Eruptive patterns and structure of Isla Fernandina, Galapagos Islands, from SPOT-1 HRV and large format camera images

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(Received 14 August 1989; in final form 8 December 1989)

Abstract. SPOT-1 HRV, and large format-camera images were used to investigate the distribution and structure of erupted materials on Isla Fernandina, Galapagos Islands. Maps of lava flows, fissures, cones and topography derived from these data allow the first study of the entire subaerial segment of this geographically remote and ecologically sensitive volcano. No significant departure from a uniform distribution of erupted lava with azimuth can be detected. Short (<4 km) lava flows commonly have their source in the summit region and longer (>8 km) lava flows originate from vents at lower elevations. Catastrophic landslides are proposed as a possible explanation for the asymmetry of the coastline with respect to the caldera.

1. Introduction
Volcanology has undergone a revolution in approach from the early days of description and classification of activity and petrology towards an intense effort to understand the internal workings of volcanoes. Field data and numerical modelling have shown that the examination of the location, morphology and composition of eruptive products can enable the internal structure of the volcano and the conditions under which eruptions may occur to be defined (Wilson and Head 1981, Holcomb 1987).

The accessibility and developed nature of the Hawaiian Islands has permitted considerable progress to be made in the understanding of Hawaiian volcanism (e.g. Decker et al. 1987). In contrast, the active volcanoes of the western Galapagos Islands (figure 1) remain poorly studied due to their isolated location, rugged terrain, lack of water and delicate ecology. Thus there is a bias in our understanding of basaltic volcanism towards the Hawaiian examples.

Despite their similar intra-plate tectonic settings, previous work indicates that there are major volcanological contrasts between the two regions. Petrologic and isotopic studies in the Galapagos fail to show any clear time transgressive sequence of eruptive activity in the direction of plate motion and the geochemical evolution of the lavas through an alkalic-tholeiitic-alkalic sequence does not occur (Chen and Frey 1983, Geist et al. 1986). In addition, the subaerial profile of the Galapagos basaltic shield volcanoes, with their steep slopes leading to a summit plateau and caldera, are very distinct from the broad low angle slopes of the Hawaiian examples (McBirney and Williams 1969, Nordlie 1973).

Satellite remote sensing studies of volcano structure and the distribution of erupted materials in the Galapagos offer scope for redressing the imbalance in our understanding of basaltic volcanism. Interactions between volcanic centres in close proximity to each other on the island of Hawaii have been shown to exert a strong influence on the location and orientation of eruptive vents (Fiske and Jackson 1972).
A synoptic view of Isla Fernandina and Isla Isabela in the western Galapagos will provide insight into how their six historically active volcanoes influence each other. Reported in this Letter are the preliminary results of an investigation of volcanism on Isla Fernandina utilizing remotely-sensed data. They not only provide a starting point for an on-going study of the archipelago but also will be used to identify sites for ground data collection and future acquisitions of Shuttle Imaging Radar (SIR-C) data.

2. Image interpretation
A SPOT-1 HRV panchromatic scene (10 m spatial resolution; waveband of 0.51–0.73 μm) collected on 27 April 1988 (figure 2) and large format camera (LFC) photographs taken during Space Shuttle Challenger mission STS 41-G in October 1984 (~7 m spatial resolution) provided cloud-free views of Isla Fernandina, which is the subaerial segment of a polygenetic volcano located at 0°37’S, 91°55’W. A set of colour hand-held camera photographs obtained during Space Shuttle mission 51-J in October 1985 were used to supplement the higher spatial resolution data. Despite the island’s location on the Equator, local wind patterns produce drought conditions. The surface materials are generally devoid of vegetation cover and temporal changes in surface appearance are controlled by arid and semi-arid weathering processes. The precise age of the erupted materials is difficult to determine—Simkin et al. (1981) document 18 eruptive events over historic time prior to 1978. When compared with Kilauea volcano on Hawaii where 60 eruptions occurred in the same time period and
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Figure 2. SPOT-1 HRV scene of Isla Fernandina. The island is approximately 30 km by 27 km in size. Image resolution is 10 m/pixel, image scene number K613J351, acquired 27 April 1988. Vertical striping is a result of optimal enhancement for the recognition of the individual lava flows. Outline indicates area enlarged in figure 6.

90 per cent of the surface is younger than 1000 years (Holcomb 1987), we estimate the age of the surface materials on Isla Fernandina to be younger than 3000 years. It should be stressed however that this figure is only an estimate.

The stereoscopic coverage provided by the LFC images was utilized to complete a topographic contour map (figure 3) that was produced originally from US Navy aerial photographs, but which gave incomplete coverage due to cloud cover (McBirney and Williams 1969). The mapping of the eruption products (lava flows and cones) and the identification of source regions (individual vents or linear fissures marked by the alignment of near vent cones) were undertaken with the aid of conventional image enhancement techniques. The surface area of each flow was used as an approximation of the eruption volume in order to make island-wide comparisons of eruptive events.

3. Eruptive patterns and morphology of Isla Fernandina

Alignment of near-vent cones along fissures has enabled the tectonic stresses acting on volcanic constructs to be evaluated (Nakamura 1977). On Isla Fernandina a total of 671 cones were identified. No attempt was made to distinguish between cinder, spatter, and tuff cones due to the inadequate spatial resolution of the images.
Figure 3. Topographic map of Isla Fernandina modified from McBirney and Williams (1969) using stereographic interpretation of large format camera images. Original contours were in 200 ft intervals which are retained in this map. Dashed contours are approximate based on this analysis.

The alignment of these cones defined 20 radial fissures predominantly located in the south and south west of the lower flanks and 18 oriented circumferentially around the north-east and south-west sides of the caldera (figure 4(a) and (b)). The caldera is seen to exert a strong influence on the eruptive fissures around the summit and we suggest that repeated collapse events within the caldera provide vertical weaknesses that become pathways for magma transport and eruption, and that the circumferential fissures are surface expressions of these pathways. On the lower flanks the orientation of aligned cones defining eruptive fissure appears to follow a complex radial pattern with respect to the caldera. The orientation of minimum principal tectonic stress within the volcanic edifice is seen to define a concentric pattern across the eastern, southern and western flanks, and there is a marked absence of fissures on the northern flank. However, it is difficult to assess the influence of the neighbouring shields on Isla Isabela on the eruptive fissure patterns on Isla Fernandina with the available satellite sensor data.

The majority of cones have a basal diameter of $< 100$ m, particularly in the case of those that delineate the circumferential fissures in the summit region. This cone size is markedly smaller than those mapped on Mauna Kea, Hawaii or Mount Etna, Italy (Wood 1979), perhaps indicating that a smaller proportion of volatiles to liquids existed in erupted magma on Fernandina compared to Mauna Kea or Mount Etna (Head and Wilson 1989).

A total of 83 lava flows were also mapped on the flanks of Fernandina (figure 5)
Figure 4. (a) Map of the distribution of near-vent cones. No attempt has been made to distinguish between cinder, spatter or tuff cones. (b) Eruptive fissure orientation inferred from the cone distribution in figure 4 (a).
from the SPOT-1 HRV image. The majority of summit eruptions produced short flows (<4 km in length) in contrast to the predominance of longer flows (>8 km) originating from vents at lower elevations. It is possible that this pattern could be the result of a split level magma chamber, as has been suggested for Piton de la Fournaise, Reunion Island (Ludden 1977), or by the tapping of a single magma chamber from progressively lower levels as has been proposed for Kilauea volcano (Epp et al. 1983). Both models would predict differences in the lava composition for eruptions that originate from high and low elevations on Fernandina, and a key objective of our long term study of this volcano is an analysis of lava flow mineralogy using Landsat Thematic Mapper and field spectrometer data.

The light image tone to the west of the caldera (figure 2) was interpreted as the distribution of tephra deposited on lava flows by base surges associated with the major caldera collapse of 1968 (Simkin and Howard 1970). The lava flows covered by this tephra appear to be unusually narrow close to the summit and to follow a distributary pattern upon reaching the lower angle slopes beneath an elevation of ~385 m. However, detailed examination of the LFC and SPOT-1 HRV images reveals that it is the levees of these flows that can be generally identified and mapped, and that the character of these western lava flows does not differ from those on the east of the island.

A comparison of the size of eruptive events indicates that no significant departure from a uniform volume of erupted lava with azimuth can be detected from the

Figure 5. Map of distribution of lava flows (stippled areas) and flow boundaries.
satellite sensor images. The origin of asymmetry of the island around the caldera has been explained by the fact that the eastern flank of the volcano is building into shallower water (Nordlie 1973). However, the very steep submarine slopes (> 32°) to the north of the island evident in the bathymetric map presented by Mc Birney and Williams (1969), and the proximity of Volcan Ecuador, a superb example of a dissected shield facing Fernandina, suggest that major landslide events on the western flank of Isla Fernandina may have played a role in producing the current coastline in a comparable manner to that seen on certain Hawaiian islands (Moore 1964, Lipman et al. 1988).

The influence of the steep upper slopes on flow morphology can clearly be observed on all parts of the island. Upon reaching the lower angle slopes, those flows that originate at high elevations show a distinct widening and development of levees and central channels (figure 6). Changes in the albedo of the flows and the along-flow

Figure 6. Enlargement of SPOT-1 HRV scene (see figure 2 for location). Arrow indicates tonal variations interpreted to be a result of lava surface texture variations produced as a result of changes in the flow regime during emplacement.
occurrence of central channels indicate that variations in the flow regime occurred during eruptions (Peterson and Tilling 1980). Unfortunately, the current data do not allow detailed evaluation of these surface textures, so that an assessment cannot be made of the relative proportions of aa to pahoehoe lava. Comparable studies have been conducted for Mauna Loa volcano (Lockwood and Lipman 1987), and have been used to interpret the volatile content of the source regions and the steepness of the terrain over which the lava flows travelled. Imaging radar offers a means to remotely interpret such distributions of lava flow types on volcanoes (Gaddis et al. 1989), and so to address this and other aspects of our long-term investigation of the volcanology and structure of Isla Fernandina we are currently planning multiple data acquisitions during the Shuttle Imaging Radar (SIR-C) missions that are scheduled to fly in 1992 and 1993.

Acknowledgments
This study was supported by grant NAGW-1162 from NASA’s Geology Program, and forms part of the Ph.D. research of Duncan Munro. The authors would like to thank George Walker and Michael Knight for reviews of an earlier draft of this manuscript and Robert Lees of SPOT Image Corporation and Bernard Molberg, Richard Monson and Brunton Schardt of NASA for assistance in obtaining the data. This is Hawaii Institute of Geophysics Contribution number 2209.

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