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The pattern of circumferential and radial eruptive fissures on the volcanoes of Fernandina and Isabela islands, Galapagos

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Abstract. Maps of the eruptive vents on the active shield volcanoes of Fernandina and Isabela islands, Galapagos, made from aerial photographs, display a distinctive pattern that consists of circumferential eruptive fissures around the summit calderas and radial fissures lower on the flanks. On some volcano flanks either circumferential or radial eruptions have been dominant in recent time. The location of circumferential vents outside the calderas is independent of caldera-related normal faults. The eruptive fissures are the surface expression of dike emplacement, and the dike orientations are interpreted to be controlled by the state of stress in the volcano. Very few subaerial volcanoes display a pattern of fissures similar to that of the Galapagos volcanoes. Some seamounts and shield volcanoes on Mars morphologically resemble the Galapagos volcanoes, but more specific evidence is needed to determine if they also share common structure and eruptive style.

Introduction

The Galapagos archipelago is a group of volcanic islands near the equator and 1000 km west of Ecuador (Fig. 1). The volcanoes are believed to have grown above a hotspot on the south side of the east-west trending Cocos-Nazca spreading center (Wilson 1963; Morgan 1971; Hey 1977; Hey et al. 1977); the hotspot is now apparently centered under Fernandina and Isabela islands. At least eight volcanoes have erupted historically (Richards 1962; Simkin et al. 1981; Simkin 1984). This paper focuses on Fernandina volcano (known locally as Volcán Cumbres), which makes up Fernandina Island, and the five major volcanoes that make up the island of Isabela: Wolf, Darwin, Alcedo, Sierra Negra, and Cerro Azul (Fig. 2). All of these volcanoes are basaltic shields with large summit calderas, and mostly erupt lavas from linear or arcuate eruptive fissures. We use the phrase "eruptive fissure" to mean a crack from which volcanic materials have erupted; it is where a dike has intersected the Earth's surface. Some previous authors have referred to these features as "fractures", a term we feel is ambiguous because it seems to imply that a system of cracks or faults predated, and then controlled the location of later eruptive activity.

The volcanoes display a distinctive pattern of eruptive fissures, consisting of circumferential fissures around the summit calderas and radial fissures lower on the flanks (Banfield et al. 1956; McBirney and Williams 1969; Simkin 1972; Nordlie 1973; Simkin 1984). The pattern of eruptive fissures reflects the orientations of underlying dikes intruded from magma reservoirs beneath the calderas. This pattern is intriguing because it is rare on other basaltic shield volcanoes, and thus has inspired much speculation about its origin and significance. Unfortunately, little detailed geologic or geophysical information about the Galapagos volcanoes has been available to constrain this speculation.

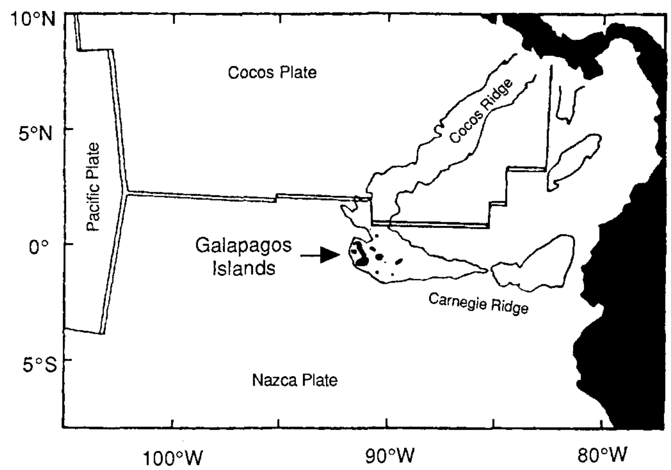

Fig. 1. Location map showing plate tectonic setting of the Galapagos Islands (Hey et al. 1980)

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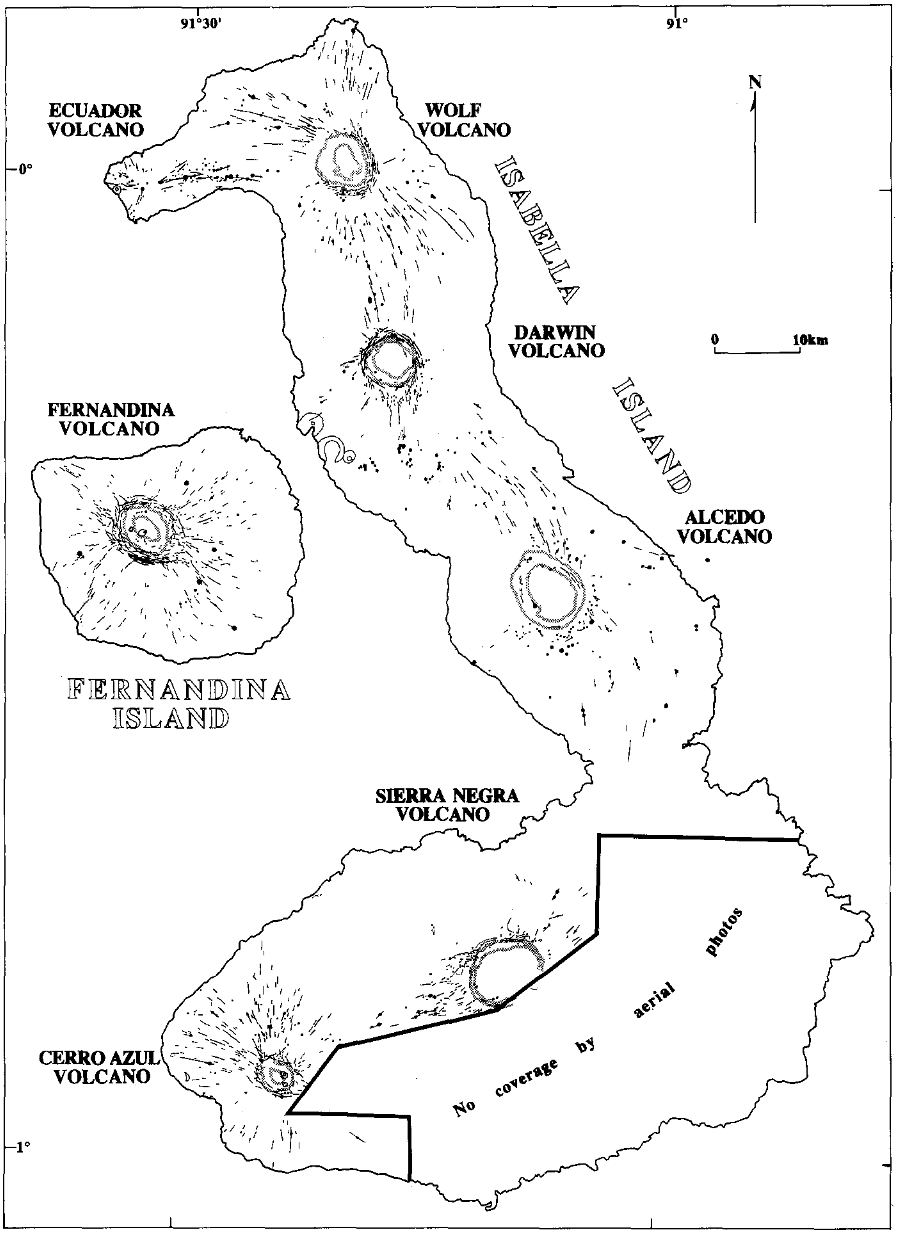
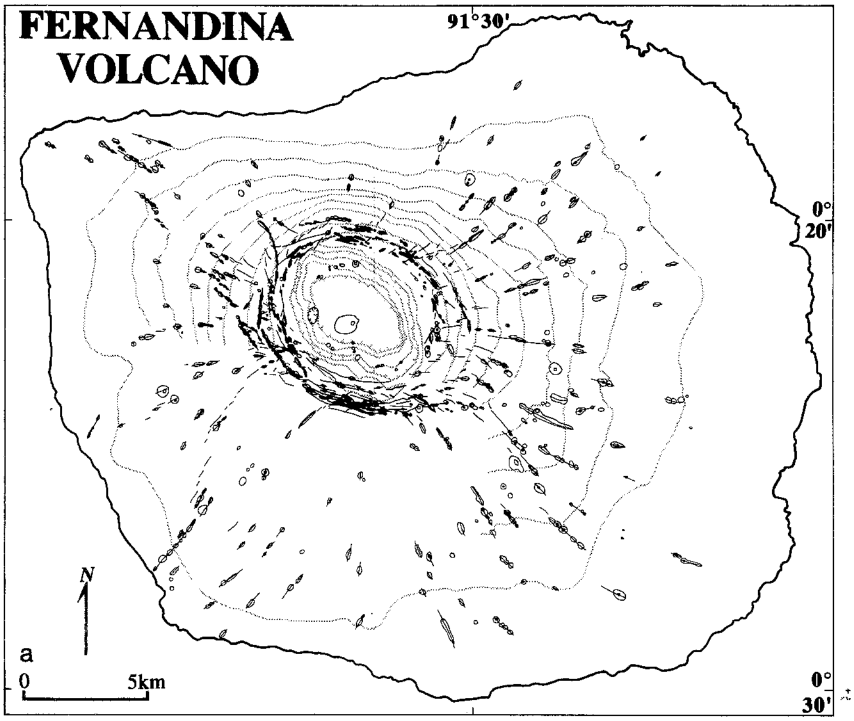


Fig. 2. Map of eruptive vents on Isabela and Fernandina islands. Outlines of caldera rims and floors at the major shield volcanoes are *stippled lines*

We present here maps of the eruptive fissures on Fernandina and Isabela islands, and characterize the fissure patterns qualitatively and quantitatively. We also examine previous interpretations of the pattern in the context of the vent maps and assess the uniqueness of the pattern.

Vent maps

The pattern of eruptive fissures has been described in general terms and has been mapped in detail locally (McBirney and Williams 1969; Delaney et al. 1973; Nordlie 1973). Munro and Mouginis-Mark (1990) mapped lava flows and identifiable eruptive vents on Fernandina Island from SPOT-1 satellite imagery and Space Shuttle Large Format Camera photographs. While satellite data is a valuable mapping tool because of its large areal coverage and uniform geometry, the spacial resolution of these images (~10 m) limited their utility for mapping small cones and eruptive fissures. The maps presented here (Figs. 2, 3, and 4) were made from 1:40000- and 1:50000-scale aerial photographs (Fig. 5) taken in 1946 and 1960 by the US Air Force in cooperation with the government of Ecuador (therefore these maps do not show fissures that have erupted since 1960). The base maps that were used are navigational charts that include some topographic information, originally produced by the US Hydrographic Office and now distributed by the US Defense Mapping Agency. We revised a few erroneous topographic contours on parts of Alcedo, Wolf, and Fernandina volcanoes by photogrammetric techniques using a Kern PG-2 stereoplotter. The location of eruptive vents was transferred from the photographs to the base maps using the PG-2 plotter.



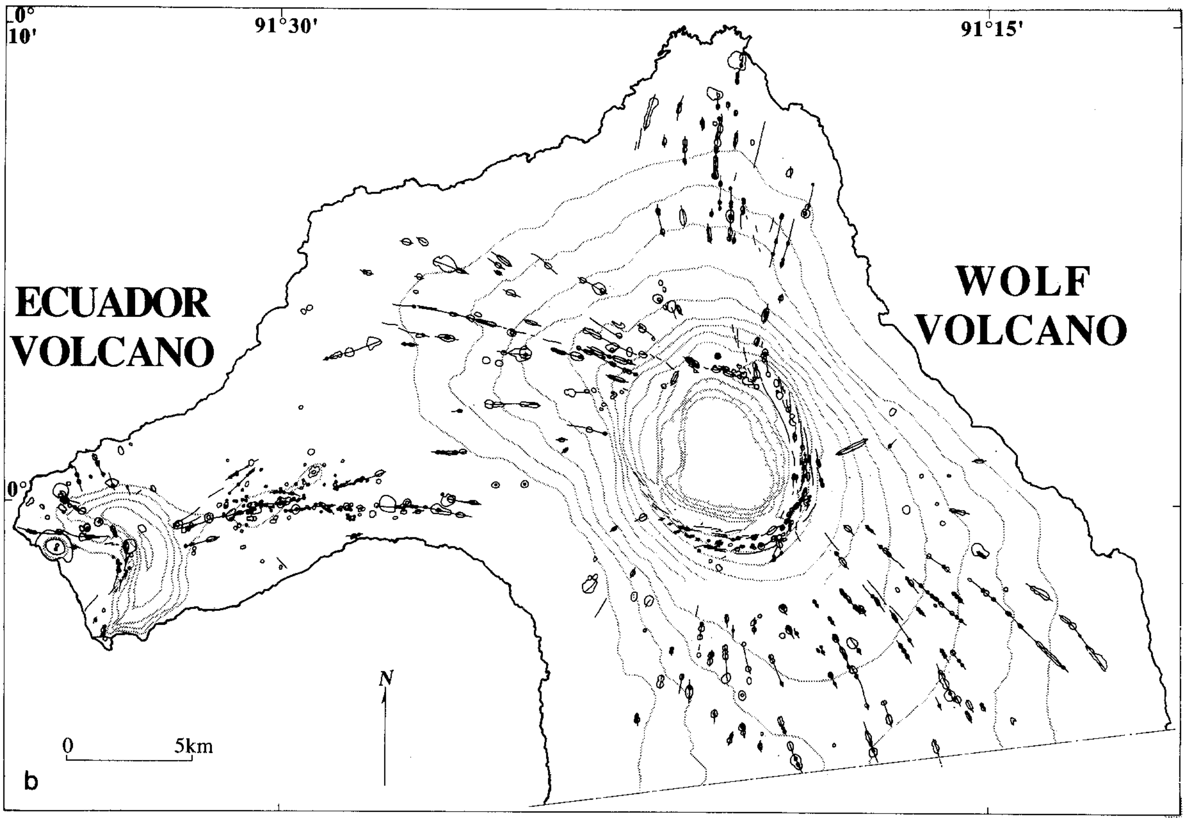


Fig. 3a–f. Maps of eruptive vents, including eruptive fissures (*lines*) and cones (*outlines*), on: **a** Fernandina, **b** Wolf and Ecuador, **c** Darwin, **d** Alcedo, **e** Sierra Negra, **f** Cerro Azul. Topographic contours where available are *stippled lines* (500 ft interval); in **e** and **f** only outlines of caldera rims and floors are shown, and *bold lines* outline edge of coverage by aerial photography

We plotted all volcanic vents visible on the photographs. These vents are marked by cinder and spatter cones and ramparts, as well as open fissures (~1 m wide) that fed lava flows without building near-vent structures; a variety of vent forms commonly formed along a single eruptive fissure. We drew lines along fissures and through cones and ramparts that were built along the same eruptive fissure. In some cases there is no gaping fissure between adjacent cones, but it is still clear they were erupted along a linear vent where cones

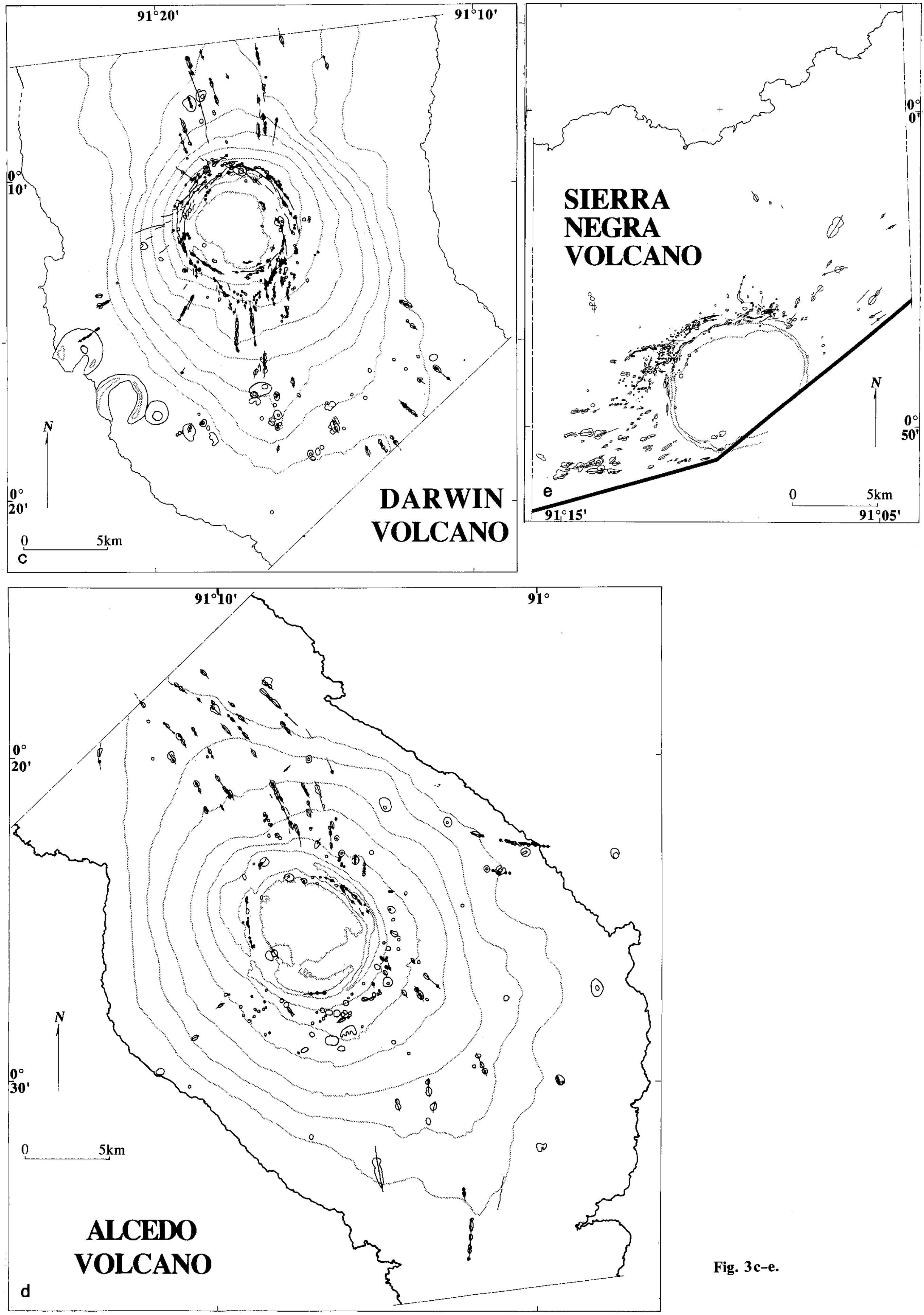

91°20'
91°10'
0° 10'
0° 20'
N
0 5km
c
DARWIN VOLCANO
0° 0'
SIERRA NEGRA VOLCANO
N
0° 50'
e
0 5km
91°15'
91°05'
91°10'
91°
0° 20'
N
0° 30'
0 5km
ALCEDO VOLCANO
d

Fig. 3c–e.

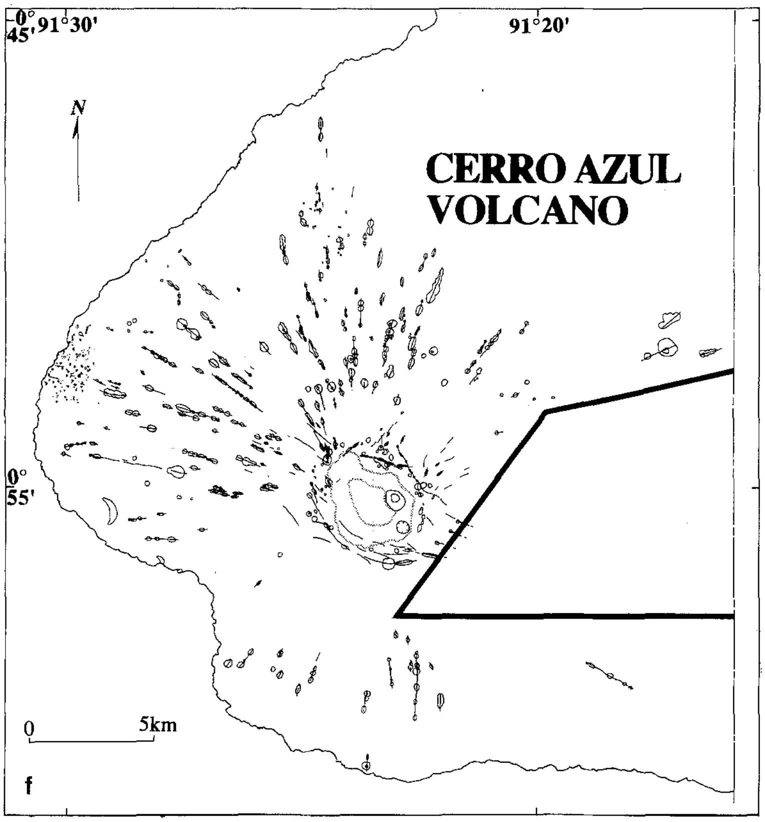


Fig. 3f.

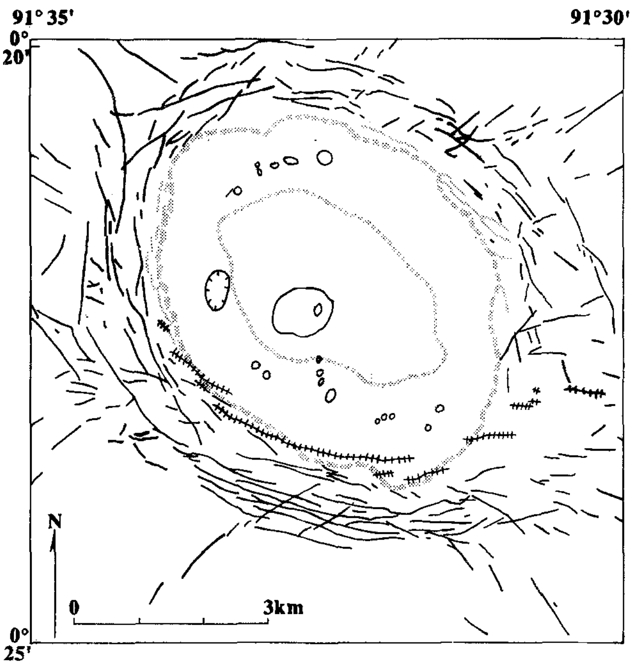


Fig. 4. Map of Fernandina summit showing caldera rim and floor (*wide gray lines*), normal faults related to caldera subsidence near caldera rim (*narrow gray lines*), eruptive fissures (*solid lines*), and cones and craters within caldera (*circular outlines*). Cones not shown outside of caldera to emphasize pattern of fissures. The set of eruptive fissures near the south rim of the caldera that formed in 1958 are *cross-hatched*

or craters have elongated outlines, or where several cones are closely spaced along a trend. Some en echelon groups of fissures formed at the same time, and are probably underlain by a single dike (Delaney and Pollard 1981; Pollard et al. 1982). If the offset between segments was $< \sim 50$ m, we linked them together along the same line, but if the offset was $> \sim 50$ m, or the timing between segments unclear, we mapped them separately.

The accuracy of vent locations on our maps is best near coastlines, and poorest inland because the photographs and base maps lack accurate geodetic control. We estimate the horizontal location accuracy to be about 100 m near the coast and about 200–400 m in inland areas; however, the trends of fissure vents are well established everywhere. The maps for southern Isabela island may have inland location errors of up to 1 km, because the base maps of this area that we used have no topographic information. Nevertheless, within relatively small areas, the locations of vents relative to each other are accurate. The southeastern end of Isabela island is covered with clouds in available aerial photographs, so it was not possible to map vents in this area.

The photogeologic mapping is supported by field observations by Chadwick in 1989 (one week at Fernandina and two days at Ecuador volcano to field check parts of the vent maps and to study the relations between vents and faults near the rim of Fernandina caldera) and Howard in 1970 (four weeks of geologic mapping at Alcedo, one week at Fernandina, one week at Wolf, and one day at Ecuador volcano).

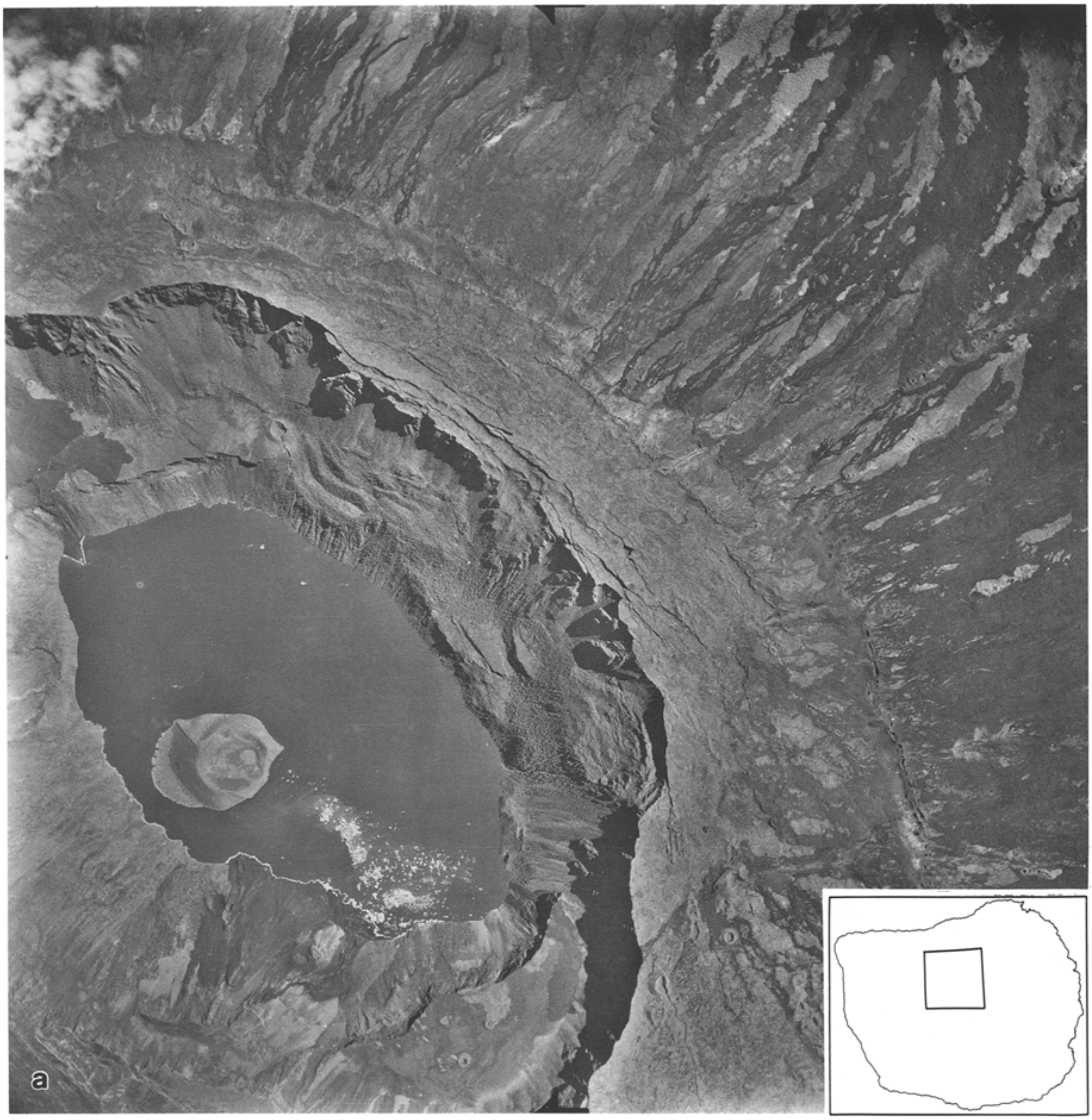


Fig. 5a–d. Aerial photographs, taken in 1946, from which the fissure maps were made: **a** Fernandina summit; **b** Wolf north flank; **c** Wolf summit; **d** Cerro Azul summit. Locations of photos indicated by *inset maps* which correspond to Fig. 3a, b, and f

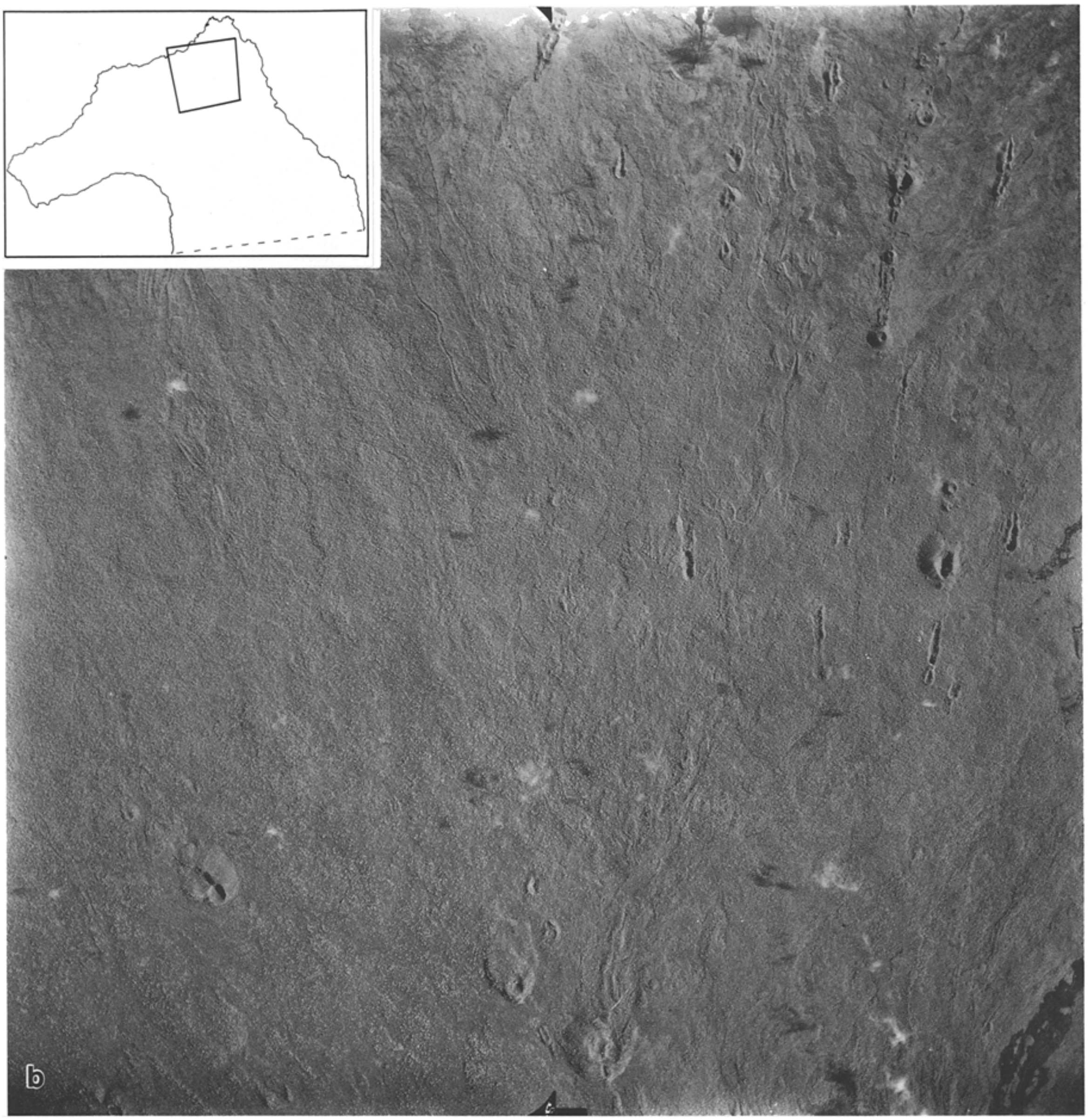
The pattern of eruptive fissures

Previous studies have described the general pattern of eruptive fissures (Banfield et al. 1956; McBirney and Williams 1969; Simkin 1972; Nordlie 1973; Simkin 1984). Here we present some additional observations from our photogeologic mapping and field work, and quantify some aspects of the pattern of fissures on Fernandina.

Circumferential fissures

Circumferential fissures are best developed on Wolf, Darwin, and Fernandina volcanoes (Fig. 3). Circumferential fissures are located both within and outside the calderas. We distinguish between these two settings, because intra-caldera eruptions commonly occur along caldera ring faults, whereas those outside the calderas do not. In the rest of this paper, we use the term "circumferential fissure" to refer only to those located *outside* the calderas.

Circumferential eruptive fissures are within 1.5 km of caldera rims. Many circumferential dikes are exposed in the walls of Fernandina and Wolf calderas. The dikes are consistently vertical or nearly so, and about 1 m thick. Dikes observed at Ecuador and Alcedo volcanoes are narrower, averaging about 0.3 m. Circumferential and radial dikes at Alcedo are exposed in the south wall of the caldera where they intrude flows and probable sills that dip 40° outward under the steep south flank of the volcano. The circumferential

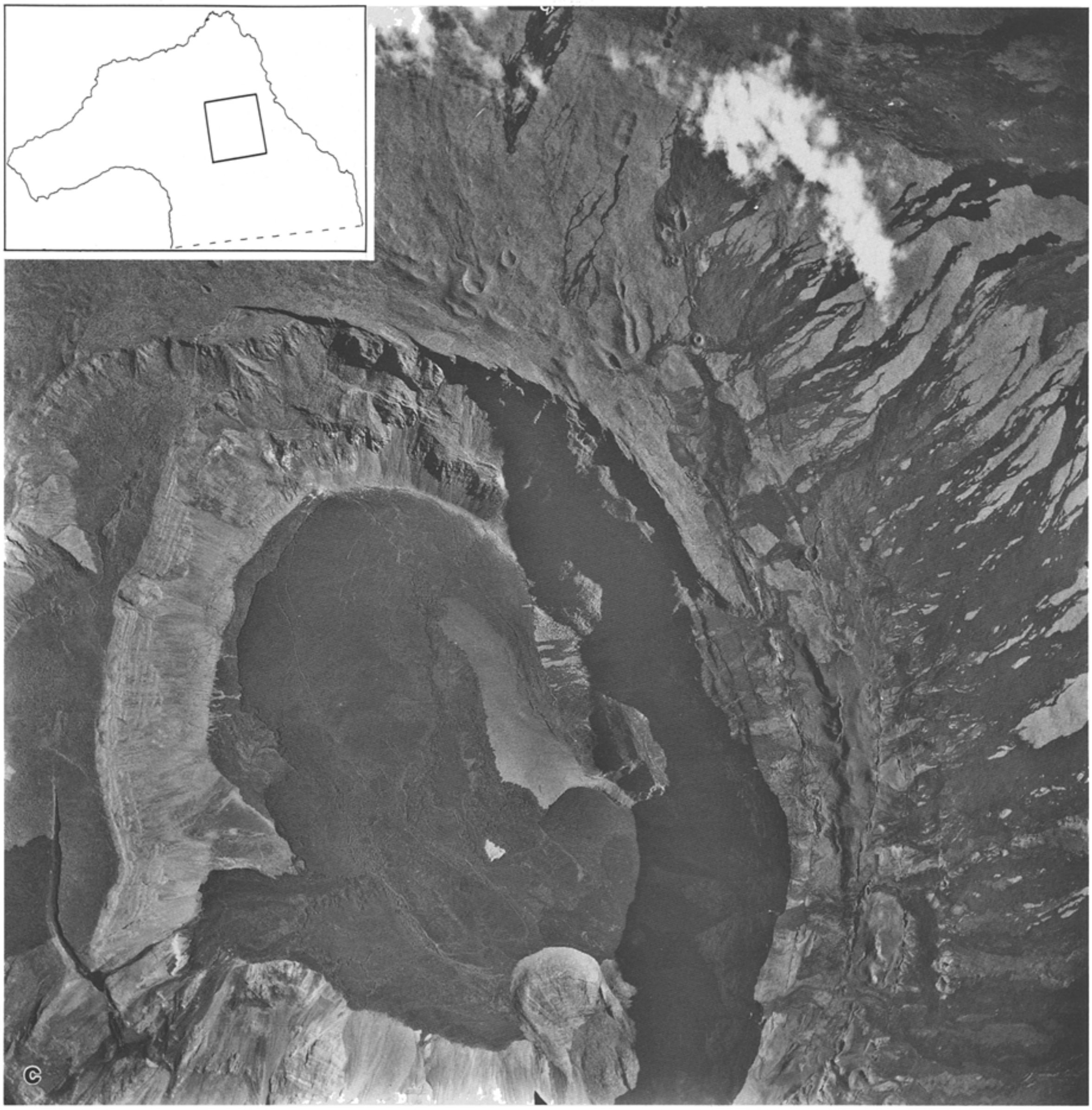


dikes there dip inward steeply at 60–90° toward the caldera.

McBirney and Williams (1969) noted at least four concentric sets of fissures around Fernandina caldera. On our vent map it is common for transects perpendicular to the rim of Fernandina caldera to cross three to six circumferential eruptive fissures, and south of the caldera transects cross up to 11 fissures (Fig. 4). McBirney and Williams (1969) also observed that the length of circumferential fissures varies, and no single fissure can be traced around a full circle. The longest circumferential fissures are about one quarter of a caldera circumference. On Fernandina, the longest circumferential fissure is 3.4 km, the average length is 0.7 km, and the cumulative length of all mapped circumferential fissures is 95 km.

Different parts of a single eruptive fissure can be oriented circumferentially and radially. For example, the 1958 eruption on Fernandina produced a set of eruptive fissures that are circumferential south of the caldera and radial east of the caldera, because the dike was intruded tangential to the caldera rim (Fig. 4). This apparently explains why there are some radial and oblique fissures near the caldera rims where circumferential fissures dominate. The sense of en echelon segments from the 1958 fissure step right along the west half and step left along the east half (Fig. 4), suggesting that the dike was more curved at depth and was trying to straighten near the surface (Delaney and Pollard 1981; Pollard et al. 1982). In contrast to this tangential arrangement, one circumferential fissure northwest of Fernandina caldera curves downslope gradually and becomes radial (Fig. 4).

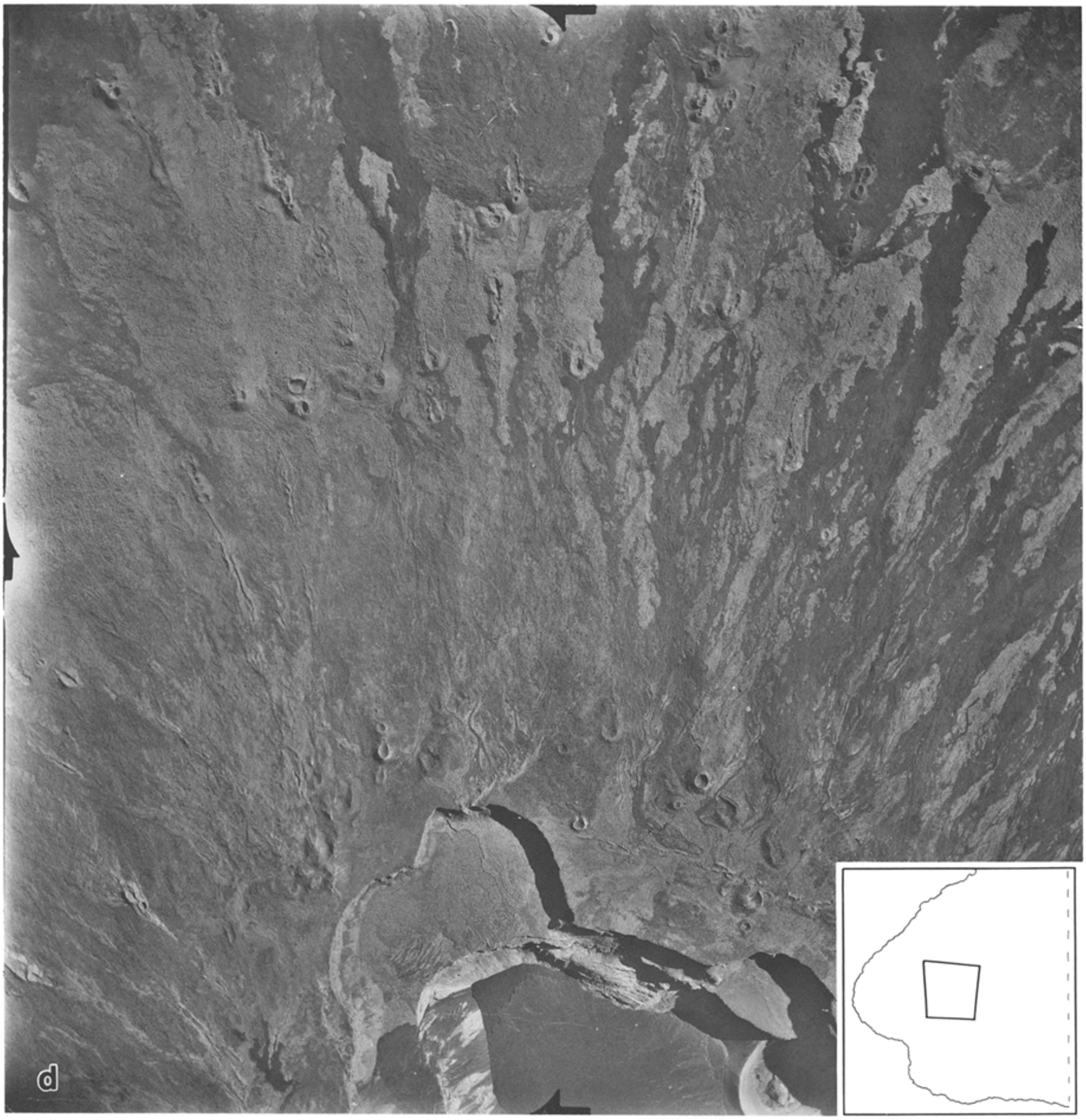
The location of circumferential vents appears to be independent of normal faults near the caldera rims along which slump blocks drop toward the calderas (Fig. 4). No vertical offset was observed in the layers adjacent to dikes in the walls of Fernandina caldera or



along the eruptive fissures on the surface, and many circumferential fissures crosscut caldera-related faults, or are located downslope from caldera rims. This indicates that the circumferential fissures are not simply leaky faults, but their underlying dikes are emplaced as distinct and independent structures and require a specific stress field suitable for the observed fissure orientations.

Other extensional structures, including open tension cracks and grabens, not directly related to caldera faulting, were found within the zone of circumferential vents during fieldwork, notably south of Fernandina caldera and east of Wolf caldera. This suggests that the zone of circumferential fissures is a zone of extension, in which dike intrusion can continue in the long term. Otherwise, repeated diking in this zone would eventually alter the stress field and prevent further circumferential intrusions.

It appears that either circumferential or radial fissuring has been dominant in recent geologic time on some volcano sectors. For example, on the north flanks of Sierra Negra and Fernandina, and the east flanks of Wolf and Darwin (Fig. 3), recent eruptions have been dominantly from circumferential fissures and few if any radial fissures are observed. In contrast, radial fissures are dominant on the west flanks of Wolf and Sierra Negra and the north flanks of Alcedo and Cerro Azul. This suggests the possibility that, at a given time, the local stress field may favor one or the other dike orientation but not both, and that perhaps periods of circumferential and radial fissuring alternate in time due to cyclic perturbations of the local stress field.



Radial fissures

The pattern of radial fissures is best developed on Cerro Azul, Fernandina, and Wolf volcanoes, and less well developed on Sierra Negra, Darwin, and Alcedo (Fig. 3). The origin of the isolated area of numerous unaligned small cones on the west coast of Cerro Azul volcano is unclear (Fig. 3f). Nordlie (1973) stated that most radial fissures were confined to the upper steep slopes of Galapagos volcanoes, but the new maps show instead that most radial fissures are found below the break in slope and that many are near the coast (Fig. 3). The longest radial eruptive fissure on Fernandina is 2.6 km, the average length is 0.6 km, their cumulative length is 114 km, and the average distance from the caldera center to the upslope end of each radial fissure is 7.9 km.

Fernandina probably has the best developed circumferential and radial fissure system of all the Galapagos volcanoes. McBirney and Williams (1969) thought that radial vents were rare on Fernandina, probably because the circumferential fissures are more densely concentrated (Fig. 6), but our mapping shows that Fernandina has more radial than circumferential fissures. We mapped 202 radial fissures, and 58 isolated cones low on the volcano flanks that we assume were also fed by radial dikes. Within about 1.5 km of the caldera rim, we mapped 132 circumferential fissures and 43 fissures that are more radial in orientation. It is ambiguous how these radial fissures within the circumferential zone should be categorized since some circumferential eruptions produce fissures that are locally radial to the caldera rim, like the 1958 eruption discussed earlier. By comparison, Munro and Mouginis-Mark (1990) map-

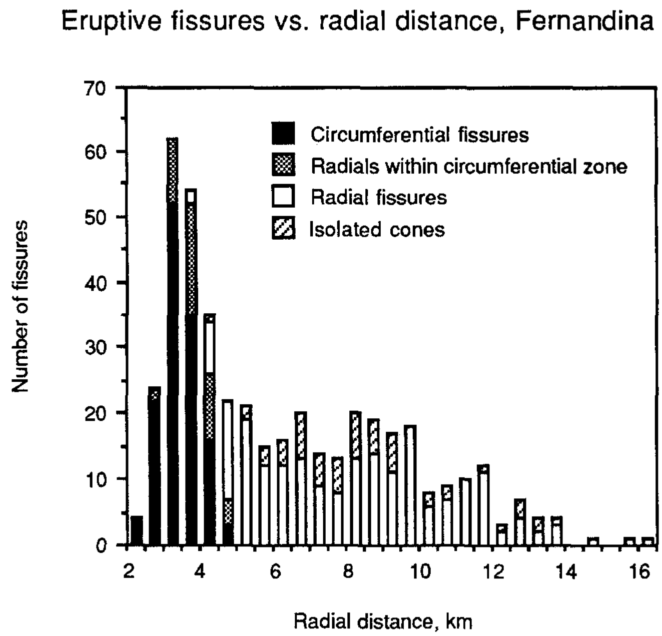
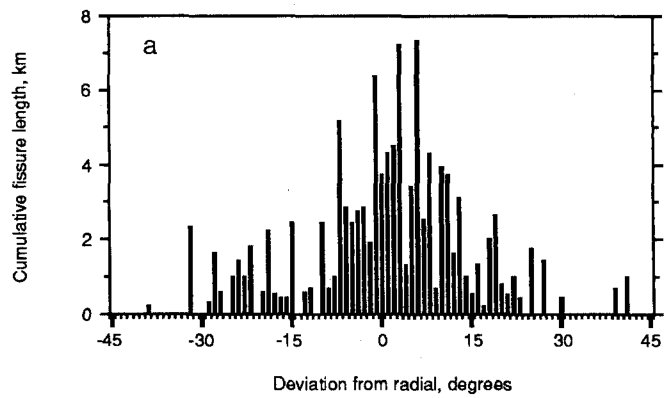


Fig. 6. Histogram of individual eruptive fissures vs. radial distance on Fernandina. Radial distances are from caldera center to the up-slope end of flank fissures. A similar plot published by Simkin (1972) is apparently of individual cones rather than eruptive fissures

ped 26 radial and 18 circumferential fissures, identified by the alignment of cones on lower resolution images from the SPOT-1 satellite and Space Shuttle Large Format Camera. They also identified 461 cones, but some are mapped where none exist on aerial photographs.

Only a few eruptive fissures on the volcano flanks are oriented at a large angle to the radial direction; for example, on the east coast and south flank of Alcedo, and the west coast of Fernandina. These "non-radial" fissures are at a relatively large distance from the calderas and their orientation may be relatively more affected by the regional stress field. A measure of the degree to which fissures on the flanks of Fernandina are radial can be obtained by subtracting the azimuth to the upslope end of each fissure from the caldera center, from the trend of the fissure itself. The caldera center is defined relative to the caldera rim. The resulting frequency distribution is bell-shaped around zero (Fig. 7a). The sign of the deviation from radial is somewhat correlated with the azimuth from the caldera center (Fig. 7b).

The trends of eruptive fissures on Fernandina are not evenly distributed. Radial fissures have two peak orientations, about 90° apart, and the circumferential fissures have one peak, close to one of the peak radial trends (Fig. 8). The azimuthal distribution of radial fissures and flank cones from the center of Fernandina caldera is highest between 120–130° and 290–300°, roughly 180° apart (Fig. 9a). These same sectors of the volcano have relatively low frequencies of circumferential fissures (Fig. 9b).



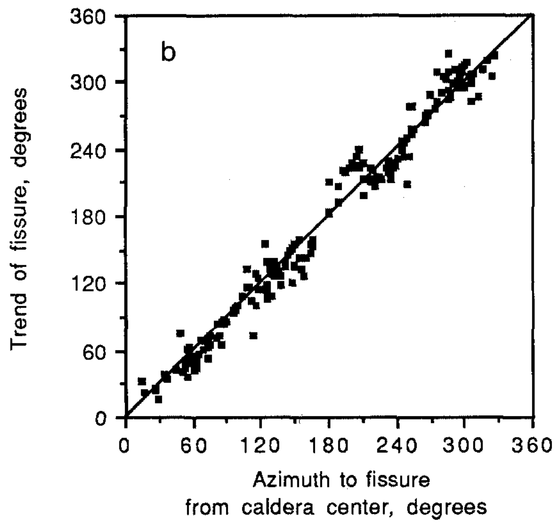


Fig. 7 a, b. Plots illustrating radial orientation of fissures on the flanks of Fernandina. **a** Cumulative length of radial fissures vs. deviation from radial (the trend of a fissure minus its azimuth from the caldera center, defined relative to the caldera rim). **b** Trend of individual fissures vs. azimuth to up-slope end of fissure from caldera center. Line of equal trends and azimuths (truly radial fissures) plotted for reference. Note that groups of points lie either above or below the line at some azimuths

The azimuthal distribution of radial fissures on the volcanoes of Isabela Island also appears to be non-random. Radial fissures are concentrated between volcanoes, parallel to lines that join adjacent calderas (Figs. 2 and 3). Radial fissures also cluster on other volcano flanks that appear to be areas or directions of preferred dike intrusion; for example north and northwest of Wolf and Cerro Azul calderas, and northwest of Fernandina caldera (Fig. 3). These clusters coincide with subtle topographic ridges that create shoreline promontories and continue in the offshore bathymetry. This indicates that the dike clusters are persistent in time long enough to construct such ridges.

Despite the clustering of some radial dikes, the Galapagos volcanoes lack distinct, narrow rift zones like those on Hawaiian volcanoes. Hawaiian volcanic rift zones are characterized by a narrow (1-3 km wide), linear zone of many eruptive fissures, open ground cracks, pit craters, fault grabens, cones and small shields (Macdonald et al. 1983; Holcomb 1987), and are sites of sec-

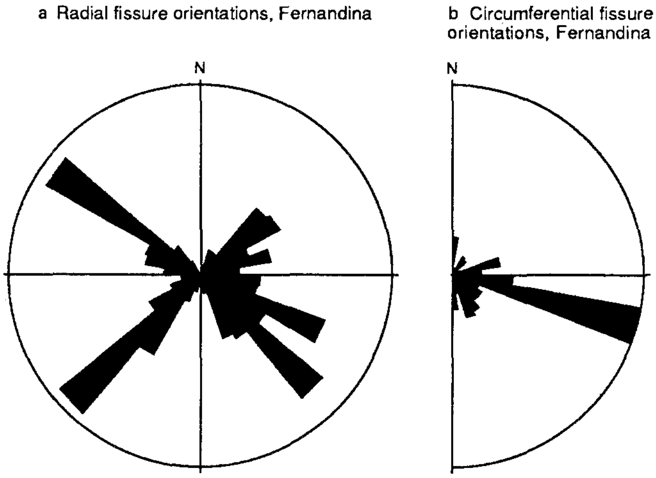


Fig. 8a, b. Rose diagrams showing orientations of (**a**) radial and (**b**) circumferential eruptive fissures on Fernandina. In (**a**) the number of fissures is 202 and the outer circle is 10%; in (**b**) 132 fissures are plotted and the outer circle is 28%. The average orientation of each fissure is plotted a number of times that is proportional to its length, so that long fissures have more weight than short ones (but plots made by giving all fissures equal weight are similar). The "downslope" direction for each radial fissure was plotted, so that they plot generally in the quadrant where they occur on the volcano. However, this is not applicable for the circumferential fissures, so only half a diagram is shown

ondary magma storage (Wright and Fiske 1971; Wolfe et al. 1987). In Hawaii the dominating gravitational stress field of a larger neighbor volcano is thought to influence the development of the rift zones (Fiske and Jackson 1972). Galapagos volcanoes may lack such rift zones because the volcanoes grow concurrently and not on a neighbor's flank (Simkin 1984). The Galapagos volcanoes also lack large normal faults like those found on the flanks of Hawaiian volcanoes, which are a consequence of rift-zone spreading (Swanson et al. 1976; Nakamura 1980; Dieterich 1988). The only faults observed on the aerial photographs outside the calderas are on the southwest flank of Cerro Azul and the west side of Ecuador volcano.

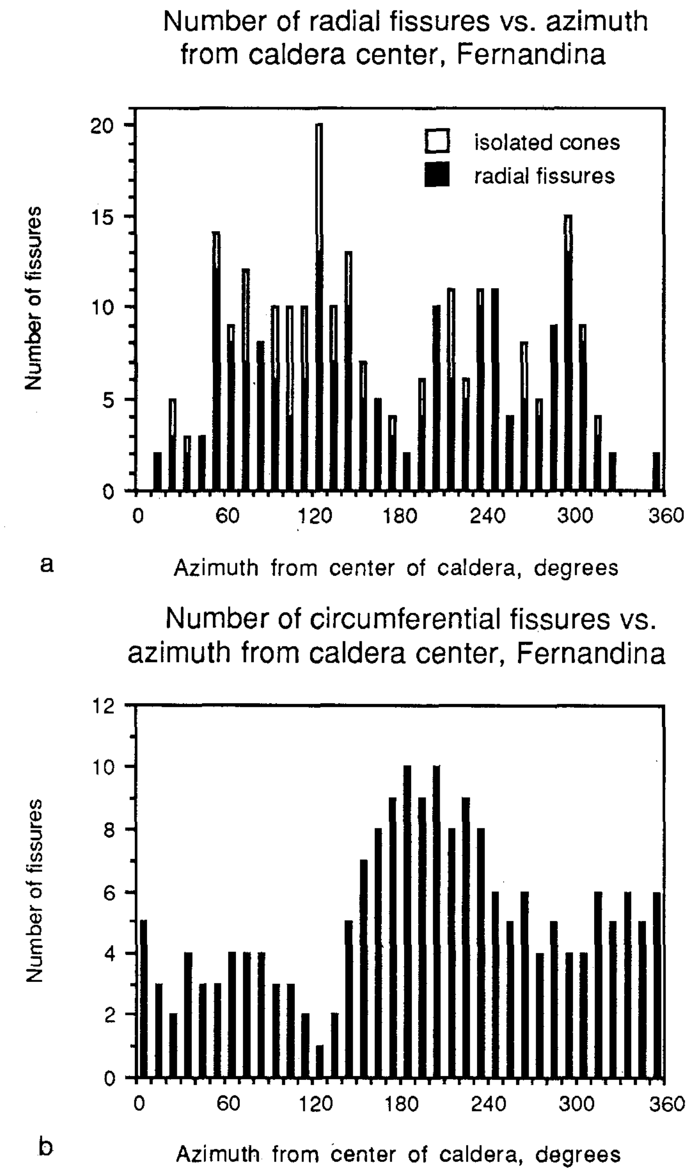


Fig. 9a, b. Plots of number of fissures versus azimuth from caldera center (defined relative to the the caldera rim) on Fernandina: **a** radial, **b** circumferential

Ecuador volcano

Ecuador volcano (Fig. 3b) is anomalous when compared to the other volcanoes on Isabela and Fernandina islands. It is smaller (maximum elevation 800 m, compared to 1080 to 1710 m at the other volcanoes), it is the only volcano from which alkalic lavas have been reported (Simkin 1984; James Allan, personal communication, 1990), and the western half of Ecuador volcano has apparently been downfaulted below sea level, leaving a headwall of cliffs. Simkin (1972, 1984) interpreted a bench half-way down the cliffs at Ecuador volcano as the remnant of a caldera floor. An alternate interpretation is that the bench is a downfaulted block from the intact half of the volcano that slumped near the time the western half was faulted below sea level. During fieldwork at Ecuador volcano, we found that part of the bench is made up of outwardly dipping lava flows, like those in the cliff face, and part is underlain by thick, coarse-grained, ponded flows suggestive of caldera fill. Thus, the evidence is equivocal whether a caldera existed at Ecuador volcano.

It is unclear how to interpret the pattern of fissures at Ecuador volcano because its structure is ambiguous. Simkin (1972, 1984) described the eruptive fissures along the downfaulted bench as circumferential. The fissures and associated vertical dikes that we observed are positioned at the front of the bench, near the inferred position of the fault that isolated the bench. If there is no caldera, these fissures could be interpreted as controlled by a non-caldera fault. Alternatively, all the fissures at Ecuador volcano could be interpreted as solely radial with a center at the east end of the fault embayment (Fig. 3b). In any case, there are no fissures at Ecuador volcano that could be considered circumferential and to have been outside a caldera.

Interpretations of the pattern of eruptive fissures

Many interpretations have been proposed to explain the significance of the pattern of eruptive fissures in the Galapagos, but no consensus has been reached, primarily because data to provide quantitative evidence are lacking. A program of volcano monitoring could provide the data needed to develop a comprehensive model of magma dynamics at Galapagos volcanoes.

Tectonic lineaments

The notion of "lineaments" in the Galapagos began with Darwin's observation that many of the volcanoes appeared to be aligned in a north-northwest direction and along roughly perpendicular lines (Darwin 1844). Authors have since hypothesized that these "Darwinian trends" represent major tectonic fractures or rifts in the underlying oceanic crust (Fig. 10) which channel magma to the surface (Banfield et al. 1956; McBirney and Williams 1969; Nordlie 1973). The identification and interpretation of lineaments is notoriously subjective (Wise 1982), and we believe this concept has been overemphasized in the Galapagos and needs to be examined critically.

Nordlie (1973) argued that deep-seated rifts are also manifested in the clusters of radial fissures between adjacent calderas on Fernandina and Isabela. However, the fissure maps show that the clusters of radial fissures are broad (5–10 km wide), not narrow linear zones, and are inconsistent in orientation from volcano to volcano (compare Figs. 2 and 10). In addition, petrologic studies show that most erupted lavas on Fernandina and Isabela are homogeneous tholeiitic basalt with shallow mineral assemblages, indicating that the lavas are erupted from well-mixed, shallow magma reservoirs and not directly from the mantle (McBirney and Williams 1969; James Allan, personal communication, 1990). The presence of collapse calderas also suggests that the magma reservoirs are shallow. Thus the dikes that feed eruptive fissures are probably also shallow, and not channelled through deep fractures in the underlying oceanic crust.

Alternative interpretations can explain concentrations of radial fissures that appear to connect adjacent volcanoes. First, where two volcanoes coalesce, a topographic ridge naturally forms by overlap of their lavas. Fiske and Jackson (1972) showed that gravitational stresses tend to concentrate diking along, or parallel to, topographic ridges. Once two Galapagos volcanoes join, therefore, radial dikes can be expected to concentrate along the ridge that joins them. Second, numerical modeling shows that the mechanical interaction of two adjacent pressurized magma reservoirs would tend to favor a concentration of dikes in the area between them.

This is illustrated by a simple two-dimensional, finite-element model (Fig. 11), in which two circular holes in a flat plate represent magma bodies in the crust; the plate is bilaterally symmetric (only one half is necessary for the numerical model). This geometry is similar to that in models used to explain dike patterns at Spanish Peaks, Colorado (Odé 1957; Muller and Pollard 1977). Pressure is applied to the holes and the stresses in the surrounding plate are calculated. A plot of trajectories of the maximum compressive stress shows orientations of potential dike intrusions. Note that stress trajectories in Fig. 11b that curve between the two holes mimic the pattern of mapped fissures between Darwin and Alcedo, and to some extent between Wolf and Darwin, Wolf and Ecuador, and Alcedo and Sierra Negra (Figs. 2 and 3). This curving pattern could also be due to the topographic ridge effect, but is not easily explained by deep tectonic fractures.

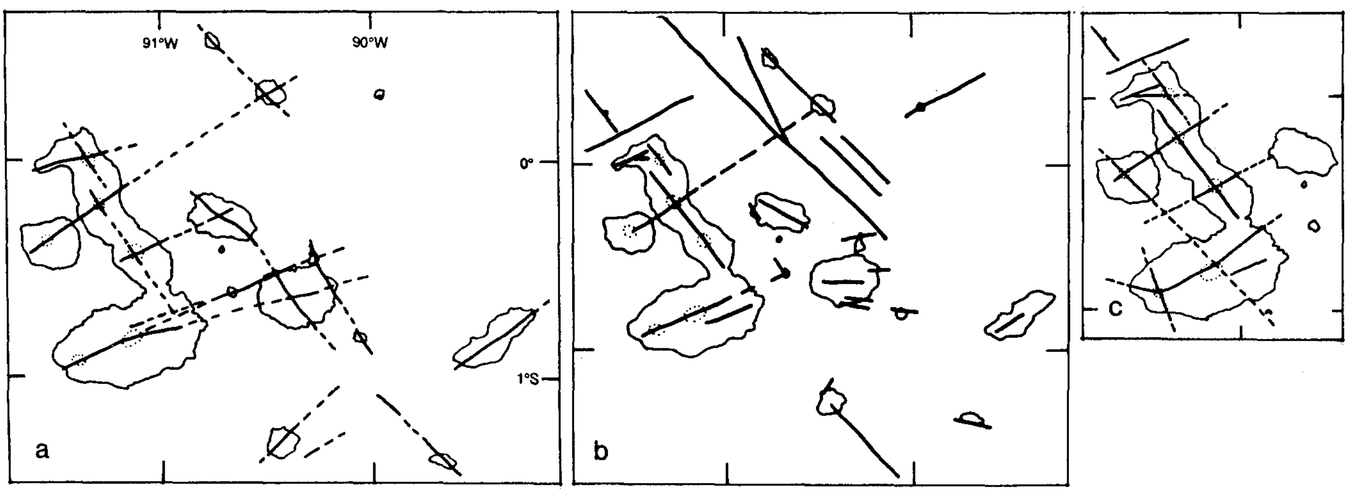


Fig. 10a–c. "Tectonic lineaments" proposed in the western Galapagos by **a** Banfield et al. (1956); **b** McBirney and Williams (1969); and **c** Nordlie (1973). Compare with Fig. 2. Some of the northwest-trending lineaments in (**b**) follow bathymetric features (not shown)

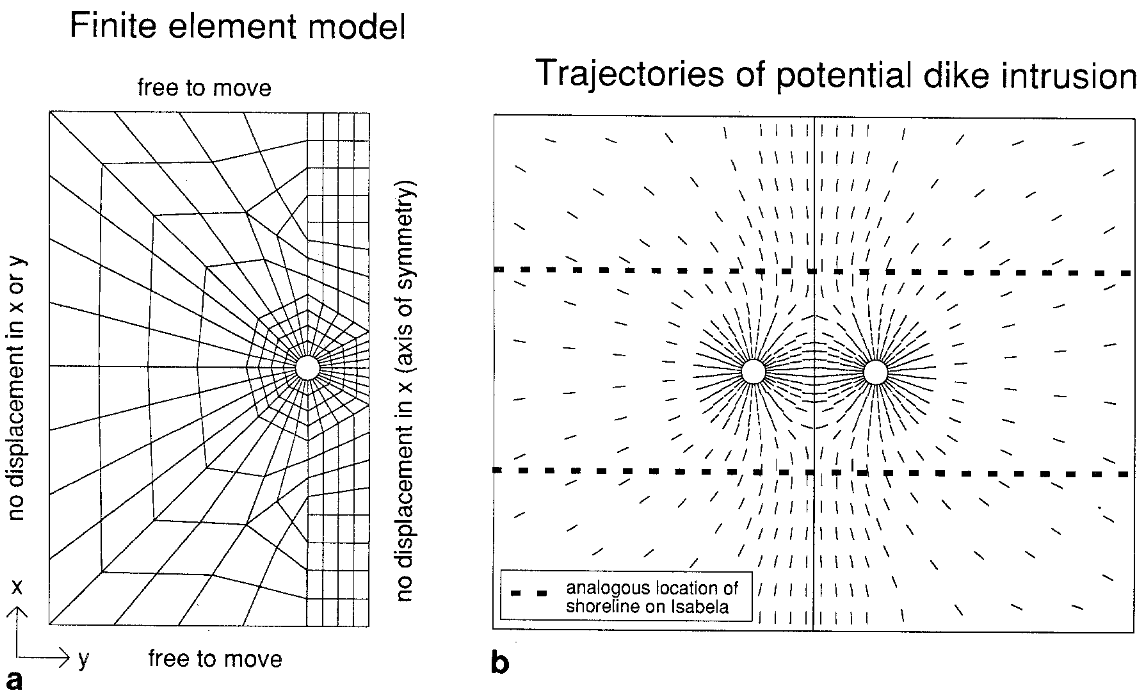


Fig. 11a, b. Finite element model representing two magma reservoirs of adjacent volcanoes on Isabela Island. **a** Model grid (assumed elastic, homogeneous, and isotropic) and boundary conditions. **b** Trajectories of the maximum compressive stress produced by pressurized reservoirs, showing orientations of potential dike intrusion. Mirror image of model shown on right for clarity. Note similarity to pattern of curving eruptive fissures between Darwin and Alcedo volcanoes in Fig. 2

The influence of postulated regional *deep structures* on the orientations of surficial eruptive fissures is thus equivocal. On the other hand, we agree in principal that cautious inspection of favored fissure orientations may help provide a guide to regional *stress direction,* because dike orientations can reflect the superposition of local and regional stresses (Nakamura 1977). The relative magnitude of the local volcanic stress field should decrease with distance from each volcanic center. On Fernandina, two observations indicate a weak preference for dikes to be oriented northwest-southeast: (1) the greatest frequency of circumferential fissures and one of the greatest frequencies of radial fissures are in this direction (Fig. 8); and (2) individual eruptive fissures curve in this direction, such as the one circumferential fissure that curves to become radial northwest of the caldera, and similarly the tangential orientation of the 1958 eruptive fissures south of the caldera (Fig. 4). An oblique fissure at the east shore of Alcedo volcano also parallels the northwest trend (Fig. 3d). Clusters of radial fissures on Cerro Azul and Wolf volcanoes trend northwest, but these volcanoes also have equally well-defined clusters to the north (Figs. 3b, 3f). Fissure clusters on other volcanoes do not have a consistent orientation. It seems unlikely that the regional stress direction varies much within the local area, and the existence of more than one favored fissure direction dilutes the potential for estimating regional stress direction. The most convincing evidence of a northwest tectonic trend is in the bathymetric alignment of volcanoes, seamounts, and submarine scarps in the northwestern part of the Galapagos platform, near the Cocos-Nazca spreading center (McBirney and Williams 1969; Simkin 1984). This observation suggests that detailed structural studies of the seafloor around the Galapagos Islands could help link the regional structure of the platform to plate boundary processes along the spreading center.

Circumferential and radial diking

The non-tectonic or volcanogenic pattern of eruptive fissures has been frequently explained in terms of mechanisms to generate fractures that could later be used as magmatic conduits. Past episodes of broad volcano tumescence and/or subsidence have been called upon to create such fracture systems (Banfield et al. 1956; McBirney and Williams 1969; Simkin 1972; Nordlie 1973; Walker 1984). However, it is not necessary to assume that major deformational events must occur *before* any diking can take place, because dikes can create their own fractures which propagate immediately ahead of the advancing magma (Pollard 1987). The propagation path of a dike is controlled by the state of stress in the host rock. Dikes are usually emplaced perpendicular to the least compressive stress, unless the magnitude of one or both of the other principal stresses is nearly the same, or the host rock is highly jointed or faulted (Anderson 1951; Pollard 1987). There is no direct evidence that dikes on Fernandina and Isabela follow a system of pre-existing joints or faults, except within the calderas. We view the pattern of eruptive fissures as a pattern of active diking rather than of pre-existing fractures. In other words, fissure orientations are controlled by the local state of stress at the time of dike emplacement, hence the pattern of fissures can be interpreted to map near-surface stress trajectories (Anderson 1951; Nakamura 1977; Pollard 1987).

Nordlie (1973) developed an evolutionary model for Galapagos volcano development based mainly on variations in topographic profiles and caldera sizes. His model included distinct stages for radial eruptions, circumferential eruptions, and caldera development. Recent advancements in understanding caldera dynamics do not support this concept of distinct stages of volcano growth. Hawaiian volcanoes were previously thought to undergo a single stage of caldera collapse at the end of shield growth (Stearns and Macdonald 1946; Macdonald 1965). However, evidence now indicates that Hawaiian calderas do not represent one restricted period in a volcano's history, but instead repeatedly fill and collapse over much of their growth (Holcomb 1981, 1987; Peterson and Moore 1987). There is also evidence for repeated caldera filling and collapse in at least Wolf and Fernandina calderas where sections of thick, flat-lying, and laterally continuous caldera-fill lavas are exposed along the caldera walls. These concepts bring into question Nordlie's relative age assignments for the volcanoes on Fernandina and Isabela, which were based largely on an evolutionary model that devotes special attention to the present widths and depths of the calderas. Today's surface features are probably a small glimpse of the long-term growth of the Galapagos volcanoes, during which calderas are common features that repeatedly fill and collapse, and both radial and circumferential eruptions occur intermittently.

Simkin (1972, 1984) and Simkin and Fiske (1986) proposed a constructional model to explain Galapagos volcano morphology in which a circular ridge forms at an early stage, built by eruptions from arcuate fractures. Once the circular ridge formed, it would be perpetuated and enhanced because, based on the model of Fiske and Jackson (1972) for linear Hawaiian rift zones, gravitational stresses in the ridge should concentrate dike intrusions along its axis. Repeated caldera collapse would help maintain the circular ridge shape. However, it is not clear how such stresses could be maintained in the long term, since repeated dike intrusion within the circular ridge would eventually alter the stress field and thus the orientation of intrusions. A stress field suitable for repeated dike intrusion is maintained along Hawaiian rift zones by faulting of the volcano flanks (Swanson et al. 1976; Dieterich 1988), but faults are rare on the subaerial flanks of Galapagos shields. Another relevant observations is from Marchena, one of the other Galapagos islands, which has a 6-km-wide caldera that is filled to overflowing by lava and tuff with only parts of the low caldera rim yet unburied (Simkin 1984; Vicenzi et al. 1990). Young circumferential and radial eruptive fissures can both be identified at Marchena, although in fewer numbers than on the volcanoes of Fernandina and Isabela. Their presence on Marchena, where a conspicuous circum-caldera topographic ridge is absent, indicates that such ridges are not the sole factor that influences the location of circumferential intrusions.

Cone sheets and ring dikes are types of arcuate or circular intrusive bodies described originally from eroded volcanic terranes (Bailey et al. 1924; Richey 1932; Anderson 1936), and they have been proposed to explain Galapagos vent patterns (Walker 1984). However, the circumferential dikes on the Galapagos volcanoes are neither cone sheets nor ring dikes, as those terms were originally used. The term ring dike is often used loosely for any arcuate intrusion, but was originally described as a discontinuous cylindrical intrusive body 50 to 2000 m thick, with roughly vertical contacts, sometimes with evidence that the central part has subsided, and having a diameter usually less than 6 km (Anderson 1936; Billings 1943). Cone sheets on the other hand, dip inward at about 45°, have a diameter of 15 to 20 km, and are 3 to 15 m thick (Richey 1932; Anderson 1936). Cone sheets and ring dikes have not been clearly documented as near-surface structures at active volcanoes.

Relation between vent pattern and volcano shape

The profiles of Galapagos volcanoes are unusual because they have steep slopes, up to 15–35°, between their broad, flat summits and the gently sloping coastal plains. This shape is not obvious on all the volcanoes, but is well developed on Fernandina, Wolf, Darwin, and Cerro Azul. For comparison, the Hawaiian volcanoes have slopes of 3–13° (Mark and Moore 1987). Some have suggested that the pattern of fissures and the shape of the volcanoes may be related. The steep slopes have been attributed to deformation due to repeated intrusions of either circumferential dikes (McBirney and Williams 1969) or radial dikes (Nordlie 1973). Similarly, Cullen et al. (1987) proposed that the shape of Galapagos volcanoes could be explained by the uplift of an originally horizontal surface, given appropriate magma reservoir geometry and loading conditions.

Simkin (1972, 1984) argued that circumferential vents dominate the growth of Galapagos volcanoes and that the shape of the volcanoes is the product of constructional volcanism. He proposed that the steep flanks can be built by the stacking of short flows from circumferential fissures near the summit. In contrast, Cullen et al. (1987) asserted that the upper slopes of Galapagos shields are too steep to have formed by the accumulation of lavas.

The constructional model is supported by the observation that the steepest slopes are located immediately downslope of the zone of circumferential fissures (Fig. 3), whereas radial vents are mostly located farther outward on the more gentle slopes. Thus circumferential vents generally feed lavas onto the steep slopes, and radial vents feed lavas onto (and construct) the gentle slopes. Furthermore, the steepest slopes (for example the north flank of Fernandina or the east flank of Wolf) have many recent circumferential vents but few radial vents (Fig. 3). These slopes remain steep almost all the way to the coast, and the break in slope that does exist

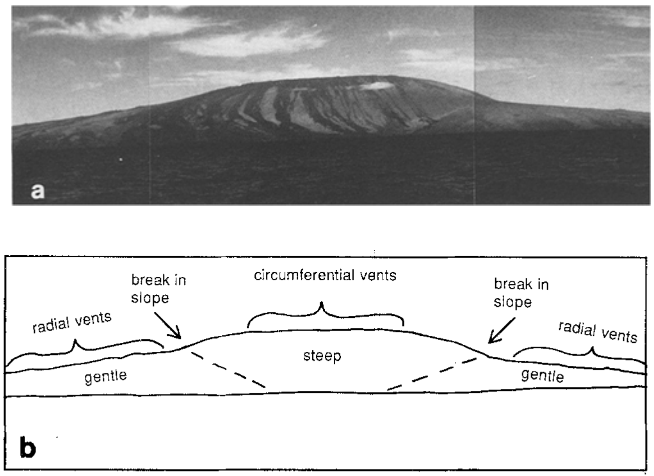


Fig. 12. a The steep east flank of Wolf volcano (photographs by C. A. Wood). **b** Sketch showing that the prominent break in slope is also a boundary between lavas from circumferential and radial vents

is attributable, in part, to lavas that have flowed from radial vents on adjacent slopes (Fig. 12). Deformation monitoring on Galapagos volcanoes could provide information about the relative importance of intrusive processes on volcano morphology.

Discussion

Remarkably few volcanoes elsewhere clearly display the Galapagos pattern of circumferential and radial eruptive fissures. Only a few subaerial volcanoes exhibit limited aspects of the pattern. Newberry volcano (Oregon, USA) has a few circumferential and many radial arrays of cones and fissures around its caldera (MacLeod et al. 1982; MacLeod and Sherrod 1988), although its flanks are gently sloping (1–8°). Within the caldera of Piton de la Fournaise volcano (Reunion Island, Indian Ocean), there is a dense network of radial and sub-concentric open cracks and eruptive fissures on the summit cone; this pattern is similar to the one in the Galapagos, but on a much smaller scale (Lénat and Bachèlery 1988; Lénat et al. 1989). Niuafo'ou volcano (Tonga Islands, South Pacific) has had several eruptions in this century from fissures parallel to, and about 1 km downslope from, its caldera rim (Newhall and Dzurisin 1988). Deception Island volcano (South Shetland Islands) has many arcuate basaltic eruptive fissures, all localized along the caldera fault (Newhall and Dzurisin 1988).

Many recent studies have observed that seamounts with calderas, summit plateaus, and steep outer slopes resemble the Galapagos volcanoes (Simkin 1972; Lonsdale and Spiess 1979; Batiza and Vanko 1983; Lonsdale 1983; Searle 1983; Fornari et al. 1984, 1987, 1988; Simkin and Batiza 1984; Simkin and Fiske 1986). Some have inferred that a similarity in shape implies a similarity in structure and eruptive style. However, the resemblance is based on gross morphology, with little or no direct evidence for circumferential and radial eruptive fissures. Also, it must be considered that the processes that produce steep volcano slopes in the marine environment are likely to be different from those on land (Searle 1983; Mark and Morre 1987; Malahoff 1989; Moore et al. 1989). Therefore, until there is clearer evidence for circumferential eruptive fissures on seamounts and a better understanding of submarine volcano-morphologic processes, it seems premature to assume that similar volcano shapes mean similar structure and dynamics.

Some shield volcanoes on Mars in the Tharsis region (Carr et al. 1977; Crumpler and Aubele 1978; Carr 1981; Greeley and Spudis 1981; Mouginis-Mark 1981; Wood 1984) resemble the much smaller Galapagos shields, in that they are isolated, symmetrical, and have similar profiles, although with low average slopes (4° for Olympus Mons). The summits of Martian shields have many caldera-related arcuate faults and grabens, but to date the highest resolution imagery available (generally 100–300 m, but 15–40 m in limited areas) makes it difficult to determine if circumferential and radial vents also exist. A few circumferential eruptive fissures have been interpreted on the broad caldera rims of Arsia Mons (Carr 1981; Mouginis-Mark 1981), and of Alba Patera (Cattermole 1986). The US Mars Observer mission (Albee and Palluconi 1990), scheduled for launch in 1992, is designed to image the surface in selective areas at ~1 m resolution and may help clarify the distribution and orientation of eruptive vents on Martian volcanoes.

The pattern of circumferential and radial eruptive fissures remains poorly documented outside of the Galapagos Islands. The pattern reflects the preferred orientations of intrusive dikes, and appears to result mainly from the interaction of local magmatic and gravitational stresses, modified to a minor extent by regional stresses. Radial dikes are common elsewhere and are readily explained by the radial stress field produced by a magmatic pressure source at the center of an axisymmetric volcanic edifice (Odé 1957; Pollard 1987). The radial pattern deviates slightly and dikes tend to be concentrated between adjacent Galapagos volcanoes, as expected from the interaction of stress fields from two sources of magmatic pressure and the gravitational effect of the topographic join between the volcanoes. The more unusual circumferential dikes have been explained as due to the gravitational stresses within a circular ridge that separates each caldera from the steep outer volcano flanks (Simkin 1972). However, it is unclear how these stresses are maintained over the long term after repeated dike intrusions. Recognition of the fissure pattern on flat-topped Marchena volcano indicates that other factors may also be important. A modeling study is underway to investigate the influence of magma-reservoir shape and other loading conditions on the pattern of dike intrusion at Galapagos volcanoes, and the mechanical effects of circumferential dike intrusions on the local stress field.

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