Active displacement partitioning and arc-parallel extension of the Aleutian volcanic arc based on Global Positioning System geodesy and kinematic analysis

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ABSTRACT

Global Positioning System geodesy and structural analysis of parts of the Aleutian island chain support the interpretation of forearc migration westward along right-lateral transcurrent faults. Measured displacements are essentially arc parallel in the eastern (Unalaska Island) and western (Attu Island) parts of the arc and vary from 3.1 mm/yr to 31.4 mm/yr, respectively. At the center of the arc (Adak) subduction of the Amlia fracture zone disrupts the pattern of arc-parallel displacement and records an upper plate velocity of 9.6 mm/yr parallel to plate motion. Where active, displacement partitioning accommodates 30%–50% of the strike-slip component of plate convergence. In the area of impeded subduction partitioning ceases, suggesting that the process is sensitive to the degree of coupling across the plate-boundary megathrust. The differential arc-parallel displacements observed at the ends of the arc together with structural relations indicate substantial arc-parallel extension, which may play an important role in exhumation of high-pressure–low-temperature metamorphic rocks in ancient arc systems.

Keywords: arc-parallel extension, displacement-field partitioning, GPS geodesy, structure.

INTRODUCTION

In subduction systems where convergence is oblique to the plate boundary, displacement is partitioned into two components (e.g., Jarrard, 1986; Avé Lallemant and Oldow, 1988). One component is essentially perpendicular to the trench and is responsible for contractional structures oriented parallel to the plate boundary. The strike-slip component of convergence causes noncoaxial shear within the upper plate and lateral displacements along one or more margin-parallel transcurrent faults (Fig. 1).

Displacement partitioning in zones of oblique convergence is documented in ancient and active systems. Evidence for partitioning comes from geological, geodetic, and earthquake focal-mechanism studies of convergent plate boundaries around the world (e.g., Oldow et al., 1989). One of the best examples of partitioning occurs on the North Island of New Zealand, where the forearc is divided into several arc-parallel belts, some with a contraction axis normal to the plate boundary and others characterized by arc-parallel dextral strike slip (Cashman et al., 1992), confirming the interpretation of geodetic measurements by Walcott (1978). Similarly, studies of earthquake focal mechanisms in active convergent-plate boundaries (e.g., Ekström and Engdahl, 1989; McCaffrey, 1992) indicate forearc shortening essentially normal to, and strike-slip displacements parallel to, the arc. These studies also suggest that partitioning generally does not occur when the angle of obliquity is small (< 20°, Ekström and Engdahl, 1989; McCaffrey, 1992). With increasing obliquity the angle between the arc-normal and the shortening direction in the forearc increases as well, and about 55% of the arc-parallel component of convergence is transmitted to the forearc or intra-arc strike-slip faults (McCaffrey, 1996).

While displacement partitioning in oblique-convergence systems is well documented, extensional structures, particularly those related to arc-parallel stretching (Fig. 1), have not been recognized as important phenomena in oblique-convergence plate boundaries. Some earthquake focal mechanisms indicate arc-parallel extension by normal faulting, but these events are often dismissed as the product of plate warping along a curved boundary (e.g., Russo et al., 1992).

With recognition that exhumation of blueschists (Avé Lallemant and Guth, 1990) in ancient subduction complexes may partly be the result of arc-parallel extension, a better understanding of extensional deformation within oblique-convergence subduction zones is mandated. Because the original plate-boundary configurations and deformation histories of most ancient systems are not well known, the role of arc-parallel extension in convergent plate boundaries can be best assessed in active systems involving young, relatively undeformed rocks. On this basis, the Aleutian arc (Fig. 2) is an outstanding candidate made more attractive because of the high convergence rate between the Pacific and North American plates.

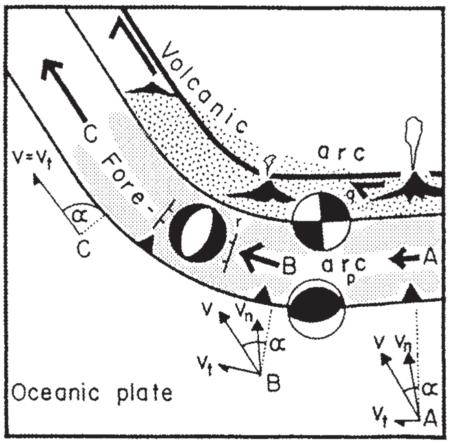

Figure 1. Hypothetical model for displacement partitioning and trench-parallel migration and extension of arc-forearc terrane due to oblique plate convergence along arcuate convergent plate boundary. Obliquity angle (α) of convergence-rate vector V between oceanic (Pacific) and volcanic arc (on North American plate) increases from A to C, from about 20° to 90°. Vector component (sub)normal to plate margin (Vn) decreases and component parallel to margin (Vt) increases from A to C. Vn is expressed by arc-normal shortening (arc-parallel folds and thrust faults) and Vt causes arc-forearc terrane to migrate westward along one or more strike-slip faults. As result of increase of Vt, arc-forearc terrane undergoes stretching (arc-perpendicular normal faults and fractures). Diagrams at p, q, and r are hypothetical earthquake focal mechanism plots related to thrusting, strike-slip faulting, and normal faulting, respectively.

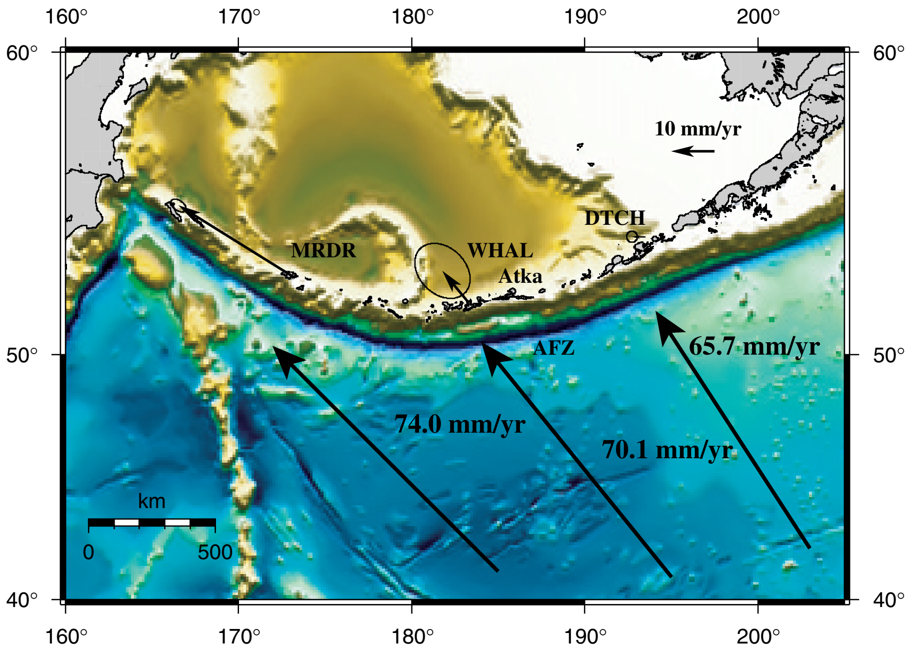

Figure 2. Map of Aleutian volcanic island arc and adjacent areas. Plate-convergence rate vectors south of arc for Attu, Adak, and Unalaska Islands according to NUVEL-1A (DeMets et al., 1994); vectors pointing away from Attu (MRDR), Adak (WHAL), and Unalaska (DTCH) are Global Positioning System determined velocities reported here. Amlia fracture zone in Pacific plate is denoted as AFZ.

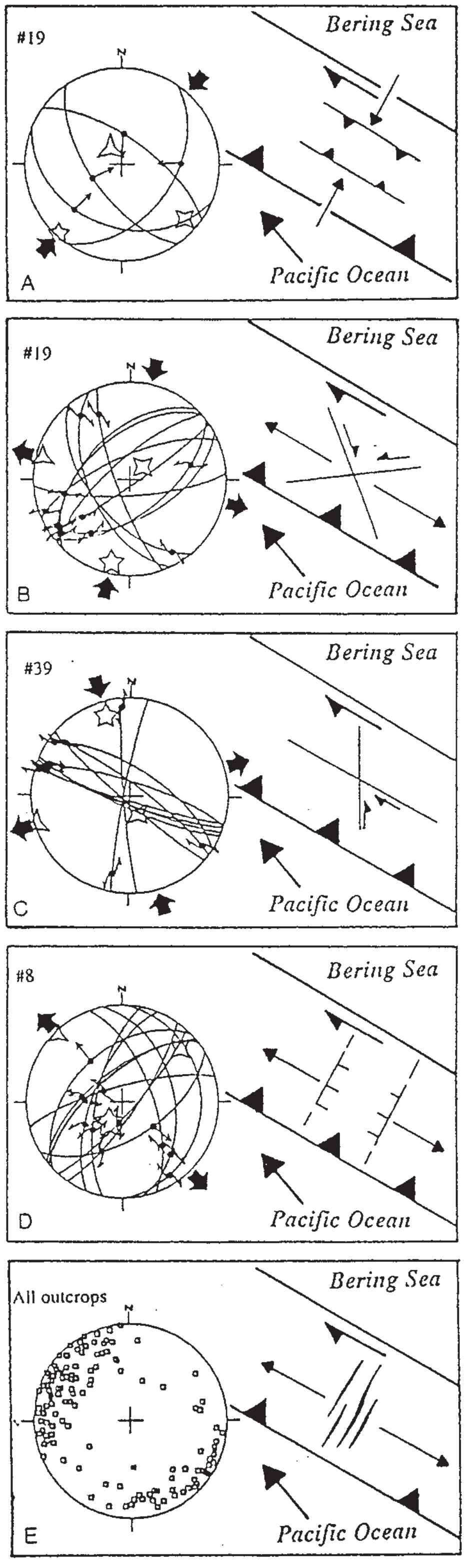

Figure 3. Structural data and interpretative sketch maps of selected outcrops on Attu Island. Structural data are shown in equal-area, lower hemisphere projections: faults and slip directions (A to D) and poles to vein-filled fractures and basaltic dikes (E) were analyzed with Angelier (1991) method: three-, four-, and five-pointed stars are identified here as major principal extension (X), intermediate principal strain axis (Y), and major contractional strain axis (Z), respectively.

ALEUTIAN ARC

The south-facing Aleutian volcanic island arc marks the boundary between the Pacific plate and the Bering Sea region of the North American plate (Fig. 2). The relative convergence between the two plates is 48 mm/yr in the east, where relative motion is normal to the arc (0° obliquity), and 78 mm/yr in the west, where convergence is almost parallel to the plate boundary (NUVEL-1A; DeMets et al., 1994).

The Aleutian arc west of the Alaska Peninsula is relatively young and formed in the mid-Eocene as an intraoceanic arc (e.g., Vallier et al., 1994). Earthquakes in the arc are dominated by contraction at the plate interface and by reverse and strike-slip focal mechanisms in the upper plate (e.g., Taber et al., 1991). The seismicity suggests active displacement partitioning within the arc in which only part of the arc-parallel component of convergence is transmitted to the upper plate (e.g., Ekström and Engdahl, 1989; McCaffrey, 1996).

The gross structural characteristics of the arc support interpretations of displacement partitioning. Bathymetric, seismic reflection, and GLORIA sidescan sonar data suggest that the Aleutian arc is cut by arc-parallel, anastomosing faults interpreted as dextral strike-slip structures (e.g., Ryan and Scholl, 1993). The possibility of large-scale longitudinal extension of the volcanic chain arises from bathymetric data and seismicity, interpreted by Spence (1977) to indicate that the central Aleutian Island chain is segmented into blocks. North-trending block boundaries are the sites of deep canyons that have asymmetric geometries, suggesting an origin as half-grabens (e.g., Spence, 1977). Geist et al. (1988) further suggested that the blocks underwent moderate clockwise rotation accommodated by left-lateral strike-slip displacements along the north-trending block-bounding faults.

STRUCTURAL ANALYSIS

To investigate the history of deformation within the arc, mapping and structural analysis have been carried out on four of the Aleutian Islands: Unalaska, Atka, Adak, and Attu (Avé Lallemant, 1996; Avé Lallemant et al., 1999a, 1999b; Comstock et al., 1999; Oldow et al., 1999). On the basis of our results, the deformation history of all islands appears to be very similar. In the following only a few examples from Attu Island are presented (Fig. 3), but they are representative of the structures found elsewhere in the arc.

The oldest structures are arc-parallel folds and thrust faults (Fig. 3A), but the most ubiquitous structures are conjugate strike-slip faults, which apparently formed by coaxial (plane strain) arc-parallel extension (Fig. 3B). A younger set of right-lateral strike-slip faults, associated with minor left-lateral shears, is oriented parallel to the arc (Fig. 3C). All these structures are crosscut by numerous normal faults (Fig. 3D) and veins and basaltic dikes (Fig. 3E) oriented at a high angle to the arc trend.

The normal faults (Fig. 3D), veins, and dikes (Fig. 3E) have orientations consistent with a 20° clockwise rotation with respect to the trend of the arc and may reflect small differential motion of tectonic blocks. In contrast, paleomagnetic observations (Harbert, 1987; Bazhenov et al., 1992) indicate substantial clockwise rotations in parts of the Aleutian arc. The large clockwise rotation recorded by paleomagnetic data, however, can be explained by westward translation of the volcanic islands along the curved plate boundary. In particular, since acquisition of remnant magnetization (ca. 50 Ma), westward migration of Attu Island accounts for about 50° of clockwise rotation and is consistent with paleomagnetic observations (Avé Lallemant, 1996).

All structures are consistent with displacement partitioning and arc-parallel extension. The arc-parallel thrusts and folds formed in response to the normal component of plate motion, whereas arc-parallel strike-slip faults record the contribution from the arc-parallel component of convergence. The conjugate strike-slip faults, normal faults, dikes, and veins record arc-parallel extension. Collectively, the structures suggest that the Aleutian arc is undergoing constrictional deformation during westward migration in response to oblique plate convergence.

GPS METHODS AND RESULTS

Global Positioning System (GPS) sites located on the Aleutian islands of Attu, Adak, and Unalaska were occupied in two campaigns during 1998 and 1999. GPS sites, consisting of metal markers fixed in bedrock, were occupied continuously over a period of 19–26 days (24 hr/day). Leica SR9500 sensors and AT504 choke-ring antennas were deployed and powered by solar panels and battery backup systems. Two earlier GPS data sets, collected in preliminary studies on Attu and Unalaska, used Trimble 4000 SSI receiver systems for a three-week period in July–August of 1996. The site on Attu is located on the southern side of the island, whereas the sites on Adak and Unalaska are located along the northern flanks of the islands.

The software BERNESE (Rothacher and Mervart, 1996) was used to process the data, which were combined with observations from International GPS System (IGS) sites in Fairbanks, Alaska, and Yellow Knife in northern Canada, which were used as reference sites for this analysis. All velocities (Fig. 2) are residuals and have North American plate motion estimated from NUVEL-1A subtracted (DeMets et al., 1994). The velocities are shown with 95% confidence ellipses. Velocity uncertainty was estimated from formal errors scaled by the root mean squared (RMS) variance of coordinate positions and a time-dependent gain factor (Brockmann, 1996). At Unalaska, the velocity is 3.1 ± 1.2 mm/yr directed N90°W ± 17.5°. Farther west, Adak shows an increased velocity of 9.6 ± 8.0 mm/yr with an azimuth of N39°W ± 25°. At the western end of the Aleutian chain, Attu records a velocity of 31.4 ± 3.0 mm/yr along an azimuth of N57°W ± 2.5°. Uncertainties for Attu and Unalaska are substantially smaller than those for Adak because velocities for the first two sites are based on three occupations, whereas that for Adak is based on two occupations.

DISCUSSION

The velocity measured on Attu (MRDR: 31.4 mm/yr) represents 49% of the arc-parallel component of the convergence-rate vector between the Pacific and North American plates (64.1 mm/yr; Fig. 2). In northern Attu, across an active dextral strike-slip fault, GPS-determined displacement rates are about 3.5 mm lower than in southern Attu (Avé Lallemant et al., 1999a), indicating that a displacement gradient exists normal to the Aleutian Trench. Two arc-parallel strike-slip faults have been identified in the forearc south of Attu (Ryan and Scholl, 1993), south of which the rate of displacement may increase to the 55% of the strike-slip component of convergence predicted by McCaffrey (1996). The velocity measured on Unalaska (DTCH: 3.1 mm/yr; obliquity of 8°) is oriented subparallel to the trench and corresponds to 34% of the strike-slip component of convergence derived from NUVEL-1A (9.2 mm/yr). Partitioning ostensibly prevails at lower obliquity than expected as based on seismicity (Ekström and Engdahl, 1989; McCaffrey, 1996). On Adak (WHAL), where convergence obliquity is nearly 30°, the velocity vector is oriented essentially parallel to plate motion and accommodates about 14% of the relative plate convergence. It is clear that partitioning is not active in this region, possibly because of subduction of the Amlia fracture zone (Fig. 2), which may increase the coupling across the megathrust, rendering partitioning inoperative. Alternatively, slip may take place on unrecognized active dextral strike-slip faults south of the Adak GPS site.

There is ambiguity in the interpretation of GPS-determined velocities. It is uncertain if observed displacements correspond to recoverable or permanent strain. Nevertheless, when taken together with structural observations, the site velocities are consistent with displacement partitioning and arc-parallel extension. The velocity of Adak, parallel to plate convergence, does not reflect displacement partitioning and may represent a transient associated with interseismic strain accumulation. Nevertheless, structures on Adak are like those observed elsewhere along the arc and support the longitudinal extension hypothesis.

Within the Aleutian arc, the development of arc-parallel stretching appears to be an important process and an intrinsic property of the curved plate-boundary morphology. By comparison with similar active and ancient systems, longitudinal extension may be a major contributor to intra-arc deformation. Longitudinal extension may play a largely unrecognized but important role in exhumation and preservation of high-pressure–low-temperature rocks (such as blueschists) formed in accretionary complexes. In a system of heterogeneous deformation, exhumation of high-pressure rocks may occur at high rates (Fig. 4), which when combined with reduced geothermal gradients associated with the subduction of cold lithosphere, may slow retrograde reactions and allow preservation of high-pressure and low-temperature mineral assemblages.

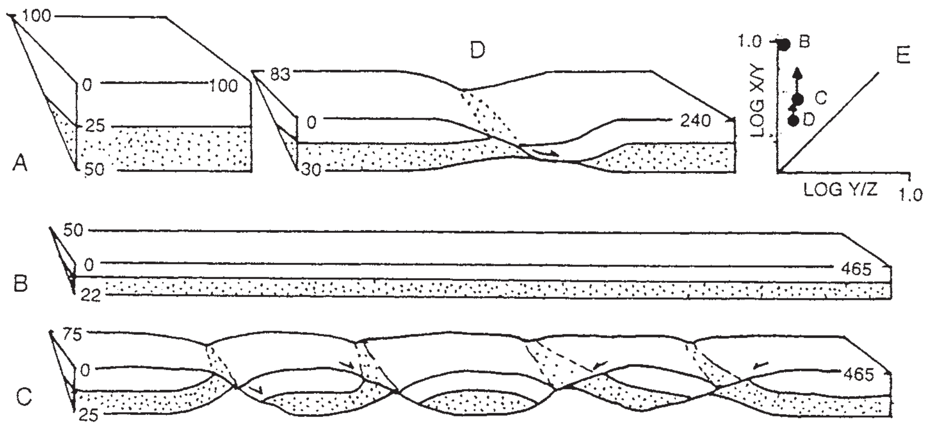

Figure 4. Hypothetical models for exhumation of deep-seated rocks such as blueschists (stippled). A: Section of undeformed accretionary wedge with blueschist formation at depth of 25 km and more. B: Since origin of Attu Island (ca. 50 Ma) rocks may have undergone homogeneous arc-parallel extension (365%; Avé Lallemant, 1996) and arc-normal contraction (50%) causing blueschist ascent to about 11 km. C: If wedge is first deformed homogeneously by 165% arc-parallel stretching and 25% arc-normal contraction, and subsequently extended parallel to arc along listric normal faults until finite extension is 365%, blueschist may be exposed or covered by thin veneer of sediments. D: If wedge deformed first by 100% arc-parallel stretching and 17% arc-normal contraction and, subsequently, another 25% extension along one normal fault, blueschist is exposed on seafloor; deformation could occur in about 25 m.y. E: State of strain, shown in Flinn diagram, is constrictive in all cases: black dots represent homogeneous ductile strain; arrowheads represent subsequent brittle strain.

CONCLUSIONS

GPS geodesy, combined with mapping and structural analysis, supports the proposition that the Aleutian arc is undergoing complex three-dimensional strain accumulation. Deformation associated with displacement partitioning is characterized by spatially segregated domains of contraction and transcurrent motion together with a significant component of arc-parallel extension. Eocene rocks are more penetratively deformed than younger units. Megascopic trench-parallel folds and thrust faults and a set of anastomosing right-lateral strike-slip faults approximately parallel the trench. The folds, thrust faults, and transcurrent faults are crosscut by numerous megascopic and mesoscopic normal faults that are oriented approximately perpendicular to the Aleutian trench. GPS determined velocities of bedrock sites, referenced to Fairbanks, Alaska, and Yellow Knife, northern Canada, show a 28 mm/yr increase from east to west along the curved arc. The differential velocities together with exposed structures support the notion that longitudinal extension within the arc is rapid and ongoing. Longitudinal extension appears to be an intrinsic property of curved island-arc systems and may play an important role in exhumation of high-pressure–low-temperature metamorphic rocks in ancient systems.

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