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Hawaiian Rifts and Recent Icelandic Volcanism: Expressions of Plume Generated Radial Stress Fields

M. Wyss
Cooperative Institute for Environmental Sciences, University of Colorado, Boulder, Colorado 80309, USA

Abstract. Hawaiian volcanoes have two to three major rift zones which radiate in three preferred azimuths of 82°, 201°, and 322° These three principal rift arms form angles of about 120° with each other and one of them is oriented approximately parallel to the youngest part of the Hawaiian Island chain. I propose that these three rift systems are plume generated, and after they are removed from the hotspot they could be considered triple junctions of aulacogens. In Iceland the idea of sea floor spreading is apparently contradicted by the distribution of recent volcanism. The Snaefellsnes volcanic zone for instance strikes EW in contrast to all other volcanic zones in the Atlantic and it terminates abruptly without being transformed by a fault into a plate boundary. The eastern volcanic zone of Iceland strikes approximately NS and also terminates without a transform fault at its southern end which is represented by Surtsey. Interpreting the Icelandic recent volcanic zones (with the exception of the Reykjanes zone) as representing the three rift arms of a hotspot removes all contradiction with the sea floor spreading hypothesis in the area.

Key words: Iceland – Hawaii – Stress – Rift – Triple junction – Plume.

Introduction

Triple-arm tear patterns (Mercedes star-like) are often observed radiating from geological features. The dimensions of these range from meters (lava and salt domes) to 100 km (mantle plumes). Usually the angle between the three tear arms is close to 120° Most often this phenomenon is interpreted as caused by radially symmetrical updoming of a brittle layer, due to the upwelling of a cylindrical or plume-like mass from below. The radial symmetry of the triple-arm pattern indicates that the stress field causing the tears is radially compressive and tangentially extensive in the horizontal plane around the center of the pattern. In addition to doming, this type of pattern could be caused by gravitational forces in a cone or thermal stresses caused by radial cooling.

Burke and Dewey (1973) proposed that plumes generate triple junctions. The conjecture is that plumes pushing through the lithosphere from below will cause a concentric uplift of the surface. Tangential stresses will then tear the crust and perhaps the lithosphere in three radial rifts which will be oriented symetrically at approximately 120° to each other. Three rifts are usually observed presumably because three rifts allow for the largest opening with the minimum rupture area, i.e., the minimum work required. Dewey and Burke (1974) further proposed that continental break-ups are initiated by chains of hotspots, the rifts of which connect to each other and thus create the jagged outlines of the resulting continental boundaries. In this scheme two rifts of each hotspot connect to the next plumes along the chain and become active spreading axes, whereas the third one becomes a failed arm or aulacogen. Hoffman et al. (1974) illustrated this point by an extinct and a currently active hotspot-generated triple junction. The Afar hotspot represents their concept of the typical case of a current plume-generated triple junction. The Red Sea and the Gulf of Aden are the active rifts with the Ethiopian rift showing minor activity, which invites the suggestion that it will cease spreading in the future and become a failed arm. One of the best documented paleo-aulacogens is the Niger delta depression. As shown by Hoffman et al. (1974) the plumegenerated triple junction that produced this failed arm also produced the sharp eastern point of South America that, with its fit into Africa's Bay of Guinea, suggested to Wegener (1924) that these continents were once joined. The characteristics of failed arms are that the initial stage of graben type normal faulting and volcanism occurred synchronously with the beginning of rifting along the successful arms and that tectonic activity will be terminated and followed by stability once the location has drifted away from the plume.

Hawaii

One of the best known hotspots is Hawaii. Wilson (1963) proposed that the Pacific plate moves rapidly to the NW over a relatively stationary mantle plume (a concept further developed by Morgan, 1971, 1972) and that therefore the Hawaiian volcanic islands are continuously removed from the plume location. Thus, a long island and seamount chain deposited on the moving lithosphere is created in the wake of the hotspot. The most active volcano is located at the southeastern-most island above the plume. Today this is Kilauea, on the island of Hawaii. Figure 1 shows the rift zones of the 5 major volcanoes on Hawaii. Macdonald (1956) recognized that these rifts and those on other Hawaiian islands (Fig. 2) form radial patterns with respect to the volcanoe summits. Fiske and Jackson (1972) combined the major rifts of the Hawaiian islands (Fig. 2) in a rose diagram of rifts radiating from the hot spot (Fig. 3). The rose diagram shows a clear pattern with three preferred directions being mapped by the longest rifts and by the largest number of rifts. Clockwise from N these directions are approximately 82°, 201°, and 322° The angles between these major rifting directions are close to 120° The clearest single example of the typical symetrical three arm system is shown by the rifts of Haleakala on Maui (Fig. 2).

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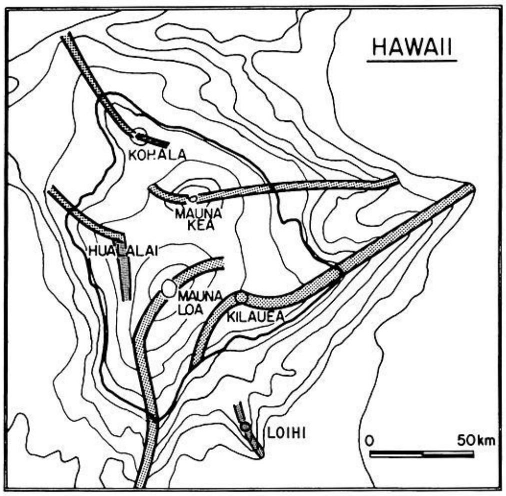

Fig. 1. Topographic map of the island of Hawaii and vicinity. Stippled pattern marks the rift zones of volcanoes. (After Fiske and Jackson, 1972)

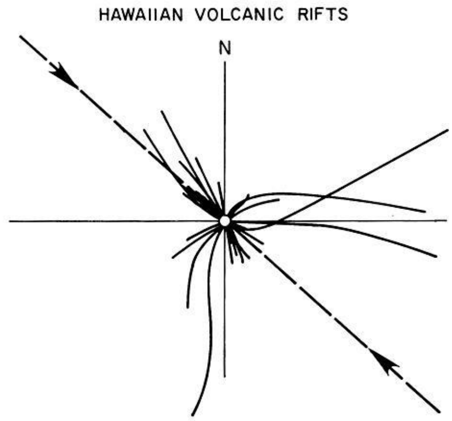

Fig. 3. Rose diagram showing 33 Hawaiian rift segments radiating from a single imaginary hotspot center (from Fiske and Jackson, 1972). The dashed line is the strike of that segment of the Hawaiian Island chain shown in Fig. 2, which is the segment where the rifts are located

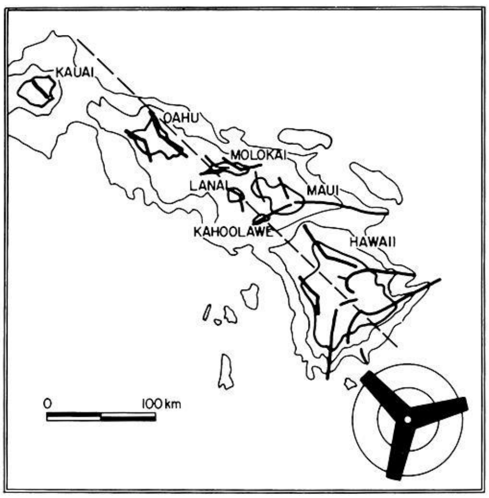

Fig. 2. Topographic map of the southeastern part of the Islands of Hawaii, Rift zones of major volcanoes from Fiske and Jackson (1972) are heavy lines. The dashed line is an approximation of the azimuthal trend of the islands shown. The shematic plume-generated triple rift zone SE of Hawaii represents the expected tectonic structure of the next island that will be generated by this hotspot

The opening and maintaining of the rift zones may be understood as huge hydrofracture experiments. The injections of magma originate from the shallow summit chamber. While the summit deflates, magma is propagating laterally at a few kilometers depth below the rift, opening cracks against the least compressive horizontal stress, with the crack (rift) propagating in the direction of the greatest principal horizontal stress. The orientation of the greatest and least principal horizontal stresses in the crust have been mapped on the basis of the strike of dike and rift systems. For instance, Nakamura et al. (1977) used the major dikes of Aleutian volcanoes to map the direction of the greatest principal stress in the horizontal plane, which was found to be oriented parallel to the local slip vector of the Pacific relative to American plate.

From the orientation of Hawaiian rifts (Figs. 1–3), I conclude that the stress field in the Hawaiian crust is characterized by compression pointing radially away from Hawaiian volcanoe summits, with extension oriented tangentially to circles around these summits. Endo and Rogers (1980) showed that earthquakes at approximately 40-km depth below the island of Hawaii also exhibit the same pattern of radially oriented *P*-axies. It is clear, therefore, that the stress field in the crust and lithosphere below the Hawaiian islands does not find its origin in dynamic forces acting on the whole Pacific plate as proposed by Jackson and Shaw (1975). Rather the radial stress field around each volcanic center must have been generated by forces at the hot spot. In a wide sense the stress field is plume-generated. As more high quality focal mechanisms become available for crustal earthquakes it is expected that the radial Hawaiian stress field will be mapped in more detail.

In addition to the radial nature of the stress field, Fig. 3 shows that Hawaiian rifts exhibit a triple-arm pattern, which remained constant in its orientation over the last few million years (the age of the island in Fig. 2). This triple-arm pattern is not commonly found in the andesitic volcanoes of subduction zones (e.g., Nakamura et al., 1977), but it is typical for the triple junctions described by Burke and Dewey (1973).

In the part of the island chain from which the data were taken the azimuth of the chain is 315° in the average, and 326° for the best data on the youngest islands (Fig. 2). The overall strike (294°) of the island-seamount chain, including the portion not represented by the rift data, was inappropriately used by Fiske and Jackson (1972) for comparison. Since the recent island chain direction is within a few degrees the same as one of the preferred major rift azimuths (322°), I conclude that the island chain controls the directions of the three arms by a mechanism which is demonstrated by the newly emerging volcano Loihi southeast of Hawaii (Moore et al., 1979).

From the submarine topography I conclude that Loihi is located at the center of a crack which built up a rift in the direction NNW-SSE (Fig. 1). This direction closely parallels the radial compressive stress field due to the active volcanoes Kilauea and Mauna Loa. Since the rifts of these volcanoes extend to distances away

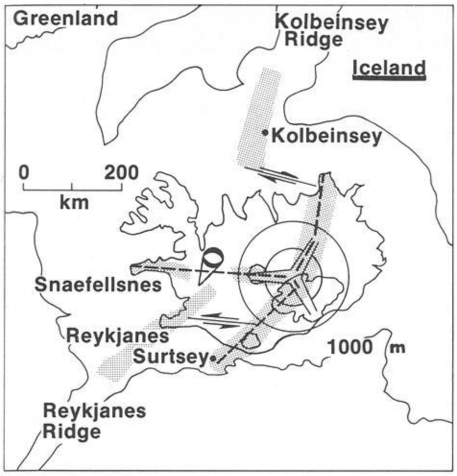

Fig. 4. Map of Iceland and mid-Atlantic rift system and 1000-m depth contour (After Sigurdsson, 1970). Shaded areas represent the neo-volcanic zones with focal mechanism from Einarsson et al. (1977). The approximate location of the plume center and its conjectured three rift arms are sketched in. It is postulated that the actual trend of two of the arms (*dashed*) is due to the dominance of the extensional stress field perpendicular to the mid-Atlantic spreading axis

from the summits beyond the location of Loihi (Fig. 1) I conclude that at Loihi magma was injected into a crust which is located within the radial stress fields of Kilauea and Mauna-Loa. If each new volcano originates in the stress field of the last ones but is located to the southeast, in accordance with the Pacific plate motion, one would expect that the initial rift will develop in the island chain direction approximately. After a new volcano like Loihi grows to be the major focus of the hot spot, it will create its own radial stress field. Then it will change from a one-crack volcano to one with the triple-arm pattern. In this way new islands with rift systems as shown schematically in Fig. 2 will be created in the distant future.

This model of the origin of Hawaiian rifts and their orientation differs from that of Fiske and Jackson (1972), who proposed that the rift orientations are controlled by local topography. I contend that on the contrary as rifts develop they orient themselves according to the local stress field and subsequently build up, by repeated fissure eruptions, the ridge topography found along them. This process is demonstrated by the Loihi rift which developed on the lowest part and beyond the gently sloping edifice of Hawaii (i.e., at oceanic depths exceeding 4,500 m). I suggest that when Loihi originally developed there was no local ridge to dictate the orientation of its rift, as required by the mechanism proposed by Fiske and Jackson (1972). Instead, the rift oriented itself according to the radial stress field of Kilauea, and then gradually a ridge was built up by eruptions along the rift.

The Hawaiian rifts show curvature and directions deviating locally from the directions expected from an ideal three-arm system generated by a plume. These deviations reflect local perturbations of the crustal stress field. The major source for such deviations are probably the proximity and buttressing of older volcanoes which existed at the time newer ones started to develop. For instance, the simultaneous activity of Mauna Loa will influence the stress field around the newer volcano Kilauea (Fiske and Jackson, 1972).

Iceland

Iceland is a major hotspot located on an actively spreading ridge in contrast to the Hawaiian hot spot. The shallow banks connecting Iceland to Greenland and Europe are taken to be the traces left by the hot spot on the respective plates. The distribution of recent volcanism in Iceland has been the subject of controversy (Pálmason and Saemundsson, 1974). The Reykjanes Ridge continues on land in Southwest Iceland in the form of the 'western volcanic zone' (Fig. 4). However, half way through Iceland this zone terminates, or turns into a neo-volcanic zone with an easterly trend to meet the 'eastern volcanic zone'. The latter crosses Iceland from Surtsey in the south to Tjörnes in the north, were a transform fault connects it to the Kolbeinsey Ridge (Saemundsson, 1974; 1978). In addition, the central EW volcanic zone is continued to the west in the Snaefellsnes volcanic zone. Opponents of the sea floor spreading idea have taken this distribution of neo-volcanic zones to indicate that spreading is not taking place in Iceland. The major facts unexplained by sea floor spreading are the transverse volcanic zone in central Iceland and Snaefellsnes, as well as the lack of a transform connection to the Atlantic spreading axis at the southern termination of the eastern volcanic zone at Surtsey. The transform fault proposed by Ward (1971) is located north of Surtsey and Heimaey along the southern coast of the main island.

If the center of the Iceland hot spot is assumed to be located as indicated in Fig. 4, one finds that the east-west volcanic zone and the northern half of the eastern volcanic zone almost perfectly fit the expected relative directions of two rift arms. The southern part of the eastern volcanic zone (terminating at Surtsey) may be the third arm. However, its direction does not match the expected direction. Instead of indicating a radially symetrical stress field of tangential tensional stress surrounding the center of the hot spot, the rifts that should run in azimuths of NNE and SE orient themselves N and SW instead. We note that these latter directions are those of the closest parts of the Atlantic spreading ridge to the N and S of Iceland, respectively. Drastic deviations of dike orientation from radial can be explained by superposition of a regional tectonic stress field and the radial stress field of a volcanic center (Muller and Pollard, 1977). In analogy, I postulate that the extensional stress field perpendicular to the spreading Reykjanes Ridge caused the arm that should have trended SE to turn into a southwestern direction so that intrusive dikes opened against the regional least compressive stress. The rift-arm orientation suggests that the regional tectonic stress field due to the mid-Atlantic ridge dominated over the plume induced stress field. This interpretation implies that the extensional stress field of oceanic ridges is still strongly extensional in the plates at distances of 200 km from the sea floor spreading centers.

The northern part of the Reykjanes Ridge deviates to the east from the trend in the southern part of the ridge, and the mid-Atlantic spreading direction is not perpendicular to the northern Reykjanes Ridge. This peculiarity can be explained by speculating that the Iceland plume-generated radial stress field is perturbing the mid-Atlantic spreading stress field enough to change the direction of the crack which can open easiest against the least compressive stress.

The same explanation can be offered for the deviating trend of the southern Kolbeinsey ridge. While the northern part of this ridge strikes NNE, its southern part swings around to a N-S direction pointing more towards the plume center.

Several authors have interpreted the Snaefellsnes and the central valcanic zone as a right-lateral fracture zone and transform fault (e.g., Sigurdsson, 1970; Schäfer, 1972). However, Einarsson et al. (1977) found focal mechanisms in the Borgarfjordur area which indicated NS extension (Fig. 4). This observation strongly supports the idea that the Snaefellsnes volcanic zone is the third plume-generated rift arm. Einarsson et al. (1977) and Einarsson (1979) offered the hypothesis of a plume-related origin of the Snaefellsnes volcanic zone as one of the two most likely explanations. Based on the fact that the center of the plume identified here is almost identical with that suggested by geochemical data (Sigvaldason et al., 1974), and that there is a close resemblance between Iceland and Hawaiian rift systems, I believe that the distribution of Icelandic volcanism represents the three rift arms of the Icelandic hot spot.

Conclusions

The geometrical similarity of the three-rift-arm pattern between Iceland and Hawaii is striking (Figs. 2 and 4). However, there are also some differences: In Iceland at least one rift arm is strongly deflected in its direction by the regional stress field which evidently is extensional perpendicular to the Reykjanes ridge. Also the Iceland hotspot is much larger than the Hawaiian one. Within the three Icelandic rift arms there are volcanoes of the size of Kilauea which seem to have their own feeder systems and which cause their own rifting episodes (e.g., Björnsson et al., 1977). To what extent a volcano like Krafla can be compared with craters within, say, Kilauea's rifts is beyond the scope of this paper. While the dominating forces creating the stress fields may be different at plate boundaries from those at intra-plate hot spots, it seems of interest to point out that the over-all patterns of rifting in Iceland and Hawaii are similar to each other and closely resemble the three-rift-arm pattern commonly associated with plumes.

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