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# Volcanic rift zones and their intrusion swarms

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## Abstract

Most volcanoes have rift zones, underlain by swarms of dykes or other minor intrusions. This paper reviews the subject and presents some new data and ideas. It plots rift zone width against length for different volcano types, and finds that the zones on strato- and central volcanoes are on the whole narrower and shorter than on other types. Among the longest and narrowest zones are those on Hawaiian shield volcanoes; there are several reasons for the focussing. Hawaiian rift zones however become diffuse when volcanic activity declines. Monogenetic volcano fields include some that have clearly identifiable rift zones, and others that have vent-fields lacking fissures or dykes. Here the vent-field justifiably can be taken to proxy for a rift zone. The zones visited in several volcanic areas, (including the Azores and Samoa), are localised by deep crustal structures or tectonic activity, and often involve strike-slip faults. This paper then suggests how insertion of dykes could cause structural changes such as bending or initiation of a rift zone, and how departures from the ''normal'' balance between magma flux and extensional strain rate could determine whether rift zones are vertical or horizontal. This leads to a possible mechanism for the circumferential (annular) rift zones of some Galapagos volcanoes. © 1999 Elsevier Science B.V. All rights reserved.

*Keywords:* volcanoes; intrusions; rift zones; dykes; conesheets; sills; Hawaii; Samoa; Galapagos

## 1. Introduction

Rifts in volcanic settings are dilational ground cracks. Those that emit lava are eruptive fissures: the sites of fissure eruptions. Groups of fissures combine to delineate rift zones. Dykes or other sheet-like intrusions are the subsurface equivalents of eruptive fissures. Swarms of these minor intrusions may contain tens to hundreds of members. Particularly intense swarms which increase very abruptly in intensity at their edges have been called coherent complexes. They occur in the core region of major volcanoes and may contain thousands of very narrow members. Sheeted complexes are similar occurrences in oceanic-spreading settings.

This paper is in part a review, but it draws heavily from examples which the author has observed in Antrim, the Azores, Hawaii, Iceland, Samoa and Scotland. It considers how features of rift zones correlate with volcano types. It examines the question of what controls the position and orientation of rift zones, whether superficial gravitational stresses on steep cones, deep crustal structures or tectonic

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activity. It examines the geometric consequences of inserting additional intrusions. It speculates on the effect of variations in the relationship between magma flux and strain rate, and it suggests an origin for annular rifts in some Galapagos volcanoes.

Recent studies on dykes have mostly dealt with emplacement mechanisms of individual members; the present paper is concerned rather with the characteristics of rift zones and congregations of dykes and kindred intrusions. Early descriptions of dyke and cone sheet and sill swarms in the Hebridean Province of Scotland by Harker (1904), Bailey et al. (1924), Richey (1932; 1939) and others were classics of igneous geology. These works have been partly updated by Speight et al. (1982), Gibson and Jones (1991) and Walker (1993), Measurements made in Hawaii by Walker (1986; 1987), in Samoa by Walker and Eyre (1995), and in Iceland by Gudmundsson (1983; 1984) and Gautneb et al. (1989) contribute to the subject.

The concepts that dykes have a bladed form, may propagate laterally from volcanic centres along rift zones, and follow neutral buoyancy levels, are important and basic, but this paper does not contribute significantly to them.

## 2. Rift zones and volcano types

### 2.1. Rift zones of Hawaiian lava shields

The narrowest and most focussed, and among the longest and straightest rift zones are those on the lava-shield volcanoes in Hawaii in their most productive (tholeiitic shield-building) stage; (Stearns, 1985; Dieterich, 1988). Kilauea volcano is in this stage. Its East Rift Zone is 50 km long on land, and extends a further 90 km under water. In the subaerial part, young eruptive fissures (mostly historic), vent edifices and pit craters are confined to a zone 1–3 km wide, (Fig. 1). Non-eruptive rifts extend to about 3 km outside this zone. The submarine part has extensive youthful pillow lavas (Lonsdale, 1989).

Walker (1992) proposed that the focussing is partly by the intense underlying dyke complex. This complex contains about 65% of dykes, and has a high bulk density (about 2.8–2.9 $Mg/m^2$). It is juxtaposed against highly vesicular lava flows having a much lower bulk density (about 2 $Mg/m^3$). The margins of the complex are neutral buoyancy surfaces to basaltic magma having a density between that of dyke complex and lavas, and incoming magma is guided along them. Dyke complexes are perceived to grow incrementally by the addition of dykes along their margins, and are self-sustaining.

Additionally, incoming magma batches are guided by the many planes of weakness (the margins of earlier dykes, and the still-hot centres of recently injected dykes) in the complex. Outcrops show a great many examples of dykes injected along such planes (Walker, 1987). A narrow rift zone would also be favoured if the high-level magma chamber is narrow.

Not all Hawaiian rift zones are narrow. As a shield volcano declines, the magma flux drops, eruptions become infrequent, and the magma becomes alkalic. Mafic and ultramafic xenoliths from crustal sources occur and indicate that high-level magma chambers have solidified (Clague, 1987). Then, vents are widely scattered as in a monogenetic volcano field, and tend to be marked by large cinder cones in place of the generally low vent edifices of the shield-building stage.

With a further decline, true monogenetic fields of the ‘‘rejuvenation stage’’, highly alkalic and carrying mantle-derived xenoliths, may develop.

### 2.2. Rift zones of strato- and central volcanoes

Miyakezima, Sakurajima and Izu-Oshima (Fig. 2) are typical medium-sized island arc stratovolcanoes. All have crater rows of historic fissure eruptions. On the first two, historic eruptions were from radial fissures. Radial fissures would be expected to develop perpendicular to the walls of an expanding magma chamber (Ode, 1957).

On Oshima, historic eruptive fissures are aligned parallel with the island elongation, as a diffuse rift zone about 5 km wide. Nakamura (1977) and Nakamura et al. (1977) showed that in many arc volcanoes such as Oshima the island elongation and rift zones are parallel with the trajectory of motion of the plate on which they are situated, being the orientation of the maximum principal stress. This rift zone orientation is, thus, tectonically controlled.

Large eroded stratovolcanoes and central volcanoes can have impressive dyke swarms. The volcano

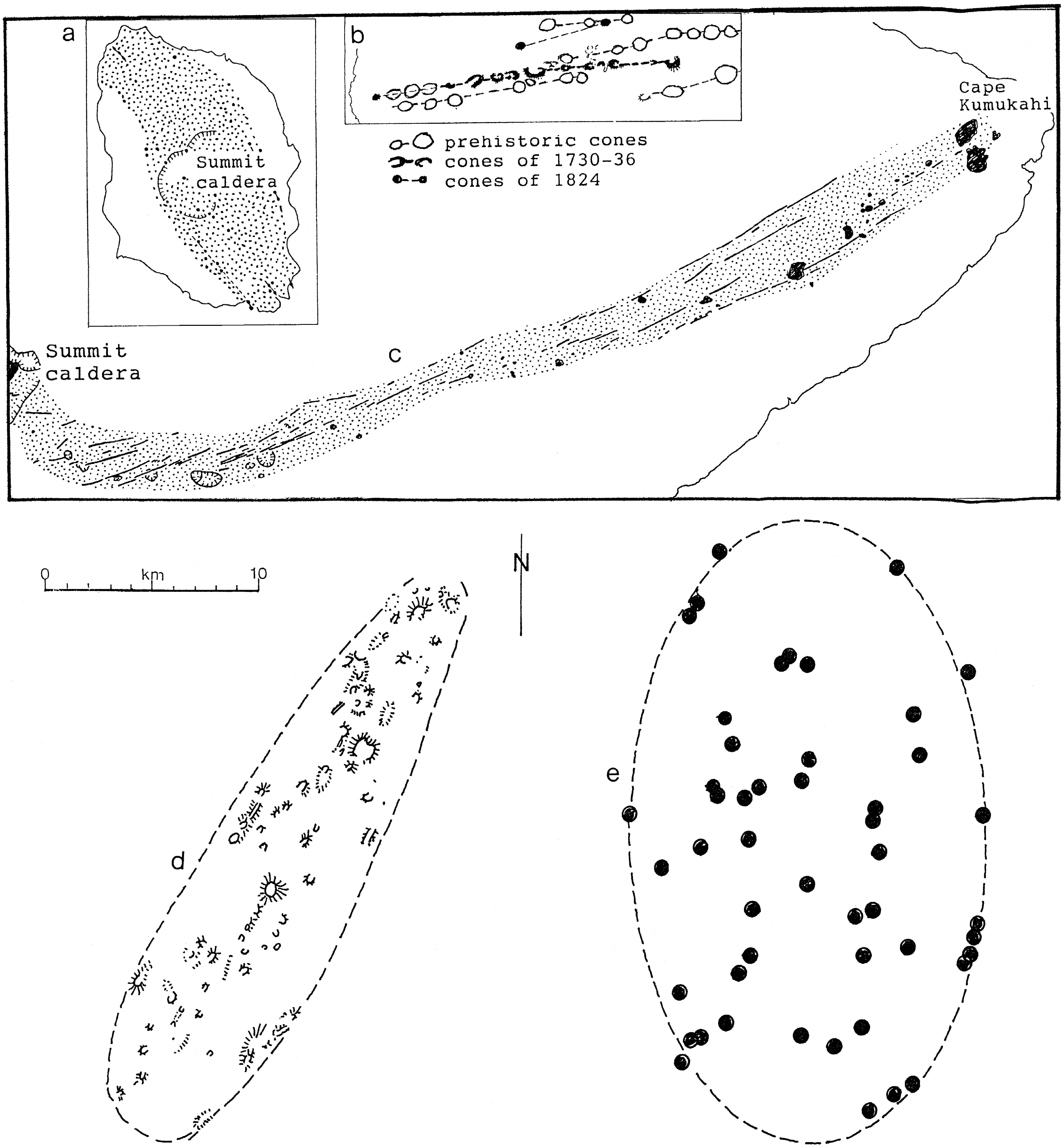


Fig. 1. Maps on the same scale showing features of rift zones. (a) Izu-Oshima (see also Fig. 2a). Rift zone stippled. (b) Part of Lanzarote, showing strong alignments of cinder cones, including those of the two historic eruptions (after Carracedo et al., 1992). (c) Kilauea's east rift zone. Short lines = historic eruptive fissures, stippled = inferred extent of rift zone (after Holcomb, 1987). (d) Vent structures in the Lunar Crater monogenetic-volcano field showing strong elongations and alignments parallel with the length of the field (after Scott and Trask, 1971). (e) Vents in the Auckland monogenetic field showing elliptical boundary (after Sporli and Eastwood, 1997).

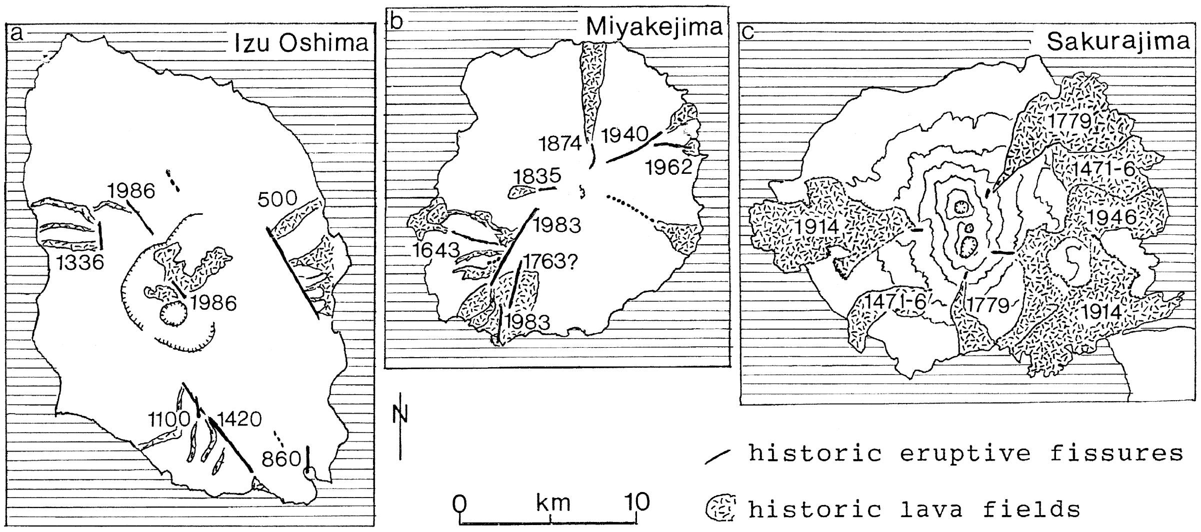


Fig. 2. Maps on the same scale of three Japanese are volcanoes. Thick lines = historic eruptive fissures. Stipple = historic lavas. On Izu-Oshima, the linear rift zone defined by historic eruptive fissures embraces most of the island width. On the other two volcanoes the rift zones are radial. On Sakurajima, three historic eruptions have occurred from vents on diametrically-opposite sides of the cone (after Aramaki and Hayakawa, 1984; Aramaki et al., 1988; Fukuyama and Ono, 1981; Tsuya, 1941).

island of Rakata, neatly truncated by the 1883 Krakatau caldera, is cut by numerous dykes, but quantitative data are lacking. The classic examples of linear swarms are those associated with the Etive and Ben Nevis calderas among the eroded Devonian volcanoes of western Scotland. Their dimensions are shown in Fig. 3. Scores of dykes occur in both, including silicic as well as mafic members. Part of a linear swarm on Hakone (Japan; Kuno, 1964) has 96 dykes averaging 2.85 m wide in 855 m across-strike distance. The swarm focussed on the Otoge ring complex (Japan; Takada, 1988) has 230 dykes with an aggregate width of 600 m.

Etna volcano lies south of the subduction zone in southern Italy. Hundreds of cinder cones occur on its flanks, and many are elongated and aligned. Lo Giudice et al. (1982) noted that many of the alignments trend NNW or NE, and proposed that they were guided by shear fractures on the African Plate, symmetrically disposed on either side of the plate-convergence direction.

High on Etna, clear relationships exist between historic eruptive fissures and the local topography (a noteworthy feature being the large landslide-generated Valle del Bove). Murray (1988) and McGuire and Pullen (1989) convincingly showed that the fissures were guided by gravitational stresses in the steep edifice. Similar features can be identified on many volcanoes.

### *2.3. Rift zones in monogenetic-volcano fields*

A monogenetic-volcano field is a volcano cluster or scatter in which each member erupts once only. The magma batches that fed them took independent paths to the surface but all stemmed from the same melting anomaly. The intervals between eruptions were so long (commonly 1–100 ka) that the path of one magma batch cooled before the next batch rose. Typical fields contain 10–100 members spread over 0.1–5 Ma. Mantle-derived ultramafic xenoliths are common, and indicate the absence of a crustal magma chamber that would otherwise trap these xenoliths (Clague, 1987).

Some fields have rift zones marked by parallel rows of elongate cinder cones, and others have scattered vents and appear to lack either cone elongations or alignments. Among the former are the Lunar Crater field in Nevada (Scott and Trask, 1971), and the young field on Lanzarote (Canary Islands; Carracedo et al., 1992). In Lanzarote the rift zone includes two historic eruptive fissures. That of

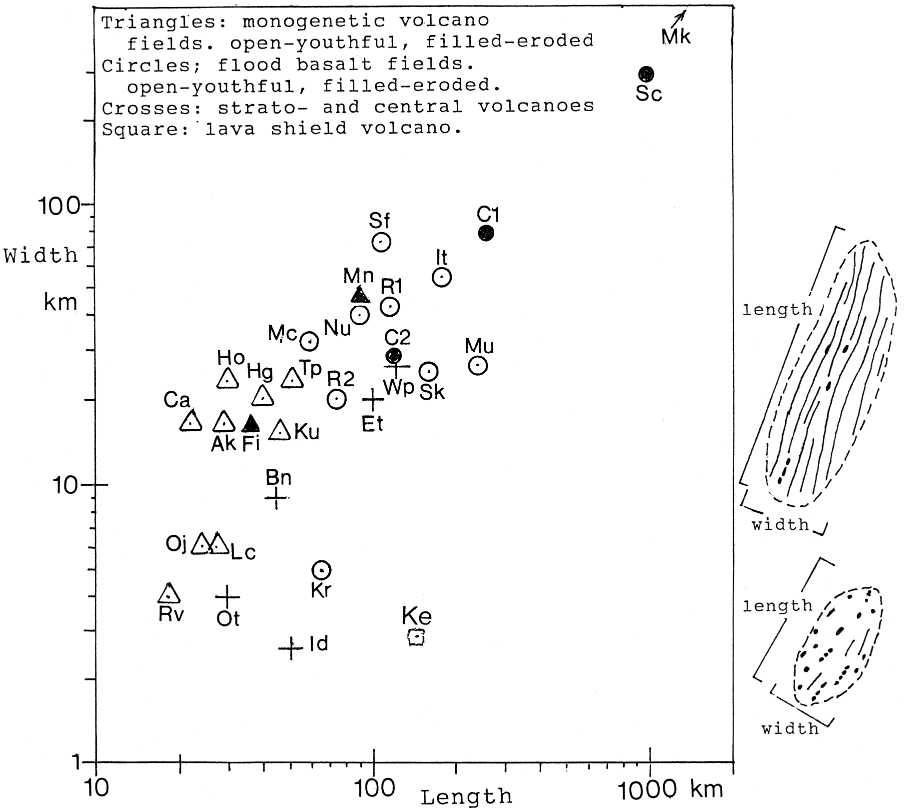


Fig. 3. Approximate rift zone width ($W$) against length ($L$) for selected examples of various volcano types. (a) Lava-shield volcano: Ke = Kilauea East Rift Zone (Holcomb, 1987). (b) Strato- and central Volcanoes: Bn = Ben Nevis and Et = Etive (Richey, 1939), Id = Independence (Moore and Hobson, 1961), Mu = Mull and Sk = Skye (Richey, 1939), Ot = Otoge (Takada, 1988), Wp = Wood's Point (Hills, 1952); (c) Flood basalt fields: C1 Columbia River, Chief Joseph and C2 Monument (Reidel and Hooper, 1989), It = Ithnaya (Camp et al. (1991), Mc = McBride and Nu = Nulla (Stephenson et al. (1980). Kr = Krafla (Saemundsson, 1980), Mk = Mackenzie (Ernst and Baragar, 1992), R1 = Rahat, N part and R2, middle part (Camp and Roobol, 1989), Sc = Scotland–Norway (Smythe et al., 1995), Sf = San Francisco (Tanaka et al., 1986). (d) Monogenetic volcano fields: Ak = Auckland (Sporli and Eastwood, 1997), Ca = Calatrava (Lopez-Ruiz et al., 1993), Fi = Fife, (Forsyth and Chisholm, 1977), Hg = Higashi-Izu (Hayakawa and Koyama, 1992), Ho = Honolulu (Stearns, 1985), Ku = Kula (Richardson-Bunbury, 1996), Lc = Lunar Crater (Scott and Trask, 1971), Mn = Monara (Roach et al., 1994), Oj = Ojikajima (Sudo et al., 1998), Rv = Reveille Range (Yogodzinski et al., 1996), Tp = Te Puke (Kear, 1961).

1730–1736 is a row 14 km long of some 15 cones up to 150 m high, and that of 1824 is a row 1.3–2.0 km farther north. These eruptive fissures are unusually closely spaced in time and space for a monogenetic field.

At the other extreme, the very extensive Michoacan–Guanajuato field (Mexico; Hasenaka and Carmichael, 1985) contains hundreds of cones, but few are elongated or aligned.

Extensional fissures are the most viable pathways for lava ascent, and may commonly be more important at deeper levels. El Jorullo, a volcano in the same field that erupted in 1759–1774, suggests an alternative. El Jorullo is a row 3.4 km long of about six cones (Segerstrom, 1950). The line is curved and the azimuth ranges over 15–20°. Strike-slip strain could have opened a curved fracture such as this and created a tectonic pullapart that was utilised by rising magma.

An eroded monogenetic field where vents occur along a fault is described by Forsyth and Chisholm (1977) from East Fife (Scotland). This, the Ardross Fault (Francis and Hopgood, 1970) has a complex history of vertical and lateral movements in the Late

Carboniferous, and most fault movement postdated the volcanism. Over 100 diatremes and basalt necks occur in this field over an area 25 km across.

Some monogenetic fields thus lack a rift zone. The area over which the vents are scattered may however be considered to proxy for a rift zone on the grounds that it is a zone wherein repeated magma ascent and lava emission events occurred, and many of the vents may pass into dykes at depth. The area over which vents are scattered likely reflects the size and form of the source melting anomaly. Sporli and Eastwood (1997) noted that vents in the Auckland field occur in an area which is perfectly elliptical in plan (Fig. 2). Several other fields approach an elliptical form, and the more clearly that the vents are aligned, the more elongate is the area, well shown by the Lunar Crater field. Possibly the melting anomaly below Auckland is circular while the elliptical surface form of the field is due to magma moving laterally along inferred dykes.

### 2.4. Rift zones in flood basalt fields

Flood basalt fields are also monogenetic in character, but their lavas tend to flood the landscape and are volumetrically larger. Mantle-derived xenoliths are lacking, suggesting that significant magma reservoirs exist in or underplating the crust. Flood basalts probably invariably erupt from fissures, except that fissures tend to evolve rapidly toward point sources as in the numerous volcanic plugs of Antrim. Vents are more widely dispersed than in monogenetic fields; for example, the hundreds of vents in the Harrat Rahat field (Arabia) occupy a band of country 280 by 40 km (Camp and Roobol, 1989).

The wide dispersal results from a wide melting anomaly or a wide magma-storage system, but another factor comes into play, namely the lateral propagation of bladed dykes out from intrusive centres. This can significantly lengthen a rift zone.

Two eroded analogues are the flood basalts of Antrim and Skye, In Antrim, dykes occur in mostly small concentrations up to about 5% over a zone about 40 km wide, and this swarm extends laterally at least 140 km. In Skye, the swarm is more concentrated and the intensity rises to about 20%. The swarm is in part related to flood basalt volcanism, and evidently in part to the later establishment of a central volcano.

In the neotectonic zones in Iceland. flood basalts have issued from a number of more or less parallel rift zones (Saemundsson, 1980). One such is that of Krafla, 65 km long by 5 km wide (the recent activity of Krafla is documented by Bjornsson et al., 1979, and Bjornsson, 1985). Each rift zone is focussed on a central volcano, and it appears that flood basalts evolve to central volcanoes as silicic volcanism becomes more voluminous.

All cratons are cut by continent-ranging Precambrian dyke swarms, for example the Mackenzie swarm (Canada; Ernst and Baragar, 1992) which is over 2500 km long by 1000 km wide. This swarm represents an ancient (1267 Ma) rift zone, and is focussed on large mafic intrusions and remnants of a flood basalt field.

Continent-ranging dyke swarms are scarce in the Phanerozoic, but a noteworthy example is the Late Carboniferous swarm in Scotland and Norway (Smythe et al., 1995), about 1000 km long by 300 km wide. This swarm has the characteristics of one associated with flood basalts, but apparently lacks a lava field. Some of the dykes are keeled or headed (W.Q. Kennedy, pers. commun.) suggestive of a bladed form and lateral propagation.

Sill swarms also occur. They have dimensions comparable with, and often underlie, flood basalts. A medium sized example is that under the flood basalts of northern Skye (Gibson and Jones, 1991), A giant sill swarm of Jurassic age occurs in the remnants of Gondwanaland in Tasmania, South Africa and the Antarctic.

Several flood basalt fields (e.g., Rahat and San Francisco) show a general progression of ages along their length. The latter shows a progression averaging 2.9 cm/year over the past 2 Ma (Tanaka et al., 1986).

## 3. Rift zones in the Azores and Samoa

These two hotspot-related island and seamount groups have multiple rift zones including many instructive examples related to tectonic activity. Volcanism in the Azores is associated with extension on

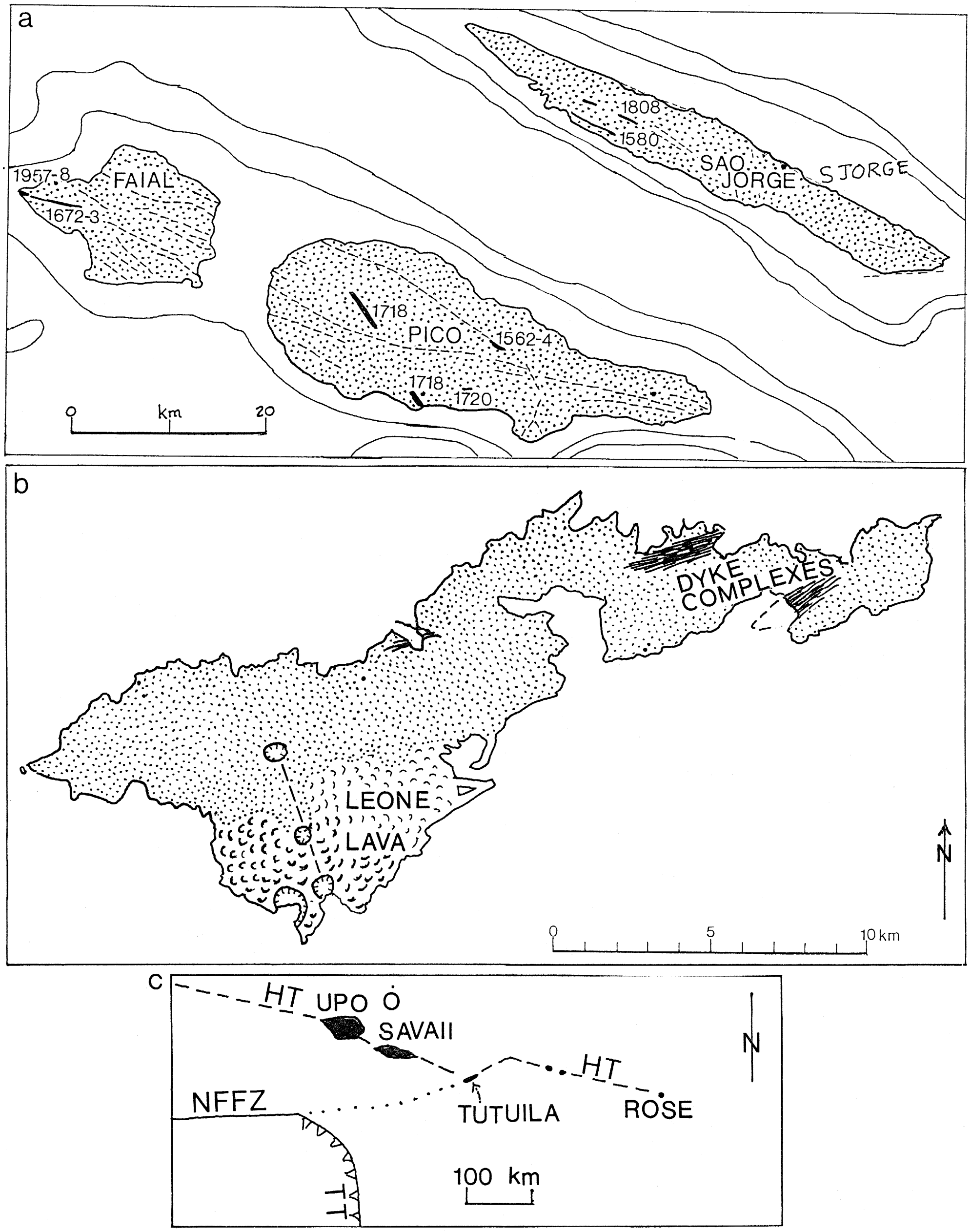


Fig. 4. Sketch maps of parts of the Azores and Samoa. (a) Three Azorean islands showing horst and graben tectonics. Thick lines = historically-active eruptive fissures. Thin dashed lines = selected faults. Some fissures parallel the main faults, but those of 1718 are oblique and may be localised on shear fractures. Isobaths 500 and 1000 m (after Machado, 1967). (b) Tutuila (American Samoa), showing dyke complexes (eroded rift zones), possibly arranged en echelon to island elongation. The very youthful craters of the Leone lava field appear to mark an incipient rift zone striking perpendicularly to the dyke complexes. (c) Anomalous strike of Tutuila on the Samoa hotspot trace (HS), approximately in line with the North Fiji Fracture Zone (NFFZ). This fault is regarded as inactive east of its join with the Tonga Trench (TT) but may have guided volcanism on Tutuila (after Walker and Eyre, 1995).

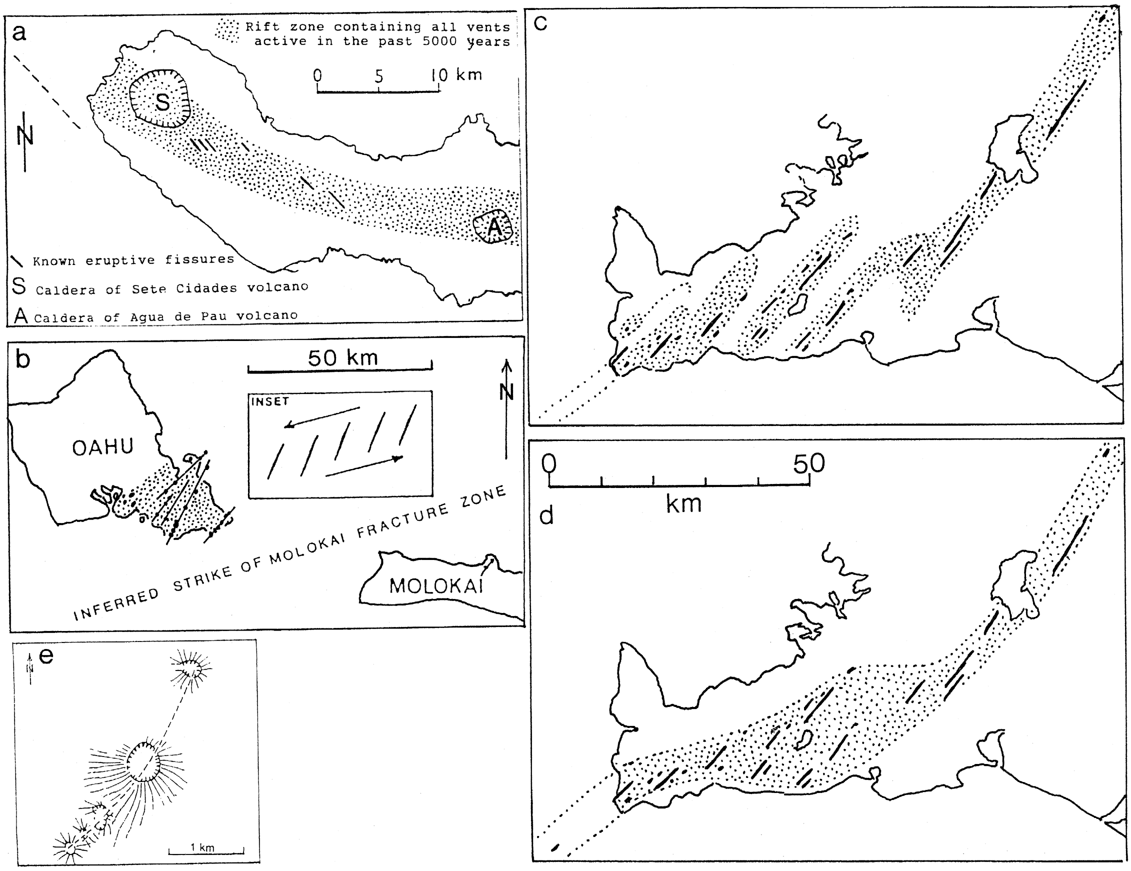


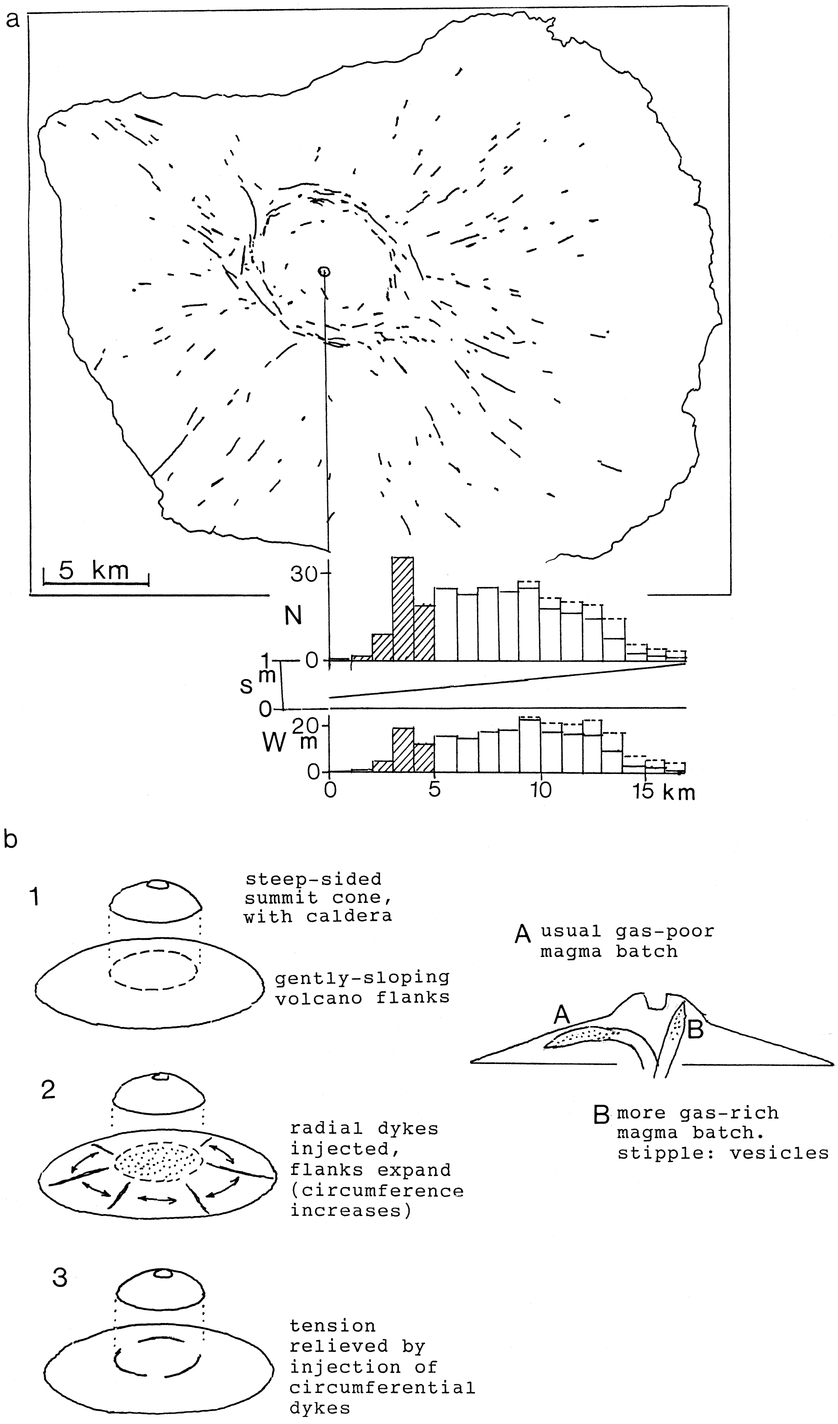
Fig. 5. Maps of other examples where eruptive fissures (thick lines) or rift zones (stippled) are arranged in echelon, suggesting guidance by shear fractures. (a) Sao Miguel (Azores), (b) the Honolulu Volcanics, a monogenetic field of the ''rejuvenation stage'' on Oahu, HI (after Stearns, 1985). (c) and (d) In the Reykanes Peninsula, SW Iceland. Stippled = rift zones, two alternative geometries. Fissures trend perpendicular to the spreading direction, but the crest of the Mid-Atlantic Ridge spreading ridge runs oblique to this. Dauteuil and Brun (1993) regard the crest as marking a narrow thermal anomaly wherein the lithosphere is thin and weak and magma is generated. Subsections (c) and (d) show two interpretations of the form of the rift zones (stippled). (e) Sketch map of Jorullo showing curved crater row (after Segerstrom, 1950). Strike-slip strain might open a narrow tectonic pullapart on the inferred underlying fissure.

the Mid-Atlantic spreading ridge, but most volcanoes occur east of the ridge where they are related to a seismically active ESE-trending fault zone. This zone, one arm of a triple junction, is a transform that links the Mid-Atlantic Ridge to Gibraltar and the Sea of Alboran (Searle, 1980).

Volcanic rift zones and faults generally having an ESE trend occur on most of the islands, and linear

Fig. 6. Radial eruptive fissures on Fernandino Island in the Galapagos (after Chadwick and Howard, 1991). The histogram *N* gives the number of fissures intersected by annular strips 1 km wide described about the volcanic centre; s gives the assumed ''standard'' average dyke widths as they vary with distance from the centre (after Walker et al., 1995); and *W* gives the resulting increase in circumference of each annulus caused by radial dykes. (b) Highly schematic exploded view of Fernandino to show how radial dykes (A) cause lateral expansion of the volcano flanks, so putting the central part in tension; some magma batches (B) enter the dome instead, where they form annular dykes.

troughs and ridges (some the sites of historic eruptions) are prominent on the sea floor. The volcanism was related by Krause and Watkins (1970) to a leaky transform fault.



Particularly noteworthy is Sao Jorge island, a horst 54 km long by 4–7 km wide, rising to 1060 m above sea level. The precipitous fault scarp along the north is remarkably straight (Fig. 4) and lacks the curved embayments and salients common on normal and listric faults. The straightness suggests that the bounding faults have an important strike-slip component. A volcanic rift zone is parallel with the faults. The latest eruption (in 1808) occurred from points along 3 km of fissure, and the position on the topographic axis may indicate a superficial gravitational control superimposed on the tectonic elements. The penultimate eruption (in 1580) was from points along a second (parallel) fissure 5 km long near the south coast.

Horst and graben faults also form prominent topographic features on the island of Faial, and in the 1957–1958 eruption over 1 m of extension and over 1 m of graben subsidence on an ESE trend occurred over the island (Machado et al., 1962).

On Sao Miguel island a volcanic rift zone (Fig. 5) marks the topographic axis between Sete Cidades and Agua de Pau volcanoes. Eruptive fissures and faults arranged en echelon trend obliquely at about 30° to the rift zone axis. Their orientation would be consistent with shear fractures generated by strike-slip strain above a locked strike-slip fault. Right-lateral strain is consistent with earthquake focal-plane solutions (Udias et al., 1976).

The island and seamount chain of Samoa is related to a hotspot currently under Rose Island (Natland, 1980; Natland and Turner, 1985). The island elongations, vent alignments, and rift zones strike mostly ESE. The island of Tutuila however is aberrant, and strikes ENE (Walker and Eyre, 1995).

Tutuila is approximately in line with the North Fiji Fracture Zone (Fig. 4), an active transform fault extending ENE from the area of Fiji to the subduction zone of Tonga (Johnson et al., 1986) beyond which it is inactive. It is speculated that strike–strike-slip motion occurred on the Fracture Zone at 1.54–1.03 Ma (radiometric ages by McDougall, 1985) when Tutuila overlay the hotspot. Furthermore, an apparent en echelon arrangement of eroded rift zones (dyke complexes) in the NE part of Tutuila may have been guided by strike-slip strain. The very young (‘‘post-erosional’’) vents on southern Tutuila are approximately perpendicular to the rift zones.

The positions and orientations of rift zones in the Azores and Samoa thus appear to be mainly tectonic in origin.

## 4. Effects of variations in magma supply and strain rates

Magma supply rate and dilational strain rate in volcanic areas are probably independent variables. The first is controlled by the thermal budget of the melting anomaly responsible for the magmatism. The second is controlled ultimately by the global pattern of plate motions. It is usually tacitly assumed that the two are in some kind of a balance: that by the time accumulated dilational strain is sufficient to make space for a dyke, enough magma has accumulated to fill a dyke fissure. If they are truly independent, there is no obvious reason why they should be in any kind of balance, and this could have some important consequences. A possible example is now considered.

Consider where there is a very robust magma-supply rate, but a small strain rate, so that in a given time several magma batches rise from source though there is only enough accumulated strain to provide space for, say, one dyke. The volcano then mainly swells vertically and accommodates the magma in sills or inclined sheets. This may explain the complex of centrally-inclined (cone) sheets in the Cuillin Hills intrusive centre (Skye; Walker, 1993). The sheets are coeval with a swarm of dykes roughly perpendicular to them. Sheets and dykes each have an aggregate width of about 1.5 km. In this particular example, some of the dykes are related to the Skye flood basalts, and an unknown proportion are related to the Cuillins intrusive centre where the sheets occur.

## 5. Effects due to changed geometry

When an intrusion is emplaced it causes spreading or swelling that permanently changes the configuration of the countryrock. The effect of a single intrusion may be negligible. but the combined effect of hundreds or thousands of intrusions exceeding 1 km in aggregate thickness is far from negligible. Two possible consequences are now considered.

### 5.1. Effects of injecting a dyke wedge

A dyke swarm forms a wedge where the aggregate dyke width decreases down-rift (a down-rift decrease in intrusion number is only partially compensated for by a down-rift increase in average dyke width (Walker et al., 1995).

Insertion of a dyke wedge generates tensile stresses which may be relieved by the formation of dykes roughly perpendicular to the main rift zone. If the dyke wedge is asymmetric because dykes are preferentially accreted on one side, then the wedge may develop a bend, and orthogonal dykes on the outer side may initiate a third rift zone at the bend. This may be the origin of the bend where Mauna Loa's SW and E rift zones join and the poorly defined (in part radial) NW rift zone occurs.

### 5.2. Annular rift zones in the Galapagos

Circumferential or annular rifting is rare but is seen in the caldera region of some shield volcanoes in the Galapagos Islands (e.g., Fernandino, Fig. 6). The volcano flanks have shallow slopes and the steep domical central part rises 600 m higher. The flanks are cut by many radial fissures (Rowland, 1996), while annular fissures occur on the dome. The origin of this distribution of rifts was discussed by Nordlie (1973) and Chadwick and Howard (1991). A somewhat different mechanism is now suggested.

The injection of radial dykes causes a general expansion of the volcano flanks. Suppose the surface of a volcano is subdivided into annular strips 1 km wide, centred on the volcano centre. On Fernandino the number of young radial eruptive fissures mapped by Chadwick and Howard intersected by each annular strip reaches a maximum of over 30 in the strips 5–10 km out from the centre (Fig. 5). The inferred radial dykes have a total width of 20 m (based on the ''standard'' dyke width vs. distance plot of Walker et al., 1995). The injection of radial dykes therefore causes a general expansion all around the volcano flanks, and an increase in the circumference by about 20 m.

This expansion puts the central dome into tension. One can speculate that only the most gas-rich magma batches had sufficient positive buoyancy to enter this part of the edifice. There, because of the extensional stress regime, these batches were emplaced along circumferential fissures. Alternatively, the tension was relieved by caldera collapse (Gudmundsson et al., 1997).

## 6. Summary and conclusions

Rift zones and underlying minor intrusion swarms occur on most volcanoes and contain the pathways taken by magmas moving through the crust. They help control the form and structure of a volcano. They may influence, or interfere with, groundwater circulation, and are heat exchangers that concentrate geothermal activity. They localise volcanic hazards, and can help motivate sector collapse, or they may buttress and effectively strengthen a volcanic cone.

Most of the examples cited in this paper are positioned and oriented by tectonic structures or by such tectonic activity as faulting and plate motion. An important minority of rift zones, not described herein, is found however on steep volcanic edifices where fissuring results from a gravitational instability of the edifice.

Conventionally, rift zones are regarded as more or less vertical structures. Because of the very close similarity between dykes, intrusive sheets and sills, and the fact that these intrusion types commonly co-exist and alternate in time at the same site, it would be logical to extend the meaning of rift zone to inclined and horizontal varieties. There is possible ambiguity in that the dip of an intrusion may be original, or may be due to post-emplacement tilting.

Conventionally, rift zones are regarded as more or less straight features. Linear rifts consisting of parallel members however form only one end of a spectrum, the other end being marked by fully radial examples. It is logical therefore for rift zones to embrace the radial examples. Swarms of conesheets and annular fissures appear to differ from straight and linear rift zones only in their curvature and annular form.

A different problem is posed by monogenetic volcano fields. These vary from conspicuously rifted examples to vent-fields in which the vents lack elongations or alignments. Very probably many of the vents issue at greater depths from dykes. Monogenetic vent-fields can, thus, also be classified as rift zones.

Whether a rift zone is straight or curved, vertical or horizontal, inwardly inclined (toward a focus or a line) or annular in form may be controlled by quite small changes in external conditions such as switchovers in the principal stress axes, based on the common occurrence in the same site of coeval groups of intrusions in two or more orthogonal sets.

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