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VOLCANOES AS POSSIBLE INDICATORS OF TECTONIC STRESS ORIENTATION — PRINCIPLE AND PROPOSAL[1]

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ABSTRACT

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A method is proposed for determining the orientation of average tectonic stress, using surface features indicating radial dike patterns of volcanoes. The approximate pattern of radial dikes is revealed by the distribution of sites of flank eruptions on the slope of polygenetic volcanoes. This conclusion is deduced from the understanding that flank eruptions are caused by the magma that laterally offshoots from the main polygenetic pipe conduit and that conduits of flank volcanoes are most probably fissure-shaped because most of them are monogenetic volcanoes. Radial dikes are more likely to develop in a direction normal to the minimum horizontal compression of the regional stress. Thus, the distribution of flank craters will be elongate in the direction of the maximum horizontal compression of the regional stress.

The regional stress can sometimes be ascribed solely to the effect of the gravity rather than tectonic stress. When a number of independent polygenetic volcanoes dotted with more than several flank volcanoes, are distributed in a belt or over a broad area, it is possible to distinguish the tectonic stress from the direct gravitational effect by the regional uniformity in orientation of the zones of flank volcanoes. When the maximum compression of tectonic stress is horizontal, the trends of the zones of flank eruptions on polygenetic volcanoes are more or less linear and parallel, and at a high angle to the trend of the main volcanic belt.

INTRODUCTION

Volcanic processes which cause extensive fracturing of rocks must be related to regional non-magmatic stress acting on the volcanic region. One such process involving fracturing is flank volcanic eruptions which are reasonably explained as surface manifestations of the formation of radial dikes. Because the orien-

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tation of dikes is affected by the existing regional stress, the distribution of sites of flank eruptions may reveal the orientation of regional stresses, in addition to the stress generated by magmatic forces. In other words, flank eruptions of polygenetic volcanoes may be regarded as large-scale repeated experiments of hydraulic fracturing using magma instead of water.

This paper is concerned with such a feature of radial dikes, as indicated mainly by flank crater distribution, and proposes to make use of this distribution as an indicator for the average orientation of tectonic stress which has prevailed in the upper crust of the volcanic area.

MONOGENETIC AND POLYGENETIC VOLCANOES

Volcanoes may be classified as either monogenetic or polygenetic, based on the number of eruptions which formed the volcanic edifices (Thorarinsson, 1960; Rittmann, 1962).

A monogenetic volcano erupts only once from a vent or a fissure and constructs a relatively small volcanic edifice such as a maar, a scoria cone, a lava dome or a shield volcano of Icelandic type. Most fissure volcanoes are monogenetic. Some monogenetic volcanoes are compound volcanoes, such as a scoria cone in a maar or a lava dome in a pyroclastic cone. They are the result of a change of the external circumference during the course of the eruption. A monogenetic volcano erupts only once and, therefore, its underground conduit is newly formed every time it erupts. Common occurrence of xenoliths in the eruptive products of monogenetic volcanoes may be related to this characteristics of their conduits.

The initial channelway for the ascent of the magma is expected to be a fissure and not a cylinder. Therefore, the conduit of a monogenetic volcano may be fissured-shaped in its essential portion, but not pipe-shaped. At a shallower depth, however, the conduits of monogenetic volcanoes may converge to form pipes, e.g. kimberlite pipes, many of which grade downward into dikes (Dawson, 1967). Monogenetic volcanoes commonly occur in groups, either as independent swarms like Westeifel maars and scoria cones, or as a part of a polygenetic volcano where they form flank volcanoes and post-caldera cones.

Polygenetic volcanoes, on the other hand, erupt repeatedly or roughly periodically from the same general vent or vents during a life-time of up to about 10^5 years. Composite volcanoes and shield volcanoes of the Hawaiian type are the best known examples of polygenetic volcanoes. They form large volcanic edifices of the order of 10^2 km^3 (composite volcanoes) and 10^4 km^3 (shield volcanoes of the Hawaiian type) in volume, are more or less conical in shape with a summit or central crater or craters. Repeated eruptions from the same vent may form a cone around the vent as well as a pipe-shaped vertical conduit which is stable enough to be continually used as the channelway for the ascending magma.

MECHANISM OF FLANK ERUPTIONS

Most flank volcanoes are monogenetic (e.g. Nakamura, 1961). Not only flank-fissure eruptions but flank eruptions in general are regarded as surface manifestations of the formation of radial dikes around the vertical, central pipe-conduit of a polygenetic volcano. This interpretation appears well established for shield volcanoes of Hawaiian type (e.g. Macdonald, 1972). What is suggested here is that essentially the same interpretation may apply to composite volcanoes.

Flank eruptions of composite volcanoes may be interpreted in the following way: prior to the eruption, magmatic pressure in the central conduit increases to the sum of both the tensile strength of the surrounding rocks and the minimum compressional stress of external origin. If the magmatic pressure is not sufficiently relieved by an eruption from the summit, a radial vertical fracture develops laterally from the central pipe and is simultaneously filled with the source magma. Here the initiation of a radial dike resembles the opening of a hydraulic fracture (Haimson, 1975). Flank eruptions occur where the dike first reaches the surface. If the available magma is of sufficient quantity and its viscosity is low enough, then the dike arrives at the surface causing a flank-fissure eruption.

This interpretation of the flank eruptions of composite volcanoes is supported by the following examples and the conclusion that composite volcanoes have stable central pipe conduits, while monogenetic volcanoes (therefore most flank volcanoes) erupt from newly made fissures.

(1) Flank eruptions are often accompanied or immediately preceded by summit eruptions. Explosive eruptions are more common from summit craters and effusive eruptions are more common from flank craters (Vesuvius, 1906, Perret, 1924; Miyake-sima, 1940, Tsuya, 1941; Etna, Rittmann, 1964).

(2) In the case of flank-fissure eruptions, the eruptive fissure usually grows down-slope and the eruptive activity endures longer at the lower portion of the fissure, erupting lava flows (Vesuvius, 1906, Perret, 1924; Hekla, 1947-48, Thorarinsson, 1950).

(3) Some flank eruptions occur simultaneously at two opposite sides on the slope, their location being symmetrical with respect to the summit (Sakura-jima, 1914, Omori, 1914—1916; Hekla, 1970, Thorarinsson and Sigvaldason, 1972; Villarrica, 1971, González, 1972; Tiatia, 1973, Doubik, personal communication, 1974).

(4) Flank volcanoes are more numerous when the magma has a low viscosity and the summit is higher (Etna volcano and Fuji volcano).

(5) The vertical crustal deformation associated with a flank (fissure) eruption is fundamentally concentric around the summit but not around the eruption site. The residual horizontal deformation is dilatational across the eruptive fissure (Sakura-jima, 1914, Omori, 1914—1916; Miyake-sima, 1940, Earthquake Research Institute, 1941; 1962, Geographical Survey Institute, 1976).

(6) A central plutonic mass and radial dike swarm are a common association found in dissected volcanic fields (Spanish Peaks, Knopf, 1936; Summer Coon volcano, Lipman, 1968).

(7) According to field observations on the lateral surface of the dikes, intrusion of magma into radial dikes proceeds outward from the center and more or less obliquely upward (Oshima, 1968; Nakamura, 1972).

From the foregoing facts and considerations, it is concluded that the distribution of flank craters on the slopes of a polygenetic volcano reveals the underground pattern of radial dikes.

RADIAL DIKES AND STRESS FIELDS

Radial dikes which are ideally radial and uniform in azimuth (Fig.1A), may show either that the magmatic pressure within the central conduit was predominant over other stresses or that they did not differ in horizontal direction. This kind of radial dike pattern seems to be more or less realized in near-vent areas, within a radius of a few kilometers, even though the overall pattern may not be ideally radial.

On the other hand, as shown in Fig.1B, at a sufficient distance from the central conduit, radial dikes sometimes tend to curve and assume a single general trend. Radial dikes surrounding the Spanish Peaks (Knopf, 1936), for example, are a classic example. The pattern of radial dikes in this area was controlled, according to the interpretation by Odé (1957), by the superposed stress systems of localized magmatic pressure around the West Spanish Peak and by a genetically independent regional stress. The plutonic mass of the West Spanish Peak is also elongated in the direction of the concentration of radial dikes. This implies that the process responsible for formation of the central conduit was also affected by the same regional stress that distorted the radial dike pattern.

The radial dike pattern indicated by the distribution of flank and post-caldera cones and craters (Fig.2) may well be the same as the case in Fig.1B in

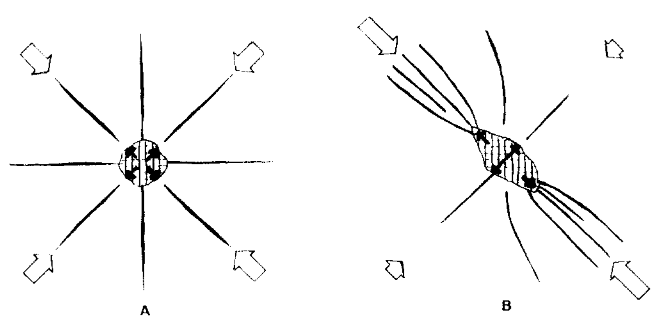


Fig.1. Idealized horizontal cross-section of a conduit of a polygenetic volcano (central plutonic mass) and radial dikes (Nakamura, 1969). A. Perfectly radial dikes under uniform stress. B. Deformed radial dikes under a differential horizontal stress.

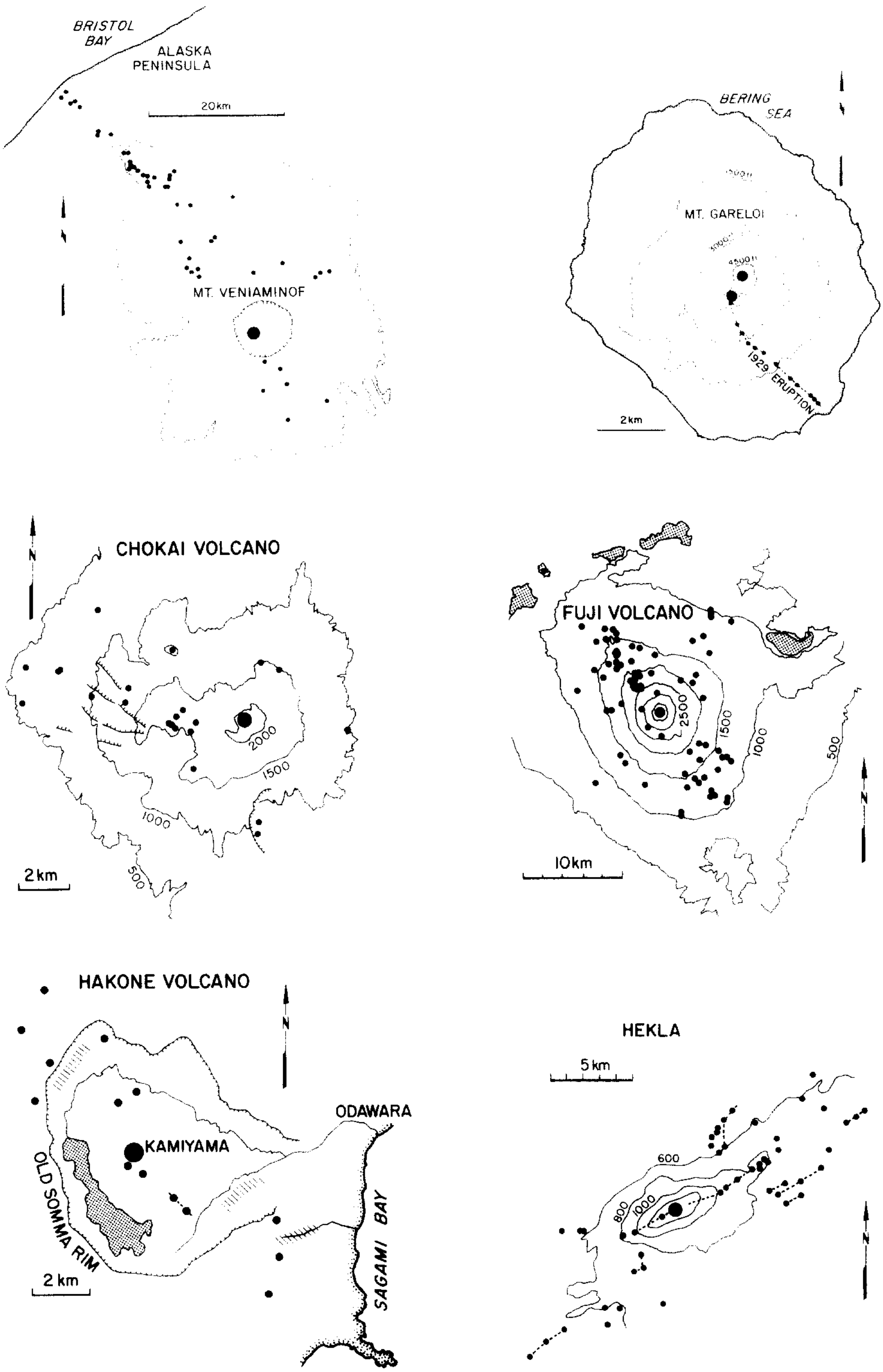
that radial dikes are formed more frequently and extend longer in a certain preferred direction. Whatever the ultimate origin may be, the significant deviation from the radiality of the dike pattern implies that the regional stress, which is independent in origin of the localized pressure of the magma in the conduit, may have influenced the pattern. In Fig.3, the structure of a polygenetic volcano with flank volcanoes under such a condition is shown in a simplified manner.

DISTINCTION BETWEEN TECTONIC STRESS AND GRAVITATIONAL FORCE

Because the stress in the horizontal plane due to gravity alone is expected to be the same in magnitude under normal conditions, the effect of gravity would usually not be part of the present problem. Under certain conditions where volcanoes lie on a tilted surface, however, a differential stress in the horizontal plane could be produced by gravitational force. Therefore, regional stress independent of local magma pressure could be the direct effect of gravitational force as well as tectonic force. Indeed, Fiske and Jackson (1972) showed that the stress caused by topographic response to gravitational force controlled the radial dike pattern of Hawaiian volcanoes. They demonstrated that when a shield volcano grows on the slope of an adjacent shield, gravity produces a tensional stress in the overlying volcanic structure in the direction of the inclination of the basal surface. This tensional stress controls the trend of radial dikes or rift zones.

If the regional stress that caused deviation to the radiality of dikes is exerted mainly by gravitational force, as it is in clustered Hawaiian shields, the following two features may be expected. First, the trend of the whole zone of flank eruptions could be curved following the underlying relief. This is the case for Hawaiian clustered volcanoes, but not for examples shown in Fig.2, in which the zones of flank-eruption sites are more or less linear. Secondly, when the trend of the zone of flank eruptions is linear, it could be variable without any common trend in neighboring volcanoes. This also is the case for Hawaiian clustered volcanoes. Therefore, when a volcano or a group of volcanoes does not bear the above two features, an interpretation, other than the gravitational effect, should be sought for the distribution of the flank-eruption site.

If the sites of flank eruptions form a linear zone passing through the summit and the trends of the zones are common or change gradually among adjacent volcanoes, then the fundamental origin of the stress which governs the trend of the zones would most probably be ascribed to a tectonic stress that dominates the entire area. Volcanoes of the southern part of the central Chilean Andes (Fig.4), those in Japan (Fig.5), Central America, and the Aleutians may be examples. In Central America and in the Aleutians, more than fifteen composite volcanoes, distributed in volcanic belts extending some 1100 km and 2000 km, respectively, have more or less linear flank volcano zones trending approximately in a north-south direction in Central America (Williams et al., 1964; McBirney and Williams, 1965; Ui, 1972a; Stoiber and Carr, 1973) and


BRISTOL BAY
ALASKA PENINSULA
20km
MT. VENIAMINOF
BERING SEA
MT. GARELOI
1929 ERUPTION
2km
CHOKAI VOLCANO
2000
1500
1000
500
2 km
FUJI VOLCANO
2500
1500
1000
500
10km
HAKONE VOLCANO
KAMIYAMA
OLD SOMMA RIM
ODAWARA
SAGAMI BAY
2 km
HEKLA
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600
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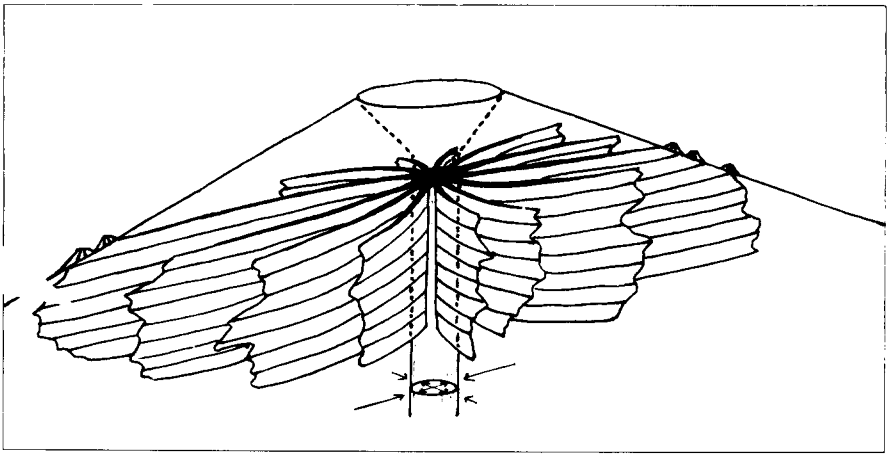

Fig.3. Diagram showing the radial dikes and flank volcanoes of a polygenetic volcano under a differential horizontal stress. The zone of flank volcanoes corresponds to the trend of radial dike concentration; hence to the trend of maximum compression of the horizontal component of the ambient stress. (After Nakamura, 1976.)

in a northwest direction in the Aleutians (Nakamura et al., 1977). Therefore, the east-northeast direction in Chile, the general west-northeast direction in Japan, the northwest direction in the Aleutian arc and Alaska Peninsula, and north-south direction in Central America are regarded as directions of the maximum horizontal compression of the tectonic stress in the respective regions.

The above conclusion is further supported when the trends of zones of flank-eruption sites coincide with the maximum compressional axis of tectonic stress in the same general area as derived from studies of active faults and focal mechanism solutions of very shallow earthquakes. This is also the case for Japan (Ichikawa, 1971; Matsuda et al., 1976).

CONTRACTIONAL OR EXTENSIONAL TECTONIC STRESS FIELD

Dikes are characteristically vertical in cross-section and develop more or less parallel to a plane defined by the maximum and the intermediate principal stress axes. On the other hand, at the earth's surface one of the principal stress axes should be vertical, since the air is incapable of sustaining a shearing stress

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Fig.2. Distribution of flank and post-caldera volcanoes on the slope and inside the caldera of composite volcanoes. Larger dots: summit or central craters. Smaller dots: eruption sites on the flank and inside the caldera. Broken lines: eruption fissures. Stippled area: lake. Height in meters unless otherwise indicated. Mt. Veniaminof, Alaska (56° 10'N, 159° 23'W) (Burk, 1965). Mt. Gareloi, Aleutian Islands (51° 48'N, 178°48'W) (Coats, 1959). Chokai volcano, Japan (39° 05'N, 140°02'E) (Ui, 1972b). Fuji volcano, Japan (35°21'N, 138°44'E) (Tsuya, 1943). Hakone volcano, Japan (35°13'N, 139°01'E). Ruled areas are the zones of exposed radial dike swarm (Kuno, 1950; Nakamura, 1969). Hekla volcano, Iceland (64° N, 19°41'W) (Thorarinsson, 1967; Thorarinsson and Sigvaldason, 1972).

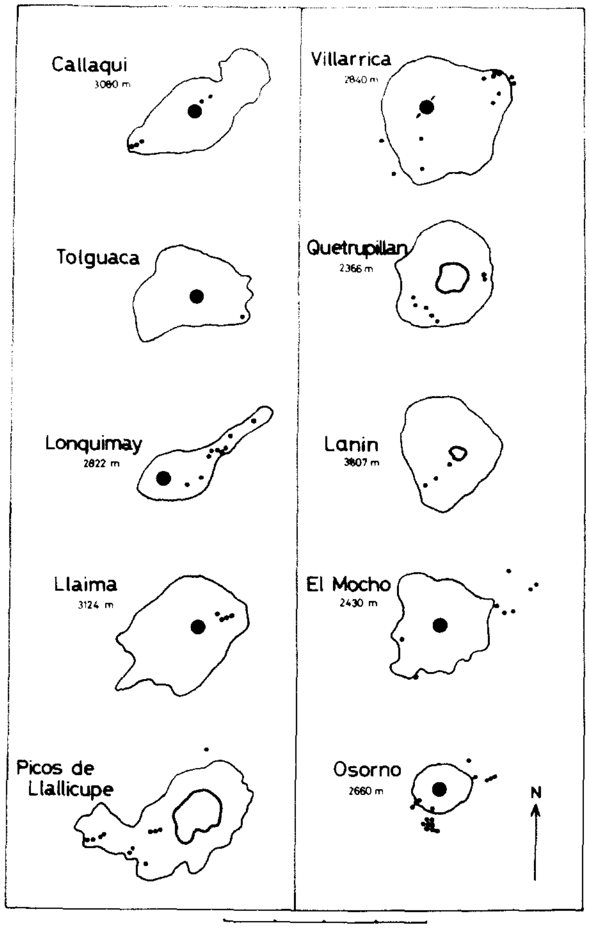

Fig.4. Flank crater distribution of volcanoes of the Chilean Andes between 37.5°S ~ 41.5°S mapped from vertical aerial photographs, 1: 40,000 in scale. Outlines of individual volcanoes are represented by snow-lines. Symbols same as in Fig.2, except that outlines of calderas are drawn instead of summit craters for Picos de Llallicupe, Quetrupillan and Lanin. For most of the volcanoes, flank eruption sites are apparently concentrated in a zone trending N65°E to S65°W ± 10°. This suggests that the trend is that of the maximum horizontal compression of the tectonic stress.

(Hafner, 1951). Two other axes should be horizontal. This condition appears to be maintained in the upper crust. For example, in Japan where the stress field is expected to suffer much tectonic disturbance, vertical null axes of the focal mechanism solutions were obtained for 98.2% (331 out of 337) of the earthquakes that occurred at or less than 20 km for the period 1926–1968 (Ichikawa, 1971).

Assuming therefore, that one of the principal axes is vertical, then the trend of the zone of flank eruption, that is the trend of the radial dike concentration, may be either the direction of the maximum compressional or intermediate

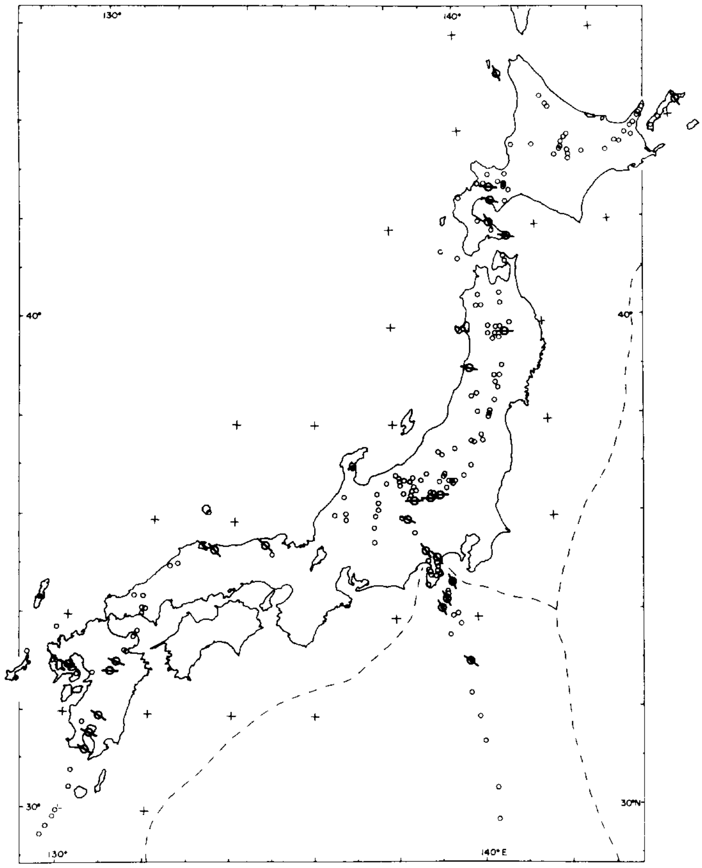

Fig. 5. Possible trend of concentration of radial dikes of Japanese volcanoes. Bar on a circle shows trend of the longer axis of the distribution of monogenetic volcanoes, post-caldera cones and independent clusters of monogenetic volcanoes. Smaller circles: Quaternary polygenetic volcanoes (Isshiki et al., 1968), which have neither more than a few flank volcanoes nor show linear or elongate patterns in the distribution of monogenetic volcanoes. Broken line: trench axis. (Nakamura, 1975.)

principal stress axes. These two cases would correspond to contractional and extensional tectonics, respectively.

A distinction between the two cases is possible from the sense of displacement of active faults in the same general area. (The term active faults is defined here as the faults that have moved repeatedly in recent geologic time, so that either they are recognized by having fault scarps or they have displaced Quaternary formations.) In areas of a contraction tectonic regime, active faults are either strike-slip and/or thrust faults and the trend of the flank crater zones should be oblique at around 45° to the strike-slip or perpendicular to the thrust faults. This is the case for most of Japan, as mentioned earlier. The Andean case is also expected to be the same, considering the long north-south-trending, dextral Atacama fault and associated conjugate faults in northern Chile (St. Amand and Allen, 1960; Okada, 1971), and a large-scale en echelon tectonic relief that suggest northeast contraction of the southern Andes (Kaizuka, 1975). In the extensional area, on the other hand, normal faults with a trend parallel to the zone of flank craters will develop as, for example, in Iceland.

There is a possibility that the two cases can be distinguished, in other words, three principal axes of tectonic stress can be determined by a certain simple geographical relation without the help of active faults or earthquake mechanism solutions. Composite volcanoes commonly define linear or curvilinear volcanic belts. From the synthesis of available data for Japan (Fig.5), south central Andes (Fig.4), the Aleutians and Central America, the angular relation between the trends of the volcanic belt and zones of flank craters appears to be different for different tectonic stress conditions. This relation is shown diagrammatically in Fig.6. In a contractional tectonic area where the maximum compressional stress is horizontal, the two trends tend to form an angle, typically a high angle, with each other (Fig.6B). In an extensional tectonic area where the maximum compressional stress is vertical, the two tend to be more or less parallel (Fig.6A).

The above angular relation would be explained as follows. Contemporary volcanic belts are mostly classified into two major categories: (1) volcanic belts of accreting plate boundaries, and (2) those associated with the converging boundaries of lithospheric plates. These correspond to volcanic belts under extensional and contractional tectonics, respectively. The trends of the extensional volcanic belts tend to become perpendicular to the separating plate motions, which exert tensional stress on the volcanic belts. Zones of flank

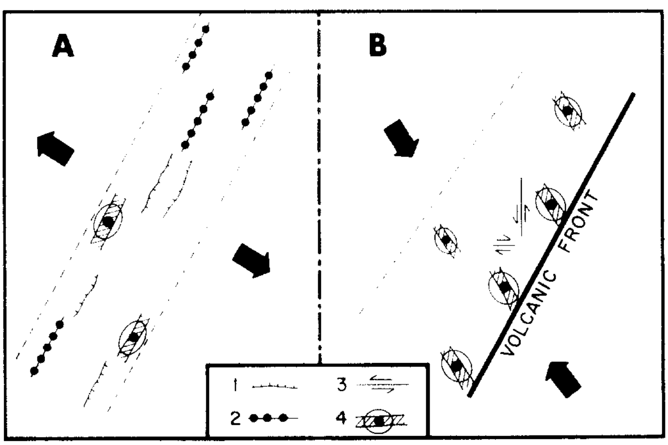

Fig.6. The angular relationship between the trends of a volcanic belt and zones of flank craters. A and B are idealized situations under extensional and contractional tectonic stress fields. A pair of solid arrows indicates the tensional stress (A) and the compressional stress (B) exerted on the volcanic belt. 1 = a normal fault; 2 = a fissure of regional fissure eruption; 3 = a strike-slip fault; 4 = a polygenetic volcano with a summit crater (dot) and a linear zone of flank eruptions (ruled area). (After Nakamura, 1974.)

craters also develop perpendicular to the tensional stress, and thus parallel to the volcanic belt. The volcanic belts in contractional tectonic areas extend parallel to the converging plate boundaries making an angle with the direction of relative convergence. Because the converging direction would be nearly parallel to the axis of the maximum compressional stress in the volcanic belt, and because the zone of flank eruptions develops in this compressional direction, an angular relationship results between the volcanic belt and zones of flank craters of individual composite volcanoes.

DISCUSSION

Weak zones vs. tectonic stress

When flank volcanoes on the slopes of polygenetic volcanoes are concentrated in a linear zone, this has been explained traditionally as indicative of the existence of "weak zones". Even if this is true, there still remains a question of why the weak zones of particular direction served as channelways for magma intrusion. Considering that the dikes were once filled with liquid magma, the magma pressure would have been equal to or larger than the ambient stress normal to the dikes, regardless of their origin whether they are new fissures or old ones. Because the tensile strength of the surrounding rocks, which must be very small due to high temperature, was effective only at the time of initial opening of the dike space, the ambient stress normal to the overall trend of the dike would be expected very close to the direction of the minimum compressional stress. Thus, I ascribe the linear distribution of monogenetic volcanoes to the presence of a regional stress.

Other features suggesting the trend of dike concentration

The channelway used by magma would have a range of azimuthal distribution around the summit crater. This is due to the effect of the mechanical heterogeneity of the surrounding rocks and possibly the temporal change of the regional stress. Thus, the actual azimuthal distribution of flank craters (i.e. radial dikes) would scatter around the average trend of the maximum horizontal compression of the regional stress. Hence, more than a few flank craters are needed to obtain a reliable direction for this stress component. This means that volcanoes of fluid magma are more suitable for this kind of study, as flank eruptions are more likely to occur when the viscosity of the magma is lower.

In this context, a significant feature would be the bending of radial fissures, an example of which is shown in Fig.2. At Mt. Gareloi the fissure starts radially southward from the summit area and bends with increasing distance from the summit. This new direction which is assumed to be asymptotic to the fissure, would be best explained as the direction of the maximum horizontal compression of the regional stress, as suggested by Coats (1959). This specific example becomes more convincing, since the zones of flank craters on adjacent volcanoes assume similar trends (Nakamura et al., 1977). A similar bending phenomenon is also observed on Etna volcano. Here, lateral eruptive centers and eruptive radial fissures (Rittmann, 1964) bend and converge asymptotically in a NNE-SSW direction. The NNE trend may be the direction of the intermediate principal stress axis, but not of the maximum of the regional stress, if one takes into account the long normal fault that may extend in the same direction along the northeast coast of Sicily (W. Alvarez, personal communication, 1976).

Contour lines of the main volcanic edifices themselves may be elongate in the same direction, provided the volume of the material erupted from the flank craters is large. All of the volcanoes in Fig.2 possess this feature. This feature of polygenetic volcanoes may also be used as an auxiliary means in ascertaining the direction of radial dike concentration.

Active normal faults sometimes develop almost exclusively within the volcanic structure or field, in the form of a parallel swarm. Examples of these are: Chokai volcano (Fig.2), Buldir volcano, Aleutian Islands (Coates, 1953) and Cerro Panalvia, southeast Guatemala (Williams et al., 1964). These kinds of normal faults would be best explained either as the surface expression of the dikes that did not reach the surface, or as the result of a local concentration of the regional stress. These normal faults could also be used as an auxiliary method for obtaining the trend of the radial dikes.

Volcanoes under contractional vs. extensional tectonics

Certain features of volcanoes are different under different tectonic conditions. Using their synthesis of chemical and age data of Cenozoic volcanic rocks of the western United States, Christiansen and Lipman (1972) and Lipman et al. (1972) showed that "fundamentally andesitic" and "fundamentally basaltic" volcanisms correlated both in time and space with the contractional and extensional tectonic styles, respectively. As they suggested, this general correlation between the chemistry of magma and tectonic styles appears to hold true for other volcanic regions of the world. This petrographic characteristic may be used as an additional key to the distinction between tectonic styles, but not as a conclusive one. This is because: (1) a physical understanding of the correlation has not been fully established, (2) there are problems concerning the recognition of magma types, and (3) the correlation applies for a group of volcanoes as a whole and not for individual volcanoes.

Another possible correlation seems to exist between the tectonic styles and types of volcanoes, i.e. monogenetic and polygenetic volcanoes. To cite rather well documented facts, (1) volcanic belts associated with converging plate boundaries, therefore supposedly under contractional tectonics, are characterized by isolated andesitic polygenetic volcanoes, especially composite ones, and (2) volcanic fields of alkali basalts and bimodal magmatism, which belong to the category "fundamentally basaltic" of Christiansen and Lipman (1972), consist commonly of clusters of monogenetic volcanoes, occurring mainly in back-arc and in continental regions. They are generally thought to have been erupted under extensional tectonics, as indicated by their frequent association with normal faulting. This correlation may partly be explained in the following way. For extensional tectonics, making a new channel for the eruption of a monogenetic volcano is mechanically much easier. For contractional tectonics, however, magma is able to rise only through an already established conduit. This correlation, however, applies to a volcanic zone or field as a whole. Composite volcanoes like Hekla occur in the Icelandic volcanic zone where active tensional tectonics are taking place. Clusters of monogenetic volcanoes, which are independent of polygenetic volcanoes, do occur in Japan, although on a smaller scale, where thrust and strike-slip faulting predominate. Therefore, this correlation could also be used as an assistance but not for distinguishing tectonic styles.

Stress orientation averaged in time

There are other well-known methods to estimate the orientation of the crustal stress. Among them are earthquake mechanism studies and in-situ stress measurements for current conditions, and studies of faults, folds, and stylolites for the past. The dike method proposed in the present paper relies on the mechanism of large-scale, deep-reaching hydraulic fracturing repeated over a long period. Hence, the orientation obtained is an averaged one for the period, say some 10,000 years, which is an important part of the life-time of a polygenetic volcano.

In this respect, the dike method is similar to the one using active faults which have been displaced repeatedly. In the older ages, however, dating of the stress field is much easier with the dike method than with that of the fault method, at least in principle. Large-scale folds could also be used to reconstruct the direction of past tectonic stress. This is, however, less reliable because gravity as well as tectonic stress can form the fold structure, at least in some cases.

It is obvious, that all available methods should be used complimentarily to obtain a comprehensive picture of the tectonic stress orientation in space and in time.

CONCLUSION

(1) Volcanoes are classified as either monogenetic or polygenetic. The feeders of monogenetic volcanoes, which include most flank and post-caldera volcanoes, are essentially dikes, while those of polygenetic volcanoes are pipes.

(2) Flank eruptions are a manifestation of formation of radial dikes underground, as indicated by the observations of actual flank eruptions and interpretation of volcanic structures. It is possible, therefore, to depict radial dike patterns from the distribution of vents on the slope of polygenetic volcanoes.

(3) The pattern of radial dikes reflects the effect of regional non-magmatic

stress system superposed on the magmatic pressure. The trends of dikes (i.e. the trend of the flank crater distribution) may concentrate in a direction of either the maximum compressional or the intermediate stress axis of the regional stress field, or collectively, in a direction normal to the minimum compressional axis.

(4) Some features other than flank craters may be used as an auxiliary means to reveal the trend of the concentration of radial dikes. These features are the bending of radial fissures, elongation of the main volcanic edifices and the swarm of parallel normal faults within the edifices.

(5) The regional stress could be considered a tectonic stress when the trends of dike concentration are linear in individual volcanoes and are, at the same time, common or change gradually among adjacent volcanoes.

(6) Whether the trend of radial dike concentration indicates maximum compressional or intermediate stress axis could be determined by the angular relation between the trends of volcanic belts and of the concentration of dikes, as well as by the sense of displacement of contemporaneous faults. Characteristics of the chemistry of magma and type of volcanoes in the volcanic belt or field may be used as auxiliary means for the same discrimination.

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REFERENCES

Burk, C.A., 1965. Geologic map of Alaska Peninsula. Geol. Soc. Am. Mem., 99, part 2, sheet 1.

Christiansen, R.L. and Lipman, P.W., 1972. Cenozoic volcanism and plate-tectonic evolution of the western United States, II. Late Cenozoic. Philos. Trans. R. Soc. Lond., Ser. A, 271: 217—248.

Coats, R.R., 1953. Geology of Buldir Island, Aleutian Islands, Alaska. U.S. Geol. Surv. Bull., 989-A: 8—9.

Coats, R.R., 1959. Geologic reconnaissance of Gareloi Island, Aleutian Islands, Alaska. U.S. Geol. Surv. Bull., 1028-J: 249—256.

Dawson, J.B., 1967. A review of the geology of Kimberlite. In: P.J. Wyllie (Editor), Ultramafic and Related Rocks. Wiley, New York, N.Y., pp. 241—251.

Earthquake Research Institute, 1941. Results of re-triangulation in Miyake-sima. Bull. Earthq. Res. Inst., 19: 544—547.

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: 299—326.

Geographical Survey Institute, 1976. Crustal deformation of Miyake-sima. Rep. Coord. Comm. Predict. Volcan. Erupt., 5: 29—32 (in Japanese).

González, F.O., 1972. Villarrica volcanic eruption, 1971. In: 1971 Annu. Rep. Center for Short-lived Phenomena, pp. 134—138.

Hafner, W., 1951. Stress distribution and faulting. Bull. Geol. Soc. Am., 62: 373—398.

Haimson, B.C., 1975. Deep in-situ stress measurements by hydrofracturing. Tectonophysics, 29: 41—47.

Ichikawa, M., 1971. Reanalysis of mechanism of earthquakes occurred in and near Japan and statistical studies on the nodal plane solutions obtained, 1926—1968, Geophys. Mag., 35: 207—274.

Isshiki, N., Matsui, K. and Ono, K., 1968. Volcanoes of Japan (1: 2,000,000 map). Geologial Survey of Japan, Tokyo.

Kaizuka, S., 1975. A tectonic model for the morphology of arc-trench systems, especially for the echelon ridges and mid-arc faults. Jpn. J. Geol. Geogr., 45: 9—28.

Knopf, A., 1936. Igneous geology of the Spanish Peaks region, Colorado. Bull. Geol. Soc. Am., 47: 1727—1784.

Kuno, H., 1950. Geology of Hakone Volcano and adjacent areas, 1. J. Fac. Sci., Univ. Tokyo, 7: 351—402.

Lipman, P.W., 1968. Geology of Summer Coon volcanic center, eastern San Juan mountains, Colorado. Q. Colo, Sch. Mines, 63: 211—236.

Lipman, P.W., Prostka, H.J. and Christiansen, R.L., 1972. Cenozoic volcanism and plate-tectonic evolution of the Western United States, I. Early and middle Cenozoic. Philos. Trans. R. Soc. Lond., Ser. A, 271: 211—248.

Macdonald, G.A., 1972. Volcanoes. Prentice-Hall, Englewood Cliffs, N.J., 510 pp.

Matsuda, T., Okada, A. and Huzita, K., 1976. Distribution map and catalogue of active faults in Japan. Mem. Geol. Soc. Jpn., 12: 185—198.

McBirney, A.R and Williams, H., 1965. Volcanic history of Nicaragua. Univ. Calif. Publ. Geol. Sci., 55: 1—65.

Nakamura, K., 1961. Stratigraphic studies of the pyroclastics of Oshima volcano, Izu, deposited during the last fifteen centuries, II. Activity of parasitic volcanoes. Sci. Pap. Coll. Gen. Educ., Univ. Tokyo, 11: 281—319.

Nakamura, K., 1969. Arrangement of parasitic cones as a possible key to regional stress field. Bull. Volcanol. Soc. Jpn., 14: 8—20 (in Japanese with English abstract).

Nakamura, K., 1972. Intrusion vectors of dike magma, its field criteria (abstract). Bull. Volcanol. Soc. Jpn., 17: 115 (in Japanese).

Nakamura, K., 1974. Volcanic alignments and their mechanism. Chidanken Sempo, 18: 75—81 (in Japanese with English abstract).

Nakamura, K., 1975. Volcano structure and possible mechanical correlation between volcanic eruptions and earthquakes. Bull. Volcanol. Soc. Jpn., 20: 229—240 (in Japanese with English abstract).

Nakamura, K., 1976. Volcano as a possible indicator of tectonic stress field. In: Volcanism of the Island Arcs, 1. Nauka, Moscow, in press (in Russian).

Nakamura, K., Jacob, K. and Davies, J., 1977. Volcanoes as possible indicators of tectonic stress orientation — the Aleutians and Alaska. Tectonophysics, in press.

Odé, H., 1957. Mechanical analysis of the dike pattern of the Spanish Peaks area, Colorado. Bull. Geol. Soc. Am., 68: 567—576.

Okada, A., 1971. On the neotectonics of the Atacama fault zone region — preliminary notes on late Cenozoic faulting and geomorphic development of the coast range of northern Chile. Bull. Dept. Geogr. Univ. Tokyo, 3: 47—65.

Omori, R., 1914—1916. The Sakura-jima eruptions and earthquakes, I—III. Bull. Imp. Earthq. Invest. Comm., 8: 1—332.

Oshima, O., 1968. Geology of Haruna volcano. Master thesis, Univ. of Tokyo, Tokyo.
Perret, F.A., 1924. The Vesuvius eruption of 1906. Carnegie Inst. Wash. Publ., 339, 151 pp.
Rittmann, A., 1962. Volcanoes and Their Activity. Interscience Publishers, New York, N.Y. 305 pp.
Rittmann, A., 1964. Vulkanisms und Tektonik des Ȧtna. Geol. Rundsch., 35: 788—800.
St. Amand, P. and Allen, C.R., 1960. Strike-slip faulting in northern Chile. Bull. Geol. Soc. Am. 71: 1965.
Stoiber, R.E. and Carr, M.J., 1973. Quaternary volcanic and tectonic segmentation of central America. Bull. Volcanol., 37: 304—325.
Thorarinsson, S., 1950. The eruption of Mt. Hekla. Bull. Volcanol., 10: 157—168.
Thorarinsson, S., 1960. The postglacial volcanism. Mus. Nat. Hist., Reykjavĩk, Misc. Pap., 25: 33—45.
Thorarinsson, S., 1967. The eruptions of Hekla in historical times. In: The Eruption of Hekla 1947—1948, I. Soc. Sci. Icelandica, Reykjavĩk, pp. 1—170.
Thorarinsson, S. and Sigvaldason, G.E., 1972. The Hekla eruption of 1970. Bull. Volcanol., 36: 269—288.
Tsuya, H., 1941. The eruption of Miyake-sima, one of the seven Izu Islands, I. Geological observations of the Miyake-sima eruption of 1940 (I), (II). Bull. Earthq. Res. Inst., 19: 163—294, 492—522.
Tsuya, H., 1943. Geological and petrological studies of volcano Huzi (Fuji), IV. Structure and distribution of parasitic volcanoes. Bull. Earthq. Res. Inst., 21: 376—393.
Ui, T., 1972a. Recent volcanism in Masaya-Granada Area, Nicaragua. Bull. Volcanol., 36: 174—190.
Ui, T., 1972b. Fault scarps on the slope of the Chokai volcano and genesis of pyroclastic rocks distributed in the skirt. In: Chokai-san-Tobishima. Yamagata Pref., pp. 8—14.
Williams, H., McBirney, A.R. and Dengo. G., 1964. Geologic reconnaissance of south eastern Guatemala. Univ. Calif. Publ. Geol. Sci., 50: 1—56.