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Volcanic Lineaments in the Indonesian Island Arcs *

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Abstract

More than four hundred linear arrangements of nearly all active volcanic loci in the Indonesian island arcs have been subdivided into small (occurring on the same volcano), medium (occupying the same volcanic range), and large (interpreted connections between volcanic loci on separate cones or ranges). Two additional size-classes, *i.e.* small to medium and medium to large volcanic lineaments contain the transitory cases.

Analyzing the orientations of the volcanic lineaments with respect to the regional structural trends and by using the most widely accepted angle of failure of 25° - 30°, it was found that more than seventy percent of the lineaments can be classified as first and second order shear, tension, and extension directions. The tension direction occurs predominantly in the large size-class contrarily to the extension direction, which is rarely large. Instead, the latter direction is most frequent as small lineaments. There are no significant differences in the number of lineaments among the six directions of failure. Almost three quarters of the remaining unclassifiable volcanic lineaments belong to the small and small to medium size-classes, which very probably reflect the influence of local structural conditions.

These data indicate conclusively that most volcanic lineaments occur along narrow zones of weakness which are genetically related to the regional structure.

Introduction

Any linear arrangement of volcanic centers is designated as « volcanic lineament ». Recognized volcanic centers comprise craters, fumaroles, solfataras, extrusive domes, and actual linear fissures upon

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or connecting volcanic bodies. Besides, in a few cases centers of activity have been connected with older, non-active plugs and domes. However, in the latter case only those linear connections which « make sense » have been included in our discussion.

Since the infancy of volcanology linear eruptions and linear arrangements of volcanic centers have been ascribed to the influence of fractures. However, to the writer's knowledge no comprehensive, quantitative study has been undertaken yet to correlate volcanic lineaments with geologic structure. Among the numerous papers on linear arrangements of volcanoes, two will suffice as examples.

Friedländer (1918) noted that there seems to be a certain regularity in the spacing of volcanoes throughout the world. He found that the Hawaiian and other Central Pacific volcanoes are mutually separated by distances of 35-40 km. In the West Indies volcanic activity is located at distances of about 80 km apart. Friedländer concluded that this regular type of spacing should reflect the thickness of the earth's crust. Furthermore, in regions where the intervolcanic distances are smaller and are variable, like in the South American Andes, Friedländer assumed a thinning of the crust over a large magma reservoir.

Kuenen (1945) has presented a thorough review of studies on linear volcanic phenomena and has added his own observations on linear volcanic arrangements in the Indonesian Archipelago. He has recognized two main groups of fissures accompanying volcanism: flank fissures occurring on the volcanic bodies and volcanoes presumably occupying basement fissures. Among the flank fissures are radial, tangential, concentric, and erratic fissures (see, Kuenen, 1945, fig. 1, p. 18). Radial fissuring by paroxysmal events is thought to be contradicted by the observed gradual, radial fissuring on Mount Etna during at least four different eruption periods. Instead, Kuenen has assumed that radial fissuring on volcanic cones is likely the result of sill-like injections into the volcano or into the neighbouring substratum, followed by upheavals and subsequently by fracturing. Concentric fractures are probably the manifestations of a ringdike-like mechanism, *i.e.* a diminishing pressure in the magma reservoir. Tangential and erratic fissures are thought to have developed through pre-volcanic faults or tension fractures. Several of such fissures in various parts of the world can be connected with tectonic lines, indeed. At last radial and tangential fissuring may also be the result of heaving and sinking of magma in its reservoir. The latter mechanism is assumed to be responsible for the bulk of fissures on volcanic bodies.

Kuenen has not wanted to speculate on the causes of the major linear arrangements of volcanoes, except that they must be related to « some major tectonic feature in the earth's crust ». As confirming evidence are put forward that the South African diamond pipes are

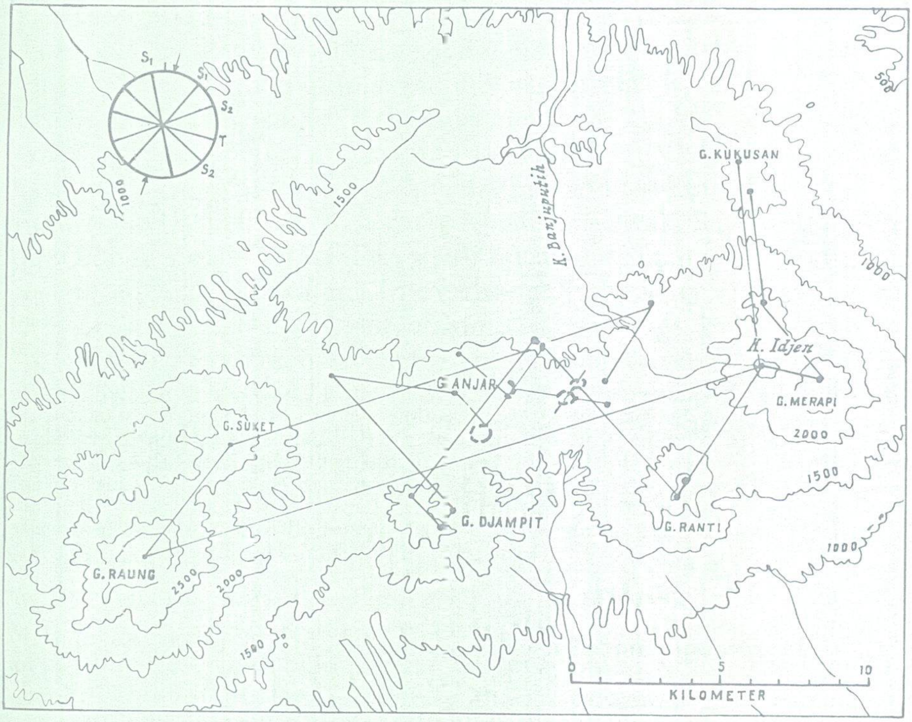

FIG. 1 - Volcanic lineaments in the Idjen Highland, East Java.
S_1 and S_2: shears of first and second orders; T: tension; E: extension. Arrow indicates regional horizontal compression striking N15°E.

connected with a huge dike; the parellelism of volcanic and tectonic lines; the location of the volcanic cones on the Laki fissure in Iceland and in Auvergne, France; the directions of many flank fissures strike parallel to the direction of volcanic rows.

Turning his attention to the Indonesian volcanoes KUENEN (1945) has found that long, straight lines occupied by more than two volcanoes are prominent features in Central — East Java — Bali and in the Halmahera islands. These linear arrangements have been attributed to the presence of tectonic fissures — with the probable exception of Bali — dipping more than 45° and probably even steeper than 70°.

In the present paper the volcanic lineaments in Indonesia will be evaluated in the light of rock-failure as is known from rock deformation laboratories and from field evidence.

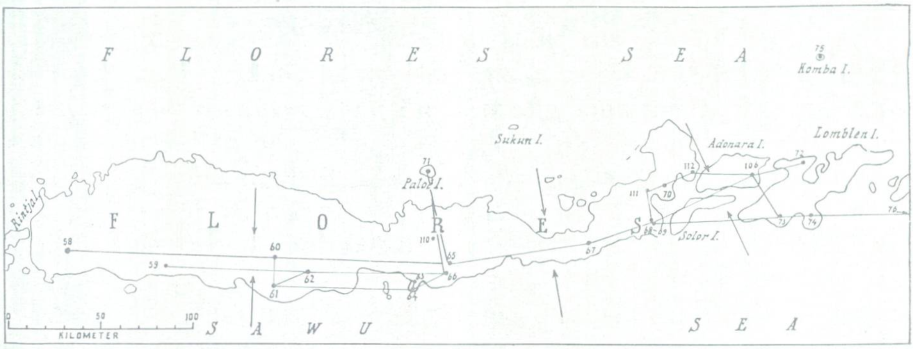

FIG. 2 - Volcanic lineaments in Flores and surroundings, Lesser Sunda Islands. Arrows indicate main horizontal stress directions. Numbers designate volcanoes according to a numbering system used by the Indonesian Geological Survey. 58: Wai Sano, 59; Potjo Leok, 60: Inie Lika, 61: Inie Rie, 62: Amburombu (Keo), 63: Pui (extinct), 64: Ija, 65: Kelimutu, 66: Sukaria, 110: Ndetu Napu, 67: Egon, 68: Lewotobi Perempuan, 69: Lewotobi Laki-laki, 111: Ili muda, 70: Leroboleng, 112: Riang Kotang, 71: Rokatenda, 106: Ili Boleng, 72: Wariran, 73: Ili Labalekan, 74: Ili Werung, 75: Batu Tara, 76: Sirung.

Measurements and Base of Volcanic Lineament Analysis

Arbitrarily the volcanic lineaments have been grouped into:

1. Small; representing lineaments on a single volcanic cone;
2. Small to medium;
3. Medium; those linear arrangements involving different volcanic cones or centers but which are still situated in one volcanic range, or which belong to one volcanic cluster;
4. Medium to large;
5. Large; those lineaments connecting volcanic centers located in different volcanic ranges or clusters.

The intermediate classes (2 and 4) have been introduced to take into account those lineaments which are transitory between respectively class 1 and 3, and class 3 and 5. It is obvious that the classification into small, medium, and large does not indicate absolute scales of lineaments. The adjectives merely serve to indicate the relative distances between the volcanic centers.

The lineaments used for the present analysis have been gleaned from published reports and papers-where some of them have already been recognised as such, like *e.g.* by TAVERNE, 1926; KUENEN, 1945; NEUMANN VAN PADANG, 1951 —, from newly interpreted relations on maps and aerial photographs. Actual measurements in the field have only been done for some of the lineaments on Anak Krakatau (Sunda Straits), Tangkuban Perahu and Papandajan (West Java), Merapi (Central Java), Kawah Idjen and extinct cinder cones in the Idjen Highlands (East Java), Sangeang Api (Sumbawa), Serua and Banda Api (Banda Sea). The interpreted lineaments generally connect at least three volcanic centers. In exceptionally obvious cases, *e.g.* where at least one other lineament of similar trend has been established, two volcanic centers have also been considered to represent a lineament. Interpretation rather than observed evidence is only fairly predominant in the recognition of the medium to large and the large size-classes of volcanic lineaments.

The lineaments have been measured as accurately as possible, however, on small scale maps they have only been recognized as classes of 5 degrees. For every volcano and for each of the ten different areas (as shown on Figure 3) the lineaments have been analyzed with respect to the regional structure while using the mechanical criteria to be described below. Then, for every area, where the structural trend is regionally homogeneous, all its lineaments have been compiled into strike frequency diagrams using units of 5 degrees. This has been done to show the lineament patterns (Fig. 3).

In the present analysis the volcanic lineaments are regarded to represent fractures. Fracture is here used to designate any line or zone of weakness in the earth's crust. It should be noted that the rectilinear nature of the lineaments only concern very steeply dipping (70°) to vertical fractures. It is possible that the curvilinear volcanic rows like the so called Inner Banda Arc, Eastern Indonesia, represent less steeply inclined fracture zones.

It is widely accepted that shear failure in brittle rock occurs along two conjugate planes making a diherdal angle — most commonly 50°-60° — which is bisected by the maximum principal stress direction (or *P*). The line of intersection is parallel to the intermediate principal stress (or *Q*). The third stress direction which is the minimum principal stress (or *R*) is perpendicular to the plane containing *P* and *Q*. Other consequences of the same stress system comprise extension fracturing in planes parallel to *P* and *Q*, tension fractures perpendicular to *P*, and shear fracturing of the second order. Extension fractures develop when the ratio *R* to *P* drops below a certain critical value, *i.e.* the stress conditions are similar to those of tension although

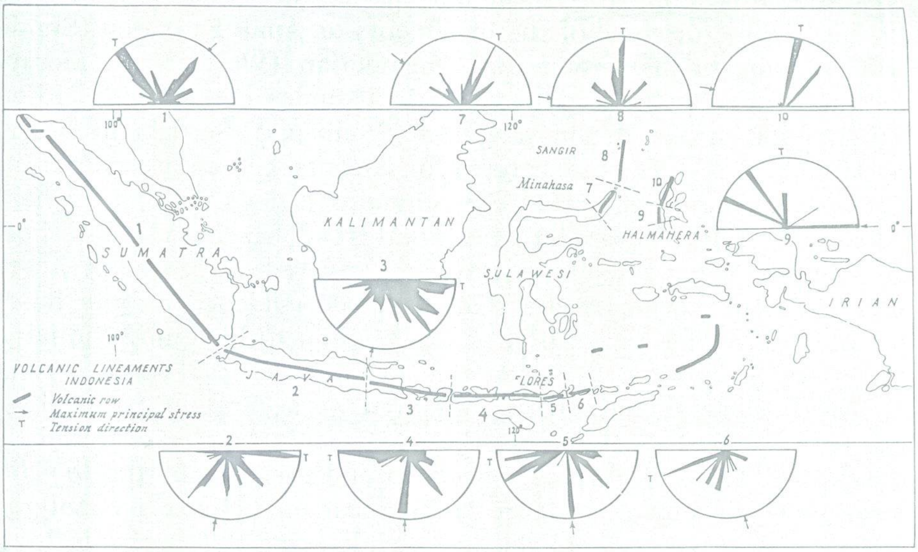

FIG. 3 - The pattern of volcanic lineaments throughout the Indonesian Island Arcs. Discussion in text.

R is still of a compressive nature. Genuine tension fractures develop as a result of relief in the *P* direction. Before the state of tension is attained, however, there will be a stress system where the former *R* and the former *P* directions have been interchangd. In that condition shearing may again occur; these shears are usually designated as shear fractures of the second order and are symmetrically arranged around the new *P*-direction (which was the original *R*-direction). The mechanical basis of rock failure is amply discussed in *Memoir 79* of the GEOLOGICAL SOCIETY OF AMERICA (1960), HILLS (1963), and JUDD (ed. 1964).

Therefore, in a completely developed fracture system the following trends exist perpendicular to the plane containing P and R.

Extension fractures (E) parallel to P.

Primary shear fractures (S_1) making acute angles (25°-30°) with and symmetrically arranged around P.

Secondary shear fractures (S_2) arranged symmetrically around the original R-direction and making similar acute angles as the primary shear fractures.

Tension fractures (T) perpendicular to P.

Hodgson (1962) has shown that by using either the « collapse model » or the « fault model » earthquake mechanism, the main horizontal stress is found to be normal to most island arcs. Recently Ritsema (1964) has examined some reliable fault plane solutions and has concluded that approximately half of the shallow earthquakes (with foci not deeper than 300 kilometers) exhibit horizontal displacements. Therefore, we may accept for the present that horizontal compression is a reality in the earth's crust and that in the Indonesian island arcs this maximum principal stress is perpendicular to the individual arcs. The latter condition is also borne out by the fold directions on the various islands.

Analysis of Volcanic Lineaments

The relations among centers of volcanic activity of all size-classes have been examined for 89 volcanoes of the 127 active centers in Indonesia. Besides, clusters of still recognizable but extinct volcanic centers which occur in the proximity of active volcanism have also been included in the present analysis. These extinct volcanic features cannot be older than the Upper Neogene and are most probably of much younger age. This assumption is supported by their morphological similarity to quite recently extinct volcanoes like *e.g.* the extinct Penanggungan volcano near Surabaja, East Java, which ended its activity only at the start of the Christian era (Kuenen, 1935). It is, therefore, reasonable to assume that the various regional stress systems have not changed during the period from Upper Neogene till the present time.

On account of the structural trends, mainly those of folds, the main horizontal stresses for the ten regions indicated on Figure 3 have been obtained as is shown in Table 1. Local variations in each

TABLE 1 - Regional structural trends derived from orogenic strikes.

Area	Island or islands	Orogenic trend	Compression
1	Sumatra - Krakatau	N135° - 140°E	N45° - 50°E
1 a	North Sumatra	N100°E	N10°E
2	West-, Central- and west part of East Java	N100°E	N10°E
2 a	West Java (Tjeremai)	?	N5°E
3	East part of East Java - Bali - Lombok	N105°E	N15°E
4	Sumbawa - West Flores	N90° - 95°E	N0° - 5°E
5	Central Flores	N80° - 85°E	N5° - 10°W
6	East Flores - Adonara - Lomblen - Pantar	N75°E	N15°W
7	Minahasa	N40°E	N50°W
8	Sangir islands	N5° - 10°E	N80° - 85°W
9	South Halmahera	N0°E	N90°E
10	North Halmahera	N15°E	N75°W

area are small and rare. They comprise among others the N100°E orogenic trend in North Sumatra which is reflected by lineaments on the Bur ni Telong volcano. The regional structural ternds of the Inner Banda Arc volcanoes and the submarine volcanoes Emperor of China and Nieuwerkerk in the western part of the Banda Sea, are not known as such. However, assuming that the connecting lines represent the orogenic trends, lineament patterns upon and between the volcanoes in question indicate genetic relations with respect to the interpreted main horizontal stresses.

Two examples of volcanic lineaments are depicted on Figures 1 and 2. Figure 1 shows volcanic lineaments on the Idjen Higland, East Java. The presently active volcanoes comprise Mount Raung and Mount Kawah Idjen. The other points designated as centers of volcanic activity are extinct volcanoes on the rim of the huge Idjen caldera and cinder cones in its central part. The main horizontal stress is directed N15°-195°E. In the NW-corner of the figure the inset circle indicates the relationships of the various lineaments to the compressional direction in terms of shear, extension, and tension fractures. It should be noted that the lineaments are not haphazardly drawn but are carefully constructed and that they are remarkably parallel. The various size-classes are well examplified in this figure. The lineament connecting Raung and Kawah Idjen is classed as medium to large because it connects two centers on two uncompletely separated volcanic clusters. The lineament Raung-Suket represents a medium class size of lineament as do the connecting lines Kawah Idjen-Kukusan, Kawah Idjen-Merapi, Kawah Idjen-Ranti, and others. The small to medium size-class is indicated among others by the lineaments of the two Ranti summits and the one containing the three extinct volcanic centers of Mount Djampit and surroundings. The

TABLE 2 - Important maxima and submaxima of volcanic lineaments as shown in Figure 3.

Compression (area)	S_1	S_2	T	E	?
45° - 50° (1)	—	—	140° - 145°	45°	—
10° (2)	40° 155° - 160°	130° - 135°	90° - 100°	355° - 5°	—
15° (3)	45° - 165°	75° - 80° 140°	95° - 110°	10° - 15°	125° - 130° 150°
0° - 5° (4)	—	—	85° - 90°	0° - 10°	140°
170° - 175° (5)	130° - 135°	60° - 65°	75° - 80°	170° - 175°	—
165° (6)	15° - 20°	50°	70° - 75°	—	30° - 35°
130° (7)	—	15°	30° - 35°	120° - 125°	50 °- 145°
95° - 100° (8)	130° - 135°	165° - 175°	0° - 10°	—	40° - 45°
90° (9)	115° - 120° 65°	150° - 155°	0°	85° - 90°	—
105° (10)	—	40°	10° - 15°	—	—

S_1 and S_2: shear direction of first and second order; T: tension direction; E: extension direction; ?: not related to the regional compression.

small class of lineaments are not well shown at this map scale, but several are indicated among the clusters of extinct centers east of Mount Anjar.

Figure 2 mainly shows large and medium to large size-classes of lineaments on Flores and the volcanic islands to the east. This figure clearly demonstrates that the larger size lineaments are mostly perpendicular to the main horizontal stress. In other words, these lineaments correspond to the respective tensional directions. Moreover, it is shown that the three different directions of horizontal compressions in this part of Indonesia are quite discrete.

Figure 3 displays the volcanic rows throughout the Indonesian arcs and indicates the patterns of lineaments in the ten different areas with different compression directions. In most regions the tension direction of lineaments is denoted as an important maximum perpendicular to the regional compression. Table 2 collects the maxima and submaxima indicated on the ten strike frequency diagrams of lineaments on Figure 3. Some of the unexplained maximal directions may still be interpreted by assuming the influence of neighbouring stress fields. The N140°E maximum of area 4 may represent the S_1-direction formed by the stress field of area 5. The N125°-130°E and N150°E orientations in area 3 may be explained as the influences of the compression that dominates area 4; these maxima are respectively S_2 and S_1. Furtheron, the N30°-35°E lineaments of area 6 may reflect a consequence of the neighbouring main horizontal stress of area 5, representing S_1-lineaments. At last the N40°-45°E lineaments of area 8 are easily explained as tension fractures due to the stress field of area 7. It appears, therefore, that among the seven dubious lineament-maxima only the N50°E and the N145°E directions of area 7 can not be explained as the result of the regional compression.

The various relations and their respective numbers of volcanic lineaments with respect to the main horizontal stresses for the different regions are shown on Table 3.

Of the 434 lineaments 73 % show genetic relations to the stress fields as first and second order shears, tension, and extension directions. Table 3 further shows that the tension type lineaments are most common in the large size-class of volcanic lineaments, while the extension type lineaments are common in the small size-class. It is typical that half of the lineaments without apparent, genetic relations to the horizontal compression belongs to the small size-class. To-

TABLE 3 - Lineament directions with respect to size class.

Lineaments	S_1	S_2	T	E	?	Total
Small	34	26	20	29	57	166
Small to medium	11	21	9	16	24	81
Medium	27	17	15	11	19	89
Medium to large	1	1	1	2	—	5
Large	10	21	41	6	15	93
TOTAL	83	86	86	64	115	434
%	19.1	19.8	19.8	14.8	26.5	100.0

S_1 and S_2: shears of first and second orders; T: tension; E: extension; ?: unclassifiable.

gether with those of the small to medium class, they constitute about three quarters of the unexplainable lineaments. It appears that these « questionable », smaller lineaments represent the influence of local stress fields. There seems to be no significant differences among the total numbers of lineaments representing the various types of fractures.

In conclusion we may recapitulate that volcanic lineaments in the Indonesian island arcs show definite genetic relations to the regional structural trends. Part of the smaller size-classes appear to reflect local stress conditions.

As a speculation we may add that the distribution of volcanic centers and clusters seems to imply that vulcanic reservoirs are discretely separated by distances of not less than 10 kilometers in Indonesia. Otherwise, we would expect trains of volcanic loci along the fracture-zones, rather than the present configuration of volcanoes standing as separate bodies or clusters.

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