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Mechanical modeling of circumferential and radial dike intrusion on Galapagos volcanoes

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Abstract

A distinctive and unusual pattern of eruptive fissures is observed on the active volcanoes of the Galapagos islands, reflecting circumferential dike intrusion near the calderas and radial dike intrusion on the volcano flanks. Elastic finite-element models were used to investigate how a stress field could be produced and maintained to promote both circumferential and radial dike emplacement. Modeling results show that magma reservoirs of Galapagos volcanoes are probably diapiric, because this shape promotes both circumferential and radial intrusions, but magma pressure alone cannot create the observed pattern of dikes. Loading by volcano growth and magma reservoir pressure could produce a stress field of suitable orientation but insufficient magnitude. The intrusion of circumferential dikes could alter the stress field in a way that promotes future radial diking, and vice versa. Faulting or slumping within the calderas or on the volcano flanks in response to repeated intrusions could also create a stress field conducive to continued intrusion.

1. Introduction

The basaltic shield volcanoes on the Galapagos islands of Fernandina and Isabela are among the most active volcanoes in the world (McBirney and Williams, 1969; Simkin, 1984). Most eruptions on these volcanoes are effusive and occur along linear eruptive fissures marked by rows of spatter and scoria cones. These fissures are surface expressions of dikes that have propagated from magma reservoirs. Eruptive fissures on the active volcanoes of Fernandina and Isabela islands form an unusual and distinctive pattern (Fig. 1); they circumscribe the summit calderas and radiate lower on the flanks (Chadwick and Howard, 1991). It is not well understood why this pattern is common on Galapagos volcanoes but rare elsewhere. In particular, the dense concentrations of circumferential eruptive fissures appear to be virtually unique to the Galapagos shield volcanoes (Chadwick and Howard, 1991). The purpose of this study is to investigate the mechanical reasons for this unusual pattern of diking.

When a dike is emplaced, it characteristically propagates perpendicular to the least principal stress (Anderson, 1951; Pollard, 1987). Therefore the pattern of eruptive fissures on Galapagos volcanoes can be interpreted as a marker of the near-surface stress field. The central mechanical problem we wish to address can be stated as follows: how can a stress field be produced to explain the pattern of diking? In other words, are radial and circumferential eruptive fissures emplaced at different times under different stress states, or can they form under one stress state but on different parts of the volcano? If the latter is true, how can a stress field be produced that abruptly changes orientation between the summit and flanks, such that the axis of the least principal stress is perpendicular to the cal-

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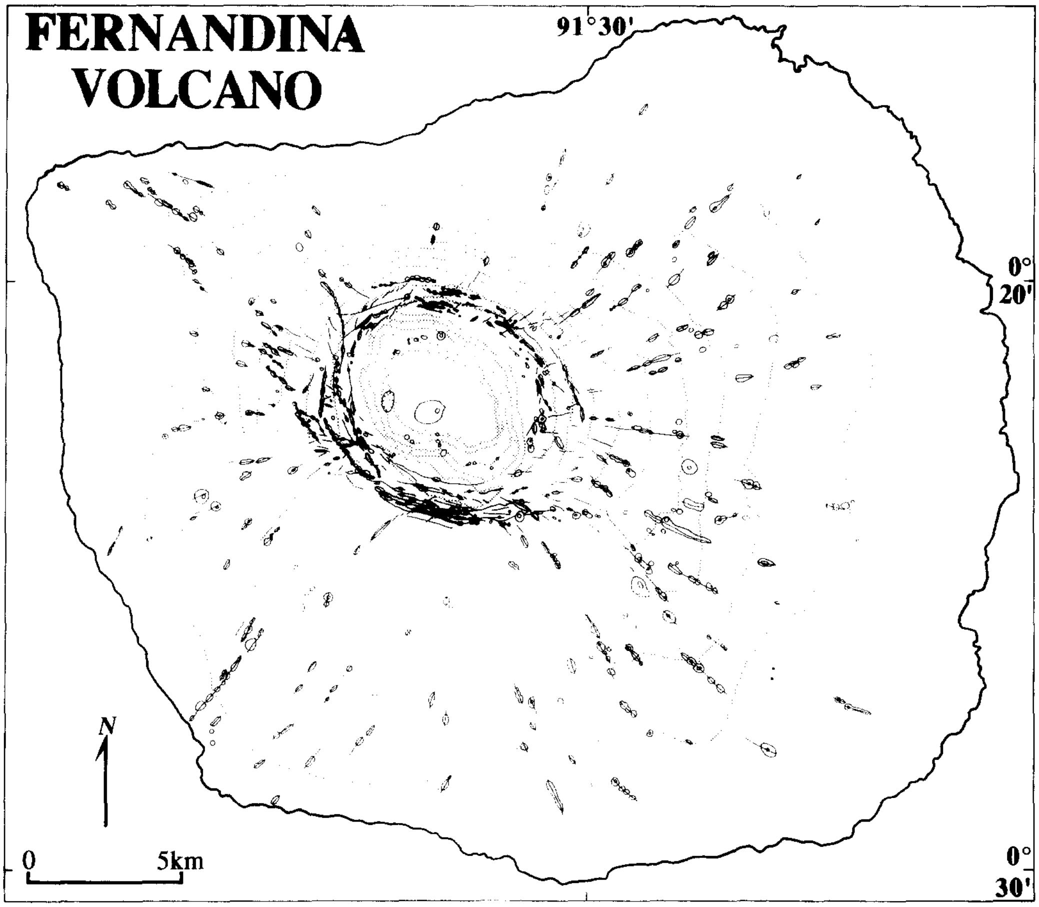


Fig. 1. Map of eruptive vents, including eruptive fissures (lines) and cones (outlines) on the island of Fernandina, Galapagos, from Chadwick and Howard (1991). Note pattern of circumferential eruptive fissures around the summit caldera and radial fissures on the volcano flanks. Topographic contours where available are stippled (500 ft interval).

dera margin at the summit but concentric on the lower flanks? Also, what is the effect of repeated dike intrusions on the state of stress in the volcano, and how can stresses suitable for this pattern of dikes be maintained in the long term?

2. Previous modeling approaches

Many previous studies have focused on stress fields around inflating or deflating magma reservoirs as an explanation for the distribution and orientation of intrusive bodies. Radial dikes are common on many volcanoes and are readily explained by the radial stress field produced by magmatic pressure at the center of an axisymmetric volcanic edifice (Odé, 1957; Muller and Pollard, 1977; Pollard, 1987). Circumferential dikes, however, are not as simple to explain. Many studies have attempted to explain the geometry of ring dikes and cone sheets observed in deeply eroded terranes in the British Isles and New Hampshire, USA (Bailey et al., 1924; Richey, 1932). The Galapagos circumferential dikes are significantly different from ring dikes or cone sheets as these terms were originally defined, particularly in terms of thickness, orientation, and geometric distribution (Chadwick and Howard, 1991). Nevertheless, previous investigations of ring dike and cone sheet intrusion are relevant to this study.

Anderson (1936) examined the stress trajectories from analytic solutions for a point source and a point push to make inferences about the intrusion of cone sheets and ring dikes. He proposed that cone sheets intruded along tensile fractures during increased magma pressure, whereas ring dikes intruded along shear fractures accompanying subsidence during decreased magma pressure. Billings (1943) proposed the opposite, that ring dikes occupy tensile fractures and cone sheets occupy shear fractures, both produced by positive magma pressure. Billings' arguments were based on field observations in New Hampshire. Robson and Barr (1964) used a two-dimensional analytical solution of an infinitely long cylinder with internal pressure in an inhomogeneously stressed infinite solid as a magma chamber model. They concluded that ring dikes intrude along tensile fractures and cone sheets along shear fractures, again the opposite of Anderson. Roberts (1970) used a similar analysis to that of Robson and Barr, but reached a different conclusion that cone sheets intruded along tensile fractures and that ring dikes could intrude along tensile or shear fractures depending on the loading conditions. Phillips (1974) agreed with Anderson, that ring dikes intrude along shear fractures when magma subsides, but argued that cone sheets also intrude along shear fractures that formed from dynamic stresses during the rapid expansion of magma. Phillips believed that only radial dikes intrude along tensile fractures during upward magma pressure. Chevallier and Verwoerd (1988, 1990) constructed numerical models to explain radial dike and conical fracture patterns at several intraplate volcanoes, and agreed with Phillips' interpretation that radial dikes followed tensile cracks and that cone fractures represent shear planes. Koide and Bhattacharji (1975) concluded that ring dikes intrude into tensile fractures during high magma pressure and cone sheets intrude into nested normal faults or tensile fractures, based on a three-dimensional analytic solution for an ellipsoidal magma reservoir in an infinite medium. These conflicting interpretations illustrate that a clear consensus does not exist to explain the formation of ring dikes and cone sheets, even though they have received considerable attention.

3. Eruptive fissures and dike intrusion on Galapagos volcanoes

Eruptive fissures on the active volcanoes of Fernandina and Isabela islands are oriented circumferentially within ~ 1.5 km of summit calderas and change to a radial orientation on the volcano flanks (Banfield et al., 1956; McBirney and Williams, 1969; Simkin, 1972, 1984; Nordlie, 1973; Chadwick and Howard, 1991). Maps of eruptive vents (Fig. 1) made from aerial photographs and field work on Galapagos volcanoes (Chadwick and Howard, 1991) yield the following observations that help us constrain our mechanical models. Most circumferential dikes exposed in caldera walls are vertical or nearly so, and usually about 1 m thick or less. The location of circumferential eruptive fissures outside the calderas is independent of caldera-related normal faults. No vertical offset is observed in the layers adjacent to circumferential dikes in the caldera walls, or along circumferential eruptive fissures on the surface, and many circumferential fissures cross-cut caldera-related faults, or are located well downslope from caldera rims. This indicates that the circumferential vents are not simply leaky faults, but are forcibly rather than passively emplaced dikes.

We interpret this pattern of circumferential and radial dike intrusion to be persistent. In other words, the circumferential and radial dikes are contemporaneous, coexistent, and a long-lived characteristic of the volcanoes. This interpretation is supported by the fact that both circumferential and radial eruptions have occurred on individual Galapagos volcanoes in historical time (Simkin et al., 1981; Smithsonian Institution/SEAN, 1989), and that some individual eruptive fissures have a circumferential orientation near the caldera and gradually curve downslope to become radial (Chadwick and Howard, 1991). In addition, all six active Galapagos volcanoes on Fernandina and Isabela islands display the pattern of circumferential and radial fissures. If fissures with the two orientations were formed under different conditions during separate evolutionary stages widely spaced in time, it seems unlikely that all the volcanoes would happen to be presently at the same transitional stage between the two. Also, the vent structures along the fissures are low topographic features (< ~ 100 m high) and so could be easily buried by subsequent lava flows. The fissure pattern must be continuously regenerated, since otherwise it would be erased in a short span of geologic time. We conclude that both circumferential and radial dikes must form within one general system of stresses that is maintained over time, although local temporal variations could favor one dike orientation over another for short intervals.

The volume of intruded dikes must be significant within Galapagos volcanoes and rough estimates of their volume can be made from the distribution of eruptive fissures. Vent maps of Fernandina volcano (Fig. 1) identify 175 circumferential vents with a cumulative length of 95 km, and 260 radial vents with a cumulative length of 114 km and an average distance from the caldera center to the upslope end of the vent of 7.9 km (Chadwick and Howard, 1991). If we assume that all dikes are vertical with a height of 2 km, a width of 1 m, and their length is only that of the fissures at the surface, this would represent an intrusive volume of about 0.2 km^3 for both circumferential and radial dikes. This volume estimate is probably too small because additional dikes may be intruded that never reach the surface, and in particular for radial dikes, it does not take into account that they most likely propagate outward from a magma reservoir beneath the caldera to their surface expression on the volcano flanks. For radial dikes, if we assume a magma reservoir radius of 2 km, similar to the caldera radius, and estimate the length of each dike to be from the outer edge of the reservoir to the downslope end of each radial vent, then the cumulative length of radial dikes is 1300 km, representing an intrusive volume of 2.6 km^3. This value probably slightly overestimates the volume of radial dikes, because a single dike may feed more than one eruptive fissure. Nevertheless, these crude estimates suggest that the volume of recent radial diking on Fernandina is about an order of magnitude larger than the volume of circumferential diking.

The total volume of dikes within Fernandina volcano must be much greater than these estimates, because we have only considered dikes that have recently formed vents at the surface and have not yet been buried by younger flows. Further estimates can be made to illustrate the increasing proportion of intrusions at depth. First let us assume that the volume of dikes inferred above is intruded into the volcano for every 100 m of lava that is added to its surface, based on the observation that it would take ~ 100 m of lava to bury all the presently exposed cinder and spatter cones along eruptive fissures. The volume of the upper 100 m of the volcano is ~ 70 km^3, and the volume of dikes within this layer would be 0.14 km^3 (based on the dike volume estimates above), or 0.2% of the layer. With this set of assumptions, the volume of dikes as a percentage of the volume of extruded lavas would double with every 100 m increase in depth, and at 2 km depth there would be 4% dikes. However, this assumes dikes are evenly distributed, whereas they are clearly densely concentrated within the zone of circumferential fissures. If we make the same calculations for an annular area around the caldera, between 2 and 5 km from the caldera center, instead of the entire volcano, and assume that all radial dikes also pass through this annular volume, then the percentage of dikes increases from 1% in the upper 100-m layer to 24% in the layer at 2 km depth. These calculations show that repeated dike intrusion leads to significant volumetric additions to the volcano in the long term which must be structurally accommodated in some way.

4. Modeling approach

How can a stress field be produced which can explain the observed pattern of dike intrusion? In evaluating the relevance and contribution of various physical processes that may affect the stress field and consequently dike emplacement, we believe two considerations are of central importance: (1) interactions to maintain the stress field for continuing dike emplacement and (2) estimation of the initial or reference stress state which is perturbed by the processes of interest.

4.1. Interactions that maintain the stress field

The emplacement of dikes alter the stress field in a manner that tends to eliminate the differential stress that permits dike intrusion and controls dike orientation. This is because the minimum principal stress, which is oriented perpendicular to the dike, will increase by an amount that is proportional to the opening of the dike. To remain open, magma pressure in the dike must equal or exceed the minimum principal stress, prior to emplacement. The principal stresses in the plane of the dike are essentially unchanged by dike intrusion. Eventually, given sufficient numbers of dikes, the stress pattern will be altered to the extent that additional dike intrusion is prevented, or a change in dike orientation results. For some volcanoes, the numbers of dikes may be small and this effect might not be important. However, for Galapagos volcanoes, the volume estimates discussed above establish that a significant percentage of the volcano consists of intruded material, suggesting that this effect cannot be ignored. Because the pattern of Galapagos eruptive fissures persists through time, a fundamental goal for understanding Galapagos volcanoes is to discover the processes that renew the stress field for continuing dike emplacement.

This approach, which places emphasis on how dike intrusion could be *sustained in the long term*, differs from most other modeling studies which consider mechanisms suitable for one cycle of intrusion. Processes which might establish a stress pattern sufficient for a single phase of dike intrusions, generally appear inadequate, acting alone, to sustain continued dike intrusion. This has been illustrated by studies of Hawaiian volcanoes. Swanson et al. (1976) were the first to recognize that repeated diking on Hawaiian volcanoes could have profound, long-term structural consequences. Hawaiian rift zones are believed to spread 2–3 km, or possibly more, over their lifetimes and this spreading is accommodated by large-scale faulting of the volcano flanks (Swanson et al., 1976; Lipman et al., 1985; Dieterich, 1988). Fiske and Jackson (1972) used gelatin models to argue that dikes are concentrated in rift zones because of gravitational spreading within a topographic ridge, and these results were generally supported by the modeling of McTigue and Mei (1981). However, the topography alone is not enough to *maintain* diking in the rift zone in the long term. Dieterich (1988) showed that faulting of the volcano flanks is not only driven by dike intrusion, but also that faulting creates a stress state that favors additional intrusion. We surmise that comparable processes could operate on Galapagos volcanoes.

4.2. Estimation of the reference stress state

In general, stresses arising from some physical process such as magma-reservoir inflation must be superposed with the prior reference stress state to obtain a total stress state, in order to interpret the potential for dike formation and dike orientation resulting from those processes. That reference state may be difficult to establish, because it may be the result of complex factors such as the details of the growth and evolution of the volcano. In the following, we have made the approximation that the reference stress state is hydrostatic or isotropic, for the following reasons. On Galapagos volcanoes, it appears that vertical dikes repeatedly feed surface eruptions, and the emplacement of each dike should tend to reduce the differential stress, moving it toward a state of hydrostatic stress by increasing the least principal stress. Following Dieterich (1988) we reason that where a vertical dike feeds a surface vent, the horizontal stress perpendicular to the dike, σ_p, following its emplacement, must equal the pressure, P_{magma}, in a standing column of magma that reaches to the surface:

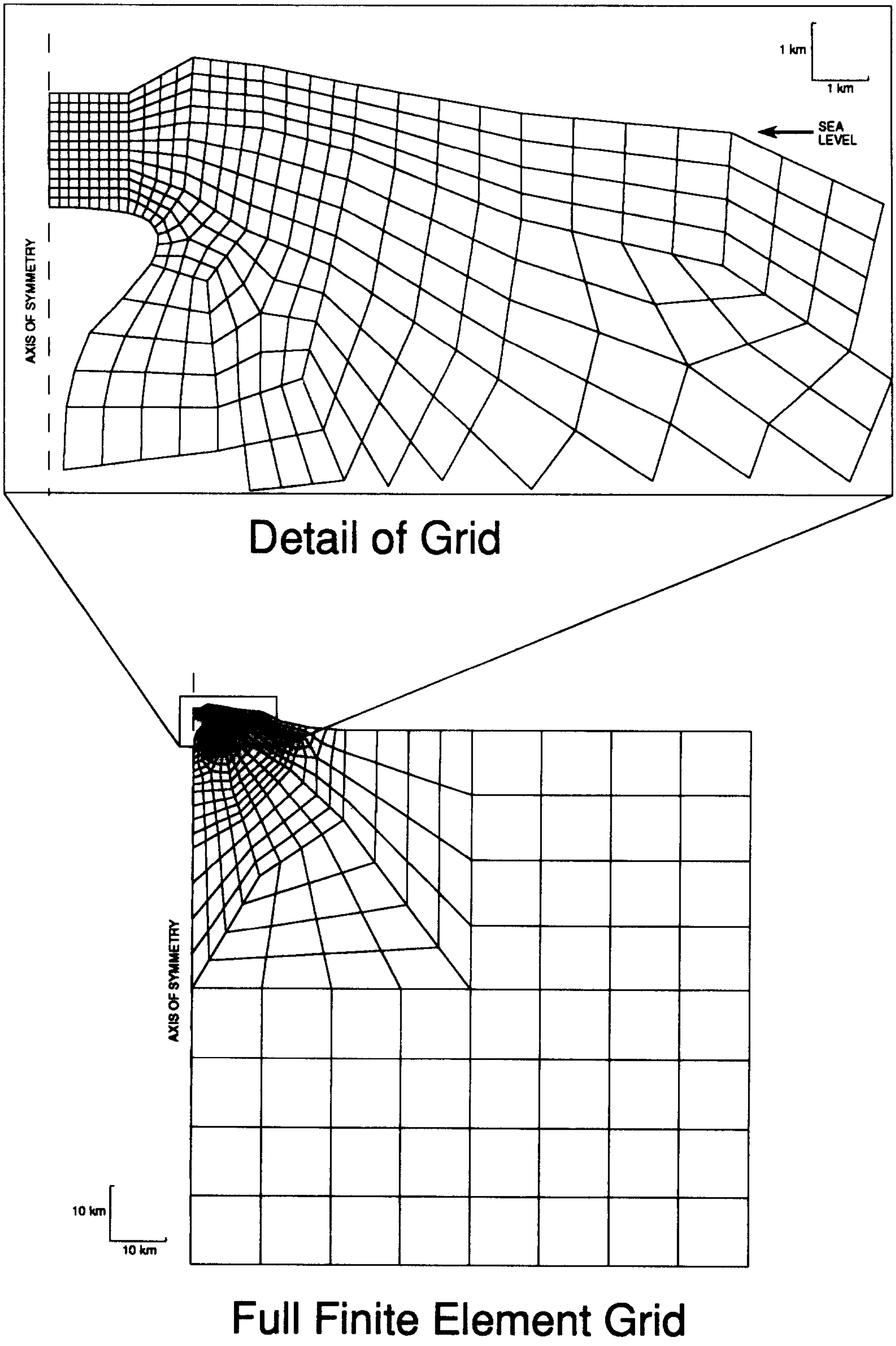
$$\sigma_p = P_{magma} = \rho_{magma} G h \qquad (1)$$

where ρ_{magma} is the density of the magma, G is the acceleration of gravity and h is the height to the surface. Assuming the density of the magma and the density of the host rock are the same, the presence of a dike feeding an eruptive fissure indicates that the least horizontal stress, σ_{h1}, equals the vertical stress $\sigma_v = \rho Gh$.

The magnitude of the third stress component, σ_{h2}, which is horizontal and in the plane of a dike reaching the surface is inferred to be greater than or equal to the other two stress components, $\sigma_{h2} \geq \rho Gh$. If σ_{h2} is originally less than σ_v, then new dikes, perpendicular to the original dike, would be emplaced and this will increase σ_{h2} until it also reaches ρGh. If σ_{h2} is greater than σ_v, then intrusion is prevented because all stresses will be equal to or greater than the maximum magma pressure and σ_{h2} will remain unchanged. In the following, we have assumed that at the reference state, $\sigma_{h1} = \sigma_{h2} = \rho Gh$, and hence, the reference stress state is hydrostatic. If, instead, σ_{h2} is actually greater than the other stress components, the principal stress orientations and magnitudes in the plane of σ_{h2} may depart from the values obtained using the assumption of hydrostatic initial stress. We further assume that the rock density equals magma density. This permits subtraction of the hydrostatic depth-dependent term, ρGh, from the stress state and magma pressure. Consequently, for computational purposes, the reference stress state is treated as a stress-free state and magma pressure may be represented as depth-independent pressure changes. Except where noted, all computations are done in non-dimensional form.

4.3. Physical processes that may alter stress state

This study explores processes that might act alone or in combination to generate stress fields compatible with the observed pattern of eruptive fissures and could


Detail of Grid

Full Finite Element Grid

Fig. 2. Example of a finite-element grid used for this numerical modeling study. Other grids were altered slightly to investigate different magma reservoir shapes, sizes and depths.

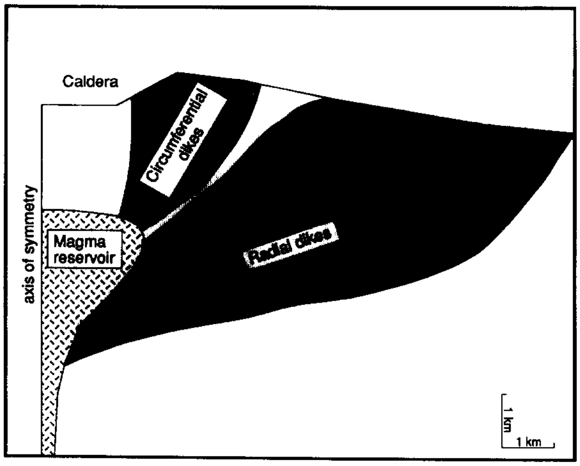


Fig. 3. Idealized cross-section of a Galapagos volcano suggesting the different areas where circumferential and radial dikes should be favored in the numerical models in order to form the pattern of eruptive fissures observed at the surface.

operate to relax the stresses built up by dike intrusions to permit continued intrusion. Five types of loading processes were considered as controls of the pattern of dikes on Galapagos volcanoes: (1) pressure changes in a near-surface magma reservoir; (2) gravitational stresses; (3) loading by lava flows; (4) dike emplacement; and (5) faulting or bulk yielding of the volcano edifice in response to stress changes due to processes (1)–(5). We discuss each of these processes individually below. Regional tectonic stresses are believed to have a second-order influence on the near-surface pattern of diking on Galapagos volcanoes and therefore are not considered in this study, because most aspects of the pattern of eruptive fissures can be explained by local volcanic or gravitational stresses (Chadwick and Howard, 1991).

To model some of these processes, we employed the finite-element method to calculate stresses in a volcano assuming a homogeneous, isotropic elastic medium. A Poisson's ratio of 0.25 is used, and other elastic parameters are non-dimensional since we are mainly interested in stress patterns rather than their magnitudes. The finite-element computer code is that used for previous volcano modeling studies by Dieterich (1988) and Yang et al. (1988). The finite-element models presented below are axisymmetric and represent radial cross sections through a Galapagos volcano (Fig. 2). We used an average topographic profile taken from Fernandina volcano, including its submarine flanks, for the upper surface of the models. The axis of symmetry of the models is fixed in the horizontal direction and free in the vertical direction, whereas the bottom and outer edges are fixed in both directions; the bottom and outer edges are at 100 km depth and 100 km in radius, so that edge effects are avoided. An ideal stress field that would favor the emplacement of the observed pattern of dikes on Galapagos volcanoes would include stress trajectories for circumferential dikes from the magma reservoir up to the surface near the caldera rim, and trajectories for radial dikes extending from a slightly deeper part of the reservoir margin to the surface at greater radial distances from the caldera (Fig. 3).

5. Effects of magma reservoir pressure and geometry

We first experimented with several idealized magma reservoir shapes, including spheres, oblate and prolate spheroids, and diapirs, at various depths, to determine the effect of these variables on the near-surface stress field produced by a uniform pressure on the reservoir walls. In Fig. 4 and subsequent figures, we plot the orientations of potential dikes, based on the computed stress fields assuming that dike orientations would be perpendicular to the least compressive stress; a dike which is oriented circumferentially (or perpendicular to the page) is plotted as a short line, whereas a radial dike (in the plane of the page) is plotted as a small circle.

Magma reservoirs that are spherical in shape produce a pattern of stresses such that potential intrusions would be circumferential near the reservoir margins, but radial orientations are favored near the surface (Fig. 4a). This tendency was also noted by Anderson (1936, p. 149). Models with a reservoir shape that is oblate (or more pancake-like) produce a similar pattern (Fig. 4b), although the circumferential trajectories have slightly different orientations near the reservoir margin. This mixed pattern of circumferential and radial trajectories appears to be incompatible with the Galapagos pattern of intrusions because it is unclear how either circumferential or radial dikes could propagate from the reservoir to the surface. Indeed, the orientation of the intermediate stress at shallow depths is nearly perpendicular to the free surface, so that even if a circumfer-

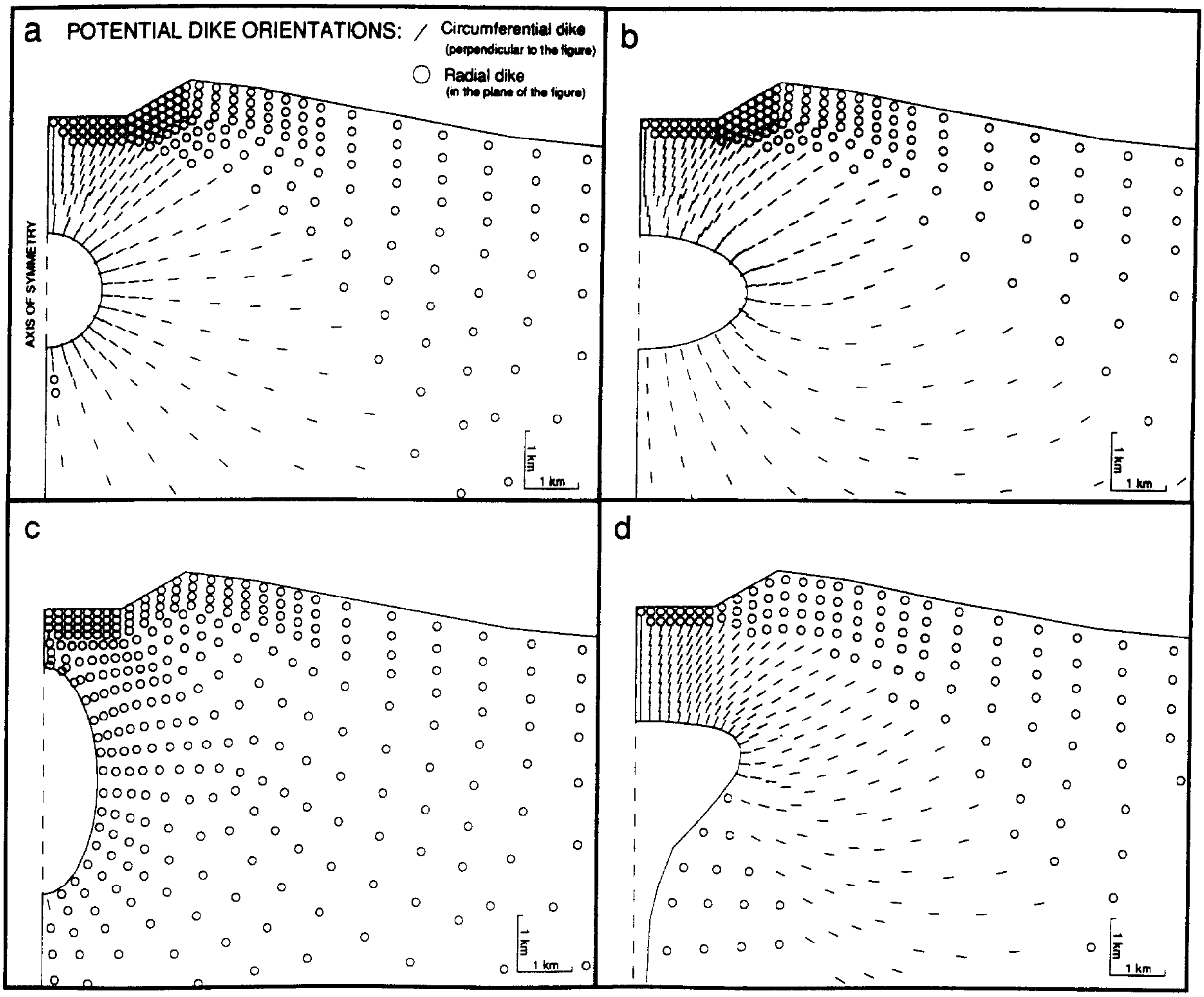


Fig. 4. Model results of stress field produced by uniform positive pressure on the walls of magma reservoirs of different shapes: (a) sphere; (b) oblate spheroid; (c) prolate spheroid; (d) diapir. Potential dike orientations are shown assuming that a dike would open perpendicular to the least principal stress; circumferential orientations are shown by short lines and radial orientations are indicated by a circle. The stress field produced is not consistent with the pattern of intrusion on Galapagos volcanoes.

ential dike intruded from the upper edge of a spherical or oblate reservoir, and propagated perpendicular to the intermediate principal stress near the surface (instead of the least principal stress), the dike would bend over and become a sill. This is shown in Fig. 5 for the case of a modified diapiric reservoir, and the result would be similar for a spherical or oblate reservoir. Magma reservoirs that are prolate in shape (or more cigar-shaped) tend to favor radial intrusions in all directions (Fig. 4c), again incompatible with the Galapagos pattern. Very similar results are obtained if the depth or width of the reservoirs is varied in the models (depth to reservoir center was varied between 2 and 7 km and reservoir radius between 0.5 and 2 km). The models presented in the figures have reservoirs centered at a depth of 3 km, but these results are representative of models with reservoirs with other depths and widths.

We also conducted experiments using a more subjective reservoir shape that we feel may be more realistic than the idealized shapes (Fig. 4d). Our preferred magma reservoir is diapir shaped with a relatively flat top, a maximum radius about equal to the caldera, and with sides that taper at depth to a vertical pipe of 100 m radius. We chose a flat-topped magma reservoir

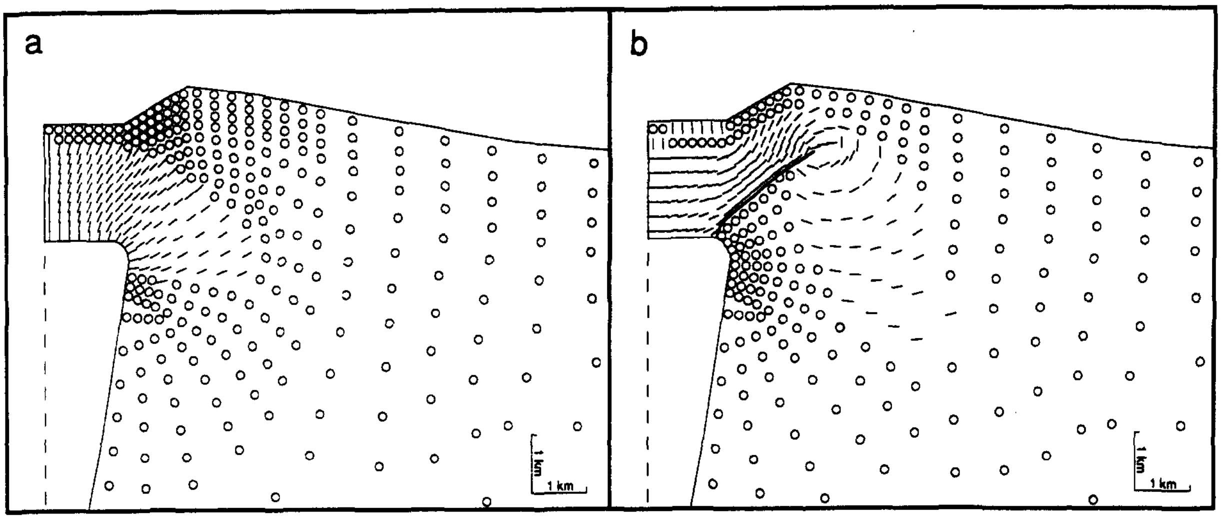


Fig. 5. (a) Model results showing potential dike orientations (same symbols as in Fig. 4) from a uniform positive pressure on the walls of a modified diapiric magma reservoir. (b) Model results after a circumferential dike (bold line) has been intruded upward from the upper outer edge of the magma reservoir, following the potential dike orientations shown in (a). The dike exerts the same outward pressure as the magma reservoir. Note that the stress field is such that if the dike continued to propagate it would bend and become a sill, and not reach the surface near the caldera rim as observed on Galapagos volcanoes.

because caldera collapse would tend to flatten the roof of a magma body, and because this shape creates a tensile stress concentration at the upper-outside corner, where circumferential dikes probably originate in order to reach the surface outside the caldera rim. Wallmann et al. (1988) made the same conclusion for ring fracture eruptions at Pantelleria, Strait of Sicily. We made the deeper parts of the reservoir more prolate in shape to promote the generation of radial dikes there. However, the initial results (Fig. 4) show that a simple increase (or decrease) in magma pressure alone is insufficient to create a stress field suitable for the observed pattern of diking on Galapagos volcanoes, regardless of reservoir shape.

6. Gravitational stresses

Stresses produced by the gravitational distortion of the volcanic edifice as it sags under its own weight have been proposed to control dike emplacement along linear ridges by Fiske and Jackson (1972). Simkin (1972) argued this concept could be applied to Galapagos volcanoes by viewing the summit areas as a circular ridge formed by the deep calderas on one side and the steep volcano flanks on the other. A proper mechanical analysis of gravitational loading, however, is not straightforward; one cannot simply "turn on" gravitational forces to affect an initially stress-free model volcano, because this is not how gravitational stresses would accumulate in the real world. In reality, a volcano grows incrementally, layer by layer. Each new layer is stress free when it is added, but its weight contributes to the stresses of all the older layers below it. Thus, properly including gravitational stresses in a model volcano is a complex problem that requires many assumptions about volcano growth. In addition, a stress state built up in this manner probably would not reflect the actual conditions, because the stresses would be continuously modified by other on-going processes during the growth of the volcano, in particular by dike emplacement. We assume that the modified stress state representing the product of all processes active during the growth of the volcano is the reference stress state discussed above, and we have not further considered gravitational loading of this type. However, in the following section we do treat changes to the reference state resulting from the weight of a layer added to the surface of the volcano.

7. Surface loading from volcano growth

We have proposed that Galapagos volcanoes, throughout their growth, always tend to evolve toward

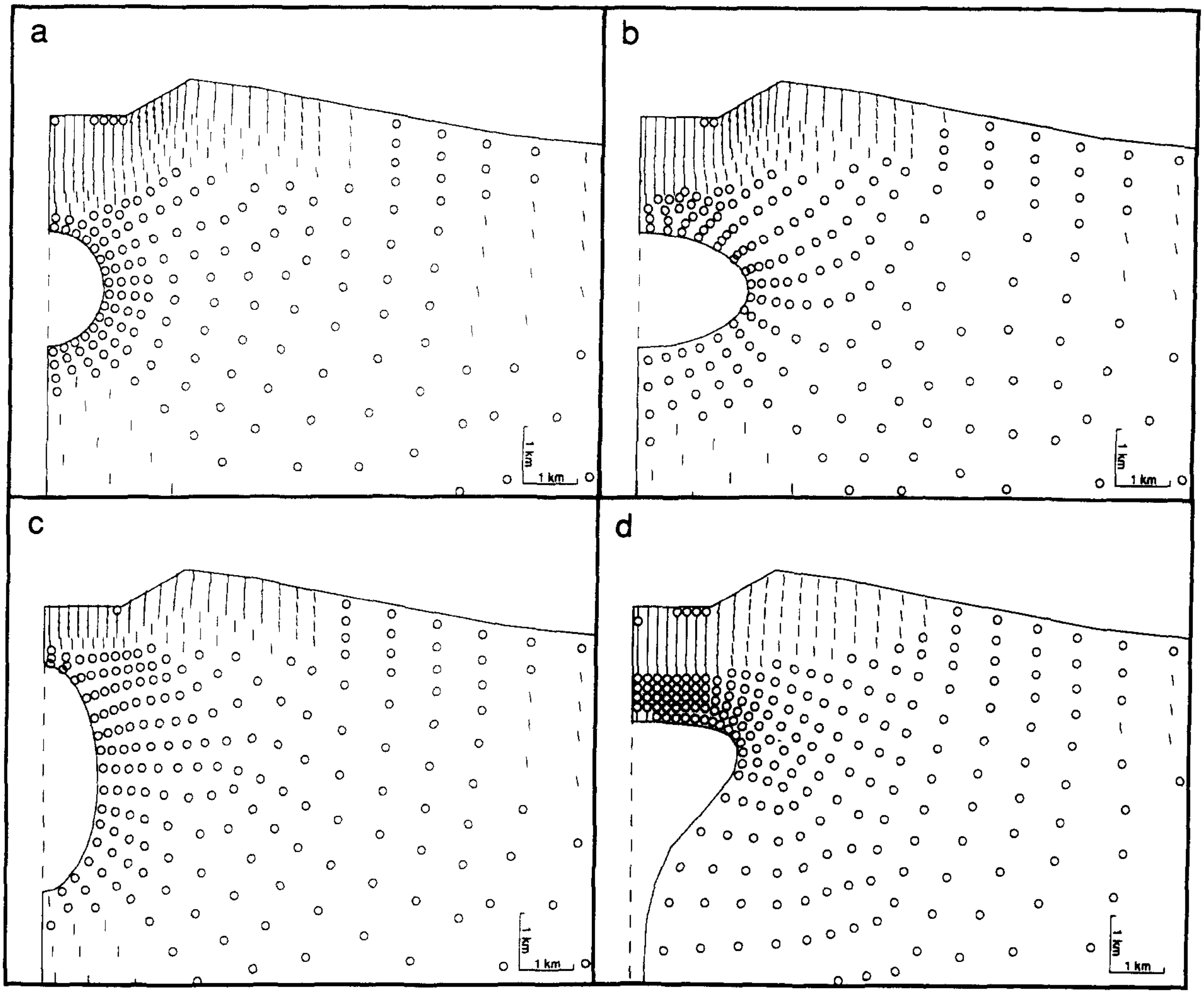


Fig. 6. Model results (same symbols as in Fig. 4) from a uniform vertical load along the surface of the volcano plus a magma reservoir pressure equal to the surface load, for different reservoir shapes: (a) sphere; (b) oblate spheroid; (c) prolate spheroid; (d) diapir. The stress field produced is closer to the desired pattern, but still not satisfactory.

the reference state of stress through the effects of dike emplacement. The weight of layers added to the surface of the volcano may alter this reference state, but continuing dike injection would tend to restore the stresses to the reference state. We have modeled the stress changes resulting from a load applied on the surface of the volcano by the incremental accumulation of a uniform thickness of lava. Murray (1988) reported a correlation between locations of thick lava flows and the siting of subsequent eruptions on Mount Etna, and proposed that surface loading by lava accumulation changes the near-surface stress field. In our model, a vertical load was applied uniformly over the topography, and an equal pressure was applied on the magma reservoir walls. This magma pressure increment is rationalized as the increased pressure required for magma to reach the new, higher topographic surface.

This combination of loads produces potential dike orientations that are closer to the observed pattern of diking than from magma pressure alone, because, near the surface, orientations are circumferential near the caldera rim and radial farther outward, but the pattern is still not ideal because near the reservoir margins radial dikes are favored on all sides (Fig. 6). If the surface load is applied only from the base of the caldera wall outward, the pattern of stress trajectories is

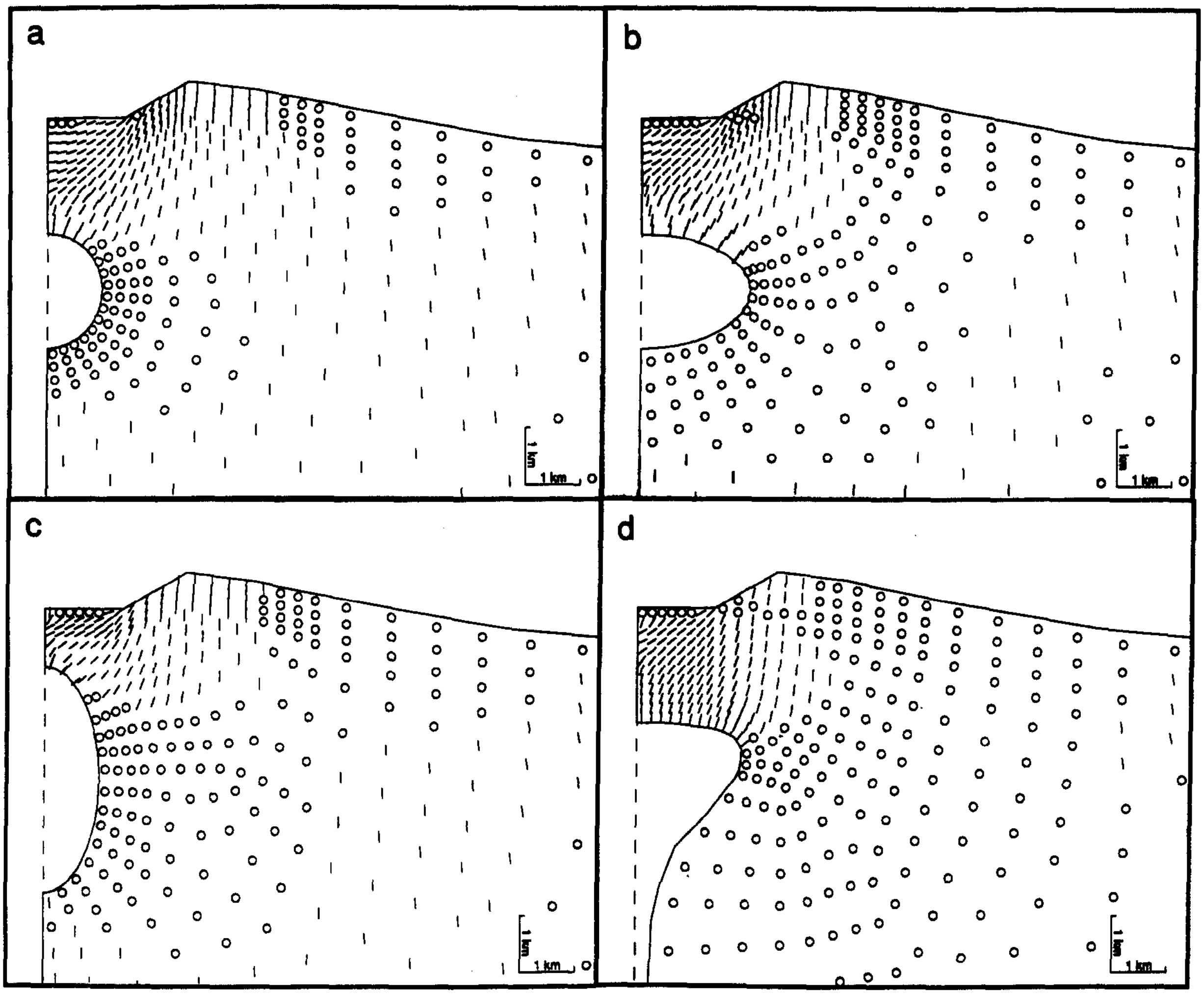


Fig. 7. Model results (same symbols as in Fig. 4) from uniform surface load applied only from the base of the caldera wall outward, plus magma reservoir pressure of the same magnitude for different reservoir shapes: (a) sphere; (b) oblate spheroid; (c) prolate spheroid; (d) diapir. The stress field produced gives the desired pattern of potential intrusion, and our preferred model is (d).

improved further, because circumferential dikes are produced from the upper surface of the reservoir and can propagate toward the caldera rim, also radial dikes are produced at greater depths from the reservoir margins and extend upward to the volcano flanks in most cases (Fig. 7). In addition, the stress concentration at the upper, outside corner of the reservoir is increased by removing the surface load along the caldera floor. These changes demonstrate that stress conditions within the area of circumferential dikes are sensitive to stresses acting on the caldera floor. The physical significance of removing the surface load from the caldera floor is ambiguous, but could approximate the stress conditions due to an increment of volcano growth modified by an increment of caldera collapse. These results and results from similar models with pressure reduction on both the walls and floor of the caldera appear to support the hypothesis that caldera collapse favors circumferential dike emplacement.

The results in Fig. 7d are our preferred model for stress state that is consistent with the observed pattern of dike intrusion on Galapagos volcanoes. A small band of radial orientations extends under the caldera rim in Fig. 7d, but this is not enough to effect the propagation of a circumferential dike (shown below). In the model, stress trajectories that are compatible with circumferential dikes do not extend much farther outward than the apex of the caldera rim, whereas circumferential eruptive fissures are observed up to 1.5 km from the rims on Galapagos volcanoes. It may be that pre-existing dikes force subsequent intrusions farther outward, as has been proposed for the curved upper East Rift Zone of Kilauea volcano (Swanson et al., 1976; Ryan, 1988).

An interesting aspect of the surface loading/growth models is that this stress-generating process is continuously renewable. That is, for every increment of volcano growth, an added stressing increment becomes available to drive further dike emplacement. From plane strain solutions of a fluid-filled crack in an infinite elastic media, we may obtain an order-of-magnitude estimate of the dike opening that would be permitted by an increment of volcano growth. The net opening, u, at the center of a dike, resulting from driving pressure, ΔP, is (Pollard et al., 1983):

$$u=\frac{\Delta P(1-\nu)L}{\mu} \tag{2}$$

where L is the half-length of the crack and ν and μ are Poisson's ratio and the shear modulus, respectively. For this case, the driving pressure is $\Delta P=P-\sigma_p$, where $P=\rho G\Delta h$ is the increased pressure required to raise the magma by the growth increment, Δh, and σ_p is the increase of the least horizontal stress due to the vertical surface loading increment. Assuming, for the order-of-magnitude estimate here, that the horizontal strain from the surface loading increment is zero, then from elasticity equations, $\sigma_p=P/3$ ($\nu=0.25$). Using a density of 3.0 g/cm^3, $\mu=4\times10^4$ MPa, $\nu=0.25$ and $L=2$ km, Eq. (2) gives about 1 m of dike opening for every kilometer of growth. Because the presently observable circumferential eruptive fissures would be buried by ~100 m of surface flows, the dikes emplaced to feed those fissures are inferred to represent about 100 m of volcano growth. Hence, Eq. (2) gives about 10 cm of dike opening that could be directly attributable to the loading stress from 100 m of volcano growth, while the total dike opening inferred from the surface fissures is about 10 m. Although the surface loading effect creates a suitable stress field for the pattern of dike intrusion, the magnitude of the stress changes is too small for this process to act alone. Other processes must also be important.

8. Effect of dike intrusions

To explore some effects of dike intrusion on the stress state, a series of models was constructed in which a circumferential dike intrudes upward to the surface. We start from the combination of surface load and reservoir pressure that produces a stress field suitable for the observed pattern of diking (Fig. 7d). Next, a dike is introduced from the upper outside corner of the reservoir, where the stress perpendicular to a potential dike along the reservoir margin is a minimum. The pressure applied in the dike is the same as in the reservoir. The length of the dike is increased in four separate stages, and the dike is propagated upward parallel to the stress trajectories in the previous stage (Fig. 8). The progressive intrusion of the circumferential dike does not significantly alter the stress trajectories above the magma reservoir, but it does change the stress field outboard of the dike in such a way that it promotes future radial diking on the volcano flanks (Fig. 8). This result illustrates how a dike intrusion can change the local stress field and the importance of considering the long-term maintenance of suitable stresses.

The relative amount of radial diking that would be permitted by the emplacement of the circumferential dike in Fig. 8 can be estimated, with the same scaling parameters that we used in Eq. (2). It is assumed that radial dikes would open by an amount that just cancels the change of hoop strain (the principal strain component perpendicular to the radial dike) caused by the emplacement of the circumferential dike. The hoop displacement, d_h, representing the radial dike opening required to cancel the change of hoop strain, ϵ_h, caused by the circumferential dike is:

$$d_h=\epsilon_h 2\pi r \tag{3}$$

where r is the distance to the axis of symmetry. Using the computed hoop strains from the model in Fig. 8d for an average circumferential dike opening of 1 m, the net radial dike opening, d_h, adjacent to the circumferential dike required to cancel the hoop strain varies from 2.0 m near the magma reservoir to 3.7 m at the surface, and at a distance to 8 km from the axis of the volcano d_h is 0.4 m from the surface to about 4 km depth. Hence, the emplacement of a circumferential dike results in stress/strain changes that could result in a comparable amount of radial dike opening.

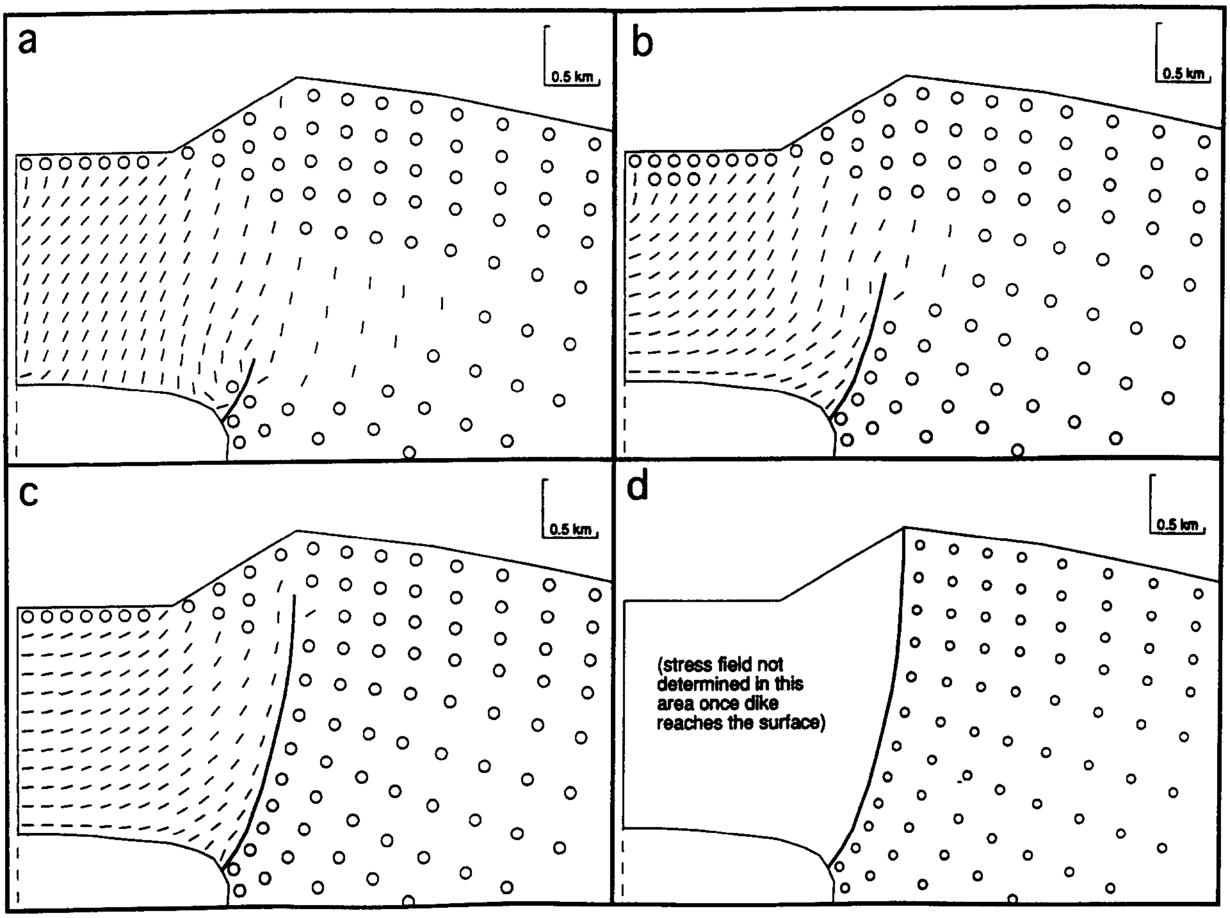


Fig. 8. Model results (same symbols as in Fig. 4) starting from the conditions shown in Fig. 7d and intruding a circumferential dike (bold line) in four increments, following the lines of potential dike orientation. Note that the stress field changes as a result of the emplacement of the circumferential dike to promote future radial dike intrusion.

Radial diking should in turn promote additional circumferential dike emplacement. In considering rift zone intrusions of Hawaiian volcanoes, Dieterich (1988) noted that yielding of the volcano, in response to elastic stresses from intrusions, will act to promote further intrusion. For the current problem, radial compressive stresses built up from circumferential intrusions (and which would eventually limit additional circumferential dikes) should be reduced by radial intrusions, based on the simple geometric argument that if the circumference of an annular segment of a volcano is increased (by a radial dike), the radius to the segment must also increase, implying radial tension between the volcano center and the segment. Thus it seems likely that circumferential and radial diking may alternate in time on a given sector of a volcano in a feedback relationship. In other words, repeated circumferential diking may gradually alter the stress field on one volcano flank so that eventually radial diking is favored. After a period of radial diking the stress field may return to that favorable for circumferential intrusions. Chadwick and Howard (1991) found that on the flanks of many Galapagos volcanoes on the islands of Fernandina and Isabela either radial or circumferential eruptions had been dominant in recent times. This is consistent with the hypothesis of alternating periods of radial and circumferential eruptions on a relatively short time scale. The historical record of eruptions on Galapagos volcanoes is short and incomplete (Simkin, 1984), and is not sufficient to test this hypothesis.

9. Faulting

To accommodate the additional volume of material due to repeated intrusion, the Galapagos volcanoes must spread by some process. At a volcano summit, the caldera and the steep flank can be viewed as forming the sides of a circular ridge (Simkin, 1972). Repeated caldera collapse (Simkin and Howard, 1970) or the failure of sections of caldera walls (Chadwick et al., 1991) are ways in which the circular ridge could be effectively spread inward. Another mechanism is by outward-directed faulting and/or large-scale slumping of a volcano's flanks. This process has been documented on Hawaiian volcanoes where large normal faults exist on volcano flanks (Moore and Peck, 1965), large historical earthquakes have been associated with large-scale deformation of unsupported volcano slopes (Tilling et al., 1976; Ando, 1979; Lipman et al., 1985) and detailed seafloor mapping around the islands reveals massive scarps and submarine landslides (Moore et al., 1989). Faulting of volcano flanks as an accommodation to dike intrusion has also been suggested to occur at Piton de la Fournaise volcano, Reunion Island (Duffield et al., 1982; Lénat et al., 1989) and many other oceanic island volcanoes (Holcomb and Searle, 1991).

It is presently unknown if faulting/slumping is an active process on the flanks of Galapagos volcanoes, but we suspect that it may be important because it could accommodate the large strains produced by repeated dike injection. Within the zone of circumferential vents on Fernandina and Wolf volcanoes, open tension cracks and fault grabens indicative of extension perpendicular to the caldera rim are observed (Chadwick and Howard, 1991). Large normal faults are rare on the subaerial flanks of Galapagos volcanoes [flank faults are only observed on the southwest coast of Cerro Azul volcano and at Ecuador volcano (Chadwick and Howard, 1991)], but the submarine flanks of the volcanoes have generally not been mapped in enough detail to determine if fault scarps exist on the offshore slopes. A small area of high-resolution Sea Beam bathymetry south of Isabela island shows steep escarpments with scalloped embayments that could be interpreted as large normal faults (Christie and Fox, 1990). Seismic swarms with earthquake magnitudes exceeding 4 or 5 are not uncommon in the Galapagos (Acharya, 1965; Simkin, 1984; Chadwick et al., 1991). Local seismic monitoring is inadequate to give much detail about the swarms, but at other well-monitored volcanoes earthquakes associated with volcanic activity are generally below magnitude 4 and larger events are usually interpreted as caused by tectonic adjustments to magma injection or withdrawal (Koyanagi et al., 1972; Filson et al., 1973; Brandsdottir and Einarsson, 1979; Klein et al., 1987). If faulting does occur on the flanks of Galapagos volcanoes, it would be expected on the flanks that are unsupported by neighboring volcanoes, such as the northern and western sides of Fernandina island and the southern and northeastern sides of Isabela island.

10. Conclusions

These numerical experiments have not addressed the question of how the pattern of diking on Galapagos volcanoes began in the first place, but only consider factors that may operate to permit the pattern to persist, once established. Why the Galapagos volcanoes appear to be different than other volcanoes is still an open question, because the mechanisms we propose could conceivably operate at any volcano. In Hawaii, young volcanoes grow under the influence of their older neighbors, which act to buttress one or more flanks of the younger volcanoes (Fiske and Jackson, 1972). The contemporaneous growth of the active Galapagos shields may be an important factor in inhibiting the formation of Hawaii-type rift zones, and developing instead Galapagos-type dike patterns (Simkin, 1984). Alternatively, Nakamura (1980) proposed that thick ocean floor sediments, on which Hawaiian volcanoes are built, act as a weak basal layer and allow the volcanoes to deform outward easily to accommodate rift zone spreading. The Galapagos volcanoes, in contrast, are built on young seafloor (Hey et al., 1977).

We conclude that the magma reservoirs of Galapagos volcanoes are probably relatively flat topped and diapiric in shape, because this shape promotes both circumferential diking from the top outer corner of the reservoir and radial diking from its tapering sides. However, an increase or decrease in magma pressure alone is insufficient to create a stress field suitable for the observed pattern of diking. Surface loading by volcano growth in combination with magma reservoir pressure could produce a suitable stress field for the observed pattern of diking. Because this stress field is renewed as the volcano grows, dikes can continue to be emplaced. We propose that this mechanism may be an important process controlling volcano dike intrusion. On volcanoes with few dikes, increasing stresses from surface growth may be sufficient to account for the density of flank intrusions. However, for Galapagos volcanoes, the stresses from this process, acting alone, are of insufficient magnitude to account for the accumulated volume of dikes. Hence, other mechanisms must also be important to maintain a stress field that would promote the observed pattern and density of intrusion.

One such process may be an alternating feedback between circumferential and radial dikes. The intrusion of a circumferential dike alters the stress field in a way that promotes future radial diking. The magnitude of the stress changes allows an amount of radial dike opening comparable to that of the circumferential dike. Similarly and in turn, the radial diking probably promotes additional circumferential intrusion. Thus, circumferential and radial diking may form under a stress pattern established by the combined influence of reservoir inflation and surface loading, with the amount of diking enhanced by feedback between radial and circumferential intrusion.

We speculate that faulting may also be a structural response to repeated intrusion, because of the high level of seismicity in the Galapagos, and may be an important additional mechanism that perturbs the volcano stresses to permit continued intrusions. More detailed seismic and deformation monitoring of Galapagos volcanoes could test these ideas.

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