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Slopes of western Galapagos volcanoes from airborne interferometric radar

Peter J. Mouginis-Mark, Scott K. Rowland and Harold Garbeil

Hawaii Institute of Geophysics and Planetology and Hawaii Center for Volcanology, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu

Abstract. The distribution of slopes on the six basaltic shield volcanoes in the Western Galapagos Islands is investigated using a digital elevation model derived from airborne interferometric radar (TOPSAR) data. These measurements have a spatial sampling of 10 m/pixel, a vertical accuracy of 3 to 5 m, and constitute the highest resolution, most complete, topographic data set available for the islands. Volcano heights are determined to range from 1,124 m (Sierra Negra) to 1,710 m (Wolf). Over extensive areas of each volcano, slopes exceed 25°, with the highest slopes being ~37° on Wolf and ~36° on Fernandina. We confirm that two morphologic subgroups exist: Cerro Azul, Fernandina, and Wolf, with deep calderas (depth between 40–60% of the subaerial height of the volcano) and steep (>20°) maximum slopes at elevations between ~60 and 80% of the volcano height; and Alcedo, Darwin, and Sierra Negra, with shallow calderas (depth <25% of subaerial height) and slopes that remain <15° until ~90% of the total height is reached. Our data show that steep slopes are not uniquely correlated with the occurrence of arcuate fissures at the summit, leaving the origin of the steep slopes unresolved.

Introduction

For over 25 years, the volcanoes of the Western Galapagos Islands have been enigmatic by virtue of their "inverted soup plate" profiles (McBirney and Williams, 1969; Nordlie, 1973). Field observations have suggested a correlation between steep slopes and arcuate fissures at the summit (Simkin, 1972, 1984), but detailed topographic analysis of these volcanoes has been hindered by the geographic isolation of the islands, the lack of complete stereo air photography, and the extreme difficulty of conducting detailed field work because of pervasive aa lava flows (e.g., Chadwick and Howard, 1991; Reynolds et al., 1995). The study of the topography of these volcanoes offers the potential for significant new insights into the structure, eruptive history, and erosion styles of basaltic shields.

Recent developments in interferometric radar remote sensing provide a method for deriving detailed topographic and slope information for volcanoes such as those in the Galapagos. In May 1993, the airborne TOPSAR instrument (Zebker et al., 1992) was flown over the western Galapagos islands of Fernandina and Isabela. Almost complete data coverage was obtained for both islands. This paper presents our preliminary analysis of the distribution of subaerial slopes and heights of these volcanoes as determined from these TOPSAR data.

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Data Quality

The TOPSAR system produces height measurements on a 10-m spatial grid. Over volcanic terrain, these data have an estimated vertical relative accuracy because of random noise in the 3–5 m range (Madsen et al., 1995; Rowland,). Based on aircraft navigational data (aircraft roll accurate to 0.01°; Zebker, pers. comm. 1996), worst case systematic errors in height measurements due to aircraft roll across the swath are ~10 m. Thus random noise and systematic height errors are not expected to be significant for this study, given that our objective is to distinguish between areas of high slopes (>21°) and low slopes (<9°) at a horizontal scale of several kilometers. Because of the 10-km swath width limitation of TOPSAR, multiple flight lines had to be flown over the islands to obtain necessary coverage, and cross-track calibration errors have produced a striping in the data that is most easily seen in the derived slope map (Fig. 1). No formal assessment of map errors has been undertaken, but visual inspection of the data indicates that the striping along N25W on Alcedo, Wolf, and Darwin, and along N60E across Sierra Negra, are artifacts. We therefore qualitatively estimate that in these places the derived slopes may be inaccurate by ~2–4°.

Although some data gaps exist, ~5,225 km^2 of the islands were imaged and merged into a single data file. The flight pattern used to maximize acquisition efficiency meant that data were acquired from two opposite look directions. Where the flight lines were spaced too far apart, areas of high relief in the far range of the swath experienced dropouts caused by image displacement (H. Zebker, pers. comm. 1996). During data processing (performed by the Jet Propulsion Laboratory), it was possible fill in some of these gaps by processing the edges of several radar swaths with partial length radar reference functions. This technique extends the imaged swath at the expense of radar resolution, but in the remaining areas even this technique resulted in the WSW-ENE gaps in the data for the caldera floors of Cerro Azul and Sierra Negra volcanoes. Comparable problems with data loss were also experienced for the eastern middle flank of Wolf volcano and the upper eastern flank of Darwin, where the steep slopes produced radar shadows.

TOPSAR data reveal that Wolf is the highest volcano, with a maximum elevation of 1,710 m. Heights for the other five

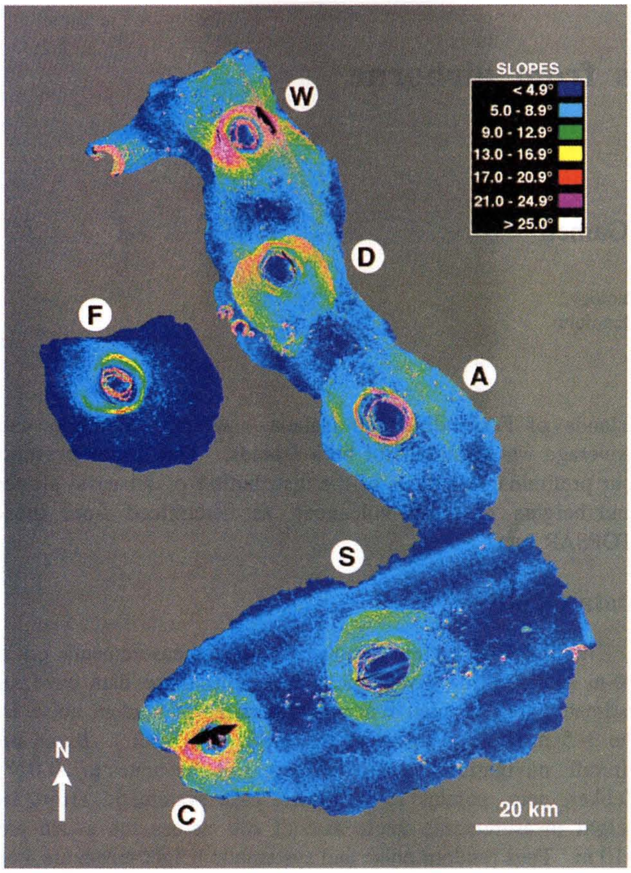

Figure 1. Slope map of the western Galapagos islands, as determined from TOPSAR data. The area shown extends from 0.10°N to 1.05°S, 90.45°W to 91.40°W. See Appendix 1 for the algorithm used to determine these slopes. Volcanoes are designated as follows: S–Sierra Negra; D–Darwin; C–Cerro Azul; A–Alcedo; W–Wolf; F–Fernandina. Data gaps on Cerro Azul, Sierra Negra, and Wolf are due to the excessive spacing between the TOPSAR flight paths and are shown in black.

volcanoes are 1,130 m (Alcedo), 1,462 m (Darwin), 1,124 m (Sierra Negra), 1,637 m (Cerro Azul), and 1,470 m (Fernandina).

Distribution of Slopes

We determined the slopes of each volcano by using a 3 x 3 pixel array, calculating slopes over a 30-m horizontal baseline with the algorithm described in Appendix 1. Figure 1 shows that the distribution of slopes is nonsymmetric with respect to the summit caldera of each volcano. Remarkably steep slopes (up to 37°) are found on the western side of Wolf, the SW flank of Cerro Azul, and the southern flank of Fernandina. The SE flank of Darwin rises gently at ~5–9° almost all the way from the coast to the summit, and comparable shallow slopes exist on the NW flank of Fernandina. Large gently sloping regions (<5°) exist around the coasts of Fernandina and Sierra Negra and the saddles between the other volcanoes, while the steep western flanks of Cerro Azul (>17°) plunge from the summit to the ocean.

Inspection of the slope map shows that narrow rift zones have not been recent features of any Galapagos volcano. Eruptions have built broad shallow-sloping saddle regions between Wolf and Darwin, between Cerro Azul and Sierra Negra, and between Darwin and Alcedo. No elongation toward an adjacent volcano is seen in the slope map that could be interpreted as a rift zone. In contrast, on the western sides of Wolf and Darwin, sharp breaks in slope within 5 km of the coast show that recent flows on the coastal plain have buried the steeper, older flanks (Chadwick and Howard, 1991).

Slope statistics were collected for each volcano in 20-m elevation intervals (Fig. 2). At this vertical resolution, a typical number of data points in each elevation interval at low elevations is 10^4 to 10^5 (i.e., 1 to 10 km^2). Within 100 m of the summit, the area of each interval falls to ~0.1 km^2 (10^3 pixels). Slopes at each elevation interval exhibit a relatively large spread with standard deviations typically ranging from 5 to 10°. The distribution of elevation vs. slope (Fig. 2) indicates two different subsets of volcanoes corresponding to volcano groupings. Type 1 volcanoes (Alcedo, Darwin, and Sierra Negra) have shallow slopes over their entire height

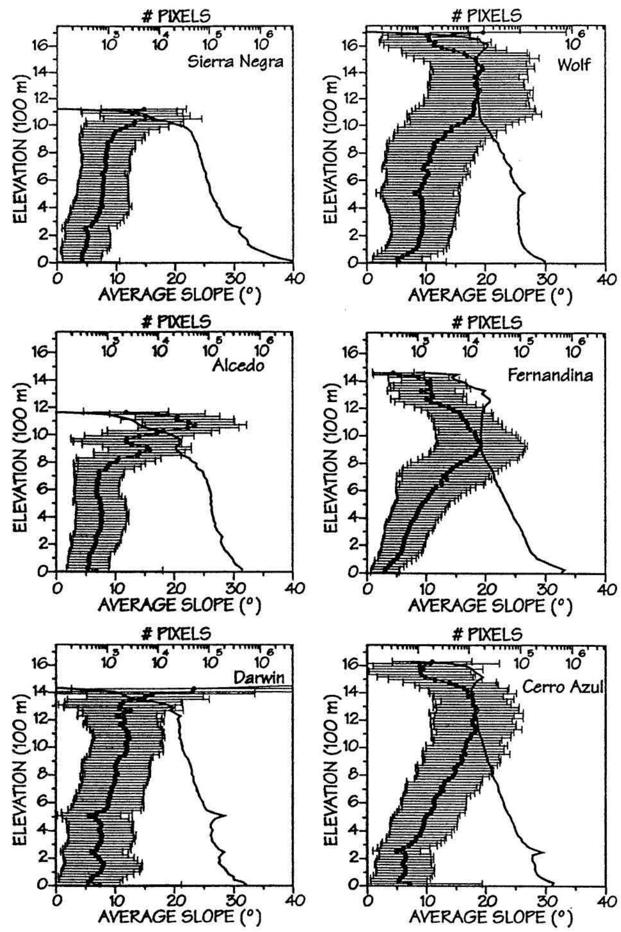

Figure 2. Distribution of the average slopes and the number of 10 x 10 m pixels at each elevation for the six western Galapagos volcanoes, using the boundaries defined by Munro (1992). Data are presented in 20-m height increments; error bars indicate 1 s.d. (typically ~5°) about the mean. Note that there are certain elevation increments on Cerro Azul, Fernandina, and Wolf where slopes are all >10°. On Fernandina, extensive areas (>20 km^2) have average slopes of >18°. The spikes in the curves of the number of pixels at elevation between 200 and 500 m are indicators of the large scale morphology of the volcanoes and correspond to the saddle regions between adjacent volcanoes. Spikes in the number curves of Alcedo, Cerro Azul, Fernandina, and Wolf at elevations >800 m indicate geomorphic units unique to each volcano that correspond to wide platforms with low slopes.

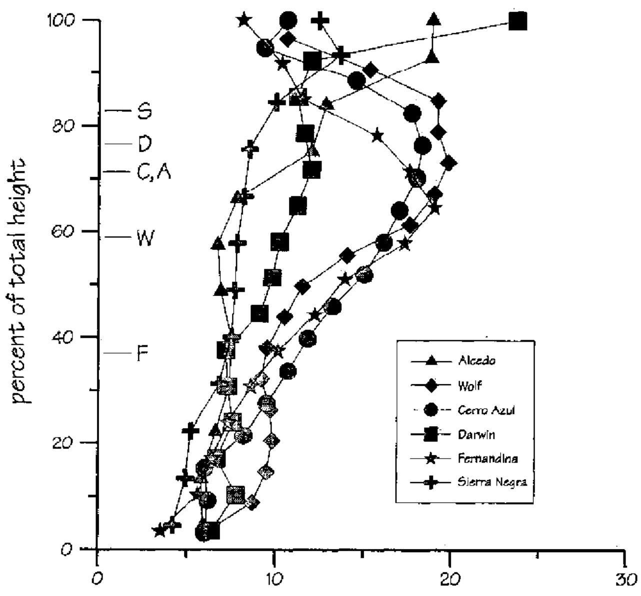

Figure 3. Average slopes for each volcano, normalized to the volcano's maximum height. The averages are the same as those shown in Fig. 2, except that they have been computed for elevation increments of 100 m. The relative depth of the caldera of each volcano is given at left (S–Sierra Negra; D–Darwin; C–Cerro Azul; A–Alcedo; W–Wolf; F–Fernandina).

range. Type 2 volcanoes (Cerro Azul, Wolf, and Fernandina) have distinctly steeper slopes at their intermediate elevations.

For ease of comparison of the slope distributions, we display the average slope at a given elevation against the normalized height of the volcano (Fig. 3). Type 1 volcanoes have flanks that steepen at a relatively constant rate from ~5° near the coast to 10–12° at ~80% of their maximum elevation. Type 2 volcanoes have flanks that grade from ~5° near the coast to as much as 20° at 75% of the volcano's height. In addition, Type 1 volcanoes all have relatively shallow calderas between 200–360 m deep, whereas Type 2 volcanoes have relatively deep calderas between 475–920 m deep. The great depth of calderas for Type 2 volcanoes is demonstrated by Fernandina, where the caldera depth is equivalent to ~60% of the subaerial volcano height, and by Wolf where the depth is ~40% of the subaerial volcano height (Fig. 3). In contrast, Type 1 volcanoes have calderas that are <25% the maximum subaerial volcano height.

Discussion

It has been proposed that steep slopes on the western Galapagos volcanoes correlate with constructional volcanism associated with near-summit circumferential fissures (Simkin, 1972, 1984; Chadwick and Howard, 1991). The gross morphology of each volcano probably results from a long accumulation of lavas that may have erupted from vents that are now buried. A comparison of our slope map (Fig. 1) and the distribution of circumferential fissures mapped by Chadwick and Howard (1991; their Fig. 3) reveals that only certain flanks on each volcano display a correlation between steep slopes (taken here to be slopes >13°) and the occurrence of arcuate fissures (Fig. 4). On many parts of Sierra Negra, Alcedo, and Wolf, the steepest flanks (slopes ≥21°) do not correlate with the occurrence of arcuate fissures at the summit. Furthermore, certain parts of Fernandina and Darwin have arcuate fissures but shallow flanks (slopes <9°). We therefore infer that the mode of formation of steep slopes is not uniquely associated with summit structure.

However, if the steep slopes were indeed primarily due to volcanism from summit arcuate fissures, then a correlation between the occurrence of these fissures and deep calderas should also exist. Our data show that the deepest calderas occur on Galapagos volcanoes that also have the steepest slopes (and typically few gradual slopes) between 60–80% of the volcano height. For Fernandina, the caldera floor is presently below the elevation of the steepest portion of the flanks (Fig. 3), and Wolf's caldera floor is now just at the elevation where the slopes increase to >18°. Simple geometry indicates that the upper part of each edifice on Fernandina and Wolf must currently consist of arcuate ridges only 2 to 3 km wide where the flanks are steepest. Given the propensity for parts of Hawaiian volcanoes to move horizontally via dike intrusion (Swanson et al., 1976), it is possible that the observed arcuate fissures at the summit of Galapagos volcanoes may also have caused movement of the upper flanks of these volcanoes (Chadwick and Howard, 1991). It is unclear if this movement would promote steep slopes by outward movement or cause oversteepening of the caldera walls with resultant inward collapse.

Chadwick and Dieterich (1995) have performed finite element analyses of the stress fields on Galapagos volcanoes that promote and maintain both circumferential and radial dike emplacement. Although no systematic field checking has been done on each volcano to search for evidence for outward or inward movement of the arcuate ridge, the general correlation between caldera depth and edifice width may warrant comparable numerical analysis to help understand volcano growth and deformation. Furthermore, the difference between Type 1 and 2 volcanoes is also corroborated by field observations which show that there are many steep dikes in the walls of the deep calderas of Cerro Azul and Wolf (Geist, pers. comm., 1996), in contrast to the shallow calderas of Alcedo and Sierra Negra, which contain only a few dikes (Geist et al., 1994; Reynolds et al., 1995). Detailed geophysical data

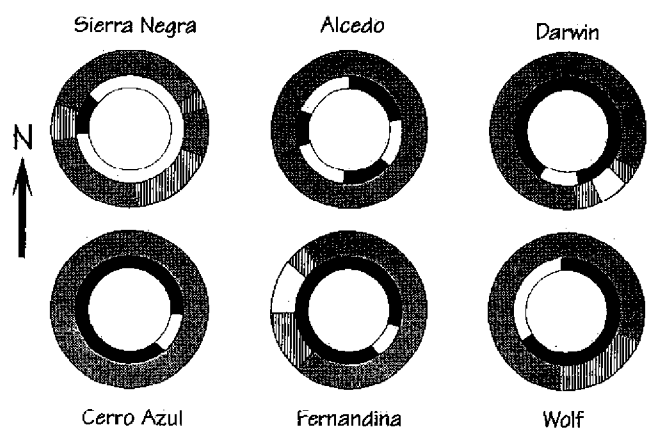

Figure 4. Azimuthal distribution of slopes 13.0 to 20.9° (vertical lines) and slopes ≥21° (gray) from TOPSAR data and the occurrence of arcuate fissures (black; from Chadwick and Howard, 1991). Only azimuthal variations in slope distribution are shown, although on some volcanoes (e.g., Darwin) there are steep slopes close to the caldera rim and near the coast.

(gravity, seismics, and deformation) would help elucidate the origin of these steep slopes; although regional gravity and seismic studies have been performed on the Galapagos Archipelago (Kaufman and Burdick, 1980; Feighner and Richards, 1994), neither of these studies had sufficient spatial resolution to resolve the structural details of each volcano.

While the internal structure of the Galapagos volcanoes remains unresolved, the TOPSAR data presented here show the value of high resolution digital topographic mapping for quantifying slopes and seeking associations between slopes and fissures. Comparable data for other basaltic volcanoes such as Erta Ale (Ethiopia), Nyiragongo and Nyamuragira (Zaire), and the Hawaiian volcanoes may provide useful analogs to these Galapagos observations. Although TOPSAR deployments will remain expensive and logistically challenging outside the United States, orbital radar interferometry is becoming a routine method for studying volcanoes (Massonnet et al., 1995; Zebker et al., 1996). Thus more digital elevation models of volcanoes will soon be constructed from orbital radar data. In addition, the planned third Space Shuttle flight of the SIR-C/X-SAR (Farr et al., 1995) will provide almost complete topographic coverage equatorward of 60°. Using these new data, it will be possible to systematically study the structure and morphology of numerous volcanoes around the world, as well as aid the prediction of flow paths of lahars and pyroclastic flows using numerical models (e.g., Wadge et al., 1994).

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Appendix 1: Definition of slopes

The slope map (Fig. 1) was determined as follows, using the method described in the LAS User Guide (1989). Taking a 3 x 3 array of TOPSAR elevation points n1 to n9 with point n5 being the center point, point n5 will have 8 neighbors spaced as follows:

n1	n2	n3
n4	n5	n6
n7	n8	n9

with a cell spacing of sp meters.

$$\text{vertical slope} = \frac{(n1 + n2 + n3) - (n7 + n8 + n9)}{2 * 3 * sp}$$

$$\text{horizontal slope} = \frac{(n1 + n4 + n7) - (n3 + n6 + n9)}{2 * 3 * sp}$$

slope at n5 = square root (vertical slope * vertical slope + horizontal slope * horizontal slope)

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P.J. Mouginis-Mark, S.K. Rowland, and H. Garbeil, Hawaii Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, 2525 Correa Road, Honolulu, HI 96822.

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