ARTICLES

Kinematics of Late Faults Along Turnagain Arm, Mesozoic Accretionary Complex, South-Central Alaska

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Abstract

Mesozoic and Cenozoic rocks of the accretionary wedge of south-central Alaska are cut by abundant late brittle faults. Along Turnagain Arm near Anchorage, four sets of late faults are present: a conjugate pair of east-northeast-striking dextral and northwest-striking sinistral strike-slip faults, north-northeast-striking thrusts, and less abundant west-northwest-striking normal faults. All four fault sets are characterized by calcite-chlorite fibrous slickenside surfaces and appear to be approximately coeval. Strongly curved slickenlines on some faults of each set reveal that displacement directions changed over time and that bulk regional deformation related to brittle faulting was strongly noncoaxial. The thrust and strike-slip faults together resulted in subhorizontal shortening perpendicular to strike, consistent with an accretionary wedge setting. Motion on the normal faults resulted in strike-parallel extension of uncertain tectonic significance.

INTRODUCTION

The consensus that subduction zones are sites of mainly contractional deformation finds support in numerous studies of accretionary wedges, where thrust faults and associated folds dominate the map-scale structure (for example, Moore and Karig, 1980). Although the roles of strike-slip and extension have been less widely appreciated, these deformation regimes are also important in some convergent plate boundary zones. Extension dominates the tectonics of outer trench slopes of deep-sea trenches, where bending of the downgoing slab generates down-to-trench normal faults with displacements up to about 1 km (Jones and others, 1978). Platt (1986) showed that extension is not restricted to the downgoing plate; accretionary wedges also may undergo significant normal faulting in order to maintain a stable wedge geometry. Some oblique subduction zones are characterized by major arc-parallel wrench faults that accommodate the strike-slip component of relative plate motion (Fitch, 1972; Dewey, 1980).

The strike-slip faults emphasized in this paper cut the overriding plate and strike at a high angle to the convergent plate boundary. Such faults facilitate bulk shortening within at least one modern accretionary wedge, the inner slope of the Aleutian Trench (fig. 1; Lewis and others, 1988). Byrne (1984) identified comparable faults cutting his Paleocene Ghost Rocks Formation in a much older part of the same accretionary wedge on Kodiak Island, south-central Alaska (fig. 1, loc. 1). Here we describe a system of conjugate strike-slip faults and related thrusts in Mesozoic rocks of this accretionary wedge, near Anchorage, about 500 km along strike from Kodiak Island. Structural analysis suggests that all but a few of these brittle faults are the product of northwest-southeast convergence. However, enigmatic, curved fibrous slickenlines (striations) reveal that slip directions changed markedly during aseismic creep, suggesting that fault-related bulk strain was strongly noncoaxial and more complex than was previously recognized for faults in comparable settings in the Aleutian Trench and Kodiak Island.

The study area along Turnagain Arm (fig. 2) includes the type locality of the McHugh Complex as defined by Clark (1972). The northwestern part of the McHugh Complex's outcrop belt is a melange composed of fragments and disrupted beds of tuff, pillow basalt, and chert, in a deformed matrix of argillite. The southeastern part of the outcrop belt is mainly composed of siliciclastic rocks, including boulder and cobble conglomerate, graywacke, and argillite; bedding is laterally discontinuous in the rare places where it can be observed. Throughout the McHugh Complex, moderate to intense stratal disruption has resulted in tectonic juxtaposition of varied rock types, at all scales. The predominant mode of early deformation was layer-parallel fragmentation (Cowan, 1985; Brandon, 1989); breakup of relatively competent beds (such as chert and tuff) was accompanied by concomitant flowage of argillite matrix into gaps. The resulting fragment foliation is the most conspicuous fabric element in the McHugh Complex in the study area; it strikes north-northeast and in most places dips steeply northwest. The foliation is commonly displaced across narrow (up to a few centimeters wide), early ductile shear zones. Clark (1972) reported prehnite-pumpellyite metamorphic facies assemblages in the McHugh Complex in the study area. The fragment foliation, ductile shear zones, and contorted prehnite veinlets are cut by abundant brittle faults, described below.

The Upper Cretaceous Valdez Group (fig. 2) consists of turbidites composed of graywacke, siltstone, black argillite, and minor pebble to cobble conglomerate. Graded beds in the Valdez Group exhibit a refracted slaty cleavage that is strong in argillite and weak in graywacke; the bedding-to-cleavage angle increases with grain size within graded beds, thereby providing a younging indicator. Brittle faults like those in the McHugh Complex cut bedding and cleavage in the Valdez Group.

BRITTLE FAULTS

We studied minor faults along a 43-km transect across the strike of the accretionary complex in Turnagain Arm during eight days of fieldwork. The faults are abundant in highway and railroad cuts, and in weathered coastal exposures on both sides of Turnagain Arm. The faults juxtapose rock types assigned to a single map unit (McHugh Complex or Valdez Group); they account for some of the discontinuity of rock types that has frustrated attempts at detailed mapping along Turnagain Arm (Clark, 1972, p. D8-D9). Prominent fibrous (calcite and chlorite) slickenside surfaces mark the faults; fiber-steps clearly reveal shear sense (fig. 3). Owing to lack of markers, the magnitude of displacement is rarely evident, but we locally observed offsets of a few tens of centimeters to a few meters. In all outcrops we studied, the faults are spaced at a few meters to tens of meters. The reasonable assumption that the faults are abundant throughout the area of figure 2 suggests that they were responsible for significant regional deformation.

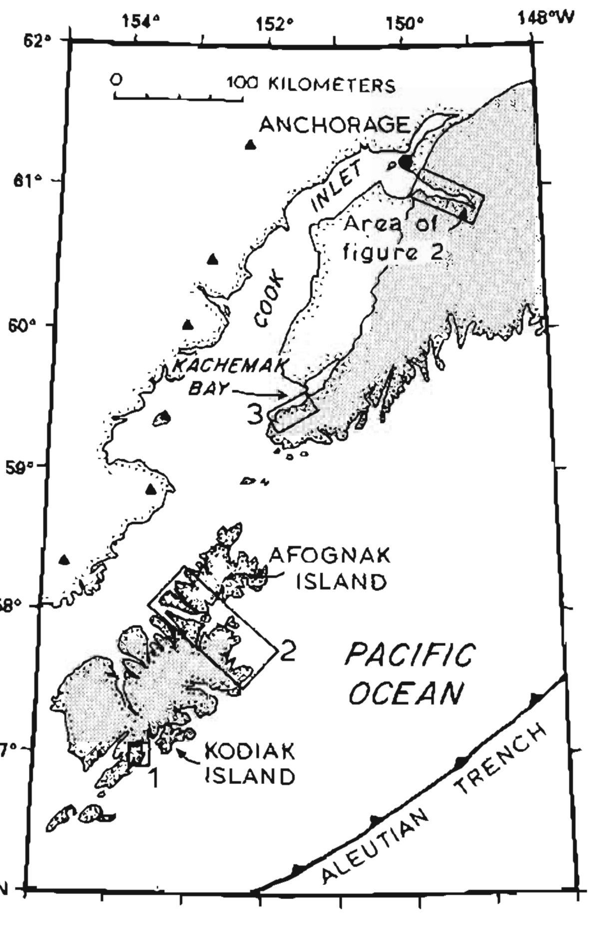


Figure 1. Locality map of south-central Alaska. Triangles, volcanoes of the Aleutian arc. Shaded area, Mesozoic-Cenozoic accretionary complex. Numbered rectangles, areas where abundant late brittle faults have been documented in the Mesozoic-Cenozoic accretionary complex. For location of map see figure 2 (inset).

We measured the attitude of 79 brittle faults and associated slickenline orientations and stepping directions at the locations shown in figure 2. Fifty of the faults cut the McHugh Complex; 29 cut the Valdez Group. We categorized the faults as contractional or extensional for slickenline rakes greater than 45°, or dextral or sinistral for rakes less than 45°. (The designations "contractional" and "extensional" here apply to faults in their present attitudes, without regard for any postfaulting rotations that might have changed the original hanging wall to the apparent footwall; see Bradley, 1989). Where appropriate, we assigned faults with two superimposed sets of slickenlines or a single set of curved slickenlines to two groups. Mean directions of lineations or poles as quoted below are visual estimates from scatter equal-area plots (fig. 4) superimposed on contour diagrams (not illustrated). The stereoplots reveal four main sets of faults on the basis of attitude and slip direction, which are summarized in figure 5.

Sets of dextral and sinistral strike-slip faults (fig. 4*E*–*G*) form what we interpret to be a conjugate pair. The dextral faults (30 examples) strike east-northeast (mean 070°) and dip steeply south (mean 70°); the sinistral faults (20 examples), strike southeast (mean 132°) and dip steeply southwest (mean 82°). Strike-slip faults of both sets are ubiquitous throughout the study area, in both the McHugh Complex and Valdez Group. A few of the faults that were classed on the basis of rake (less than 45°) as strike-slip faults have unusually gentle dips (fig. 6*A*).

We measured 25 contractional faults in the study area. Following Butler (1982), we use the term "thrust" for all contractional faults, regardless of dip angle. Most of the thrusts, termed synthetic thrusts below, strike south-southwest (mean 209°), and dip northwest (mean 64°)(fig. 4*A*, *B*); a few antithetic thrusts strike north-northeast and dip southeast. The mean attitude of synthetic thrusts is subparallel to fragment foliation in the McHugh Complex and bedding in the Valdez Group. The mean hanging-wall movement direction of synthetic thrusts is 102° updip. Although a few thrusts are present throughout the study area, they are abundant only directly east of the two map-scale faults: (1) at the Potter Marsh weigh station (fig. 2, loc. 1), cutting melange of the McHugh Complex immediately east of the

Knik fault (a segment of the Border Ranges fault), and (2) near Indian (fig. 2, loc. 2), cutting metasedimentary rocks of the Valdez Group in the strongly deformed footwall of the Eagle River fault. The concentration of minor thrusts in these two areas supports previous interpretations that both major faults underwent thrust displacement, at least during relatively late stages in their histories.

The study area also includes a few normal faults; we found 11 examples. Despite some scatter (fig. 4*C*), most of the faults strike east-southeast (mean 117°) and dip southwest (mean 59°). The mean hanging-wall movement direction is about 228°.

Many of the brittle faults along Turnagain Arm have slickenlines that are curved by as much as 55° within the fault plane (figs. 3, 7). Stepping directions provided a basis for determining the beginning and end of a given crystal fiber; hence we were able to class each fault as clockwise (10 examples) or counterclockwise (20 examples) on the basis of the sense of slickenline curvature when the fault plane was viewed from above (fig. 7*C*, *D*).

The curved slickenlines are intriguing but difficult to interpret. The most significant conclusion we can draw is that bulk deformation related to brittle faulting was strongly noncoaxial. All faults with curved slickenlines strike between 050° and 230° (strike directions assigned according to the right-hand rule; see fig. 7*A*, *B*) , whereas only two-thirds of faults with straight slickenlines have strikes in the same range; the significance of this finding is unclear. Also inexplicable is the observation that counterclockwise slickenlines appear to converge toward a southwest-plunging zone (fig. 7*C*), whereas clockwise slickenlines appear to diverge from a southwest-dipping girdle (fig. 7*D*). On several strike-slip faults, slickenline curvature was sufficient to change the plunge direction of the instantaneous slip vector. Where this occurred on nonvertical faults, the component of dip-slip motion must have changed sense as the plunge

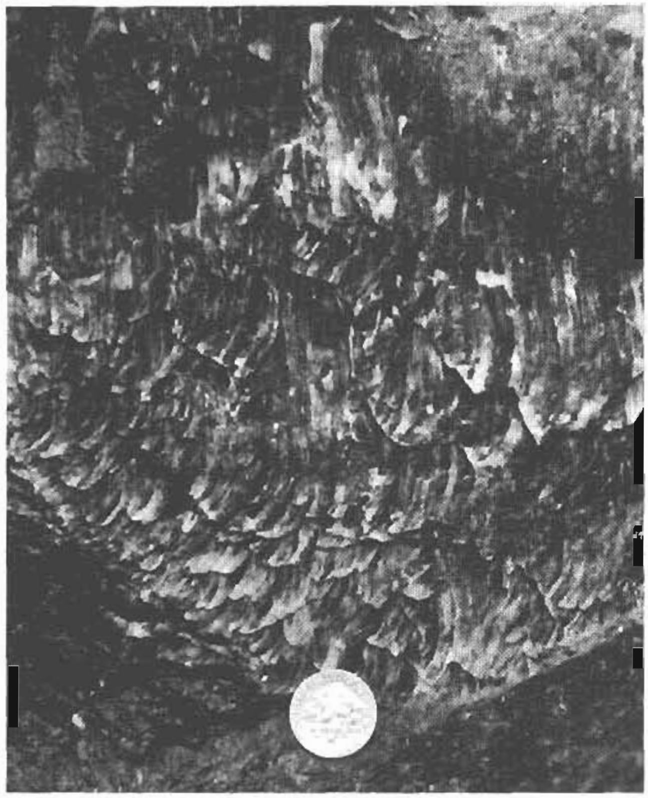


Figure 3. Slickensided high-angle fault surface with curved fibrous slickenlines. Missing block (where photographer was standing) moved down with respect to preserved block. Youngest part of a given slickenline is immediately adjacent to step where it ends. Coin is 17 mm across.

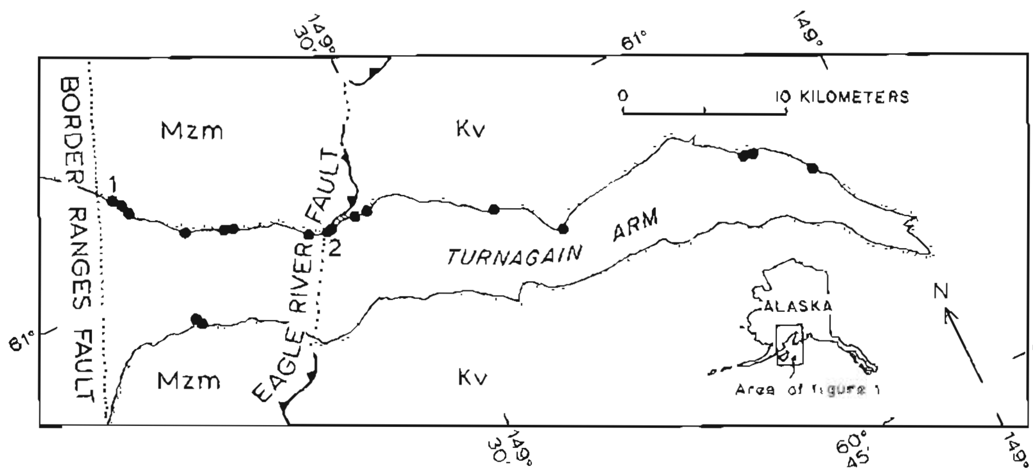
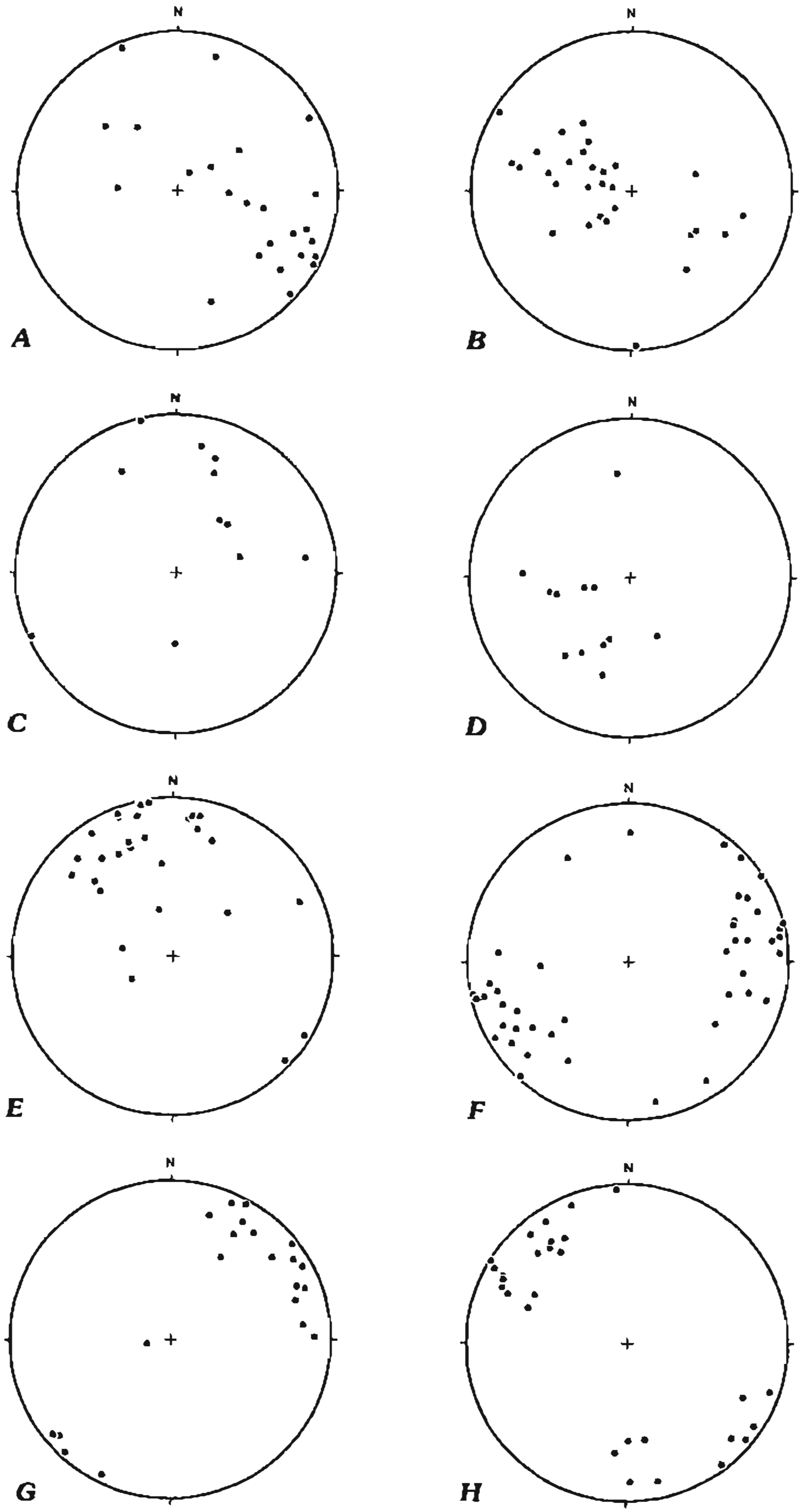


Figure 2. Generalized geologic map of Turnagain Arm. Dots, locations where minor faults were studied; numbers 1 and 2 refer to localities mentioned in text. Mzm, Mesozoic McHugh Complex; Kv, Cretaceous Valdez Group. Faults dotted where concealed; sawteeth on upper plate of Eagle River thrust fault. Modified from Magoon and others (1976).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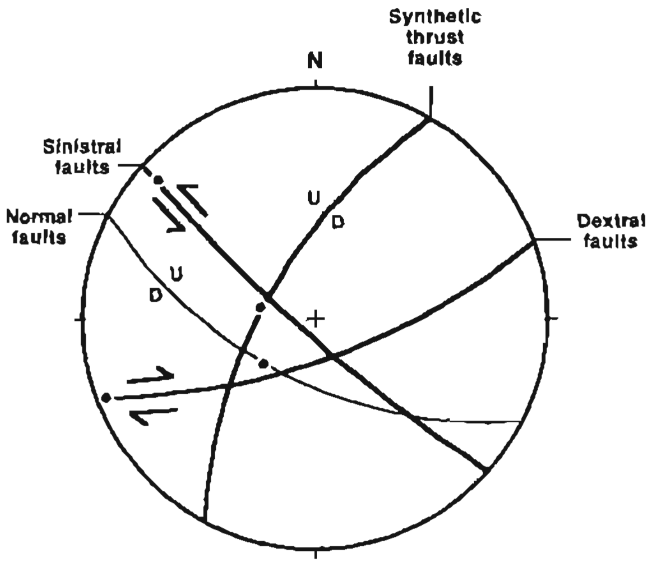

Figure 5. Lower hemisphere, equal-angle projection summarizing attitudes of major fault sets and slip directions (dots). Minor normal-fault set is not as well defined as other sets. Arrows show relative movement on sinistral and dextral faults. U, upthrown side; D, downthrown side.

direction of the slickenlines changed. Thus, judging from present attitudes, several faults in Turnagain Arm appear to have evolved from transpressional to transtensional structures (or vice versa) during fault motion.

Possible origins of curved slickenlines include (1) rotation of a fault block about an axis normal to the fault plane (rotational-translational fault motion of Mandal and Chakraborty, 1989) and (2) incremental change in translation direction (curvilinear-translational fault motion of Mandal and Chakraborty, 1989); note the exact analogy to curved fibers in dilatant veins as described by Durney and Ramsay (1973). The first mechanism is unlikely for the Turnagain slickenlines, because the radius of slickenline curvature on a given fault is constant, rather than increasing with distance from a rotation axis (fig. 8). It is fortunate that the first mechanism (fig. 8*A*) did not operate, for if it had, any paleomagnetic or paleocurrent data from Turnagain Arm probably would be spurious. We instead attribute the curvature to the second mechanism (fig. 8*B*).

Similar styles suggest that the four main fault sets—thrust, dextral, sinistral, and normal faults—are approximately coeval; any differences in age are probably minor.

◀ Figure 4. Lower hemisphere, equal-area projections for fault plane and slickenlines from localities shown in figure 2. *A*, Poles to thrust-fault planes. *B*, Thrust-fault slickenlines. *C*, Poles to normal-fault planes. *D*, Normal-fault slickenlines. *E*, Poles to dextral-fault planes. *F*, Dextral-fault slickenlines. *G*, Poles to sinistral-fault planes. *H*, Sinistral slickenlines. Curved slickenlines in *B*, *D*, *F*, and *H* represented by both initial and final attitudes.

All four fault sets include examples with straight and curved fibrous slickenlines that consist of calcite and chlorite (based on hand-sample identification). In only one place were we able to observe a crosscutting relation (a sinistral fault cutting an older thrust); many additional observations of this type would be necessary to establish a meaningful sequence of events. Together, the faults may represent an orthorhombic fault set (Reches, 1983; Krantz, 1989), to the extent that orthorhombic fault theory can be applied to noncoaxial deformations.

TECTONIC SIGNIFICANCE

Late brittle faults like those along Turnagain Arm appear to be widespread in the arc-trench gap of south-central Alaska. The pattern of faulting is especially similar to that described in the Paleocene Ghost Rocks Formation on southern Kodiak Island (fig. 1, loc. 1), where Byrne (1984, p. 27) reported the following sequence of late faults:

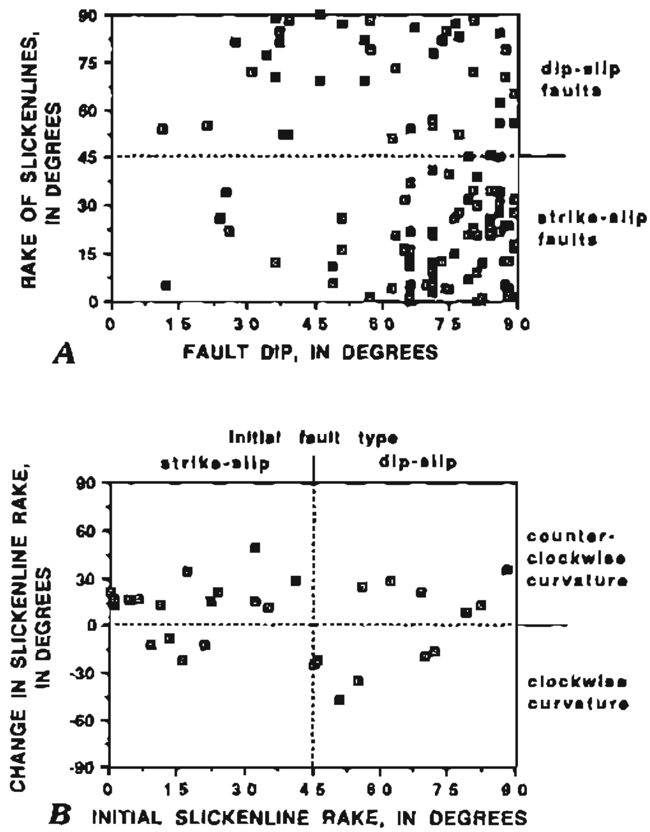

Figure 6. *A*, Plot of fault dip versus rake of slickenlines. Faults classed as strike slip on the basis of rake include several with anomalously gentle dips. Curved slickenlines are represented by both initial and final attitudes. *B*, Plot of initial rake versus change in rake on faults with curved slickenlines. Straight slickenlines would plot on horizontal dashed line. Counter-clockwise curvatures (plotted as positive) predominate. Curved slickenlines occur on faults of all initial rakes.

(1) a conjugate pair of east-striking dextral and north-striking sinistral strike-slip faults; (2) a conjugate pair of northwest-dipping synthetic and minor southeast-dipping antithetic thrusts; and (3) a conjugate pair of east-striking normal faults. Each fault set on southern Kodiak Island appears to have its counterpart along Turnagain Arm; orientations differ slightly but the overall configurations are qualitatively alike.

On Afognak Island and northern Kodiak Island (fig. 1, loc. 2), Sample and Moore (1987) identified a comparable assemblage of late faults cutting the Upper Cretaceous Kodiak Formation (the along-strike correlative of the Valdez Group): (1) northeast-striking dextral strike-slip faults (conjugate sinistral faults were not reported); (2) northwest-dipping thrusts; and (3) normal faults with highly variable strikes. The relative age of these three fault sets is unknown, but like the Turnagain Arm faults, they postdate penetrative deformation.

Recent mapping in the Kachemak Bay region (fig. 1, loc. 3) also has revealed abundant brittle faults (D.C. Bradley and S.M. Karl, unpub. 1989 field notes): (1) northwest-striking thrusts; (2) sinistral strike-slip faults with highly variable strikes; and (3) abundant normal faults with highly variable strikes. Dextral strike-slip faults are rare. Whereas

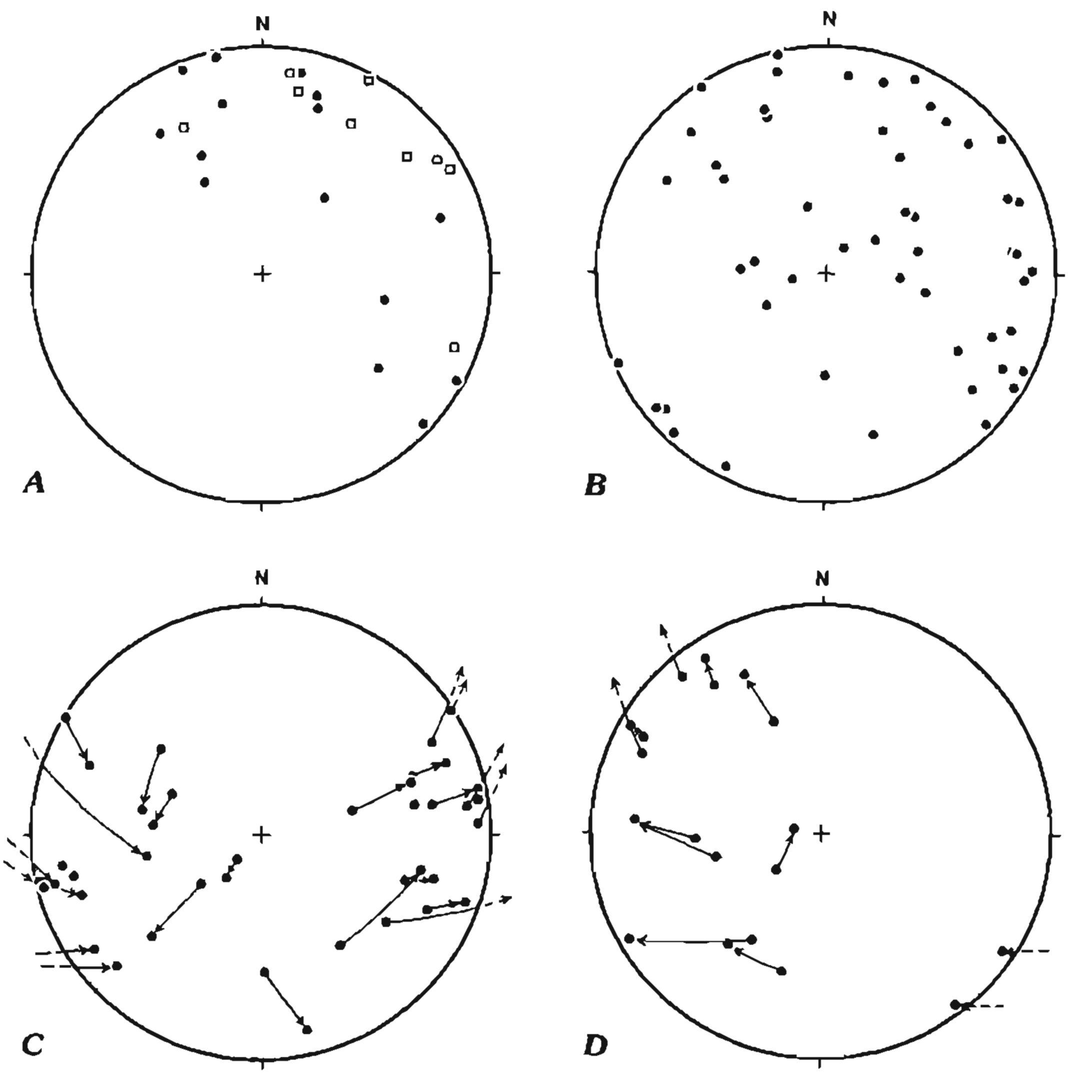

Figure 7. Lower hemisphere, equal-area projections. *A*, Poles to fault planes and associated curved slickenlines. Squares, slickenlines with clockwise curvature when viewed from above; dots, slickenlines with counterclockwise curvature when viewed from above. Note absence of faults that strike between 230° and 050°. *B*, Poles to faults with straight slickenlines. Note abundance of faults that strike between 230° and 050°. *C*, Slickenlines with counterclockwise curvature. Arrows show change in attitude through time. Some slickenline trajectories leave edge of net (dashed arrows) and reappear on opposite side. Only representative trajectories are shown where data are cluttered. *D*, Slickenlines with clockwise curvature, which are less abundant than counterclockwise lines.

more data are needed to clarify the pattern and kinematics of late faulting, the available data at least support the contention that late brittle faults are widespread, if not omnipresent, along a 500-km segment of the accretionary wedge.

In all four areas in figure 1 where late brittle faults have been studied, the attitudes of thrusts indicate subhorizontal northwest-southeast shortening. In addition, in Turnagain Arm and southern Kodiak Island, conjugate strike-slip faults indicate shortening in the same direction. Figure 9 shows how both thrust and conjugate strike-slip faults might have facilitated shortening within the southern Alaska accretionary wedge during Cretaceous and (or) Cenozoic time. Figure 9 also serves as a schematic depiction of the active tectonics of the Aleutian inner trench slope (compare with fig. 13 in Lewis and others, 1988).

One possibly significant difference between Turnagain Arm and southern Kodiak Island is that the intersection between conjugate strike-slip faults along Turnagain Arm plunges about 70° SE.; the corresponding maximum shortening direction plunges about 20° NW. (both estimates from fig. 5). In contrast, on southern Kodiak Island, the conjugate fault intersection is vertical, and the corresponding maximum shortening direction is horizontal. Byrne (1986) cited the latter fact as one line of evidence against rotation of the subduction complex toward the arc during subsequent growth of the accretionary wedge; he concluded instead that the wedge had been uplifted vertically to its present position above sea level, without rotation. If the conjugate strike-slip faults along Turnagain Arm share a common origin with those on southern Kodiak, their present attitude would indicate rotation during uplift of the wedge. Independent evidence that might provide a test for this suggestion has not yet been sought.

It is not clear how the normal faults, which strike almost perpendicular to the thrusts, might fit into the tectonic setting shown in figure 9. One possibility is that the normal faults are akin those which Platt (1986) attributed to extensional collapse of an accretionary wedge that has been oversteepened beyond its critical taper. However, a significant difference is that normal faults in Platt's (1986) model strike parallel to rather than perpendicular to the plate boundary; accordingly, a three-dimensional modification to Platt's (1986) model, involving nonplane strain, would be required to explain the Turnagain Arm normal faults. Another possibility is that the normal faults record Paleogene subduction of the Kula-Farallon spreading center. In the latter case, the normal faults might be expected to relate to igneous rocks attributed to the same event. Additional fieldwork along Turnagain Arm and in Kachemak Bay will address these and many other questions raised by the present study.

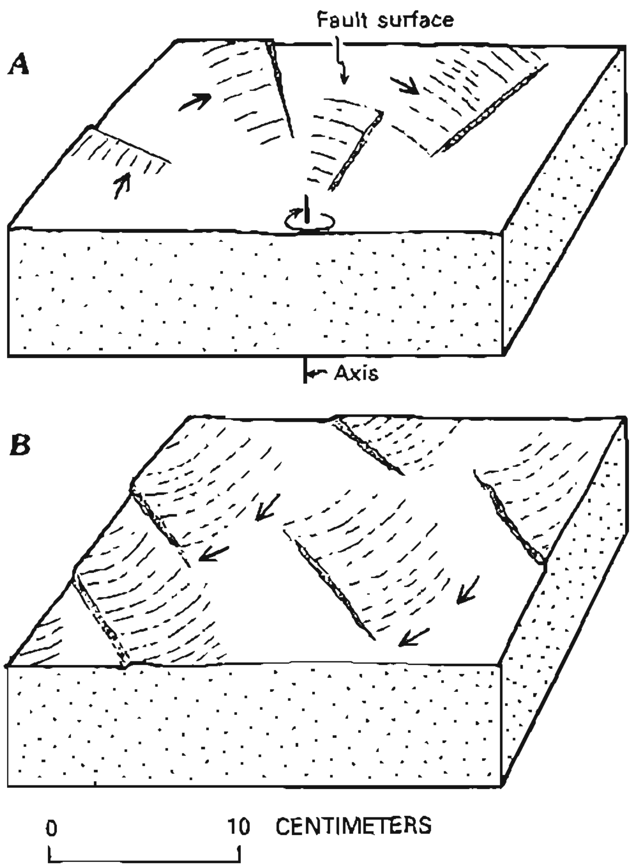

Figure 8. Two mechanisms capable of producing curved slickenlines. *A*, Rotation about an axis normal to fault plane. Slip direction (arrows), sense of displacement, and amount of curvature of slickenlines all vary systematically with position on fault surface with respect to rotation axis. *B*, Change in translation direction, without rotation. All slickenlines have similar trajectories. Second mechanism is indicated for faults with curved slickenlines along Turnagain Arm.

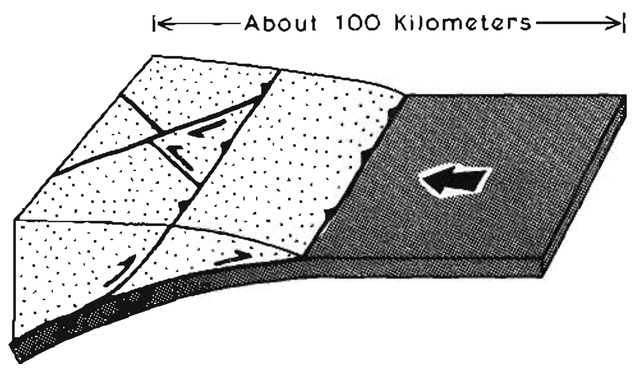

Figure 9. Schematic block diagram of frontal part of an accretionary wedge (stipple) above a subducting oceanic plate (gray), showing how conjugate strike-slip faults and thrusts (small arrows) like those along Turnagain Arm might have accommodated shortening driven by plate convergence (large arrow gives direction). By analogy with Aleutian accretionary wedge (Lewis and others, 1988), thrust faults are active at and near toe of wedge, and strike-slip faults are active closer to arc. Magmatic arc is about 100 km to left. Normal faults are not shown but would strike about perpendicular to thrust faults.

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