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# THE ORIGIN OF SUMMIT BASINS OF THE ALEUTIAN RIDGE: IMPLICATIONS FOR BLOCK ROTATION OF AN ARC MASSIF

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*Abstract.* It is proposed that many summit basins along the Aleutian Arc form from the clockwise rotation of blocks of the arc massif. Summit basins are arc-parallel grabens or half-grabens formed within the arc massif and are commonly located near or along the axis of late Cenozoic volcanism. Geomorphically, the Aleutian Arc appears to consist of contiguous rhombic blocks of varying size, tens to hundreds of kilometers in length. The boundaries between adjacent blocks are delineated by fault-controlled canyons that cut the southern slope of the arc transverse to its regional trend. Evidence that these blocks have rotated clockwise is provided by the triangular-shaped summit basins bordering the blocks to the north, oblique physiographic trends, offsets in the summit platform, and broad deflections in the southern slope of the arc. We present a model for block rotation that involves translation of blocks parallel to an arc. It is suggested that block rotation, which appears to have accelerated in late Cenozoic time, is linked to (1) a shift in the Euler pole for the Pacific plate, (2) the consequential start-up of late Cenozoic volcanism, (3) improved interplate coupling instigated by sediment flooding of the Aleutian Trench, and (4) westward subduction of northeast striking segments of the inactive Kula-Pacific Ridge.

## INTRODUCTION

The Aleutian Ridge consists of an island-crested cordillera--the Aleutian Arc--and a broad forearc region dominated geomorphically by the Aleutian Terrace (Figure 1).



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The igneous massif of the arc includes many actively subsiding intra-arc or "summit" basins. Prior studies of these basins by Scholl et al. [1975b] recognized their extensional origin and drew attention to the tectonic implications of arc dismemberment at a convergent margin.

The first models for summit basin development relate to the vertical forces of arc magmatism. The correlation between summit basins and offsets in the volcanic alignment trend (Figure 1) suggests that basin formation is somehow related to the magmatic front of the arc [Scholl et al., 1983; Geist et al., 1985]. Perry and Nichols [1966], Marlow et al. [1970], and Anderson [1971] proposed that the arc was crestally distended from magmatic ascension, and either magmatic withdrawal [Marlow et al., 1970] or extrusion down the northern insular slope [Perry and Nichols, 1966] formed the summit basins. Rather than involving magmatic ascension, Grim and Erickson [1969], Spence [1977], and House and Jacob [1983] later postulated that fracture zones spread as they are subducted beneath the Aleutian Arc, creating a loss in magmatic head and consequently causing subsidence in the crust of the arc directly above the fracture zones. Although Amlia and Amukta basins could have evolved in response to the subduction of Amlia Fracture Zone south of the basins, this model cannot explain the occurrence of other summit basins that are not aligned with known Pacific plate fracture zones (Figure 1).

We postulate instead that summit basins reflect shear and normal stresses transmitted to the arc from the obliquely converging Pacific plate. Various authors have suggested block rotation models to explain basin formation and transverse faulting in a strike-slip environment. Basins in southern California, such as the Los Angeles, Santa Lucia, Santa Maria, and Cuyama basins, are thought by Luyendyk et al. [1980] to have formed by block rotation between a Pacific-North American plate shear couple. Block rotation models have also been used to reconcile structures with conflicting orien-

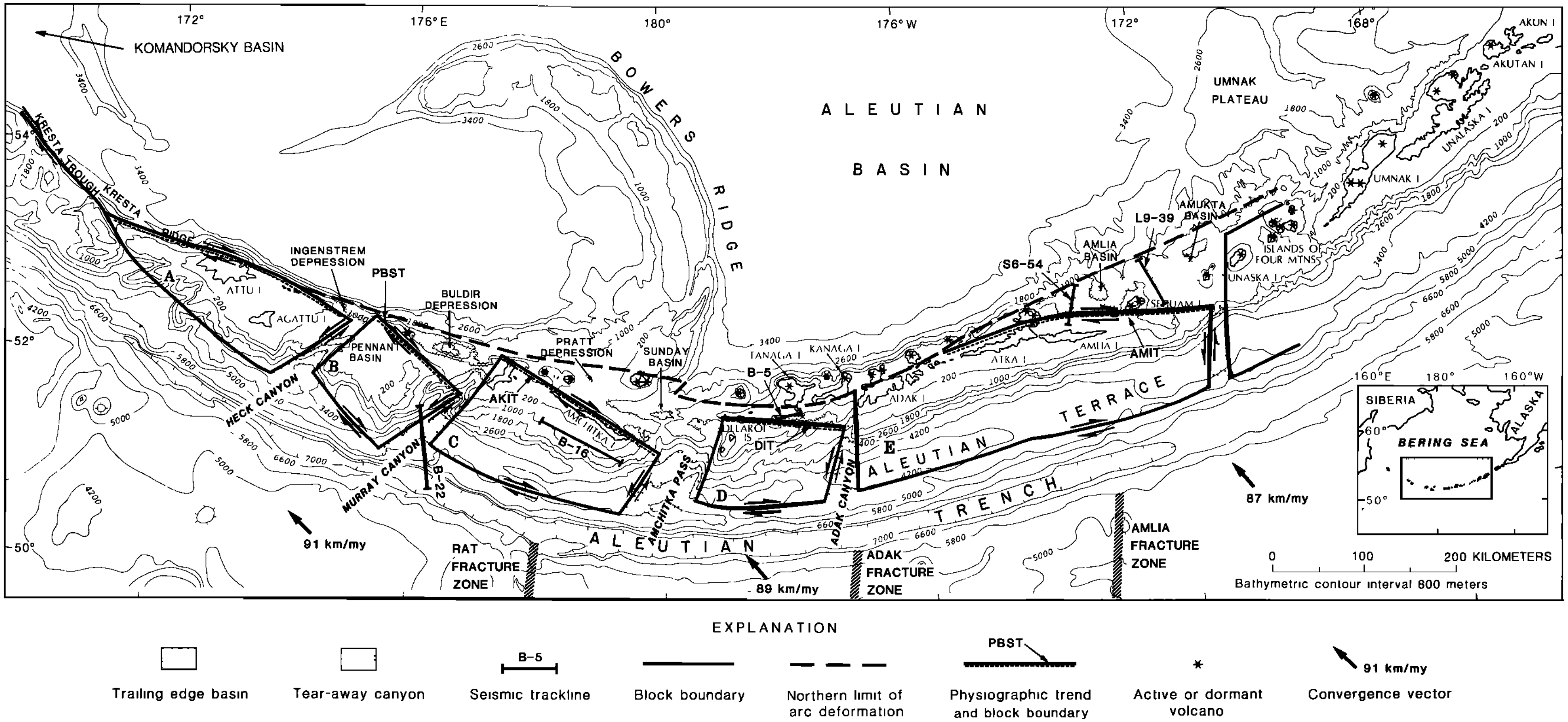


Fig. 1. Bathymetric map of the central and western Aleutian Arc (contour interval: 800 m.). Major summit basins and transverse tear canyons indicated by shading. Active and dormant volcanoes designated by stars. Convergence vectors shown with associated linear velocity [Engebretson et al., 1986]. Block boundaries approximate areas of cohesive movement and were identified using detailed bathymetric maps by Nichols and Perry [1966]. Northern block boundaries are located along southern margin of trailing-edge extension; eastern and western boundaries are located along transverse canyons; and southern boundaries are located along presumed trench-slope overthrust. The blocks are designated as follows: A: Near block; B: Buldir block; C: Rat block; D: Delarof block; E: Andreanof block. Dashed line locates the inferred southern extent of the undeformed North American plate. Lineaments include PBST, scarp along northeast side of Pennant basin; AKIT, Amchitka Island trend; DIT, Delarof Island trend; AMIT, Amlia Island trend. Track lines of seismic reflection profiles referenced in other figures are indicated.

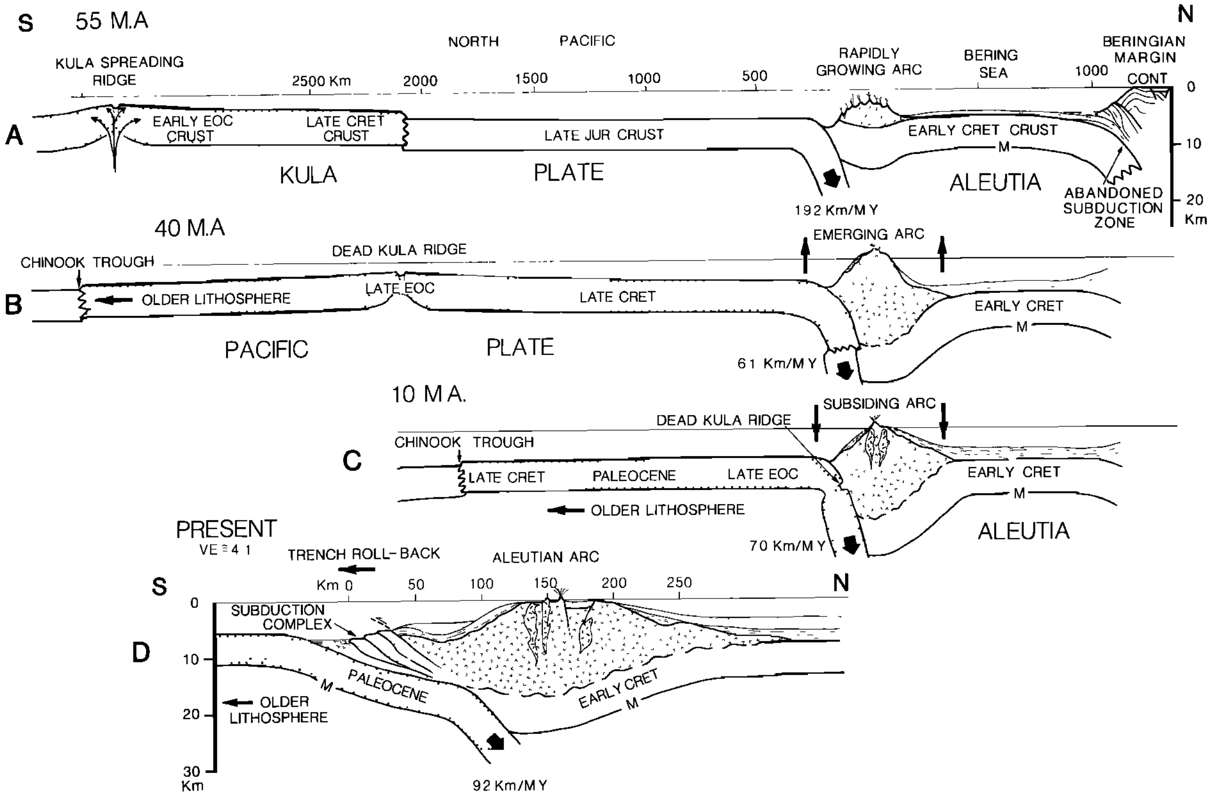


Fig. 2. Schematic diagram illustrating the tectonic history of the Aleutian Arc (taken from Scholl et al. [1987]). Linear convergence velocities are from Engebretson et al. [1986] at 173°E longitude. (a) At 55 Ma, active spreading at the Kula Ridge between the Pacific and Kula plates, initial subduction at the Aleutian Arc, and cessation of subduction at the Beringian margin occurred contemporaneously. (b) By at least 40 Ma, spreading at the Kula Ridge had ceased, and the Aleutian Arc underwent regional uplift attributed to the subduction of more buoyant Pacific lithosphere of the former Kula plate. (c) At roughly 10 Ma, subduction of the dead Kula Ridge initiated regional subsidence of the arc as increasingly older lithosphere was subducted. (d) Starting at about 5 Ma to the present, the subduction complex and the forearc region formed, owing to an abrupt increase in trench floor turbidite sedimentation. Accelerated block rotation of the Aleutian massif began approximately at this time.

tations in Iran [Freund, 1970a], the Galilee [Freund, 1970b; Ron et al., 1984], the Mojave desert of California [Garfunkel, 1974], and within the San Andreas Fault zone [Nicholson et al., 1986]. Recently, Cowan et al. [1986] linked the orientation of crustal blocks caught in the Sovanco Fracture Zone of the Pacific plate to block rotation. In an island arc setting, McCabe [1984] has shown that differential rotation of arc segments can result from the collision with thick crustal masses (e.g. seamounts) on the subducting plate. For these and other tectonic settings, MacDonald [1980] has described various schematic block rotation models to explain paleomagnetic declination anomalies.

The Aleutian Arc provides an excellent opportunity to study block rotation because many of the associated structural features are evident from its physiography. In addition, seismic reflection data provide a means of analyzing deformation of the rotated blocks and the surrounding framework at depth. In continental studies, trailing-edge depressions are infrequently observed, and accordingly, other mesoscopic mechanisms have been employed to accommodate movement between the rotated block and the surrounding framework [Garfunkel and Ron, 1985]. Although deformation of the Aleutian Arc is complex, macroscopic features related to block rotation are evident.

## TECTONIC FRAMEWORK

Various models for the evolution of the Aleutian Arc have been proposed since the appearance of the pioneering paper of Coats [1962]. (These include Shor [1964], Pitman and Hayes [1968], Scholl et al. [1968], Grow and Atwater [1970], Marlow et al. [1973], and Scholl et al. [1975a].) Most interpretations are consistent with a two-stage constructional/destructional history for the arc related to Cenozoic plate motions in the Pacific region. Recent reviews of the geologic history of the arc are presented by Scholl et al. [1983, 1987] and Vallier et al. [1988].

The Aleutian Arc originated when the north Pacific subduction zone of the Kula plate shifted southward from the Koryak and Beringian continental margin to the present offshore position of the arc (Figure 2a) [Scholl et al., 1987]. The 50-55 m.y. age for the oldest rocks found on the Aleutian Islands [Rubenstone, 1984; Scholl et al. 1986] suggests that subduction at the Beringian continental margin ended in earliest Tertiary time. Voluminous magmatic growth built the bulk of the arc by middle Eocene time and started to diminish by at least 40 Ma [DeLong et al., 1975; Scholl et al., 1987]. The decrease in magmatism at this time coincides with a change in the motion of the Pacific plate, 43 Ma, and the contemporaneous abandonment of the Kula-Pacific spreading center, 43-45 Ma [Engebretson et al., 1986; Lonsdale and Smith, 1986]. The new plate configuration resulted in a marked decrease in the rate of subduction from as much as 200 km/m.y. for the Kula plate prior to 43 Ma, to 58-70 km/m.y. for the Pacific plate (including the remains of the old Kula plate). (All subduction rates and azimuths refer to those reported by Engebretson et al. [1986] relative to the North American plate at 173°W longitude.) The shift at 43 Ma, signaled by the bend in the Emperor-Hawaiian seamount chain [Dalrymple et al., 1980; Duncan and Clague, 1985] also increased the obliquity of subduction, further contributing to the reduction of magma generation along the arc. Rocks that formed the bulk of the Aleutian Ridge in Eocene time are collectively referred to as the lower series [Scholl et al., 1983].

The Oligocene and Miocene history of the arc was marked by the intrusion of epizonal plutons accompanied by uplift and warping of the crestal region [Marlow et al., 1973; Citron et al., 1980]. Uplift was probably initiated by the subduction of younger and more buoyant oceanic lithosphere as the Kula Ridge approached the arc from the south (Figure 2b) [Scholl et al., 1987]. Igneous and sedimentary rocks of Oligocene and Miocene age constitute the stratigraphic middle series of the Aleutian Ridge [Scholl et al., 1983].

Tectonic sinking of the ridge along with localized extensional deformation of the crestal region characterizes the late Cenozoic history of the arc (Figures 2c and 2d). Regional subsidence has been attributed to subduction of segments of the long-dead Kula Ridge beginning at about 10 Ma [Engebretson et al., 1986; Lonsdale and Smith, 1986], and the consequential underthrusting of increasingly older and denser oceanic lithosphere beneath the arc. Summit basins formed beginning in late Miocene to early Pliocene time, and were subsequently filled with sediment derived from ridge crest denudation and late Cenozoic volcanism [Geist et al., 1987]. The latest volcanic episode, starting 5 Ma, coincided with an increase in the rate of Pacific plate subduction to approximately 87 km/m.y. at a more northerly azimuth [Engebretson et al., 1986]. Sedimentary and igneous rocks that accumulated in Pliocene and Quaternary time form the stratigraphic upper series of the Aleutian Ridge [Scholl et al., 1983].

## PRESENT BLOCK GEOMETRY

East of 171°E longitude (near Attu Island), five major blocks are identifiable along the Aleutian Arc: Near block, Buldir block, Rat block, Delarof block, and Andreanof block (Figure 1). The block boundaries shown in Figure 1 are highly idealized and attempt only to delineate regions of cohesive movement bounded by zones of the arc that are significantly disrupted by normal and strike-slip faults. The boundaries are located chiefly on the basis of geomorphic evidence, using 100-fathom (182.9 m) contour interval bathymetric maps [Nichols and Perry, 1966], and seismic reflection profiles. The northern boundaries of the blocks are defined as the southern edge of the corresponding summit basins. The eastern and western boundaries, in most places, are constrained by the location of major transverse canyons. The southern boundaries are located along the seaward edge of the arc massif, which, inferred from multichannel seismic data, overthrusts a thick accretionary wedge or subduction complex in the vicinity of the trench-slope break (Figure 2d). In the absence of seismic data coverage, the southern boundary is roughly constrained by the trend of the trench-slope break and the southern insular slope.

Near block, extending from Kresta Trough to Heck Canyon (Figure 1), is internally deformed by arc-parallel strike-slip faults, which we interpret as arising from highly oblique convergence along the western part of the Aleutian Arc. Narrow and deeply incised arc-paralleling canyons, such as Kresta Trough, are probably expressions of these faults [Scholl et al., 1987]. Ingenstrem Depression, a narrow summit basin, bounds the block to the northeast (Figure 1) and is associated with the westernmost known location of late Quaternary volcanism [Scholl et al., 1976].

Buldir block is bounded to the west and to the east by Heck and Murray Canyons, respectively, and to the north near the southern edge of Buldir Depression (Figure 1). We suspect that the southern boundary of the block lies near the trench-slope break, as evidenced by a deflection of the trench slope south of the southeastern corner of the block. Buldir Depression, an unusually deep summit basin with geomorphic evidence of active volcanism on its floor [Marlow et al., 1970], formed as a summit basin north of Buldir block. Pennant Basin, on the other hand, lies within the boundaries of Buldir block (Figure 1) and is formed by a downflexure of the basement surface adjacent to the northern bounding scarp as seen on multichannel seismic reflection data [Scholl et al., 1987].

Rat block extends from the well-defined western boundary at Murray Canyon to a less well-defined eastern boundary at a broad zone of deformation in the Amchitka Pass region (Figure 1). Several small summit basins separated by narrow horst blocks lie between Rat block and Bowers Ridge. Pratt Depression and Sunday Basin are two of the larger basins formed to the north of Rat block.

Delarof block extends from a down-to-the-west transverse scarp bordering the Amchitka Pass region to seismically active Adak Canyon (Figure 1). Although there are no large summit basins bordering the Delarof block to the north, a narrow extensional valley borders the west trending bathymetric high surmounted by the Delarof Islands as seen on bathymetric and seismic data (Figure 3). Also, small summit basins, since filled by detritus from nearby volcanic centers, may have formed to the north near Tanaga and Kanaga islands. Numerous small transverse canyons cutting the southern margin of the Delarof block suggest that it has been segmented into several small subblocks.

The Andreanof block, as described by Spence [1977], is bordered to the west by Adak Canyon and to the east by a broad canyon south of Yunaska Island (Figure 1). To the north, the eastern part of the Andreanof block is bordered by Amlia and Amukta basins, two of the largest summit basins along the arc. Isopach maps from seismic reflection data indicate that the two basins formed as a down-to-the-north half-graben (Figures 4 and 5), which later separated into two

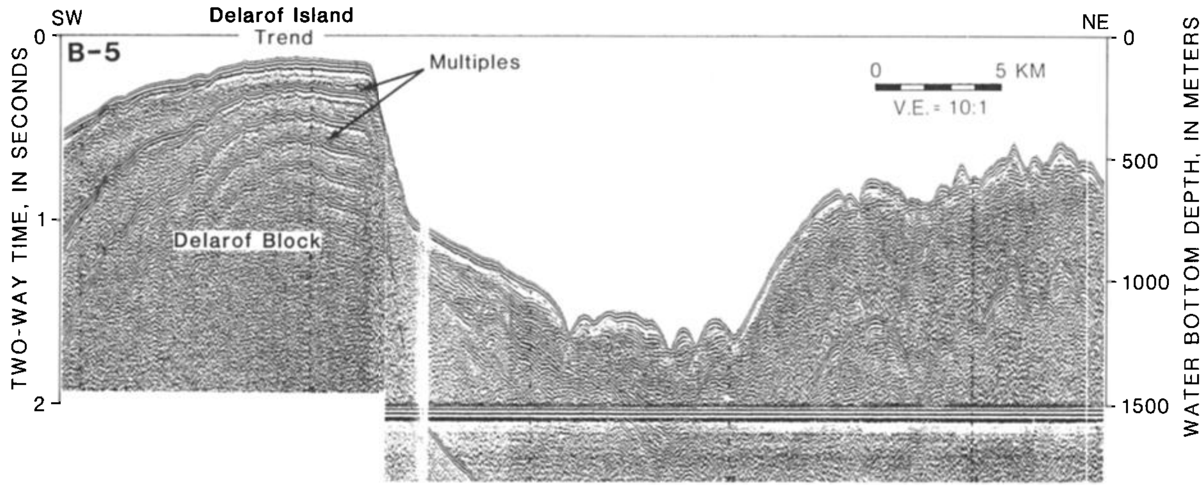


Fig. 3. ENE-WSW single-channel seismic line B-5 from the Delarof Island trend, across a recently formed extensional valley, and onto the summit platform near Kanaga Island (see Figure 1 for location).

depocenters by the formation of the Seguam volcanic complex [Geist et al., 1987]. The southern margin of the block is most likely located near the trench-slope break, oriented subparallel to the Aleutian Trench.

## EVIDENCE FOR BLOCK ROTATION

The geomorphology of the Aleutian Arc (Figure 1) suggests that blocklike segments of the arc have undergone clockwise rotation about a vertical axis. Many elongate crestal trends, such as those surmounted by Amchitka and Amlia islands, appear to have been rotated 15° to 25° from the regional trend of the arc. Other oblique-trending features include basin-bordering scarps. We propose that summit basins are "trailing-edge" depressions formed in the wake of a clockwise-rotating block as it tears away and moves westward from the unrotated massif. The southern slope of the arc correspondingly deviates in places from an arc-parallel alignment and protrudes into the forearc region of the Aleutian Terrace (for example, the southern margin of Buldir and eastern Andreanof blocks, Figure 1).

The interblock boundaries are considered to be surficially manifested by transverse canyons that disrupt the southern slope of the Aleutian Ridge (for example, Murray and Adak canyons). These canyons are fault-controlled, as first described by Gates and Gibson [1956] and further elaborated on by Spence [1977]. Based on bathymetry and single-channel seismic records, transverse canyon faults appear to commonly exhibit both normal, down-to-the-west displacement and left-lateral displacement that offset the southern slope (Figure 1). Transverse canyon faults also deform the blocks themselves (for example, Bird, and Seymour canyons traversing Rat block, Figure 6), but generally exhibit much less relief than transverse canyon faults at block boundaries.

For example, the effects of rotation of Buldir block through the forearc region are shown on single-channel seismic line B-22 (Figure 7). The profile extends from the eastern edge of the block, across the forearc basin, southeast-

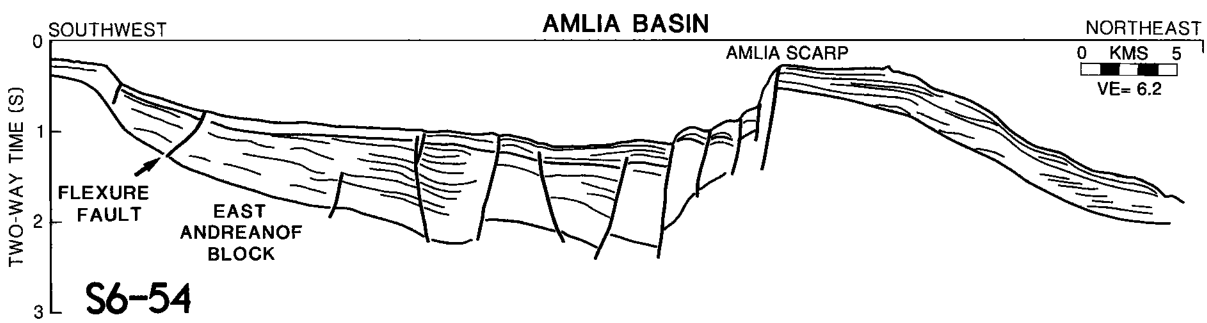


Fig. 4. Interpreted line drawing of N-S single-channel seismic line S6-54 across Amlia Basin, separating eastern Andreanof block from unrotated massif to the north (see Figure 1 for location). Section exhibits the half-graben structure of Amlia Basin and the large vertical displacement across the northern boundary fault expressed by Amlia scarp.

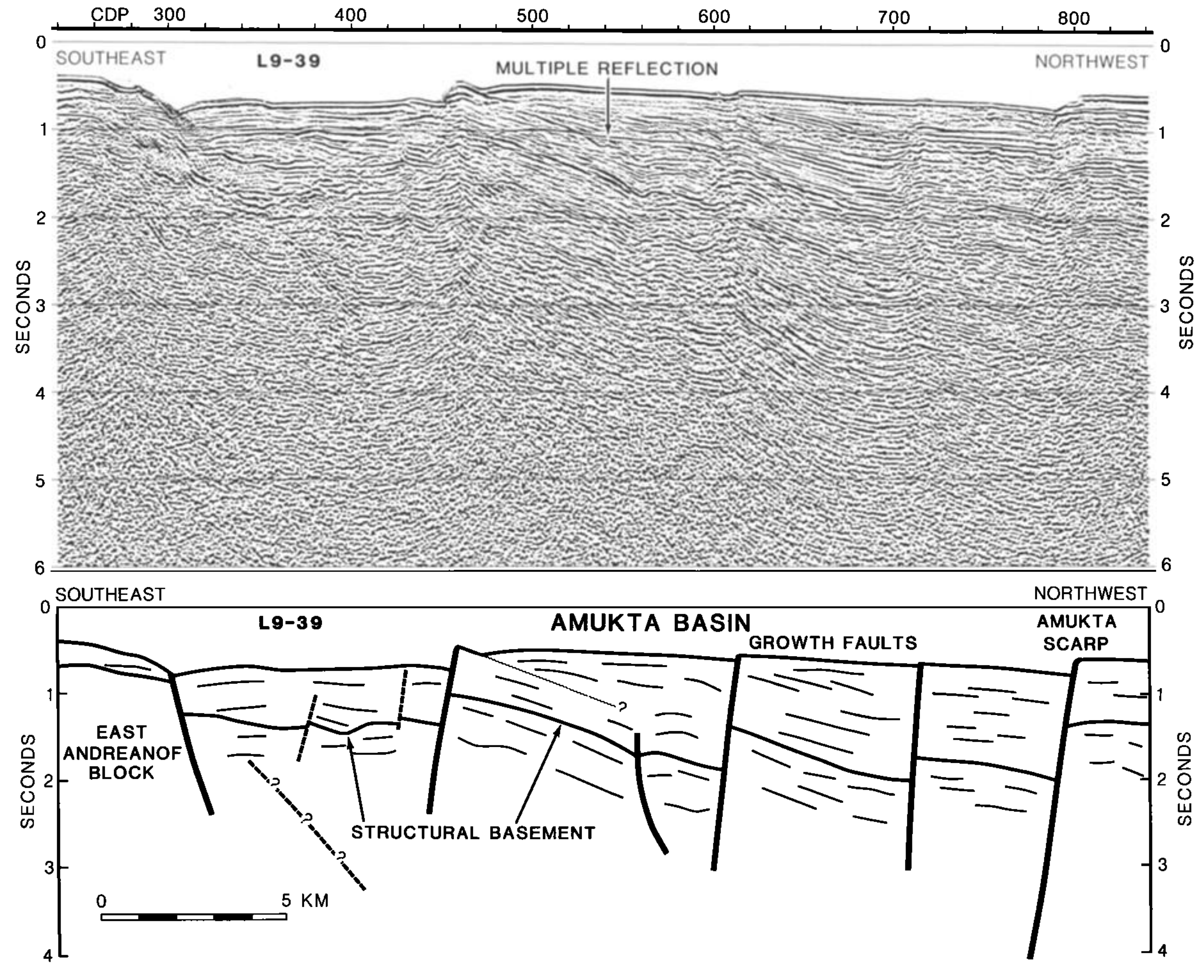


Fig. 5. N-S multichannel (24-fold) seismic line L9-39 across Amukta Basin, separating eastern Andreanof block from unrotated massif to the north (see Figure 1 for location). Like Amlia Basin, Amukta Basin is a half-graben, but with less displacement across the northern boundary fault expressed by Amukta scarp.

ward to the Aleutian Trench (Figure 1). The thick, forearc sequence of upper series deposits abruptly terminates against the edge of the block. Although termination of upper series beds against the canyon wall is partially related to basin edge deposition, the downsection increase in dip toward the wall, the presence of high-angle faults disrupting the basinal section, and basement and sedimentary rocks suspended higher on the canyon wall imply that the eastern edge of Buldir

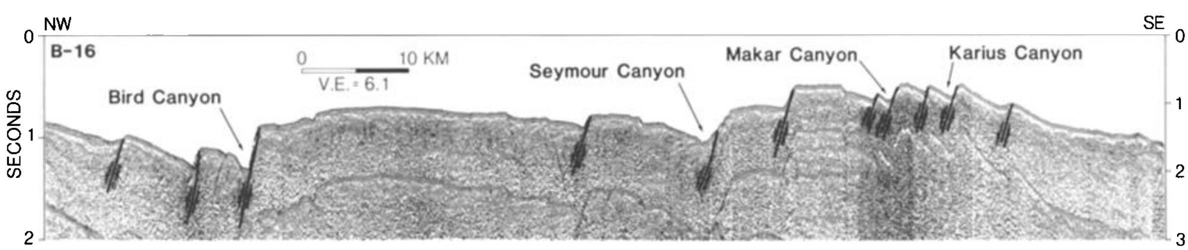


Fig. 6. ESE-WNW single-channel line B-16 traversing Rat block. Note the characteristic down-to-the-west displacement along the intrablock transverse faults.

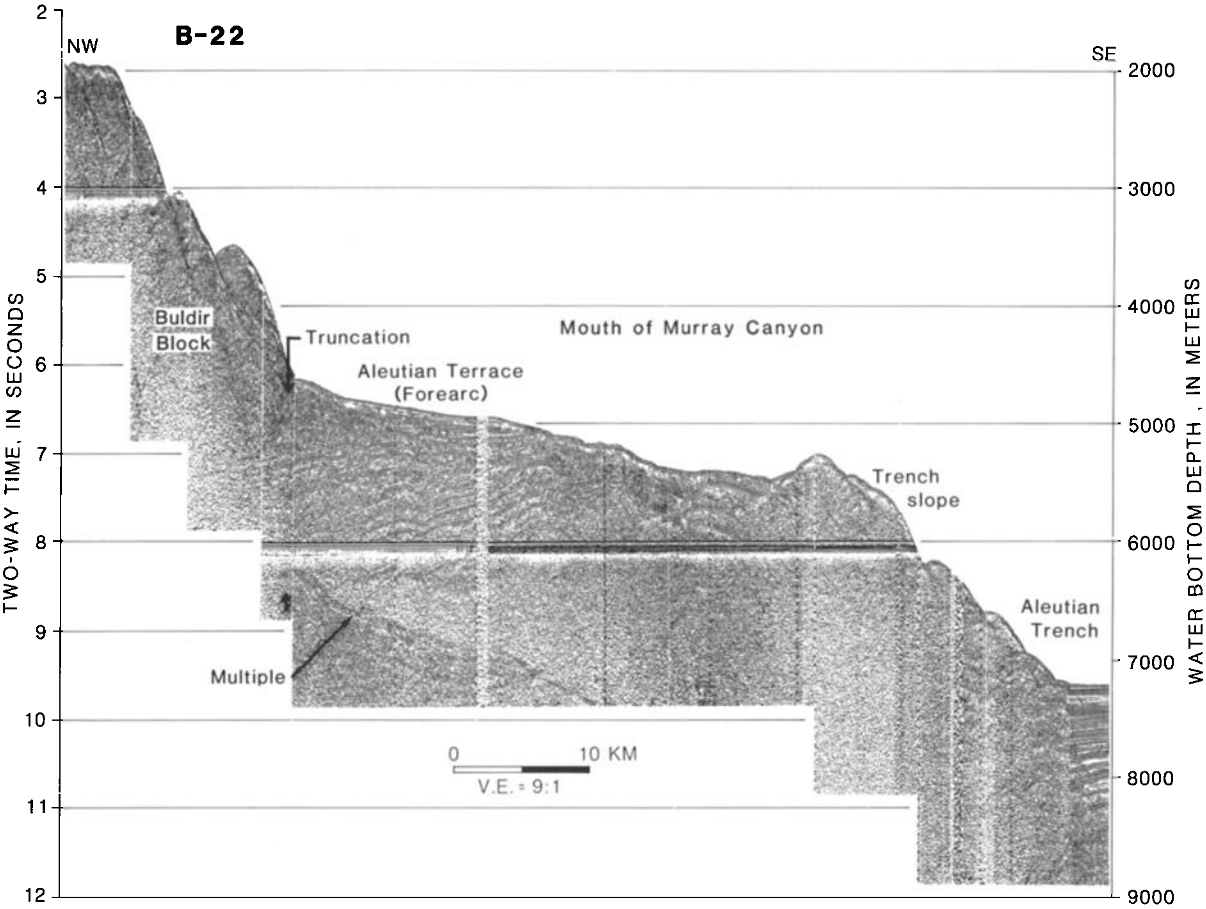


Fig. 7. NW-SE single-channel seismic line B-22 across the eastern boundary of Buldir block (see Figure 1 for location). The line traverses the eastern part of Buldir block, the forearc basin, the trench-slope break, and the Aleutian trench.

block is a late Cenozoic fault scarp. Normal displacement is inferred from the single-channel seismic data, and left-lateral displacement is inferred from the bathymetry.

From the orientation of fault scarps bordering the summit basins and lineaments oblique to the trend of the arc, an estimate can be made for the amount of rotation each block has incurred since the time of formation of summit basins (5-10 Ma). Table 1 lists the estimated rotation for each block and the lineament used for measurement. As noted in Table 1, we view the Andreanof block to consist of an eastern and western sector based on geomorphic evidence for different amounts of rotation, including a prominent change in the regional strike of the southern slope of the arc. Western Andreanof block appears unrotated, while the southern slope of eastern Andreanof block deviates well into the forearc, suggesting a significant amount of flexing between the two sectors and arc-parallel extension in the region of Atka Island.

Each block appears to have been rotated clockwise about a vertical axis located near the northwestern corner of the block. The amount of rotation generally increases from east to west (Table 1), with the exception of Near block, which is dominated by the effects of right-lateral shear deformation probably arising from highly oblique subduction. Many summit basins (Amlia-Amukta, Sunday, and Buldir, for example) form between the rotated and unrotated parts of the arc massif. These basins characteristically have a large surface area (1500-2500 km$^2$) and great depth to basement (2-5 km). The size and shape of these basins depend on the following factors: (1) amount of block rotation, (2) arc-parallel length of the block, and (3) cohesiveness of the rotated block as it tears away from the adjoining platform. Other basins (Pennant, for example) form on either the rotated or unrotated portions of the massif from distributed extensional deformation and downwarping arising from the rotational movement.

Paleomagnetic data support the contention that segments of the arc massif have undergone clockwise rotation. Cores of upper Eocene to lower Oligocene rocks on Umnak Island [Harbert et al., 1984a,b] and Amlia and Adak islands [Harbert et al., 1985] document a significant clockwise rotation of the magnetic declination vector since initial magnetization. Using the paleomagnetic data, Harbert [1987] indicates that Amlia Island has rotated clockwise 70°±23° since early Oligocene time. The amount of paleomagnetically measured clockwise rotation along the length of the arc ranges from 10° to 70° (W. P. Harbert, personal communication, 1986)

TABLE 1. Estimated Clockwise Rotation of Aleutian Blocks (See Figure 1)

| Block | Rotation | Lineament |
|---|---|---|
| Near | 3° | Scarp bordering Ingenstrem Depression |
| Buldir | 23° | Scarp bordering Pennant Basin (PBST) |
| Rat | 20° | Amchitka Island lineament (AKIT) |
| Delarof | 14° | Delarof Island lineament (DIT) |
| Western Andreanof | 0° | none |
| Eastern Andreanof | 15° | Amlia Island lineament (AMIT) |

and probably attests to not only late Cenozoic rotation but older episodes of rotation in Tertiary time.

Although the shallow crustal seismicity of the Aleutian Arc is difficult to interpret tectonically because of the predominance of low-magnitude events, the complexity of the crustal velocity structure, and the diversity of focal mechanism solutions (E. R. Engdahl, personal communication, 1986), some earthquakes can be linked to interblock motion and rotation. For example, an event on July 4, 1966, at an approximate depth of 13 km near the boundary of the Rat and Delarof blocks is interpreted to reflect left-lateral movement along an arc-normal fault [Stauder, 1968]. (It should be noted, however, that using the other nodal plane produces an equally valid interpretation of right-lateral movement along an arc-paralleling fault arising from oblique subduction.) Shallow events at the extreme western end of the arc [Stauder, 1968] and near Adak Island [LaForge and Kisslinger, 1978] and Atka Island [Ekström and Dziewonski, 1986] also support right-lateral shearing of the arc. In contrast, detailed studies by LaForge [1977], LaForge and Kisslinger [1978], and LaForge and Engdahl [1979] show that seismicity in the Adak Canyon region (the boundary between the Delarof and western Andreanof blocks) is a result of arc-parallel tension, suggesting that in this locality, normal faulting is predominant. The lack of any consistent shallow crustal events arising from arc-normal oriented extension or compression seems to indicate that block rotation along the northern and southern boundaries is generally aseismic. However, the location of the interblock boundaries is supported by the fact that most deep earthquake aftershock sequences are commonly confined to the region enclosed by the block boundaries [Mogi, 1969; Stauder, 1972; Spence, 1977], suggesting that the blocks are generally more coupled to the underthrusting plate than to each other.

## MODEL FOR BLOCK ROTATION

### *Model Description*

In developing a kinematic model to explain block rotation of the Aleutian massif, a simplified model can be considered where a series of blocks are affected by equal and opposite forces applied at a constant angle along the boundary common to all blocks. In the example shown in Figure 8, although there is no strike-slip movement across the common boundary, the forces are not aligned with the interblock boundaries, producing strike-slip movement across these boundaries and rotation of the blocks [Nur et al., 1986] (Figure 8b). Where the blocks pivot depends upon the geology of the arc. Pivot about a northwest corner axis, as we envision for the Aleutian Arc, can be explained by lower cohesive strength of the massif parallel to the arc along the magmatic front.

In addition to rotation, block translation parallel to the arc must be included to account for the lack of observed compressional features that would otherwise develop across

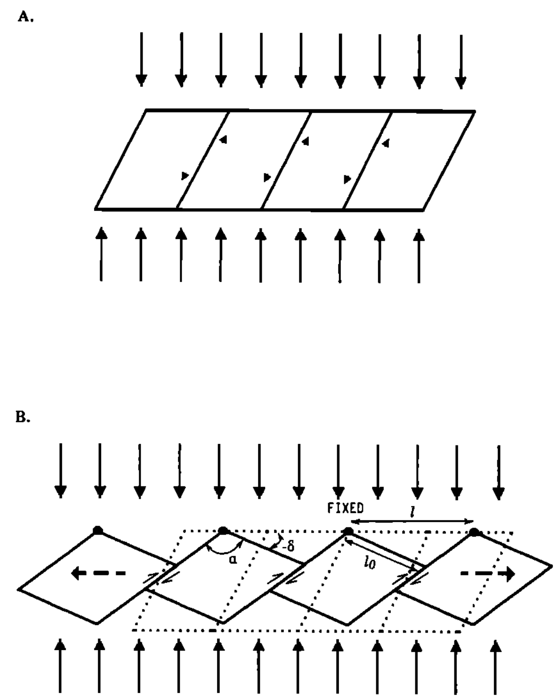


Fig. 8. Simplified model illustrating the origin of rotational movement across a zone of distributed deformation. (a) Rotation occurs if the boundary forces are not aligned with the interblock boundaries. Rotation is clockwise if the forces are oriented counterclockwise from the inter-block boundaries, counterclockwise if they are oriented clockwise from the inter-block boundaries. (b) If the pivot points are free to move along the boundary, but remain in contact with it, the blocks move past each other with strike-slip motion. Unrotated position of blocks shown with dashed lines. The parameters used in equation (1) are annotated: $\delta$, the angle of rotation, $\alpha$, the angle the interblock boundaries make with the common boundary of the blocks prior to rotation (the orientation of unrotated fracturing), $l_0$, the distance between pivot points prior to rotation, and $l$, the distance between pivot points after rotation. Heavy dashed arrows show the direction of block translation away from the fixed pivot point.

interblock boundaries if the pivot points remained fixed. The fact that transverse canyon faults of the Aleutian Arc appear to have normal components of slip, in addition to left-lateral displacement, suggests that the pivot points of the blocks do not stay fixed relative to the unrotated framework, but propagate with increasing speed westward along the northern boundary of the arc. A structural model that includes the combined effects of rotation and translation (Figure 8b) was developed by Freund [1974], Ron et al. [1984], and Garfunkel and Ron [1985]. Garfunkel and Ron [1985] explain that the gaps formed behind the trailing edge of the block are "misfits" in the idealized model and usually are not seen in geologic settings. However, for the Aleutian Arc, the Sovanco Fracture Zone [Cowan et al., 1986], and the southern California basins [Luyendyk et al., 1980], the "misfits" are geologically realized as highly extended basinal areas.

Certain geometric relationships are evident from models of Figure 8b as described by Ron, et al. [1984] and Garfunkel and Ron [1985]. If the pivot points remain in contact with the boundary originally common to all blocks, but are free to move along that boundary, Garfunkel and Ron [1985] showed that the spacing between pivot points increases after rotation by a factor $\lambda$, the elongation, where

$$\lambda = \frac{l}{l_0} = \frac{\sin(\alpha)}{\sin(\alpha - \delta)} \tag{1}$$

In equation (1), $\delta$ is the angle of rotation (counterclockwise rotation is positive), and $\alpha$ is the orientation of unrotated fracturing or the angle between the interblock boundary and the boundary originally common to all blocks (Figure 8b). Garfunkel and Ron [1985] also define a parameter $\kappa$ equal to the ratio of the fault displacement (right-lateral is positive) to the spacing between faults. For the idealized model of Figure 8b, $\kappa$ is identical for each block. Garfunkel and Ron [1985] relate $\kappa$ to the model parameters through the following equation:

$$\kappa = \frac{\sin(\delta)}{\sin(\alpha)\sin(\alpha - \delta)} \tag{2}$$

In Table 2, the parameters $\alpha$, $\delta$, $l_0$, and $l$ are listed for each of the Aleutian blocks. The error range listed arises from the irregularity and multiple orientations of physiographic trends used to define these parameters. Total elongation of the arc

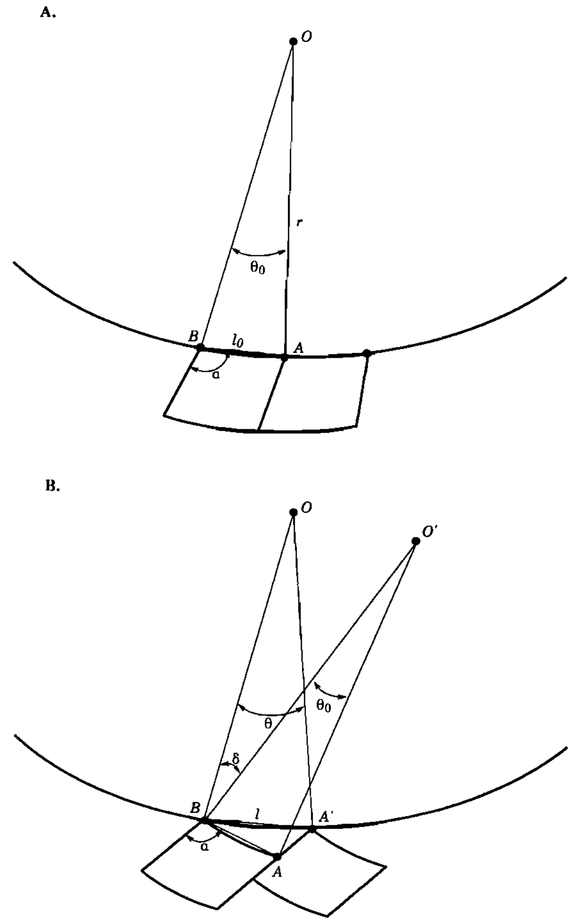


Fig. 9. Block rotation and translation along an arc. (a) Prior to rotation, point $O$ is the center of the unrotated arc segment; $\alpha$ is the angle the interblock boundaries make with the chord $AB$; $l_0$ is the length of the chord between pivot points prior to rotation; and $\theta_0$ is the angle subtended by arc $AB$. (b) The arc between pivot points lengthens after rotation from arc $AB$ to arc $A'B$. $O'$ is the center of the rotated arc segment; $\delta$ is the angle of rotation; $l$ is the length of the chord between pivot points after rotation; and $\theta$ is the angle subtended by arc $A'B$.

TABLE 2. Geometry Parameters for Aleutian Blocks (See Figure 10)

| Block | $\delta(\pm 3°)$ | $\alpha(\pm 3°)$ | $l$ (±25 km) | $l_0$ (±25 km) |
|---|---|---|---|---|
| Near | -3° | 120° | 212 | 200 |
| Buldir | -23° | 104° | 151 | 118 |
| Rat | -20° | 102° | 208 | 193 |
| Delarof | -14° | 86° | 141 | 138 |
| Western Andreanof | 0° | 108° | 151 | 151 |
| Eastern Andreanof | -15° | 107° | 270 | 242 |

due to block rotation using known values of $\alpha$ and $\delta$ in equation (1) is 9%, equal to that derived from the ratio of the sum of $l$ to the sum of $l_0$ for all of the blocks. Because the amount of rotation changes along the arc, $\kappa$ is not expected to be the same for each of the blocks.

The rotation model for rectilinear blocks [Garfunkel and Ron, 1985] can be modified to consider block rotation along an arc of radius $r$ from center, $O$ (Figure 9a). The initial distance between pivot points is $r\theta_0$, where $\theta_0$ is the angle subtended by the arc $BA$. Angle $\alpha$, defined as before, is the angle between chord $BA$ and the interblock boundaries. The block is rotated through an angle $\delta$, moving the center of the arc segment from $O$ to $O'$ (Figure 9b). The arc between the pivot points after rotation is arc $BA'$, subtending the angle $\theta$. Therefore, the elongation ratio, $\lambda$, is given by

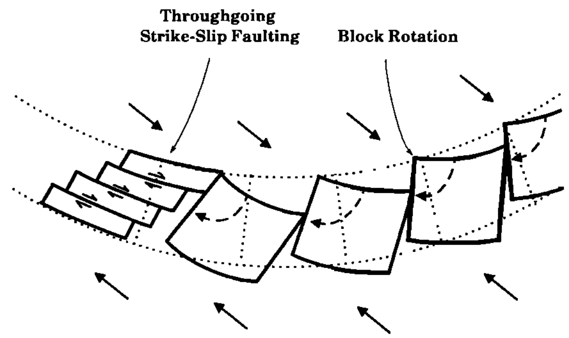


Fig. 10. Rotation of blocks along an arc with a constant orientation of forces. The obliquity of the force field with respect to the arc increases to the left, as does the magnitude of the shear couple and the amount of block rotation. Increasing amounts of rotation in the direction of block translation creates geometric gaps between blocks that are interpreted to correspond to transverse tear canyons. Block rotation continues until the arc-parallel shear stress reaches a critical point where throughgoing strike-slip faults are prevalent.

$$\lambda = \frac{BA}{BA'} = \frac{r\theta}{r\theta_0} = \frac{\theta}{\theta_0} \qquad r \neq 0 \tag{3}$$

The center of the undeformed arc ($O$) and the angle between pivot points ($\theta$) are usually easier to determine than $O'$ and $\theta_0$. Therefore, it is useful to express $\theta_0$ and the elongation, $\lambda$, in terms of $\theta$, $\alpha$, and $\delta$. For triangle $A'BA$,

$$A'BA = \delta + O'BA - OBA'$$

Therefore, angle $A'BA$ equals $\delta+\frac{1}{2}(\theta-\theta_0)$, and angle $BA'A$ equals $180°-\delta-\frac{1}{2}(\theta-\theta_0)-\alpha$. The law of sines dictates that

$$\frac{\sin(\alpha)}{l} = \frac{\sin\left[180°-\dfrac{\theta-\theta_0}{2}-\delta-\alpha\right]}{l_0}$$

or

$$\frac{\sin(\alpha)}{2r\sin\left[\dfrac{\theta}{2}\right]} = \frac{\sin\left[\dfrac{\theta-\theta_0}{2}+\delta+\alpha\right]}{2r\sin\left[\dfrac{\theta_0}{2}\right]}$$

Reducing gives $\theta_0$ in terms of $\theta$, $\alpha$, and $\delta$:

$$\theta_0 = 2\tan^{-1}\left[\frac{\cos(\alpha-\delta)-\cos(\alpha-\delta+\theta)}{2\sin(\alpha)-\sin(\alpha-\delta)+\sin(\alpha-\delta+\theta)}\right] \tag{4}$$

with the limitation that

$$\frac{\theta_0}{2} \geq \theta-180°+\alpha-\delta$$

Note that neither $\lambda$ nor $\theta_0$ depends on $r$, the radius of the arc. Total elongation of the arc predicted by this model is 10%, slightly larger than elongation predicted by the rectilinear model.

*Additional Considerations*

The tectonic setting and the forces acting upon the Aleutian Arc are more complex than assumed by the previously described translation-rotation model. First, rotationally induced translation of blocks parallel to the arc poses the interesting question of which of the blocks' pivot points remained fixed with respect to the North American plate and in which direction block propagation occurred. If the pivot point of Buldir block has remained fixed over time, blocks east of Buldir block must have translated eastward with respect to the North American plate. In this case, the easternmost block would have been thrust against the eastern sector of the Aleutian Arc or the connecting Alaska Peninsula. A more plausible case is that the pivot point of the easternmost block remained fixed and all other blocks have translated to the west. The effects of westward translation may have been taken up by a complex zone of shear deformation west of Buldir block, or possibly linked to spreading in the Komandorsky Basin (Figure 1) during late Tertiary time [Bogdonov and Neprochnov, 1984]. Of course, any of the pivot points may have remained fixed, or different points may have been fixed at different times. However, it seems more likely that the blocks would be structurally anchored next to the Alaska Peninsula where the magnitude of the arc-parallel shear couple is greatly diminished.

Second, the westward increase in the amount of block rotation can be related to an increase in the obliquity of convergence and a higher convergence rate farther from the Euler pole of the Pacific plate. An increase of block rotation in the direction of block propagation produces gaps between blocks in the geometrical model as shown in Figure 10. These gaps, similar to but smaller than the summit basins, reflect extension in an arc-parallel direction, explaining the occurrence of transverse normal faults and associated tear canyons (Figure 6). Thus, the apparently conflicting strain indicated by the normal component of displacement on summit basin faults (arc-normal extension) and transverse canyon faults (arc-parallel extension) is resolved by a block rotation model that involves increasing amounts of rotation in the direction of block translation. From Near block westward, the arc-parallel component of shear stress exceeds a value such that block rotation is replaced by throughgoing arc-parallel strike-slip faulting (Figure 10).

Third, some blocks may splinter upon rotation, forming narrow horst blocks separated by trailing-edge basins as observed with Rat block (Figure 1). Splintering may be due to a widening of a zone of low cohesive strength parallel to the arc, or to multiple zones of low cohesive strength. Basins located within blocks rather than behind the trailing edge, such as Pennant Basin, may be a preliminary stage of block splintering reflected by distributed extensional downwarping of the basement surface.

Finally, the nature of block rotation at depth is not addressed by the two-dimensional model. Rotational deformation may grade downward to homogeneous deformation as crustal ductility increases [Garfunkel and Ron, 1985] or may end abruptly along a detachment surface. For the latter possi-

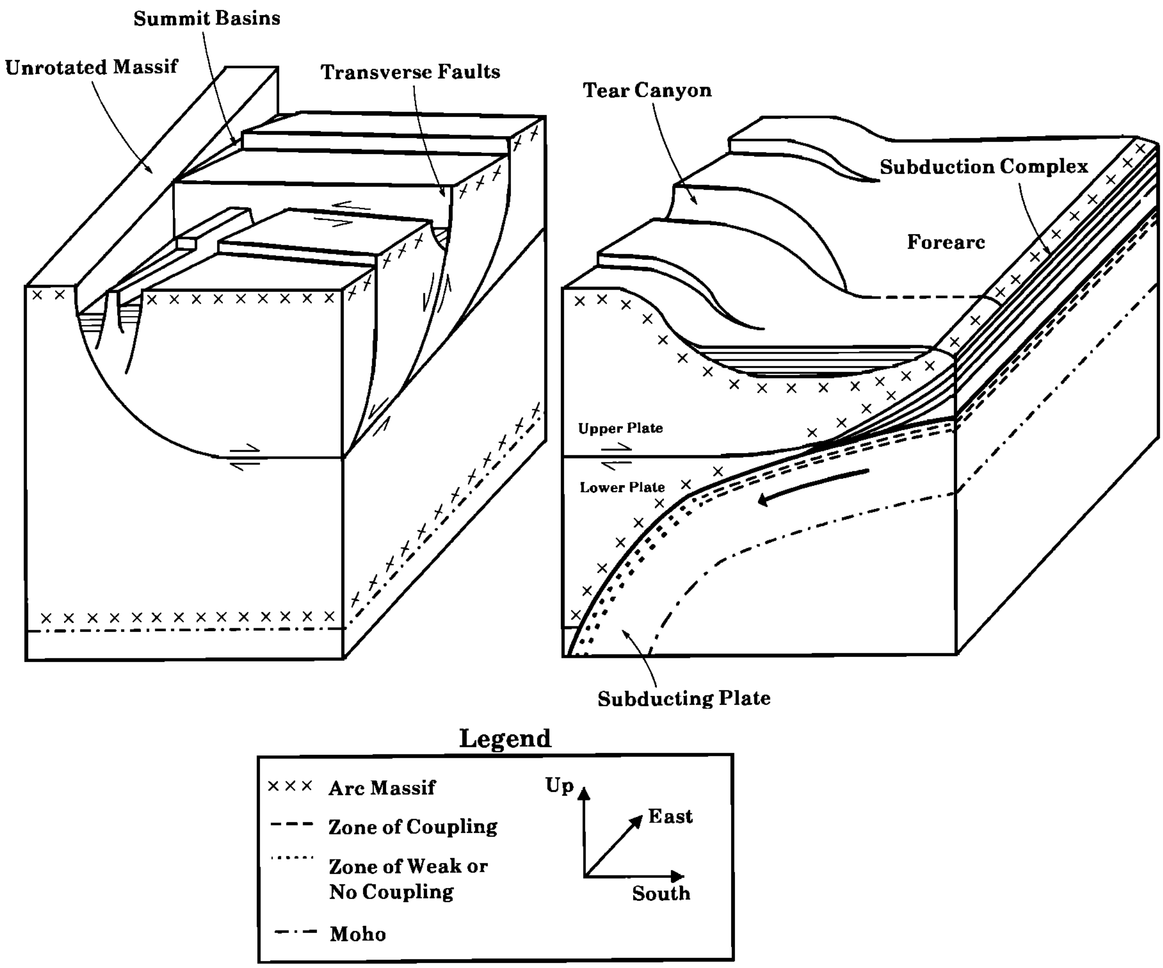


Fig. 11. Schematic, exploded block diagram illustrating a possible configuration for faulting related to block rotation. In addition to the blocks rotating about a vertical axis trenchward and eventually over the accretionary complex, the blocks are rotating about a horizontal axis from down-to-the-west displacement on transverse faults. The detachment fault shown extending from the summit basins to the subduction complex is one possible explanation for how rotational deformation is accounted for at depth. Arc-normal basal shear across the detachment is intended only to represent rotational movement of blocks in the upper plate and not horizontal movement of the lower plate transmitted by the subducting lithosphere.

bility, a detachment surface underlying the Aleutian Arc is envisioned to project to the surface at the northern edge of the summit basins and ramp over the subduction complex at its southern edge (Figure 11).

*Tectonic Causes for Block Rotation*

The important question to be addressed is the tectonic conditions necessary for block rotation. Block rotation of the Aleutian arc may have existed since the formation of the arc, providing an explanation for the occurrence of lower and middle Tertiary basinal strata uplifted and exposed on many of the Aleutian Islands [McLean et al., 1983; Hein et al., 1984] and the discrepancy between paleomagnetically measured rotations [Harbert, 1987] and late Cenozoic rotation measured from the geomorphology of the arc. However, certain changes in the interaction between the Pacific and North American plates is likely to have initiated the latest phase of block rotation.

As indicated by the upper series age of basin fill and of related extensional faulting on the islands [e.g., Panuska, 1980], modern summit basins began to appear in late Miocene to early Pliocene time, concurrent with four other tectonic changes: (1) the start-up of the latest phase of arc magmatic activity about 5-6 Ma related to a more normal direction and a higher rate of subduction along the Aleutian margin [Engebretson et al., 1986]; (2) the late Cenozoic formation of the Aleutian Terrace forearc basin [Scholl et al.,

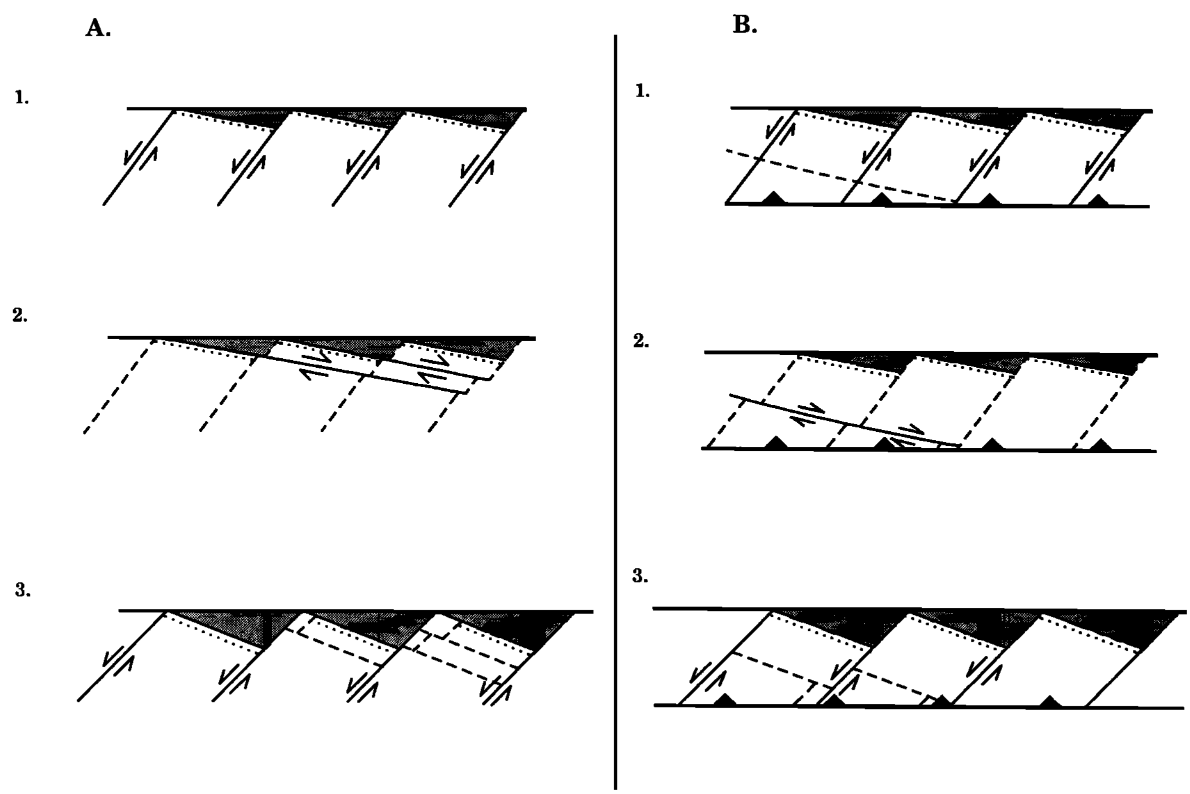


Fig. 12. Schematic diagram illustrating block rotation with throughgoing strike-slip faulting near (a) the trailing edge and (b) the leading edge. Shaded region represents gap between rotated and unrotated arc massif. Stage 1: Clockwise block rotation causes left-lateral slip along inter-block boundaries. Stage 2: Right-lateral strike-slip faulting offsets left-lateral faults (dashed). Stage 3: Resumption of block rotation occurs along reactivated left-lateral faults.

1983, 1987; Harbert et al., 1986]; (3) the related formation of a massive accretionary wedge in response to sediment flooding of the Aleutian Trench [McCarthy et al., 1984; McCarthy and Scholl, 1985]; and (4) the late Cenozoic subduction of northeast trending segments of the dead Kula-Pacific spreading ridge beneath the western sector of the arc [Engebretson et al., 986; Lonsdale and Smith, 1986]. We speculate that the Pacific and North American plates were weakly coupled during most of Tertiary time, but as the accretionary wedge grew in late Cenozoic time, dewatered and compacted sediment was subducted beneath the forearc massif [McCarthy and Scholl, 1985], increasing interplate coupling [Ruff and Kanamori, 1983] and promoting block rotation. Improved coupling west of Buldir block may have also attended the collision between the arc and the northeasterly trending Kula Ridge as the ridge swept beneath this sector of the arc [Lonsdale and Smith, 1986]. At about the same time, the onset of volcanism along the arc is thought to have diminished the cohesive strength of the massif, making the blocks more susceptible to failure along the thermally softened magmatic front. The westernmost known location of arc volcanism at Ingenstrem Depression coincides with the westernmost block undergoing rotation. Since all three of the events occurred penecontemporaneously, it is difficult to determine the primary cause that initiated block rotation.

## EFFECTS OF BLOCK ROTATION

### *Structural Effects*

Certain structural and volcanic effects observed along the arc can be attributed to block rotation. Summit basin grabens and half-grabens are considered to be extensional structures formed behind the trailing edge of the rotating block (Figure 11). Because lateral (westward) translation of the blocks is thought to accompany rotation, normal faulting may be interrupted by right-lateral faulting as shown schematically in Figure 12a. This bimodal style of faulting may explain the complex nature of faulting along the northern margin of the arc.

Along inter block boundaries, transtensional faults are interpreted to result from increasing amounts of rotation in the direction of block propagation. These faults often form large transverse canyons that widen away from the pivot points as shown in Figure 10. Normal displacement, in addition to left-lateral slip, predominantly occurs down to the west, implying that the blocks also rotated about a horizontal axis, in a clockwise sense looking north (Figure 11). Minor transverse wrench faults with the same sense of displacement deform the rotated blocks between and parallel to the major block bounding transverse faults.

The leading edge of the block is predominantly affected by compression against the accretionary wedge and underlying subducted oceanic crust, although compression may be mitigated by trench rollback. Along the seaward edge of the Aleutian Terrace, folding and thrust faulting of the arc massif is prevalent near the trench-slope break (Figure 11) [Vallier et al., 1988; Scholl et al., 1987; Ryan and Scholl, 1985]. Leading-edge compressional deformation is complex. It can, in part, be involved with the deformation of the underthrusting accretionary wedge [McCarthy and Scholl, 1985]. As rotation progresses, blocks are observed to produce geomorphic deflections in the strike of the landward trench slope. Faulting at the leading edges of Near, Buldir, and Rat blocks is thought to be further complicated by throughgoing right-lateral faults that periodically transport slivers of the massif westward (Figure 12b). This style of deformation gives the southern margin of the blocks a notch-like appearance as, for example, observed with Buldir block and may explain the difference between the arc-normal width at opposite ends of the eastern Andreanof and Rat blocks (Figure 1).

### *Volcanic Effects*

Kay et al. [1982] postulate that magmatic geochemistry is controlled by the tectonic location of magma bodies within segments of the arc. The segment boundaries they described, in most areas, correspond to block boundaries described in this text. They note that tholeiitic differentiation trends relate to a faster magmatic ascent through more fractured lithosphere located at or near interblock boundaries. Calc-alkaline trends, on the other hand, attest to slower ascent through less fractured lithosphere within the blocks.

Block rotation may provide the tectonic control on magmatic ascent and, therefore, the differentiation trends of the volcanoes. Most of the Aleutian volcanoes (except for volcanoes on Seguam and Amukta Islands) are located north of the rotated blocks, on unrotated massif. If the massif extensionally fractured in the wake of the rotating block, faster magmatic ascent should occur near the trailing edge, thus fostering tholeiitic volcanism. This hypothesis is supported by the location of the large tholeiitic complex on Semisopochnoi Island opposite Sunday Basin and calc-alkaline volcanoes near the pivot points of Buldir, Rat, and western Andreanof blocks (Figure 1) [Kay et al., 1982]. At first, the tholeiitic center on Atka Island, located in an area of little rotational movement, appears to be an exception to this model. However, flexure of the Andreanof block at this location could presumably produce the necessary fracturing. We agree with Kay et al., [1982] that tectonic segmentation of the overriding plate appears to control the eruption location of the two differentiation trends.

Concerning the location of the volcanic centers, the effect of block rotation is minimal, because relatively few of the volcanoes are actually located on the rotated massif (Figure 1). The offset in the volcanic alignment trend is more aptly explained by changes in the configuration of the underthrusted plate across subducted fracture zones [Grim and Erikson, 1969; Spence, 1977; House and Jacob, 1983]. These authors note that older and denser crust subducting at a steeper dip on one side of the fracture zone results in a trench-volcano gap shorter than the gap created by subducting younger crust on the opposite side of the fracture zone.

## CONCLUSIONS

We propose that the Aleutian Arc massif is segmented into blocklike sectors that have rotated clockwise in late Cenozoic time, forming summit basins in their wake. The size of a trailing-edge summit basin depends on how much the block has rotated, the arc-parallel dimension of the block, and whether the block splintered upon rotation to form many small summit basins. The primary evidence for block rotation comes from the bathymetry and seismic profiles of the arc and the fabric of faulting associated with summit basins, although paleomagnetic and, to a lesser extent, seismicity data support block rotation.

A model for block rotation in the Aleutians must include translation of the blocks along the arc, because interblock compression is typically not observed. A rotation model proposed by Ron et al. [1984] and Garfunkel and Ron [1985] modified to account for the arcuate shape of the Aleutian Ridge, adequately describes block rotation and translation along the Aleutian Arc, with three additional considerations. First, the pivot point of the easternmost block probably has remained fixed with respect to the North American plate, and all other blocks have moved westward along the arc. Second, the magnitude of shear stress affecting the arc varies with the angle of convergence, causing an increase in the amount of rotation to the west and arc-parallel extension along interblock boundaries. Third, the blocks can splinter upon rotation in response to changes in the cohesive strength of the massif. Although block rotation may have been a continual process since at least middle Eocene time, accelerated fragmentation and splaying of the arc during the past 5 to 6 m.y. presumably reflects a change in the convergence vector at 5 Ma, the rapid growth of a massive accretionary wedge, and possibly the subduction of northeast striking segments of the dead Kula-Pacific spreading ridge beneath the western sector of the arc. It is suggested that an increase in lower-plate coupling beneath the outer part of the forearc provides the driving mechanism for accelerated block rotation in late Cenozoic time. Along with formation of summit basins, block rotation is thought to have produced or promoted the following effects: (1) behind the trailing edge, large amounts of crestal extension and changes in the magmatic differentiation trend along the chain of island arc volcanoes; (2) along inter-block boundaries, large canyons exhibiting left-lateral and normal, down-to-the-west offsets; and (3) ahead of the leading edge, possible overthrusting of the arc massif over the accretionary wedge in the vicinity of the trench-slope break.

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