 7. Geomorphological parameters of cinder cone age plotted against ^{14}C age. The data are from Paricutin, El Jorullo, El Jabali, El Huanillo, La Mina, El Pueblito, Las Cabras, and El Pelon (Table 2). The data for Cerro El Metate are excluded because the cone shape is greatly modified by lava flows on the slope. Dashed lines are fitted by eye.

The morphologic indicators of age include: (1) the ratio of cinder cone height to basal diameter (H/D); (2) maximum slope angle (θ_{max}), taken as the average of several field measurements from different directions; (3) average slope angle (θ_{ave}), which is calculated as $\tan^{-1}$ (H/r), where r is given in Fig. 4; (4) the difference between the maximum and the average slope angles; (5) gully density, defined as the number of gullies determined from air photographs normalized to 90° of arc; and (6) the geomorphological classification of lava flows, as summarized in Table 4. Important measured variables are displayed in Fig. 7. These indices are relatively easily obtained from topographic maps, air photographs, or field observations.

TABLE 4

Geomorphological classification of lava flows

	Flow margins	Indiv. flow units	Pressure ridges	Soil	Tree shrub cover	Culti-vation	Cinder cone	Age
Hv	○	○	○	×	×	×	Paricutin El Jorullo	1943–1952 AD 1759–1774 AD
		○	○	×	○	×	El Jabali El Metate La Taza	3,830 y.B.P. 4,700 y.B.P. 8,430 y.B.P.
Plv_4	○	○	○	△	○	×	La Mina	17,170 y.B.P.
Plv_3	○	△	○	△	△	△	El Pueblito Las Cabras	29,000 y.B.P. >40,000 y.B.P.
Plv_2	○	×	×	○	×	○	Pelon	0.37 Ma
Plv_1	△	×	×	○	×	○		

○ = feature is distinctly observed or abundant.
△ = feature is somewhat recognizable or moderately abundant.
× = feature is obscure or scarce.

RADIOMETRIC DATES AND CINDER CONE AGES

Radiocarbon dates

Carbon 14 dates were obtained for 8 charcoal samples from cinder cones in the earlier stages of degradation (Table 2). The charcoal was collected from soil just beneath the ash and lapilli at distances of 500 m to 2000 m from a cinder cone. At this distance, the continuity of the tephra from the cone is obvious. Charcoal was found at the contact of the soil and ash and up to 20 cm below it. This indicates a close temporal relationship between charcoal formation and airfalls; thus the ^{14}C dates are used to represent the age of eruption. Most of the cones dated are relatively large and from the plateau (with a relatively cold and wet climate).

Cinder cone geomorphological parameters are plotted against the ^{14}C ages in Fig. 8. Clearly, no significant change with age occurs in the H/D ratio or in the cone slope angles; both maximum and minimum values are found to remain constant within the ^{14}C span of 40,000 years. The maximum slope angle, 33° to 34°, is the initial cone slope angle and remains constant for about 40,000 years; the average slope angle shows a greater but inconsistent variation. Accordingly, the difference between maximum and average slope angles will not be meaningful. These three parameters indicate that the initial form of these cinder cones has been slow to change over a period of at least 40,000 years. During this period, major erosional processes of landsliding and gullying (Segerstrom, 1950; Wood, 1980b) have yet to modify the shape of cinder cones which are largely comprised of permeable scoriae and lapilli.

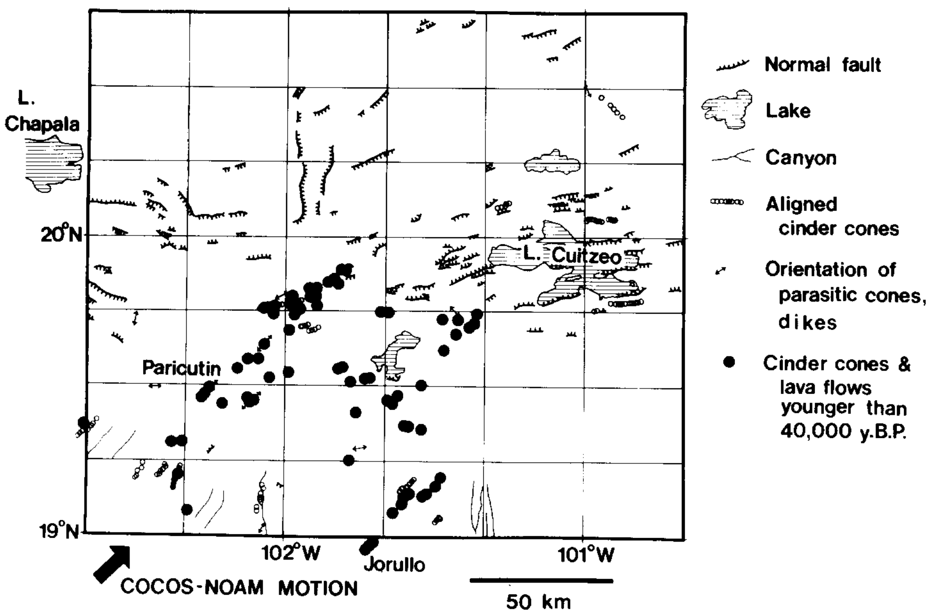

Fig. 8. Alignments of cinder cones, their vents and dikes, and normal faults in the MGVF. Large dots indicate cinder cones and lava flows younger than 40,000 years. Arrow shows the relative motion vector of the Cocos and North America plates. Map area same as in Fig. 2 except at the eastern margin.

Conversely, gully density shows a consistent change from 30/90° to 10/90° over 40,000 years, although there is some scatter of the data due to influence of vegetation, visibility of gullies, prevailing wind and weather, and cinder cone size. Smaller cones are expected to develop fewer gullies due to their smaller area and the shorter runoff distance of rainfall water. Also, gullying may play a minor role in the degradation of cones under dry climate. In general, cinder cones in the lowland (relatively hot and dry climate) are rounded, show little gullying, and are similar to those of the San Francisco volcanic field in Arizona (mean annual precipitation, 490 mm by Ruffner, 1980) (Colton, 1937; Wood, 1980b).

Geomorphological classification of lava flows is another useful age index for their associated cinder cones, and the surface features of lavas are correlated with radiometric dates in Table 4. The lava flows and associated cinder cones are classified into three groups: Holocene volcanoes (Hv), which are younger than 10,000 years B.P., and the youngest two groups of Pleistocene volcanoes (Plv_4, Plv_3). Cerro Las Cabras and other similar lava flows are arbitrarily subgrouped into Plv_{2-3}, since they have surface features between Plv_2 and Plv_3.

K-Ar dates

K-Ar dates were obtained for lavas and scoriae of more degraded cinder cones (Table 2). Cerro Pelon (0.37 ± 0.05 Ma) shows a significant difference in all parameters compared to cones younger than 40,000 years B.P; H/D ratio decreases to 0.12, maximum and average slope angles decrease to 28° and 19°, respectively. An apparent "young" value of gully density (11/90°) may be coincidentally due to a dry climate, as discussed above. The lava flows associated with this cone are classified as Plv_2 (Table 4). Note from Table 4 Plv_2 (and possibly Plv_{2-3}) lava flow morphology represents a longer time span than that of the youngest three groups. For this longer period, erosional processes became significant in changing the form of cinder cones.

The Santa Teresa cone west of Celaya, Guanajuato (2.78 Ma ± 0.07) is probably one of the oldest in the MGVF. It has an almost flat shape, being partly buried by sediments but is recognized as such by an openpit quarry. Another K-Ar age is known for the San Nicholas maar near Valle de Santiago; juvenile scoriae of the maar give an age of 1.2 Ma (Murphy and Carmichael, 1984).

LATE PLEISTOCENE–RECENT ERUPTION HISTORY

The calibrated geomorphological classification of lava flows combined with the gully density allows estimation of the relative ages of cinder cones and lava flows. The number of Holocene and Late Pleistocene volcanoes (Hv, Plv_4, and Plv_3) are 16, 27, and 35 respectively; thus an estimated 78 volcanoes erupted within the last 40,000 years. These volcanoes include mostly cinder cones, but also some lava flows not associated with cones and two shield volcanoes with summit cones. These young volcanoes are situated only in the southern part of the volcanic field, between 200 and 300 km from the Middle America Trench in an area of 15,000 km^2.

Structural control of eruptive vents

Structural alignments of cinder cones and other volcanoes which have erupted within the last 40,000 years are notable (Fig. 8). One such alignment includes Paricutin and extends about 100 km farther to the northeast. Another 40 km long alignment of volcanoes which includes El Jorullo in the south also shows a NE direction. Although there is some scatter of cones, these alignments suggest crustal fractures along which magmas ascended. The direction of these younger cone alignments coincides with the relative motion vector of the Cocos and North America plates (and the direction perpendicular to the minimum horizontal compressive stress) consistent with the idea that tectonic stresses control the location of magmatic conduits, (Nakamura, 1977; Nakamura et al., 1977). In the southern part of the field, older parasitic cones and closely-associated cinder cones also show NE alignments. Additional tectonic information is difficult to obtain because the region is almost completely covered by young volcanic products.

In the northeastern part of the field, the relationship between tectonic stress and cinder cone alignments is more obvious. The area surrounding Lake Cuitzeo is characterized by E—W normal faults and parallel alignments of cinder cones. These faults may be related to the E—W-trending Chapala graben structures just west of the volcanic field.

MAGMA OUTPUT RATE

Multiple vents like those in the MGVF imply an absence of long-lived shallow magma reservoirs characteristic of composite volcanoes, since on the evidence of Volcán Paricutin and Volcán El Jorullo, the vents had been active for less than 20 years. An exponential decrease of effusion rate at Volcán Paricutin indicates that no new magma batches were supplied during eruption (Scandone, 1979), and it has been suggested that the magma came from a deep reservoir (Wadge, 1981). If the formation of a shallow magma reservoir is prevented by a small magma supply rate, a field of cinder cones is

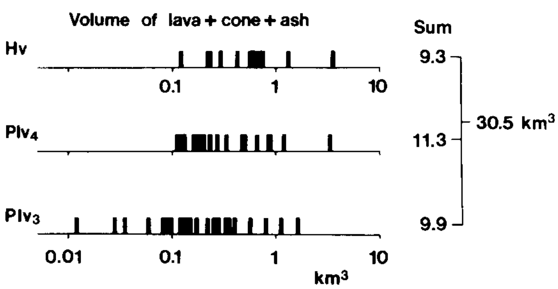

Fig. 9. Calculated dense rock (2.7 g/cm^3) equivalent volumes of the Late Pleistocene to Recent volcanoes in the Michoacán—Guanajuato Volcanic Field. The symbols, Hv, Plv_4, and Plv_3 represent the geomorphological stages of lava flows (Table 4). Cone volume was calculated as a symmetrical truncated cone. Each lava flow volume was calculated as the product of area and average thickness. Volume of airfall ash was assumed to be 7.73 times that of the associated cone after Fries (1953). All volume data were corrected for vesicularity by assuming that lava flows have 30% porosity (Fries, 1953), both airfall ash and cinder cones have 50% porosity. Volumes of deposits were not adjusted for erosion and burial by alluvial sediments, which may account for the smaller volumes of Plv_3 volcanoes.

more likely to form instead of a composite volcano (Fedotov, 1981; Hildreth, 1981; Fig. 15; Walker, 1983).

Overall magma output rate was calculated for the MGVF for the last 40,000 years. Magma eruption volumes (dense rock equivalent) for the Holocene and late Pleistocene (Hv, Plv_4 and Plv_3) are 9.3, 11.3 and 9.9 km^3, respectively (Fig. 9). Thus, 30.5 km^3 of magma was discharged over 40,000 years in an area of 15,000 km^2, yielding an overall magma output rate of 0.8 km^3/1000 years; this can also be represented by a rate calculated for unit length parallel to the Middle America Trench and is approximately 0.005 km^3/km per 1000 years.

A comparison with other composite volcanoes at convergent plate boundaries is made in Fig. 10. Magma output rates of 13 composite volcanoes from Japan, USSR, and America range from 0.4 to 270 km^3/1000 years (Crisp, 1984). In Mexico, the output rates of Colima and Ceboruco are 2.7 km^3/1000 years and 6 km^3/1000 years, respectively (Luhr and Carmichael, 1980, 1982; Nelson, 1980). In contrast Sierra La Primavera rhyolitic complex has a relatively low magma output rate of 0.5 km^3/1000 years (Crisp, 1984; Mahood, 1980, 1981; Wright, 1981). The entire MGVF is among the smallest (Fig. 10).

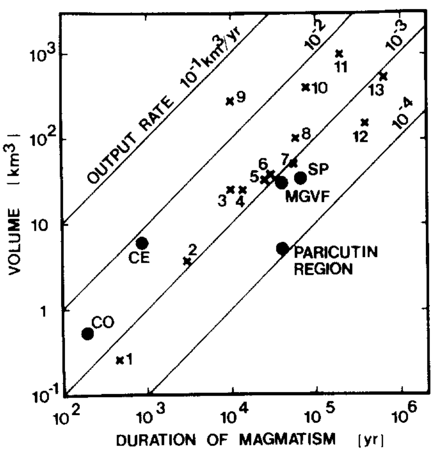

Fig. 10. Magma output rates of volcanoes at convergent plate boundaries shown on a logarithmic plot of discharge volume against duration of magmatism. Diagonal lines indicate equal magma output rates. Filled circles represent the Mexican volcanoes: *CO* = Colima after the 1818 major ash flow eruption (Luhr and Carmichael, 1980, 1982); *CE* = Ceboruco after the Plinian eruption of Jala pumice (1000 years ago) (Nelson, 1980); *SP* = Sierra la Primavera during and after the ash flow eruption of the Tala Tuff (95,000 years ago) (Mahood, 1980, 1981; Wright, 1981; Crisp, 1984); *MGFV* = Michoacán-Guanajuato Volcanic Field (this study). Crosses represent the volcanoes from other regions (Wadge, 1982; Crisp, 1984): *1* = Arenal, Costa Rica; *2* = Kaimondake, Japan; *3* = Edgecumbe, USA; *4* = Sakurajima, Japan; *5* = Oshima, Japan; *6* = Asama, Japan; *7* = Fuego, Guatemala; *8* = Avachinsky, USSR; *9* = Kluychevskoy, USSR; *10* = Fuji, Japan; *11* = Shiveluch, USSR; *12* = Hakone, Japan, *13* = Calabozos caldera, Chile. Magma output volume of the Paricutin region (Fig. 3) is also plotted.

Whether the magma discharge volume of the MGVF is equivalent to a composite volcano is difficult to estimate. Those volcanoes whose output rates were calculated for comparison have surface areas less than 500 km^2 (Crisp, 1984), whereas the last 40,000 years of activity in the MGVF covers an area of 15,000 km^2. Although the surface area of a volcano does not necessarily reflect its source, the MGVF is likely to sample a larger area of magma source region than a composite volcano, since composite volcanoes in most volcanic arcs have an average spacing closer than the dimensions of the MGVF (ca. 200 km). As an attempt to make a reasonable basis for comparison, high cone density areas in Fig. 8 are assumed to represent a magma batch equivalent to that of a single composite volcano. For example, the Paricutin region (Fig. 3) yields a magma output rate of 0.12 km^3/1000 years, which is about 1/7 of the entire MGVF. This value is the lowest among the reported magma output rates at convergent plate boundaries. These calculations indicate that the magma discharge rate for the MGVF is smaller than that of a single composite volcano despite the evidence of geographically extensive volcanic activity. It seems that the myriad vents of the MGVF reflect a small magma discharge rate, and probably a small supply rate to the lower crust.

CONCLUSIONS

(1) The Michoacán—Guanajuato Volcanic Field (MGVF) contains 1,040 volcanoes within an area of 40,000 km^2. Most of these are cinder cones but also include lava domes, maars, tuff rings, shield volcanoes, and coneless lava flows.

(2) The median-sized cinder cone in the MGVF is 90 m high and has a basal diameter of 800 m, a crater diameter of 230 m and a volume of 0.021 km^3. For lava flows, the median thickness is 40 m and the median length is 3 km.

(3) Gully density normalized to a 90° arc and the geomorphological classifications of lava flows are sensitive indicators of cinder cone age but have only been calibrated for the last 40,000 years.

(4) Some of the late Pleistocene—Recent volcanoes form NE alignments, which parallel the relative motion vector for the Cocos—North America plates.

(5) For the last 40,000 years, the average magma output rate in the MGVF is 0.8 km^3/1000 years, and in the Paricutin region, 0.12 km^3/1000 years, a value small in comparison to a composite volcano.

ACKNOWLEDGEMENTS

We thank Dr. J.F. Luhr for his continued guidance in volcanology and Prof. G.A. Mahood for K-Ar dates. Radiocarbon dates were made by Teledyne Isotopes. Thanks are also offered to many U.C. Berkely students, especially R. Ludwin, M. Kokinos, and S. Keating for their assistance in the field, and to M. Wopat for helping to measure cinder cones. A. Millar and W. Chavez improved the English. Comments by Drs. B.H. Baker, J.F. Luhr, K. Nakamura, M. Sakuyama, H. Ferriz, S. Linneman, and an anonymous reviewer greatly improved the manuscript. The support of NSF EAR 81-03344, EAR 82-19945 (Carmichael) is acknowledged.

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