Volcanoes as Possible Indicators of Tectonic Stress Orientation—Aleutians and Alaska

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Volcanoes as Possible Indicators of Tectonic Stress Orientation—Aleutians and Alaska[1])

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Abstract – A new method for obtaining from volcanic surface features the orientations of the principal tectonic stresses is applied to Aleutian and Alaskan volcanoes. The underlying concept for this method is that flank eruptions for polygenetic volcanoes can be regarded as the result of a large-scale natural magma-fracturing experiment. The method essentially relies on the recognition of the preferred orientation of radial and parallel dike swarms, primarily using the distribution of monogenetic craters including flank volcanoes. Since dikes tend to propagate in a direction normal to the minimum principal stress (T-axis), the method primarily yields the direction of the maximum horizontal compression (MHC) of regional origin. The direction of the MHC may correspond to either the maximum (P-axis) or intermediate (B-axis) principal stress.

The direction of MHC obtained at 20 volcanoes in the Aleutian arc coincides well with the direction of convergence between the Pacific and North American plates. This result provides evidence that in the island arc the inferred direction of MHC is parallel to the maximum principal tectonic stress. In the back-arc region, general E–W trends of MHC are obtained from seven volcanic fields on islands on the Bering Sea shelf and the mainland coast of Alaska. These volcanic fields consist mostly of clusters of monogenetic volcanoes of alkali basalt. In the back-arc region, the trends of MHC may correspond to an E–W intermediate, a vertical maximum, and a N–S minimum principal stress.

Implications for the tectonics of island arcs and back-arc regions are: (1) volcanic belts of some island arcs, including the Aleutian arc, are under compressional deviatoric stress in the direction of plate convergence. It is improbable that such arcs would split along the volcanic axis to form actively spreading marginal basins. (2) This compressional stress at the arc, probably generated by underthrusting, appears to be transmitted across the entire arc structure, but is apparently replaced within several hundred kilometers by a stress system characterized by horizontal extension (tensional deviatoric stress) in the back-arc region. (3) The volcanoes associated with these two stress systems differ in type (polygenetic vs. monogenetic) and in the chemistry of their magmas (andesitic vs. basaltic). These differences and the regional differences in orientation of the principal tectonic stresses suggest that the back-arc stress system has its own source at considerable depth beneath the crust.

Key words: Stress field, regional; Volcanic dike pattern; Tectonics of Aleutians and Alaska; Flank crater distribution.

Introduction

The orientation of tectonic stress[4]) which has existed in recent times in the upper crust of volcanic regions can be revealed by certain volcanic surface features which

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[4]) For brevity, we refer to the directions of the principal stresses of tectonic origin by the phrase 'orientation of tectonic stress'; recognizing implicitly that stress is a tensor.

indicate the trend of zones of concentration of dikes underground (NAKAMURA 1969 and 1977). The preferred orientation of dikes indicates the direction of the maximum horizontal compression (MHC).

The present paper applies the technique of finding the direction of MHC to Aleutian and Alaskan volcanoes, presents the stress orientations obtained for this region and discusses some mechanical problems related to the tectonics of island arcs and back-arc regions. The basic data for this study were derived from maps of volcanic features and active faults.

Method

Only a brief account of the method for obtaining the orientation of tectonic stress from volcanic features is given here. The method is described and discussed in detail by NAKAMURA (1977). The underlying concept is that the volcanoes may be regarded as large-scale natural magma-fracturing experiments (YODER 1976, p. 179–180), repeated over a long period of time. Essentially, the method relies on determining the trend of dike swarms which tend to develop normal to the minimum compression or parallel to the maximum horizontal compression of regional origin.

For polygenetic volcanoes (i.e., composite volcanoes[5]) and shield volcanoes of Hawaiian type), the most significant and easily recognizable surface expression of the average trend of the dikes is the direction of the long axis of the distribution of flank craters. Because flank eruptions are understood to emanate from radial dikes underground, the strikes of radial dikes are approximately inferred by lines connecting the summit or main crater with individual flank craters. Then the long axis of their distribution gives the average strike along which dikes best develop (Fig. 1). Post-caldera cones are dealt with similarly.

For volcanic fields consisting of clusters of monogenetic volcanoes, the method is rather straightforward. The average strike of eruptive fissures and alignment of monogenetic craters are taken as the surface expression of the dike trends. In this case, magma is understood to be supplied largely from below, since there is no principal polygenetic vent from which magma offshoots radially.

Some other features may be used as an auxiliary means for determining the direction of MHC: e.g., bending of radial eruptive fissures, horizontal elongation of the edifice of polygenetic volcanoes, and parallel normal faults within the volcanic edifices or fields. The bending of fissures may be caused by the change of governing stresses from magmatic pressure near the vent to regional tectonic stresses away from the central craters. Elongation of the main volcanic edifice can result from accumulation of volcanic material from flank craters, the distribution of which is similarly elongated. Normal faults may be the surface manifestation of dikes that did not reach the surface.

[5]) 'Composite volcano' is used for stratovolcano.

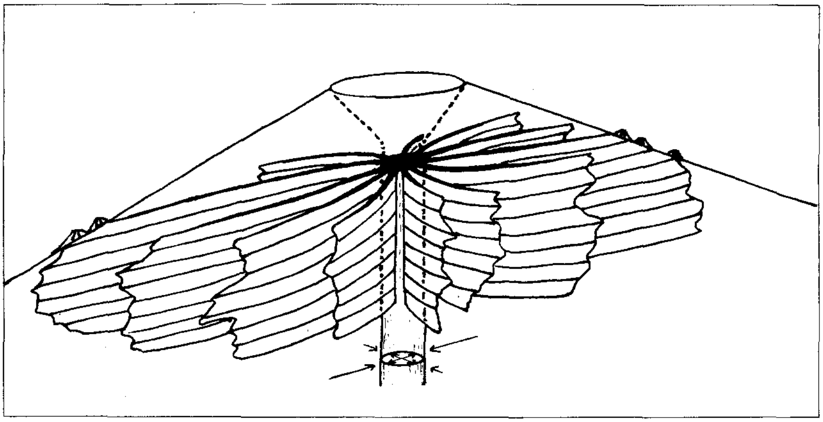

Figure 1
Diagram showing the radial dikes and flank volcanoes of a polygenetic volcano under a differential horizontal stress. The zone of flank volcanoes corresponds to the trend of radial dike concentration, and hence to the trend of the maximum compression of the horizontal component of the ambient stress (NAKAMURA, 1977).

The average strike of these features indicates the direction of either the maximum or the intermediate principal stress of regional origin in the vicinity of the volcano. Therefore, we further have to determine: (1) whether this average strike represents the maximum or the intermediate principal stress, and (2) whether the regional stress is of tectonic origin or the effect of some other source, the most important of which would be the gravitational stresses due to topography of the volcano.

To discriminate between the maximum and intermediate principal stresses within a volcanic belt, the angular relation between the trend of the volcanic belt and the preferred orientation of radial dikes can be used.

In the typical case of an island arc, in which the maximum principal stress is horizontal, the trend of the volcanic belt makes a high angle with the strike of the concentration of radial dikes at individual composite volcanoes. In the other case, for a region of extensional tectonics in which the maximum principal stress is vertical, the dike trends tend to be aligned with the axis of the volcanic belt.

The sense of relative motion across active faults distributed in the same general area can be used as well. The chemistry of magmas and types of volcanoes also may be used as auxiliary means to discriminate between the two stress systems.

If the regional stress in and around polygenetic volcanoes is caused by gravity sliding, then the zones of flank craters may be curved rather than linear; following the contour of the regional slope responsible for the downhill tensional stress. Also, if the strikes of the slopes vary, the strikes of the zones of craters may be variable among adjacent polygenetic volcanoes. Therefore, if the zones of flank craters are linear at individual volcanoes and if the strikes of the zones are common or change only gradually, tectonic stresses may most probably be responsible for the regional

Table 1

Region[1]	No.[1]	Volcano[1]	Number of vents[2]	Length (km)[3]	Width (km)[4]	Elongation[5]	Fault[6]	Azimuth (from north)[7]	Quality[8]	Lat. (°N)	Long. (°W)[9]	A, B, or C[1]	Type of Volcano[1]	Main rock types[1]
Western Alaska and Bering Sea Islands	87	Imuruk Lake	78	57	39		++	45° ± 15°	G	65.433	162.717	B? and C	scoria cones, small shield volc.	oliv. basalt, andesite
				45	41		+	40°E ± 20°	P	~65.767	~164.000			
	88	Kookooligit Mtns.	200+	33	6	++		80°W ± 5°	E	63.567 ~63.650	170.092 ~170.672	A or B	sh. volc., sc. cones	oliv. basalt
	89	St. Michael Island	9+	10	2.9	+		60°W ± 10°	G	63.433 ~63.541	162.000 ~162.317	B and C	lava cones, maars?	oliv. basalt
	91	Ingakslugwat Hills	25+	30	30			90°E ± 20°	P	61.300 ~61.583	163.767 ~165.150	C	sc. cones	oliv. basalt
	93	Nunivak Island	99	50	22	+		80°W ± 10°	G	59.750 ~60.438	165.625 ~167.438	B and C	sh. volc.?, sc. cones	basalt
	96	St. Paul Island	45+	12	8		+	55°W ± 10°	G	57.108	170.092	B? or C	sc. cones, maars	basalt
				8	10		+	50°E ± 20°	G	~57.250	~170.417			
	99	St. George Island	16	13	7.1		++	70°E ± 20°	G	56.540 ~56.610	169.460 ~169.782	C	sc. cones	basalt, andesite?
Alaska Peninsula and Aleutian Islands and Range	100	Buldir	(1)	(5)	(0.2)	+	++	60°W ± 10°	P	52.317	−175.767	B	Stratovolcano	basalt, andesite
	101	Kiska	(4)	(5.6)	3.8			50°E ± 25°	VP	52.100	−177.600	A	Stratovolcano	andesite
	102	Segula	ca10	6	2.1	+		40°W ± 10°	G	52.016	−178.133	A or B	Stratovolcano	basalt, andesite
	104	Little Sitkin	(1)	(3.5)	(1.1)	+	+	65°W ± 15°	P	51.950	−178.533	A	Stratovolcano	bas., and., dac., rhyodac.
	107	Gareloi	(13)	(5)	(1.7)	+		45°W ± 5°	G	51.800	178.800	A	Stratovolcano	basalt, andesite
	112	Moffett	7	8	4.6			50°W ± 10°	G	51.933	176.750	C	Stratovolcano	basalt, andesite
	113	Adagdak	(1)	(4.5)	0.5		++	60°W ± 10°	P	51.983	176.600	C	Stratovolcano	basalt, andesite
	114	Great Sitkin	6	8.5	2.4			35°W ± 10°	G	52.067	176.117	A	Stratovolcano	basalt, andesite
	131	Vsevidof	(6)	(8)	11			65°W ± 20°	P	53.133	168.700	A	Stratovolcano	basaltic and., and., rhyodac.
	132	Recheshnoi	8	18	16		+?	70°W ± 10°	P	53.150	168.550	B?	Stratovolcano	and., bas., rhyol.
	133	Okmok	55	40	14	+	+	60°E ± 10°	VP	53.417	168.050	A	shield like Stratovolcano	basalt., and., rhyol.
	135	Bogoslof	8	2.2	0.2	+		25°W ± 5°	P	53.933	168.033	A	Stratovolcano	basalt, andesite
	136	Makushin	23	24	27		+	60°W ± 15°	VP	53.867	166.933	A	Stratovolcano	basalt, andesite
	138	Akutan	(1)	(6)	0			60°W ± 15°	VP	54.133	166.000	A	Stratovolcano	basalt, andesite
	154	Dana	4	6.5	2.5	(+)		40°W ± 10°	G	55.617	161.183	B	Stratovolcano	basalt?, andesite?
	165	Veniaminof	ca50	60	(14)	+		35°W ± 5°	E	56.167	159.383	A	Stratovolcano	basalt, andesite
	157	Purple (Black) Peak	5	10	(3.5)	(+)		55°W ± 15°	G	56.555	158.785	B	Stratovolcano	basalt, andesite
	158	Antakchak	(6)	(6)	5			15°W ± 25°	P	56.883	158.167	A	Stratovolcano	dac., and., basalt
	174	Iliamna	7	10	5	+		25°W ± 10°	G	60.033	153.100	A	Stratovolcano	andesite
	178	Spurr	(2)	(3.5)	1.6	+		20°W ± 20°	VP	61.317	152.133	A	Stratovolcano	basalt, andesite?
East and Southeast Alaska	186	Edgecumbe	20	22	9	+		40°E ± 10°	E	57.012	135.767	A, B, or C	Stratovolcano	andesite, basalt

Table 1

Probable azimuths of concentration of radial and parallel dikes of Aleutian and Alaskan volcanoes. Data sources are given in the text. Description of columns:

(1) Type of volcano or volcanic field, after SMITH and SOULE (1973).
   (A) Active volcanoes having historic records of eruptions or active solfataras,
   (B) Volcanoes having no recorded eruptions nor active solfataras, but suspected to have been in eruption during historic time or past 2,000 years,
   (C) Post-Miocene volcanoes other than A or B.

(2) Number of flank and post-caldera cones other than the summit or *main crater for volcanoes 100–186, and probable monogenetic vents for volcanoes 97–99*. Parenthesis indicates that they are distributed only on one side of the main crater.

(3) Longest distance between craters measured in the direction of the given azimuth.

(4) Width of the zone of monogenetic craters as defined by 95% of them. Parenthesis indicate that their distribution is limited to one side of the main crater.

(5) Crosses show that the contour lines are elongated in the general direction of the azimuth.

(6) Presence of normal faults in the general direction of the azimuth is indicated by crosses.

(7) Azimuth of the probable preferred orientation of dikes as obtained principally from the distribution of craters and supplementally from elongation areas and fault trends.

(8) Quality of azimuths, E: excellent, G: good, P: poor, VP: very poor.

(9) Aerial extent of volcanic fields for volcanoes 87–99, and location of the main craters for volcanoes 100–186.

stress rather than gravitationally induced stresses. The same argument can be applied to volcanic fields of monogenetic volcanoes.

A total of 103 volcanoes and volcanic fields in the Aleutians and Alaska were listed by SMITH and SOULE (1973) as post-Miocene volcanoes. They tabulated the names of volcanoes and volcanic fields along with number (from 85 to 187), geographical location, size, degree of recent activity, type of volcanoes, and their main rock type. These volcanoes were grouped geographically by them into the following three regions:

(1) Western Alaska and Bering Sea Islands (85–99)
(2) Alaska Peninsula, Aleutian Islands and Aleutian Range (100–179).
(3) Eastern and Southeastern Alaska (179–187).

The 103 volcanoes are studied mainly by means of published geologic and topographic maps and literature, most of the references for which are given by SMITH and SOULE (1973). Among 15 volcanic fields listed for western Alaska and the Bering Sea Islands, accurate descriptions of crater distributions are available for seven fields: five from geologic maps and two (88 and 89) from topographic maps. For the remaining eight volcanic fields, little information is available regarding features indicative of orientation of dikes.

For 51 of 79 volcanoes listed in the Alaska Peninsula and the Aleutian Islands and Aleutian Range, geologic maps of variable quality were available. Among the fifty-one volcanoes, twenty have features indicative of a preferred orientation of radial dikes.

In eastern and southeastern Alaska, only one volcano, Mt. Edgecumbe, among nine shows the above features. Six volcanoes in the Wrangell Mountains are deeply ice-covered. Prindle volcano is a single scoria cone. The Rivillagigedo volcanic field consists of randomly scattered basaltic products.

For the twenty-eight volcanoes and volcanic fields which showed a preferred orientation of radial dikes, information derived from the above mentioned maps was used to obtain probable azimuths of their dike concentrations. This information and the resulting azimuths are summarized in Table 1, columns 5–9. Geographical distributions of craters are shown in Fig. 2 for the individual volcanoes listed in Table 1, except the volcanoes Ingakslugwat Hills (91), Akutan (138), and Spurr (178). Each of the latter two has only one flank eruption site.

Description

The above information given in Table 1 and Fig. 2 is supplemented by a brief description of each individual volcano in the following paragraphs. The volcano numbering system is that of SMITH and SOULE (1973) and is the same as that used in Table 1. A few volcanoes not listed in Table 1 are also described, since they have possible information on the preferred orientation of dikes.

Western Alaska and Islands of the Bering Sea

87. Imuruk Lake volcanic field (HOPKINS 1963)

The Imuruk Lake volcanic field, on the Seward Peninsula, consists of numerous scoria cones and lava flows.

> 'The volcanic vents rarely lie in sharply defined alignments: however, they do tend to cluster in major NW-trending swarms and minor NE-trending swarms generally parallel to the two systems of faults observed in the Imuruk Lake area. One exceptionally well-defined alignment is expressed by 6 vents trending northeastward.' (HOPKINS 1963)

The 'major trend' described above by Hopkins lies in a N45°W direction and is over 50 km long; the 'well-defined alignment' strikes N40°E and is 6 km long. Normal faults with NW or NE trends are widely distributed in the volcanic field. The NW-trending faults are better developed (Fig. 2).

88. Kookooligit Mountains (SMITH and SOULE 1973; US Geological Survey St. Lawrence topographic map at the scale of 1:250,000).

The Kookooligit Mountains volcanic field, which occupies the north central part of St. Lawrence Island, may be regarded as a low shield volcano which is elongated in a N80°W direction (Fig. 2). Most of the more than 200 vents, largely scoria cones, are distributed within a linear crestal zone of the shield. The zone strikes N80°W.

89. St. Michael's Island volcanic field (HOARE and CONDON 1971a and 1:63,360 series of topographic maps of Alaska, St. Michael B–1, C–1, and C–2).

St. Michael's Mountain, located in the middle of St. Michael's Island in Norton Sound, is about 170 m high. The summit area, defined by the 350 ft (110 m) contour line, is 1.2 km long, 0.3 km wide and is elongated N60°W. The contours above 150 ft (46 m) show an edifice elongated in the same direction (Fig. 2). To the northwest and southeast of the mountain, there are at least nine maar-like depressions that are more or less circular in plan view and surrounded by possible crater walls a few to several tens of meters high.

Stuart Island, which is included in St. Michael's Island volcanic field by SMITH and SOULE (1973) and located several kilometers NW of St. Michael's Island, consists of Stuart Mountain to the east and the younger West Hill to the west. Stuart Mountain is elongated in a N60°W direction and has a possible flank volcano 2.8 km from the summit, on the S85°E flank. West Hill has four possible flank craters on the NW and SE flanks. They define a linear zone 5 km long which strikes N65°–70°W.

93. Nunivak Island volcanic field (HOARE *et al.* 1968).

The topographic configuration of the Nunivak Island volcanic field on the Bering Sea shelf appears to constitute a low broad shield which is roughly elongated in a

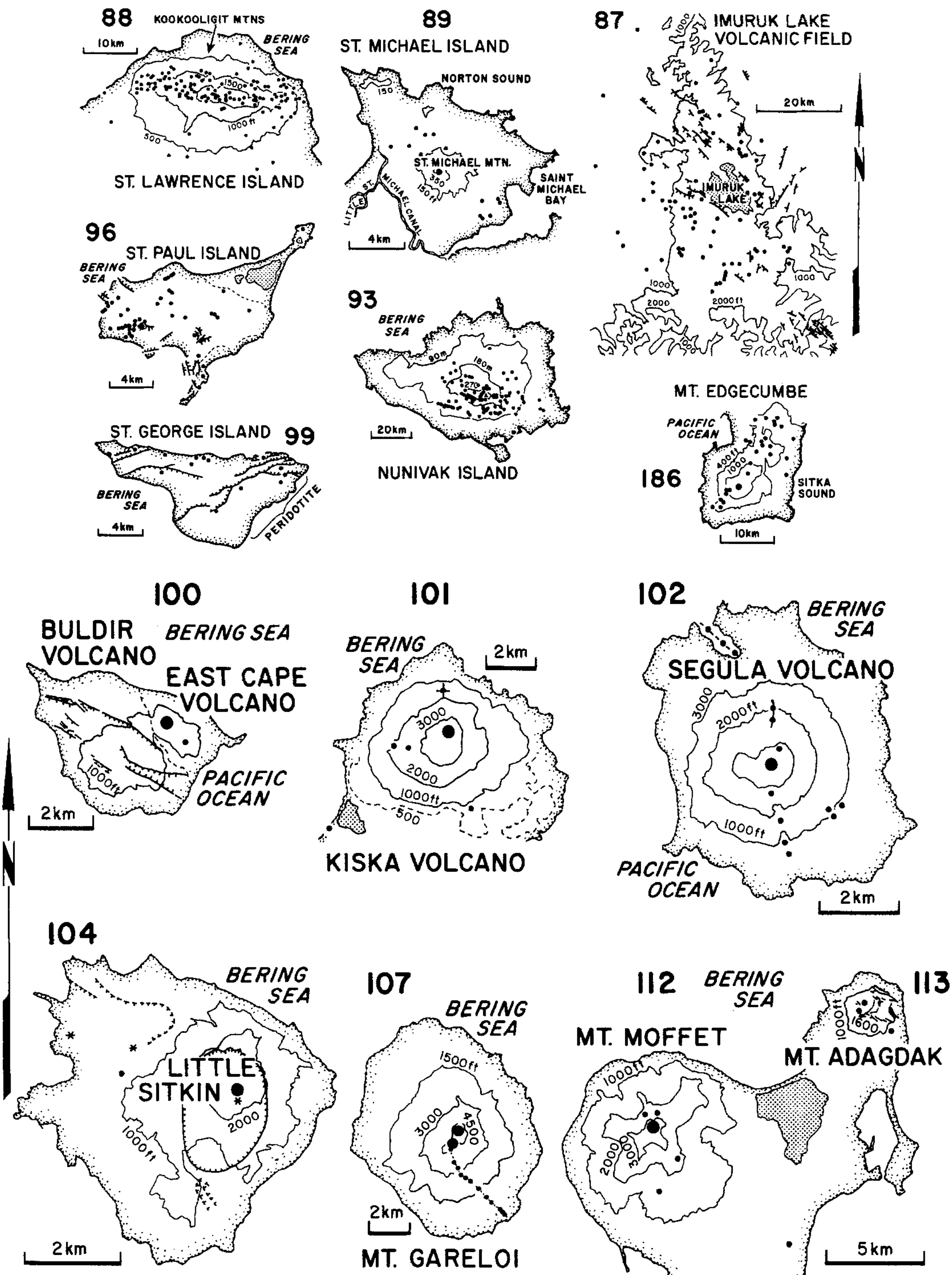

Figure 2 (*cont.*)

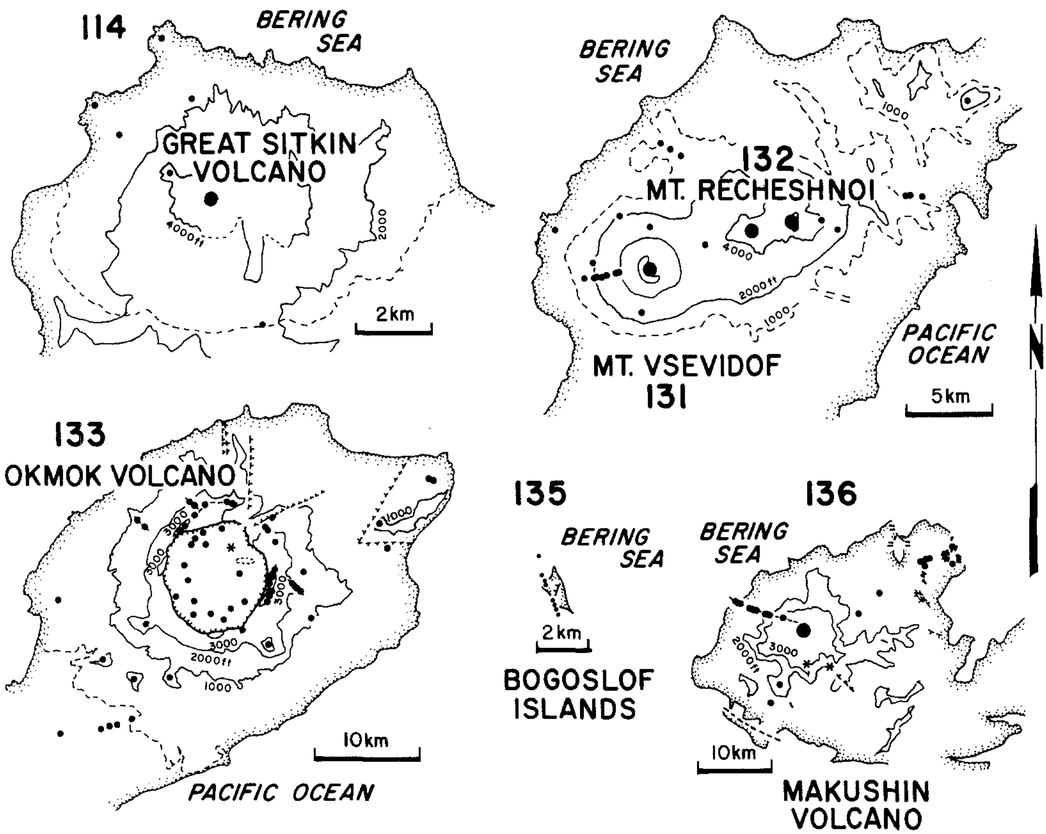

Figure 2 (*cont.*)

Distribution of craters of 25 volcanoes and volcanic fields in the Aleutian and Alaskan region as listed in Table 1 and described in the text. Larger circles: central polygenetic vents. Smaller circles: monogenetic vents. When they constitute an eruptive fissure they are tied by a line. (Broken) lines: (inferred) normal faults. Downthrown side is marked by bars. Stippled area: lake. Stars: solfataric field. Height in feet, unless otherwise indicated. Short bars for Makushin volcano (136): dikes. Thin broken lines of Kiska (101), Great Sitkin (114) and Okmok (133) volcanoes and St. Paul Island (76) are boundaries in the surface geology. Data sources are indicated in the text following the name of the volcano and the volcanic field in the chapter describing each volcano.

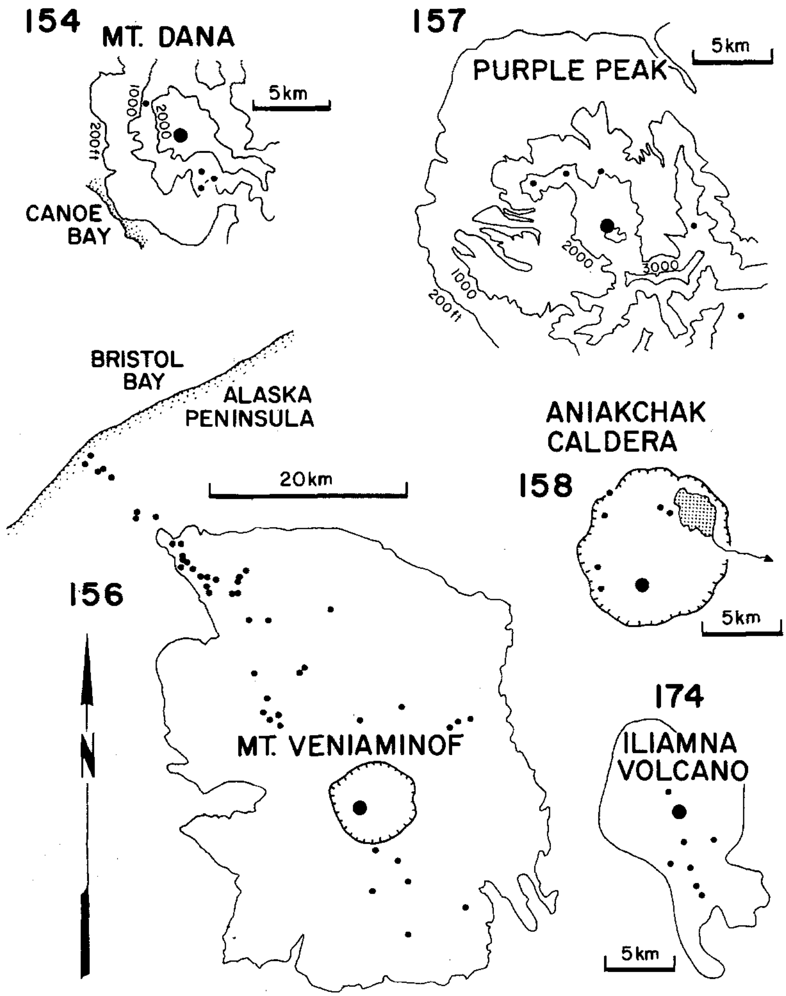

Figure 2

N75°W direction. Roberts Mountain (solid triangle in Fig. 2), 550 m in height, marks the summit of the shield. The distribution of about one hundred scoria cones on the higher part of the island is elongated N80°W. Southwestern vents about 8 km in length show alignment, striking N80°W. Most of these scoria cones are the product of very recent eruptions of alkali basalt. Volcanic activity has occurred discontinuously during the past 6.4 my. During this period, the center of activity migrated eastward on the island. The western, ventless area represents the site of earlier activity.

96. St. Paul Island (Cox *et al.* 1966).

St. Paul Island, one of the Pribilof islands on the Bering Sea shelf consists of more than 45 monogenetic volcanoes (scoria cones and tuff cones) and basaltic lava flows.

The oldest rocks are dated as 0.36 ± 0.10 my. Three NE alignments of craters are evident. Their strikes and lengths are: N55°E, 1 km; N68°E, 2 km; and N45°E, 1.5 km. A 1 km-long alignment in a N60°W direction is also observed. Normal faults are widely distributed on the island. Their strikes concentrate in ENE and NW directions (Fig. 2).

99. St. George Island (COX *et al.* 1966).

St. George Island, one of the Pribilof Islands, is much eroded and nearly flat. Volcanic eruptions took place during 2.2–1.6 mybp on this island. About 16 vents are identified. They do not show any obvious alignment, however. Normal faults are extensively developed on this island. They strike more or less in an ENE direction. At least one vent is located on a fault. In the eastern part of the island, the faults are downthrown on the NW side. Along the SE coast, there are exposures of serpentinized peridotite which lie unconformably below the volcanic rocks (Fig. 2).

91. Ingakslugwat Hills (COONRAD 1957, HOARE and CONDON 1971b).

The Ingakslugwat Hills volcanic field is one of the most recently active areas in the Yukon-Kuskokwin delta region.

> 'Numerous small spatter and breccia cones about 100 feet high occur on the NW side of the volcanic area. Some of these are alined WNW and apparently define a fracture.' (HOARE and CONDON 1971b)

There is a 6.5 km-long eruption fissure striking N75°E in the NW part of the field. Another possible eruptive fissure in the middle of the field is 6.5 km long and strikes in a N70°E direction.

Alaska Peninsula, the Aleutian Islands and Aleutian Range

100. Buldir Island (COATS 1950).

Buldir Island, the westernmost Aleutian island with recent volcanic activity, consists of two composite volcanoes: Buldir volcano and the younger East Cape volcano. East Cape volcano has a dome on its southeast flank. On the dissected Buldir volcano, a series of recent normal faults strike N55°–70°W (Fig. 2). The topographically higher sides are generally downthrown.

101. KISKA volcano (COATS *et al.* 1961).

Four flank eruption sites are recognized on the geologic map of Kiska volcano (Fig. 2). One located S50°W and 8 km from the summit is completely outside the volcanic edifice. A flank eruption took place in 1962–64 on the slope due north of the summit (COATS 1964). The volcano is slightly elongated in a N70°E direction.

102. Segula volcano (NELSON, 1959).

The zone of flank craters on Segula volcano trends N30°–35°W. A cove on the north coast of the island is, in its configuration, very much like the one formed during the 1965 fissure eruption of Taal volcano, Philippines (MOORE *et al.* 1965). The cove was probably formed by phreatomagmatic explosions which occurred on a fissure trending N50°W. This fissure is not radial in direction. This may be the result of bending as is the case at Gareloi volcano (107).

104. Little Sitkin volcano (SYNDER 1959).
The only flank crater mapped on this volcano is on the western slope. There are three major fumaroles, aligned N70°W (Fig. 2). Four roughly radial normal faults are distributed on the NW and S flanks.

107. Mt. Gareloi volcano (COATS 1959).
A prominent feature of Mt. Gareloi is a radial fissure formed during its 1929–30(?) eruption. The fissure starts southward from the summit area and within 2 km it assumes a southeasterly trend (Fig. 2). There is an indication that the magma which erupted from the fissure travelled laterally, without being mixed, from the central conduit where it had been gravity-differentiated. The change in azimuth of the fissure is best explained by the increasing effect with distance away from the central conduit of the regional stress over the local magma pressure (ODÉ, 1957).

111. Kanaga volcano (COATS 1956).
Near the summit of this nearly conical volcano, there are three radial elongate depressions, one on the northwest and two on the southeast, aligned in a N65°–70°W direction over a distance of slightly more than 0.5 km (L. SNYDER, personal communication, 1976). According to him, there were major fumaroles in these depressions in 1952. Three recent flows are supposed to have erupted from a fissure 0.24 km from the center of the volcano. The orientation of the fissure is not known.

112. Mt. Moffett, Adak Island (COATS 1956).
Flank eruption sites are indicated by five basalt domes on the deeply dissected composite volcano (Fig. 2).

113. Mt. Adagdak volcano, Adak Island (COATS 1956).
At the summit of this volcano, there are two andesitic domes. In Fig. 2 these domes are marked by the same symbol as the basaltic one on the southeastern flank. The location of the former two indicates that of the main vent. The basaltic dome is S50°–60°E of the main vent. The summit area is cut by a swarm of recent normal faults trending N50°–80°W, the youngest one having been displaced possibly a few thousand years ago. The summit side of each of these faults is generally downthrown.

114. Great Sitkin volcano (SIMONS and MATHEWSON 1955).
There are six flank volcanoes on Great Sitkin. Extending several hundred meters

due south of the south-flank eruption site (Fig. 2) is a fumarolic field containing hot springs, mud pots, and fumaroles. It is not known whether the heat source of the fumaroles is related to the Great Sitkin volcano or to the surrounding Sand Bay volcanics which unconformably underlie the Great Sitkin volcanics.

131. Mt. Vsevidof, Umnak Island (BYERS 1959).

The volcano Mt. Vsevidof lies on the western flank of Mt. Recheshnoi. Five flank craters and a slightly curved eruptive fissure are on the western half of the volcano (Fig. 2). The eruptive fissure trends S75°W at the upper and EW at the western, lower end. This 2.3 km long fissure appears to be too short and too close to the central vent and its radial stress field to show distinct influence of the regional stress field. Presumably the effect of this stress field would be a straight WNW trend for the lower end of the fissure. The youngest two craters are possibly historic and located due north and south of the summit.

132. Mt. Recheshnoi, Umnak Island (BYERS 1959).

Two summit craters are suggested from the shape of Mt. Recheshnoi volcano. Flank volcanoes include three andesitic cinder cones, three rhyolite domes about 9 km due east of the eastern summit and aligned in a N80°W direction, an elongate mafic basalt vent complex which trends N60°W, and an andesitic lava dome on the northeast flank (Fig. 2).

In the northeastern sector of the volcano there is a nearly linear, N50°W-trending, topographic depression which is observable from the 1,000 ft. contour lines. We suspect that this depression is a graben bounded by normal faults.

133. Okmok volcano, Umnak Island (BYERS 1959).

Okmok volcano is a basaltic shield volcano covered with recent andesitic pyroclastic flows. The summit has collapsed, forming a caldera about 9 km in diameter. In Fig. 2, about 55 eruption sites are indicated, 15 inside the caldera and 40 on the outer slope, which include six topographically prominent pre-caldera flank cones. One of the cones located on the SE flank, Tulik (134), is counted as an independent volcano by SMITH and SOULE (1973). The overall trend of the distribution of eruption sites is in a N60°E direction. Eruption sites in the caldera are distributed in a roughly circular zone along the periphery of the caldera floor. There is a field of thermal springs elongate in a E–W direction on the eastern caldera floor. Outside the caldera on the upper northern and eastern slopes, there are two roughly concentric ridges. They are marked by eruption sites of basalt and rhyolite, and may be remnants of earlier ring fissures. Three possible eruption fissures of short length are found on the eastern and western slopes trending in a NW direction. Several faults, possibly normal faults, are inferred in the NE sector.

135. Bogoslof volcano (BYERS 1959).

Bogoslof Island, located northward and off of the major Aleutian arc ridge, is one of the 'disappearing islands', which represent the subaerial parts of a mostly submarine composite volcano with a basal diameter of over 20 km and relief of about 300 m. Several lava domes and spines of basalts of slightly alkalic composition were formed repeatedly during the last two centuries. The eruption sites fall on a nearly straight line. In Fig. 2, the outline of the island in 1935 is shown.

136. Makushin volcano, Unalaska Island (DREWES *et al.* 1961).

Makushin volcano, which occupies the northwestern part of Unalaska Island, consists stratigraphically of the Makushin volcanics and Eider Point basalt. The latter lies unconformably on the deeply dissected surface of the Makushin volcanics and older rocks. Volcanic rocks of possible flank cones of Makushin volcano are apparently mapped as the Eider Point basalt. In Fig. 2, they are mapped as flank cones. It is doubtful, however, whether all the Eider Point basalt can be regarded as products of flank vents of Makushin volcano.

Vents of the Eider Point basalt are distributed in a ENE, NW and SSW sectors of Makushin volcano. In the northwestern sector there is an eruption fissure defined by linearly aligned craters, 9 km in length, trending in a N75°W direction. The fissure slightly bends at the coastal area assuming a N60°W direction. Dikes related to Makushin volcanics are also exposed. They are most abundant in the northeastern areas where numerous vents of the Eider Point basalt are located. The trend of the dikes is variable, but E–W and NW directions prevail.

Normal faults are found trending in general WNW to NW directions. Lineaments observed on the aerial photographs have dominant NW and WNW trends, especially in the northern parts of Unalaska Island.

138. Akutan volcano (BYERS *et al.* 1949).

Only one flank eruption site, which possibly formed in 1852, is known and is 5.8 km from the summit on the northwest coast of the volcanic island.

149–153. Pavlof and adjacent volcanoes, Alaska Peninsula (KENNEDY *et al.* 1955, BURK 1965).

Mt. Emmons, Mt. Hague, Double Crater, Pavlof volcano and Pavlof Sister are composite volcanoes which form a nearly continuous ridge about 20 km long on the Alaska Peninsula. Fourteen scoria cones are distributed on the ridge. It is difficult, however, to estimate with confidence any trend of the distribution of flank eruption sites on individual composite volcanoes.

154. Mt. Dana, Alaska Peninsula (BURK 1965).

Four domes are mapped on the NW and SE flanks of Mt. Dana volcano (Fig. 2). The summit dome appears to be either elongate in a N40°W direction or composed of two domes aligned in that direction.

156. Mt. Veniaminof, Alaska Peninsula (BURK 1965).

Mt. Veniaminof is dotted with some 50 flank volcanoes, mostly scoria cones. They are concentrated in a long linear zone striking N35°W, extending through the summit (Fig. 2).

157. Purple (Black) Peak, Alaska Peninsula (BURK 1965).

Five vents are mapped on this deeply dissected volcano (Fig. 2). The volcanic edifice is slightly elongated in a N40°W direction.

158. Aniakchak volcano, Alaska Peninsula (BURK 1965).

Six post-caldera cones are distributed in a sector NW of Vent Mountain, possibly the principal crater (Fig. 2). No craters are mapped outside the caldera.

174. Iliamna volcano, Cook Inlet region (GRANTZ *et al.* 1963).

Based on topographic considerations, seven subsidiary craters including a possible 4 km long eruptive fissure, are inferred from a geologic map showing the distribution of lava flows of Iliamna volcano (Fig. 2). The possible fissure strikes S20°E. The volcanic edifice is elongate in a S30E direction.

178. Spurr volcano, Cook Inlet region (JUHLE *et al.* 1955).

Mt. Spurr last erupted in 1953 from a subsidiary crater, 3.3 km south of the highest peak. If we regard the peak as a part of the eastern caldera rim (R. L. SMITH, personal communication, 1976), then the eruption site is located to the southeast of the center of the volcano which is covered by snow and ice.

Eastern and southeastern Alaska

816. Edgecumbe volcano (LONEY *et al.* 1975).

Scoria cones on the northeastern slope might be flank volcanoes of a possibly independent composite volcano, 'Crater ridge', located just northeast of Edgecumbe volcano. In Table 1, they are included among the flank volcanoes of Edgecumbe. Even if they are excluded, the azimuth given in the Table remains the same (Fig. 2).

Results

Probable azimuth of dike concentration

For 28 volcanoes and volcanic fields discussed above, probable azimuths of zones of concentration of flank craters, which are thought to represent the trends of dikes are summarized in column 9 of Table 1 and shown in Fig. 3. These azimuths are derived from the data presented in Fig. 2 and in the previous chapter. For most volcanoes the azimuth is obtained directly from the distribution of craters. This is the case for volcanoes 88, 89, 91, 112, 114, 135, 138, 154, 156, 157, 174, 178, and 186.

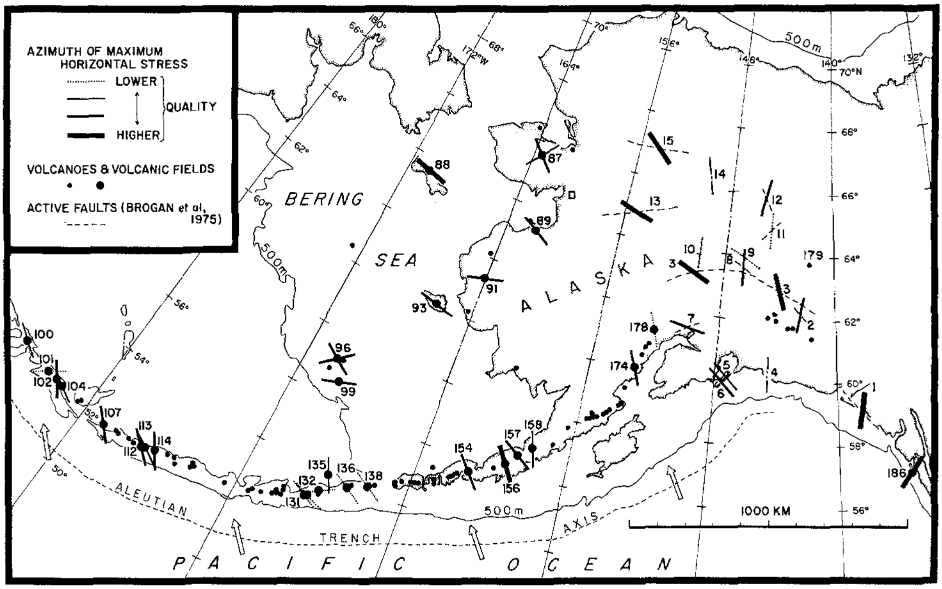

Figure 3
Azimuth of the maximum horizontal compression due to the contemporary stress system deduced from post-Miocene volcanoes (SMITH and SOULE 1973) and active faults (BROGAN *et al.*, 1975). Volcanoes (solid circles) for which the azimuth is indicated are marked by larger circles. Azimuth is given four different grades of quality. Numbers attached to volcanoes and faults are the same as in Tables 1 and 2. Open arrows: direction of motion of Pacific plate relative to North American plate after MINISTER *et al.* (1974). Square: epicenter of the earthquake shown in Fig. 4. For details see text.

When flank craters are distributed on one side of the main polygenetic vent, the azimuth of the zone of crater distribution is less well defined. Volcanoes 131 and 158 are examples.

When bending of a radial fissure is observed, the final direction which is assumed at the portion of the fissure most distant from the summit is taken as the most significant direction. Volcanoes 102, 107, 131, and 136 are examples.

In the western Alaska–Bering Sea shelf region the probable azimuths of zones of dike concentration have a dominant east–westerly trend. In the Aleutian Islands–Alaska Peninsula–Aleutian Range region these azimuths have a dominant northwesterly trend, with two exceptions: Kiska (101) and Okmok (133). Within each of these regions (especially the second one) the individual azimuths derived for a given volcano or volcanic field are strikingly consistent with the dominant regional trend.

Evaluation of quality of the azimuth

The quality or reliability of the obtained azimuth as representative of the average trend of zones of dike concentration is different for different volcanoes. For example, the N35°W direction at Mt. Veniaminof leaves little doubt about accuracy and temporal stability, because the zone of flank eruption is very well defined by a large number of monogenetic vents. In contrast, the N20°W direction at Mt. Spurr is rather uncertain and does not offer any evidence of temporal stability. Therefore, we classify the azimuths into four quality ranks: excellent (E), good (G), poor (P) and very poor (VP).

High ranks are assigned when: (1) the azimuth is well defined by the crater distribution; that is, when the number of craters is large, the zone of crater distribution is long, the ratio between 'length' and 'width' is large and the azimuth of the zone parallels individual eruptive fissures, (2) flank craters are distributed on both sides of the main crater, (3) elongation of the edifice of polygenetic volcanoes is observed and/or subparallel normal faults are distributed in the volcanoes and volcanic fields trending in a direction similar to that of crater distribution.

In practice, the highest quality (E) is given to volcanoes with more than 20 craters in a zone with 'length' longer than 20 km and with the 'length'/'width' ratio larger than 2, and when at least one of the subsidiary features ('elongation' and 'faults') is observed, and the azimuth is defined within $\pm 10°$. The lowest quality, VP, is assigned to volcanoes whose zones of distribution of flank craters are poorly defined or when: (1) only one flank crater is known and no other features are observed (Spurr, 178 and Akutan, 158), (2) the azimuth changes drastically when a single crater is removed (Kiska, 101), (3) the trend of eruptive fissures makes a high angle with the trend of the zone defined by the overall distribution of craters (Okmok, 133 and Makushin, 136).

Stress orientation obtained from active faults

For obtaining the average orientation of tectonic stress during recent geologic times, active faults have a significance similar to the present method that uses volcanic features. Active faults in Alaska studied by BROGAN *et al.* (1975) are used both to check the result obtained by the present study of volcanoes and to cover a wider area so that regional discussions may be more meaningful. Data described by BROGAN *et al.* (1975) are used almost exclusively, because they mapped the distribution of active faults in a wide enough area with uniform standards.

What is obtained from the strike and sense of movement of faults is primarily the direction of principal horizontal shortening (PHS; LENSEN 1961 and LENSEN *et al.* 1971). The direction of PHS is perpendicular to the fault strike for a pure reverse fault, about 45° to the strike for a pure strike-slip fault and parallel to the strike for a pure normal fault. The direction of PHS is assumed here to be a good approximation for that of the maximum horizontal compression (MHC) as discussed, e.g. by LENSEN *et al.* (1971) and PAVONI (1971).

Azimuths of PHS obtained from 15 active faults are tabulated in Table 2 and mapped in Fig. 3. BROGAN *et al.* (1975) described 22 faults. Seven of them are discarded in Table 2, however, because they are either unclear in the sense of motion

Table 2

Azimuth of maximum horizontal shortening associated with active faults in Alaska

Name[1]	Strike (N)[1]	Sense[1-2]	Length (km)[1]	Azimuth (N)[3]	Quality[4]
1. Fairweather	38°W	D	200	7°E	E
2. Totschunda	35°W	D	65	10°E	G
3. Denali	E–W	D	2,000<	70° – 15°W	E
4. Ragged Mountain	N	N	24	0°	P
5. Hanning Bay	NE	R	6	45°W	P
6. Patton Bay	NE	R	62	45°W	G
7. Castle Mountain	55°E	D	45	80°W	G
8. McGinnis Glacier	NW	D	50	0°	G
9. Donnelly Dome	55° ~ 85°W	N	8	55° ~ 85°W	VP
10. Healy Creek	E	R	18	0°	P
11. Shaw Creek	45°E	S?	150	0°	VP
12. Tintina	25° ~ 30°E	D	100	15° ~ 20°E	G
13. Kaltag	65°E	D	400	70°W	E
14. Dall Mountain	NS ~ 23°W	N	30	NS ~ 23°W	P
15. Kobuk-Alatna Hills	EW	D	270	45°W	E

[1] After BROGAN *et al.*, 1975.

[2] D: dextral strike-slip, S: sinistral strike-slip, N: normal, R: reverse.

[3] Azimuth of the maximum horizontal shortening given by strike and dominant sense of movement of the fault.

[4] Same as in Table 1. For details, see text, p. 17.

(six faults) or less than 5 km in length (one fault). Because the azimuths are deduced solely from the dominant sense of motion, they may bear errors of up to a few tens of degrees.

The quality of the obtained azimuth is evaluated and classified as excellent, good, poor or very poor, keeping in mind the quality given to those azimuths obtained from volcanoes. Excellent quality is given when the length of a fault system is longer than 200 km and the sense of motion is well established. Very poor quality is given to a fault system either when less than 10 km in length or the sense of displacement is highly uncertain.

Most of the active faults mapped by BROGAN *et al.* (1975) and shown in Fig. 3 are in interior Alaska. Therefore, most of the azimuths of PHS determined from faults are not directly comparable to the azimuths of MHC determined from volcanoes. However, for the three faults closest to the Bering Sea shelf – western Alaska region (western Denali, Kaltag, and Kobuk-Alatna Hills) the azimuths of PHC (all of the highest quality) are in the sector WNW to NW, in good agreement with the azimuths of MHC determined from volcanoes for this region. In south central Alaska, near the eastern terminus of the Aleutian arc, the azimuths of PHS are in the sector WNW to N, in only poor agreement with the two azimuths of MHC (174 and 178) determined for the Aleutian Range. In southeastern Alaska the north-northeasterly azimuth of PHS for the Fairweather fault (highest quality) is in good agreement with the northeasterly azimuth of MHC for Mt. Edgecumbe (186).

Discussion

Western Alaska and Bering Sea (back-arc) region

Probable azimuths of dike concentrations for volcanoes (hereafter simply referred to as azimuths) are generally oriented east-westerly (E–W ± 50°) in this back-arc region that extends 1,000 km in N–S and 500 km in E–W directions. In addition to this general feature, the azimuths systematically change trend from northwesterly in the northern part to southwesterly in the southern part of the region (Fig. 4). This systematic change in trend becomes better defined when the quality of

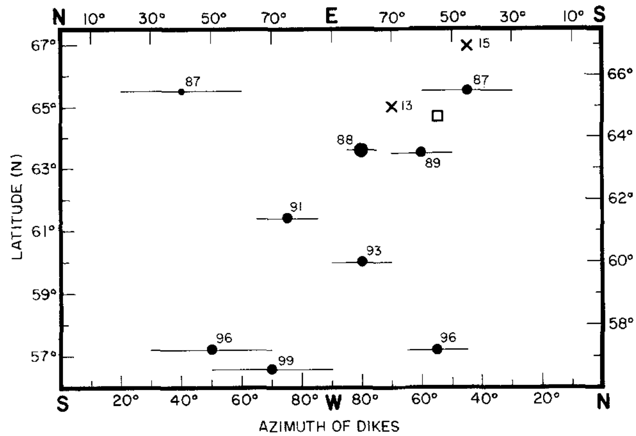

Figure 4

Change of the probable azimuths of dike concentrations with latitude for volcanoes of the western Alaska–Bering Sea region. Volcanoes are shown by solid circles. Size of the circle corresponds to the quality of the obtained azimuth. Attached numbers refer to those used in Table 1. Note that two possible azimuths are plotted for volcanoes 87 and 96. Crosses are those obtained by active faults whose data are given in Table 2. Square shows the orientation of the intermediate-stress axis of an earthquake (location in Fig. 3) with focal mechanism solution of normal-fault type (SYKES and SBAR 1974).

the azimuth determination is considered; e.g., the northeasterly azimuth of the Imuruk Lake field (87) is more poorly determined than the northwesterly one (Fig. 2).

The systematic geographical distribution of volcano-derived azimuths and their conformity with the azimuths obtained from active faults (Figs. 3 and 4) strongly suggest that they represent the orientation of the maximum horizontal compressive stress of tectonic origin in the entire region.

Another notable feature of this region is that two different azimuths are obtained sometimes at single volcanic fields (87 and 96). This may indicate that the direction of the maximum horizontal compression changed or rather fluctuated in orientation with lapse of time. This might be the case if the magnitudes of the two horizontal principal stresses are similar. The horizontal stress is likely, though not conclusively, to be either the minimum or intermediate principal stress. Then the resultant tectonic style would be extensional. This is also supported by the presence of an active normal fault (14) and of a normal-faulting type earthquake (Figs. 3 and 4; SYKES and SBAR 1974) in the same general area. The following volcanic features may also support this conclusion:

(1) Volcanoes in this back-arc region do not define a narrow volcanic belt.
(2) Their magmas are characteristically olivine-basalt or alkali basaltic.
(3) They consist of clusters of monogenetic volcanoes and are classified as volcanic fields by SMITH and SOULE (1973). Kookooligit Mountains (88), St. Michael's Island (89) and Nunivak Island (93) might be classified as central volcanoes forming low shields, however (Fig. 2).

Moreover, there is a possibility that the same stress field, with the maximum stress in the vertical direction, prevails in the entire back-arc region north of the Aleutian–Wrangell volcanic belt. This is suggested by a rather uniform petrographic province of alkalic affinity which may stretch from the western Alaska volcanic fields to Prindle volcano, 179 (FOSTER *et al.* 1966) in the east, some 200 km northeast of Wrangell Mountains.

Alaska Peninsula and the Aleutian Islands and Range

Ninety percent of the probable azimuths of dike concentration of volcanoes in this narrow volcanic belt trend N45°W $\pm$ 30° which is normal to oblique to the strike of the volcanic belt (Table 1, Fig. 3). This fact strongly suggests that the maximum horizontal compressive stress, which determined the azimuths, is tectonic in origin and that the azimuths are parallel to the maximum principal stress (NAKAMURA 1977). This conclusion is supported by comparison of the azimuths with the directions of relative motion between the Pacific and North American plates (Fig. 5). Ninety percent of the volcano-derived azimuths are within 20° of the expected sloping line that gives the azimuths of the relative plate motion at individual volcanoes derived from computations by JACOB *et al.* (1977).

The scatter of individual azimuths around the value expected from the relative plate motion may be the result of local mechanical heterogeneities, rather than deviations in the regional stress field. This is suggested by the better fit of the azimuths of higher quality to the expected value (Fig. 5). Consider the azimuths at two volcanoes, Kiska (101) and Okmok (133), which strongly deviate from the expected orientation; the azimuth for Kiska volcano (101) is dependent primarily on the location of a flank crater on the extreme southwest (Fig. 2). Excluding this point, this still poorly determined azimuth becomes northwesterly. Since this particular

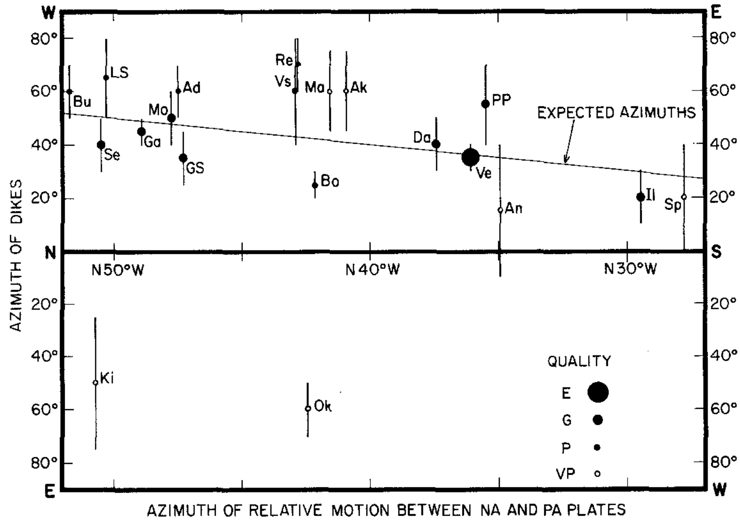

Figure 5
Comparison between the probable azimuths of dike concentration of volcanoes in Aleutian arc (Table 1) and the direction of relative motion between the Pacific and North American plates at individual volcanoes (JACOB *et al.* 1977). The diagonal solid line indicates the locus along which the two directions (slip vectors and dike distributions) coincide. Quality grades (Table 1) of the azimuths are shown by the different circle sizes; highest quality has the largest circle, 'poor' and 'very poor' are not differentiated.

vent is located totally outside the volcanic edifice, there might be a problem in assigning it as a flank vent of Kiska volcano. For this reason, the azimuth, N50°E, for Kiska volcano is considered rather questionable.

The N60°E azimuth for Okmok volcano (133) is ranked as very poor in quality because the NW trend of three eruption fissures is nearly normal to the long axis of the distribution of flank craters. In addition to this feature, Okmok volcano has some other features that are exceptional for volcanoes in the Aleutian arc. Okmok is essentially a basaltic shield volcano, while all the other volcanoes in the Aleutian arc are composite volcanoes (SMITH and SOULE 1973). The development of circular instead of radial structures is remarkable on this volcano. Post-caldera cones, aligned along the periphery of the caldera floor (Fig. 2) appear to indicate ring fissures. Outside the caldera, the northern arcuate ridge and the eastern arcuate ridge also represent parts of ring fissures. The scatter in trends of roughly radial normal faults is so large that some make a right angle with each other (Fig. 2). All these features are more or less suggestive that the magnitude of two horizontal principal stress axes are rather close and that the maximum principal stress is vertical, at least near the summit region. Alternatively, the stress field in the vicinity of Okmok volcano may have been quite variable in time. The data are insufficient to establish this explanation, however.

Comparing the azimuths obtained from the easternmost Aleutian volcanoes (174, 178) with the one obtained from the Castle Mountain fault (7), we find poor agreement (Fig. 3). However, the direction of PHS indicated by the Castle Mountain fault (7) may actually strike in a more northwesterly direction if the dip-slip component given in Table II is taken into account. This fault has a dip-slip component with the north side up. Such dip-slip displacement exists also on neighboring thrust faults (5, 6 and 10). Therefore, assuming that the dip-slip component is of a reverse-faulting type, the given azimuth of N80°W should rotate somewhat clockwise. Furthermore, according to DETTERMAN *et al.* (1974), the displacement of the Castle Mountain fault 'has involved predominantly dip-slip reverse movement in the Late Tertiary (mainly post-Oligocene)' and 'the most recent breaks along the fault most probably originate through roughly 2.3 m of dip-slip movement'. On the other hand, the azimuth (N20°W) for Spurr volcano is of very poor quality (see description). The azimuth for Iliamna volcano could be oriented westerly, if we consider a possible down-slope bend towards east of the inferred fissure on the southeast flank (Fig. 2).

Eastern Alaska region

Only one azimuth has been obtained in this region. Edgecumbe volcano (186), however, may well represent the direction of the maximum horizontal tectonic stress of the surrounding region. The azimuth, N40°E, has high quality and coincides very well with the direction of the principal horizontal shortening N35°–40°E, indicated by a nearby, possibly active, dextral strike-slip fault, the Chatham Strait fault, that runs in a N10°W direction for more than 400 km (LONEY *et al.* 1975).

Arc and back-arc region

From the results thus far discussed and shown in Fig. 3 the overall pattern of the azimuths of maximum horizontal compression in the Aleutian and Alaskan regions can be seen to have the following features: (1) Along the consuming plate boundary, the azimuths are nearly parallel to the directions of relative motion between the North American and Pacific plates. In this case it is reasonable to infer that the azimuth of MHC corresponds to the direction of the maximum principal stress. (2) Along the dextral strike-slip or transform segments of the plate boundaries, the azimuths are obliquely rotated in a clockwise sense from the strike of the boundary. (3) The stress trajectories implied by the pattern of these azimuths spread inland in a curved fan shape with the axis of symmetry running roughly in a N25°–30W direction from the eastern end of the Aleutian trend (Fig. 3). These trajectories curve westward into the Bering Sea shelf back-arc region where they become almost perpendicular to the azimuths of MHC for the central Aleutian arc. The overall pattern is crudely similar to the result of PAVONI (1971). In his global map of 'principal horizontal pressure as derived from recent and late Cenozoic tectonics', four trajectory lines gradually approach a west-northwesterly trend in the Bering Sea from an almost north-south trend in eastern Alaska.

Considering the time during which the volcanoes and faults have been active, the above overall stress pattern may have been maintained for at least tens to hundreds of thousands years and probably longer.

Most features obtained by the present study appear to be explained, at least qualitatively, by the relative plate motion alone. Even the more east-westerly trend in northwest Alaska may be explained by a simple elastic plate model with driving forces of ridge push, trench pull and drag force (RICHARDSON *et al.* 1976). The nearly right-angle relation between azimuths of the central Aleutians and the immediate back-arc region may be difficult, however, to explain by such a simple model. Another explanation of the observed pattern might be that the stress system in the back-arc region has its own origin compatible with an upward movement beneath the back-arc lithosphere. This suggestion is supported by the difference in geographical distribution and in chemistry of associated magmas between volcanoes of the arc and back-arc regions, respectively.

Provided the origins of the tectonic systems are different for the arc and back-arc regions, an interesting implication emerges which demands that the compressive stress at the arc, probably generated by the convergence of plates, is transmitted towards the back-arc region for only about 500 km where it is gradually replaced by a tensional stress system of different origin. Such a situation should in some cases favor opening of marginal seas (KARIG 1974). On the other hand, the observed pattern implies also that if back-arc spreading takes place at all, it should occur not within the island arc volcanic belt, but within a subparallel linear region a few hundred kilometers behind the arc. Within arcs where the strike of the maximum horizontal compression is normal or oblique to the arc axis, e.g., as in the Aleutians (this study), Japan and central Chile (NAKAMURA 1977), splitting of the arc along its axis is mechanically impossible.

In terms of the three-dimensional principal stress system, the obtained azimuths of MHC correspond most probably to the direction of the maximum principal stress in the overthrusting plate near the island arc, while these azimuths probably correspond to the direction of the intermediate principal stress in the back-arc region. In the Aleutian arc case, the boundary between compressional and tensional stress regions passes somewhere south of the Pribilof Islands (96 and 99), north of the Healy Creek fault (10), and somewhere between the Wrangell Mountains and Prindle volcano, north of the Denali fault system (3).

Conclusion

Application of the method that uses volcanic features as indicators of the average, long-term orientation of tectonic stress, as proposed by NAKAMURA (1977), is demonstrated in the Aleutian–Alaska region by mapping the obtained azimuths of maximum horizontal compression. The internal consistency of this mapping and its successful correlation with the expected stress field in the Aleutian arc reconfirms our basic premise that flank eruptions result from the formation of radial dikes, the average orientation of which is controlled by tectonic stress. This confirmation also encourages us to extend the method to radial and parallel dikes of the geologic past. Extension to the past would imply that if combined with accurate dating of intrusive rocks one could reconstruct similar maps for trajectories of tectonic stress orientation for various geologic epochs.

The long-term stress pattern can be checked by, or provide an evaluation of, short-term or transient stress indicators such as seismic focal mechanism solutions and *in situ* stress or strain measurements.

The strike and sense of motion on major faults also provide long-term information on the orientation of tectonic stress. The mapped pattern of the azimuths of the maximum horizontal compression obtained from volcanoes and faults is internally consistent and a reasonable interpretation is possible in terms of relative motion of elastic plates of the Pacific and North America. In the back-arc area, however, it is necessary to assume an independent stress source which causes tensional deviatoric stress in the overlying lithosphere.

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