STRUCTURAL FABRIC OF A MÉLANGE
KODIAK ISLANDS, ALASKA

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ABSTRACT. A Cretaceous mélange of sedimentary and igneous rocks is exposed along the northwestern shoreline of the Kodiak Islands, southwestern Alaska. Detailed structural study in five widely separated subareas indicates that the mélange is geometrically coherent. The mélange contains first-generation folds that are closed, moderately disharmonic, and tend toward parallel geometry. They have an axial-plane foliation that parallels the regional foliation in the mélange. The first-generation folds and associated foliation formed before the peak prehnite-pumpellyte-facies metamorphism of the mélange. Second-generation folds and possibly related shears respectively fold and cut across the foliation. A plot of all first-generation fold axes defines a plane that dips steeply to the northwest and coincides with the modal foliation and axial surface. Slip lines for the first deformation, determined by the separation-arc technique and the method of axial fabrics, plunge steeply to the northwest, lie in a northeasterly striking slip plane, and demonstrate northwest-over-southeast relative movement. The first deformation is interpreted as a response to emplacement of the mélange into the hanging wall of a subduction zone with subsequent landward tilting to the present steeply dipping configuration. The azimuth of the restored mean slip line (N88°E ± 11°W) apparently represents the direction of relative plate motion during mélange emplacement in the Late Cretaceous.

INTRODUCTION

Mélanges are a distinctive structural association occurring in many orogenic zones throughout the world (for example Hsü, 1974; Wood, 1974a; Kay, 1976; Blake and Landis, 1973; Bradshaw, 1973; Hamilton, 1974). They are intensely deformed rock units commonly associated with high pressure-low temperature metamorphic rocks. Moreover, they form portions of linear belts of deep-sea rocks that are paralleled by magmatic arcs and associated belts of low pressure-high temperature metamorphic rocks. Mélanges have been interpreted as remnants of ancient subduction zones (for example Dewey and Bird, 1970; Ernst, 1970; Page, 1970; Hamilton, 1969; Mitchell and Reading, 1971; Dickinson, 1971; Cowan, 1974). However, controversy exists as to whether mélanges originate by purely tectonic or a combination of sedimentary and tectonic processes (Maxwell, 1974; Cowan, 1976). As used in this paper, mélange designates a mappable rock unit composed of variously deformed blocks and slabs of brittle material dispersed in a foliated, ductile matrix. Thus, mélange describes a particular structural style and does not require the presence of "exotic" lithologic components (see Cowan, 1974).

Most structural studies of mélanges have concentrated on map-scale relationships, variations in textural reconstitution, and the correlation of map-scale structure to regional tectonic elements (for example Suppe, 1973; Duffield and Sharp, 1975; Gilbert, 1973; Christensen, 1973; Raymond, 1973). Statistical structural studies of mélanges have been hampered by their inherently poor exposure and lack of suitable fabric elements. However, at least one detailed kinematic analysis has been com-

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pleted in a mélangé-bearing terrain of the Coastal Belt Franciscan Complex of California (Beutner and Hansen, 1975a,b).

This paper presents the results of a structural analysis of a mélangé exposed in fiords along the shores of the Kodiak Islands. Our work has focused on strip mapping of shoreline exposures and collection of minor structural data along serial cross sections through the mélangé. The rock fabric permits a kinematic interpretation of slip lines and slip planes active during the structural emplacement of the mélangé. Furthermore these geometrically derived movement patterns lead to deduction of the slip vector between the ancient convergent crustal plates.

**GEOLOGIC SETTING**

The continental margin of southwestern Alaska has been the site of repeated pulses of magmatism and accretion of deep-sea rocks beginning in the Late Triassic and continuing today (Burk, 1965, 1972; Plafker, 1972; Reed and Lanphere, 1973). The Mesozoic and Cenozoic accretionary sequence is particularly well exposed on the Kodiak-Kenai shelf landward of the modern Aleutian Trench (fig. 1). The oldest accreted rocks consist of a blueschist and greenschist terrane that was metamorphosed and presumably emplaced about 190 m.y. BP (Forbes and Lanphere, 1978; Cardon and others, 1977). This schist belt is succeeded on its seaward margin by a mélangé, the Uyak Complex, which was apparently emplaced during the Late Cretaceous (Connelly, 1978). The mélangé is in turn underthrust on its seaward margin by a latest Cretaceous (Maastrich-
tian) turbidite sequence, the Kodiak Formation (Jones and Clark, 1973; Moore and Connelly, 1977). A completely deformed turbidite sequence of Paleogene age occurs on the seaward margin of the Cretaceous rocks (Moore, 1969). Miocene and Pliocene sediments have been dredged from the trench-slope break, and deformed Quaternary rocks have been drilled from the lower slope of the Aleutian trench (Kulm and others, 1973). In total, the Kodiak shelf and slope exhibits one of the most complete and best exposed accretionary sequences known anywhere in the world.

Our structural analysis has concentrated on the Uyak mélange of the northwestern Kodiak Islands. The Uyak mélange is composed of blocks of ultramafic and gabbroic rocks, pillowed and massive greenstone, radiolarian chert, sandstone, and minor limestone in a matrix of interbedded gray chert and argillite. This assemblage is interpreted as a deep-sea sedimentary and igneous sequence that was complexly deformed and mildly metamorphosed during emplacement (Hill, 1975; Connelly, 1978). Metamorphism of pelitic-pumpellylite facies suggests that the bulk of the mélange was buried 9 to 15 km (Connelly, 1978).

MAP-SCALE: STRUCTURAL GEOLOGY

A shoreline map of the Uyak mélange at a scale of 1:63,360 (Connelly and Moore, 1977) provides a basis for drawing sequential cross sections (fig. 2) through the subareas, where detailed structural data was collected. The map, cross sections, and outcrop observations indicate that the greenstone, graywacke, gabbroic and ultramafic rocks, and radiolarian chert occur in relatively isolated slabs as compared to the more abundant gray-chert-and-argillite matrix. The boundaries between the slabs and the matrix are represented as sharp lines at the scale of the cross section but are mostly commonly transitional in the field because the contrasting rock types are faulted and intercalated at their contacts. Also the gray chert and argillite matrix (fig. 2) includes many slabs and blocks of sandstone, greenstone, radiolarian chert, and limestone too small to be mapped at 1:63,360. Map- and cliff-scale observations indicate that most of the brittle lithologies are more lensoid than equidimensional in shape, although equidimensional blocks were noted in some outcrops and in hand specimen. Patterns of blocks and slabs as seen on the geologic map (Connelly and Moore, 1977) and in cross sections (fig. 2) document a macroscopic mélange foliation striking northeast and dipping steeply northwest. Contacts between lithologic units are almost always sheared and may juxtapose sedimentary rocks of contrasting depositional environments.

We never observed knocker topography (blocks or slabs exposed in relief) in the Uyak mélange, possibly because the present silification of the mélange matrix makes it nearly as resistant to erosion as the included slabs or because slab-matrix contacts are transitional.

The geologic map and cross sections provide no concrete evidence of large-scale folds, although some map patterns would permit these structures. No systematic variation in attitudes which might reflect folds
Fig. 2. Cross sections through Uyak mélange. See figure 6 for locations. Northwest to left, southeast to right. Question marks on section E to E'' indicate areas where structure is obscured by alluvial cover, not shown on section. Bold lines designate major faults. Contacts within the Uyak Complex are sheared and probably are all faults of small displacement.
were observed. The graywacke units are usually massive and lack facing indicators; all top directions determined from pillow lavas face to the northwest. If large-scale folds were presents they have been sheared out; alternatively, the large-scale deformation may have been accomplished principally by thrusting.

The Uyk mélange is bounded by conspicuous faults. To the northwest it is in contact with schist (fig. 2, sec. B, D), granitic rocks (fig. 2, sec. A, C), and a forearc volcaniclastic sequence, the Shuyak Formation (fig. 2, sec. E). To the southeast the Uyk mélange is underthrust by an Upper Cretaceous turbidite sequence, the Kodiak Formation, along a fault dipping about 45 degrees northwest. The juxtaposition of the schist terrain, Uyk mélange, and Upper Cretaceous turbidite sequence forms an imbricate structure (fig. 2, sec. B, D) in which the oldest and most highly metamorphosed rocks are the highest structural unit. Within the Uyk mélange a smaller scale imbricate structure is suggested by the pattern of slabs (fig. 2), the shearing and faulting within the mélange, and the northwesterly facing directions of the pillows greenstone.

DESCRIPTION OF MÉLANGE FABRIC

Foliation

The map-scale planar fabric defined by slabs of the mélange parallels a penetrative foliation visible in outcrop, hand specimen, and thin section. The penetrative foliation is most conspicuously shown by the planar distribution of pieces of chert in a scaly argillite matrix (pls. 1, 2-B, 3-B). The foliation surfaces of the argillite are locally polished but not commonly slickensided. Since the gray chert and argillite unit is both the most ductile and the most abundant lithology of the mélange, it forms the matrix surrounding other rock types (fig. 2; pl. 3-B). Locally the foliation cuts across bedding (pl. 1-A). At one outcrop folded planar chert layers with an axial-plane foliation are dismembered and transposed into this foliation over a distance of a meter (pl. 2). It is tempting to assume that all discontinuous chert layers originate from transposition; however, the irregularity of chert beds in some undeformed pelagic rock sequences (Bailey, Irwin, and Jones, 1964, p. 69) suggests that some of the discontinuity may be primary.

Microscopically the foliation in the argillite is shown by a fabric of anastomosing opaque films spaced > 1 mm to << 1 mm that curve around equidimensional to lensoid chert fragments. Opaque minerals show pressure shadows composed of quartz fibers. Although the pressure shadows indicate extension subparallel to foliation, their exact angular relationships to the foliation and the incremental strains have not been determined.

In the greenstone the foliation is reflected by the orientation of lithologic layering in hyaloclastite and rarely by flattened pillows. Radiolarian chert layers may be boudinaged or reoriented parallel to the foliation or both. In the wacke the foliation is manifested microscopically by lensoid silicate grains and orientation of pelitic folia. The foliated wackes
Foliation. (A) Foliation in argillite (dipping steeply to left) cutting across sedimentary layering of tuff bed. (B) Foliation, dipping to right, crosscut by later shear zones, dipping to left, to produce sigmoidal boudins.

Transportation of sedimentary layering. (A) Fold in gray chert and argillite with axial-plane foliation. Scale equals 15 cm. (B) Same outcrop as A, 80 cm to right, increase in intensity of foliation with brecciation of chert layers. Larger chert boudins and surviving fold hinges indicated by dashed outlines. Width of view 40 cm.
Folds in gray chert and argillite. (A) Small hinge in chert; note axial-plane foliation. Width of view is about 25 cm. (B) Isolated fold hinge of limestone in argillite. Note foliation trending horizontally across outcrop.

belong to textural zone 2 in terms of the metamorphic reconstitution of sandstones defined by Blake, Irwin, and Coleman (1967) and Bishop (1972), but most of the Uyak wackes are of zone 1 (macroscopically non-foliated).

The foliation parallels the axial plane of many first-generation folds (pls. 2, 3, 4). Commonly first-generation folds are best defined by chert layers, but the axial-plane foliation is developed in intercalated argillite
and tuff layers. The penetrative foliation is cut across by apparently nonsystematic shears and fractures (pl. 1-B). These shear zones may be in part related to second-generation folding, but they have not been investigated in detail.

**Folds**

Although map- and cliff-scale folds were not observed in the Uyak mélange, measurable outcrop-scale folds are common. The geometry and orientation of these folds have been studied in some detail; however, their
proper interpretation requires separation of the various fold generations. Basically we recognize two phases of folding in the Uyak mélange: a first generation of folds with axial surfaces parallel to the foliation and a second generation that folds or kinks the foliation.

First-generation folds.—The first-generation folds in the Uyak mélange are developed most commonly in the chert and argillite units and in-bedded chert, although limestone and tuff layers are also folded. These folds are distinguished from later folds by their axial-plane foliation, the parallelism of their axial surfaces to the regional foliation, the planar distribution of their fold axes, and a distinct set of geometric characteristics or style described below. First-generation folds may occur in detached, isolated, and irregular layers (pls. 2-B, 3), which may be remnants of originally more complete folds or folds of irregular primary sedimentary layers.

For our geometric description and kinematic analysis we utilize first-generation folds in chert and limestone from the gray chert and argillite unit and folds in bedded chert. The following geometric description is based on measurements on photographs from 66 profile sections. We describe the folds to characterize the mélange fabric quantitatively, to demonstrate that the folds are homogenous, and to show that they are suitable for kinematic analysis. Each fold is described using seven elements of its shape and related fabric, the first six of which must be measured in profile section. These elements are called style elements, the use of which is discussed in detail elsewhere (Hansen, 1971; Wheeler, 1973a,b,c; King, 1973; King and Wheeler, 1978; Schmit, 1974). They are: (1) overall fold geometry in terms of classes 1A to 3 (Ramsay, 1967, p. 365-366) based on visual comparison of a layer’s thickness on the hinge and both limbs; (2) hinge curvature estimated from templates (fig. 3) (King, 1973); (3) interlimb angle (Ramsay, 1967, p. 349-350); (4) D/S, ratio of depth or length (D) of axial surface to perpendicular spacing (S)

![Fig. 3. Templates used in estimation of limb and hinge curvatures (King, ms; Wheeler, 1978).](image-url)
between adjacent axial surfaces (fig. 4A); (6) H/S, ratio of height (H) or crest to trough amplitude (measured parallel to axial surface) to spacing (S) (fig. 4A); (7) presence or absence of cleavage and its relationship to bedding. Note that the depth-spacing (D/S) and height-spacing (H/S) ratios provide an objective measure of harmonicity and degree of over-folding, respectively.

The results of the style analysis of the 66 folds are as follows: (1) The modal and median fold geometries are 1B (parallel), and 90 percent of the folds are 1B or 1C; individual chert beds are predominantly 1B, while whole folds tend toward 1C, and ductile beds are mostly 1C; (2) the modal and median hinge curvatures are respectively gently curved and moderately curved, with 82 percent of the hinges in these two classes; (3) modal and median limb curvatures are both moderately curved, with 80 percent of the hinges either moderately curved or curved; (4) interlimb angles are distributed symmetrically about a median and a mean of 54 degrees but broadly dispersed with half the 65 measurements falling between 35 and 73 degrees inclusive (fig. 4C); (5) D/S values are positively skewed about a median of 5.4 and a mean of 6.0, with half the 24

![Diagram](image)

**Fig. 4.** Numerical style elements of Uyak Complex. (A) Height (H), spacing (S), and depth (D) of model fold. H and S measured where fold is best developed. (B) Histogram of depth/spacing ratios. (C) Histogram of interlimb angles. (D). Histogram of height/spacing ratios.
measurements between 3.8 and 7.6 exclusive (fig. 4B); (6) H/S values are positively skewed about a median of 1.2 and a mean of 1.3 with half the 34 measurements between 0.9 and 1.5 inclusive (fig. 4D); (7) argillite and tuff beds show slaty cleavage parallel to axial surfaces of minor folds whereas chert beds are mostly uncleaved (pls. 2, 3, 4-A).

The preceding measurements indicate that the typical first-generation fold is closed, moderately disharmonic, and tending toward parallel geometry. None of the histograms of style elements show significant bimodality, which supports our conclusion that these folds represents a single generation of structures. Furthermore, the statistical methods of King (1973), King and Wheeler (1973), and Schmit (1974) show that folds in bedded chert do not differ significantly in style from folds in interbedded chert and argillite.

The first-generation folds are one of the most basic structural features of the mélange, but do they represent a style of deformation characteristic of mélange? In general, first-generation folds resemble folds formed in a shear zone in style and relative orientation (Hansen, 1971) but differ from one group of slump folds (see Conditions of Deformation, below). Two sets of folds from Devonian rocks of the eastern Plateau Province of the central Appalachians have been analyzed by methods used in this paper (Wheeler, 1975a,b) and provide a basis for detailed comparison with the Uyak folds. The folds from the Appalachians apparently developed in shear zones within major anticlines that grew during the northwestward transport of the Appalachian foreland. Visual comparison of histograms of style elements indicates that the Uyak folds closely resemble the Appalachian examples in terms of geometry, hinge curvature, limb curvature, and D/S values. However, the Uyak folds have distinctly smaller interlimb angles and higher H/S values than the Appalachian folds. These differences are to be expected, if the Uyak folds have undergone unusually severe flattening perpendicular to their axial surfaces. We conclude that the Uyak folds are generally like folds formed in other shear zones but vary in details of tightness and overfolding from the Appalachian examples. Whether the Uyak folds are diagnostic of mélange or whether mélange has a diagnostic fold style cannot be answered until further comparable data are available.

Second-generation folds.—Only sixteen second-generation folds were observed and measured during study of the Uyak mélange. These folds are distinct from the first-generation folds, since they fold and kink the foliation and are commonly highly harmonic. At two localities in the Gurney area second-generation folds were seen refolding first-generation folds. D/S ratios of the second-generation folds are high with axial surfaces usually extending across an entire outcrop. The axial surfaces of the second-generation folds strike northeasterly and dip steeply northwest and southeast but demonstrate no obvious conjugate relationship; the second-generation fold axes show no systematic patterns of asymmetry. Some of the shears and fractures cutting across the foliation may be related to the second-generation folds.
ORIENTATION OF MÉLANGE FABRIC

The orientation of the minor fabric of the mélangé has been documented in five large subareas extending for 200 km along the northwestern shoreline of the Kodiak Islands. The available structural data indicate that each subarea is reasonably homogenous.

The fold axes, poles to axial surfaces, and foliation planes have been plotted on equal-area nets for the individual subareas (Connelly and Moore, 1977) and for the entire region (fig. 5). Additional plots of fold axes and poles to foliation are presented by subarea for the purpose of determining slip lines (figs. 6, 7). In each case the fold axes are distributed along steeply dipping, northeasterly striking great circles. The modal

Fig. 5. Fold axes, poles to axial surfaces, and poles to foliation for all five subareas of Uyak Complex. Lower-hemisphere equal-area projections. Note planar distribution of fold axes and coincidence with modal axial surface and modal foliation.
axial surface, the plane defined by the locus of fold axes, and the modal foliation plane are all sub-parallel. The same orientation and parallelism of fabric elements is shown by a composite plot for the entire region (fig. 5). The orientation data, taken together, indicate that the mélange is structurally coherent and in this sense not chaotic. Thus, even though lithologic units have been attenuated and mixed, the structural response of the mélange has been regionally coherent and has produced systematic fabric patterns.

DETERMINATION OF SLIP LINES AND SLIP PLANES

Defining the kinematics of mélange emplacement bears critically on the regional interpretation of such a rock unit. The kinematics can be described in terms of: (1) a slip plane or planar shear zone along which

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**Fig. 6.** Slip lines determined by separation-arc technique, lower-hemisphere equal-area projections. Note that separation arc narrows to separation line in Shuyak and Raspberry subarcs. Slip line (triangle) determined from method of axial-surface fabrics. Cross-section lines refer to figure 2. Note separation of fold axes into fields of alternate asymmetry, and consistency of slip-line determinations within and between subarcs. U and D specify the relative sense of up and down movement in the slip plane along a line contained within the separation arc. See Table 1 for details of orientation data.
Fig. 7. Slip lines determined by method of axial-surface fabrics. Zone axis is a π axis to poles to axial surfaces determined by least-squares technique (see table 1 for error estimate). Great circle is slip plane from figure 6. Slip line represents intersection of slip plane and circle defined by pole to slip plane and zone axis.
deformation occurred, (2) a slip line or direction of relative movement within the slip plane, and (3) the sense of relative movement along the slip line. This usage of slip line and slip plane (after Hansen, 1971) refers to the direction of displacement of the deforming mass and its surroundings and not to the movement pattern between layers within individual folds. The first-generation folds of the Uyak mélange have an analogous style to folds elsewhere for which slip lines and slip planes have been successfully determined by the separation-arc technique and the method of axial surface fabrics, and independently checked (Scott and Hansen, 1969; Hansen, 1971).

Separation-arc Technique

Both field examples and experiments indicate that shear zones can generate systems of folds of parallel geometry the planar distribution of whose axes coincides with the slip plane of the shear zone (Hansen, 1967, 1971; Scott, 1969). Typically the planar distribution of fold axes defines a great circle with axes distributed into fields of alternate asymmetry separated by an arc (separation arc). For flexural-slip folds the separation arc most probably delimits the slip line. The sense of relative movement along the slip line can be determined by inspecting the predominant sense of asymmetry on either side of the slip line as limited by the separation arc. According to Hansen (1971, p. 51) application of the separation arc technique requires that: (1) the folds belong to a single generation; (2) they are of a single order; (3) they are located between two adjacent axial surfaces of the next lower order; (4) the folded layers were planar before folding; and (5) the folds from which the separation angle is obtained are the latest generation. Our analysis of style suggests that all the folds we describe as first generation are indeed of a single generation. Although these folds ranged in amplitude from centimeters up to a meter, none of the smaller measured folds were obviously parasitic or of a higher order relative to a larger outcrop-scale fold. The lack of demonstrated map-scale folds precludes the evaluation of condition (5). The bedded chert layers were certainly planar before folding. The chert layers in the gray chert and argillite may have been discontinuous; however, discontinuous chert layers commonly form along bedding planes in undeformed pelagic rocks, and overall they approximate planar surfaces (Bailey, Irwin, and Jones, 1964, p. 69). Finally, the first-generation folds are not the latest generation, but the second-generation folds are not penetrative and do not seem to affect the geometry of the first-generation structures significantly.

Recent studies by Reches and Johnson (1976) indicate that the sense of overturning of small-scale asymmetric folds may not necessarily reflect the direction of layer-parallel shear. These authors have found that folds formed in lubricated multilayers are overturned in the direction of shear, whereas those formed in multilayers with high frictional resistance between layers yield an asymmetry opposite to the applied shear. Since most of the Uyak folds are of chert or limestone with interbedded argil-
lite, their asymmetries probably reflect the direction of layer parallel shear in a simple manner.

The data from each of the five subareas of the Uyak mélange provide the basis for specifying five slip planes and five slip lines. The orientations of folds are plotted for each subarea (fig. 6); symbols designate the asymmetry and show whether the fold was measured in a slab or matrix lithology. In each case the great circle fitted to the distribution of all fold axes specifies the slip plane (table 1, line 3). The fields of opposite asymmetry define narrow separation arcs that are presumed to contain the slip lines. The folds with clockwise asymmetry plunge primarily to the northeast, and the folds with counter-clockwise asymmetry plunge primarily to the southwest, indicating movement of northwest over southeast along the steeply plunging slip lines. The asymmetry of individual folds is on the average 85 percent consistent with the slip lines determined by fold asymmetry.

The fold axes from slab and matrix lithologies do not show consistently separate patterns of orientation and asymmetry; we therefore felt justified in combining them into a common data set. This result is surprising in that one might expect the slabs to rotate in the slip plane independently from the matrix. Apparently their tabular shape counteracted any tendency toward independent motion.

It is improbable that the pattern of consistency of fold asymmetry we observe was sampled from a population of folds with random asymmetry (table 1, line 9); according to the statistical test applied, we can be 99 percent confident that the predominant pattern asymmetry of fold axes on each side of the separation arc in each subarea is real. Nevertheless, it is worthwhile to consider the factors that may cause the inconsistent fold axes: if there exist undetected map-scale first-generation folds, then local reversals in asymmetry could have occurred on their limbs; small errors in measurement could transpose an axis across a narrow separation arc; the direction of slip may have varied during the finite length of time required for the accretion of the mélange; earlier first-generation folds may have been rotated by later first-generation folds, later undetected faults, or second-generation folds. Some reversals in asymmetry may be due to presence of local sequences with high contact strengths as proposed by Reches and Johnson (1976). In any case, the 85 percent consistency of the observed fold axes and their demonstrated statistical significance (table 1, line 9) indicate that none of the above effects was sufficiently strong to obliterate the structural coherency of the mélange.

Method of Axial-Surface Fabrics

Asymmetric flexural or flexural-slip folds with a planar distribution of axes may show a common intersection of fold axial surfaces, the zone axis (Hansen, 1967; Scott and Hansen, 1969). Scott and Hansen (1969) showed that a great circle passed through this zone axis, and a pole to the slip plane intersects the slip plane within the separation arc defined by
| Table 1
Summary of kinematic analysis |
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<tr>
<td>Subareas</td>
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<tr>
<td>1. Number axial surfaces (AS)</td>
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<td>2. Number hinge lines (HL)</td>
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<td>4. Orientation of slip line (SL)</td>
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<td>5. Width of separation arc (SA)</td>
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<td>7. Consistency of HL consistent (C):</td>
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<td>11. Avg deviation of AS from zone axis</td>
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Slip plane (line 3) estimated as a visual fit of a great circle to a projection of the hinge lines. Slip line (line 4) calculated by method of axial surface fabrics. Relationship between slip line and separation arc (line 6) gives degree of agreement between separation-arc technique and method of axial-surface fabrics. Line 7 shows consistencies of hinge-line asymmetries relative to northwest-up sense of movement in separation arc and on slip plane. P-value (line 3) is the probability that a consistency value as large as or larger than the observed value could have arisen by chance (see Wheeler, 1978). The low P-values allow us to be more than 99 percent confident that the predominant asymmetry indicated by our sample is representative of all Uyak folds. The average deviations of hinge lines from the slip plane (line 10) and axial surfaces from the zone axis (line 11) provide respective estimates of the uncertainty of the slip plane and slip line determinations.
the fields of alternate asymmetry of the fold axes. Thus this intersection provides a semi-independent determination of the slip line and possible confirmation of results obtained by the separation-arc technique.

The conditions for the application of the method of axial-surface fabrics are largely the same as those for the separation-arc technique (described above) and are approximately satisfied by the first-generation folds. However, we must be certain that the axial surfaces of the Uyak first-generation folds have not been refolded to produce a zone axis artificially. Second-generation folding is neither intense nor pervasive. The few available second-generation axial surfaces strike northeast; folding along these axial surfaces could not generate out of the first-generation axial surfaces, a zone axis plunging steeply to the northwest, as observed in each of the five subareas (fig. 7). Furthermore, we see no systematic map-scale variations in the orientation of fold axial surfaces or foliation that might indicate long wavelength second-generation folding.

The poles to fold axial surfaces, the zone axis of the axial surfaces, the slip plane, the pole to the slip plane, and the derived slip line are all shown on figure 7. The zone axis has been determined as a π axis to the poles to the axial surfaces by a least-squares technique (Ramsay, 1967). The average deviation of the individual axial surface from the zone axis (table 1, line 11) is 13 degrees in all subareas excepting Uyak where it is 20 degrees. This number provides an estimate of the uncertainty of the derived slip line. The slip lines (table 1, line 4) lie within the separation arcs in three subareas (Uyak, Uganik, and Raspberry) and show discrepancies of 22 and 12 degrees in the Gurney and Shuyak subareas respectively (table 1, line 6).

Discussion and Summary of Slip-Line Data

One can justifiably question the use of the separation-arc technique and the method of axial-surface fabrics to determine slip lines and slip planes in an intensely deformed mélange. Here we discuss some of the theoretical questions regarding the development of the separation arc and zone axis. The available data do not allow complete understanding of the evolution of these geometric features. Nevertheless, the empirical fact that the slip lines and slip planes are resolved with confidence, consistent between subareas, and geologically reasonable indicates that the above mentioned techniques can extract meaningful structural results from the Uyak mélange.

Groups of folds with narrow separation arcs have been shown to form initially with diverse orientations (Hansen, 1971). Other examples of folds with diverse orientations have alternate explanations. Borriadaile (1972) proposed constrictive flow to account for the rotation of fold axes toward the direction of principal extension and called upon continued folding to produce additional axes nearly normal to the extension direction. Sanderson (1973) proposed a model for the rotation of folds initially formed subparallel to Y toward X during extension in the X-Y plane
(X and Y are maximum and intermediate axes of strain ellipsoid). The rotation of the fold axes during continued deformation would narrow but not obliterate the separation arc, since the fold axes could not rotate beyond the direction of maximum extension. Thus the narrow separation arcs we observe could be the result of a progressive deformation involving the formation of asymmetric folds and their subsequent rotation during extension associated with the development of the foliation.

The zone axis has been interpreted as the direction of extension common to the folds that define it (Hansen, 1967). While this interpretation may hold for a single stage of fold development with diverse orientation of axial surfaces, it probably would not be valid for rocks subject to progressive deformation. For example an initially developed zone axis would rotate toward the direction of maximum extension during continuing deformation. Thus, the slip line determined from the zone axis could record the combined effects of folding and later extension.

At our present state of investigation we cannot resolve hypothetical stages of progressive deformation within the first-generation folding of the Uyak mélange. Therefore, in practice we define their possibly combined result as our first deformation and accordingly summarize our kinematic information.

The summary of slip-line data indicates a consistently steep plunge to the northwest (fig. 8). Since the ambiguity is within the error of field measurement, slip lines limited by narrow separation arcs (< 6°) are specified as lines and combined with specific determinations by the axial-surface fabrics method. The vector mean of these slip lines has a 95 percent confidence limit of 11°, assuming a spherical normal or Fisherian distribution (Watson, 1966). Since the slip lines show no systematic variation along 200 km of structural strike, we feel that the mean slip line can be applied to the entire mélange.

**CONDITIONS OF DEFORMATION**

The interpretation of the slip-line data within the regional framework depends in part upon specifying the conditions of deformation. Here we evaluate the evidence for surficial slumping as opposed to tectonic deformation during the emplacement of the Uyak mélange.

Typical criteria for the recognition of surficial slump deformation include the restriction of folds to a single bed, the up-section truncation of folds along a sedimentary contact, and undeformed burrows cutting across deformed material (Hobbs, Means, and Williams, 1976; Kleist, 1974). None of the above indicators of slump folding was observed anywhere in the Uyak mélange. Alternatively, the first-generation folds could be interpreted as recycled slump folds, subsequently sheared into the mélange. However, a comparison of style elements of Uyak folds and one group of known slump folds (Woodcock, 1976) argues against this possibility. Compared to the Uyak folds, Woodcock’s slump folds show significantly lower mean and modal interlimb angles and higher mean height/spacing ratios (estimated from Woodcock’s “length and
height" data). Thus, it is unlikely that the Uyak folds originated as slump folds like those described by Woodcock, unless the Uyak folds were unfolded during subsequent deformation.

The axial-plane foliation associated with the Uyak folds apparently formed under significant confining pressure and is consistent with their tectonic origin. The foliation is defined by fractured and locally recrystallized silicate mineral grains and anastomosing opaque films. Although recrystallized quartz, chlorite, and prehnite may locally define the

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Fig. 8. Slip-line summary. Slip lines determined from narrow separation arcs (<5°) and method of axial-surface fabrics indicated by closed circles on stereographic projection (inset). Triangle represents vector mean and is enclosed by 95 percent cone of confidence. Horizontal arrow depicts azimuth of restored mean slip line. Map shows slip lines individually restored around axis of tilting and plotted by subarea. Arrows indicate movement of underthrusting relative to over-thrusting plate. CMF and BBF respectively indicate Castle Mountain and Bruni Bay faults.
foliation, they more commonly occur in cross-cutting vein fillings. Also
prehnite forms radiating fans cutting across the foliation (Connelly, 1978).
Apparently the foliation continued to form after metamorphism began,
but the latter peaked after the foliation had developed.

In summary, the absence of evidence for soft-sediment origin plus
the association with a foliation formed under significant confining pres-
sure argues for the tectonic origin of the first-generation folds of the Uyak
mélange.

TECTORIC INTERPRETATION OF MÉLANGE STRUCTURE

A tectonic interpretation of the Uyak mélange must explain its
abundance of oceanic rock types, the strong asymmetry and planar dis-
tribution of the first-generation folds, the foliation, the current steep
orientation of the foliation and fold axial surfaces, and the occurrence
definition preceding the peak of metamorphism. The radiolarian
cherts (Connelly, 1978) and the basaltic rocks of the Uyak mélange (Hill
and Gill, 1976) are of oceanic origin and must have formed seaward of
any ancient subduction zone. To accrete these and probably other rocks
of the Uyak mélange, they must be transferred from the underthrusting
plate to the overthrusting plate. Hence, they must pass through any
master shear zone separating the two plates (fig. 9A). The pronounced
seaward overturning and the planar distribution of the Uyak folds are
explained most simply by deformation in this shear zone. It is reassuring
that folds with comparable geometry and orientation have been found
to form in planar shear zones elsewhere (Scott, 1969; Hansen, 1971).

The transposed foliation and widespread brittle fracture of the Uyak
mélange are consistent with its initial deformation during underthrust-
ing. Underthrusting to moderate depths (9-15 km for Uyak mélange)
along a shallowly inclined subduction zone could involve enormous
strains and high strain rates. The completion of first-generation deforma-
tion before the metamorphic peak suggests that the rocks were rapidly
emplaced before they could equilibrate thermally, which is also consist-
tent with underthrusting in a subduction zone.

Earthquake focal mechanisms (for example, Stauder and Mualchin,
1976), patterns of surface deformation associated with modern subduction
zones (Plafker, 1972), and seismic reflection profiles (for example, Seely,
Vail, and Walton, 1974) all indicate that underthrusting is shallowly
inclined (<20°) at depths less than 60 km. The Uyak mélange was under-
thrust to about 15 km, yet the fold axial surfaces, the foliation, the slip
planes, and the slip lines all dip or plunge steeply. This discrepancy is
probably explained by landward tilting, possibly due to imbrication be-
neth the seaward margin of the mélange (fig. 9B, C, D) (Seely, Vail, and
Walton, 1974; Karig and Sharman, 1975). The second-generation folds
and various shears cutting across the foliation probably formed during
landward tilting. The second-generation structures may be accounted for
by the seaward migration of the tilt axis, which causes broad folding of
previously accreted rocks on its landward side (fig. 9C, D). The pre-
Fig. 9. Particle trajectory for Uyak mélangé. (A) Underthrusting along master shear zone with development of first-generation folds. (B) Tilting with minor underthrusting. (C, D) Landward tilting. Shaded portions of accretionary prism (B, C, D) represent material emplaced during each phase of tilting. Note seaward migration of axis of tilting and consequent broad folding (second generation?) of accretionary wedges landward of tilt axis. (E) Total particale motion composed of underthrusting and tilting components.
dominant orientation of second-generation fold axes parallel to the structural strike of the mélange is consistent with this origin.

The structural and metamorphic history of the Uyk mélange can be interpreted in terms of an expected particle trajectory in a subduction zone. The Uyk mélange records the effects of a unique particle trajectory, whereas many are presumably possible; one is shown in figure 9. The inferred particle trajectory is composed of components of underthrusting in a master shear zone and uplift due to landward tilting. The axis of tilting for any time period is defined by the intersection of two planes approximating the upper and lower boundaries of the accretionary wedges emplaced during that interval (shaded wedges in 9B, C, D). The axis of tilting migrates seaward, leading to a tilting path composed of several arcuate segments.

Although the fabric of the Uyk complex suggests rapid decrease in the pervasive effects of underthrusting following accretion, the rock mass could have been further underthrust by movement along well defined non-penetrative faults. These faults could cause various offsets in the smooth tilting and uplift curve depicted in figure 9B, C, D. Erosion of substantial volumes of material from the uplifted accretionary wedges is inherent in the construction of figure 9 (also see Platt, 1975) and consistent with the recycled deep-sea detritus observed in the Uyk mélange (Connelly, 1978). In summary, figure 9 depicts one of the simplest possible trajectories for the Uyk mélange that would explain its intense early deformation, subsequent kinking, and steeply inclined fabric. Other more complex trajectories are possible and may include dynamic uplift in addition to landward tilting (Silling and Cowan, 1977), compression of the accreted wedge (Seely, 1977), and gravitational flow (Elliot, 1976; Hamilton, 1977).

**REGIONAL INTERPRETATION OF SLIP LINES**

We believe the first-generation deformation records the initial emplacement of the Uyk mélange within the hanging wall of the subduction zone. In order to assess the significance of the slip lines, they must be restored to their presumed shallow inclination. We do not know the exact dip of the original deformation zone, but analogies to modern subduction zones suggest that it was probably about 10 degrees and certainly less than 20 degrees. In view of this ambiguity we have restored the slip lines to horizontal following the practice used for slip vectors derived from focal mechanism solutions. The accretion of Upper Cretaceous and lower Tertiary deep-sea sequences seaward of the Uyk mélange probably produced most, if not all, its landward tilting. We assume that accretion and consequent tilting were uniform along structural strike and therefore restore the mean Uyk slip line around a horizontal axis trending N44°E symmetrical to the outcrop patterns of the Cretaceous and lower Tertiary rocks. Although non-uniform accretion has been shown to occur (Karig and Sharman, 1975), the resulting plunge and change in trend of the axis of tilting is slight and can be neglected.
The mean azimuth of the restored slip lines (N38±11W°) (fig. 8) is interpreted as the azimuth of movement or *slip vector* between the upper and lower plates in the subduction zone. The slip lines have also been individually restored (fig. 8).

Studies of earthquake focal mechanisms (Fitch, 1972) show that the total slip vector at some convergent plate boundaries is composed of two components, one within the subduction zone and another along a major strike-slip fault within the magmatic arc, 100 to 300 km landward of the trench. Accordingly the slip vector from the Uyk mélange may represent but one component of the total convergence vector. To test this possibility we have examined evidence for displacement along major faults in the Alaska-Aleutian Range (fig. 8): the Bruin Bay fault shows a maximum left-lateral displacement of 19 km since the Late Triassic (Detterman and Hartsock, 1966) and the Lake Clark-Castle Mountain fault displays a right-lateral offset of 13 km since the Triassic (Ivanhoe, 1962). Although undocumented strike-slip faulting may occur northwest of the Kodiak Islands, the established strike-slip offsets along the known faults are small relative to the expected magnitude of underthrusting during the Late Cretaceous. Therefore, slip vector from the mélange is probably a good approximation of the total convergence vector between the oceanic plate and adjacent magmatic arc plate.

If the slip vector records the convergence direction between the oceanic and magmatic arc plates during Uyk accretion, then the great circle normal to the slip vector should pass through the pole of rotation for these plates. The Uyk mélange was probably accreted in the Late Cretaceous during several tens of millions of years. Hence, the slip vector may represent finite relative plate motion. While the specific position of the finite pole cannot be defined from our data, the slip vector and its associated great circle provide valuable constraints for tectonic interpretations.

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