Bull Volcanol (1992) 55:97–109

Bulletin of Volcanology

The caldera of Volcan Fernandina: a remote sensing study of its structure and recent activity

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Received January 4, 1992/Accepted July 9, 1992

Abstract. Air photographs taken in 1946, 1960, and 1982, together with SPOT HVR-1 images obtained in April and October of 1988, are used to characterize recent activity in and around the caldera of Fernandina Volcano, West Galapagos Islands. The eruptive and collapse events during this time span appear to be distributed in a NW-SE band across the summit and caldera. On the flanks of the volcano, subtle topographic ridges indicate that this is a long-term preferred orientation of extra-caldera activity as well (although radial and arcuate fissures are found on all sectors). The caldera is formed from the coalescence of multiple collapse features that are also distributed along a NW-SE direction, and these give the caldera its elongate and scalloped outline. The NW and SE benches consist of lavas that ponded in once-separated depressions that have been incorporated into the caldera by more recent collapse. The volume of individual eruptions within the caldera over the observed 42 years appears to be small ($\sim 4 \times 10^6$ m^3) in comparison to the volumes of individual flows exposed in the caldera walls (~ 120–150×10^6 m^3). Field observations (in 1989) of lavas exposed in the caldera walls and their cross-cutting relationships show that there have been at least three generations of calderas, and that at times each was completely filled. An interplay between a varying supply rate to the volcano and a regional stress regime is suggested to be the cause of long-term spatial and volumetric variations in activity. When supply is high, the caldera is filled in relative to collapse and dikes tend to propagate in all directions through the edifice. At other times (such as the present) supply is relatively low; eruptions are small, the caldera is far from being filled in, and dike propagation is influenced by an extra-volcano stress regime.

Key words: Galagapos – caldera morphology – stress orientations – intra-caldera – structure – temporal variations – tectonic control

Introduction

The Galapagos volcanoes have been the subject of numerous overview studies (e.g. Richards 1962; McBirney and Williams 1969; Nordlie 1973; Simkin 1984), and some detailed work. The geographic isolation and difficult working conditions of these volcanoes mean that remote-sensing studies (e.g. Chadwick and Howard 1991; Munro et al. 1991; Munro 1992), although unable to replace the detail available to ground observers, offer a synoptic viewpoint that is useful for making inferences about structures and processes. Both aerial photographs (1946, 1960, and 1982) and SPOT HRV-1 images (1988) have been used in the present study and they provide a punctuated view of the most recent 42-year history of the caldera.

The purpose of this study is to examine the structure, dynamics, and recent history of the Fernandina caldera by incorporating a sequence of temporally spaced images as well as ground observations. This is done by noting the spatial and temporal distribution of eruptive and volcano-tectonic features including vents, fissures, and centers of collapse. With such a data set, the processes and stresses that govern caldera activity at Fernandina can be interpreted. By then combining our observations to the (lamentably sparse) historic record of activity, general conclusions about the variations in eruptive output can be made. A secondary objective is to describe the 1988 intra-caldera avalanche and eruption from a remote sensing viewpoint to help formulate a strategy of event description in partial preparation for the upcoming Earth Observing System (Mouginis-Mark et al. 1989, 1991).

Calderas are common features of basaltic shield volcanoes. They have been inferred to form by a number of mechanisms including dropping as a piston into a magma chamber (e.g. Macdonald 1972; Williams and McBirney 1979), large-scale slumping (Duffield et al. 1982; McGuire and Pullen 1989), and localized sagging because of excess loading by cumulates and intrusives (Walker 1987, 1988). Additionally, the formation of calderas has been ascribed to distinct stages in the lifetime

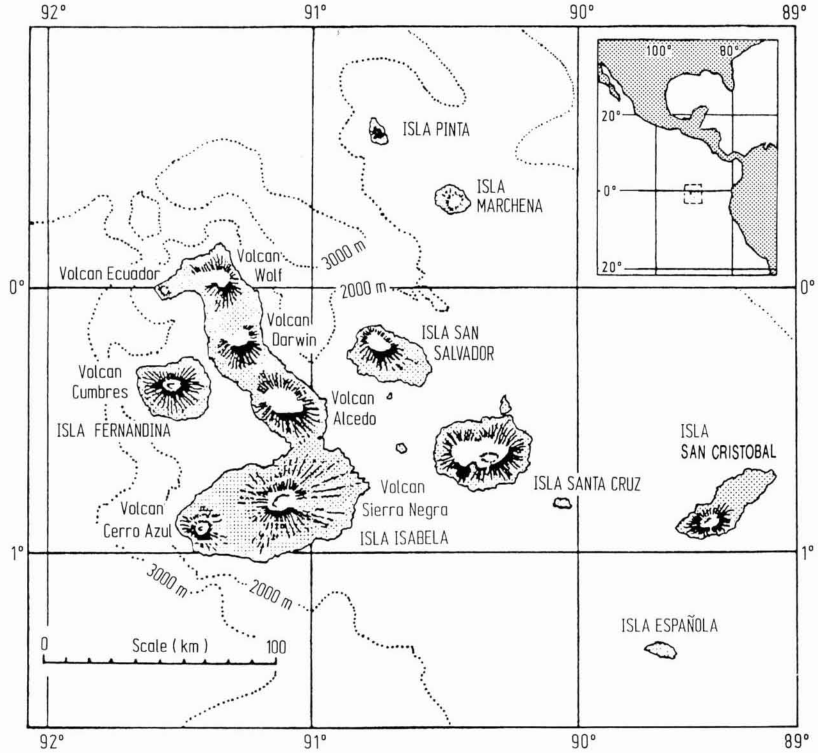
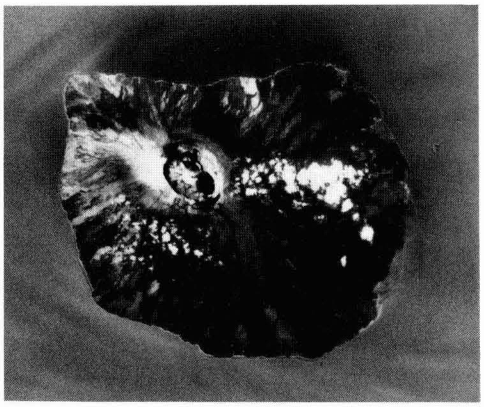


Fig. 1. Location map of the Galapagos Islands (slightly modified from Simkin and Howard 1970). *Inset:* Large.format camera photograph of Isla Fernandina taken from the space shuttle 8 October 1984



of basaltic shields (e.g. Stearns 1946; Nordlie 1973; Williams and McBirney 1979; Macdonald et al. 1983); only recently has it become apparent that calderas are the surface manifestation of an underlying magma chamber (e.g. Macdonald 1965; Simkin and Fiske 1986) rather than the result of any single event, and are thus as long-lived as the chamber.

Discrete collapse events do occur at basaltic calderas, and serve to increase their sizes. In contrast, intra- and near-caldera eruptions fill them in. Walker (1988) compiled the collapse and infilling history of Kilauea's caldera (after Macdonald 1972), and determined that even though the overall shape and size has not changed significantly since the arrival of Westerners in the late 1700s, a total of 1 km^3 of material per century has sunk into the edifice. A similar volume has been lost at Mauna Loa (Lockwood and Lipman 1987). Fernandina (sometimes called Volcan Cumbres; Fig. 1) is the site of the largest caldera collapse event on a basaltic volcano in recorded history. This collapse (in 1968) involved the engulfment of 1–2 km^3 of material as well as an eruption and extensive seismicity (Simkin and Howard 1970; Filson et al. 1973). A recent intra-caldera avalanche event at Fernandina took place some time between 14–16 September 1988, and involved the falling in of a portion of the caldera wall, the deposition of 0.9 km^3 of debris onto the caldera floor, and a small intra-caldera eruption (Chadwick et al. 1991). The caldera continues to be an area of active mass-wasting, and in February 1991 another intra-caldera eruption took place (Perez-Oviedo 1991).

The caldera is elongated in a NW-SE direction (6.6 km NW-SE by 4 km NE-SW). It is ~1 km deep at its maximum, and the walls slope inward at 30–50°. The caldera is surrounded by a subhorizontal area termed the 'summit platform' by Nordlie (1973). Exposed in the walls of the caldera are extensive sequences of lava flows (most of them thick and flat-lying), numerous dikes, and a few pyroclastic units. Most of the inner caldera walls are covered with talus. We follow the convention of using the terms 'inboard' and 'outboard' to refer to respectively, directions radially toward or away from the volcano center.

The remotely sensed data

Vertical aerial photographs of the caldera were taken in 1946, 1960, and 1982, and we present sketch maps drawn from them. The 1946 and 1982 photos are published in a number of references (e.g. Simkin 1984) and are not reproduced here. SPOT HRV-1 images were collected on 27 April and 25 October 1988 in panchromatic mode (black and white) at 10 m resolution (Chevrel et al. 1981). The quality of reproductions of the aerial photographs in the literature is such that they can be easily compared to the otherwise lower-resolution SPOT images. Some changes in shape (i.e. of benches and the caldera rim) are due to parallax distortion from differing view angles.

1946 Aerial photograph

The map drawn from the 1946 aerial photo (Fig. 2) shows the caldera to consist of multiple levels. The lowest is occupied by a lake approximately 3.5 km long by 2 km wide, elongate in the same NW-SE direction as the caldera. A pyroclastic cone forms an island near the

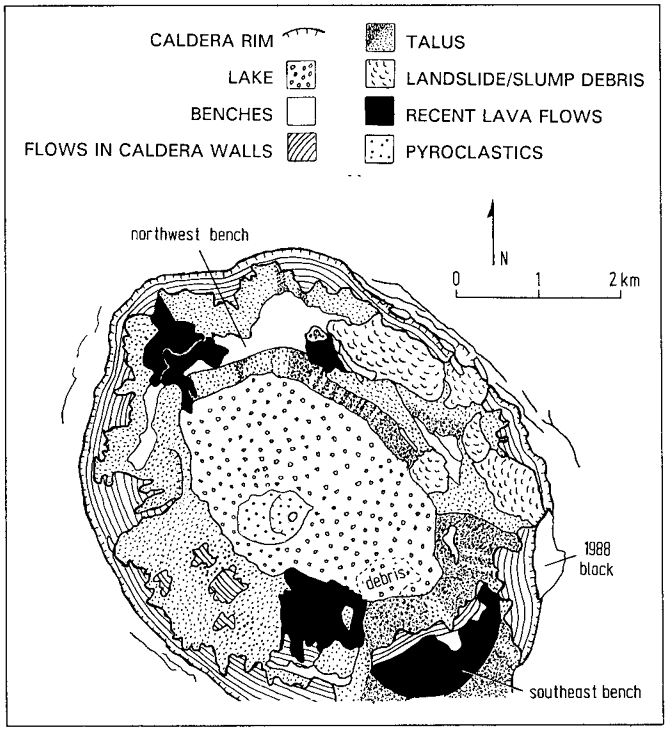


Fig. 2. Sketch map of the Fernandina caldera drawn from a 1946 aerial photograph (published in Simkin 1984). Note that the NW bench can be extended around to the west and east, probably representing a previous caldera floor

western margin of the lake. Outcrops of intact flows are exposed just below the caldera rim extending in places almost to the lake, as well as in small isolated windows, but most of the caldera walls consist of talus. To the south and west, the tallus extends almost continuously from just below the rim to the lake.

The main structural features are large horizontal-topped benches, numerous fractures around the caldera out to ~0.5 km from the rim, and segments of in-slumped caldera wall. The NE bench extends ~3 km around the northwestern end of the caldera and is broken by numerous fractures. Its outboard margin is buried by talus and its inboard margin drops steeply to the lake shore. Remnants of a horizontal layer that is mostly covered by talus and large slumps extend from the east end of the NW bench almost to the SE bench. This layer is most probably a continuation of the NW bench, and represents a previous level of the caldera floor consisting of ponded flows. The talus slope below this layer was the slip face of the 'inner boundary fault' of Simkin and Howard (1970). It was along this 'fault' that the down-dropping of 1968 took place.

The SE bench is nearly semi-circular in plan view and occupies an alcove in the SE end of the caldera. Its elevation is ~100 m higher than the NW bench (Defense Mapping Agency map #22542), suggesting that it is a separate structure. This relationship is discussed in greater detail later.

There are five low-albedo (and therefore probably recent) lava flows visible in the 1946 photo. One covers the SE bench and was erupted from vents either on the caldera rim or at the back of the bench. Another occurs just west of the SE bench and forms a prominent dark talus-like deposit that extends down the lower 2/3 of the inner caldera wall into the lake. This flow possibly erupted from the narrow shelf ~1 km west of the SE bench. Two lava flows are located on the NW bench. The older was erupted from the back of the bench and one lobe went down the face of the bench to form a small peninsula in the lake. The younger flow erupted from vents high on the NW wall, and piled up against the back of the earlier flow. The fifth young flow within the caldera erupted from a small cinder cone at the easternmost end of the NW bench. Dark talus extends down to the lake from the edge of the flow so it also probably reached the lake.

The northeastern rim of the caldera is considerably more fractured than other sections, and many sliver-like sections of the summit platform up to 1 km long and ~100 m wide are separated by large tensional cracks. The section that avalanched in 1988 is such a block and is located at the easternmost part of the caldera. The inner walls of the NE part of the caldera contain five areas of large broken blocks separated by fractures roughly parallel to the caldera walls, and these are labeled 'landslide/slump debris' on Fig. 2. Most have come down from the upper caldera walls to lodge at the elevation of the NW bench.

In summary, the 1946 view of the caldera shows that the walls are steep and unstable, and that the area outboard of them is under radial tension. Additonally, most of the walls are covered by talus. Recent eruptions took place at the NW and SE ends. The NW bench and its extensions indicate a shallower caldera in the recent past (about 2/3 the depth of the present one).

1960 Aerial photograph

The eruption of 1958 (Richards 1962; Simkin et al. 1981) was bracketed by the photographs of 1946 and 1960, and reported to have taken place from vents near the SE, SW, and W rim of the caldera (Fig. 3). Lava from the W and SW fissures flowed outboard from the vents, partially accumulating between and being diverted by prominent pyroclastic cones. The lava from the SE fissures also flowed onto the outer flanks but flowed inboard as well. The major change observed in the 1960 photo is that the entire caldera floor is covered by lava. This lava appears to be pahoehoe; the flow field consists of numerous flow units, sinuous channels, tumuli, elongate lava rises, and rise pits (e.g. Walker 1991). Additionally, a 'bathtub ring' or 'black ledge' (e.g. Richter et al. 1970) that formed by subsidence and/or degassing, can be seen near the SE and NW ends of the flow field.

This pahoehoe flow field laps against the caldera walls and pyroclastic cone to about the same height as did the 1946 lake. Without knowing the bathymetry of the lake it is possible only to roughly estimate the volume of the lava flow that replaced it. Assuming a con-

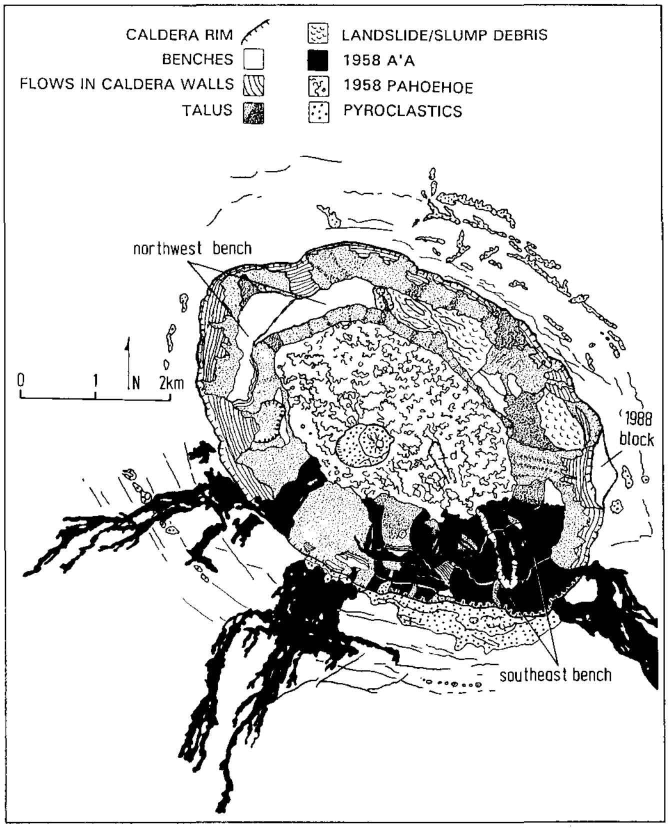


Fig. 3. Sketch map of the Fernandina caldera drawn from 1960 aerial photographs (kindly provided by K Howard, USGS). New features are the result of the 1958 eruption. Note elongate depression 'd' on the caldera floor from which the 1958 pahoehoe apparently emanated (the *squiggly lines* represent tumuli, lava rises, and lava rise pits; Walker 1991). This depression may or may not have been a vent; it is aligned with a prominent channel (*hatchured*) on the SE bench

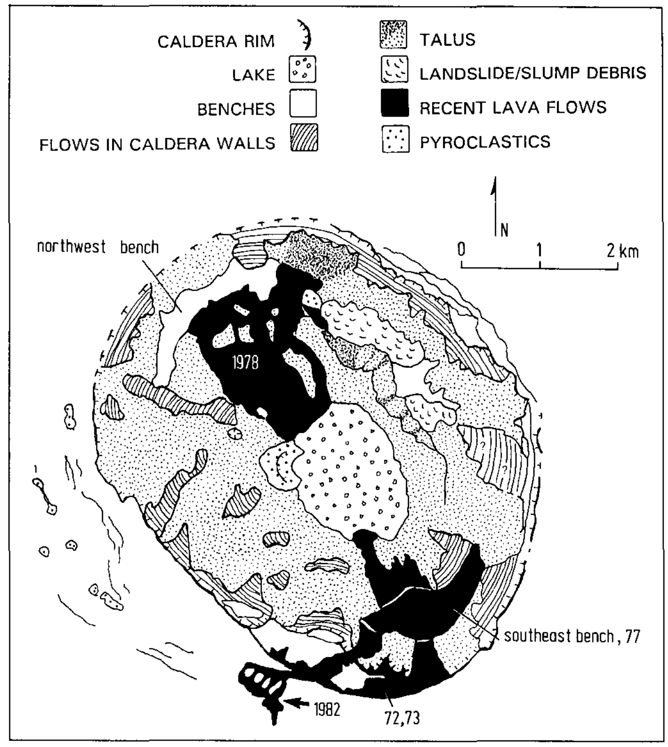


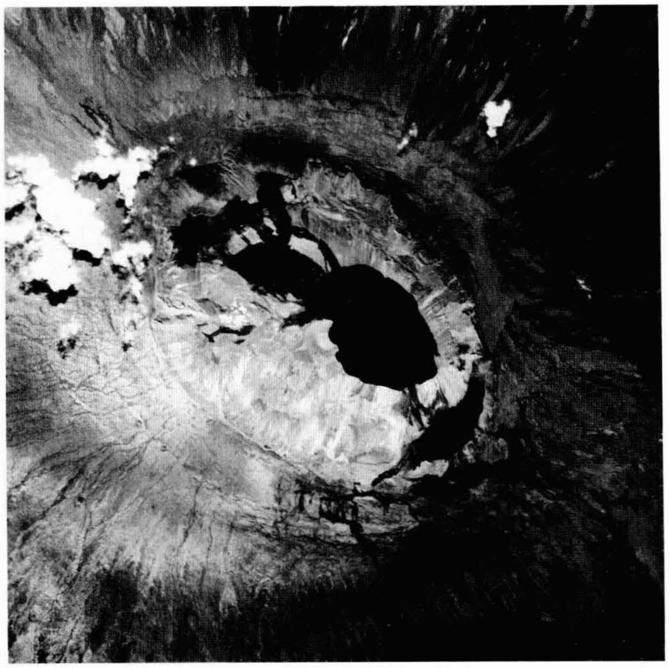
Fig. 4. Sketch map of the Fernandina caldera drawn from a 1982 aerial photograph (published in Simkin 1984). Note that a new lake has formed, although much smaller in size and centred in a new position because of the 1968 caldera collapse

stant thickness of 5 m, and an area of 6.2 km^2, the volume is 31×10^6 m^3. We consider this to be a minimum volume. No vent for this flow is visible on the caldera floor and the most likely source appears to have been the SE fissures. The lava formed a channel as it flowed inboard across the SE bench, and a prominent elongate depression on the caldera floor lines up with the channel. Although this depression may have been a vent, more likely the lava flowed down the face of the bench, pooled in this depression, and from here flowed more slowly onto the caldera floor. Although the eruption from the SE vents was apparently at a high rate (forming a'a flows on the outer SE flank), on the caldera floor where it was able to divide into numerous radiating flows each with only a small volumetric flow rate, pahoehoe was the result (Rowland and Walker 1990).

1982 Aerial photograph

The large caldera collapse of 1968 caused most of the changes between the times of the 1960 and 1982 photos (Fig. 4). As described by Simkin and Howard (1970), this event involved the downdropping of the southeastern portion of the caldera by as much as 350 m, and because the northwestern portion did not drop, a trap-door-like structure was proposed. The lake disappeared during the collapse but by the time of the 1982 photograph, 14 years of rainfall had re-established a smaller lake in the southeastern part of the caldera. On the eastern wall of the caldera, the large slumps have become less prominent, mainly due to burial by talus. Most of the fractures at the eastern edge of the caldera rim (where not obscured by clouds) appear not to have been changed by the 1968 events. Large amounts of dust were generated during the 1968 collapse which greatly obscured both on-site and remote observations, and a phreatomagmatic ash mantled the western slopes (Simkin and Howard 1970; Simkin 1984). Many of the prominent lava flows visible in the 1946 and 1960 photos both inside and outside the caldera are obscured by this dust and ash in the 1982 photo.

Other than the lake, young lava flows are the prominent low-albedo features in the caldera. Eruptions in 1972, 1973, and 1977 from near the SE rim covered the SE bench (Simkin 1984) and flowed into the lake, forming a small peninsula. The 1978 eruption (McClelland et al. 1989) took place from vents on the NW bench, and lava flowed across the bench, down its face, down the sloping surface formed during the 1968 collapse, and into the northwestern end of the lake. The 1982 eruption above the SW rim formed the most recent flows. Other than its cover of new lava, the SE bench appears to have undergone no structural changes. In summary, the major structural features seen in the 1982 photo are similar to those in the 1946 and 1960 photos, namely steep unstable caldera walls and eruptive activity mainly at the NW and SE ends.



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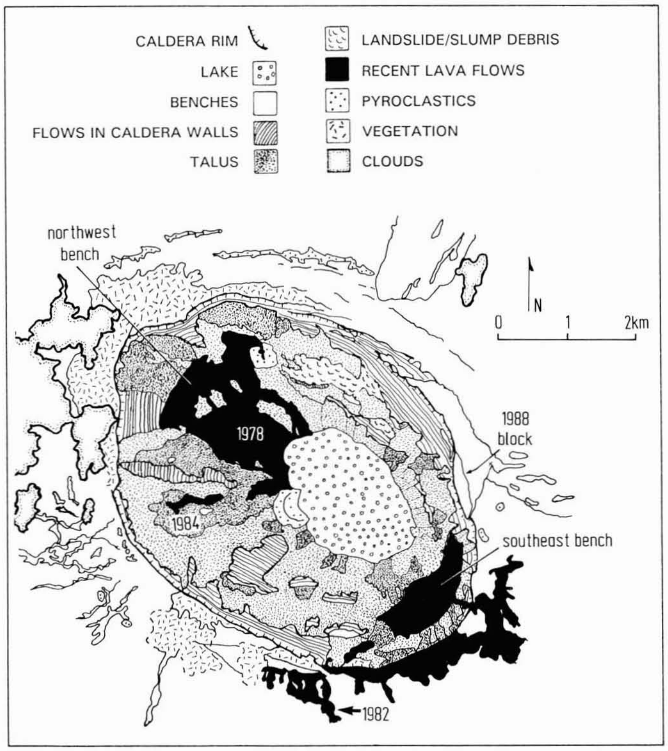


b

Fig. 5. a SPOT scene of Fernandina collected 27 April 1988 (view from W at 17.5° from nadir). The solar incidence angle was 61.4° from the ENE. Note the lake in approximately the same position as in 1982, and the extensive 1978 lavas erupted from the NW bench. **b** sketch map of (a)

The April 1988 SPOT scene

The first SPOT scene used in this study (Fig. 5) was obtained on 27 April 1988 and shows little change since the 1982 photo. The notable differences are that the level of the lake has risen slightly to submerge a greater proportion of the 1978 lavas. The 1984 lava flow (McClelland et al. 1989) shows up prominently. It flowed east from the base of the western wall.

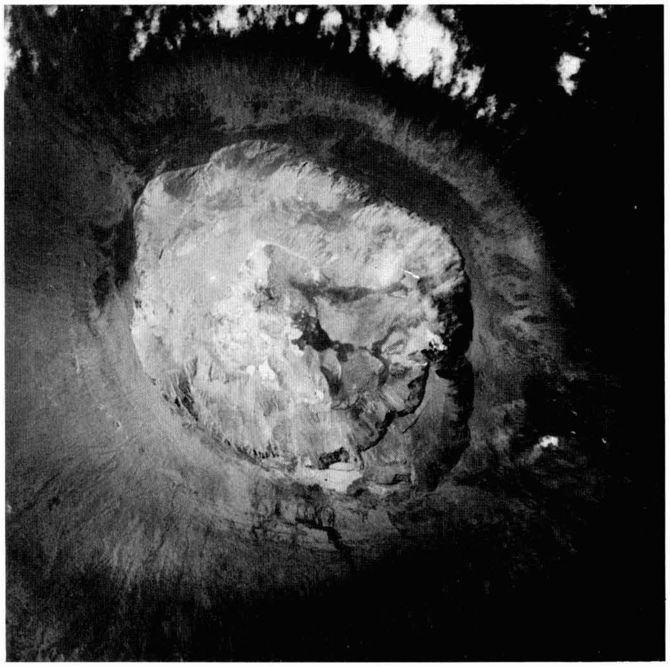
The NE rim of the caldera is still the most conspicuously fractured. Most of these blocks are 1–2 km long and a few hundred meters wide. The prominent horizontal layer that extends from the NW bench still exists as a topographic break with talus above and below, but it is now cut by numerous convex-inboard fractures. In general, the April SPOT scene shows much the same as the 1982 photo with regard to structural features, and mainly shows the addition of the 1984 flow and a slight rise in lake level; there was no significant activity in the caldera, either eruptive or tectonic, between 1982 and April 1988.

The October 1988 SPOT scene

The second SPOT scene (Fig. 6) was imaged shortly after the September 1988 avalanche and eruption, and shows a much-changed caldera floor. In addition to the disappearance of the lake (it was displaced northwestward and seeped into the avalanche deposit; Chadwick et al. 1991), numerous smaller mass-wasting events have taken place, mostly around the less-steep southern walls. Whereas in April 1988 there were many outcrops of intact caldera wall rock here, this portion is almost entirely covered by talus in the October scene. Additionally, a fracture developed in the SE bench which is about 1 km long and is 100–400 m from its inboard edge.

High-albedo lake sediments occupy much of the western part of the chaldera floor. They indicate the position of the lake after it was displaced westward by the avalanche material (Chadwick et al. 1991). The avalanche deposit itself has a medium albedo, and appears as two main lobes with a lava flow occupying the low area between them. The orientation of these lobes suggests that the avalanche at first flowed southwestward before turning in a more westerly direction, and may have been emplaced in two events. According to Chadwick et al. (1991) the avalanche rapidly displaced the lake to the west and came to rest partially submerged. Isolated dark spots 100–200 m across are thus hummocks of the avalanche that protruded above the new lake level. The texture of the part of the avalanche that did not go underwater is smooth in the SPOT scene, which may indicate a covering of dust. The most southerly lobe of the avalanche has a fingered margin where it contacts the lake sediments. The avalanche also buried the large pyroclastic cone that had survived the caldera collapse of 1968.

Lava flows were erupted associated with the 1988 events, but their timing relative to that of the avalanche is uncertain. Chadwick et al. 1991 interpreted that the a



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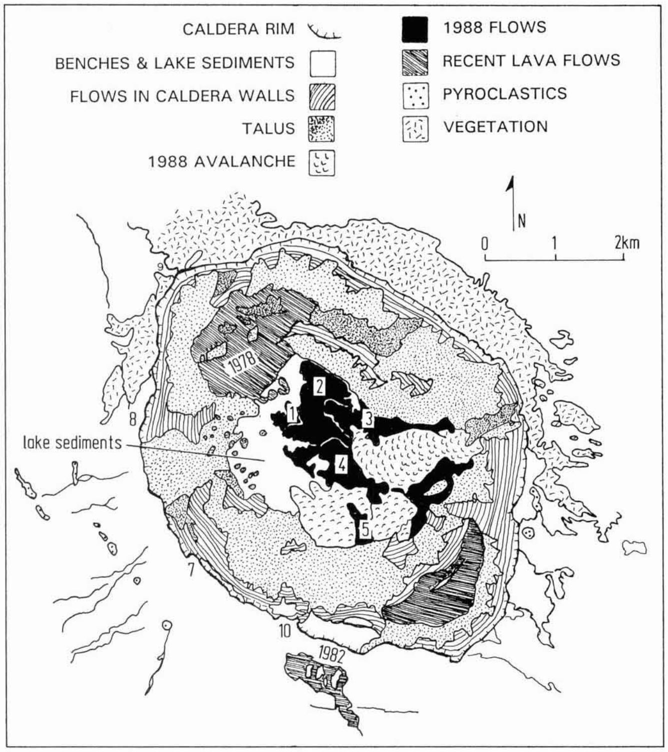

Fig. 6. a SPOT scene of Fernandina collected 25 October 1988 (view from W at 22° from nadir). The solar incidence angle was 67.2° from the ENE. The apparent change in the outline of the caldera is due to the different viewing geometry. Major changes since the April scene include the disappearance of the lake, the deposition of the debris avalanche and lake sediments, the emplacement of the new lava flows, and an overall muting of features due to dust. **b** Sketch map of (a), *numbers* on flows indicate inferred order of eruption, and *numbers* around W rim indicate locations from which photographs of Figs. 7–10 were taken (all by P Mouginis-Mark in late September 1989)

avalanche and eruption occurred hours apart but could not eliminate the possibility that the avalanche might have preceded the eruption by many months (but report that it had not occurred as of April/May 1988). Unfortunately, because the pre-avalanche SPOT scene was taken in April 1988 no further constraints on the timing are provided. The 1988 lavas are the darkest features in the post-avalanche SPOT scene and they can be divided into five flows. These flows issued from vents below the base of the avalanche scar and flowed westward over the avalanche. The SPOT data yields a flow area of $1.9\,km^2$, and an estimated thickness of 3–4 m (from field observations) gives a volume of $6\text{–}8 \times 10^6\,m^3$. Chadwick et al. (1991) estimated a lava flow volume of $4\text{–}20 \times 10^6\,m^3$ based on an average thickness of 1–5 m, and an area of $3.7\,km^2$.

Using the October SPOT image, we have subdivided the 1988 lava into flow units based on albedo differences and shadows cast by flow margins. The two earliest and westernmost flows are the most extensive and have the highest albedo. They are almost completely surrounded by the light-colored sediments and may have flowed into and under the surface of the displaced lake. A covering of ash that settled out of the lake as well as pyroclastic deposits were reported on these flows (Chadwick et al. 1991), and these account for the higher albedo. By September/October of 1989, rain had washed the dust coating off the flows (Fig. 7). The two latest flow units are very dark in the October SPOT scene, and possibly erupted after most of the dust had settled. The fifth flow unit is the most southerly and in the SPOT image is not continuous all the way to the vents; it has apparently been partially covered by smaller mass-wasting events subsequent to its eruption.

One of the most obvious features of the post-avalanche SPOT scene is the lack of contrast between lithologic units that in the pre-avalanche scene were easily discernible. This is especially the case within the caldera; the upper parts of the 1978 flows have essentially disappeared (the lower parts were buried by the 1988 avalanche). Outside the caldera, particularly on the upper western slopes, the prominent gullies cut into the 1968 ash cannot be discerned in the October scene. Although some of this effect may be due to the different lighting and viewing geometries, most of this overall muting of the image is probably due to a cover of dust generated during the avalanche event that then settled out to form a relatively monochromatic layer. By 1989, a year of rainfall had washed this dust away; the 1978 flows were again obvious (Fig. 8). Possibly, the sediments in the floors of the gullies may have been wet at the time of the April image but dry in October.

The lower limit of the section of caldera wall that became the avalanche of 1988 is near the level of the prominent horizontal layer that extends around the NE wall, which, as noted earlier, probably represents a former caldera floor. This layer is not exposed in the scar left by the 1988 avalanche meaning that the old caldera boundary fault was inboard of the 1988 scar. With this elevation as an approximate position of the bottom of the avalanche block, a rough calculation can be made

Fig. 7. Photograph (looking NE) across the Fernandina caldera. Dark and light units on caldera floor are 1988 flows and lake sediments, respectively. Medium-albedo unit in nearground is 1988 avalanche

Fig. 8. Photograph of the 1978 lava flows on the NW bench taken from the western rim of the caldera. Note that unlike in the October 1988 SPOT scene taken ~1 year earlier, the flows' dark albedo stands out sharply

of its volume prior to the avalanche event. It is ~2 km long, ~0.3 km wide at the top, and ~0.8 km wide at the bottom (assuming a 50° pre-avalanche slope). These dimensions yield a volume of 0.66 km^3. This is about two-thirds of the volume of debris calculated post-avalanche by Chadwick et al. (1991). The discrepancy may be due to the higher porosity of jumbled avalanche material compared to intact caldera wall. This would help explain the rapidity with which the displaced lake seeped into the deposit. Furthermore, Chadwick et al. (1991) proposed that at least some of the 1988 lava erupted up through the avalanche deposit. Magma may also have intruded and inflated the debris yielding a larger post-avalanche volume.

Interpretation of the two SPOT scenes reveals the extensive changes associated with the September 1988 event, and the synoptic viewpoint provides a good

Table 1. Comparison of remotely sensed observations (this study) and ground observations (Chadwick et al. 1991) with regard to the 1988 avalanche and eruption

Remote sensing	Ground observations
Lake gone	Lake gone
New flows (5 units/lobes)	New flows
Lava flow area	Lava flow area and volume
Contrast muted	Dust and scoria deposits
Pyroclastic cone gone	Pyroclastic cone gone
Avalanche block gone	Avalanche block gone
Avalanche maybe 2 lobes	Composition of avalanche blocks
New fracture on SE bench	Seismicity
	Scouring by sloshed lake
	Detailed elevation and slope changes
	On-going processes (sinking lake, moving flows, phreatic explosions)

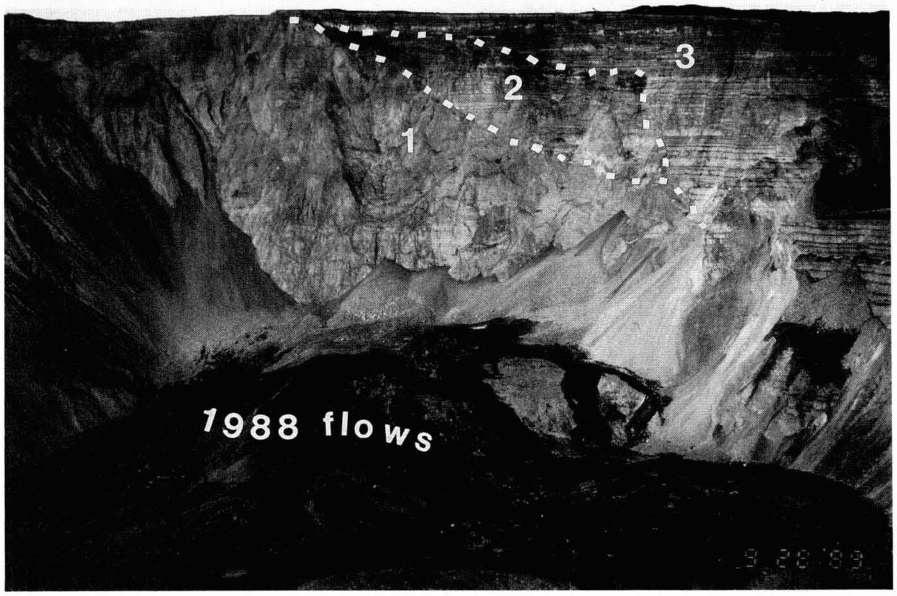

Fig. 9. Photograph of the scar left by the 1988 avalanche. Unit boundaries discussed in text. Note that flows of units 2 and 3 are thick and flat-lying, whereas those of unit 1 are too thin to be discernible (and are irregular)

Fig. 10. Photograph of the SE bench. Note the cover of young lavas and the dark talus formed when they spilled over the inboard edge of the bench. Note also that there is no correlation of flows exposed within the bench with those in the curved caldera wall behind; it is not a collapse structure

complement to the ground observations. Table 1 compares these two data sets. Additionally, as with the previous aerial photos and SPOT scene, the longer-term patterns of unstable caldera walls and the NW-SE distributed eruptive and mass-wasting activity continued through late 1988.

Field observations of the caldera wall

We made observations of the Fernandina caldera in September-October of 1989. Exposed in the caldera wall at the location of the 1988 avalanche is evidence of previous events of caldera collapse and refilling (Fig. 9).The oldest lavas comprise unit 1 and are interpreted here to be extra-caldera flows based on their lack of consistent lateral extent and irregular character. They have been cut by a sloping erosional surface which was then filled in by the lavas of unit 2. The unit 2 lavas were in turn cut by a subsequent destructional event and filled in by the lavas of unit 3. The boundary in which the unit 3 lavas ponded is outside of the present caldera wall. Thus at least three caldera generations are indicated: (1) that which cut unit 1 and within which unit 2 ponded; (2) that which cut unit 2 and within which unit 3 ponded; and (3) the present caldera.

Inspection of the caldera walls shows that except for unit 1 in the 1988 avalanche scar, most of the exposed flows are laterally extensive and relatively thick (~10 m), indicating that they ponded within a depression. Excellent examples are exposed within and behind the SE bench (Fig. 10). It is instructive to make rough calculations of their volumes. A 10-m-thick flow covering the area of the SE bench has a volume of $8.8 \times 10^6\,m^3$. If the SE bench is considered to presently be ~1/2 of its former area (see below) the volume increases to $\sim 17 \times 10^6\,m^3$. If the prominent layer extending from the NW bench is a single flow, it once covered more than 1/2 the area of the present caldera and at 15 m thick, a rough estimate of its volume is $185 \times 10^6\,m^3$.

The volumes of historic intra-caldera flows are estimated to be $31 \times 10^6\,m^3$ in 1958 (this study), $\sim 9 \times 10^6\,m^3$ in 1978 (McClelland et al. 1989), 4–$20 \times 10^6\,m^3$ in 1988 (Chadwick et al. 1991; this study), and slightly more than the 1988 volume in 1991 (Perez-Oviedo 1991). The sum of these is $\sim 85 \times 10^6\,m^3$, half the volume of the single flow that comprises the top of the NW bench and its extension. The single historical collapse event in 1968 removed 1–$2 \times 10^9\,m^3$ (Simkin and Howard 1970), an order of magnitude more material than has been emplaced historically by intra-caldera flows. The period of time covered by this study is extremely short compared to that represented by the caldera walls; however, for the caldera to have at any time been full to the level indicated by lavas exposed high in the present walls, the relative volumes of collapse and infilling would have to have been different.

Discussion

Caldera dynamics

The Fernandina caldera is a structure in which at times material is withdrawn from below. In 1968 this withdrawal was apparently from beneath a relatively restricted region. The inner walls of the caldera are then oversteepened and avalanche inward as in 1988. In cross section, the overall shape of the collapsing zone is probably akin to a funnel, and the center of the funnel appears to be under the southeastern portion of the caldera; this was the deepest part of the pre-1988 lake (Chadwick et al. 1991), and was the center of subsidence during the 1968 collapse (Simkin and Howard 1970). As noted earlier, Walker (1988) has determined that the cumulative shape of all collapse events at Kilauea caldera since the late 1870s is also funnel-shaped; however, during this period of time infilling events have kept pace so that the Kilauea caldera has maintained a flat floor.

The elongate nature of the caldera outline suggests that it formed by the coalescence of more than one collapse feature. The SE end of the caldera presents the best example of such a smaller feature. The flows exposed in the SE bench are flat-lying (Fig. 10), and it is not possible to match the flows exposed below the surface of the bench with flows exposed in the caldera walls above. This lack of correspondence and the ponded nature of the flows leads to the suggestion that the SE bench is the remnant of a partially filled in pit crater that has now been exposed by subsequent caldera collapse (e.g. McBirney and Williams 1969; Simkin and Howard 1970). The benches are more likely to be preserved at the NW and SE portions of the caldera because the smaller radius of curvature of the walls there gives better support.

The summit of Fernandina is, therefore, very unstable and the entire area demarcated by circumferential fissures is apparently under inwardly radial tension and able to fall into the caldera. This tension means that dikes in the summit region will tend to propagate in a direction that allows their direction of opening to also be radial with respect to the caldera; the resulting dike/vent orientations are arcuate and sub-parallel to the caldera walls (Munro 1992). The outermost circumferential fissures and vents indicate the extent of this zone of strong inward-directed tension and also correspond roughly to the outer margin of the relatively flat 'summit platform' of Nordlie (1973). It is here proposed that inboard of this outer margin most of the lavas are ponded (which corresponds well with their thickness, horizontal attitude, and lateral extent in the caldera wall exposures), and that the outer margin itself represents the outermost extent of any inward collapse (Fig. 11). However, there may never have been a single caldera of this size. Simkin (1972) presented a similar distribution of ponded and flank flows; however, the boundary between them proposed in that model was a constructional one consisting of an annulus of short-length flows.

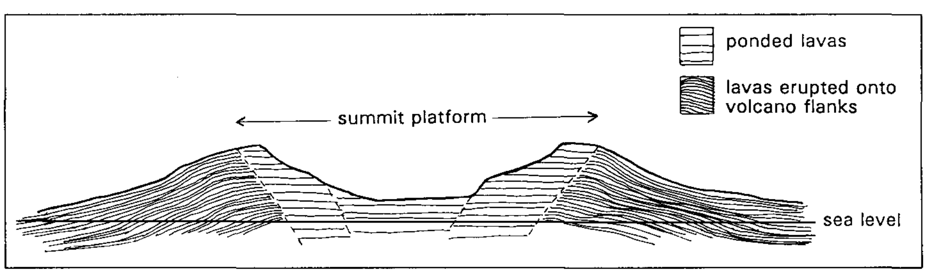

Fig. 11. Diagramatic cross-section of Fernandina (surface profile without vertical exaggeration from Nordlie 1973). The sub-horizontal 'summit platform' (Nordlie 1973) in the model presented here corresponds to the extent of strong inward tension (due to the caldera) and the area in which arcuate fissures are found. It also corresponds to the extent of ponded lavas within previous collapse events, and may or may not have been occupied by a single depression at any one time

Distribution of structural and eruptive features

Historical eruptive and destructional events at the summit are distributed along a NW-SE band that is here suggested to be related to the structure of the volcano. Including the young (dark) flows in the 1946 photo, there have been 16 recent eruptions in or near the caldera. Figure 12 compiles these, and shows that except for part of the 1958 eruption, all have taken place in a broad NW-SE band across the summit. A compilation of the published eruptive record for Fernandina is presented in Table 2, and it can be seen that although eruptions on the flank have been rare, the NW-SE predominance exists for them as well. Munro (1992) notes a subtle topographic ridge radiating SE from the caldera, and topography (e.g. DMA map #22542) shows a similar ridge to the NW. These are also zones of concentrated fissures and vents (McBirney and Williams 1969; Nordlie 1973; Munro and Mouginis-Mark 1990; Chadwick and Howard 1991; Munro 1992). Munro (1992) suggests that these ridges are possibly poorly developed rift zones. The short remotely sensed time window into the eruptive history of Fernandina may therefore correspond well with the longer duration (but not observed) distribution of flank eruptions. The elongation of the caldera is also in this direction, and as it is formed by the coalescence of aligned smaller collapse features, indicates a preferred orientation of magma storage zones within the volcano. Thus the deep central plumbing, shallow central plumbing, and flank plumbing of the volcano have this preferred NW-SE alignment.

The significance of this preferred alignment is somewhat unclear. The caldera of Mauna Loa is elongate in a direction that corresponds to its rift zones (Fig. 13), and is clearly constructed of multiple centers of collapse (e.g. Macdonald 1972). The magma storage zones into which these collapses occur are therefore also aligned. In Hawaii, rift zones are proposed to form because volcano-wide stress regimes (due mainly to growing up through the pre-existing flank of an older neighbor) cause dikes to propagate in directions that keep them parallel to intra-volcano boundaries (e.g. Fiske and Jackson 1972). Galapagos rift zones are much more

Table 2. Compilation of the eruptive history of Fernandina from Simkin et al. (1981) and McClelland et al. (1989) for only those eruptions where locations were reported. Note the predominance of events in a NW-SE (*italics*) orientation

Year	Location
1813	S flank
1825	E summit and *SE flank*
1846	E flank
1927	*SE coast*
1958	*SE*, SW, and W caldera rim
1961	*SE* flank
1968	*SE* flank
1968	W caldera wall
1972	*SE bench*
1973	*ESE wall*
1977	*SE bench*
1978	*NW bench*
1982	upper S flank
1984	W caldera wall
1988	*ESE caldera*
1991	*ESE caldera*

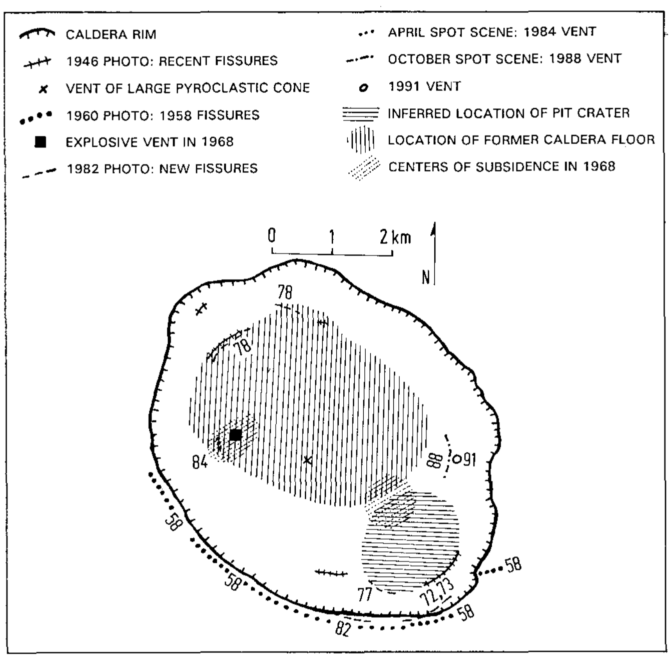

Fig. 12. Generalized map of the Fernandina caldera to show the cumulative distribution of eruptive and structural features determined from the remote sensing data. Note the concentration along a general NW-SE orientation

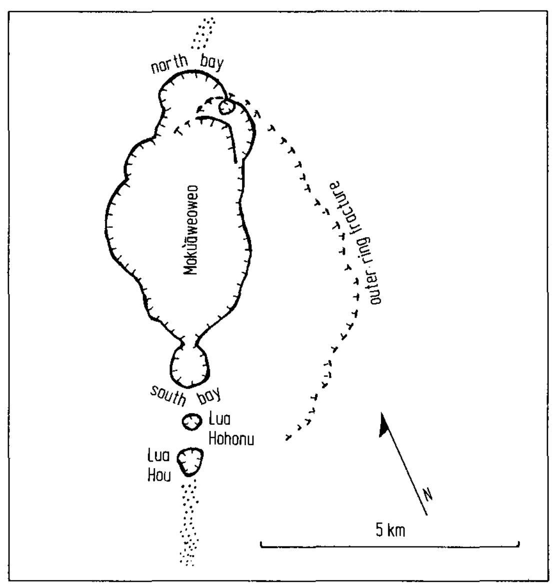

Fig. 13. Simplified map of Mokuaweoweo, the caldera of Mauna Loa Volcano, Hawaii. Note that the main caldera consists of the coalescence of a number of smaller collapse features. The two most distinct are the north bay and south bay. Note also that the direction of elongation corresponds to the orientation of the two principal rift zones (*stippled pattern*)

poorly developed, possibly due to the facts that adjacent volcanoes are farther apart relative to their sizes, and that they are growing contemporaneously (Simkin 1984); none establish stress regimes that others must follow. The development of preferred directions of dike propagation in the Galapagos may instead be influenced by regional stresses (Nordlie 1973); however, the preferred directions are not consistent from volcano to volcano (Chadwick and Howard 1991; Munro 1992), and are also affected by shield-specific stress orientations due to, for example, steep subaerial and submarine scarps (Munro 1992). The NW-SE structural trend suggested in this study does, however, correspond with numerous structural lineaments on the surrounding sea floor (McBirney and Williams 1969; Simkin 1984; Chadwick and Howard 1991), and would seem to indicate NE-SW tension. This direction is sub-perpendicular to the absolute direction in which the Nazca plate is moving (ESE; Hey et al. 1972).

Regional tectonic stresses have been proposed to govern the orientation of eruptive fissures on Mt. Etna (McGuire and Pullen 1989). At Mt. Etna, the upper part of the volcano is dominated by gravitational stresses due to the edifice itself as well as the presence of the Valle del Bove, a breached caldera that forms a steep-walled amphitheater-headed valley on the ESE flank. Lower on Mt. Etna, regional tectonic stresses appear to govern the direction of dike propagation. The distribution of eruptive fissures in and around the Fernandina caldera may also be affected by two multiple regimes: the historic fissure locations and the broad topographic ridges show a NW-SE preference; near-summit fissures tend to parallel the caldera walls; and radial fissures can be found on all sectors. Thus although at times the distribution of magma excursions at Fernandina may be governed by a large-scale stress orientation, at other times it is not, and furthermore if a dike happens to reach the surface near a caldera wall, its final orientation is most strongly affected by the presence of that caldera wall (Munro 1992).

These options at Fernandina differ from the better-known Hawaiian examples where magma excursions are concentrated along well-developed rift zones throughout the shield-building stages of the volcanoes. The major difference seems to be that in Hawaii, once rift zones are established seaward displacement of the rift zone maintains constant cross-rift tension (e.g. Fiske and Jackson 1972; Dieterich 1988), and thus a favorable direction of intrusion. Volcan Fernandina is essentially surrounded by neighboring volcanoes, making lateral expansion and displacement difficult, and there is little subaerial evidence of large-scale movement (e.g. faults). Furthermore, the Galapagos volcanoes lack the thick sediment layer between the volcano-seafloor interface that is interpreted to aid seaward displacement in Hawaii (e.g. Nakamura 1982).

An additional difference between the Galapagos and Hawaii shield volcanoes is the lack in the historical record at Galapagos of long-duration low-output eruptions, which in Hawaii generate tube-fed pahoehoe lava flows. As noted by Simkin (1984) a'a predominates the surfaces of the Galapagos shields; we estimate the surface of Fernandina to be ~90% a'a, indicating that recent prehistoric activity has shown a paucity of pahoehoe-forming eruptions. At both Kilauea and Mauna Loa, the most recent episodes of caldera-filling were achieved by such long-duration eruptions at the summits (Holcomb 1987; Lockwood and Lipman 1987). These eruptions require a stable and thermally efficient plumbing system, which in turn implies a high magma supply rate to the volcano. When magma supply is lower, this efficient magma transport system does not develop, and individual eruptions are of smaller volume (although they may be at higher discharge rates). All the Galapagos volcanoes with deep calderas might thus be considered to be in stages of relatively low supply compared to periods in the past.

A model for Fernandina is now presented to account for the NW-SE alignment of eruptive and collapse features, the smaller volume of recently erupted lavas compared to those exposed in the caldera walls, and the lack of pahoehoe on the surface. In this model (Fig. 14) the direction of regional least compressive stress is oriented NE-SW, the long-term rate of caldera subsidence is constant, and the magma supply rate to the volcano allowed to vary. When magma supply is low (as is proposed to be the case at present), the regional stress regime determines the orientation of dike propagation and leads to

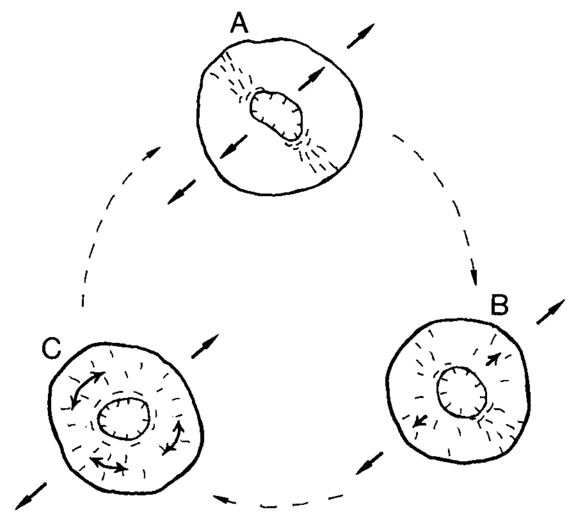

Fig. 14. Diagrams to show the (possibly cyclic) variation in preferred intrusion locations at Fernandina that may result from combining variations in supply rate with regional NE-SW tension. *Hatchured line* indicates caldera, *small line segments* indicate surface expressions of dikes, and *heavy arrows* indicate directions of least compressive stress for the volcano (onshore) and general region (offshore). A: (at present) Low supply rate results in small eruptions, caldera subsidence outpaces infilling, and the regional stress regime determines the preferred intrusion direction (dikes are concentrated along a NW-SE band). B: Magma supply rate increases and the SE and NW directions become unable to accommodate all the intrusions; eruptions take place elsewhere on the volcano. C: High magma supply rate results in many large eruptions on all sections of the volcano, caldera filling outpaces subsidence, and the weak NE-SW regional tension direction is overwhelmed by edifice stresses (circumferential tension)

the observed NW-SE bias. The proposed low magma supply rate is still sufficient to maintain the magma chamber; however, eruptions will tend to be of small volume and be unable to keep up with subsidence into the magma chamber. This leads to a deep and large caldera.

When the magma supply increases, the 'rift zones' soon become 'full' because without the ability to extend laterally, continued injection in these directions renders them less favorable for intrusion (e.g. Dieterich 1988). Eventually all azimuths of dike propagation become equally favorable and vents form at all orientations. The other consequence of increased magma supply is that the plumbing system becomes more thermally and hydraulically efficient, and long-duration (pahoehoe-producing) eruptions are more likely. Many large-volume near-summit eruptions may eventually fill the caldera. The evidence in both the caldera walls and the caldera outline supports the fact that there have been multiple caldera-collapse events and more than one generation of caldera. The periods of time required to fill each one prior to being exposed by collapse had to have been long enough to accumulate sequences of flows 500–1000 m thick.

The historic record is very short compared to the age of the volcano, and this must always be kept in mind when suggesting both patterns and changes in patterns. The model presented here only accommodates the observations of preferrentially oriented small volume recent eruptions, large-volume eruptions in the past, and the construction of (subtle) topographic ridges. It also is consistent with alignment of features seen on the surrounding ocean floor, and the fact that all of the active volcanoes on Isla Isabela also show concentrations of fissures at azimuths within 20° of those of Fernandina (although some have other concentration directions as well; Munro 1992). One possible cause for variations in supply to Fernandina is that the Galapagos hot spot is supplying seven volcanic centers, unlike the Hawaiian hotspot which is supplying three. It is reasonable to expect that one or a few of these seven centers is/are periodically more active than the others. Even though in the short historic time window Fernandina has been more active than the other Galapagos volcanoes, the small volume of these eruptions and the depth of its caldera are suggested here to represent a low supply rate relative to periods of time in the past. The paucity of pahoehoe extends this low-supply period back as far as the time required to resurface the volcano. Age dates, geochemistry, and further fieldwork would go a long way towards understanding the Galapagos volcanoes.

In conclusion, a remotely sensed data set covering nearly 45 years of activity at Fernandina plus field observations have been used to study its caldera. The caldera has undergone numerous episodes of collapse and infilling, and the locus of recent intrusive, extrusive, and collapse events is oriented along a NW-SE direction. Additionally, recent eruptions have been small compared to those exposed in caldera outcrops. A variable magma supply rate may be changing the relative influences of edifice-induced versus regional stress regimes, and is here suggested to be the cause of temporal variations in fissure orientations and relative caldera filling versus caldera collapse.

Acknowledgements. We would like to thank P Mouginis-Mark, V Perez-Oviedo, and L Wilson for helpful discussions, particularly while in the field. Reviews by W Chadwick and T Simkin led to a much improved manuscript. G Walker, P Mouginis-Mark and M Robinson also critically read the manuscript and provided many useful suggestions. We also thank K Howard for loaning us the 1960 aerial photos, and T Simkin for sending a copy of Simkin and Fiske (1986). The help of the Charles Darwin Research Station and the Galapagos National Park Service, our guides, and the captain and crew of the Isla Gardner is gratefully acknowledged. H Garbeil assisted with the image processing. This work was funded by NASA grant #NAGW-1162 from the Geology Program and JPL grant #958457 from the SIR-C Program, and forms part of the Phd research of Duncan Munro. This is SOEST publication no. 3058 and Planetary Geosciences contribution no. 697.

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