Morphometry of Central American Composite Cones

by Debbie L. Cipolletti

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ABSTRACT OF THE THESIS

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by Debbie L. Cipolletti, M.S.

Thesis Director: Dr. Michael J. Carr

Topographic profiles of Central American volcanoes were digitized from 1:50,000 scale maps and power, exponential, and linear fits were calculated by least squares. The power function, $y = a * x^{b}$ used in allometric analysis was found to be a poor fit to the data. The exponential curve, $y = a * e^{(b * x)}$ proved to be the best fit in 22 out of 24 cases, and a regional variation similar to that exhibited by crustal thickness was shown to exist in the derived values for the exponent (b) and the coefficient (a) of the exponential function.

Volcanoes of central Costa Rica exhibit markedly different morphology than the rest of the Central American volcanoes. This morphologic anomaly may result from the complex tectonic regime associated with Central Costa Rica.

Multivariate cluster analysis was used to identify groups or clusters of volcanoes based on similar morphology. One resulting cluster (Group 5) was interpreted as an artifact of the clustering procedure. The remaining four groups or clusters were suggested to represent "morphotypes" and appear to be tectonically controlled.

Dedication

I dedicate this thesis to my father, George C. Moberger, for being an inspiration and a great source of strength for me.

Acknowledgements

I would like to thank my advisor, Dr. M.J. Carr, for the numerous suggestions and advice he gave throughout the course of this study. I would also like to thank Dr. M. Feigenson and Dr. R. Forsythe who were committee members for this thesis.

I also want to thank the entire faculty staff at Rutgers University, Department of Geological Sciences. Their interest and concern for their students was very evident throughout my years at Rutgers.

I would like to extend my deepest appreciation to my husband, Robert Cipolletti, for his love, support, and understanding throughout my years of graduate studies. A very special thank you also to my parents who have always been there for me, sharing in my happiness and my sorrow.

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Introduction

The Central American volcanic belt represents one of the most active continental volcanic areas in the world. The volcanic front extends from the Mexico-Guatemala border to central Costa Rica and includes 40 active volcanic centers. Consequently, Central America is an ideal place to test different hypotheses governing volcano shape and the tectonics of convergent plate margins.

I extend the previous work done by Wood (1980 and 1978) and Pike (1978) on the general morphological parameters of composite volcanoes. I present topographic profiles of 24 Central American volcanoes. Data are from 1 : 50,000 scale topographic maps. I measured various morphological parameters from these maps and topographic profiles.

A major goal of this project was to determine if allometry could be applied to the shape of volcanoes. Allometry is the study of the relative rates of change between two variables within a system. Static allometry refers to the interrelations between two variables at a single time. Dynamic allometry on the other hand refers to the changes that occur between two variables over a period of time.

I attempted to perform a static allometric analysis on the two dimensional shape of Central American volcanoes. Ideally, this type of analysis should distinguish the effects of size from the effects of shape and enable me to compare and contrast the shape of volcanoes along the front without introducing any bias caused by differences in scale.

I applied Shteynberg and Solov'yev's (1976) dimensionless analysis of volcano shape to the Central American belt. Shteynberg and Solov'yev (1976) defined new morphological parameters for stratovolcanoes. Shteynberg and Solov'yev proposed that volcano shape was comprised of an upper linear cone, whose constant slope reflected the angle of repose and a lower basal cone with a progressively more gentle slope that was related to stresses acting on the base of the cone.

I applied multivariate statistical analysis to a number of morphological parameters for Central American volcanoes to determine if clusters or groups of volcanoes could be distinguished solely on the basis of similar morphology.

Purpose

The purpose of this theses, then is fivefold, and can be outlined as follows:

1) To digitize topographic profiles of the Central American volcanoes.

2) To calculate the best fit or least-square equation to the topographic profiles using power (allometric analysis), exponential, and linear equations.

3) To apply the Shteynberg and Solov'yev (1976) dimensionless analysis af volcano morphology to the Central American front. Is there a significant relationship between the radius of the cross section of the basal cone width and the radius of the cross section of the upper cone? If so, is this relationship dependent upon the angle of repose?

4) To determine if there are any inherent groups or clusters of Central American volcanoes that have similar morphology. Multivariate statistics were performed via the SYSTAT software package (Wilkinson, 1986) on a number of morphometric parameters for the Central American volcanic front.

5) To contstuct "morphotypes" which represent the average dimensions of the groups or clusters identified by cluster analysis. To determine if volcano morphology and segmentation of the volcanic front are related. Do certain morphotypes occur at or near segment boundaries while others occur within segment boundaries?

Description of Previous Models of Volcano Shape

Hydraulic Resistance Model

Lacey et al. (1981) attempted to explain the near perfect cone shape of Mount Fuji in Japan in terms of hydraulic resistance to the flow of magma. Lacey suggested that this phenomenon could produce asymmetric cones if parasitic centers of volcanism were present or if significant erosion or explosive volcanism had taken place.

Lacey et al. (1981) modeled the flow ot magma through the volcanic edifice while assuming the volcano was composed of uniform porous material. Ideally, the surface of the volcano would be defined as the constructional sum of many small lava flows. Each lava flow that reached the surface would extend the edifice and solidify so that the flow increased the hydraulic resistance of that part of the edifice and successive eruptions would have to occur at other locations. Lacey et al. (1981) suggested that successive eruptions would follow the path of least hydraulic resistance. Lacey et al. (1981) also suggested that volcano shape could be predicted by an equipotential surface for the flow of magma through a uniform porous medium, with magma taking the path of least hydraulic resistance to the surface.

Furthermore, Lacey et al. (1981) implied that volcanoes grow vertically until they reach a critical height. This critical height was suggested to be dependent upon the thickness of the lithosphere. Lacey et al.

implied that growth beyond the critical height would have to occur laterally.

Wadge and Francis (1982) and Wood (1978 and 1982) objected to Lacey's theory and suggested that vertical growth could continue beyond a critical height, but, the reason why so few volcanoes are observed at heights greater than 2.5 to 3 km is due to caldera collapse and not the cessation of vertical growth.

Wood (1982) and Wadge and Francis (1982) objected to the assumptions and results of the Lacey et al. (1981) model. As a result, I placed a higher priority on other morphological studies.

The Wood Model

Pike (1976) defined and measured a number of morphometric parameters for extraterrestrial volcanoes. Wood (1978) studied the statistical relationships between Pike's (1976) morphometric parameters for 26 circum-Pacific composite volcanoes. Wood hand-picked "ideal" composite cones from the entire circum-Pacific region excluding those stratovolcanoes which had calderas and those that failed to possess an "ideal" cone shape. Wood measured basal cone width (WcO), summit crater width (Wcr), crater depth (Dcr), and edifice cone height (HcO). Least squares analysis revealed linear variations that Wood suggested to represent uniform cone growth. Wood found a significant statistical relation ($r = .95$) to exist between edifice cone height (HcO) and basal cone width (WcO) based on measurements from 17 stratovolcanoes. No significant relation was found between crater depth and crater width. The population of stratovolcanoes used in Wood's study ranged in volume from 0.17 to 395 km^3.

The Shteynberg and Solov'yev Model

Shteynberg and Solov'yev (1976) suggested that the shape of a stratocone represents a free-flowing cone with the slope angle equal to the angle of repose. They defined the morphological parameters BH, LH, BR, and LR, where BH is the height of the upper linear cone, BR is the radius of the upper cone, LH is the height of the basal cone, and LR is the radius of the basal cone (see Figure 1).

Shteynberg and Solov'yev (1976) suggested that the shape of a volcano is dependent upon the stresses acting on the base of the structure. They determined that a regular free-flowing cone shape could be retained during the growth process until the compressive stress at the base of the structure reached a maximum, Γ_p. The maximum compressive stress would then be proportional to the limiting shear stress and would serve to limit the height of the upper cone, BH (Shteynberg and Solov'yev, 1976).

By assuming that the cone was a solid, homogenous body, Shteynberg and Solov'yev (1976) determined the limiting height of the regular cone. The average stress at the base of the cone would be equal to :

$$(1) \qquad \Gamma = G/S = .33\gamma\, SBH/S = .33\gamma BH$$

where G is the weight of the cone, S is the area of the base of the cone, γ is the density of the rocks, and H

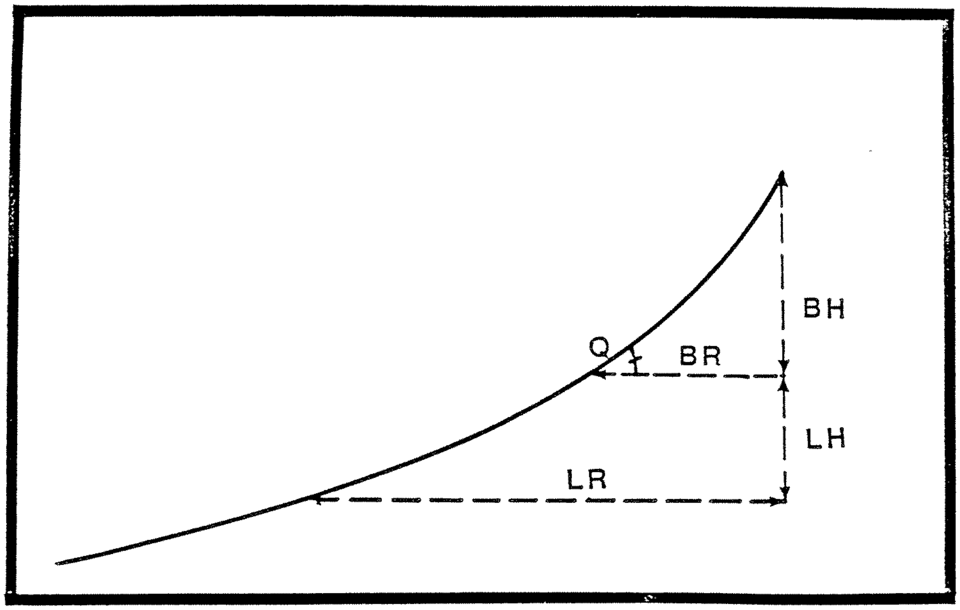


Figure 1. Morphological parameters BH, LH, BR, LH and Q after Shteynberg and Solov'yev (1976).

is the height of the cone. From equation (1), the limiting height of a free-flowing volcanic cone would be equal to :

$$(2)\ BH_{lim} = 3\Gamma_p/\gamma$$

where Γ_p is the tensile strength (the breaking stress of the material from compression). Shteynberg and Solov'yev (1976) determined that the limiting height for volcanoes in Kamchatka ranged from 2 - 2.5 km, with Γ_p = 50 - 150 kg/cm^2, and the average γ (density) = 1.2 - 2.2 g/cm^3.

Theoretically, the shape of a regular, free-flowing cone would change if the limiting height was exceeded because the stresses acting on the base of the structure would reach a limiting value, Γ_p.

Shteynberg and Solov'yev (1976) thought of the lower part of the structure (below the upper cone) as a body at constant strength. The stresses acting on any horizontal area below the upper cone would then be equal to Γ_p. The portion of the structure below the cone would be subjected to the effects of the weight of the limiting cone, G, and of its own weight. The area of a cross section, F, at a distance LH from the base of the cone would equal to:

$$(3)\ F = G/\Gamma_p\ e^{(\gamma BH/\Gamma_p)} = \pi(LR)^2$$

Substituting G = .33γ SBH = .33γ BR^2 BH, BR = BH cot

Q, and $\Gamma_p / \gamma = .33\ BH_{lim}$, yielded equation (4), where LR is the radius of the cross section at a height LH below the base of the upper cone.

$$(4)\ LR = BRe^{3LH/2BH}$$

Shteynberg and Solov'yev divided LH, BR, and LR, by BH to obtain dimensionless parameters LHB, BRB, and LRB, where LHB = LH/BH; BRB = BR/BH; and LRB = LR/BH. Substituting these values into equation (4) yields:

$$(5) LRB = BRB * e^{(3/2 * LHB)}$$

Therefore, log (LRB) = log (BRB) + 3/2 * LHB * log (e). For a log - linear plot of LRB vs LHB, the intercept is equal to log (BRB). Log (BRB) is also equal to the cotangent of the angle of repose for the regular, free-flowing cone.

Shteynberg and Solov'yev (1976) also suggested that when the limiting height of the cone is exceeded, the stresses acting on the base of the cone cause radial fissures to form. Since the position of subordinate vents is often controlled by radial fissures, they believed there was a connection between the height of the volcano and the presence of subordinate vents as well as the formation of fissures in the base of the cone.

Methodology

Data were collected from many different sources. A nearly complete collection of 1 : 50,000 scale topographic maps were available. I excluded volcanoes with obvious calderas but did not limit my study to those volcanoes with "ideal" cone shapes. I measured basal cone width and edifice height on 1 : 50,000 scale topographic maps. I found this to be a difficult task because the Central American countries are almost entirely composed of volcanic products and as a result, it was difficult to determine where the "prevolcanic" terrain if any was located. I decided to use the values that Carr (1984) calculated for edifice height. I calculated the basal cone widths by measuring the diameter of the cross section a distance equal to HcO km below the summit. For those volcanoes that were elliptical rather than cone shaped, I measured the basal diameter along the strike of the volcanic front. These values along with Carr's edifice height values are listed in Table 2.

The 1: 50,000 scale topographic maps allowed topographic profiles to be digitized via a BASIC computer program, PROFILE, which interfaced an IBM PC, a 36" x 24" GTCO DIGI-PAD, and an HP 7470A plotter. Profiles were centered at the central vent or summit of the volcano. A 20 m contour interval was used whenever possible. All profiles extended radially away from the summit or central vent. The regional elevation was used as the base elevation and this was determined from the topographic map. Several radial profiles were generated for many of the Central American volcanoes. Volcano profiles were then plotted at various scales and vertical exagerations.

Landsat photos and space shuttle photos were also available so that a regional perspective could be gained for the entire volcanic arc.

Functional analysis of volcano shape was attempted by a computer program ALLOFIT. The ALLOFIT computer program fit power, exponential, and linear equations to the volcanic profiles and performed least-square analysis to determine the best fit. The ALLOFIT program also derived the coefficients for the equations being fit to the topographic profile and plotted the volcanic profile and the fitted curve for each type of equation.

The equations determined to be the best-fit or least-square were then compared to determine which function (power, exponential, or linear) best described Central American volcano shape. Allometric analysis can be applied only if a least-squares power function is determined to have the best fit to the topographic profile.

The morphological parameters originally suggested by Shteynberg and Solov'yev (1976) were measured directly from the topographic profiles for the individual volcanoes (see Fig. 1). The height of the upper linear cone is BH. The radius of the cross section a distance BH from the summit or central vent is BR. The height of the basal cone, LH, is the distance from the base of the upper linear cone to the bottom of the basal cone. The radius of the basal cone, LR, is the radius of the cross section a distance LH from the upper cone, or a distance (BH+LH) from the summit. These values were chosen somewhat arbitrarily because in some instances it is very difficult to determine where the upper cone terminates and where the basal cone begins. Every effort was made to reduce bias of the data set by relying on the ALLOFIT computer program to fit a least squares exponential or linear curve to the upper cone. The value of BH would then be the difference in elevation from the beginning and ending elevation for the least-squares curve for the upper cone. The value of BR was measured directly from the topographic profile simply by extending a horizontal line across the base of the upper cone and measuring the radial distance.

I eventually was able to create a large data file with all the morphologic parameters for each individual volcano. These variables included edifice height, basal cone diameter measured along strike to the volcanic front, the angle of repose, and all the Shteynberg and Solov'yev variables.

I then applied various clustering algorithyms to this data set by using the SYSTAT computer software statistics package with the IBM PC (Wilkinson, 1986). I used Euclidean distance and Pearson correlation matrices to determine if any groups of volcanoes clustered together. A standardized Euclidean distance matrix was finally chosen because this type of clustering algorithym has been shown to work best for a data set that includes variables of different scale (Davis, 1973). This type of clustering will not bias the data set towards the largest scale variable.

A cophenetic value of .33 was used to define groups of volcanoes. The cophenetic value is the level where clustering occurs. Theoretically, these groups or clusters of volcanoes should have similar morphology.

I constructed "morphotypes" from the average dimensions of the groups or clusters identified by the cluster analysis. I compared these "morphotypes" with the observed topographic profiles. I investigated where the "morphotypes" were located in terms of a segmented volcanic front.

Tectonic Setting

The Central American volcanic front begins in northwestern Guatemala at Tacana volcano and extends approximately 1100 km to the Irazu-Turrialba complex in central Costa Rica. The volcanic front forms parallel to the Middle America Trench and is a product of the Cocos-Caribbean plate convergence (Molnar and Sykes, 1969). The Cocos plate is presently being subducted below the Carribbean plate at rates of convergence which vary from 6.9 cm/yr in northwestern Guatemala to approximately 8.5 cm/yr in southeastern Costa Rica (Cross and Pilger, 1982). This tectonic regime is further complicated by North American plate interaction along the transform boundary between the Carribbean and North American plates (Molnar and Sykes, 1969). The exact location of the North American - Cocos - Caribbean triple junction is not known, however, others have suggested that the westernmost extension of the boundary is around 30 km north of Tacana volcano, Guatamala (Carr, 1984; Burbach et al, 1984; Cross and Pilger, 1982). The southeastern boundary of the volcanic front is located at the intersection of the Middle American trench and a proposed transform fault at the eastern edge of the Cocos plate (von Andel et al., 1971).

Kelleher and McCann (1976) suggested that the subduction of anomalously thick aseismic ridges with a

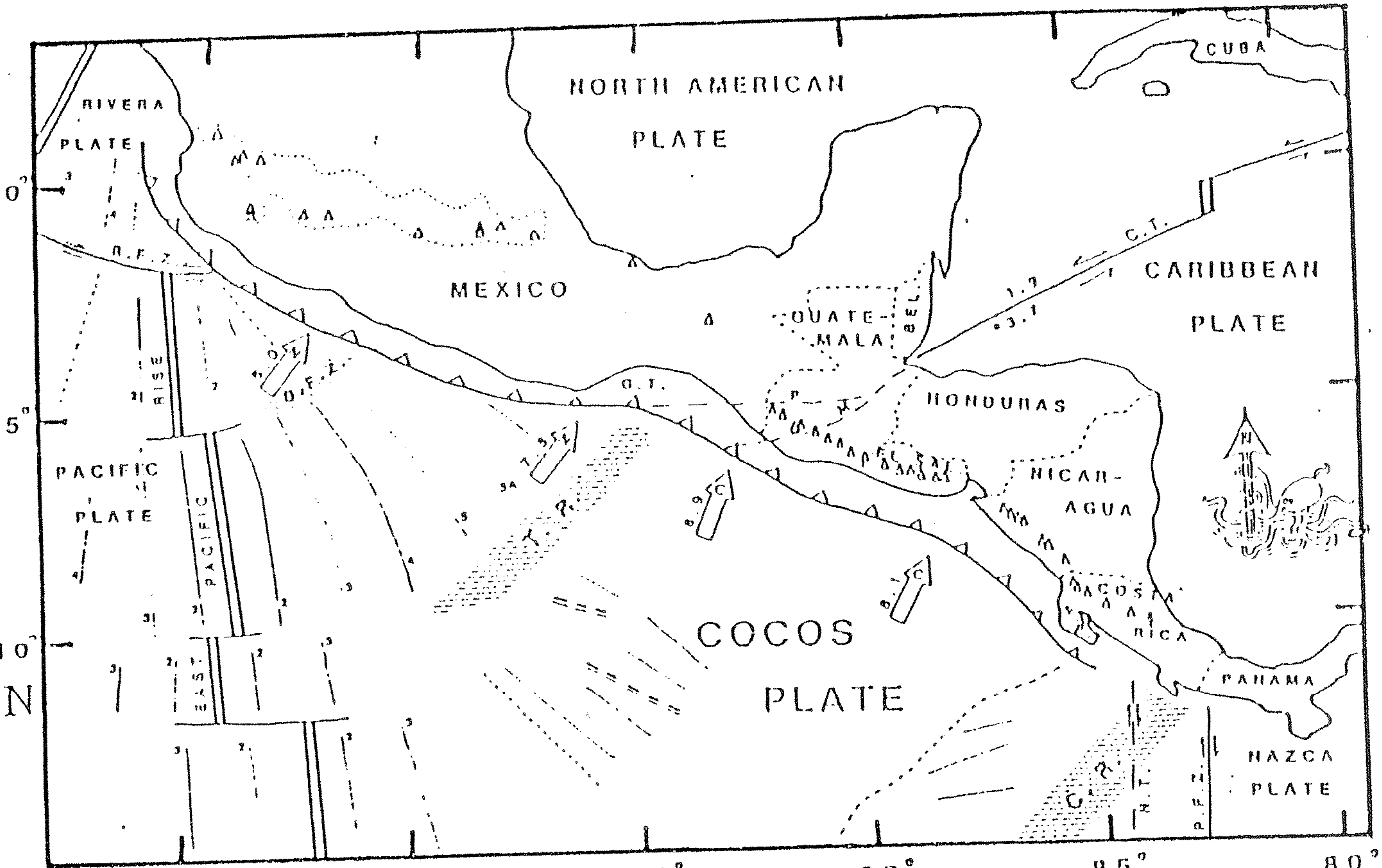


Figure 2. Tectonic framework of the Middle America Region. (From Burbach et. al., 1984).

reduced average lithospheric density would be more bouyant and act to either resist or terminate subduction. The Cocos Ridge is an example of an aseismic ridge that is resisting subduction and the ridge is presently redefining the Cocos - Nazca plate boundary (Vogt et al, 1976). The dip of the Benioff zone beneath central Costa Rica and adjacent to the Cocos Ridge and trench intersection, appears to be substantially reduced (Burbach et al, 1984).

Stoiber and Carr (1973; and Carr and Stoiber, 1978) subdivided the volcanic front into eight segments which parallel the trench and are characterized by offsets in the strike of the volcanic front. Seismic data indicate that individual volcanic lineaments trend parallel to the strikes of the underthrusting plate segments (Carr, 1976; Dean and Drake, 1978). Carr et al, (1979) used earthquake foci to define the inclined seismic zone and showed an increase in the dip of the Benioff Zone exists approximately beneath the volcanic front. A paucity of seismic data was also noted for this depth interval. Carr suggested that these features indicate a common depth of melting for each segment and the possible source region of magmas which supply the volcanic front.

Seismologists (Burbach and Frohlich, 1986; Burbach et al., 1984) have concluded that there are few seismologically definable offsets in the descending slab. Teleseismic data and local network data enabled

Burbach and Frohlich (1986) to argue that the descending slab beneath Middle America is composed of only three segments. Limited resolution of seismic data precluded seismologically defined segments similar to the volcanologically and geologically defined segments. The volcanologic segmentation model remains the best model for enabling regional comparisons of volcanoes for the purpose of this study.

Curve Fitting for Volcanic Profiles

Data were collected from 1:50,000 scale topographic maps. In many cases, several topographic profiles were taken to insure that the data was collected properly. In addition, profiles were taken in different directions away from the central vent or summit. The ALLOFIT program required user interaction to identify the beginning and ending elevations of the portion of a profile that the user wished to analyze.

A power function ($y = a * x^{b}$), an exponential function ($y = a * e^{(b * x)}$), or a linear function ($y = a * x + b$) can be fit to the selected profile. Regardless of the function chosen, ALLOFIT would determine the best fit curve within the limits of the domain by minimizing the differences between the observed profile and the calculated curve.

A standard coordinate system was automatically initiated by the ALLOFIT program with the origin being equal to the ending or base elevation of the portion of the curve being examined. The ALLOFIT program calculated the coefficients and exponents (and y-intercept for the linear function) for the chosen function that best fit the observed profile. The reference coordinate system allowed comparison of the exponents of the calculated least squares curve. For the power or exponential functions, volcanoes with similar slopes or similar shape should have similar values for the exponent. Of course, this similarity is dependent upon the elevations input by the user because the uppermost cone has a steeper often exponential shape and the lower portion of the volcano may have a more gradual or less steep slope. This is true even for those volcanoes that could be best described by two exponential least-square curves for different elevations.

The ALLOFIT program also printed the residual sum of the squares so that the best fit curve could be determined between the three different functions that were available. The power, exponential, or linear equation with the smallest residual sum of the squares was selected as the best fit curve for that portion of the volcano.

Figure 3 is a plot of the observed topographic profile and the calculated exponential curve for Aqua volcano from 3788 m to 2000 m . The residual sum of the squares was equal to 45.95 km^2 .

The exponential curve proved to be the best-fit function for 20 of 24 volcanoes examined (see Table 1). Many volcanoes required two exponential curves to adequately describe their two dimensional shape.

The power function, $y = a * x^b$, was applied to every volcanic profile, but found to be a poor description of the actual data. Thus, static allometry was found to be inapplicable to this study because the exponential curve proved to be the best - fit function for the majority of Central American volcanoes.

Table 1. Results of the Curve Fits

Volcano	# curves	Type	Elev	$(Y-Y(I,J))^2$	a	b
Tajumulco	1	E	4000-1300	42.58	4.325	-0.160
Santa Maria	2	E	3772-2000	863.65	3.842	-0.202
"		E	2000-1060	800.47	3.060	-0.130
Atitlan	2	E	3500-1500	3145.43	3.619	-0.224
"		E	1500-760	420.64	2.438	-0.124
Toliman	1	E	3134-1800	1269.21	3.165	-0.226
Fuego	2	E	3763-1700	21.89	3.791	-0.208
"		E	1700-800	632.26	2.563	-0.114
Acatenango	3	L	3976-2060	18.9	1.948	0.622
"		E	2060-1600	4.45	3.552	-0.163
"		L	1600-1400	4.45	1.393	0.089
Aqua	2	E	3788-2000	55.81	3.805	-0.224
"		E	2000-1600	45.73	3.094	-0.158
Pacaya	2	E	2540-1600	1723.81	2.544	-0.222
"		E	1600-1400	60.71	2.109	-0.126
Santa Ana	2	E	2365-2000	207.11	2.351	-0.188
"		E	2000-1100	4130.62	2.216	-0.136
San Salvador	2	E	1780-1300	98.35	2.201	-0.243
"		E	1300-500	1831.79	1.841	-0.156
San Vicente	2	E	2181-1140	2951.53	2.167	-0.336
"		E	1140-200	145.18	2.008	-0.241
San Miguel	1	E	2129-200	1375.01	2.22	-0.379
ElHoyo	1	E	1000-100	0.29	1.006	-0.386
Momotombo	2	E	1119-560	55.39	1.236	-0.705
"		E	560-40	32.15	1.634	-0.812
Mombacho	1	E	1180-300	905.16	1.347	-0.457
Maderas	2	L	1394-500	657.65	0.456	0.470
"		L	500-40	657.65	0.007	0.131
Concepcion	2	E	1540-500	273.12	1.939	-0.642
"		E	500-40	26.89	1.541	-0.567
Rincon	2	E	1861-1320	4045.91	1.844	-0.298
"		E	1320-500	163.62	1.593	-0.177
Arenal	1	E	1600-500	163.36	1.661	-0.534
Platanar	2	E	2183-1700	43.25	2.179	-0.215
"		E	1700-500	2097.49	1.998	-0.167
Poas	2	E	2708-2200	965.34	2.688	-0.071
"		E	2200-1800	22.15	2.633	-0.076
Barba	2	E	2880-2640	460.03	2.835	-0.042
"		E	2640-1820	3880.51	3.035	-0.080
Irazu	2	E	3364-2900	532.37	3.333	-0.060
"		E	2900-1100	311.17	3.409	-0.087
Turrialba	2	E	3329-2400	3.75	3.371	-0.157
"		E	2400-1500	294.55	3.124	-0.116

P - power function $Y = a * X^b$
E - exponential function $Y = a * e^{(b * X)}$
L - linear function $Y = a * X + b$

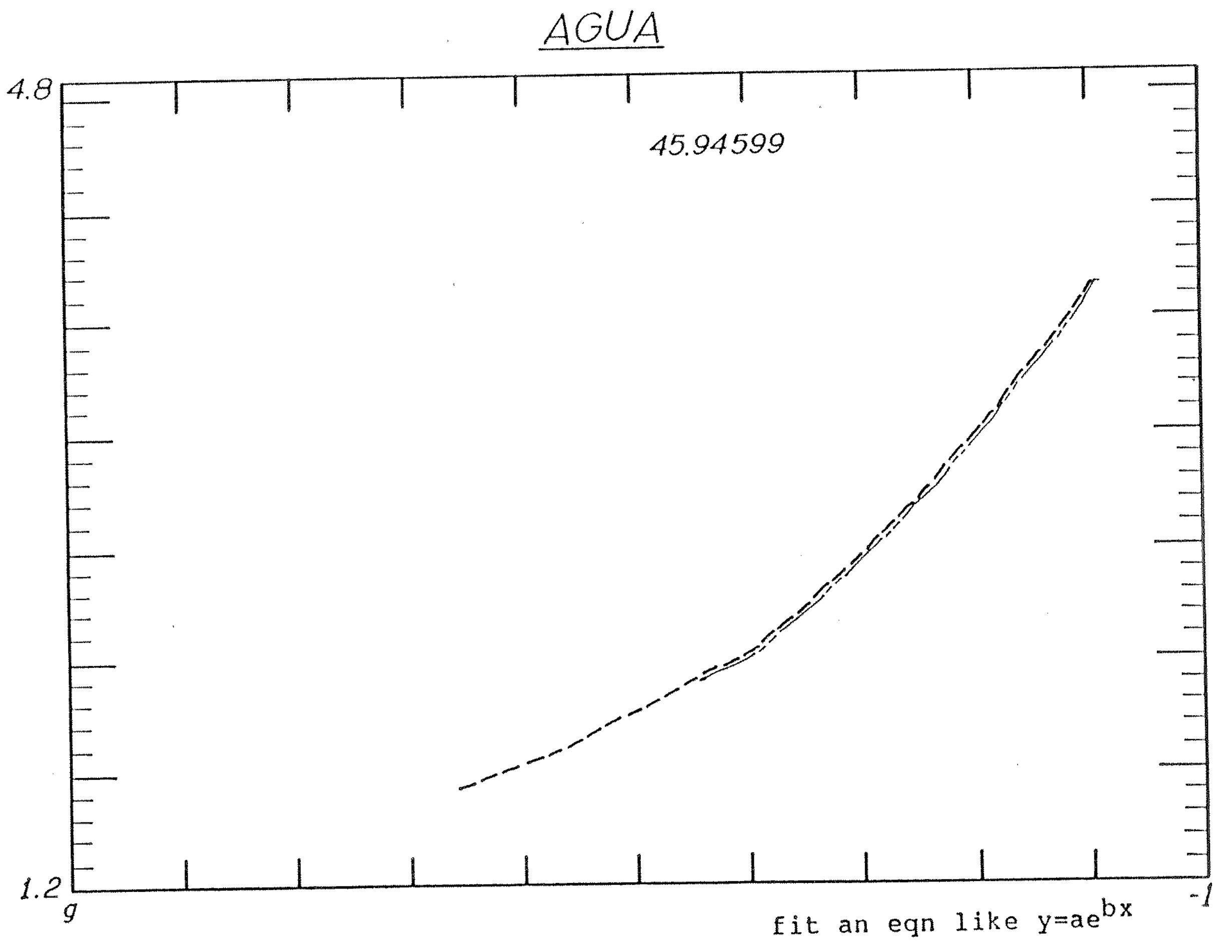


Figure 3. ALLOFIT topographic profile of Agua volcano with least-square exponential fit.

Regional Variation in Exponential Fits

Figure 4 is a plot of the regional variation in the (a) coefficient and (b) exponent of the best-fit curve for Central American topographic profiles as a function of the distance along the volcanic arc. The distance along the arc is increasing from northwestern Guatamala to central Costa Rica. The exponent of the least-square exponential function has a regional variation in Central America similar to the regional variations in edifice height and crustal thickness (Carr, 1984). This regional variation is mimicked by the values of a and b in Table 1 and Figures 4A and 4B.

Figure 4A shows the regional variation in (a) the coefficient of the exponential least-square curve(s). The value of the coefficient, (a), is directly related to the exponent, (b), and the edifice height with greater values occuring for the Guatemalan and central Costa Rican volcanoes.

The smaller and shorter volcanoes of Nicaragua needed smaller exponents in order to achieve an angle of repose close to 30 degrees, whereas, the larger and higher Guatemalan volcanoes can achieve the same angle of repose with larger exponents. One might therefore suggest that throughout most of Central America, the regionally varying edifice height and the regionally constant angles of repose interact to create the different volcanic landforms. One possible exception to

Table 2. Edifice Height and Basal Cone Diameter for Central American Volcanoes

Volcano	Edifice Cone Height HcO km	Basal Cone Diameter WcO km
Tacana	1.90	----
Tajumulco	2.05	8.60
Santa Maria	1.80	12.0
Atitlan	2.0	16.55
Toliman	.91	----
Fuego	2.16	12.0
Acatenango	2.16	19.0
Aqua	2.16	24.2
Pacaya	----	10.2
Tecuamburro	1.35	12.5
Apaneca	1.40	----
Santa Ana	1.80	24.0
San Salvador	1.45	16.6
San Vicente	1.65	12.0
Tecapa	1.35	----
Usultan	1.14	5.78
Tigre	1.40	----
San Miguel	1.85	12.7
Conchagua	1.24	9.0
San Cristobal	1.55	----
Casita	1.31	12.9
Telica	.85	11.55
El Hoyo	.99	12.5
Momotombo	1.10	7.65
Momotombito	----	14.0
Masaya	.55	----
Mombacho	1.25	14.0
Concepcion	1.60	13.0
Madera	1.38	10.25
Orosi	1.20	----
Rincon	1.50	18.0
Miravalles	1.60	7.0
Tenorio	1.50	13.0
Arenal	1.10	6.40
Platanar	1.49	11.65
Porvenir	1.58	----
Poas	1.70	18.8
Barba	1.90	23.7
Irazu	2.00	26.0
Turrialba	1.90	13.7

---- data not available

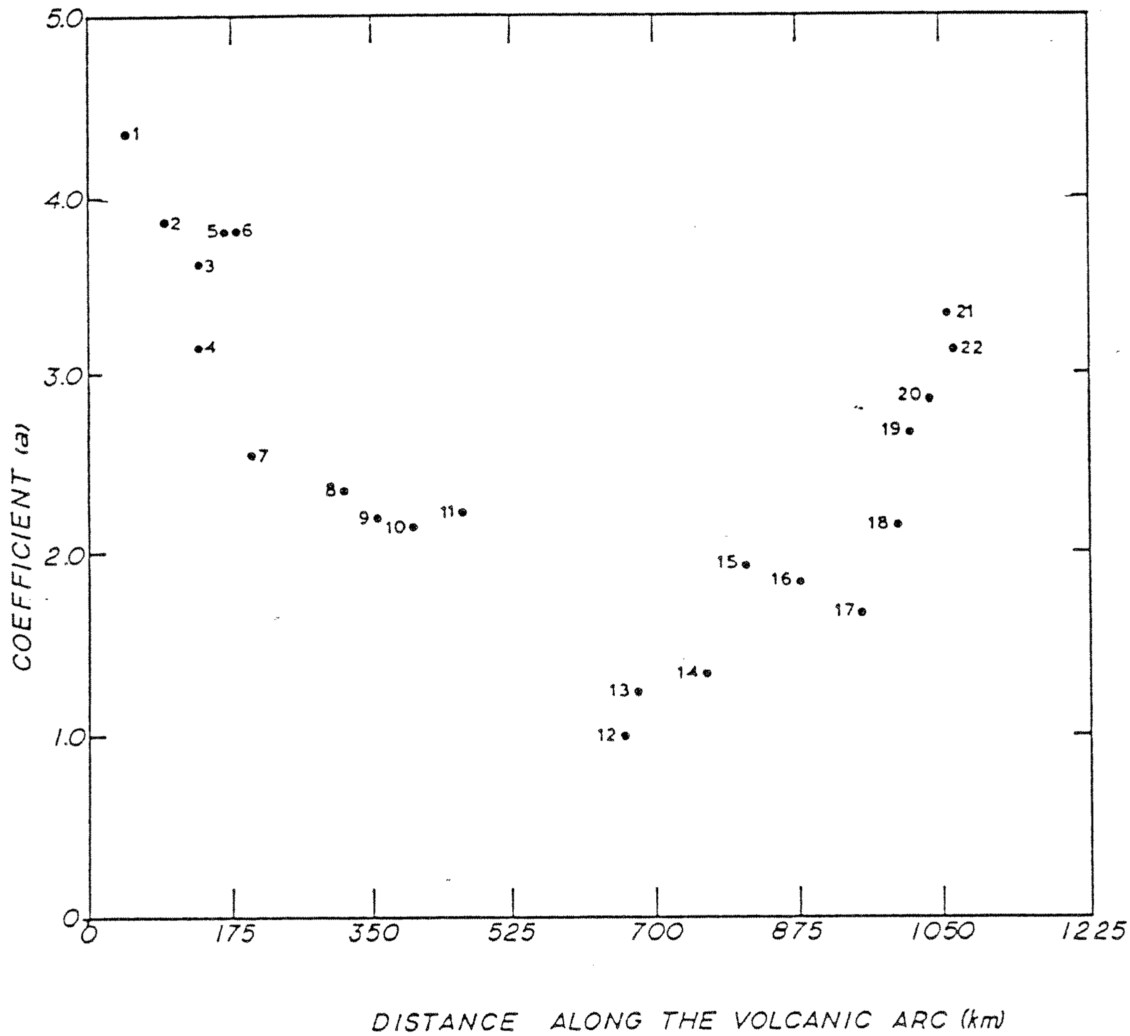


Figure 4A. Regional variation in coefficient of exponential best fit curve versus the distance along the volcanic arc.

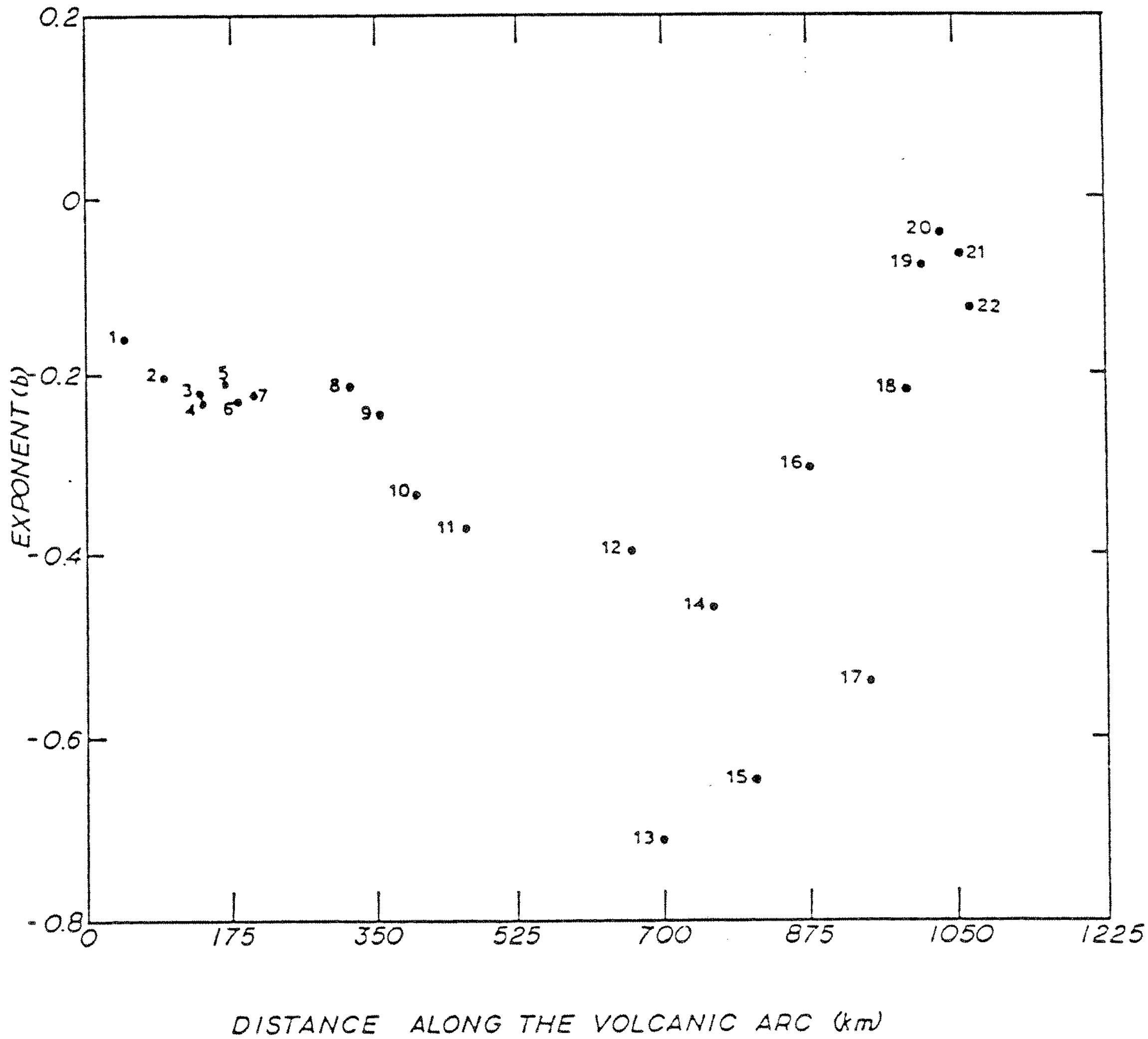


Figure 4B. Regional variation in exponent of the exponential best fit curve versus the distance along the volcanic arc.

FIGURE 4: KEY

1 = Tajumulco
2 = Santa Maria
3 = Atitlan
4 = Toliman
5 = Fuego
6 = Agua
7 = Pacaya
8 = Santa Ana
9 = San Salvador
10 = San Vicente
11 = San Miguel
12 = El Hoyo
13 = Momotombo
14 = Mombacho
15 = Concepcion
16 = Rincon
17 = Arenal
18 = Platanar
19 = Poas
20 = Barba
21 = Irazu
22 = Turrialba

this is central Costa Rica. Central Costa Rican volcanoes exhibit markedly different shapes than the rest of the Central American volcanic front. Central Costa Rican volcanoes have smaller edifice heights and smaller slopes than Guatamalan volcanoes, yet the Costa Rican volcanoes require larger values for the exponents of the least-square exponential curve. One possible explanation for this behavior is the different type of crust in central Costa Rica. Oceanic crust is present beneath central Costa Rica whereas, continental crust is present in Guatemala, Nicaragua and El Salvador (Pichler et al, 1973). Perhaps the less dense oceanic crust exerts a different influence on volcano morphology than does continental crust.

Application of Shteynberg and Solov'yev Model

I applied a morphometric analysis originally suggested by Shteynberg and Solov'yev (1976) to the mature Central American composite volcanoes. I excluded volcanoes that had large caldera complexes. I measured the values of BH, BR, LH, and LR directly from the digitized topographic profiles. Table 3 lists the values of BH, LH, BR, LR, BRB, LRB, LHB and the angle of repose for Central American stratovolcanoes.

The angle of repose for Central American volcanoes ranges from 9.1 to 32.4 degrees for Barba and Atitlan volcanoes, respectively. The average angle of repose for Central American volcanoes is 27.6 degrees.

The Shteynberg and Solov'yev (1976) study showed that on a log-linear scale, (Log LRB vs LHB), the LRB-intercept should equal the cotangent of the angle of repose. That is, the angle of repose, cot Q, equals log BRB. Figure 5 is a log-linear plot of LRB vs LHB for Central American volcanoes, plotted as a function of the angle of repose. Figure 6 is a plot of the logarythmic difference between LRB and BRB vs LHB for Central American volcanoes. Theoretically, figure 6 shows the relationship between log (LRB) and LHB independent of the angle of repose.

Table 3. Characteristics of Central American Volcanoes

Volcano	BH	LH	BR	LR	LHB	BRB	LRB	repose
Tajumulco	1.260	.660	2.359	4.000	.524	1.872	3.175	28.1
Santa Maria	1.686	.614	4.160	7.344	.364	2.467	4.356	22.1
Atitlan	1.387	.710	2.188	4.125	.512	1.578	2.974	32.4
Toliman	0.930	.408	1.564	2.600	.439	1.682	0.439	30.7
Fuego	2.065	.598	3.913	7.120	.290	1.895	3.448	27.8
Acatenango	1.875	.503	3.119	4.913	.268	1.663	2.620	31.0
Aqua	1.647	.515	3.000	5.029	.313	1.821	3.053	28.8
Santa Ana	0.750	.383	2.308	4.513	.511	3.077	6.017	18.0
San Salvador	0.514	.186	1.371	2.571	.362	2.667	5.002	20.6
San Vicente	0.997	.250	1.994	3.188	.251	2.000	3.197	26.6
San Miguel	0.972	.500	2.156	3.756	.514	2.218	3.864	24.3
Telica	0.255	.159	0.448	1.086	.624	1.757	4.259	29.7
El Hoyo	0.320	.270	0.900	2.472	.844	2.813	7.725	19.6
Momotombo	0.561	.350	1.122	2.687	.624	2.000	4.790	26.6
Mombacho	0.523	.284	1.318	2.682	.543	2.520	5.128	21.6
Concepcion	1.018	.295	1.727	2.818	.290	1.696	2.768	30.5
Madera	1.000	.300	2.632	4.160	.300	2.632	4.160	20.8
Rincon	0.518	.341	1.000	2.773	.658	1.931	5.353	27.4
Arenal	0.909	.193	1.591	2.261	.212	1.750	2.487	29.7
Platanar	0.891	.500	2.440	5.257	.561	2.738	5.900	22.1
Poas	0.761	.227	3.227	5.027	.298	4.240	6.606	13.3
Barba	0.545	.432	3.400	5.682	.793	6.239	10.426	9.1
Irazu	1.149	.596	5.000	8.707	.519	4.352	7.578	12.9
Turrialba	0.969	.469	2.275	4.406	.484	2.348	4.547	23.1

H, h, R, and r in km
LHB = h/H, BRB = R/H, LRB = r/H
repose in degrees

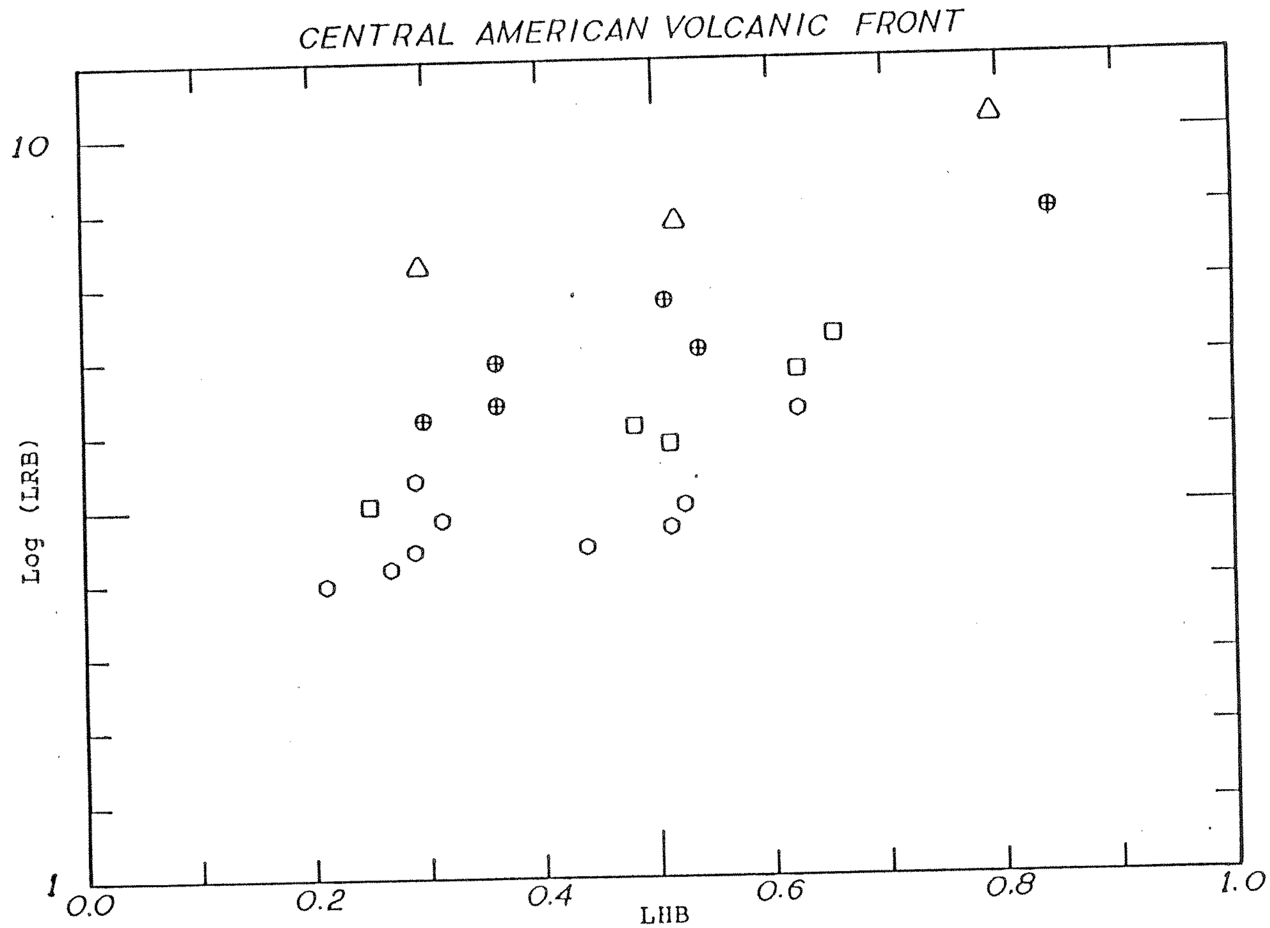


Figure 5. Plot of log (LRB) versus LHB as a function of the angle of repose; △ = 9-13, ⊕ = 18-22, □ = 23-27, ⬡ = 28-32.

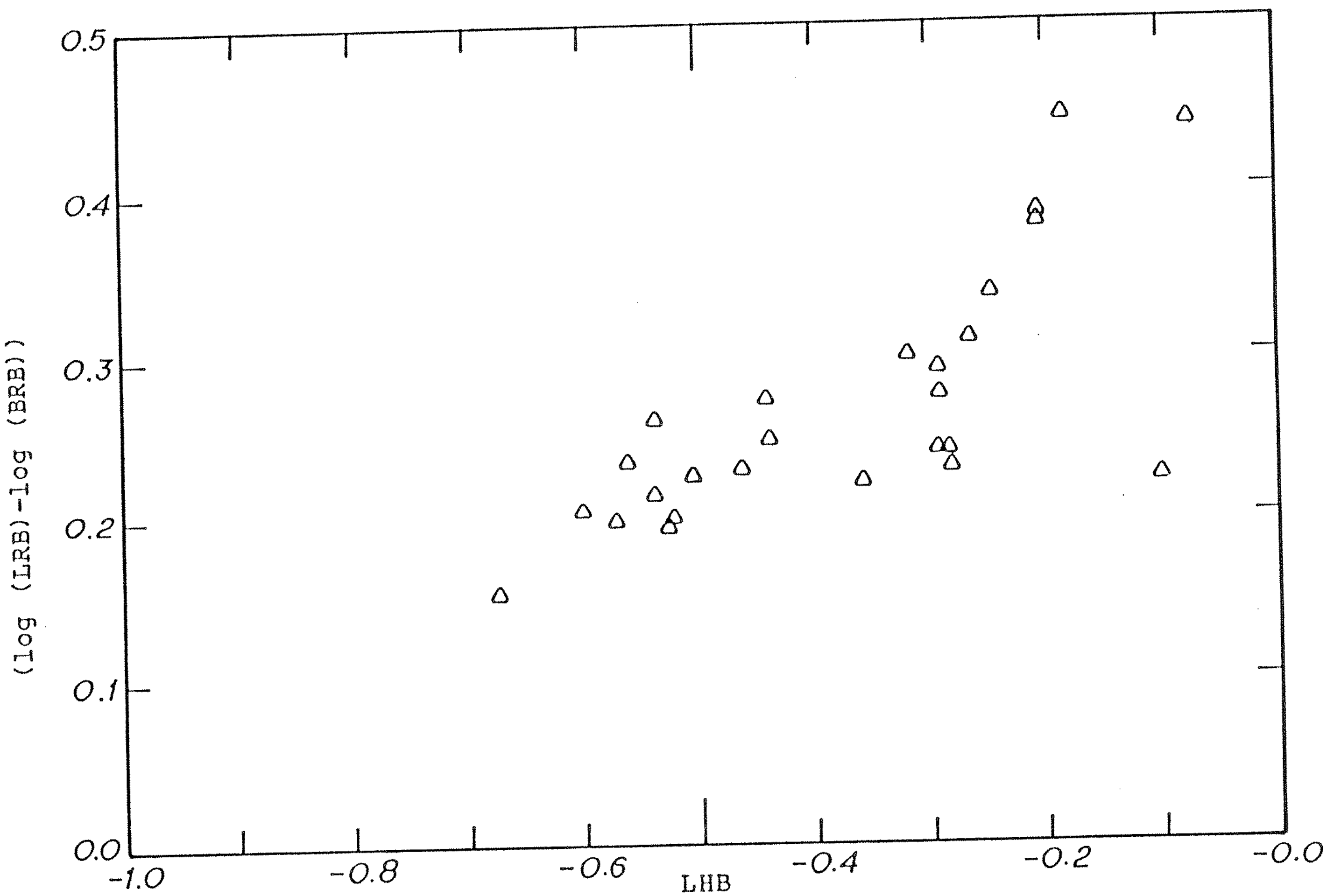


Figure 6. Plot of (log (LRB)-log (BRB)) versus LHB independent of the angle of repose.

Cluster Analysis

I created a large data base of morphological parameters for 24 Central American volcanoes and analysed it using the 2.0 SYSTAT (Wilkinson, 1986) microcomputer software for statistics. The morphological parameters included were all of the Shteynberg and Solov'yev (1976) parameters (i.e. BH, LH, BR, LR, BRB, LRB, and LHB), the edifice cone height (H_cO), the basal cone diameter (W_cO), and the angle of repose. Because the data included variables of different scale (i.e. the measurement units were not consistent across all variables), it was necessary to standardize the data set prior to initiating any clustering algorithyms. The SYSTAT software package (Wilkinson, 1986) computed a standardized unitless form by subtracting from each observation the mean of the data set and then dividing by the standard deviation. The standardized data file that resulted was a file of z scores for each observation. The transformed data set had a mean equal to zero and a variance equal to one. Standardizing prior to computing distance measurements ensured that each variable was weighted equally (Davis, 1973). Otherwise, the clustering algorithym would have been influenced most strongly by the variable which had the greatest magnitude.

The Systat software package modules are capable of performing a variety of statistical analysis including multiple regression analysis and cluster analysis.

Cluster analysis is a multivariate procedure used for detecting natural groups of data into a hierarchical classification.

The CLUSTER module computed a distance matrix for those cases specified. All distances were computed by the cluster module via pairwise deletion of missing values so that missing data does not influence the clustering process. The distance matrix that resulted was a measure of resemblance or similarity between pairs of objects. The coefficient of resemblance could have been either the correlation coefficient or a standardized n-space Euclidean distance called d_{ij}. I used a Euclidean distance clustering technique with a single linkage method. The single linkage method takes the distance between 2 objects or clusters as the distance between the two closest objects.

If there are n objects with m measurements on each object, a n x m similarity matrix will be computed where the euclidean distance is $d_{ij} = (x_{ik} - x_{jk})^2$. If d_{ij} is a small distance, the 2 objects are similar or "close together". Dissimilarity between the two objects is indicated if d_{ij} is a large distance. The distance coefficient, d_{ij}, is not constrained within 1 and -1 like the correlation coefficient and the resulting similarity matrix may produce a more effective dendrogram especially if a few of the objects are very dissimilar (Davis, 1973).

Clustering analysis of Central American composite cones produced five groups or "morphotypes" based on different morphometric parameters (see Fig. 7). The cophenetic value or level of clustering was .33.

The first group of volcanoes (referred to as Group 1) included Irazu, Barba, Poas, and Santa Ana volcanoes. This group of volcanoes includes the largest Central American composite cones with an average edifice height of 1.85 km, and an average basal cone diameter of 23.13 km. Most notably, Group 1 volcanoes have a very small angle of repose ranging from 9 - 18 degrees. These volcanoes are also among the most voluminuous as measured by Carr (1984).

The second group of volcanoes (referred to as Group 2) includes Concepcion , San Vicente, and Arenal volcanoes. These volcanoes are much smaller than those volcanoes in Group 1 and have an average edifice height of 1.45 km and an average basal diameter of 10.47 km. These volcanoes also have a much steeper angle of repose (approximately 29 degrees) than those volcanoes in Group 1. In addition, the upper cone of the volcano is more well defined and the height BH (after Shteynberg and Solov'yev) averages .98 km in comparison to .79 for those in Group 1. The radius of the upper cone BR, is only half that of Group 1.

The third group of volcanoes (referred to as Group 3) includes Tajumulco, Atitlan, Aqua, Fuego, and Santa

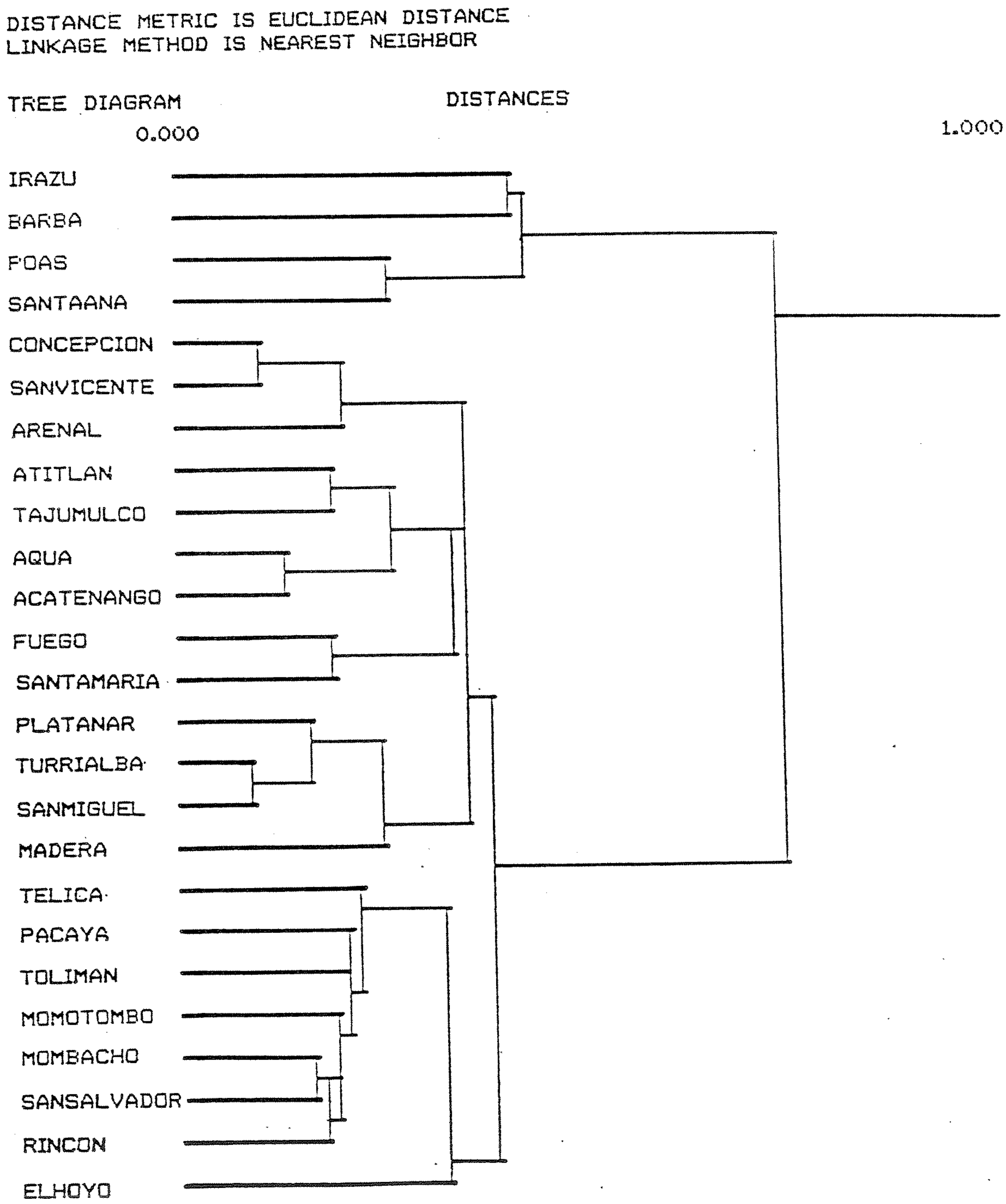


Figure 7. Cluster dendogram produced from cluster analysis using Wilkenson, (1986).

Maria volcanoes. All of these volcanoes lie within the beginning 185 km of the volcanic front in northwest Guatamala. This suggests that the shape of the volcanoes in Group 3 may be tectonically controlled. Volcanoes in this group have the greatest average edifice height (2.1 km) and an average basal diameter of 15.4 km. These volcanoes also have a steep angle of repose with the average being 28.4 degrees. Volcanoes in this group tend to exhibit the classic or "ideal" cone shape that Wood (1978) described. This group has the largest upper cone height, BH, nearly double that of all the other groups.

Another group of volcanoes (referred to as Group 4) consists of Platanar, Turrialba, San Miguel and Madera volcanoes. These volcanoes have an average edifice height of 1.66 km and an average basal diameter of 12.08 km. This group appears to be similar to those volcanoes in Group 2 except that these volcanoes (Group 4) have a wider upper cone (greater BR) and smaller angle of repose (22.6) than those in Group 2.

The last group of volcanoes (referred to as Group 5) has the most morphologic variability. Telica, Pacaya, Toliman, Momotombo, San Salvador, Rincon, and El Hoyo volcanoes are included in Group 5. These volcanoes range in edifice height from .85 km (Telica) to 1.5 km (Rincon). The basal diameter also ranges from 7.25 km (Toliman) to 18.0 km (Rincon). The angle of repose varies from 20 to 30 degrees. This group of volcanoes may represent an anomalous group of volcanoes that are morphologically dissimilar from the other four groups of volcanoes rather than morphologically similar to each other. In fact, at the cophenetic value of .33, El Hoyo still did not cluster with any other volcanoes. I lumped El Hoyo into Group 5 because I felt that this group represented a "potpourri" of volcano shapes linked together because these volcanoes were not morphologically similar to volcanoes in Groups 1 - 4.

Group 5 volcanoes may have clustered together only as a result of the clustering technique. Cluster analysis can produce clusters that are not "real". Factor analysis would have to be performed to determine if these clusters are "real" or only an artifact of the clustering technique.

It does, however, seem reasonable that Groups 1 - 4 may represent "real" clusters or "morphotypes" for Central American composite volcanoes. Figure 8 illustrates the 4 "morphotypes" that I constructed based on the cluster analysis. The sketch for each "morphotype" represents the average dimensions for all the volcanoes assigned to that group.

For Groups 1 - 4, the previously described least-square exponents and coefficients have similar values within each group. This is not rurprising because both are dependent upon the edifice height. The edifice height was one of the parameters used to define the groups or clusters.

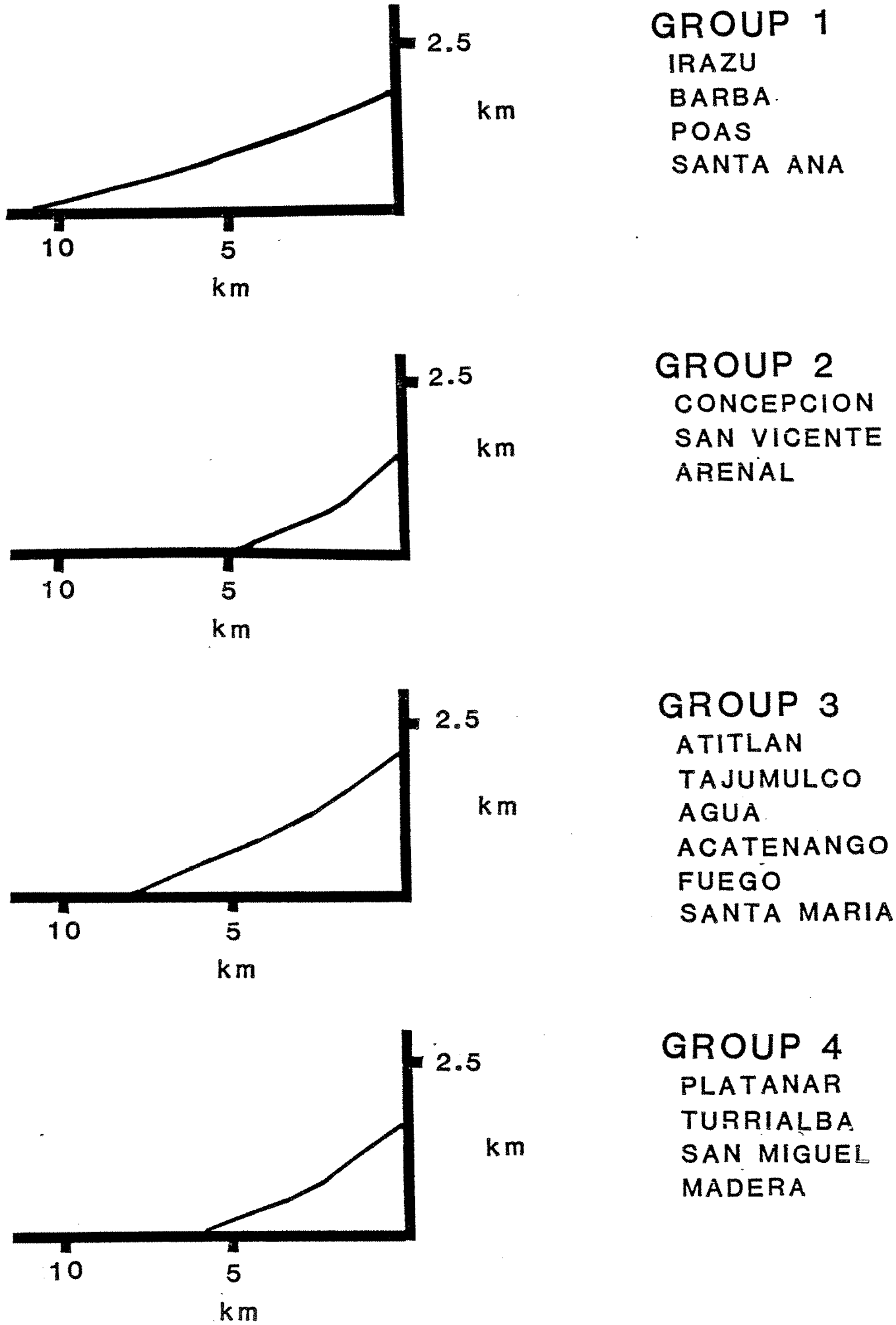


Figure 8. Four "morphotypes" interpreted from dendogram produced using Wilkenson, (1986) cluster analysis.

Table 4. Parameters of Central American Volcano Clusters

	HcO	WcO	BH	LH	BR	LR	Repose
<u>Group 1</u>							
Irazu	2.0	26.0	1.15	.60	5.00	8.71	12.9
Barba	1.9	23.7	0.55	.43	3.40	5.68	9.1
Poas	1.7	18.8	0.76	.23	3.23	5.03	13.3
Santa Ana	1.8	24.0	0.75	.38	2.31	4.51	18.0
<u>Group 2</u>							
Concepcion	1.6	13.0	1.02	.30	1.73	2.82	30.5
San Vicente	1.65	12.0	1.00	.25	1.99	3.19	26.6
Arenal	1.1	6.4	0.91	.19	1.59	2.26	29.7
<u>Group 3</u>							
Atitlan	2.0	16.6	1.39	.71	2.19	4.13	32.4
Tajumulco	2.05	8.6	1.26	.66	2.36	4.00	28.1
Aqua	2.16	24.2	1.65	.52	3.00	5.03	28.8
Acatenango	2.16	19.0	1.88	.50	3.12	4.91	31.0
Fuego	2.16	12.0	2.07	.60	3.91	7.12	27.8
Santa Maria	1.8	12.0	1.69	.61	4.16	7.34	22.1
<u>Group 4</u>							
Platanar	1.49	11.65	0.89	.50	2.44	5.26	22.1
Turrialba	1.90	13.70	0.97	.47	2.28	4.41	23.1
San Miguel	1.85	12.70	0.97	.50	2.16	3.76	24.3
Madera	1.38	10.25	1.00	.30	2.63	4.16	20.8
<u>Group 5</u>							
Telica	0.85	11.55	0.26	.16	0.45	1.09	29.7
Pacaya	--	10.20	0.54	.29	1.06	1.83	27.2
Toliman	0.91	7.25	0.93	.41	1.56	2.60	30.7
Momotombo	1.10	7.65	0.56	.35	1.12	2.69	26.6
Mombacho	1.25	14.00	0.52	.29	1.32	2.68	21.6
San Salv.	1.45	16.60	0.51	.18	1.37	2.57	20.6
Rincon	1.5	18.00	0.52	.34	1.00	2.77	27.4
El Hoyo	0.99	12.50	0.32	.27	0.90	2.47	19.6

H_cO, W_cO, BH, LH, BR, and LR in kilometers

Segmentation and Volcano Shape

Stoiber and Carr (1973) divided the Central American volcanic arc into seven segments based on differences in the strike of the volcanic front. The seven lineaments were characterized by similar volcano morphology, fault patterns, and distribution of shallow earthquakes. Segment boundaries occurred at major offsets in the strike of the front, and were characterized by faulting transverse to the front, clusters of cinder cones occuring behind the front and concentrations of shallow earthquakes occuring adjacent to the front. Historically, some of the most catastrophic volcanic eruptions have occured at segment boundaries in Central America.

Carr (1976) refined the Central American segmentation model by dividing Costa Rica into two separate segments with the segment boundary located near Arenal volcano. Carr's eight segments for the Central American volcanic front varied in length from 45 to 240 kilometers.

Figure 9 shows the segmented Central American volcanic front. The stipled areas represent the segment boundaries proposed by Carr (1976). The five groups or clusters of volcanoes which I recognized using cluster analysis, are represented by different symbols.

Group 1 volcanoes (plotted as solid triangles in Fig. 9) are large volcanoes with very shallow slopes.

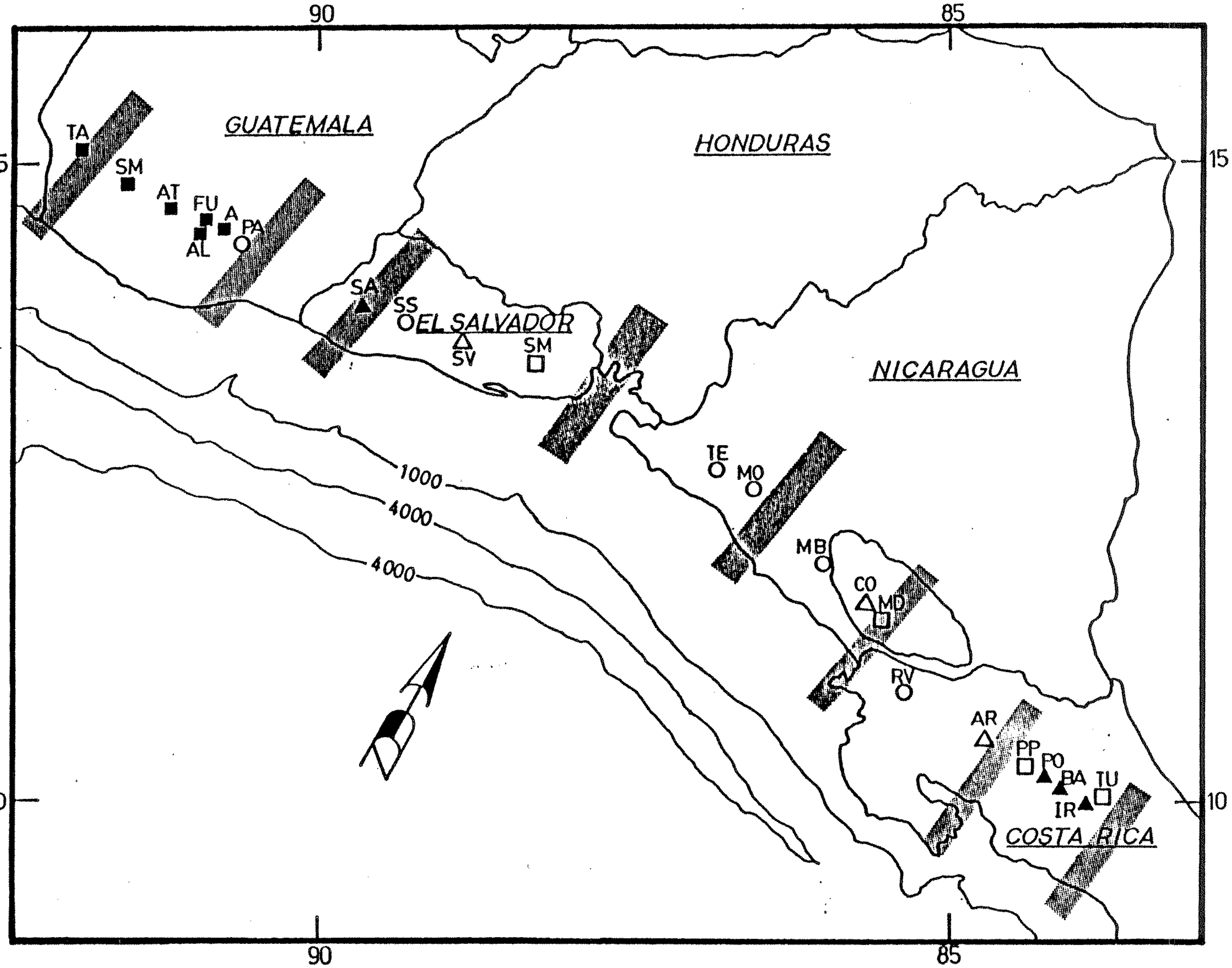


Figure 9. Location of groups of volcanoes in the segmented Central American volcanic front.

FIGURE 9: KEY

TA = Tajumulco
SM = Santa Maria
AT = Atitlan
TO = Toliman
FU = Fuego
AL = Acatenango
A = Agua
PA = Pacaya
SA = Santa Ana
SS = San Salvador
SV = San Vicente
SM = San Miguel
TE = Telica
MO = Momotombo
MB = Mombacho
CO = Concepcion
MD = Maderas
RV = Rincon de la Vieja
AR = Arenal
PP = Platanar
PO = Poas
BA = Barba
IR = Irazu
TU = Turrialba

With the exception of Santa Ana in El Salvador, Group 1 volcanoes are found only in Central Costa Rica. The exponents of the least-square function for the upper cone range from -.07 to -.04. These are the largest values for the upper cone exponents in all of Central America.

Group 2 volcanoes (plotted as open triangles in Fig. 9), are found mostly near segment boundaries. The exponents of the least-square function describing the upper cone range from -.6 to -.3. This group is characterized by the smallest upper cone exponents.

Group 3 volcanoes (plotted as solid squares in Fig. 9), are located only in Guatemala. Exponents range from -.23 to -.20, with the exception of Tajumulco (-.16), and are located mostly in Central Guatemala.

Group 4 (plotted as open squares in Fig. 9), also occur mostly near segment boundaries. Exponent values range from -.39 to -.16, with the exception of Maderas which is the only Central American volcano with a linear least-square curve.

Group 5 volcanoes were previously interpreted as an artifact of the clustering technique. These volcanoes were plotted as open circles in Fig. 9.

Conclusions

I examined the morphology of the Central American volcanic front and attempted to apply various analysis techniques to morphologic data collected from computer generated topographic profiles.

The relationship between edifice height and basal cone width for Central American volcanoes was found to be log-linear rather than linear as previously suggested by Wood (1978). This suggests that the edifice height and basal cone diameter have an exponential relationship with the smallest H_c O and W_c O having a near linear relationship, the intermediate H_c O and W_c O exponentially or logarithymically related, and the largest H_c O and W_c O with an increased linear slope.

I fit least-square or best-fit power, exponential, and linear equations to topographic profiles of 24 Central American volcanoes.

The power function, $y = a * e^{b * x}$, used in allometric analysis, proved to be a poor fit to the actual topographic data. Instead, the exponential curve proved to be the best-fit function for this study.

The standard reference coordinate system employed by the ALLOFIT program allowed me to compare values of the derived exponents and coefficients of the least-square exponential curve. A regional variation similar to that proposed by Carr (1984) for crustal thickness was recognized for both the derived exponents and coefficients. The crustal thickness, exponent, and coefficient tend to be greatest for Guatemalan and Costa Rican volcanoes and smallest for Nicaraguan volcanoes.

The smaller and shorter volcanoes of Nicaragua needed smaller exponents in order to achieve an angle of repose close to 30 degrees. The larger and higher Guatemalan volcanoes can achieve the same angle of repose with larger exponents. Throughout most of Central America, the edifice height and the angle of repose interact to create different volcanic landforms. In Central Costa Rica, however, the volcanoes tend to have smaller edifice heights and smaller angles of repose than the Guatemalan volcanoes. The oceanic crust beneath Central Costa Rica may influence the observed morphology and serve to limit the edifice height and the angle of repose. This oceanic crust is younger and less dense than the continental crust beneath Guatemala, Nicaragua, and El Salvador (Pichler et al, 1973). Since, the crustal thickness is similar in Guatemala and Central Costa Rica, one might expect to observe similar volcano morphology. The Costa Rican volcanoes, however, are much shorter, flatter and broader than their Guatemalan counterparts. The geochemistry of the central Costa Rican volcanoes is also markedly different from the rest of the Central American front (Milionis, 1987). Clearly, distinct geologic phenomena are influencing the behavior of the Central Costa Rican volcanoes. The aseismic Cocos

Ridge intersects the Middle America trench near Central Costa Rica. This aseismic ridge influences the subduction zone geometry and eventually results in the termination of the Central American front to the south. The less dense and younger oceanic crust may exert a more dominant influence on the volcano morphology than the crustal thickness. Clearly, the Costa Rican volcanoes exhibit unique volcano morphology and geochemistry.

The Shteynberg and Solov'yev (1976) model applies well to the Central American volcanic front. I measured the values of BH, LH, BR, LR, LRB, BRB, and LHB, and the angle of repose for Central American stratocones.

I used multivariate cluster analysis techniques to identify different groups or clusters of volcanoes based on similar morphology. Morphological parameters used in the cluster analysis included all the Shteynberg and Solov'yev (1976) parameters, as well as the edifice cone height, basal cone diameter, and angle of repose.

The data set was standardized prior to initiating any clustering algorithyms to ensure that no scale bias influenced the resulting dendogram. Euclidean distance cluster analysis produced a dendogram for Central American stratovolcanoes. At a cophenetic value of .33, the dendogram produced five groups or clusters of volcanoes.

Factor analysis is a statistical method that is commonly used to test the validity of clustering techniques. Factor analysis was not undertaken in this study. Therefore, any conclusions that are drawn solely from the results of the clustering procedure are tenuous at best. Groups of volcanoes identified via the clustering program must be seriously scrutinized. This method should be used only as a tool in discriminating morphologic variations among Central American volcanoes.

Consequently, I interpreted the Group 5 volcanoes to represent an "imaginary" cluster which resulted as an artifact of the clustering technique. I believe that the volcanoes in group 5 were clustered together because they were more morphologically dissimilar from Groups 1 - 4 volcanoes. Volcanoes assigned to Group 5 exhibit the most variation in morphology.

The remaining four groups of volcanoes were interpreted as "real" clusters of composite cones. Figures 10A, 10B, 10C, and 10D illustrate how similar the volcanoes assigned to each group actually are. I constructed 4 "morphotypes" for Central American composite cones based upon the average dimensions of volcanoes assigned to the 4 groups.

GROUP 1
FIGURE 10A

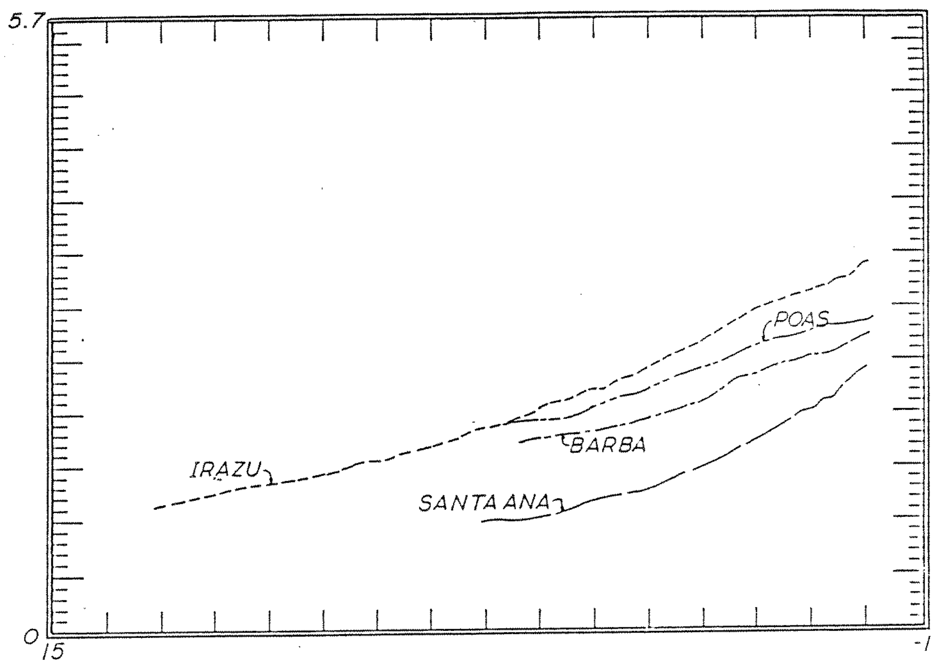
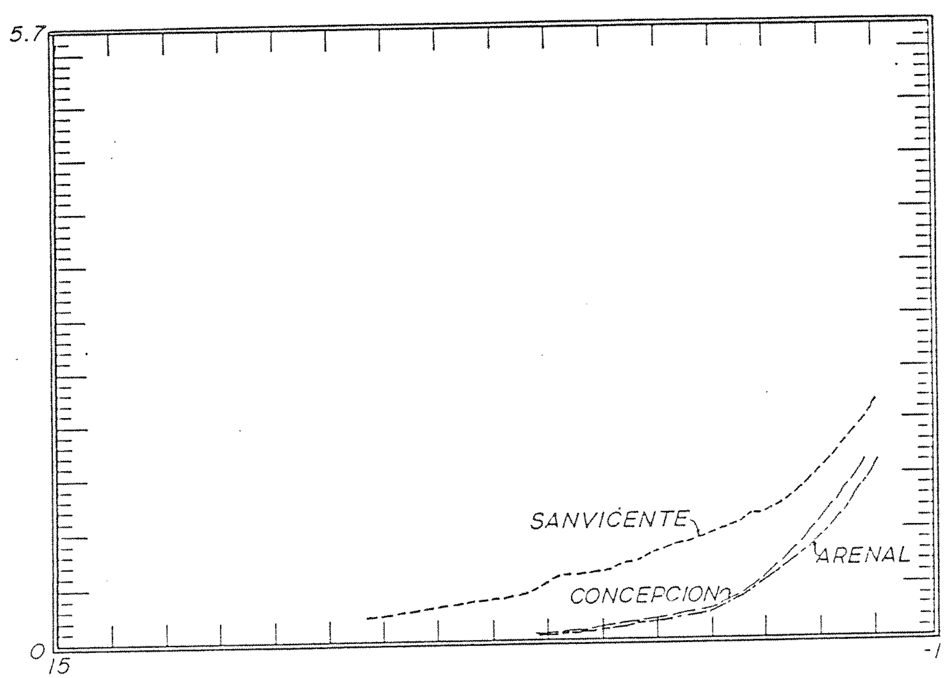
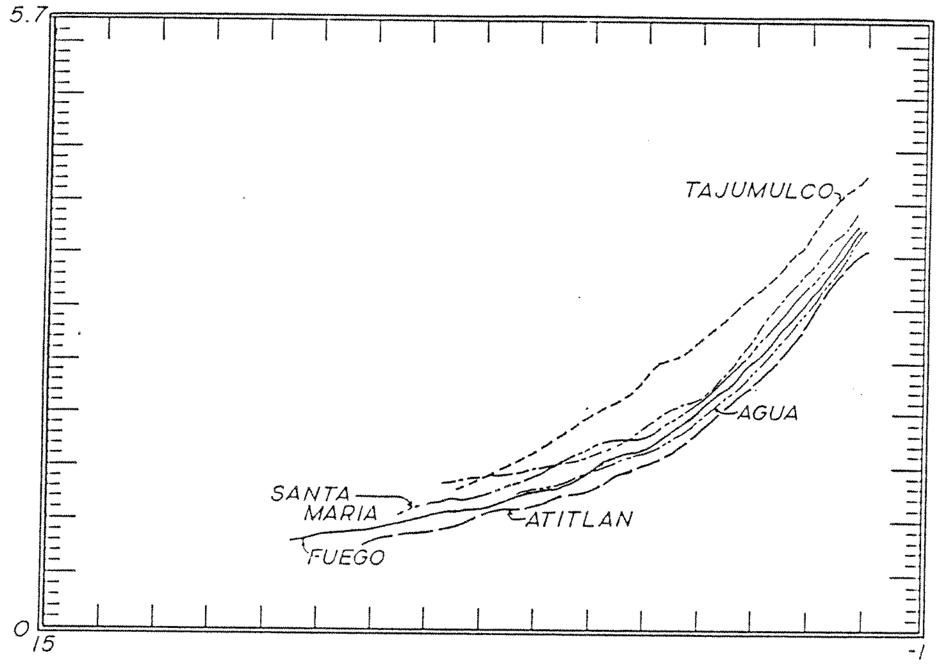


Figure 10. Topographic profiles of volcanoes assigned to Groups 1, 2, 3, and 4.

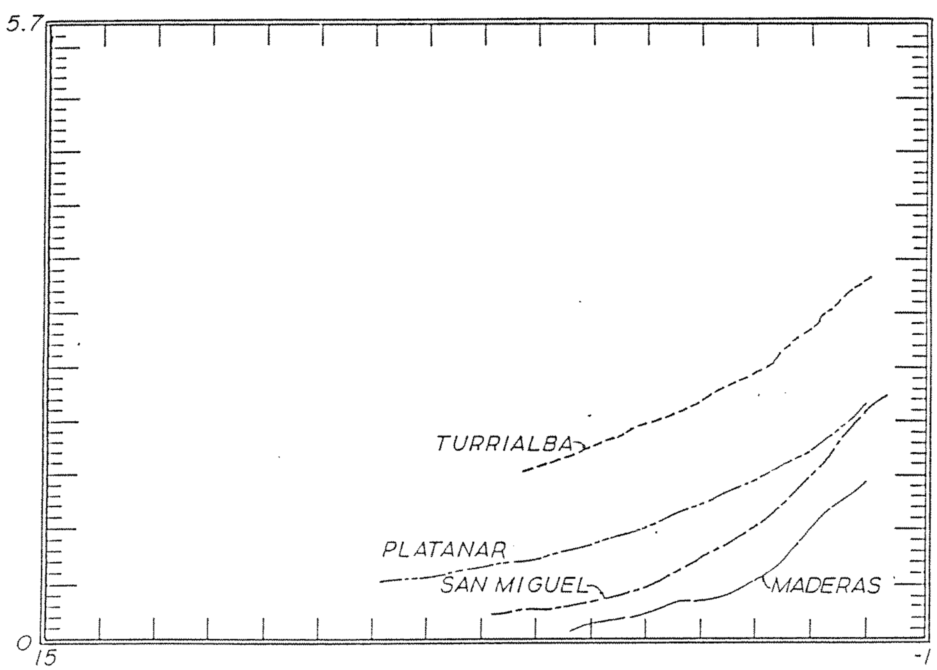
GROUP 2
FIGURE 10B



GROUP 3
FIGURE 10C



GROUP 4
FIGURE 10D



The four "morphotypes" appear to be tectonically controlled. Volcanoes assigned to Group 1 (except for Santa Ana) are located in Central Costa Rica. Volcanoes assigned to Groups 2 and 4 are found mostly near the segment boundaries proposed by Carr, (1976). Group 3 volcanoes are limited entirely to Guatemala and except for Tajumulco are specifically limited to the Central Guatelala segment.

References

Angevine, C.L., Turcotte, D.L., and Ockendon, J.R., 1984. Geometrical form of aseismic ridges, volcanoes, and seamounts. Jour. of Geophys. Res. v. 89, p. 11287-11292.

Bull, W.B., 1975. Allometric change of landforms. Geol. Soc. Am. Bull. v.80, p. 1489-1498.

Burbach, G.V., Frohlich, C., Pennington, W.D. and Matumoto, T., 1984. Seismicity and Tectonics of the Subducted Cocos Plate. Jour. of Geophys. Res. v.89, p. 7719-7735.

Burbach, G.V., and Frohlich, C., 1986. Intermediate and Deep Seismicity and Lateral Structure of Subducted Lithosphere in the Circum-Pacific Region. Jour. Geophysics, v. 24, p. 833-874.

Carr, M.J., Stoiber, R.E., and Drake, C.L., 1974. The segmented nature of some continental margins. In: <u>The Geology of Continental Margins</u>. C.A. Burk and C.L. Drake, eds., Springer Verlag, Hamburg.

Carr, M.J., 1976. Underthrusting and Quaternary faulting in Central America. Geol. Soc. Amer. Bull., v. 88, p. 151-156.

Carr, M.J., and Stoiber, R.E., 1977. Geologic setting of some destructive earthquakes in Central America. Geol. Soc. Amer. Bull., v. 37, p. 326-337.

Carr, M.J., Rose, W.I., and Mayfield, D.G., 1979. Potassium content of lavas and depth to the seismic zone in Central America. Jour. Volcano. Geotherm. Res., v. 5, p. 387-401.

Carr, M.J., 1984. Symmetrical and segmented variation of physical and geochemical characteristics of the Central American volcanic front. Jour. Volcan. Geother. Res. v. 20, p. 231-252.

Cross, T.A. and Pilger, R.H., 1982. Controls of subduction geometry location of magmatic arcs, and tectonics of arc and back-arc regions. Geol. Soc. Am. Bull. v. 93, p. 545-562.

Davis, J.C. <u>Statistics and Data Analysis in Geology</u>., John Wiley & Sons, New York, 1973.

Dean, B.W., and Drake, C.L., 1978. Focal mechanism solutions and tectonics of the Middle America arc.

Jour. Geology, v. 86, p. 111-128.

Francis, P.W. and Abbott, B.M., 1973. Sizes of Conical Volcanoes. Nature v. 244, p. 22-23.

Kelleher, M., and McCann, W., 1976. Bouyant zones, great earthquakes, and unstable boundaries of subduction. Jour. Geophys. Res. v.81, p. 4885-4890.

Lacey, A., Ockendon, J.R., and Turcotte, D.L., 1981. On the geometrical form of volcanoes. Earth Planet. Sci. Let. v. 54, p. 139-143.

Mammerick, J., and Klittgord, K.D., 1982. Northeast Pacific Rise: Evolution from 25 m.y. B.P. to present. Jour. Geophys. Res. v. 87, p. 6751-6759.

McBirney, A.R., Sutter, J.F., Naslund, H.R., Sutton, K.G., and White, C.M., 1974. Episodic volcanism in the central Oregon Cascade range. Geology, v. 2, p. 585-589.

Minster, J.B., and Jordan, T.H., 1978. Present day plate motions. Jour. Geophys. Res., v. 83, p. 5331-5354.

Molnar, P., and Sykes, L.R., 1969. Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. Geol. Soc. Am. Bull. v. 80, p. 1639-1684.

Pichler, H., and Weyl, R., 1973. Petrochemical aspects of Central American magmatism. Geol. Rund., v. 62, p. 357-396.

Pike, R.J., 1978. Volcanoes on the inner planets - some preliminary comparisons of gross topography. Proc. Lunar Planet. Conf. 9th., p. 3239-3273.

Shteynberg, G.S., and Solov'yev, T.V., 1976. The shape of volcanoes and the position of subordinate vents. Izv. Earth Phys. v. 5, p. 83-84.

Stoiber, R.E.,and Carr, M.J., 1973. Quaternary volcanic and tectonic segmentation of Central America. Bull. Volcanol. v. 37, p. 304-325.

Vogt, P.R., Lowrie, A., Bracey, D.R., and Hey, R.N., 1976. Subduction of aseismic oceanic ridges: effects on shape, seismicity, and other characteristics of consuming plate voundaries. Geol. Soc. Am. Spec. Pap. 172, 59 pp.

Wadge, G., and Francis, P.; 1982. A porous folow model for the geometrical form of volcanoes --- critical comments. Earth Planet. Sci. Lett. v. 57, p. 453-455.

Wood, C.A., 1978. Morphometric evolution of composite volcanoes. Geophy. Res. Lett. v. 5, p. 437-439.

Wood, C.A., 1980. Morphometric evolution of cinder cones. Jour. Volcanol. Geophys. Res. v. 7, p. 387-413.

Wood, C.A., 1982. On the geometrical form of volcanoes --- comment. Earth Planet. Sci. Lett. v. 57, p. 451-452.