

# Morphometry and evolution of arc volcanoes

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## ABSTRACT

Volcanoes change shape as they grow through eruption, intrusion, erosion, and deformation. To study volcano shape evolution we apply a comprehensive morphometric analysis to two contrasting arcs, Central America and the southern Central Andes. Using Shuttle Radar Topography Mission (SRTM) digital elevation models, we compute and define parameters for plan (ellipticity, irregularity) and profile (height/width, summit/basal width, slope) shape, as well as size (height, width, volume). We classify volcanoes as cones, sub-cones, and massifs, and recognize several evolutionary trends. Many cones grow to a critical height (~1200 m) and volume (~10 km<sup>3</sup>), after which most widen into sub-cones or massifs, but some grow into large cones. Large cones undergo sector collapse and/or gravitational spreading, without significant morphometry change. Other smaller cones evolve by vent migration to elliptical sub-cones and massifs before reaching the critical height. The evolutionary trends can be related to magma flux, edifice strength, structure, and tectonics. In particular, trends may be controlled by two balancing factors: magma pressure versus lithostatic pressure, and conduit resistance versus edifice resistance. Morphometric analysis allows for the long-term state of individual or volcano groups to be assessed. Morphological trends can be integrated with geological, geophysical, and geochemical data to better define volcano evolution models.

## INTRODUCTION

Volcano edifice shape and size result from the interplay between constructive and destructive (erosional and deformational) processes (Fig. 1A). During a volcano's life, its shape

evolves depending on the prevailing processes. Thus, volcano morphology potentially contains information on the balance of such factors as age, growth stage, composition, eruption rate, vent position and migration, degree of erosion,

lava/tephra ratio, and deformation, and ultimately on underlying factors such as magma flux and tectonic setting.

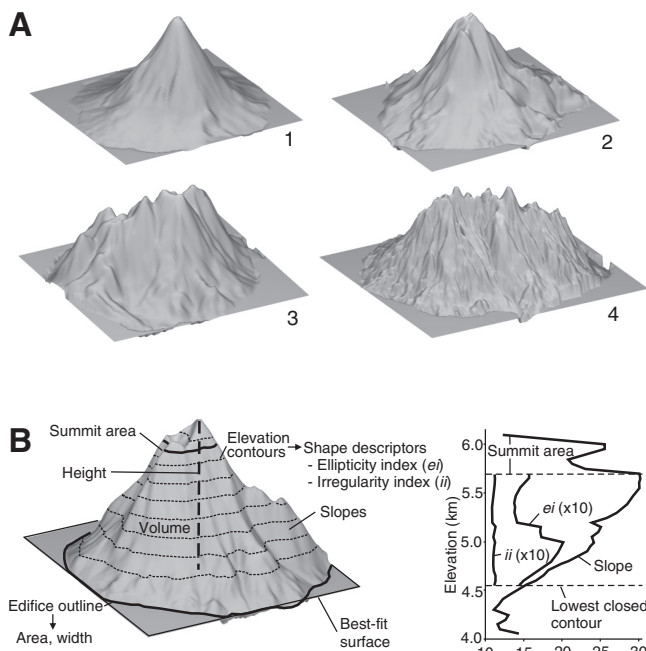
Since Cotton (1944) there have been relatively few studies of volcano morphology, although Francis (1993) and Thouret (1999) gave broad overviews. The morphometry of some specific volcano types has been studied in detail, such as cinder cones (e.g., Wood, 1980; Riedel et al., 2003), oceanic shields (e.g., Cullen et al., 1987; Michon and Saint-Ange, 2008), seamounts (e.g., Smith, 1996), and extraterrestrial volcanoes (e.g., Plescia, 2004). Systematic morphometric studies of polygenetic arc volcanoes are scarce at both individual and regional scale (e.g., Wood, 1978; Lacey et al., 1981; Carr, 1984; van Wyk de Vries et al., 2007), leading to varying morphological classifications that lack consensus, with different and overlapping terms such as simple, composite, compound, complex, cluster, multiple, twin, shield-like, and collapse scarred (e.g., compare classifications given in Macdonald, 1972; Pike and Clow, 1981; Francis, 1993; Simkin and Siebert, 1994; Davison and De Silva, 2000). Clearly, detailed morphometric studies are needed for a more rigorous quantitative classification and a better understanding of volcano shape evolution. Hone et al. (2007) went in this direction by means of cladistic analysis.

We present a morphometric analysis of polygenetic volcano edifices from two continental subduction arcs, the Central American Volcanic Front) and the southern Central Andes Volcanic Zone. We quantify, characterize, and classify volcanic edifice morphology, and then detect shape evolution trends that we relate to evolutionary processes. Here we specifically look for and interpret general trends; complementary detailed analyses of individual volcanoes should be a subsequent step.

## MORPHOMETRIC PARAMETERS

We have used 90 m spatial resolution digital elevation models (DEM) from the Shuttle Radar Topography Mission (SRTM). This is the best high-resolution global DEM data set (e.g., Rabus et al., 2003), and it is adequate for

**Figure 1. A:** Three-dimensional (3-D) images derived from Shuttle Radar Topography Mission digital elevation models showing different shapes of arc volcanoes. 1—Concepción (11.538°N, 85.623°W), simple symmetrical cone; 2—Ollagüe (21.308°S, 68.180°W), more complex cone; 3—Aucanquilcha (21.225°S, 68.469°W), composite volcano with a sub-conical shape; 4—Rincón de La Vieja (10.809°N, 85.319°W), complex massif. **B:** 3-D image of Araucario (24.297°S, 67.783°W) showing acquired morphometric parameters and corresponding diagram of elevation versus slope, ellipticity index, and irregularity index. See the Data Repository (see footnote 1) for all locations and data.



morphometric studies of stratovolcanoes (e.g., Wright et al., 2006; Kervyn et al., 2008). We have analyzed 59 Central American Volcanic Front and 56 southern Central Andes Volcanic Zone edifices (see the GSA Data Repository<sup>1</sup> for table, map, and additional material). Selected volcanoes have shown Holocene activity (Smithsonian Institution database, Siebert and Simkin, 2002) or are morphologically fresh. The seamless SRTM DEMs from the CGIAR-CSI (Consultative Group on International Agricultural Research–Consortium for Spatial Information) were used (Jarvis et al., 2008).

A basic morphometric uncertainty is the selection of volcano extent, as the aprons can merge with the surrounding landscape. We thus restrict our analysis strictly to the edifices, as they are generally clear landforms. Consequently, size data are an estimation of edifice size only and not total erupted volume. The outline of each edifice was user-estimated (details in the Data Repository).

Morphometric parameters were acquired using an expressly written IDL (interactive data language) code (MORVOLC; see the Data Repository for detailed descriptions of the parameters used). Basal area and width are obtained from the outline. The outline is also used to compute a best-fit surface from which height and volume are derived (Fig. 1B).

The shape of elevation contours at 50 m intervals is described using two independent indexes (Fig. 1B): (1) ellipticity index (*ei*), which quantifies contour elongation; and (2) irregularity index (*ii*), which quantifies contour irregularity or complexity. The *ei* and *ii* of successive contours define two independent profiles that together summarize volcano plan shape (Fig. 1B).

Slope values are derived from the DEM, from which total, flank, and maximum interval average slopes are calculated, as well as average slopes as a function of height (Fig. 1B). A summit area is calculated as the area above which slopes strongly decrease (Fig. 1B). The average slope values between successive height intervals define a profile that, together with height/width ( $H/W_B$ ) and summit width/base width ( $W_s/W_B$ ) ratios, summarize volcano profile shape (Fig. 1B).

## CHARACTERIZATION OF VOLCANO MORPHOMETRY

The Central American Volcanic Front and the southern Central Andes Volcanic Zone volca-

noes have a wide variety of shapes and sizes. They are contrasting examples of continental margin arcs: the Central American Volcanic Front is developed on thin to thick crust, contains many young and historically active volcanoes, and has a humid, erosive climate; the southern Central Andes Volcanic Zone is on thick crust, most volcanoes are dormant or extinct, and it has a very arid, low-erosion climate.

Figures 2–4 graphically display the morphometric features (also see Table DR1 in the Data Repository). Edifices of both arcs are grouped into four main shape classes: cone, sub-cone, massif, and shield. This classification is not absolute, as there is gradation and overlap in the data; it is based on a first-order grouping using the  $H/W_B$  ratio, then refined using the  $W_s/W_B$  ratio, the *ei* and *ii*, and the average flank slopes. Field knowledge and qualitative evaluation of DEMs, satellite images, and geological maps were used to sort out quantitatively uncertain cases. The morphometric differences between cones and massifs are clearly evident, while sub-cones are transitional. Within each type, differences between Central American Volcanic Front and southern Central Andes Volcanic Zone edifices can be found, but are small compared to differences between types. Shields are only found in the Central American Volcanic Front; they form a special subset of volcanoes with large calderas that we do not consider here.

## Cones

Cones have a simple conical shape, with circular base and steep, smooth concave profile. Their heights are 350–2250 m and volumes are  $<1 \text{ km}^3$  to  $75 \text{ km}^3$  (Fig. 2). They have elevated  $H/W_B$  ( $>0.15$ ), small summit areas ( $W_s/W_B <$

0.25), and circular (low *ei*) and regular (low *ii*) plan shapes (Fig. 3). Average flank slopes are  $21^\circ$ – $34^\circ$  and maximum interval slopes are  $27^\circ$ – $37^\circ$  (Figs. 3 and 4). There is a  $\sim 300 \text{ m}$  height interval at 1140–1430 m (corresponding to volumes of  $9$ – $13 \text{ km}^3$ ) where there is a clear lack of cones (only one volcano, Azufre, is present) (Fig. 2). The cones above this “cone gap” have slightly lower  $H/W_B$ , generally higher  $W_s/W_B$ , and are more irregular and elliptical (Figs. 3 and 4). Within this large cone subgroup is a set of paired or twin cones (Atitlán-Tolimán, Fuego-Acatenango, and San Pedro–San Pablo), which are characterized by higher  $W_s/W_B$  ratios and *ei* values (Fig. 3).

## Sub-Cones

Sub-cones have intermediate  $H/W_B$  of  $0.10$ – $0.16$ ; their  $W_s/W_B$ , plan shapes and slope values are very variable, but are also intermediate (Figs. 3 and 4). The larger sub-cones (volumes  $> 13 \text{ km}^3$ ) tend to be more irregular than the smaller ones (Fig. 4). With the exception of unusually large Pular-Pajonales, the sub-cones have heights of  $400$ – $1400 \text{ m}$  and volumes between  $1$  and  $46 \text{ km}^3$ . The lack of larger sub-cones with sizes equivalent to the larger cones and massifs creates a “sub-cone gap” at heights  $>1400 \text{ m}$  and volumes  $>46 \text{ km}^3$  (Figs. 2 and 3). There are different edifice types within the sub-cone class; some (e.g., Maderas) have low ellipticity and smaller summit areas, while others (e.g., Lascar, Aucanquilcha), are more elliptical and have larger summit areas.

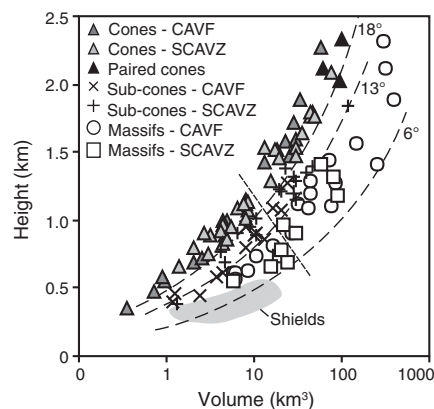
## Massifs

Massifs have low  $H/W_B$  ( $<0.10$ ), large summit areas ( $W_s/W_B > 0.30$ ) and low average slopes (average flank slopes  $<20^\circ$ ) (Figs. 2–4). They are irregular and usually quite elliptical (Fig. 3). The smallest massif volumes are  $5$ – $6 \text{ km}^3$ , larger than the smallest cones and sub-cones. The massif volume range is continuous up to  $\sim 90 \text{ km}^3$ ; five larger massifs are then found with volumes  $>150 \text{ km}^3$  (Fig. 2). These are the five central Costa Rica volcanoes, which are a particular case of huge massifs with more shield-like shapes. Shape parameters of massifs do not vary systematically with size, except for a slight increase in irregularity (Figs. 3 and 4).

## DISCUSSION: THE EVOLUTION OF VOLCANO SHAPES

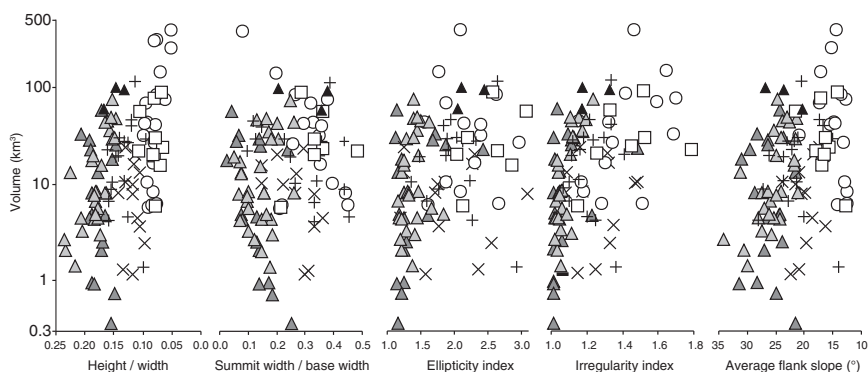
The wide variety of volcano shapes and sizes probably represents different growth stages. As the smallest volcanoes are all cones, a small ( $<1 \text{ km}^3$ ) conical edifice can be considered a morphometric starting point. From this simple, symmetrical, and smooth conical shape (e.g., Izalco), a range of evolutionary trends of volcano growth can be recognized (Fig. 5).

The most easily recognizable trend is where conical shape is conserved with vol-

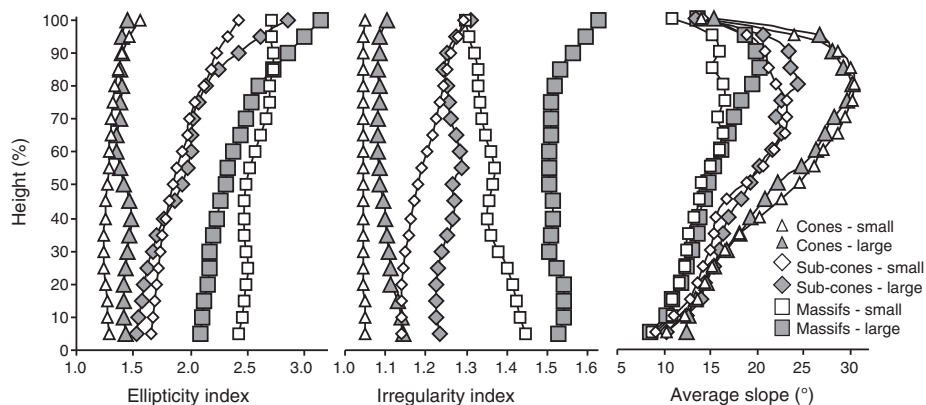


**Figure 2. Height versus volume diagram showing different types of studied volcanic edifices from Central American Volcanic Front (CAVF) and southern Central Andes Volcanic Zone (SCAVZ). Curves correspond to slopes of theoretical regular cones, which approximately separate three main edifice types. Straight line is threshold used to separate between small and large edifices in the text and in Figure 4.**

<sup>1</sup>GSA Data Repository item 2009151, Appendix (morphometric parameter acquisition and description), maps of the Central American Volcanic Front, and Table DR1 (location and morphometric details of all volcanoes used in this study), is available online at [www.geosociety.org/pubs/ft2009.htm](http://www.geosociety.org/pubs/ft2009.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



**Figure 3. Volume versus several shape parameters showing variations of shape with size of different volcanic edifice types. Symbols as in Figure 2.**



**Figure 4. Height versus plan (ellipticity and irregularity indexes) and profile (slope) shape parameters showing variation in average profiles of different volcanic edifice types and sizes.**

ume (Fig. 5). This simple evolution represents volcanoes that have one dominant vent and that lack major structural complications. This cone trend is continuous until the cone gap. Even before reaching the cone gap complexities do appear, but they do not alter significantly the overall shape of the edifice: for example, El Tigre has a tectonic scarp cutting its southern flank and thus has higher *ii* values; Vallecitos has more than one vent and thus is slightly elongated.

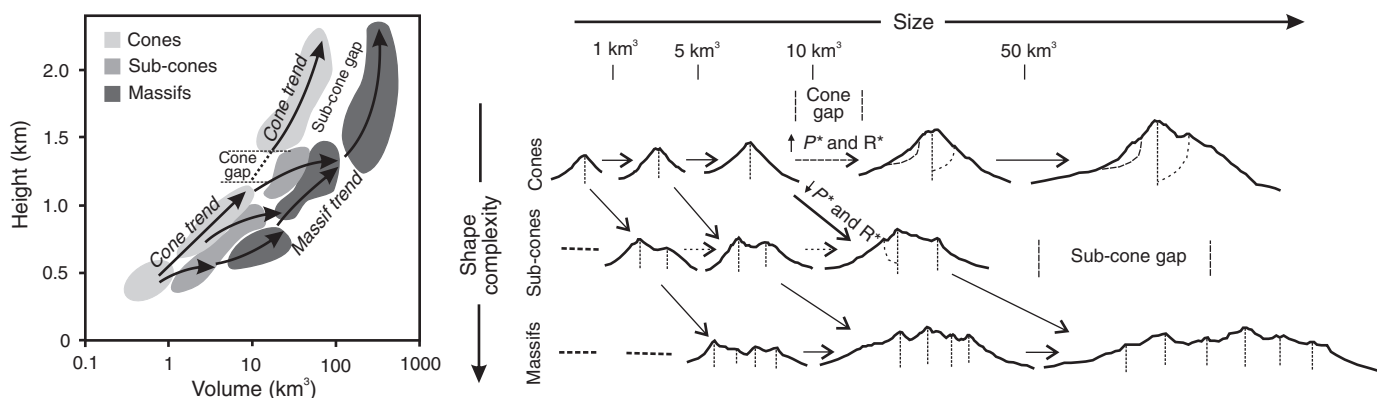
Evolution from cones toward sub-cones and massifs can occur before or at the cone gap height interval (Fig. 5). Evolution from initial cones toward more complex shapes is supported by detailed studies of individual volcanoes such as Lascar (Gardeweg et al., 1998) and Aucanquilcha (Klemetti and Grunder, 2008). The smaller sub-cones (e.g., Conchaguita, Irruputuncu) are elliptical and have large summit areas; they have more than one main vent and may evolve from cones by vent migration,

and they usually have a smooth conical profile in one direction but are elongated ridges in the opposite direction. Mid-sized sub-cones (e.g., Pacaya, Lascar) have shapes similar to the smaller sub-cones; they do not necessarily have more vents or a greater complexity, suggesting that they evolve from mid-sized cones rather than from smaller sub-cones.

The cone-sub-cone-massif evolution is characterized by volume increase with minor height increase ( $H/W_B$  decreases), enlargement of summit area ( $W_s/W_B$  increases), and increasing complexity (*ii* and *ei* increase). Once mid-sized massifs are formed (e.g., Telica, El Hoyo) they can continue growing toward larger massifs with increasing complexity, producing a massif trend (Fig. 5). Larger massifs can also evolve from mid-sized cones and sub-cones. Massifs have many, generally aligned, vents; they tend to form elongated ridges (e.g., Rincón de la Vieja, Olca-Paruma), but can also form irregularly shaped clusters (e.g., Cerro Bayo).

The cone gap height interval coincides with an interval of abundant sub-cones and massifs (Fig. 2), while at greater heights the sub-cone gap occurs (Figs. 2 and 5). The cone gap interval may reflect a critical height range from where two distinct evolutionary paths are possible; cones either continue growing upward and become large cones, or they grow sideways and become large sub-cones and massifs, resulting in a scarcity of cones at this height range.

Which of these paths a cone takes may partly depend on the balance between magma pressure ( $P_M$ ) and lithostatic pressure ( $P_L$ ), factors commonly used to explain maximum edifice heights (e.g., Eaton and Murata, 1960; Davison and De Silva, 2000). A pressure balance,  $P^* = P_M/P_L$  can describe this effect:  $P^*$  will tend to decrease with height (as  $P_L$  increases) and summit eruptions will become increasingly less likely. Only those cones with high enough  $P_M$  will be able to maintain a high  $P^*$  and continue growing as large cones. Cones with lower  $P^*$  will not be able to erupt from their main vents, favoring shallow magma storage and the opening of new



**Figure 5. Left: Height versus volume diagram showing fields of three main types of volcanic edifices and possible evolutionary trends. Right: Possible evolutionary growth paths of volcanoes starting from small simple cone.  $P^*$  is pressure balance and  $R^*$  is resistance balance**

side vents. Such volcanoes will probably evolve toward sub-cones with increasingly complex shapes, larger summit areas, and more vents, until eventually becoming massifs.

Another important factor is the balance between conduit resistance ( $R_c$ ) and edifice resistance ( $R_e$ ). We suggest a simple resistance balance,  $R^* = R_e/R_c$ , where if  $R_c$  is low (e.g., open magma-filled conduit),  $R^*$  will be high and the cone will continue growing through its main conduit. In contrast, if  $R^*$  is low, either because of a blocked conduit (high  $R_c$ ) or low edifice resistance (low  $R_e$ ), then vent migration will dominate.  $R_e$  will depend on cone material and the degree of fracturing and faulting, which will be related to structural conditions. The cone gap may be a point where  $P^*$  and  $R^*$  reduce to a critical threshold. This threshold may be reached earlier if  $R_e$  is lowered by structural instabilities, favoring evolution toward small and medium-sized sub-cones at heights below the cone gap.

Large cones will be most prone to gravitational spreading (e.g., Concepción) and sector collapses (e.g., Ollagüe, Socompa). Spreading will slowly lower height and increase width, while sector collapse will rapidly reduce height and regularity. However, many edifices that have undergone these processes maintain their conical shape, possibly because of growth after or during these events (e.g., Ollagüe; Vezzoli et al., 2008); only cones that cease to be active for long periods will be significantly modified by sector collapse or spreading, evolving toward sub-conical shapes (e.g., Maderas, Mombacho).

There are known geographical variations of edifice morphometry in the Central American Volcanic Front (e.g., Stoiber and Carr, 1973; Weyl, 1980). These can be often related to local tectonics: for example, in Nicaragua, sub-cones and massifs are located on fault zones, while cones are on undisturbed crust (van Wyk de Vries, 1993; van Wyk de Vries et al., 2007). In addition, one of us (van Wyk de Vries, 1993) showed that each morphological type of volcano had different magma types and eruptive styles. Massifs may be complexes with shallow magma storage, while cones develop predominantly deep magma chambers. These observations show the potential for coupling tectonic, magmatic, eruptive, and morphological phenomena into one unified volcano evolutionary model.

## CONCLUSIONS

Using morphometric parameters, volcano morphology can be summarized and quantified. We find that volcanoes can be grouped into distinct morphometric classes that suggest distinct evolutionary trends. Despite different settings, the two studied arcs have volcanoes that are in similar morphometric classes. This suggests that volcano morphometry depends on general processes. Hence, we can make general statements about morphological evolu-

tion and obtain a generalized model (Fig. 5). We anticipate that this model will be applicable to other volcanic settings.

From initial small cones several shape evolution trends are possible that depend on the prevailing processes, especially pressure and resistance balances ( $P^*$  and  $R^*$ ). If no tectonic complications arise, small cones grow until reaching ~1200 m. Before reaching this height, cones can evolve to sub-cones and eventually massifs due to structural conditions or unusually low  $P^*$ . At ~1200 m, cones reach a critical height (low  $P^* + R^*$ ) and most start growing sideways by forming new vents, and evolve to sub-cones and massifs. Those with high enough  $P^*$  and  $R^*$  will continue growing as cones. These larger cones will be prone to sector collapse and gravitational spreading, but they retain their overall conical shapes.

This study shows how volcano morphometry can be used to obtain information on processes operating during volcano construction. It also contributes toward a more precise and quantitative classification of volcanoes and a characterization of shape evolution trends for arc volcanoes. Such a classification, and its resultant interpretation of evolutionary trends, provides the framework for examining related structural, magmatic, and eruptive processes.

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