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Computer-simulation models of scoria cone degradation in the Colima and Michoacán-Guanajuato volcanic fields, Mexico

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RESUMEN

Se reporta la aplicación de un modelo computacional de diferencias finitas para simular el proceso de erosión en conos de ceniza, empleando un algoritmo lineal o no lineal basado en la ecuación de difusión. Este modelo es aplicado a la determinación de edades para los conos más antiguos de los campos volcánicos de Michoacán-Guanajuato y de Colima, México. Se obtienen edades de 100,000 años para Michoacán-Guanajuato y de 250,000 años para Colima. El modelo tridimensional puede simular la evolución erosional del Volcán Telcampana, Colima. Se discuten posibles efectos de cambio climático en la historia erosional.

PALABRAS CLAVE: Simulación por computadora, volcanismo, Colima, Michoacán-Guanajuato, conos de ceniza, difusión, modelado geomorfológico.

ABSTRACT

Scoria (cinder) cone degradation can be correlated with the length of time a cone has been exposed to erosive conditions, and the systematic decrease with increasing age of cone height, cone height/width ratio, and slope is the basis for relative dating of cones by comparing their morphometric parameters. Degradation of scoria cones in the Colima and Michoacán-Guanajuato volcanic fields, Mexico, offer an example of how the morphologic changes associated with increasing age can provide a basis for dating cones by a relative scheme or a relative scheme calibrated by radiometric dates. To further study the degradational evolution of scoria cones, a computer model for simulating their erosion has been formulated. This model can utilize either a linear or a nonlinear diffusion-equation algorithm expressed in finite-difference form to operate upon a three-dimensional scoria cone input as a matrix of elevation values. Aided by calibration with computer-simulated degradation, cone erosion rates were calculated for the younger scoria cones in the Michoacán-Guanajuato volcanic field. These erosion rates were then extrapolated to determine the ages of the older cones in this volcanic field as well as in the nearby Colima volcanic field. The oldest cone age group in the Michoacán-Guanajuato field has an estimated mean age of approximately 100,000 years B.P., while the oldest cone age group in the Colima field has an estimated mean age of approximately 250,000 years B.P. The erosional history of these small-volume basaltic centers may reveal the effects of climate change. Erosional modifications of Volcán Telcampana, a scoria cone in the Colima volcanic field, were simulated by the three-dimensional computer model.

KEY WORDS: Computer simulation, Colima volcanic field, Michoacán-Guanajuato volcanic field, scoria or cinder cones, diffusion, geomorphological models.

INTRODUCTION

Most scoria cones (also known as cinder cones) are conical structures of ballistically ejected fragments topped by a bowl-shaped crater. These small volcanoes are often found clustered by the dozens or even hundreds in volcanic fields or on the flanks of larger volcanoes. They may be the most common volcanic landform (Wood, 1980a).

Assuming an initial conical form, erosional modifications of scoria cones commence with rounding of the crater rim, decrease in cone height, crater infilling, development of debris aprons to enlarge the basal diameter or width of the cone, and the possible inception of gullies on cone slopes. Progressive modifications include a decrease in maximum and average cone slope angle, complete crater infilling to leave a scoria mound, an increase in width and depth of any gullies, and a continuing increase in cone width at the expense of cone height as eroding material continues downslope transport. Further erosion reduces the cone to a shield-like hill with a low cone height/width ratio. The erosional modifications of scoria cones can be correlated with the length of time a cone has been exposed to erosive conditions, and the progressive decrease of cone height (H_{co}), cone height/width ratio (H_{co}/W_{co}), and slope angle with increasing age is the basis for relative dating of cones by comparative measurements.

Morphometric parameters were calculated for 13 scoria cones in the Colima volcanic field, Mexico (Figure 1). Since these cones have not yet been dated, their geomorphologic characteristics can be employed as indices of age to derive a relative-dating scheme. A second data set is provided by Hasenaka and Carmichael (1985a, 1985b), who determined the morphometry and age assignments for 107 scoria cones in the Michoacán-Guanajuato volcanic field of central Mexico (Figure 1).

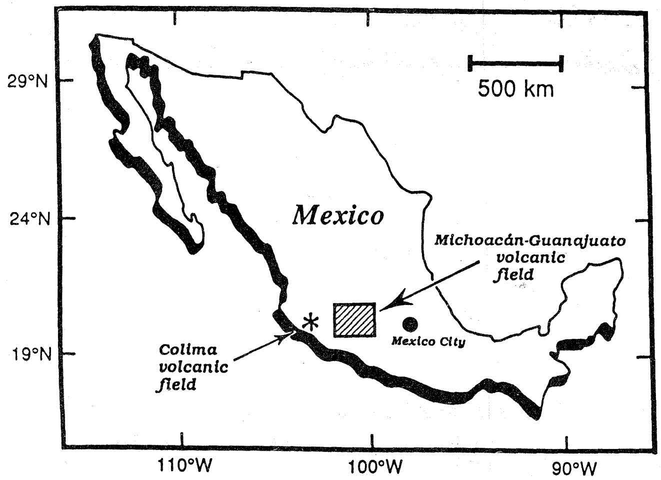

Fig. 1. Location of the Colima and Michoacán-Guanajuato volcanic fields, Mexico.

The relatively simple morphology and internal structure of scoria cones is ideally suited to study their long-term degradation by a diffusion-equation method because they form rapidly and their original morphometric parameters can be estimated with a relatively high degree of certainty. On a macroscopic scale in a geomorphologic system, diffusion is the process by which matter (e.g., soil, rock fragments, cinders) is transported from one part of the system to another by random movements. A computer model for simulating the erosion of scoria cones has been formulated to investigate their degradational evolution (Hooper and Sheridan, 1991; Hooper, 1994). This model can utilize either a linear or a nonlinear diffusion-equation algorithm expressed in finite-difference form to operate upon a three-dimensional scoria cone input as a matrix of elevation values. The linear version of the model assumes that downslope movement is directly proportional to surface gradient to the first power and simulates erosion by rainsplash (raindrop impact), soil creep, freeze-thaw movement, and bioturbation. Mathematically more complex, a nonlinear version of the model is utilized to simulate erosion by slope wash with gullying.

PREVIOUS RESEARCH

A few authors have employed comparative morphology of scoria cones within a chosen volcanic field to establish a relative-age scheme or a relative-age scheme supplemented by chronometric dates. In an early study, Colton (1967) classified the basaltic flows and scoria cones of the San Francisco volcanic field, Arizona, into five stages based upon degree of comparative degradation and weathering (oxidation of fragmentary material). After reviewing the morphometry of several scoria cones in the Lunar Crater volcanic field of Nevada, Scott and Trask (1971) noted that the angle of slope, as well as the relative length of the line of maximum slope compared to the height of the cone, might provide an index ratio of age. They derived the relative ages for 15 cones in this volcanic field. Porter (1972) made extensive morphometric measurements of parasitic cones on the flanks of Mauna Kea, Hawaii.

Bloomfield (1975) studied the comparative morphology of scoria cones and lava flows in the Chichináutzin volcanic field of central Mexico. He used morphologic parameters and devised a calibration scheme from radiocarbon dates of charcoal and paleosols to establish the relative ages for 41 cones in this late Quaternary field. Martin del Pozzo (1982) later determined the geomorphologic parameters for 146 cones in a different region of the same volcanic field.

Wood (1980b) stressed the importance of climate on cone erosion. He was among the first to use the method of grouping cones into different age categories and then comparing and contrasting their changing morphometric parameters. His morphometric analyses clearly demonstrated a decrease in both cone height/width ratio (H_{co}/W_{co}) and average cone slope angle with an increase in age.

Luhr and Carmichael (1981) examined 11 late Quaternary cones of the Colima volcanic complex, Mexico, and devised a preliminary estimation of their ages by comparing averaged maximum slope angles. In a detailed geomorphologic study, Dohrenwend *et al.* (1986) used radiocarbon and K-Ar analyses to date 11 cones in the Cima volcanic field, California, and provided an example of scoria cone degradation under arid conditions.

COLIMA AND MICHOACAN-GUANAJUATO VOLCANIC FIELDS

A chain of three andesitic composite volcanoes dominates the southern end of the Colima graben, Mexico, and displays a southward propagation of volcanism. This volcanic complex consists of the moderately eroded peaks of Volcán Cantaro to the north, while 15 km further south lies Nevado de Colima, the tallest volcano in the group with an elevation over 4200 m. The active Volcán de Colima (about 3880 m a.s.l.) is the southern-most volcano in the chain. More than a dozen scoria cones occur primarily on the graben floor surrounding the larger Colima group composite volcanoes (Figure 2). Robin *et al.* (1987), Luhr and Prestegaard (1988), Robin *et al.* (1991), and Stoops and Sheridan (1992) provide further information regarding this volcanic complex.

Luhr and Carmichael (1981) analyzed the petrology and geochemistry of 11 late Quaternary scoria cones and associated lavas of the Colima volcanic field. They report that nine of the cones produced basic alkaline lavas and scoria ranging in composition from basanite to minette. The remaining two cones have a calc-alkaline composition. Each of the cones from the Luhr and Carmichael study was examined as part of the geomorphologic analysis. Although lacking the distinctive cone-and-crater morphology, Cerro Los Olotes and a cone near Sayula were interpreted as scoria cones and added to this study. These two cones have apparently already lost their crater to erosion.

The Michoacán-Guanajuato volcanic field of central Mexico covers approximately 40,000 km² and contains more than 1000 scoria cones, shield volcanoes, maars, lava domes, and lava flows lacking an apparent vent (Hasenaka and Carmichael, 1985a, 1985b; Connor, 1987; Ban *et al.*,

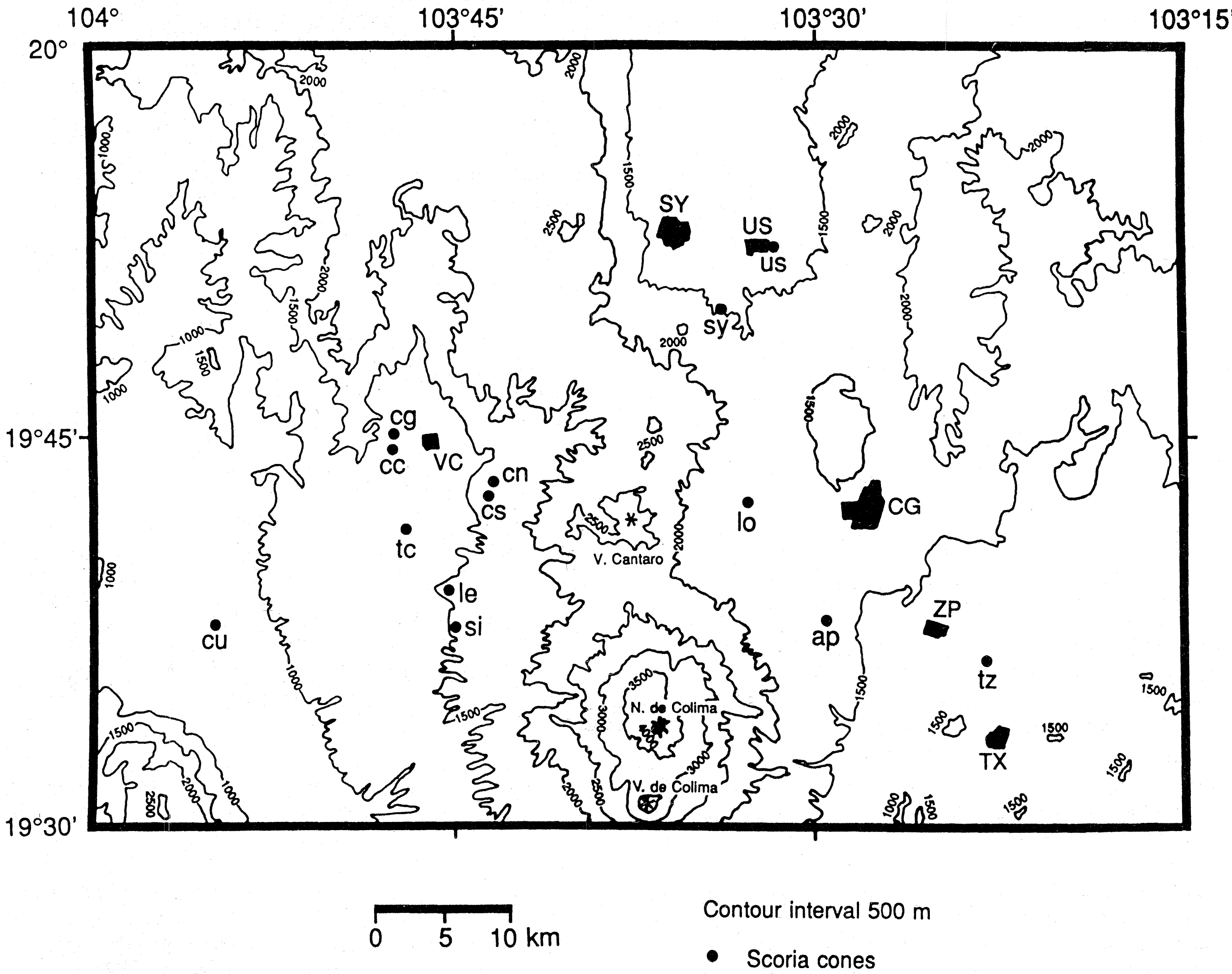

Fig. 2. Location map of the scoria cones and composite volcanoes of the Colima volcanic field, Mexico. Cone abbreviations in order of relative age, youngest to oldest: Volcán La Erita (le), V. Apaxtepec (ap), V. Telcampana (tc), El Carpintero Norte (cn), V. Comal Grande (cg), V. El Comal Chico (cc), Sayula (sy), V. San Isidro (si), El Carpintero Sur (cs), Usmajac (us), V. Tezontal (tz), Cuauhtemoc (cu), and Cerro Los Olotes (lo). Abbreviations for cities: Ciudad Guzman (CG), Sayula (SY), Tuxpan (TX), Usmajac (US), Venustiano Carranza (VC), and Zapotiltic (ZP).

1992; Hasenaka *et al.*, 1994) (Figure 1). Two historical eruptions have occurred at Volcán Paricutín (1943-1952) and Volcán El Jorullo (1759-1774). For the geomorphologic classification of lava flows, Hasenaka and Carmichael (1985a, 1985b) followed the nomenclature of Bloomfield (1975), who classified volcanoes into Holocene (Hv) or Pleistocene (Plv4, Plv3, Plv2, and Plv1 - youngest to oldest) age groups depending upon the preservation and characteristics of surface features on associated lava flows. Hasenaka and Carmichael (1985a, 1985b) subdivided Plv3 into Plv3 and Plv2-3 according to the amount of soil development, and defined Hv, Plv4, and Plv3 to be younger than 40,000 years B.P.

METHODS OF MORPHOMETRIC ANALYSIS

Morphometry was calculated by topographic maps, field measurements, and field photographs. The maps (Instituto Nacional de Estadística Geografía e Informática - DETENAL) have a scale of 1:50,000 and a contour interval of either 10m or 20 m. Geologic maps were also consulted when available. The morphometric parameters H_{co}/W_{co} and maximum cone slope angle act as indicators of cone age. Cone height (H_{co}) is defined as the difference between average basal elevation and maximum crater rim or summit elevation. Cone width or basal diameter (W_{co}) is calculated as the average of the maximum and minimum basal diameters for each cone. This is essentially the same methodology described by Settle (1979) and employed by other researchers, including Hasenaka and Carmichael (1985a, 1985b).

The ratio H_{co}/W_{co} should decrease with an increase in age as erosion diminishes cone height by transporting material to debris aprons surrounding the cone base. Values of H_{co}/W_{co} for youthful, Holocene to late Pleistocene cones usually range from 0.17 to 0.22 (Porter, 1972; Bloomfield, 1975; Wood, 1980a, 1980b; Martin del Pozzo, 1982; Hooper, 1994).

Although this research will focus most heavily upon H_{co}/W_{co} values, the decrease in the maximum cone slope angle with an increase in age provides another comparative morphometric measurement by which to establish the relative ages of scoria cones. Maximum cone slope angles can be measured in the field or determined from the spacing of contour lines on topographic maps. For most scoria cones, the maximum slope angle of unconsolidated lapilli, cinders, and bombs is greatest when they are first deposited. Erosional processes thereafter transport material from the upper portion of the cone to debris aprons and also into the crater itself. This advancement of erosion produces a gradual decrease in both the average and maximum slope angle with time as the cone becomes more rounded and the debris aprons increase in size around the base and lower flanks. Downslope transport degrades the cone so that the maximum slope angle is less than the angle of repose of the initial cone. Scott and Trask (1971) were the first to identify the usefulness of this parameter for deriving relative cone ages. For youthful, Holocene to late Pleistocene cones, maximum slope angles typically range from 29° to 35° (Scott and Trask, 1971; Wood, 1980b; Hasenaka and Carmichael, 1985b; Dohrenwend *et al.*, 1986; Hooper, 1994).

GEOMORPHOLOGIC ANALYSIS FOR THE COLIMA VOLCANIC FIELD

Scoria cones at the Colima volcanic field have not yet been dated by radiometric or other chronometric techniques. However, a relative-age scheme was devised based upon their comparative morphology. The H_{co}/W_{co} ratio and maximum slope angle were determined for each cone, and the resulting values were then ranked or ordered. The sum of the rankings as well as the degree of crater erosion determined the relative-age placement (or geomorphologic dating) of the cones. Results from gully analysis were inconclusive, but this methodology incorporates most of the available geomorphologic information. Using this simplistic scheme of morphology and morphometry, each cone was also placed into one of three relative-age groups. The first group, designated Qy (for youngest Quaternary cones) encompasses youthful cones that have not completely lost their crater to infilling from erosion and have high H_{co}/W_{co} and maximum slope values. Cones that have lost their crater to erosion and have low H_{co}/W_{co} and maximum slope values comprise unit Qo, the oldest of the Quaternary cones. Cones with intermediate morphometric parameters are designated Qm for Quaternary-middle or intermediate unit. The morphometric data for the cones of the Colima volcanic field are compiled in Table 1 and the results of this relative-age scheme are presented in Table 2. The rela-

Table 1

Morphometry of scoria cones of the Colima volcanic field, Mexico

Name/Relative age	H_{co}(m)	W_{co}(m)	H_{co}/W_{co}	Max. Slope	D_{cr}(m)	W_{cr}(m)	Lat (N)	Lon (W)
			Group Qy (Youngest)					
Volcán La Erita	190	1080	0.176	34.5°	b[2]	b[2]	19°39'	103°45'20"
V. Apaxtepec	90	638	0.141	35.5°	30	175	19°37'30"	103°29'45"
V. Telcampana	160	862	0.186	32.0°	40	312	19°41'15"	103°47'
El Carpintero Norte[1]	100	588	0.170	33.7°	30	250	19°43'30"	103°43'30"
V. Comal Grande	165	900	0.183	29.5°	80	419	19°45'	103°47'45"
V. El Comal Chico	120	912	0.132	33.2°	40	275	19°44'20"	103°47'40"
			Group Qm (Intermediate)					
Sayula[1]	140	1000	0.140	22.8°	-	-	19°50'	103°34'
V. San Isidro	150	1165	0.129	26.6°	b[2]	b[2]	19°37'30"	103°45'
El Carpintero Sur[1]	130	990	0.131	25.6°	-	-	19°42'50"	103°43'50"
			Group Qo (Oldest)					
Usmajac[1]	60	438	0.137	21.5°	-	-	19°52'20"	103°31'55"
V. Tezontal	40	425	0.094	24.6°	?[3]	?[3]	19°36'	103°23'30"
Cuauhtemoc[1]	60	540	0.111	22.8°	-	-	19°37'45"	103°55'
Cerro Los Olotes	80	650	0.123	21.8°	-	-	19°42'30"	103°33'

Explanation: H_{co} = cone height in meters; W_{co} = cone width in meters; Max. Slope = maximum cone slope angle; D_{cr} = depth of crater in meters; W_{cr} = width of crater in meters; and location is in latitude (north) and longitude (west).
[1]Informal name (see also Luhr and Carmichael, 1981).
[2]b = breached.
[3]Crater measurements hindered by quarry (cinder pit).

Table 2

Geomorphologic dating of scoria cones of the Colima volcanic field, Mexico

Name/Relative age (ordered)	H_{co}(m)	W_{co}(m)	H_{co}/W_{co}	Order	Max. Slope	Order	Crater
			Group Qy (Youngest)				
Volcán La Erita	190	1080	0.176	3	34.5°	2	yes-breached
V. Apaxtepec	90	638	0.141	5	35.5°	1	yes
V. Telcampana	160	862	0.186	1	32.0°	5	yes
El Carpintero Norte[1]	100	588	0.170	4	33.7°	3	yes
V. Comal Grande	165	900	0.183	2	29.5°	6	yes
V. El Comal Chico	120	912	0.132	8	33.2°	4	yes
			Group Qm (Intermediate)				
Sayula[1]	140	1000	0.140	6	22.8°	10t	no
V. San Isidro	150	1165	0.129	10	26.6°	7	breached, heavily infilled
El Carpintero Sur[1]	130	990	0.131	9	25.6°	8	no
			Group Qo (Oldest)				
Usmajac[1]	60	438	0.137	7	21.5°	13	no
V. Tezontal	40	425	0.094	13	24.6°	9	no(?)[2]
Cuauhtemoc[1]	60	540	0.111	12	22.8°	10t	no
Cerro Los Olotes	80	650	0.123	11	21.8°	12	no

Explanation: H_{co} = cone height in meters; W_{co} = cone width in meters; Max. Slope = maximum cone slope angle, and t = tie.
[1]Informal name (see also Luhr and Carmichael, 1981)
[2]Crater measurements hindered by quarry (cinder pit).

tive ages are in close agreement with results from Luhr and Carmichael (Table 1, p. 130, 1981). The mean H_{co}/W_{co} values for each of the three cone groups are presented in Table 3.

Table 3

Mean scoria cone height/width values for the Colima volcanic field, Mexico

Cone age group	n	Mean H_{co}/W_{co} with 1 σ
Qy (youngest)	6	0.164 ± 0.021
Qm (intermediate)	3	0.133 ± 0.005
Qo (oldest)	4	0.116 ± 0.016

Explanation:
n=number of cones, and mean H_{co}/W_{co} (cone height/cone width ratio) with one standard deviation (± 1 σ).

GEOMORPHOLOGIC ANALYSIS FOR THE MICHOACAN-GUANAJUATO VOLCANIC FIELD

Hasenaka and Carmichael (1985a, 1985b) compiled the location and geomorphologic parameters for 1040 volcanic vents in the Michoacán-Guanajuato volcanic field of central Mexico. Of these, 901 volcanic centers were classified as either cinder (scoria) cones or lava cones. Their geomorphologic classification utilized gully density normalized to 90° of arc, surface morphology of associated lava flows, H_{co}/W_{co}, maximum slope angle, and average slope angle. The scheme they employed grouped many, but not all, of the volcanic landforms into one of six relative-age units, from youngest to oldest: Hv, Plv4, Plv3, Plv2-3, Plv2, and Plv1. Units younger than 40,000 years B.P. (Hv, Plv4, Plv3) were calibrated by radiocarbon dates from seven scoria cones. They assigned relative ages to a total of 107 scoria cones, but seven of these cones were excluded from the present geomorphologic analyses because they had a height less than 50 m and may not be mature vents (McGetchin *et al.*, 1974). Of the remaining 100 cones, 36 were classified and calibrated by Hasenaka and Carmichael as being younger than 40,000 years B.P. Their survey concentrated mainly on the younger volcanic landforms; older units were not calibrated by radiocarbon dating and their sampling did not include extensively eroded volcanoes.

Mean H_{co}/W_{co} values for cones in each of the six age groups were calculated and demonstrate a systematic decrease from 0.184 for the Holocene cones, Hv, to 0.135 for the oldest Pleistocene unit, Plv1 (Table 4). Mean ages for the three youngest cone groups were determined from Hasenaka and Carmichael (1985a, 1985b) and Hasenaka (pers. comm., 1994) and yielded the following classification: Hv from 0 to 10,000 years B.P. with a mean of 5000 years B.P.; Plv4 from 10,000 to 25,000 years B.P. with a mean of 17,500 years B.P.; and Plv3 from 25,000 to 40,000 years B.P. with a mean of 32,500 years B.P. All remaining units or cone age groups are older than 40,000 years B.P., and estimates of their mean age will be calculated in a later section.

Table 4

Mean scoria cone height/width values for the Michoacán-Guanajuato volcanic field, Mexico

Cone age group	n	Mean H_{co}/W_{co} with 1 σ
Hv (0-10,000 years)[1]	7	0.184 ± 0.039
Plv4 (10,000-25,000 years)	11	0.160 ± 0.027
Plv3 (25,000-40,000 years)	15	0.158 ± 0.038
Plv2-3 (>40,000 years)	6	0.146 ± 0.026
Plv2 (>40,000 years)	55	0.143 ± 0.036
Plv1 (>40,000 years)	6	0.135 ± 0.030

Explanation:
n=number of cones, and mean H_{co}/W_{co} (cone height/cone width ratio) with one standard deviation (± 1 σ).
[1]Relative-age units from Hasenaka and Carmichael (1985a, 1985b) and Hasenaka (pers. comm., 1994).

DIFFUSION-EQUATION MODEL

Several workers have applied a diffusion-equation model to two-dimensional profiles to determine the age of fault scarps and marine, lacustrine, or fluvial terrace scarps (Nash, 1980a, 1980b, 1984; Hanks *et al.*, 1984; Mayer, 1984; Andrews and Hanks, 1985; Pierce and Colman, 1986; and Andrews and Bucknam, 1987). Bursik (1991) used a nonlinear diffusion-equation model to determine the relative ages of glacial moraines in the Sierra Nevada, California.

Fundamental assumptions of a diffusion-equation model include local conservation of mass and downslope transport proceeding at a rate proportional to a power of the slope and slope length. This can be expressed in two dimensions as:

$$M = D\ x^m \left(\frac{\partial z}{\partial x}\right)^n \tag{1}$$

where M is the rate of downslope transport or mass flux, D is a constant of proportionality (where the transport rate coefficient and density have been combined to produce the diffusion coefficient) that is assumed not to vary with position or time, x is a horizontal distance, $\partial z/\partial x$ is the topographic gradient for a two-dimensional profile orthogonal to the hillslope. The exponential parameters m and n are a function of the erosional process and are discussed below. Numerous theoretical and observational studies have presented evidence supporting the validity of Equation 1 (e.g., Gilbert, 1909; Lawson, 1915; Ellison, 1944; Schumm, 1956; Culling, 1960, 1963, 1965; Scheidegger, 1961; De Ploey and Savant, 1968; Hirano, 1968; Mosley, 1973; Nash, 1980a, 1980b; and Andrews and Bucknam, 1987).

Sediment transport processes on slopes are either linearly diffusive if downslope movement is directly proportional to the surface gradient to the first power, or nonlinearly diffusive if downslope movement is more slope-length dependent and not proportional simply to the local slope to the first power. Linear diffusive agents of erosion include rainsplash (raindrop impact), soil creep, freeze-thaw movements, and bioturbation (e.g., Culling, 1960, 1963, 1965; Kirkby, 1971; Carson and Kirkby, 1972; Young, 1972; Pierce and Colman, 1986; Colman, 1987). Chase (1992) also includes talus formation and slumping. For these processes the downslope movement is directly proportional to surface gradient to the first power and m=0 and n=1.

Dynamic simulation models that treat the transport of material must consider the conservation of mass. Such continuity relations have been applied to hillslopes (Kirkby, 1971) and state that an increase or decrease in the downslope flow rate of material over a straight line segment of the hillslope will cause the elevation of the segment to decrease or increase with time. In the simpler two-dimensional form this relationship can be expressed as:

$$\frac{\partial z}{\partial t} = \frac{\partial M}{\partial x} \tag{2}$$

where t is time.

Finally, combining Equations (1) and (2) will yield the linear diffusion equation, which can now be written to describe a three-dimensional landform:

$$\frac{\partial z}{\partial t} = D_x\ \frac{\partial^2 z}{\partial x^2} + D_y\ \frac{\partial^2 z}{\partial y^2} \tag{3}$$

where x is the first horizontal coordinate direction, y is the second horizontal coordinate direction, z is the vertical coordinate direction or elevation (the "diffusing substance"), D_x is the diffusion coefficient in the x-direction, and D_y is the diffusion coefficient in the y-direction. This equation assumes that the rate of diffusive flow varies according to direction (i.e., it is anisotropic) and can easily be simplified for isotropic diffusion. Equation (3) has the same form as the diffusion equation used in analyses of chemical dispersion and conductive heat flow. In a geomorphologic study, this equation signifies that convex-upward topography erodes and concave-upward topography aggrades.

A second category of transport processes to be modeled includes slope wash (soil wash or sheet wash) both with and without gullying. These are nonlinear diffusive processes and are more complex to describe mathematically, yielding m=0.3-1.0 and n=1.3-2 for slope wash without gullying; and m=1-2 and n=1.3-2 for slope wash with gullying (e.g., Kirkby, 1971; Carson and Kirkby, 1972; Young, 1972; Pierce and Colman, 1986; Colman, 1987).

To derive the nonlinear diffusion equation, a generalization of Equation (1) can be stated in two dimensions:

$$M = F\left(x, \frac{\partial z}{\partial x}\right) \quad (4)$$

where the function F is arbitrary, making downslope transport or mass flux a nonlinear function of slope. The diffusion coefficient is incorporated in function F. Therefore, the nonlinear diffusion equation for a three-dimensional landform can be written as:

$$\frac{\partial z}{\partial t} = \frac{\partial}{\partial x}\left[F\left(x, \frac{\partial z}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[F\left(y, \frac{\partial z}{\partial y}\right)\right] \quad (5)$$

For computer applications and a numerical solution, the diffusion equation was translated to a three-dimensional, explicit finite-difference scheme utilizing a grid of unit cells each with a topographic elevation (z-direction) and extending in the x- and y-directions. Finite-difference analysis simulates the movement of material into (aggradation) or out of (erosion) the cell being evaluated in a manner proportional to the elevation difference between neighboring cells (i.e., slope) and the erodibility (i.e., diffusion coefficient) of the original cell. The net result is to smooth or "diffuse" topography.

MODEL ASSUMPTIONS

For this study, computer simulation by a diffusion-equation model treats the internal structure of a cone — loose pyroclastic layers occasionally interbedded with agglutinated layers or lava flows— as a homogeneous unit that does not produce a significant variation in erosion rate when observed over a period of tens to hundreds of thousands of years. This model does not treat certain secondary or external modifications: breaching, lateral fluvial dissection of cone flanks, and partial burial by lava flows, alluvium, aeolian material, or ash-fall deposits.

To briefly address these omissions, breached cones can be expected to erode faster than unbreached cones because a portion of the cone has already been removed (i.e., potential mass to be eroded has already been subtracted). The erosion of a breached cone can easily be simulated by changing the initial morphology of the model cone.

Computer simulation of fluvial dissection has been treated by other authors (e.g., Ahnert, 1976; Willgoose *et al.*, 1991), but under most circumstances the lateral fluvial dissection of cone flanks does not occur until the very latest stages of cone degradation. The simpler dissection of cone flanks by intermittent gully processes is encompassed by the slope wash with gullying model.

Partial burial of the cone can occur by a variety of processes. Wood (p. 149, 1980b) comments that scoria cone modification in the San Francisco volcanic field of Arizona, in general, is not appreciably affected by later lava flows. Accretionary mantles with abundant aeolian material, ranging from nearly zero to 3 m in thickness, have been measured on basaltic lava flows in the Cima volcanic field of the Mojave Desert, California (Wells *et al.*, 1985). Flows in this field are less than 1.1 m.y. in age. While the roughness of scoria cone slopes may provide a trap for aeolian fines, the overall contribution of aeolian and alluvial material to modification is judged to be minimal for most cones. Abrasion by sand and dust is not considered to be an effective agent of scoria cone erosion (see also Laity, 1994).

The extent to which burial by ash or lapilli affects the rate of erosion remains problematical. Segerstrom (1950) observed that erosion was at least briefly accelerated on scoria cones that were draped by ash from the 1943-1952 eruption of Volcán Paricutín in Mexico. He listed several factors to account for the accelerated erosion: (1) Heavier sediment load and larger grains have greater cutting power; (2) Protective cover provided by vegetation has been destroyed; and (3) Rill and gully erosion of the Paricutín ash may continue to erode into the older surface after the ash is stripped away. In one example, Segerstrom supported his observations by measuring increased gully incision on the flanks of Cerro de Cutzato, a scoria cone located approximately 6 km east of Paricutín and upon which was deposited about 0.45 m of ash. In the San Francisco volcanic field of Arizona, the Sunset Crater eruption of approximately 900 years B.P. (Smiley, 1958) deposited a widespread pyroclastic sheet which is identifiable by field observations and denoted in the geologic maps of the area by Moore and Wolfe (1976, 1987). However, gully formation is uncommon in the San Francisco field, suggesting that there has not been an acceleration of erosion. In discussing this same topic, Wood (p. 153, 1980b) states that "enhanced erosion due to deposition of Sunset ash does not appear to have been important." As a first order attempt to model the effects of partial cone burial, the simulation algorithm could be modified by incorporating a digitized isopach to accommodate the influence of burial by a variety of materials. Any cones with morphologic anomalies or a suspect degradational evolution can be excluded from morphometric analysis.

SIMULATION RESULTS

Computer simulation provides an efficient methodology to model three-dimensional landform modification under a variety of assumptions, conditions, and cases. The simulation of cone erosion employed a unit cell size of 4 X 4 m and operated upon a 400 X 400 (1600 X 1600 m) grid or matrix of elevation values from a digitized scoria cone with a fully-developed, youthful, and idealized morphology. The initial morphology of the model or test cone used in the simulations approximated a right circular cone truncated at the top by an inverted cone to simulate the crater. Geometry of the model cone was determined by measuring from topographic maps the morphometry of 70 fully-developed, youthful (Holocene to latest Pleistocene), and unbreached cones from several volcanic fields in a variety of locations (see Appendix). The objective of this selection was to obtain the pristine morphology of the typical, unbreached scoria cone. Geometric relations and the arithmetic means were then used to construct the model cone that was used in the simulations (Table 5). The mean and first standard deviation for the maximum cone slope angle, calculated from the 70 surveyed cones, is 32.11 ±2.88°. This differs from the value of 30.2° calculated by geometric relations for the model cone. However, this discrepancy is easily explained since the model cone is an idealized representation of a symmetrical and nonelongated landform with a centered, symmetrical, and nonelongated crater. Actual cones always show at least a small degree of nonsymmetry and elongation which will inevitably leave different portions of the cone having slightly different slope angles.

Table 5

Parameters and initial values for the finite-difference grid and modeled scoria cone

Unit cell size = 4 X 4 m
Grid or matrix size = 400 X 400 cells (1600 X 1600 m)
Cone height, H_{co} = 170 m
Cone width (basal diameter), W_{co} = 876 m
Cone height/width ratio, H_{co}/W_{co} = 0.194
Crater width (or crater diameter), W_{cr} = 292 m
Crater depth, D_{cr} = 67 m
Crater width/cone width ratio, W_{cr}/W_{co} = 0.333
Crater depth/crater width, D_{cr}/W_{cr} = 0.229
Initial maximum and average cone slope = 30.2°
Volume = 0.05 km³

Computer simulation was conducted with a model diffusion coefficient of D=1.0 and stopped after 300,000 time steps (Figure 3). A time step or time increment is one pass through the computer algorithm evaluating the grid of digital topography. Simulations employing the linear model used values of m=0 and n=1 in Equation (1), while the nonlinear (slope wash with gullying) model operated with values of m=2 and n=2. Progressive degradation was observed from the initial conical form (time step 0), through rounding of the crater rim and crater infilling, through a stage with a mound or shield-like hill, and finally into a low-relief landform with a low H_{co}/W_{co} ratio. These morphologic changes are demonstrated in a series of profiles or cross-sections taken through the center of the model cone during simulated erosion (Figure 4). A fundamental difference in hillslope processes is illustrated by examining the cone flanks in these profiles: relatively slow mass movement by simulated soil creep and rainsplash processes has yielded a convex hillslope typical of linear diffusion, whereas relatively more rapid mass movement from simulated overland flow processes such as slope wash has yielded a concave hillslope typical of nonlinear transport laws.

The progressive pattern of erosion displayed by the series of profiles in Figure 4 offers the possibility of loosely fitting actual cone profiles with normalized profiles from the diffusion-equation model. A "best-fit" approximation of actual (or field) data to model data could be used to correlate or calibrate the two different sets of profiles.

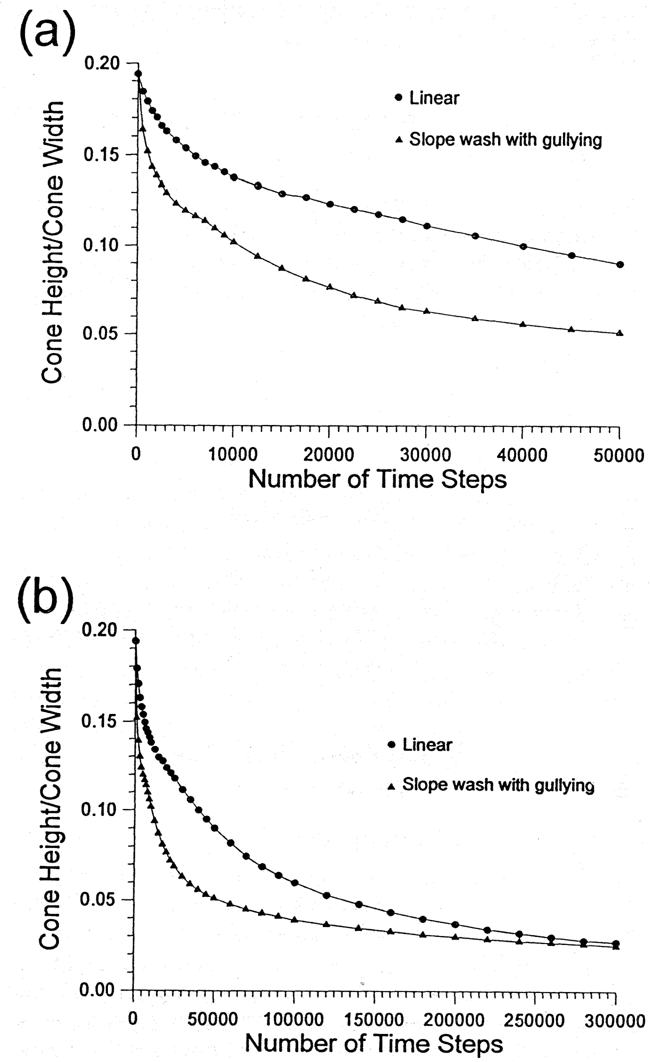

Fig. 3. Plot depicting the decrease in cone height/width (H_{co}/W_{co}) with increasing age (measured in time steps) for computer-simulated erosion of the modeled scoria cone by two different transport laws. Time steps 0 to 50,000 are displayed in (a), while time steps 0 to 300,000 are shown in (b).

Both computer modeling and field observations suggest that crater infilling is a major modification during cone degradation. At first material is transported down both the external cone slope and internal crater slope. Once the crater is completely infilled (see Figure 4), material can be transported down only the external or outer slope. Therefore, the final stage of crater infilling is marked by a shift in the general pattern of downslope transport and is a critical point in the course of morphologic modification of the cone. In a simple classification, youthful cones possess a crater while older cones have lost the crater to erosion.

CALIBRATION OF RESULTS

The rate of scoria cone degradation in the Colima and Michoacán-Guanajuato volcanic fields can be compared

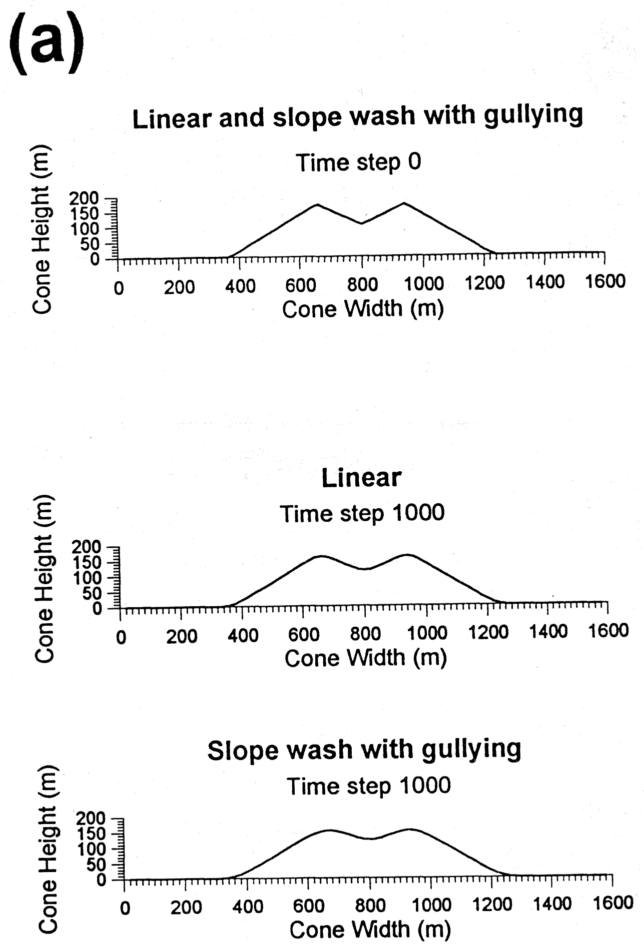

Fig. 4. (a, b, c, d). Profiles taken at appropriate time intervals during computer-simulated erosion record the changing morphology of the model scoria cone. These profiles are taken through the center of the model cone and are displayed without vertical exaggeration. Progressive degradation is observed from the initial conical form (time step 0), through rounding of the crater rim and crater infilling, through a stage with a mound or shield-like hill, and finally into a nearly flat landform (time step 300,000). The crater is completely infilled by time step 6,500 for the nonlinear model and by time step 15,500 for the linear model. A time step (or time increment) is one pass through the computer algorithm evaluating the grid of unit cells.

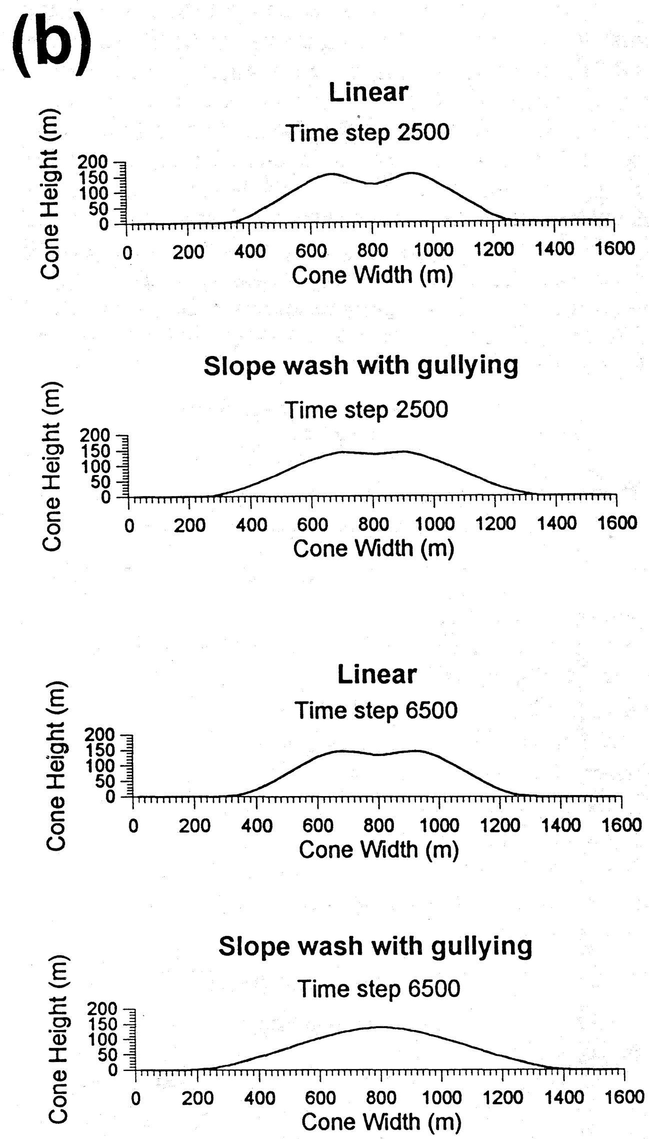

Fig. 4. (Cont.)

with the rate of simulated degradation. Scoria cones at Colima have not been dated by radiometric or other chronometric techniques. However, the radiometrically-dated cones of the Michoacán-Guanajuato field permit the establishment of a calibrated chronometric scheme that can be applied to the Colima cones based upon the assumption that the volcanic fields have a similar climate.

The Colima volcanic field occupies portions of the states of Colima and Jalisco, while the Michoacán-Guanajuato volcanic field includes the northern half of the state of Michoacán and the southern half of the state of Guanajuato. The basal elevations for the Colima cones are generally between 1400 and 1800 m. Basal elevations are more variable for the cones of the Michoacán-Guanajuato field, ranging from approximately 1200 m in the relatively warm and dry climate of the lowlands in the southern portion of the field to about 2600 m in the relatively cool and wet climate of the Southern Mexican Plateau. Climatic tables for representative cities in the area show that Morelia in northern Michoacán has an elevation of 1923 m, an annual daily mean temperature of 17.7°C, and an annual mean precipitation of 755 mm; while the city of Guanajuato in central Guanajuato State has an elevation of 2037 m, an annual daily mean temperature of 17.9°C, and an annual mean precipitation of 668 mm (Mosiño-Alemán and García, 1974). Climatic tables were not available for any city within the region of the Colima volcanic field, but mean annual temperature and precipitation maps published by these same authors reveal that there are relatively minor climatic variations between the two volcanic fields, mostly related to elevation. Therefore, for determining erosion rates for this study, the climatic setting for both volcanic fields is assumed to be similar.

The procedure to calibrate the rate of degradation of actual cones with model results commences with plotting the

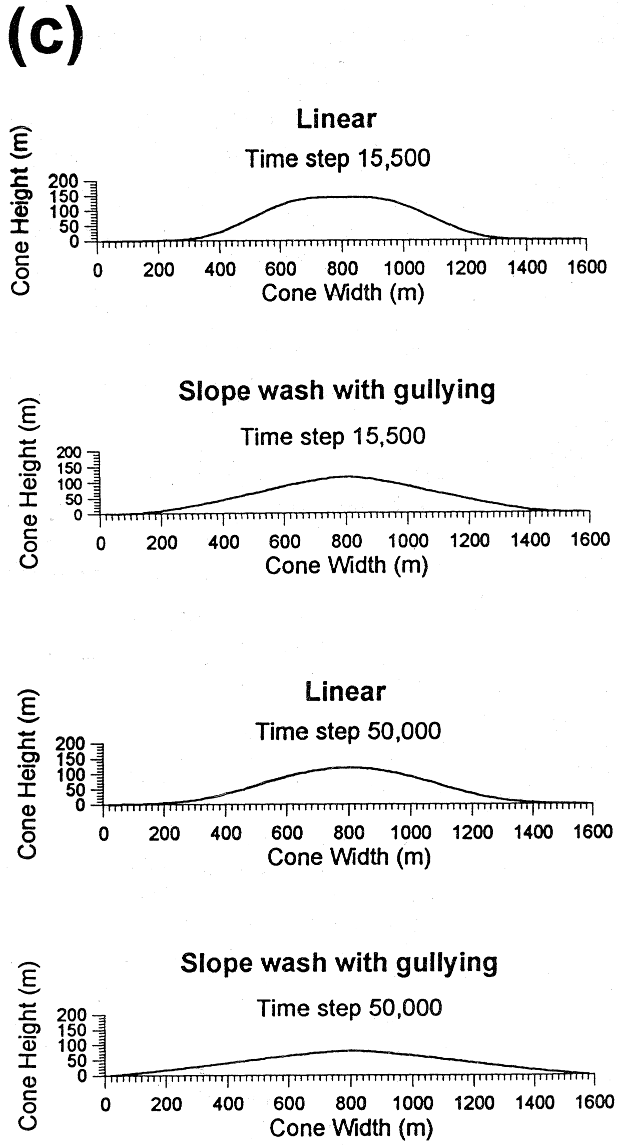

Fig. 4. (Cont.).

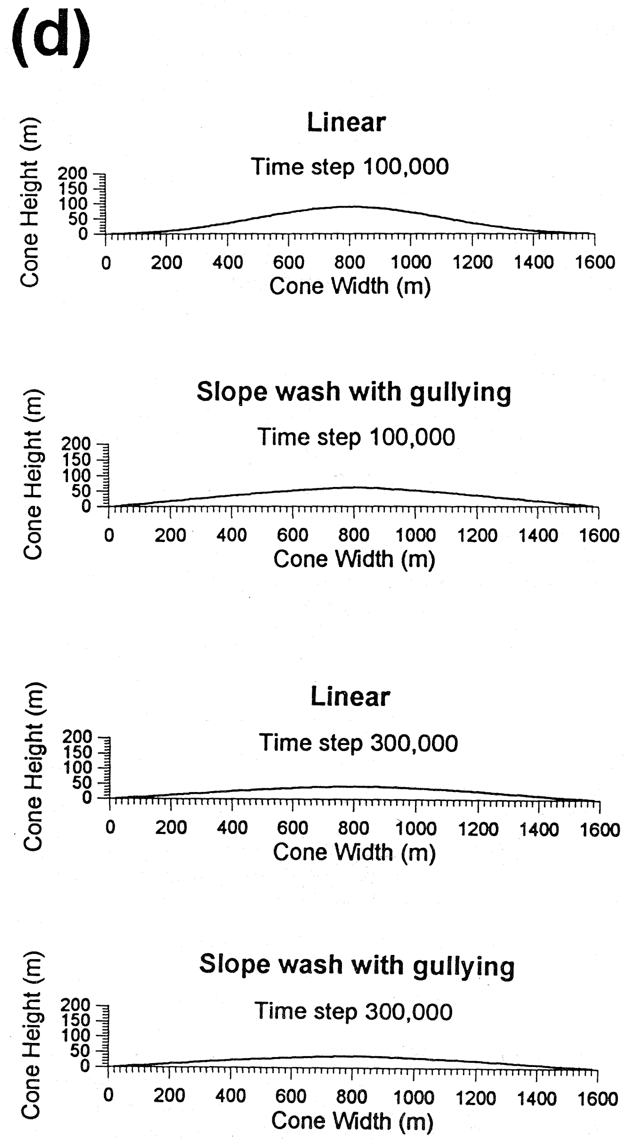

Fig. 4. (Cont.).

mean H_{co}/W_{co} value for each cone age group versus the respective mean value of the calibrated relative age. Then either statistical methods or best-fit approximations could be used to match or superimpose the model degradation curve derived from computer simulation with the degradation curve derived from actual cone morphometry. Because of the fundamentally different transport laws, separate erosion rates are determined for the linear and nonlinear diffusion models. Once the actual and model results have been calibrated, the degradation curve from the computer model can be used to estimate the age of cone age groups that have not yet been dated. This method essentially provides calibrated relative ages.

As an example of this procedure, mean H_{co}/W_{co} values (from Table 4) for the youngest Michoacán-Guanajuato cone age groups were plotted versus their previously determined mean ages. These are the cone groups classified by Hasenaka and Carmichael (1985a, 1985b) as being younger than 40,000 years B.P. (i.e., Hv, Plv4, and Plv3). Superimposed upon these data are the calibrated curves for the linear diffusion-equation model (Figure 5a) and the nonlinear diffusion-equation or slope wash with gullying model (Figure 5b). The H_{co}/W_{co} values are employed to correlate the two separate time scales. The poor alignment of group Plv4 in Figure 5a may be the manifestation of slope wash processes that are not defined to be simulated by the linear model. Alternatively, the anomalous positioning of group Plv4 could simply be a statistical consequence. However, since the effect is present in results from both the linear and nonlinear models (Figure 5), an alternative explanation may be a period of increased erosion, presumably the product of increased rainfall. This hypothesis will be discussed further in a later section.

Mean ages of the Plv2-3, Plv2, and Plv1 cone groups were determined by plotting the intersection of their mean H_{co}/W_{co} values with the results from the calibrated simula–

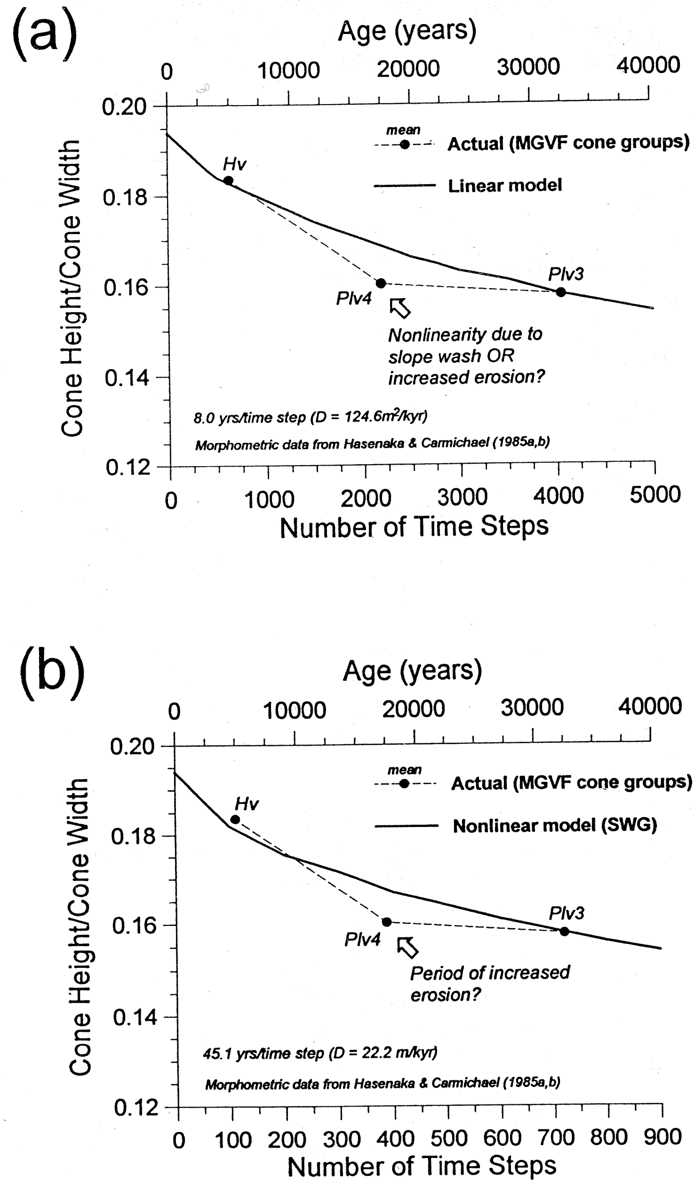

Fig. 5. Figures illustrating the calibration of actual cone degradation with model cone degradation. Mean H_{co}/W_{co} values for three cone age groups (Hv, Plv4, Plv3) from the Michoacán-Guanajuato volcanic field (MGVF) are plotted versus the mean of their respective calibrated relative ages (confidence limits omitted for clarity). Superimposed upon these data are the calibrated curves from the linear diffusion-equation model (a) and the slope wash with gullying (SWG) or nonlinear model (b).

tion models (Figure 6). Ages for these groups have not previously been determined. Based upon this method, the estimated mean age of group Plv2-3 varies between 56,000 years B.P. if derived from the linear model and 61,000 years B.P. if derived from the nonlinear model. Similarly, the estimated mean age of group Plv2 varies between 65,000 years B.P. (linear model) and 68,000 years B.P. (nonlinear model), and the estimated mean age of group Plv1 varies between 94,500 years B.P. if determined from the linear model and 111,500 years B.P. if determined from the nonlinear model (Table 6).

Table 6

Estimated mean ages for scoria cone groups in the Michoacán-Guanajuato volcanic field, Mexico

Cone age group	Mean age (years) by linear model	Mean age (years) by nonlinear model
Hv	(5,000)[1]	(5,000)[1]
Plv4	(17,500)[1]	(17,500)[1]
Plv3	(32,500)[1]	(32,500)[1]
Plv2-3	56,000	61,000
Plv2	65,000	68,000
Plv1	94,500	111,500

Explanation:
[1]Mean age derived from Hasenaka and Carmichael (1985a, 1985b) and Hasenaka (pers. comm., 1994).

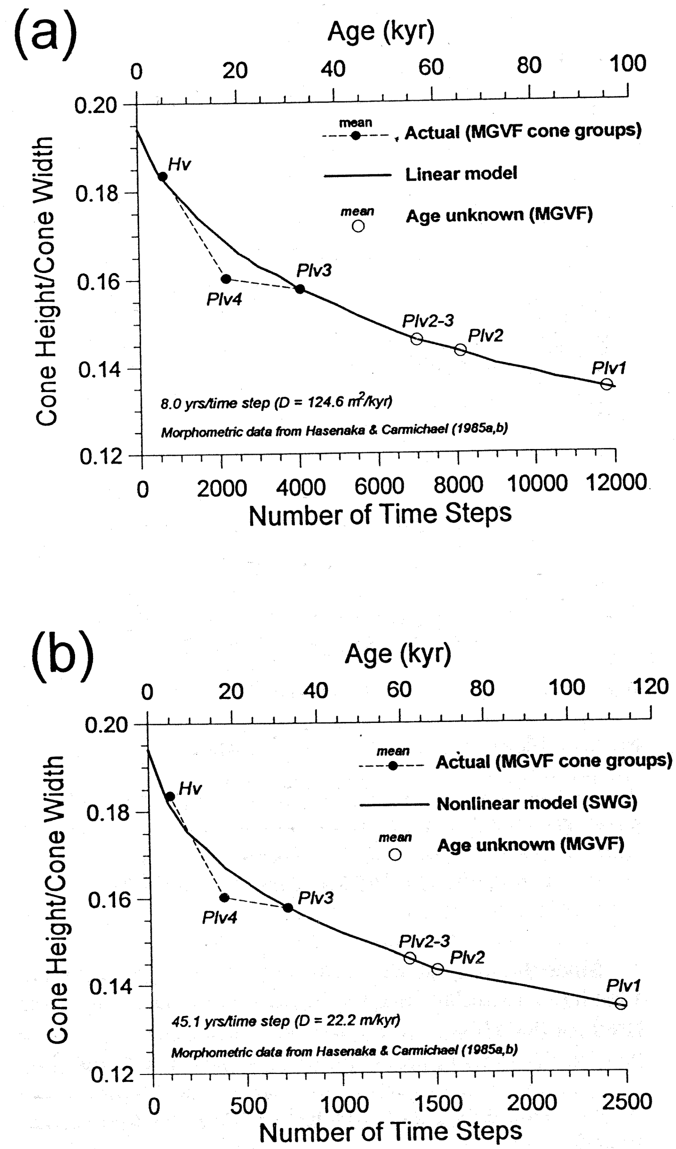

Fig. 6. Plots illustrating the estimation of the mean age for cone groups Plv2-3, Plv2, and Plv1 from the Michoacán-Guanajuato volcanic field (MGVF). Mean H_{co}/W_{co} values (confidence limits omitted for clarity) for all six cone age groups are plotted versus the calibrated results from the linear diffusion-equation model (a) and the slope wash with gullying (SWG) or nonlinear model (b).

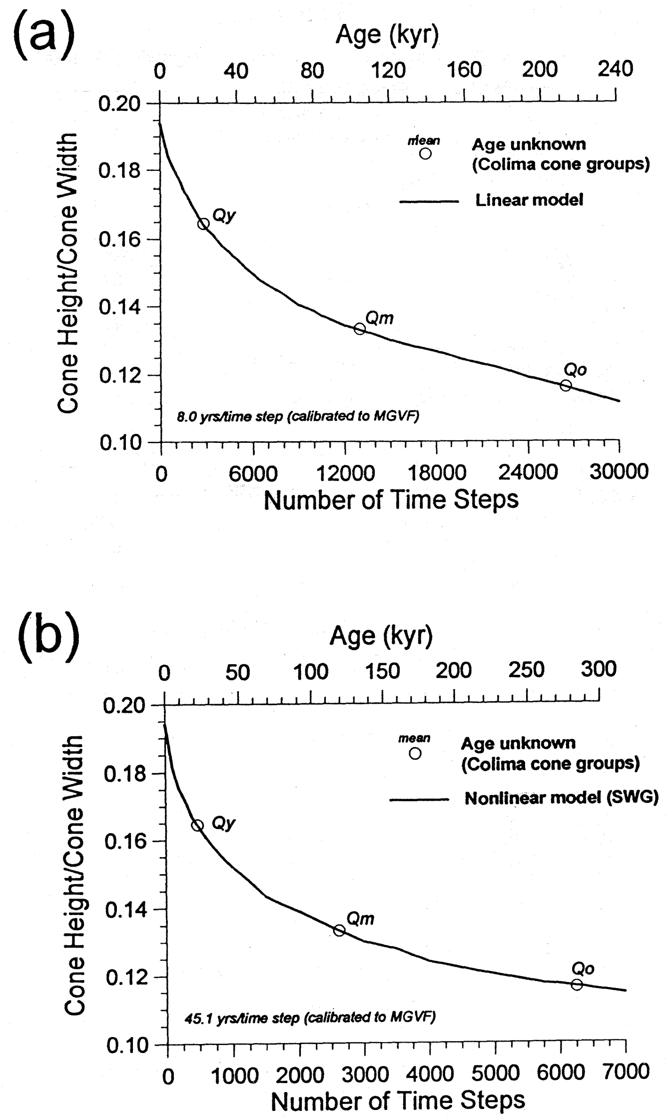

Fig. 7. Figures illustrating the estimation of the mean age for cone groups Qy, Qm, and Qo from the Colima volcanic field, Mexico. Mean H_{co}/W_{co} values (confidence limits omitted for clarity) for the cone age groups are calibrated with the rate of degradation calculated for the Michoacán-Guanajuato volcanic field. The Colima cone groups are plotted versus results from both the linear diffusion-equation model (a) and the slope wash with gullying (SWG) or nonlinear model (b).

Since the assumption has been made that the two study sites have a similar climate, the rate of degradation calculated for the Michoacán-Guanajuato field can be applied to the Colima field in order to estimate the ages of the three cone groups. Employing the same technique, mean H_{co}/W_{co} values for the Colima cones (Table 3) were plotted with the calibrated simulation results from the Michoacán-Guanajuato field. The results yield an estimated mean age for the youngest Colima cone group (Qy) that varies between 22,000 years B.P. if derived from the linear model and 21,500 years B.P. if derived from the nonlinear model. Similarly, the mean age of the intermediate cone group (Qm) is estimated to vary between 104,000 years B.P. (linear model) and 118,000 years B.P. (nonlinear model), while the mean age of the oldest cone group (Qo) is estimated to vary between 212,000 years B.P. (linear model) and 280,000 years B.P. if derived from the nonlinear model (Figure 7 and Table 7). The oldest Colima cones would correspond in age to an intermediate period in the evolution of Nevado de Colima (Robin *et al.*, 1987). At least one cone (Volcán Apaxtepec) may have a Holocene age as indicated by its youthful surface character and unmodified state of preservation of the associated lava flow (see also Luhr and Carmichael, 1981). Possible future absolute age data for the Colima cones would prove or disprove these age assignments.

Table 7

Estimated mean ages for scoria cone groups in the Colima volcanic field, Mexico

Cone age group	Mean age (years) by linear model	Mean age (years) by nonlinear model
Qy (youngest)	22,000	21,500
Qm (intermediate)	104,000	118,000
Qo (oldest)	212,000	280,000

Explanation:
Cone degradation calibrated to equal the erosion rate of cones in the Michoacán-Guanajuato volcanic field, Mexico.

An inverse-solution approach was used to determine the diffusion coefficient for cone erosion in each volcanic field and solved for D_f in the relationship:

$$D_f \ t_f = D_m \, t_m \qquad (6)$$

where D_f is the diffusion coefficient for a cone age group or a similar collection of cones in the volcanic field, t_f is the mean age for the cone age group or cones in the volcanic field, D_m is the diffusion coefficient used in computer simulations, and t_m is the model age as measured in computer time steps or increments. The values for t_m were found by matching the H_{co}/W_{co} values from computer simulations with mean H_{co}/W_{co} values for each cone age group or collection of cones. Once this relationship has been solved, the length of a computer time step can easily be calculated as years per time step. For the linear model the diffusion term has dimensions [length^2/time] and can be expressed in units of square meters per thousand years [m^2/kyr]. For the nonlinear slope wash with gullying model the diffusion term has dimensions [length/time] and has units of meters per thousand years [m/kyr].

The diffusion term derived for the Michoacán-Guanajuato volcanic field can be compared with preliminary and similarly obtained results from the volcanic fields in the southwestern United States (Table 8). This comparison reveals the importance of climate. The arid climate of the

Cima volcanic field in the Mojave Desert of California yields the lowest diffusion coefficient values (lowest erosion rate), while the Michoacán-Guanajuato volcanic field, having more abundant rainfall, has the highest diffusion coefficient values (highest erosion rate).

Table 8

Comparison of diffusion coefficient (D) values for several volcanic fields

Volcanic field/Location	Linear model D (m^2/kyr)	Nonlinear model D (m/kyr)	Climate
Michoacán-Guanajuato, central Mexico	124.6	22.2	Temperate-tropical
Springerville, Arizona (U.S.A.)	24.4	6.3	Semi-arid
San Francisco, Arizona (U.S.A.)	24.1	5.3	Semi-arid
Cima, California (U.S.A.)	8.2	1.5	Arid

Explanation:
D = diffusion coefficient, a measure of the erosion rate.
Data for Arizona and California volcanic fields from Hooper (1994).

CLIMATE APPLICATIONS

A further review of Figure 5 suggests the possibility of correlating an increase in the erosion rate for cone group Plv4 from the Michoacán-Guanajuato volcanic field with a possible increase in effective rainfall during the last glacial maximum. There is uncertainty in reconstructing past climates. Debate continues as to whether the last full-glacial (Wisconsin) climate was mild and wet or cold and dry in the southwestern United States (e.g., Brakenridge, 1978; Van Devender and Spaulding, 1979; Wells, 1979; Galloway, 1983; Spaulding and Graumlich, 1986). Perhaps even more uncertain is whether the assumptions and models establishing the climate regime of the southwestern United States can be extrapolated into the more southern latitude of the volcanic province of central Mexico. Paleoclimatic data for central Mexico are scarce, but Bradbury (1971) analyzed lacustrine sediments from a core drilled in Mexico City and established a stratigraphic sequence of diatom assemblages for interpreting the climate and limnologic history of ancient Lake Texcoco. He reports that there is evidence to suggest that the Holocene climate is possibly drier than the climate during the last glacial maximum. Heine (1977) reconstructed climatic snow lines for several high volcanic peaks in central Mexico and identified a glacial advance about 12,100 years B.P., apparently as a result of increased precipitation. This evidence is not conclusive regarding a "pluvial" or rainier climate in central Mexico during the last full-glacial period, but it does raise the possibility that increased effective precipitation resulted in an increased scoria cone erosion rate during the latest Pleistocene (Figure 8). Furthermore, this suggests that the combination of detailed chronometric data and a sufficient number of scoria cones covering a desired time period could be used to identify erosion cycles or climatic fluctuations.

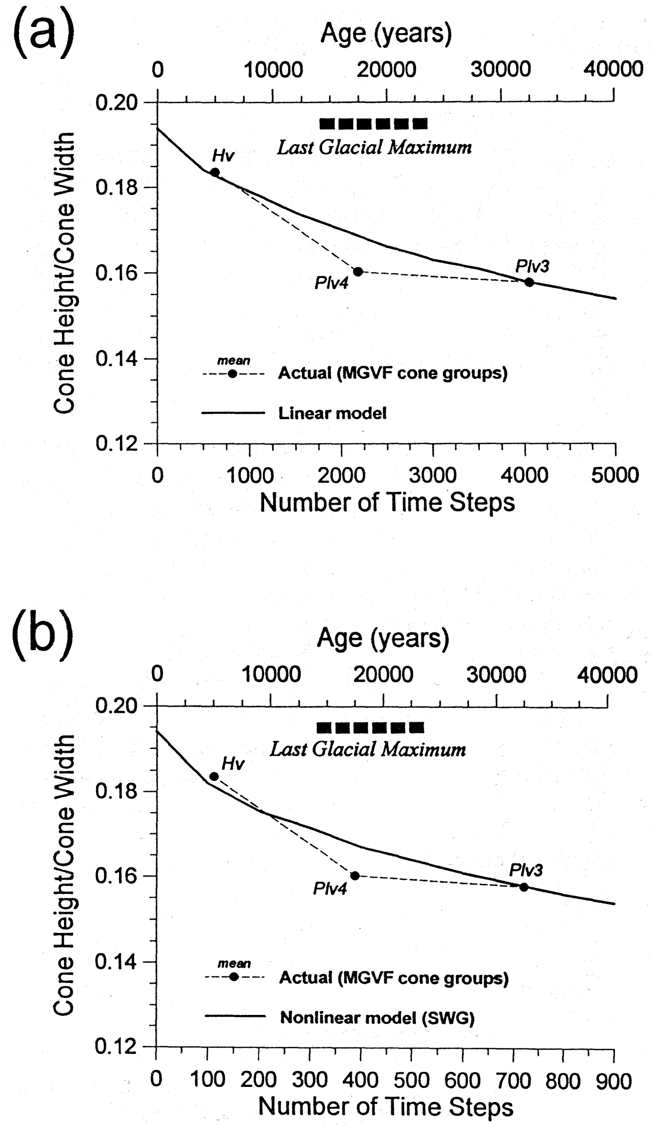

Fig. 8. Plots depicting the approximate age of the last glacial maximum coinciding with a period of increased erosion in the Michoacán-Guanajuato volcanic field (MGVF). Cone age group data is calibrated with curves from the linear diffusion-equation model (a) and the slope wash with gullying (SWG) or nonlinear model (b).

APPLICATION OF COMPUTER-SIMULATED EROSION TO VOLCAN TELCAMPANA

The linear diffusion-equation model was applied to Volcán Telcampana to estimate its future degradational evolution. One of the youngest scoria cones in the Colima volcanic field, Volcán Telcampana has a height of 160 m and is slightly breached on both the south and northwest flanks. Cone width was determined to be 862 m with crater width measuring 312 m. Crater depth was calculated to be 40 m, but erosion has already contributed to its partial infilling. The surrounding terrain slopes gently downhill to the northwest (Figure 9).

A digital topographic data set or digital terrain model (DTM) of Volcán Telcampana and the surrounding area was created by digitizing a 1600 X 1600 m subset of the 1:50,000-scale topographic map. An elevation was assigned to each 4 X 4 m cell either directly by the digitizing procedure or by the interpolation routine, a modified version of an inverse-squared distance weighting technique by Clarke (1990). This grid of topographic data was then read as input for the linear diffusion-equation model and subjected to simulated erosion using a diffusion coefficient of D = 1.0.

The extent of degradation was periodically sampled, as illustrated in Figure 10. After 9,000 time steps, cone height displayed a decrease from 160 m to 144 m or a decrease in elevation from 1460 m a.s.l. to 1444 m a.s.l. Erosion has left the crater almost completely infilled. If one assumes this cone had approximately the same initial geomorphologic parameters as the model cone used in the computer simulations and that it will experience the same general erosion rate as the cones in the Michoacán-Guanajuato volcanic field, then after 9,000 time steps Volcán Telcampana has undergone the equivalent of 72,000 years of simulated erosion by linear diffusive processes.

By time step 25,000 all traces of the crater have been removed and cone height has decreased to 133 m (1433 m a.s.l.). At this stage of degradation the cone has a smooth, rounded summit and a maximum cone slope angle of 21°, a decrease from the initial maximum slope angle of 32°. The H_{co}/W_{co} value has similarly decreased to 0.140 from an initial value of 0.186. This is how the cone may look 200,000 years into the future. The combination of this simulation and an analysis of cone degradational trends suggest that 100,000 to 200,000 years are required to completely infill the crater of an average scoria cone in the Colima and Michoacán-Guanajuato volcanic fields. As anticipated, this is a more rapid erosion rate than that found at the more arid San Francisco, Springerville, or Cima volcanic fields in the southwestern United States (Table 8). Scoria cones in these fields generally lose their craters to infilling in approximately 500,000 to 750,000 years (Hooper, 1994).

Further erosion reduces the cone to a low-relief, shield-like hill, as displayed in time step 75,000. Cone height and maximum cone slope angle have diminished to 105 m (1405 m a.s.l.) and 11°, respectively. In this advanced stage of degradation, H_{co}/W_{co} has been reduced to approximately 0.085 and the cone has experienced 600,000 years of simulated erosion.

IMPLICATIONS AND CONCLUSION

Changes in scoria cone morphology can be correlated with the length of time a cone has been exposed to erosive

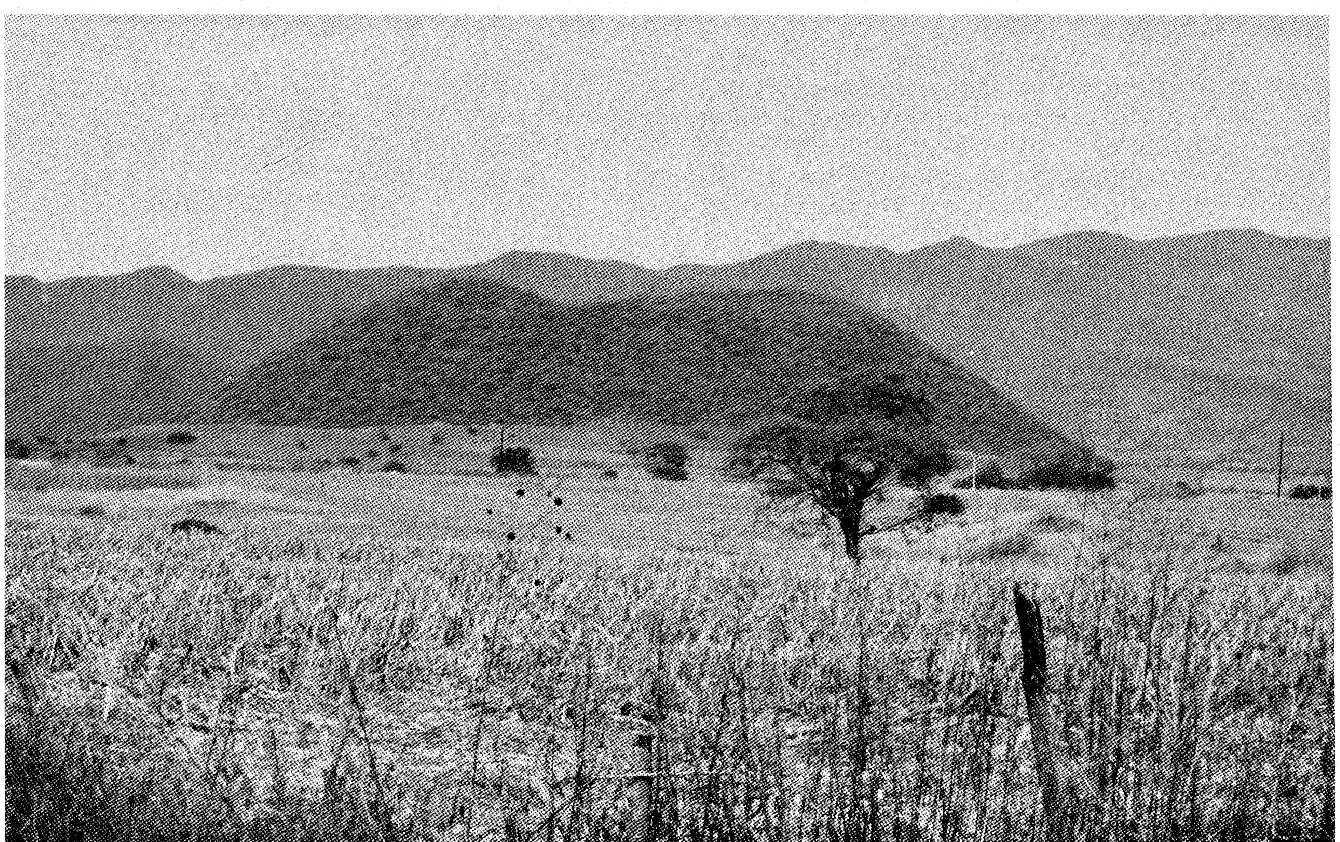

Fig. 9. View of Volcán Telcampana (Colima volcanic field, Mexico) looking toward the northwest.

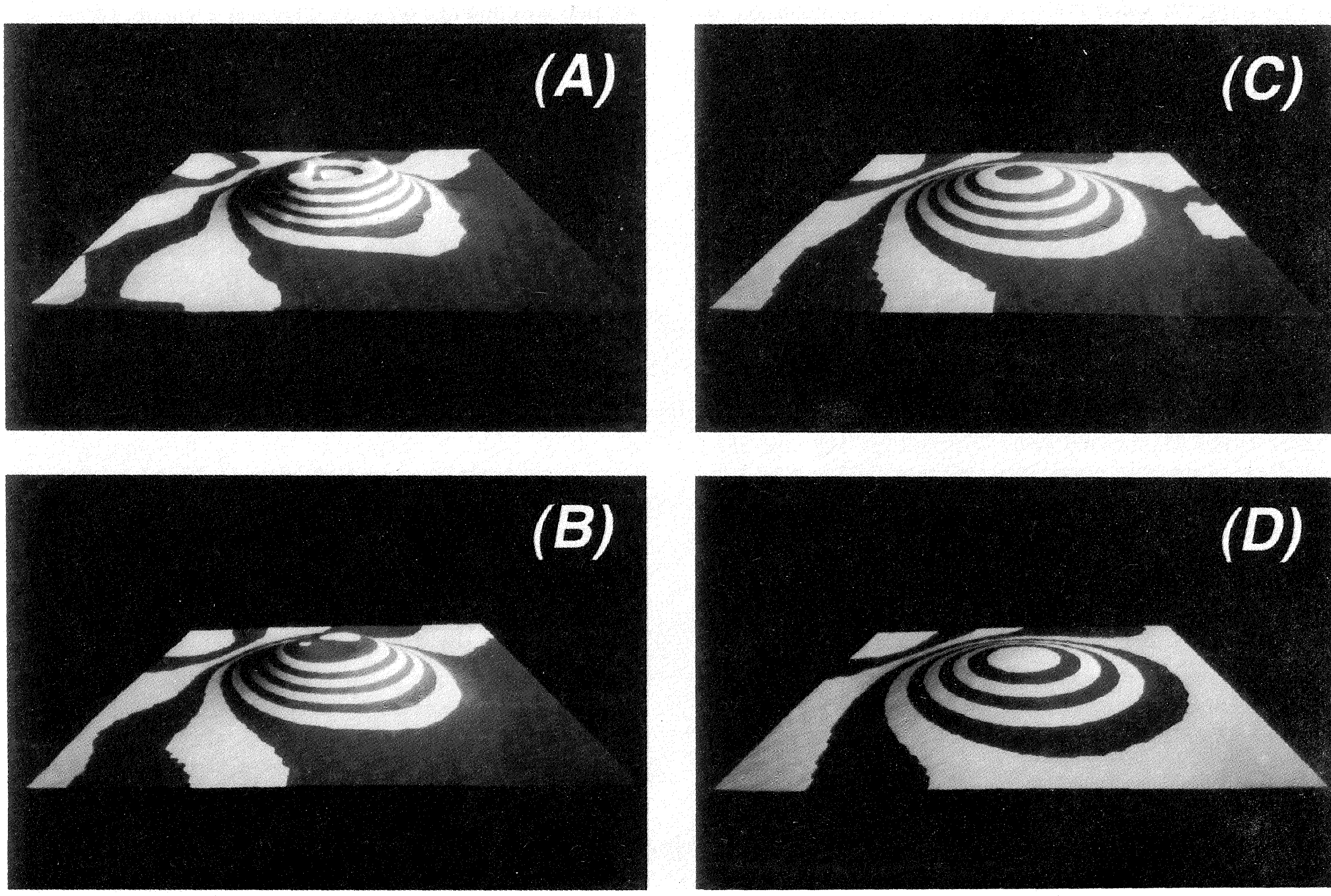

Fig. 10. A series of photographs of Volcán Telcampana display the results of erosion by a linear diffusion-equation method. Three-dimensional views exhibit different stages of degradation, beginning with the initial conditions (time step 0) prior to the commencement of simulated erosion (a). After 9,000 time steps crater infilling is nearly complete (b). By time step 25,000 all traces of the crater have been removed (c). Degraded cone of Volcán Telcampana after 75,000 time steps (d). North is to the top in each photograph and each color band represents approximately 13 m in thickness.

conditions since age is the significant factor distinguishing the progressive geomorphologic transformations exhibited by a group of these landforms. Assuming an initial conical form, modifications of scoria cone morphology commence with the rounding of the crater rim, decrease in cone height, crater infilling, and development of debris aprons to enlarge the basal diameter or width of the cone. Progressive modifications include a decrease in maximum and average cone slope angle, complete crater infilling to leave a scoria mound or dome, and a continuing increase in cone width at the expense of cone height as eroding material continues downslope transport. Further erosion reduces the cone to a shield-like hill with low maximum and average slope angles and a low H_{co}/W_{co} ratio. Variations in internal structure, particle size, welded or agglutinated layers, and secondary or external modifications may produce slight deviations in this general degradation pattern. Cone age estimates could be influenced by the type of simulation model employed and the possibility of immature vents. The climatic setting will determine which erosional processes dominate. Since the diffusion coefficient is assumed to be constant, any deviation in erosion rate may be linked to climate change. The combination of detailed chronometric data and a sufficient number of scoria cones covering a desired time period could be used to identify erosion cycles or climatic fluctuations.

The rate of scoria cone degradation in the Colima and Michoacán-Guanajuato volcanic fields was calibrated with the rate of computer-simulated degradation. Hasenaka and Carmichael (1985a, 1985b) classified 36 scoria cones in the Michoacán-Guanajuato volcanic field into three age groups (Hv, Plv4, and Plv3) younger than 40,000 years B.P. Calibrated simulation results were then employed to determine that the mean age of group Plv2-3 varies between 56,000 years B.P. if derived from the linear diffusion-equation model and 61,000 years B.P. if derived from the nonlinear diffusion-equation model. Similarly, the estimated mean age of group Plv2 varies between 65,000 years B.P. (linear model) and 68,000 years B.P. (nonlinear model), and the estimated mean age of group Plv1 varies between 94,500 years B.P. (linear model) and 111,500 years B.P. (nonlinear model). Since the assumption has been made that the two volcanic fields have a similar climate, the rate of degradation calculated for the Michoacán-Guanajuato field can be applied to the Colima field in order to estimate the ages of its three relative-age cone groups. Employing the same method, the estimated mean age of the youngest Colima cone group (Qy) varies between 22,000 years B.P. if derived from the linear model and 21,500 years B.P. if derived from the nonlinear model. The mean age of the intermediate cone group (Qm) is estimated to vary between 104,000 years B.P. (linear model) and 118,000 years B.P. (nonlinear model), while the mean age of the oldest cone group (Qo) is estimated to vary between 212,000 years B.P. (linear model) and 280,000 years B.P. (nonlinear model). Future work may verify these age assignments, or at least aid in the calculation of an improved dating scheme and erosion rate.

The degradational pattern witnessed in field observations and map measurements was simulated by the computer model. Simulated cone morphology and the morphology of undated cones in a volcanic field can be calibrated with morphometric parameters, as well as with cross-sectional profiles, of cones that have been dated by radiometric techniques. Other possible calibration methods include least-squares fitting of morphometric parameters (Wood, 1980b) and comparative fitting of normalized cone cross-sectional profiles. The advantage of each of these methods is that a cone of an unknown age can be loosely assigned an age by comparing the morphometric parameters of the cone in question with the spread of the morphometric parameters occupied by a calibrated or dated group of cones from the same volcanic field. The accuracy and precision of these techniques does not permit them to replace absolute age data, but they can separate, for example, late Pleistocene scoria cones from early Pleistocene cones. Therefore, comparative morphology of cinder or scoria cones is a potentially useful dating tool for volcanic fields.

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APPENDIX

Morphometry of 70 Holocene and latest Pleistocene scoria cones

Location/Name	H_{co}[1]	W_{co}	H_{co}/W_{co}	Max Slope	W_{cr}	D_{cr}	Lat	Lon
San Francisco volcanic field, Arizona (U.S.A.):								
Sunset Crater	314	1630	0.193	32.7°	530	134	35°21'45"N	111°30'15"W
Merriam Crater	370	1844	0.201	30.8°	540	132	35°20'N	111°17'15"W
Maroon Crater	138	854	0.162	29.2°	274	59	35°18'30"N	111°21'30"W
SP Mountain	250	1201	0.208	34.3°	380	122	35°35'N	111°37'50"W
Saddle Mountain	268	1202	0.223	29.2°	434	110	35°26'15"N	111°44'W
Lassen volcanic center, California (U.S.A.):								
Hat Mountain	203	1190	0.170	28.0°	339	74	40°30'30"N	121°25'W
Hall Butte	179	875	0.204	31.7°	214	57	40°42'N	121°33'W
Eiler Butte	104	611	0.170	28.3°	178	34	40°43'N	121°33'W
Cinder Cone	179	865	0.207	32.6°	268	69	40°32'30"N	121°19'W
Unnamed	115	643	0.179	27.7°	137	30	40°39'N	121°32'W
Sand Mountain volcanic field, Oregon (U.S.A.):								
Sand Mtn. (north cone)	225	1071	0.210	30.9°	348	85	44°23'20"N	121°55'50"W
Sand Mtn. (south cone)	231	1012	0.228	31.6°	389	140	44°23'N	121°55'50"W
Nash Crater	267	1148	0.232	35.6°	262	72	44°25'10"N	121°56'55"W
Unnamed	173	809	0.214	27.8°	207	57	44°22'N	121°56'W
Cima volcanic field, California (U.S.A.):								
Unnamed (Cone G)	167	940	0.178	30.3°	315	50	35°12'30"N	115°48'W

			Mauna Kea volcano, Hawaii (U.S.A.):					
Puu Kole (I)	128	595	0.215	29.1°	167	30	19°45'5"N	155°25'20"W
Puu Kole (II)	101	476	0.212	28.3°	198	40	19°53'10"N	155°27'10"W
Hookomo	99	631	0.157	30.6°	268	62	19°44'N	155°27'10"W
Huikau	101	666	0.152	32.0°	298	88	19°42'45"N	155°26'15"W
Kalaieha	80	352	0.227	34.3°	90	22	19°42'20"N	155°26'15"W
Puu Ka Pele	136	750	0.181	33.3°	381	87	19°46'10"N	155°38'10"W
Puu Hau Kea	104	607	0.171	36.2°	202	37	19°49'N	155°28'30"W
Puu Loa	143	833	0.172	23.7°	181	43	19°46'N	155°23'5"W
Puu Makanaka	157	1065	0.147	36.8°	422	102	19°50'40"N	155°25'45"W
Puu Hoaka	145	774	0.187	26.8°	250	35	19°51'30"N	155°26'15"W
Kaikipauula	166	690	0.240	31.9°	226	51	19°55'15"N	155°29'30"W
			Haleakala volcano (Maui), Hawaii (U.S.A.):					
Puu Naue	127	577	0.220	27.6°	220	66	20°43'15"N	156°11'15"W
Halalii	85	518	0.164	34.2°	220	61	20°43'20"N	156°12'10"W
Puu o Maui	187	765	0.244	36.2°	178	65	20°43'15"N	156°13'15"W
			Mojave Desert, California (U.S.A.):					
Pisgah Crater	92	488	0.188	30.9°	220	25	34°45'N	116°22'30"W
Amboy Crater	74	476	0.156	35.8°	250	32	34°32'45"N	115°47'30"W
			Raton-Clayton volcanic field, New Mexico (U.S.A.):					
Capulin Mountain	330	1550	0.213	36.1°	413	122	36°47'N	103°58'20"W
Baby Capulin	76	455	0.167	28.4°	188	46	36°49'N	103°56'15"W
			Newberry volcano, Oregon (U.S.A.):					
Lava Butte	163	702	0.232	36.2°	173	60	43°55'N	121°21'20"W
			Big Pine volcanic field, California (U.S.A.):					
Red Mountain	201	1202	0.167	33.9°	333	56	37°1'50"N	118°17'15"W
			Craters of the Moon, Idaho (U.S.A.):					
Crescent Butte	119	881	0.135	28.3°	318	73	43°25'N	113°30'W
			Mt. Etna volcano, Sicily (Italy):					
Monte Gorna	142	625	0.227	29.3°	205	63	37°38'55"N	15°4'50"E
Monte Serra Pizzuta	117	500	0.234	28.2°	275	40	37°38'30"N	15°1'E
Monte Minardo	179	875	0.204	34.6°	238	54	37°44'N	14°52'15"E
Monte Lepre	143	800	0.179	33.7°	262	84	37°45'N	14°55'E
			Chichináutzin volcanic field, Mexico:					
Volcán Holotepec	120	625	0.192	31.5°	200	60	19°5'20"N	99°29'W
Volcán El Tezontle	190	1300	0.146	33.7°	500	120	19°2'5"N	99°27'40"W
Volcán Cuautl	160	750	0.213	33.6°	250	60	19°9'50"N	99°25'15"W
Volcán Negro	170	800	0.212	31.0°	250	80	19°9'55"N	99°22'45"W
Volcán Pehualtepec	170	900	0.189	34.6°	325	90	19°13'N	99°24'W
Volcán Texontepec	130	700	0.186	33.5°	225	50	19°14'30"N	99°24'45"W
Volcán Ololica	155	1012	0.153	31.0°	388	60	19°3'40"N	99°2'W
Volcán El Hoyo	80	483	0.166	36.2°	300	50	19°5'30"N	99°10'W
Volcán Tesoyo	180	1275	0.141	35.0°	470	110	19°5'45"N	99°13'20"W
Volcán Pelado	195	1015	0.192	33.7°	383	75	19°9'N	99°13'W
Volcán Teuhtli	120	643	0.187	33.7°	188	30	19°13'20"N	99°1'50"W
Volcán Yololica	140	828	0.169	31.4°	282	40	19°13'15"N	99°10'40"W
Unnamed	160	831	0.192	27.1°	430	100	19°9'10"N	98°55'55"W

			Michoacán-Guanajuato volcanic field, Mexico:					
Volcán Parícutin	220	950	0.232	35.0°	250	65	19°29'30"N	102°15'5"W
Volcán El Jorullo	310	1540	0.201	37.0°	450	150	18°58'20"N	101°43'5"W
Cerro El Cajete	110	612	0.180	33.5°	220	55	19°22'20"N	101°36'50"W
Cerro Prieto	290	1395	0.208	32.3°	440	100	19°17'55"N	101°32'55"W
Cerros Cuates (west)	120	675	0.178	32.4°	260	45	19°46'50"N	101°58'20"W
Cerros Cuates (east)	120	550	0.218	30.7°	130	30	19°46'55"N	101°57'55"W
Cerro San Miguel	250	1160	0.216	35.0°	295	30	19°36'35"N	102°5'50"W
C. San Miguel (Velaz.)	230	1250	0.184	35.1°	260	45	19°48'10"N	101°58'30"W
Cerro La Arena	180	825	0.218	34.2°	240	40	19°46'30"N	101°54'30"W
Cerros Cumbuan (west)	150	800	0.188	34.6°	250	45	19°39'N	102°3'35"W
Cerro Yondima	240	1055	0.227	34.2°	325	65	19°36'5"N	102°6'35"W
Cerro Los Amoles	140	825	0.170	33.0°	285	45	19°35'20"N	102°7'50"W
Cerro Santa Cruz	240	1038	0.231	32.7°	262	60	19°31'20"N	102°5'55"W
Cerro Piruani	150	838	0.179	32.3°	288	50	19°30'50"N	102°6'35"W
			Colima volcanic field, Mexico:					
Volcán Telcampana	160	862	0.186	32.0°	312	40	19°41'15"N	103°47'W
Volcán Comal Grande	165	900	0.183	29.5°	419	80	19°45'N	103°47'45"W
			Tolbachik volcanic center, Kamchatka (Russia):					
Gorshkov's Cone	299	1154	0.259	30.9°	351	134	55°41'N	160°13'E

Explanation:
[1]H_{co}=cone height in meters, W_{co} = cone width or basal diameter in meters, Max Slope = maximum cone slope angle in degrees, W_{cr} = crater width or basal diameter in meters, D_{cr} = depth of crater in meters, Lat = latitude, and Lon = longitude.

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