

WHY DO LONG RIFT ZONES DEVELOP
BETTER IN HAWAIIAN VOLCANOES
— A POSSIBLE ROLE OF THICK
OCEANIC SEDIMENTS

by

KAZUAKI NAKAMURA

Earthquake Research Institute, University of Tokyo
Bunkyo-ku, Tokyo 113. Japan

ABSTRACT

Rift zones are one of the characteristic features of Hawaiian volcanoes. They are long narrow zones of flank fissure eruptions but are distinct from ordinary flank eruption sites on polygenetic volcanoes in that eruptions, and therefore dike intrusions, occur repeatedly at the same general place for a long time and thus cause a considerable distance of horizontal spreading. This spreading should somehow be accommodated and the direction of the minimum compressive stress should remain the same after accommodation in order for a new dike to intrude in the same orientation.

The Krafla spreading events in Iceland between North American and European plates revealed that the process of the lithospheric spreading is similar to that observed for Hawaiian volcanic activities, including rift zone eruptions.

Accreting plate boundaries may be understood as consisting of chain of linear rift zones and their source polygenetic centers where the magma supplied from the asthenosphere is temporarily stored.

Horizontal spreading caused by repeated dike intrusions has been accommodated in the case of the accreting plate boundaries by the lateral separation of lithosphere over asthenosphere. In the case of Hawaii sliding of the volcanic edifice over deep sea sediments may be the analogous mechanism such as appears to have occurred during the 1975 Kalapana earthquake which was anticipated by SWANSON et al. (1976) as one of the repeated events as the east rift zone has continuously dilated. Lack of rift zones in otherwise similar Galapagos shields which sit over the young ocean floor with higher relief is consistent with this view.

HAWAIIAN RIFT ZONES

Hawaiian rift zones are the channelways to bring the lava to the flanks of shield volcanoes. According to MACDONALD (1972), typically, there are three rift zones radiating from the summit with angles of about 120° between them. Usually, however, two of the rift zones are much more prominent than the third (Fig. 1). The major rift zones range from one to four kilometers in width and contain hundreds of fissures that served as eruptive vents. These are marked at the surface by open cracks, spatter ramparts, rows of spatter cones, collapse craters, and shields of Icelandic type (i.e. monogenetic). At depth, where they have been exposed by cutting of canyons into the older shields, the rift zones are seen to consist of innumerable parallel thin dikes.

Some rift zones extend more than a hundred kilometers from the summit. FURUMOTO (1978) estimated the depth of

SYMPOSIUM ON THE ACTIVITY OF OCEANIC VOLCANOES

the parallel dikes of the rift zone as deep as 5 to 7 kilometers, who constructed a structural model of Kilauea volcano on the basis of seismic velocity structure (HILL, 1969), Bouguer gravity anomaly (KINOSHITA et al., 1963) and some other geophysical observations (FURUMOTO and KOVACH, 1979; BROYLE et al., 1979).

Rift zones are one of the major characteristics of Hawaiian shields. WILLIAMS and MCBIRNEY (1979) classified polygenetic shield volcanoes into Hawaiian and Galapagos types. Rift zones are not observed in smaller Galapagos shields, otherwise similar oceanic, basaltic shields volcanoes, nor in stratovolcanoes (composite volcanoes), the commonest type of polygenetic volcanoes.

This short paper is an abbreviated and modified version of my previous paper in Japanese (NAKAMURA, 1980).

PROBLEMS

The aggregate thickness of the parallel dikes composing a rift zone frequently attain the width of the order of a kilometer or more (MACDONALD, 1956). The room occupied by the width of the dikes should somehow have been accommodated without much mechanical difficulty. What is the mechanism responsible for such an accommodation under an intraplate situation?

The same problem may be addressed in terms of the stress field near the rift zone. Dikes tend to develop in the plane perpendicular to σ_3 ($\sigma_3 < \sigma_2 < \sigma_1$), or parallel to σ_1 and σ_2 . On the other hand, the magnitude of stress in the direction of the previous σ_3 should increase due to the shortening caused by dike intrusions. Then there should be a certain mechanism to maintain the same direction of σ_3 after repeated

dike intrusions, so that a new dike can intrude in the same orientation. What is such a mechanism for maintaining the same direction of σ_3 ?

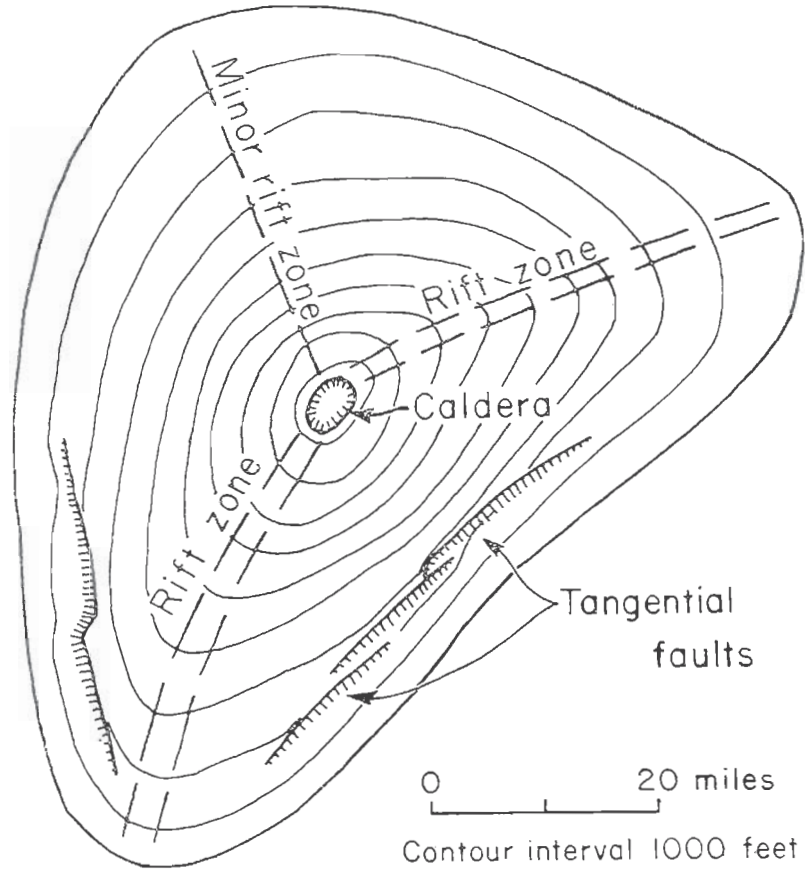


Fig. 1 — Plan of a typical Hawaiian shield volcano showing the radiating rift zones, caldera and tangential faults. MACDONALD, 1956.

PREVIOUS WORKS

MACDONALD (1956) attributed the radial pattern of the rift zones to a magmatic force thrusting up the central portion of the volcanic edifices. He explained the tangential faults (Fig. 1) by the same mechanism. Later studies revealed, however, that the volcanic edifices have subsided (HILL, 1969; ZABLOCKI et al., 1974) and is subsiding (MOORE, 1970), when the rift zone eruptions are vigorously going on. It may be concluded that the radial pattern certainly indicates the point source mechanism which works principally as horizontally expanding force (ODÉ, 1957; NAKAMURA, 1977) rather than an upthrusting one. The horizontally expanding source may be able to explain the flank (fissure) eruptions but it does not explain the reason why the extensive diking repeated many times in a few particular directions is possible.

FISKE and JACKSON (1972) demonstrated the role of gravitational force in determining the orientation of the rift zones. They classified Hawaiian shields into two categories, the one grew over the relatively flat ocean floor (isolated type) and the other grew on the flanks of the adjacent shield (buttressed type) (Fig. 2). In the case of the buttressed shields, they argue that radial dikes propagate in the direction perpendicular to the maximum inclination of the underlying slopes. In the case of isolated shields, FISKE and JACKSON (1972) maintain that the strike of repeated dike intrusions follow the crest of the initially formed ridges.

Because FISKE and JACKSON (1972) are concerned mainly with the plan view configuration of the rift zones, they did not explain how the aggregate thickness of the dikes is accommodated and the stress field remains the same in orientation of the principal axes after repeated intrusions.

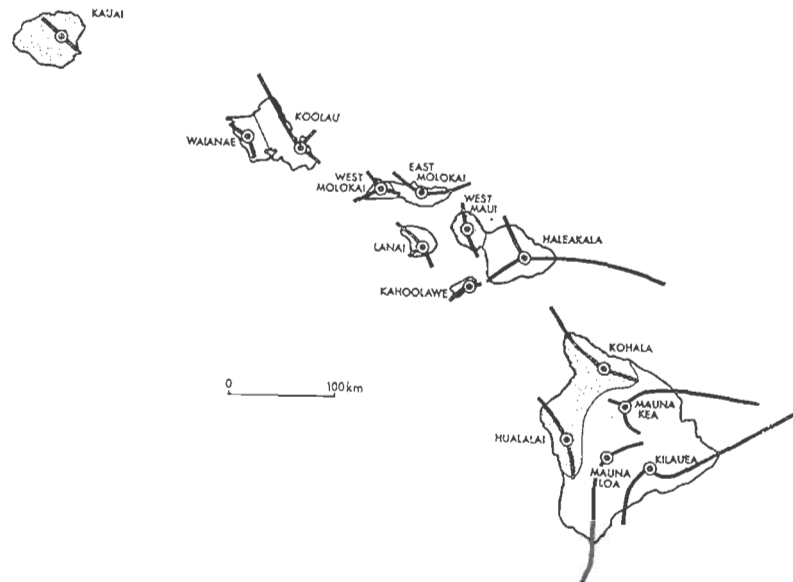


Fig. 2 — Map showing the southeastern part of the Hawaiian Archipelago. The 6 volcanoes shown in the stippled pattern grew as isolated edifices. The 7 unshaded Volcanoes grew later and were buttressed by the earlier formed edifices. FISKE and JACKSON, 1972.

WYSS (1980) regarded the plan view pattern of Hawaiian rift zones as essentially controlled by a point source of force, i.e. a hot spot, and thus radiating from individual volcanoes in the same three directions with an angle of about 120° . He also argues against the interpretation by FISKE and JACKSON (1972) citing the north-south direction of the elongation of Loihi seamount located 30 km south of the island of Hawaii. Loihi should elongated, according to WYSS (1980) in a northeast-southwest direction parallel to the regional contour lines, if FISKE and JACKSON's interpretation holds. However, the length of the long axis of Loihi seamount (ca 20 km) appears to be too short to justify the argument of WYSS.

SYMPOSIUM ON THE ACTIVITY OF OCEANIC VOLCANOES

It may be rather difficult to view the rose diagram of Hawaiian rift zones (Fig. 3) as radiating in three principal directions. Moreover, his argument fails to explain the lack of similar rift zones in other volcanoes of the hot spot origin, like Galapagos.

Briefly, it seems to me that the problem raised in this paper has not been considered seriously.

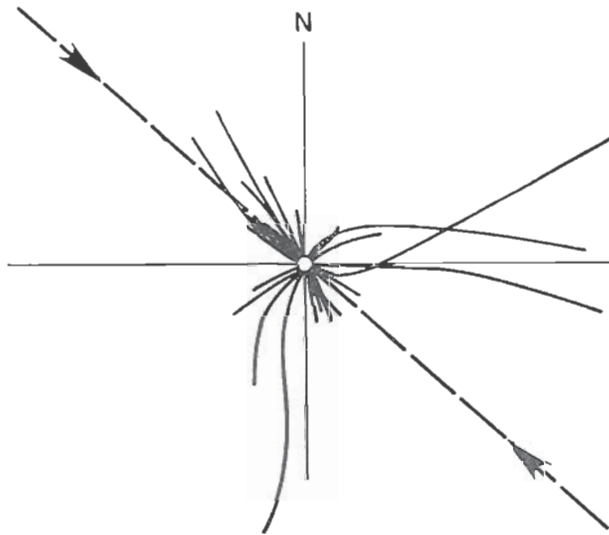


Fig. 3 — Rose diagram showing 33 Hawaiian rift zones radiating from a single imaginary center. From FISKE and JACKSON, 1972. The dashed line is the strike of the Hawaiian island chain as drawn by WYSS, 1980.

IMPLICATIONS OF RECENT KRAFLA EVENT
IN ICELAND

Currently occurring event at Krafla in Iceland showed us detailed processes of spreading and accretion of the lithospheric plate (BJÖRNSSON et al., 1979). The process is essentially the same with the rift zone activity of Hawaiian volcanoes,

that is, the magma supplied nearly constantly (TRYGGVASON, 1980) from the deep source is temporarily stored in a shallow magma reservoir beneath the center of the Krafla caldera (EINARSSON, 1978), one of the polygenetic volcanic centers in the neovolcanic zone in Iceland, the accreting plate boundary (SAEMUNDSSON, 1978). The storage causes inflation of the caldera region (TRYGGVASON, 1980). Intermittent deflation events are associated with extensive lateral dikeing from the reservoir into the axial zone of the plate boundary (BRANDSDOTTIR and EINARSSON, 1979; EINARSSON and BRANDSDOTTIR, 1980; TRYGGVASON, 1980; LARSEN et al., 1979), resulting in the spreading and accretion of the European and North American plates.

The Krafla event implies that the axis of the accreting plate boundary, in general, consists of a series of polygenetic centers with shallow magma reservoir and linearly radiating rift zones (SAEMUNDSSON, 1978; BJÖRNSSON et al., 1979). Here the rooms for dike intrusions have been accommodated by the separation of the lithosphere «sliding» over the asthenosphere. Therefore, if there is an analogous mechanism in Hawaii, it will be an answer to our problem.

THE 1975 KALAPANA EARTHQUAKE

The 1975 Kalapana earthquake (M_s : 7.1) occurred at the southeast coast of the island of Hawaii and was studied by ANDO (1979) and FURUMOTO and KOVACH (1979). The fault parameters given by these authors are generally similar. In Fig. 4, the two possible fault planes by ANDO (1979) are given. According to these authors, a significant portion of the Kilauea's south flank slid south-southeastward by several meters over a nearly horizontal fault plane, with the depth 7 to 10 km. This depth coincides with the upper surface of the oceanic

SYMPOSIUM ON THE ACTIVITY OF OCEANIC VOLCANOES

crust underlying the volcanic edifice (HILL, 1969). Therefore, the sliding which caused the Kalapana earthquake may have occurred in the oceanic sediment layer beneath the volcanic edifice (FURUMOTO and KOVACH, 1979; ANDO, 1979).

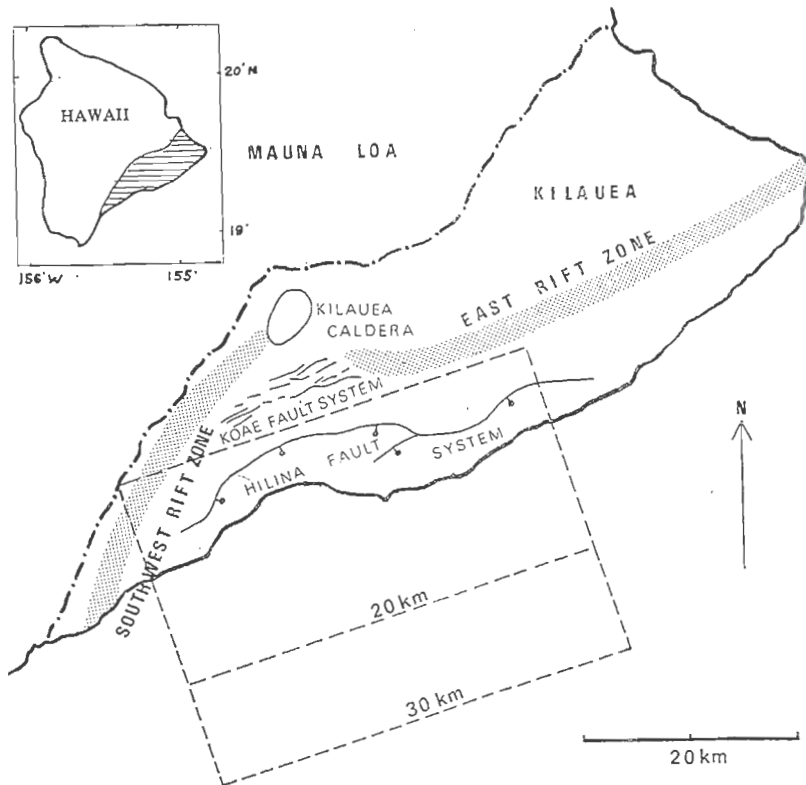


Fig. 4—Simplified map showing the location of east and southwest rift zones, Koae and Hilina fault systems of Kilauea volcano and the nearly horizontal two possible 1975 fault planes (squares). After ANDO (1979).

Moreover, the 1975 Kalapana earthquake had been anticipated by SWANSON et al. (1976) as one of the repeated steps to accommodate the south-southeast contraction of the Hilina

fault zone, which, in turn, had been associated with the south-southeast dilation of the east rift zone and the Koa'e fault system.

After the Kalapana earthquake, the activity of Kilauea volcano appears to be characterized by more frequent intrusive events without surface eruptions, similar to the state of the volcano in the earlier half of this century (SWANSON et al., 1976) which followed the previous Kalapana type earthquake in 1868 (ANDO, 1979). These observations also support the interpretation by SWANSON et al. (1976) and ANDO (1979) that the 1975 Kalapana earthquake was one step of repeated process to accommodate the long continued rift zone dilation.

Thus, the case which has enabled to accommodate the room for repeated dike intrusion into rift zones may be found in the existence of thick enough oceanic sediment beneath the volcanic edifice (NAKAMURA, 1980). The sudden loading of volcanic material over the sediment may produce anomalously high pore pressure which reduces the frictional resistance for the overlying body to slide easily.

DISCUSSION

The thickness of the oceanic sediments beneath the Hawaiian volcanoes may be estimated from the age of the crust at the time of the initiation of the volcanism at the site and from the average rate of accumulation of sediments. Age of the crust in the above sense may be 80 Ma or more in Hawaii (PITMAN et al., 1974). Average rate of accumulation over the crust of present Hawaiian region is estimated at several to 10 mm/ka (LISITZIN, 1972). Then the thickness of sediment layers may be calculated as several hundred meters. Observed thicknesses of sediments are 580 m at DSDP Site 313, 1600 km west of Hawaii (THE SHIPBOARD SCIENTIFIC PARTY, 1975) and 280 m at Site 163, 1200 km southeast of Hawaii (VAN ANDEL et al., 1976).

SYMPOSIUM ON THE ACTIVITY OF OCEANIC VOLCANOES

In the equatorial Galapagos region, accumulation rate attains 35-50 m/Ma (LONSDALE and KLITGORD, 1978). Age of the oceanic crust underlying Galapagos volcanoes is estimated to range one to eight Ma (HEY, 1977). Age of the volcanoes is a few Ma or younger (COX and DALRYMPLE, 1966). Therefore, the period of deep sea sedimentation before the initiation of the volcanic activity may be a few to 5 Ma at most. Thus, the sediments may be well below 250 m in thickness in Galapagos region, less than one half of that of Hawaii.

In addition to the thinner sediment layer in Galapagos, basement topography appears to be unfavorable in Galapagos to form an extensive sliding plane in the sediments. When observed near the triple point between Pacific, Cocos and Nazca plates, the portion of the plates that was formed at the Nazca-Cocos (Galapagos) spreading center is much richer in topographic relief than the Pacific plate (HEY et al., 1977). Northwest of the Galapagos islands, the ocean floor is cut by closely spaced faults with the scarp 10 to 280 m in height averaging 50 m (KLITGORD and MUDIE, 1974).

The comparison of sediment thickness and basement topography also support the present hypothesis that the existence of thick enough sediment layer plays an important role in the formation of long rift zones of Hawaiian volcanoes. If this hypothesis holds in general, it may be expected that rift zones are expected to develop better in Oceanic volcanoes formed on older crust than those formed on younger crust near the spreading centers

CONCLUSION

Hawaiian rift zones may have developed under the gravitationally controlled stress field as FISK and JACKSON indicated. What have kept the gravitational stress field function for a long time during the repeated dike intrusions into the rift zones, may well be the existence of thick enough oceanic sediment beneath the volcanic edifice. Rapid accumulation to form volcanic edifices may have formed anomalously high pore pressure, and thus reducing the frictional resistance for the edifice to slide. Smoother basement topography beneath the sediments may also be a factor to form an extensive sliding plane in the sediments.

ACKNOWLEDGEMENTS

Critical comments to NAKAMURA (1980) by Masanori Sakuyama and Shun'ichiro Karato were helpful and are deeply acknowledged. Interest of Donald A. Swanson and Hans-Ulrich Schmincke to the present study was encouraging. The work was mostly carried out during my 1980 stay in the University of Lille 1 in France (host: Jacques Charvet) and in the Ruhr University of Bochum in Germany (host: Hans-Ulrich Schmincke) supported by the funds of the French Ministry of the Universities and the German Research Association.

REFERENCES

- ANDO, M., 1979 : The Hawaii earthquake of November 29, 1975 : low dip angle faulting due to forceful injection of magma. *J. Geophys. Res.*, 84, p. 7616-7626.
- BJÖRNSSON, A., JOHNSEN, G., SIGURDSSON, S., THORVERGSSON, G., TRYGGVASON, E., 1979 : Rifting of the plate boundary in north Iceland. *J. Geophys. Res.*, 84, p. 3029-3038.
- BRANDSDOTTIR, B. and EINARSSON, P., 1979 : Seismic activity associated with the September 1977 deflation of the Krafla central volcano in NE Iceland. *J. Volcanol. Geotherm. Res.*, 6, p. 197-212.
- BROYLES, M. L., SUYENAGA, W. and FURUMOTO, A. S., 1979 : Structure of the lower east rift zone of Kilauea volcano, Hawaii, from seismic and gravity data. *J. Volcanol. Geotherm. Res.*, 5, p. 317-336.
- COX, A. and DALRYMPLE, G. B., 1966 : Paleomagnetism and potassium-argon ages of some volcanic rocks from the Galapagos Islands. *Nature*, 209, p. 776-777.
- EINARSSON, P., 1978 : S-wave shadows in the Krafla caldera in NE-Iceland, evidence for a magma chamber in the crust. *Bull. Volcanol.*, 41, p. 1-9.
- and BRANDSDOTTIR, B., 1980 : Seismological evidence for lateral magma intrusion during the July 1978 deflation of the Krafla volcano in NE-Iceland. *Jour. Geophys.*, 47, p. 160-165.
- FISKE, R. S. and JACKSON, E. D., 1972 : Orientation and growth of Hawaiian volcanic rifts: the effect of regional structure and gravitational stresses. *Proc. R. Soc. Lond., Ser. A*, 329, p. 299-326.
- FURUMOTO, A. S., 1978 : Nature of the magma conduit under the east rift zone of Kilauea Volcano, Hawaii. *Bull. Volcanol.*, 41, p. 435-453.
- FURUMOTO, A. S. and KOVACH, R. L., 1979 : The Kalapana earthquake of November 29, 1975 : an intraplate earthquake and its relation to geothermal processes. *Phys. Earth Planet. Int.*, 18, p. 197-208.

- HEY, R., 1977 : Tectonic evolution of the Cocos-Nazca spreading center. Geol. Soc. Amer. Bull., 88, p. 1404-1420.
- , JOHNSON, G. L. and LOWRIE, A., 1977 : Recent plate motions in the Galapagos area. Geol. Soc. Amer. Bull., 88, p. 1385-1403.
- HILL, D. P., 1969 : Crustal structure of the island of Hawaii from seismic refraction measurements. Bull. Seismol. Soc. Amer., 59, p. 101-130.
- KINOSHITA, W. T., KRIVOY, H. L., MABEY, D. R. and MACDONALD, G. R., 1963 : Gravity survey of the island of Hawaii. U.S. Geol. Surv. Prof. Pap., 475-C, p. C114-C116.
- KLITGORD, K. D. and MUDIE, J. D., 1974 : The Galapagos spreading center : A near-bottom geophysical survey. Roy Astro. Soc., Geophys. Jour., 38, p. 563-586.
- LARSEN, G., GRÖNVOLD, K. and THORARINSSON, S., 1979 : Volcanic eruption through a geothermal borehole at Namafiall, Iceland. Nature, 278, p. 707-710.
- LISITZIN, A. P., 1972 : Sedimentation in the world ocean. Soc. Econ. Paleont. Mineral., Spec. Publ., 17, 218 pp., Tulsa.
- LONSDALE, P. and KLITGORD, K. D., 1978 : Structure and tectonic history of the eastern Panama Basin. Geol. Soc. Amer. Bull., 89, p. 981-999.
- MACDONALD, G. A., 1956 : The structure of Hawaiian volcanoes. Verh. Koninkl. Nederl. Geol. Mijnb. Geno, 16, p. 274-295.
- , 1972 : Volcanoes, 510 pp., Prentice-Hall, New Jersey.
- MOORE, J. G., 1970 : Relationship between subsidence and volcanic load, Hawaii. Bull. Volcanol., 34, p. 562-576.
- NAKAMURA, K., 1977 : Volcanoes as possible indicators of tectonic stress orientation — principle and proposal. J. Volcanol. Geotherm. Res., 2, p. 1-16.
- , 1980 : Why do long rift zones develop in Hawaiian volcanoes — a possible role of thick oceanic sediments. Bull. Volcanol. Soc. Japan., 25, p. 255-269.

SYMPOSIUM ON THE ACTIVITY OF OCEANIC VOLCANOES

- ODÉ, H., 1957 : Mechanical analysis of the dike pattern of the Spanish Peaks area, Colorado. Bull. Geol. Soc. Amer., 68, p. 567-576.
- PITMAN, W. C., III, LARSON, R. L. and HERRON, E. M., 1974 : Isochron map and age map of ocean basins. Geol. Soc. Amer., Boulder.
- SAEMUNDSSON, K., 1978 : Frissure swarms and central volcanoes of the neovolcanic zones of Iceland. In Crustal evolution in north-western Britain and adjacent regions, p. 415-432.
- SWANSON, D. A., DUFFIELD, W. A. and FISKE, R. S., 1976 : Displacement of the South flank of Kilauea volcano : The result of forceful intrusion of magma into rift zones. U.S. Geol. Surv. Prof. Pap., 963, 39 pp.
- THE SHIPBOARD SCIENTIFIC PARTY, 1975 : Site 313 : Mid Pacific mountains. Initial Rept. of the DSDP, 32, p. 313-390.
- TRYGGVASON, E., 1980 : Subsidence events in the Krafla area, north Iceland, 1975-1979. J. Geophys., 47, p. 141-153.
- VAN ANDEL, T. H., HEATH, G. R. and MOORE, T. C. JR., 1976 : Cenozoic history of the central equatorial Pacific : A synthesis baser on Deep Sea Drilling Project Data. A.G.U. Geophys. Monogr., 19, p. 281-295.
- WILLIAMS, H. and MCBIRNEY, A. R., 1979 : Volcanology. Freeman and Cooper, San Francisco, 397 pp.
- WYSS, M., 1980 : Hawaiian rifts and recent Icelandic volcanism : expression of plume generated radial stress fields. J. Geophys., 47, p. 19-22.
- ZABLOCKI, C. L., TILLING, R. I., PETERSON, D. W., KELLER, G. W. and MURRAY, J. C., 1974 : A deep research drill hole at the summit of active volcano, Kilauea, Hawaii, Geophys. Res. Lett., 1, p. 323-326.