Deformation History of the McHugh Complex, Seldovia Quadrangle, South-Central Alaska

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Abstract

Detailed mapping (scales 1:1,140 and 1:6,000) at three large, recently deglaciated exposures in the Seldovia quadrangle, south-central Alaska, has clarified aspects of the structural history of the McHugh Complex. At Grewingk Glacier, the McHugh Complex consists of multiple fault slices of relatively coherent basalt, chert, and graywacke, each up to a few tens of meters thick, bounded by zones of mesoscale mélange. We interpret the mesoscale mélanges as having formed in thrust zones, and the map pattern as resulting from thrust repetition of an originally simple oceanic-plate stratigraphy. Late brittle faults belong to six sets, some of which are significant enough to cause mappable offsets. A prominent set of dextral faults strike east-northeast (set I), and a conjugate set of sinistral faults strike north-northwest (set II); displacement on fault sets I and II resulted in orogen-parallel extension. Minor east-striking normal faults that dip north and south (sets V and VI) also were responsible for some orogen-parallel extension. Minor north-striking, west-dipping late thrust faults (set IV) are subparallel with the present convergent margin. North-striking dextral faults (set III) offset the earlier dextral faults of set I. Displacement on fault set I was approximately coeval with injection of silicic to intermediate dikes of early Eocene age. Poles to dikes and dike transforms together indicate a mean extension direction of 345°. We interpret the dikes and associated strike-slip faults of sets I and presumably II as the result of subduction of the Kula-Farallon Ridge. The origin of the other late structures is not yet clear; they might relate to northward strike-slip motion of the Chugach terrane, formation of the southern Alaska orocline, critical taper adjustments of the accretionary wedge, or some other cause.

INTRODUCTION

The McHugh Complex of south-central Alaska (fig. 1) is generally interpreted as part of a Mesozoic accretionary prism, the Chugach terrane, that formed by offscraping and (or) underplating at an ancient subduction zone, outboard of the composite Peninsular-Wrangellia-Alexander superterrane (Plafker and others, 1989). Regional geologic relations, plate-circuit reconstructions, and paleomagnetic data together suggest that several important younger events also may have affected the McHugh Complex. These include northward coastwise strike-slip of the entire Chugach terrane (Coe and others, 1985), oroclinal bending to form the southern Alaska orocline (Coe and others, 1985), subduction of the Kula-Farallon Ridge (Marshak and Karig, 1977), and piecemeal or wholesale accretion of Upper Cretaceous and Cenozoic flysch that now occupies the region between the McHugh Complex and the Aleutian Trench (Plafker and others, 1989).

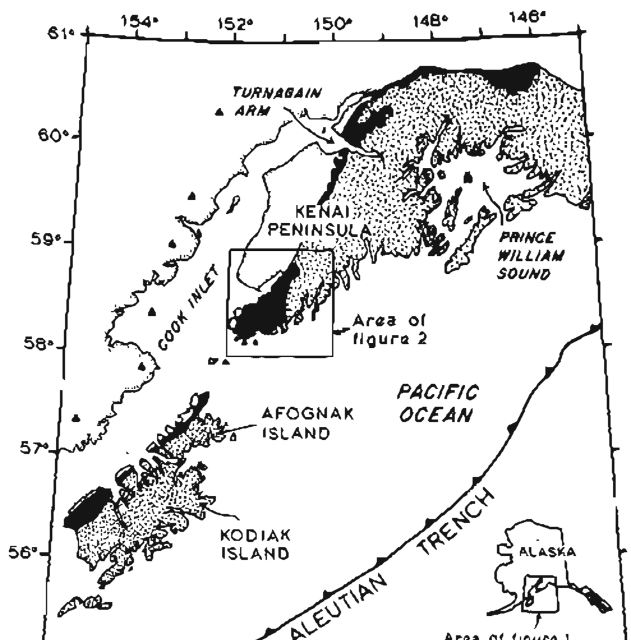


Figure 1. Locality map of south-central Alaska. Triangles, volcanoes of Aleutian arc; black, McHugh Complex, including Kachemak "terrane," and correlative Uyak Complex in Kodiak and Afognak Islands; stipple, other parts of Mesozoic–Cenozoic accretionary complex, including Valdez Group of Chugach terrane and Orca Group of Prince William terrane.

This paper presents new structural data from the Seldovia quadrangle (figs. 1, 2) bearing on these postulated events. Our findings on the early deformation history mainly stem from detailed (1:1,140 scale) mapping at the terminus of the Grewingk Glacier (fig. 2, loc. 2). Conclusions about the nature of late deformation at Grewingk Glacier are supplemented by less detailed 1:6,000-scale mapping at the termini of the Dixon and Wosnesenski Glaciers (fig. 2, locs. 1 and 3, respectively). Rapid ice retreat (up to 1.3 km in the last 40 yr) has left polished *roche moutonee*, hundreds of meters across, of nearly 100 percent bedrock exposure at the three areas. The structure of the McHugh Complex in these areas is complicated but not entirely chaotic, and can be resolved through detailed mapping.

REGIONAL GEOLOGY

The Seldovia quadrangle (fig. 1) lies in the arc-trench gap of the present-day Aleutian subduction system; our detailed map areas are about 35–40 km above the Benioff Zone (for example, Jacob, 1986). We have subdivided Mesozoic rocks in figure 2 into six belts. (1) Mesozoic volcanogenic strata of magmatic-arc affinity (Kelley, 1980) lie farthest inboard and comprise the **Peninsular terrane** of Jones and others (1987); younger Tertiary strata in this area define the Cook Inlet Basin, which is the active forearc basin of the Aleutian arc. (2) The **McHugh Complex** (Clark, 1973) is part of the Chugach terrane of Jones and others (1987), a Mesozoic accretionary wedge. Rock types include variably disrupted greenstone, chert, argillite, graywacke, conglomerate, outcrop-scale mélange, and rare limestone. (3) The **Valdez Group**, also part of the Chugach terrane, flanks the McHugh Complex on the southeast. It consists of Upper Cretaceous turbiditic graywacke, slate, and conglomerate, and mélange belonging to type I of Cowan (1985).

Included within the limits of the area mapped as the McHugh Complex in figure 2 are three additional map units of problematic tectonic affinity; whether these rocks are part of the Peninsular terrane ("upper plate") or accretionary wedge ("lower plate") is debatable. (4) The **Seldovia metamorphic belt** (Seldovia schist terrane of Cowan and Boss, 1978) is a narrow zone, metamorphosed to blueschist facies, along the inboard margin of the accretionary wedge. Rock types include marble, quartzite (metachert), metapelite, and metabasite. Comparable protoliths all occur within the McHugh Complex (albeit in different proportions), which otherwise is metamorphosed to prehnite-pumpellyite facies. Recent work has shown that mélange of the McHugh Complex occurs in narrow bands on both sides of the metamorphic belt (D. Bradley and S. Karl, unpubl. field mapping, 1989). (5) The **Kachemak "terrane"** of Jones and others (1987) consists of intensely faulted pillow and massive basalt, overlain by complexly folded and faulted radiolarian chert, now known to range in age from Middle Triassic to Early Jurassic (C. Blome, oral commun., 1991). Stratigraphic nomenclature for these rocks has yet to be formalized, and the structure is far more complex than it would seem from the simple map pattern on the compilation map of Magoon and others (1976). It is not clear that there are any compelling lithologic differences between chert and basalt within the area identified by Jones and others (1987) as the Kachemak "terrane", and chert and basalt within the outcrop belt of the McHugh Complex. The only mappable difference is that the McHugh Complex also includes abundant graywacke and argillite. On the basis of similar radiolarian age ranges in cherts of the McHugh Complex and Kachemak "terrane", Blome and others (1990) suggested that the Kachemak "terrane" may be merely a part of the McHugh (accretionary) Complex in which the basalt-chert association dominates the outcrop. (6) In the Seldovia quadrangle, the **Border Ranges ultramafic and mafic complex** of Burns (1985) consists of at least seven separate bodies of mafic and ultramafic plutonic rocks that occur as fault-bounded slices within the outcrop belt of the McHugh Complex (fig. 2).

STRATIGRAPHY OF THE McHUGH COMPLEX

Despite structural disruption, locally preserved stratigraphic relations and fossil ages within the McHugh Complex and Kachemak "terrane" permit a crude reconstruction of an original stratigraphy (fig. 3*A*) that is now repeated by numerous thrust faults. It is uncertain whether any ultramafic or mafic plutonic rocks of the lower part of this inferred stratigraphic succession are exposed within the McHugh Compex. The ultramafic body at Red Mountain (loc. 7 in fig. 2), which otherwise would seem a likely candidate, has magmatic-arc affinity and, according to one interpretation (Burns, 1985), is part of the original basement of the Peninsular terrane. Mafic volcanic rocks within both the McHugh Complex as mapped by Magoon and others (1976) and the Kachemak "terrane" of Jones and others (1987) include variably altered pillow basalt, hyaloclastic basalt, and massive basalt; the McHugh Complex, in addition, contains cataclastically microbrecciated basalt that in hand sample resembles a volcaniclastic rock (commonly designated "tuff" in the field). At several places in the Kachemak "terrane" (for example, loc. 4, fig. 2), radiolarian chert overlies pillow basalt. Chert in the McHugh Complex and Kachemak "terrane" includes gray, green, red, and black radiolarian-bearing ribbon chert, interbedded on a scale of a few centimeters with argillite; faulting and disharmonic folding are pervasive. Radiolarian ages in both the McHugh Complex (from Turnagain Arm and Seldovia) and the Kachemak "terrane" range from Late Triassic to Early Cretaceous (Nelson and others, 1987; Blome and others, 1990; C. Blome, oral commun., 1990). At locality 5 (fig. 2), graywacke conformably overlies ribbon chert that yielded Pliensbachian (Early Jurassic) radiolarians (C. Blome, oral commun., 1990). Graywacke in the McHugh Complex mainly occurs as amalgamated massive turbiditic sandstone (facies B of Mutti and Ricci-Lucchi, 1978) but also includes horizons of up to 50 percent interbedded argillite (facies C and D). Conglomerate and associated graywacke occur in massive zones hundreds of meters thick (facies A of Mutti and Ricci-Lucchi, 1978). Weakly deformed, gently dipping interbedded argillite and siltstone is present at Jakolof Bay (loc. 8 in fig. 2). Outcrop-scale mélange also is abundant. We interpret its origin as structural, not stratigraphic, as described below.

Implicit in figure 3*A* is the assumption that the basalt, chert, and graywacke each occur at a single relative position in the stratigraphic succession. Because some chert is younger than at least some graywacke, either

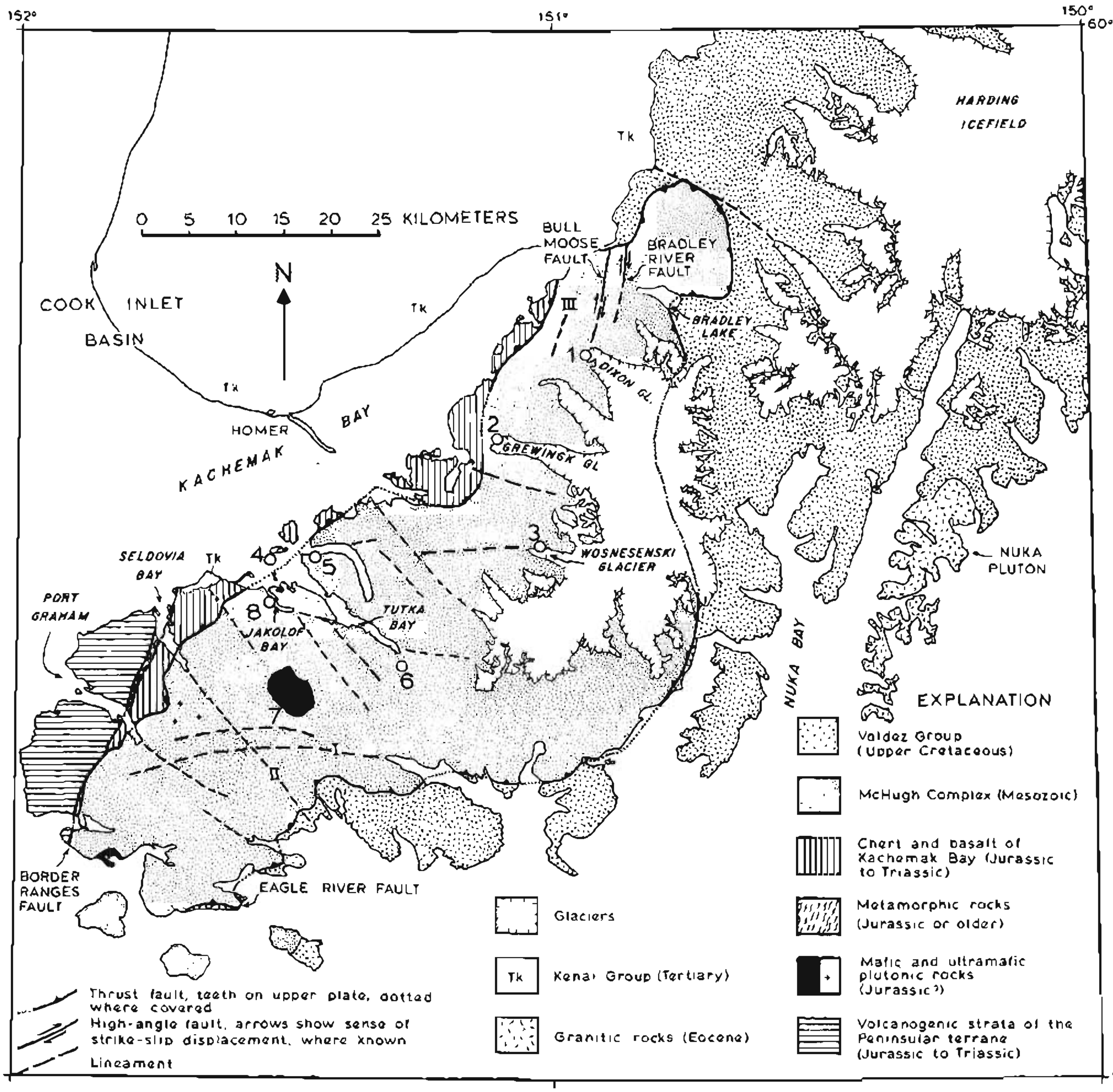


Figure 2. Generalized geologic map of eastern two-thirds of Seldovia quadrangle. Arabic numbers refer to localities mentioned in text; Roman numerals identify faults representative of fault sets I, II, and III. Modified from Magoon and others (1976).

their mutual contact is strongly diachronous or a second chert unit overlies the graywacke.

Following an original suggestion by Connelly (1978) for the Uyak Complex (a McHugh correlative along strike on Kodiak Island; fig. 1), we illustrate in figure 3*B* how the components of the McHugh Complex and Kachemak "terrane" might be related paleogeographically. According to this model, the basalts formed at a spreading center (or, perhaps equally likely, at an off-axis seamount), and the conformably overlying cherts were subsequently deposited as the oceanic plate was conveyed toward a convergent plate boundary. The argillite, graywacke, and conglomerate were deposited in the trench, mainly on the descending plate along the outer trench slope and trench axis. The mildly deformed argillite and siltstone at Jakolof Bay (fig. 2) may have been deposited on the inner trench slope, atop the accretionary prism. A key aspect of this general model (and a similar model for accreted rocks in Japan by Matsuda and Isozaki, 1991) is that deposition and subduction-ac-

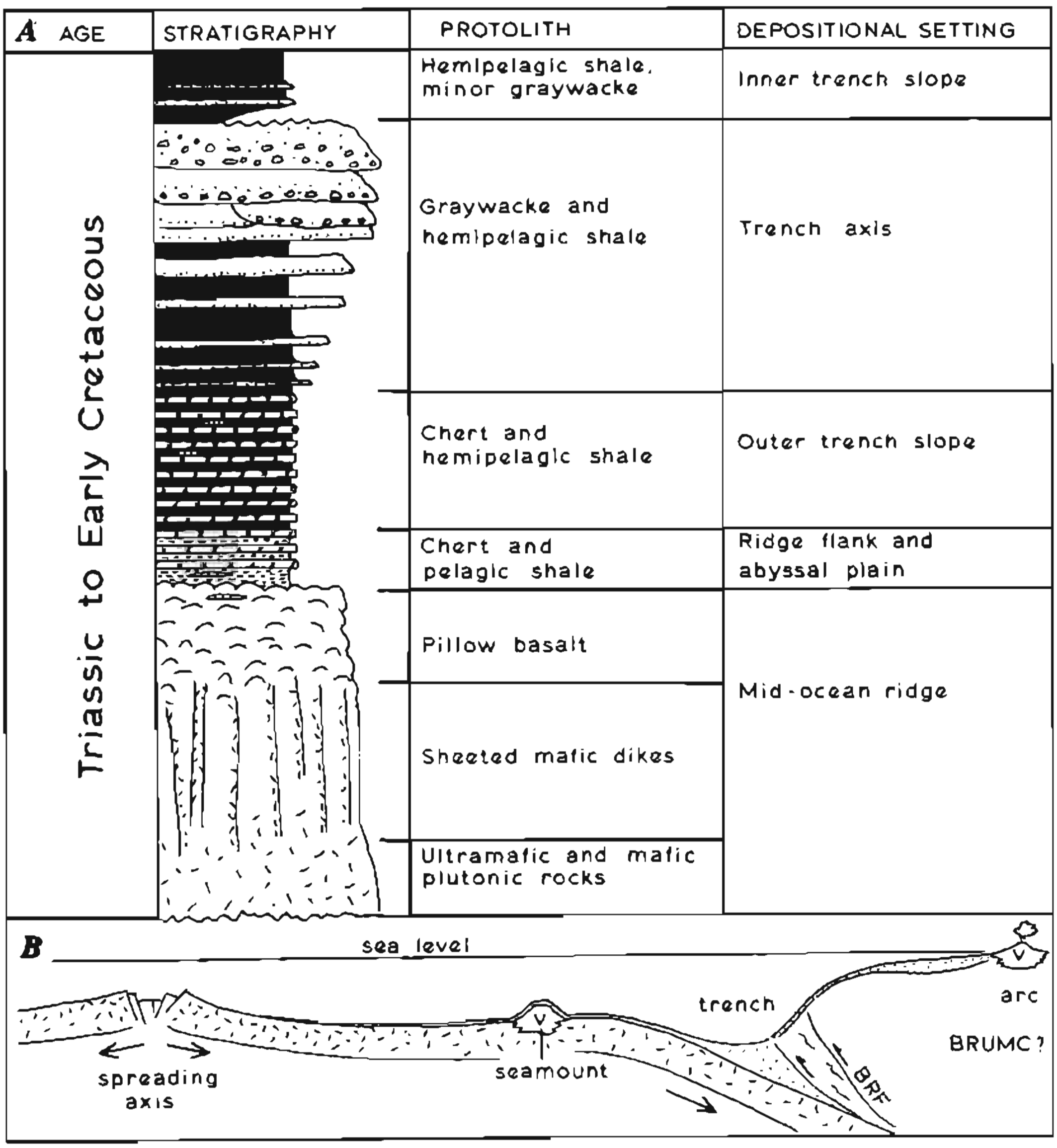


Figure 3. *A*, Generalized stratigraphy of McHugh Complex in Seldovia quadrangle, showing inferred relations among rock types prior to deformation within accretionary wedge. Specific radiolarian age ranges are not given, pending work in progress. *B*, Cross section from an oceanic spreading center to a subduction zone, modified from Connelly (1978). This conceptual model illustrates how varied rock types comparable to those within Kachemak "terrane" of Jones and others (1987) and McHugh Complex might have been conveyed into trench and either subducted or incorporated into accretionary wedge. BRF, Border Ranges fault zone; BRUMC, Border Ranges ultramafic-mafic complex of Burns (1985); V, seamount volcanics.

cretion are steady-state, continuous, overlapping processes, *not* one-time events. This pattern inevitably leads to diachronous relations: contacts between basalt, chert, and graywacke in two different offscraped or underplated slices of the oceanic plate should differ in age; likewise, deformation of one part of the mélange might predate the existence of some or all protoliths in a different part of the mélange.

Our stratigraphic model accounts for basalt and cherts of the Kachemak "terrane" as the basement and pelagic cover of an oceanic plate that has largely vanished down a subduction zone. Jones and others (1987) regarded the basalt and cherts of Kachemak Bay as a tectonostratigraphic terrane that was distinct from the surrounding McHugh Complex. Alternatively, we suggest that the siliciclastic strata of the McHugh Complex were deposited on top of the chert and basalt of the Kachemak "terrane" and were subsequently offscraped and (or) underplated at the subduction zone. Detailed mapping at Grewingk Glacier (fig. 4*A*) provides structural evidence for thrust repetition that is consistent with this scenario.

SEDIMENTARY AND EARLY TECTONIC STRUCTURES AT GREWINGK GLACIER

Bedding

At Grewingk Glacier (fig. 4), graded beds, upright with tops toward the northwest, are locally preserved in the graywacke (fig. 5*A*). Well-preserved bedding in the ribbon cherts is roughly parallel with that in the graywacke, but tops are unknown. Bedding is rarely preserved in the greenstones. The pattern of bedding poles in figure 5*A* is consistent with deformation by offscraping and (or) underplating in a subduction zone that was subparallel with the present one. If the Chugach terrane underwent coast-parallel strike-slip translation and oroclinal rotation during Tertiary time (see, for example, Plafker and others, 1989), then the McHugh Complex subduction zone more likely dipped to the northeast.

Early Tectonic Contacts

Most contacts between the map units at Grewingk Glacier are early tectonic contacts. These early faults or shear zones are typically uneven, deformed surfaces that contrast markedly with the late, straight faults described later. Some early faults are associated with thin (up to a few centimeters) veins of quartz-chlorite-calcite, commonly with thin selvages of wall rock. The early tectonic contacts locally truncate bedding (fig. 4*B*), but statistically the two fabric elements are essentially parallel (fig. 5*A*, *B*). We suggest that at least some early tectonic contacts initiated as bedding-parallel to low-angle thrust faults through subhorizontal strata; this interpretation is consistent with the repetition of rock types whose inferred stratigraphy is shown in figure 3. Some early tectonic contacts probably underwent large displacements, whereas others probably are minor movement surfaces related only to rheological contrasts between units that remain in their original stratigraphic order.

Mélange, Broken Formation, and Pebbly Mudstone

The entire outcrop at Grewingk Glacier is mappable at 1:63,360 scale only as mélange. However, at 1:1,140 scale, it is possible to map individual belts of greenstone, chert, and graywacke that are a few meters to tens of meters wide. In some places, slices become so narrow and interfaulted that even at 1:1,140 scale, they can only be mapped as mélange (fig. 4*A*). We refer to these zones as "mesoscale mélanges." They contain blocks of greenstone, chert, graywacke, and rare limestone set in an argillite matrix; different mélange zones contain different block assemblages (see numbers along base of fig. 4*B*). The blocks typically are elongate lozenges up to a few meters long and lie either in fault contact with other blocks or within a matrix of less competent black argillite. Where blocks are smaller (up to a few tens of centimeters), we have mapped these as zones of "pebbly mudstone" (fig. 6*A*), a field term that we use without any implied genetic connotation. Pebbly mudstone grades into "broken formation" (another field term used without any genetic connotation), which consists of variably pulled-apart beds of graywacke and chert (fig. 6*A*) in argillite matrix. In zones of broken formation, one or more competent beds commonly can be traced across the outcrop essentially unbroken, whereas other beds are extended on small faults into rhomboidal bed fragments that are aligned parallel to throughgoing bedding. Bedding disruption during development of broken formation was accomplished by movement along an intricate network of cataclastic shear zones [web structure of Cowan (1985) and Byrne (1984)]. In thin section, these are seen to be zones of significant grain-size reduction. Broken formation and pebbly mudstone exhibit a prominent layering, which is defined by both phacoidal cleavage of argillaceous matrix and by *XY* planes of fragments (fig. 5*C*). This mélange foliation is essentially parallel to both bedding and early tectonic contacts.

Early Bedding-Extensional Shear Bands

Mélange foliation and early thrust faults are commonly offset across shear bands that, where present, are

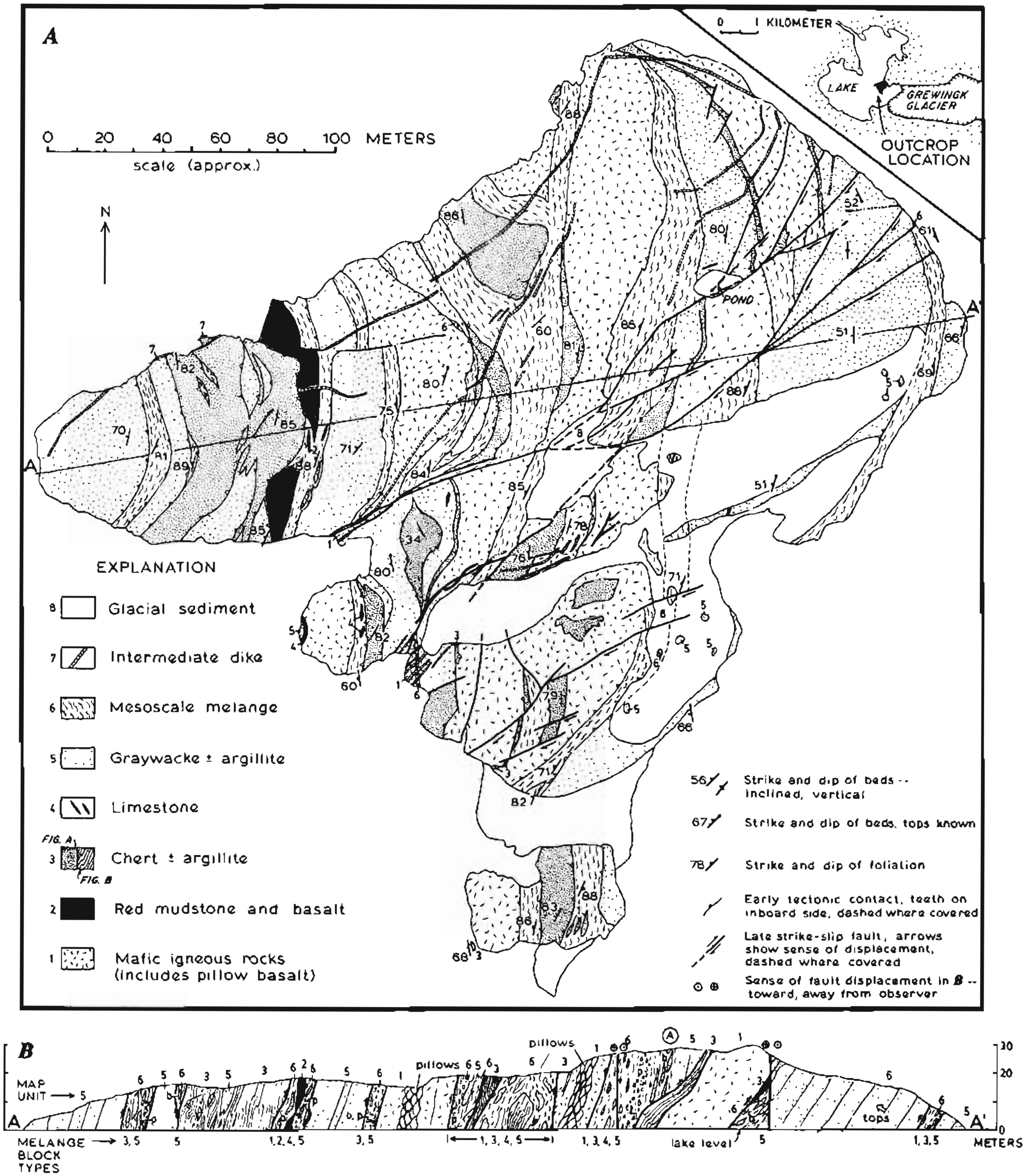
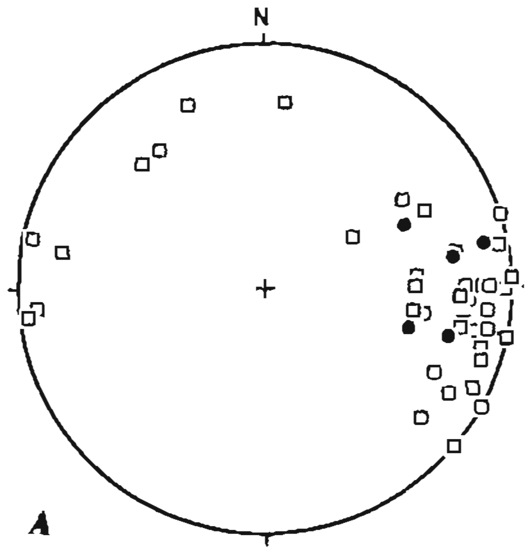
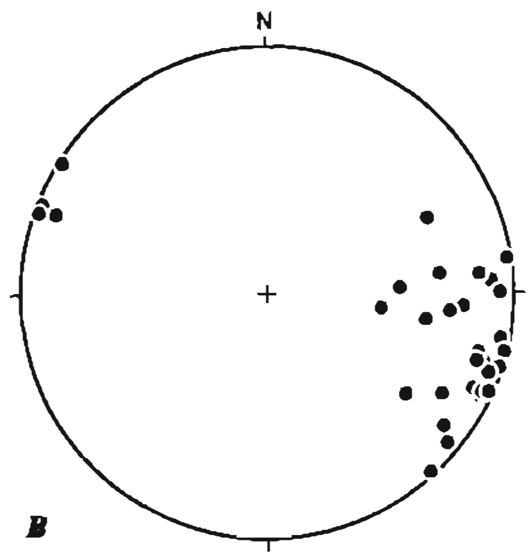
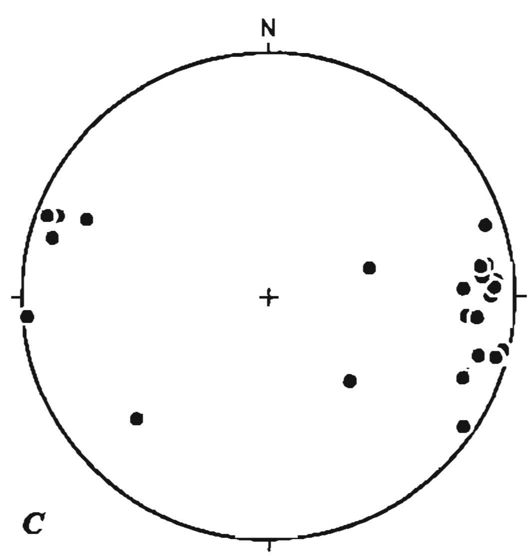


Figure 4. *A*, Geologic map (original scale 1:1,140) of McHugh Complex near lower terminus of Grewingk Glacier. Numbers indicate rock units in explanation. Map area is at locality 2 in figure 2. Inset shows location of ice front in late 1980's. *B*, Cross section A–A', showing repetition along early contractional faults of various ocean-floor rock types that comprise McHugh Complex. Numbers below cross section identify types of blocks in mesoscale mélange zones. b, broken formation; p, pebbly mudstone. No vertical exaggeration.







spaced a few tens of centimeters to several meters apart. The shear bands are mesoscopically ductile; layering shows conspicuous drag adjacent to the shear bands. In cross-sectional views, the shear bands cause offsets of up to a few meters (fig. 6*B*, *C*). A stereoplot of shear bands is shown in figure 7*A*; their significance is discussed below.

LATE STRUCTURES AT GREWINGK, WOSNESENSKI, AND DIXON GLACIERS

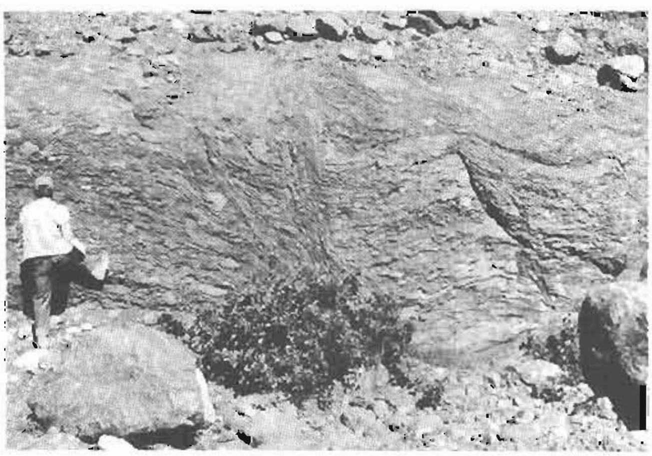
Brittle Faults

Late brittle faults occur throughout the area underlain by the McHugh Complex in the Seldovia quadrangle. We recognize three sets of late faults that are important on a regional scale (fig. 2): (I) older east-northeast-striking dextral faults; (II) northwest-striking lineaments that we interpret as conjugate sinistral faults related to set I; and (III) younger dextral faults that strike approximately north. In our detailed study areas (figs. 4, 8), prominent late faults belonging to sets I and III cause mappable offsets of up to a few tens of meters. At the outcrop scale, very minor late faults, too small to cause mappable offsets, are abundant. These belong to sets I, II, and III, as well as to three additional fault sets: (IV) west-dipping thrust faults, and (V and VI) conjugate north- and south-dipping normal faults. Equal-area projections of fault planes and associated slickenlines at Grewingk Glacier are displayed in figure 9. In all cases, only crystal fibers with unambiguous stepping directions are plotted. For ease of comparison, the stereonets are displayed in the same order as those from comparable late brittle faults along Turnagain Arm (see Bradley and Kusky, 1990). The average attitudes of the fault sets are summarized in figure 9.

At Grewingk and Wosnesenski Glaciers (figs. 4*A*, 8*A*), the most prominent late faults belong to set I: dextral strike-slip faults that strike about 070° (range about 060° to 100°). The largest dextral map separation of subvertical mélange units at Grewingk Glacier is about 50 m; subhorizontal fibrous slickensides with dextral steps confirm the shear sense (fig. 9*E*, *F*). At Wosnesenski Glacier, faults of set I cause dextral map separations of subvertical mélange units of up to about 20 m. Elsewhere in the Seldovia quadrangle, prominent,

◄ Figure 5. Lower-hemisphere equal-area projections from McHugh Complex at Grewingk Glacier. *A*, Poles to bedding. Filled circles, upright bedding; open squares, stratigraphic tops unknown. *B*, Poles to fragment foliation in mesoscale mélange. *C*, Poles to early faults and shear zones. Mean tectonic strike is about 020°.

A



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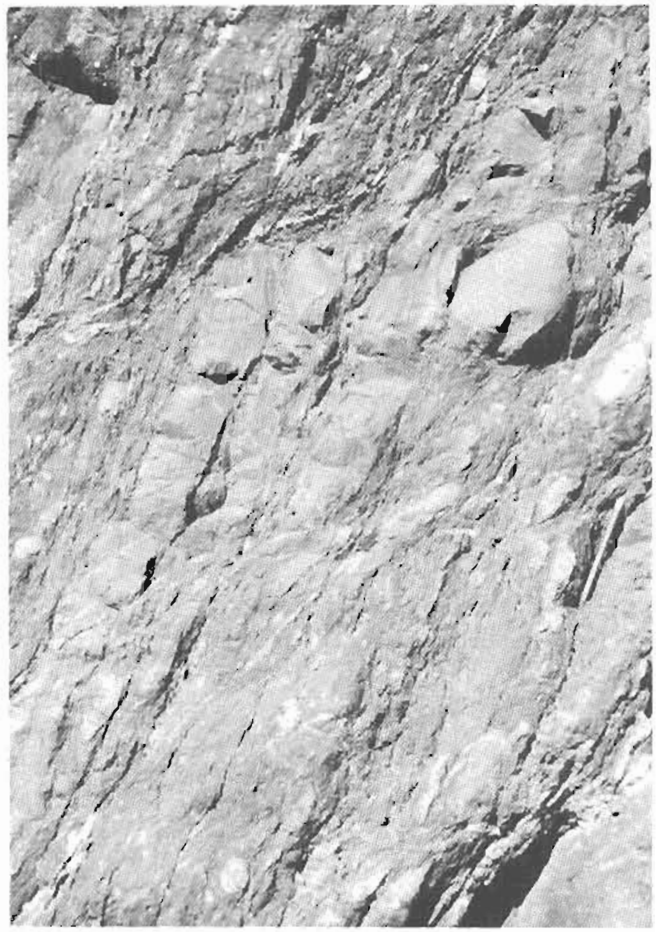


C

D

Figure 6. *A*, Pebbly mudstone grading into broken formation, McHugh Complex, Grewingk Glacier. Elongate bed fragments and equant "clasts" are mainly graywacke and black cherty argillite; matrix is phacoidally cleaved argillite. *B*, Early layer-extensional shear bands (moderately to steeply right-dipping) causing apparent normal offset of mélange foliation (gently dipping) in McHugh Complex at Dixon Glacier. *C*, Early shear band that extends steeply dipping layers, causing apparent contractional offset of mélange foliation in McHugh Complex at Grewingk Glacier. If shear band formed before layering was rotated to its present steep dip, shear band would have had an initial normal offset, like those in *B*. *D*, Transform offset across an intermediate dike, McHugh Complex, Dixon Glacier.

approximately east-trending lineaments can be traced for distances of several kilometers (fig. 2); most of these probably correspond to faults belonging to set I.

Although only one mappable sinistral fault was encountered in the three detailed map areas (at Grewingk Glacier; fig. 4*A*), northwest-trending lineaments (average trend about 320°) that we interpret as probable sinistral faults are conspicuous in the region (fig. 2). The best evidence that these are sinistral faults comes from the Bradley Lake area (fig. 2), where one such lineament, which trends about 310°, is responsible for 30-m sinistral map separation of mélange units (Woodward-Clyde Consultants, 1979, p. 47); the fault is truncated by the Bradley River fault (see below). Northwest-striking sinistral faults are common in Kodiak and Turnagain Arm (Bradley and Kusky, 1990). Very minor sinistral faults at Grewingk Glacier, too small to be mappable, mainly strike about northwest, but there is considerable scatter of dips and dip directions (fig. 9*G*, *H*). We suggest that northwest-striking, high-angle sinistral faults constitute an important set of late faults in the McHugh Complex, which we assign to set II.

Approximately north-striking (000° to 025°) dextral strike-slip faults, assigned to set III, cause mappable offsets at Wosnesenski and Dixon Glaciers (fig. 8). Elsewhere in the Seldovia quadrangle, north-trending lineaments were first recognized as dextral faults during engineering geology studies for the Bradley Lake Hydroelectric Project (fig. 2). The Bradley River fault dextrally offsets a vertical east-west dike by about 300 m (Woodward-Clyde Consultants, 1979, p. 19). A similar but smaller fault recognized in the Bradley Lake project, the Bull Moose fault (Woodward-Clyde Consult-

E

The transform does not cut country rock beyond the dike and hence was only active during dike emplacement. *E*, Leucocratic dike truncated by late, east-northeast striking dextral fault zone (parallel to pencil in lower half of photograph), Grewingk Glacier near pond (fig. 4*A*). Fragments of dike are entrained in fault breccia and displaced dextrally.

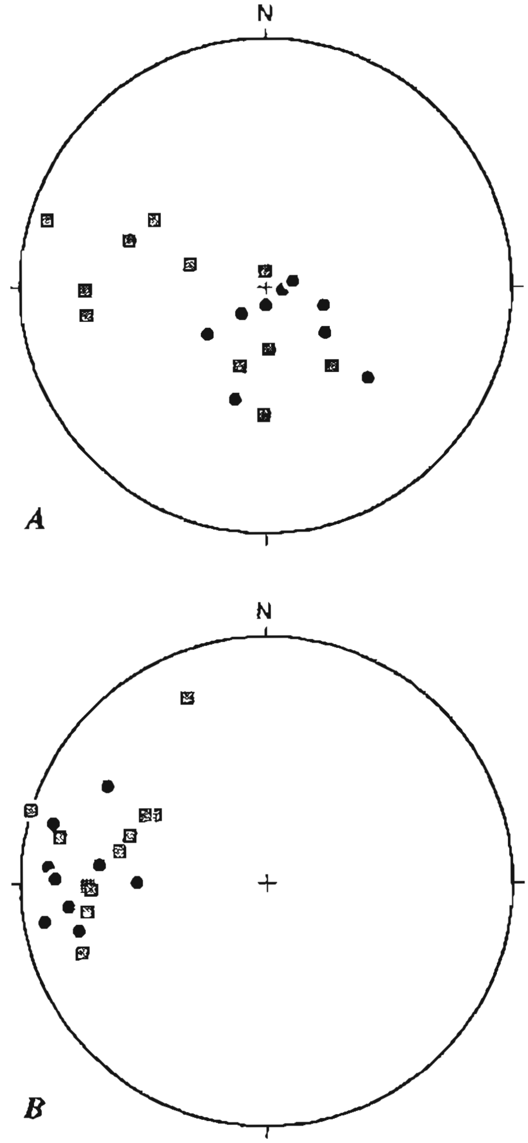


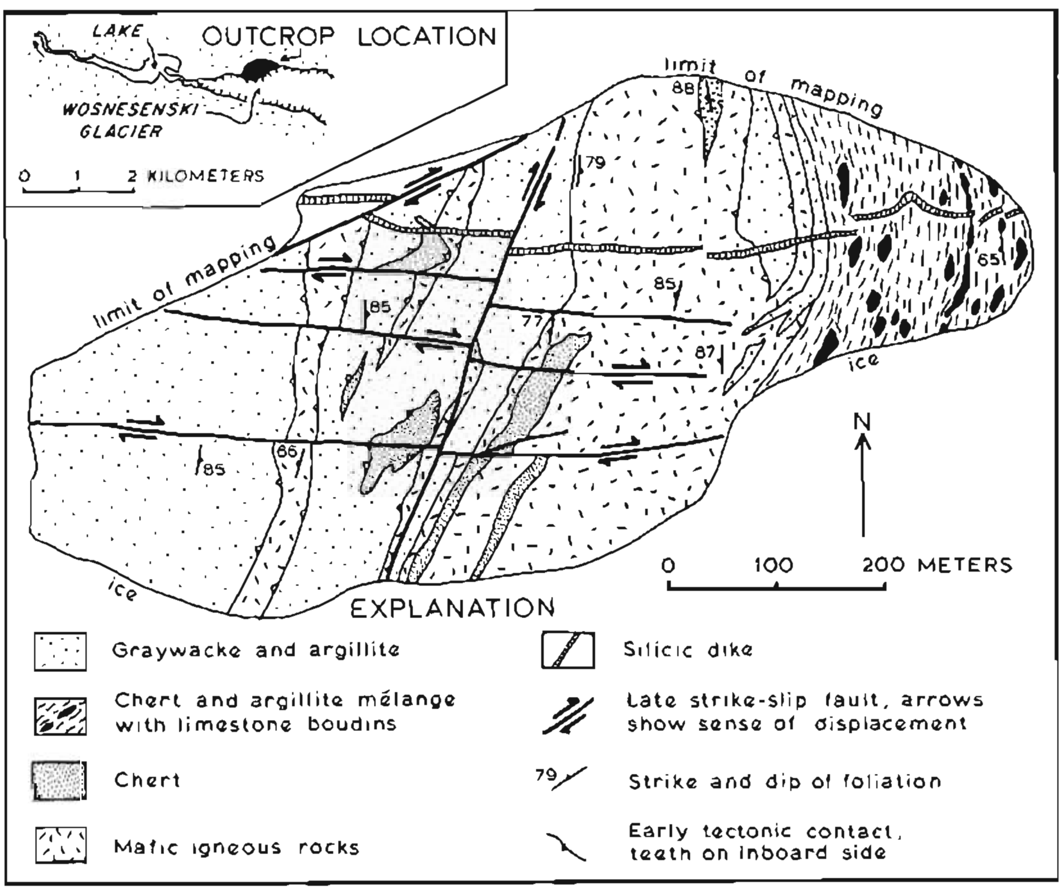
Figure 7. Lower-hemisphere equal-area projections from McHugh Complex at Grewingk Glacier. *A*, Poles to early layer-extensional shear bands. In all cases, apparent hanging wall moved to east, but some of shear bands are apparent thrust faults, whereas others are apparent normal faults. Filled circles are from Grewingk Glacier; shaded squares are from elsewhere in McHugh Complex in Seldovia quadrangle. *B*, Poles to same faults subject to tilt correction (by strike rotation) of bedding or fragment foliation; actual tilt-correction paths are different for each datum because of variable attitudes of layering. Resulting tighter clustering of poles supports interpretation that these structures all originated as early ductile normal faults and were then variably rotated into their present attitudes.

ants, 1979, p. 20), can be traced as a topographic lineament to the terminus of Dixon Glacier (fig. 8*B*), where we found that it dextrally offsets a subvertical east-striking dike by about 15 m. At Wosnesenski Glacier, a minor north-northeast-striking fault offsets both an east-striking dike and east-striking dextral faults by about 15 m (fig. 8*A*). Thus, fault set III is younger than both fault set I and the dikes. At Grewingk Glacier, minor dextral faults plot in two clusters, one corresponding to set I (mean strike and dip 240°, 85° N.), and the second corresponding to set III (mean strike and dip 173°, 43° W.). Fault set IV consists of minor late thrusts with considerable scatter, which, on average, strike about north and dip west (mean strike and dip 181°, 52° W.)(fig. 9*A*, *B*). Fault sets V and VI form a conjugate pair of minor late normal faults that strike east and dip moderately north and south (mean strike and dip 268°, 62° N. and 093°, 31° S., respectively). These faults are poorly developed structures of minor significance at Grewingk Glacier.

To summarize observed cross-cutting relations, fault sets I and II are cut by fault set III; relative ages of the other fault sets are unknown.

Dikes

Northeast-striking intermediate to silicic dikes (fig. 6*D*) cut mélange fabric and extensional shearbands throughout the Chugach terrane in the Seldovia quadrangle. In the detailed study areas, dike widths vary from a few centimeters to 2.5 m. Dike margins are commonly chilled. Chert xenoliths are common, as is dike-parallel flow banding. In places, the margins are irregular; elsewhere, they are sharp and it is possible to match opposite sides. An apparent opening direction of about 345° is revealed by the attitude of dike normals and transform offsets (fig. 10). Transform offsets like that in figure 6*D* are exactly analogous to transform offsets of mid-ocean



A

Figure 8. A, Detailed geologic map (original scale 1:6,000) of McHugh Complex at lower terminus of Wosnesenski Glacier. Inset shows position of ice front in late 1980's. Map area is at locality 3 in figure 2. *B*, Detailed geologic map (original scale 1:6,000) of McHugh Complex at lower terminus of Dixon Glacier. McHugh Complex here is not readily divisible into mappable units. Map area is at locality 1 in figure 2.

ridges (Wilson, 1965). The fault in figure 6*D* connecting the two dike segments moved only during dike intrusion and does not cut country rock beyond the dike; the sense of motion in figure 6*D* was left-side-up, not right-side-up. On the basis of mutually cross-cutting relationships, dike emplacement appears to have been coeval with movement on fault set I. Some of the dikes are offset by fault set I (fig. 6*E*), whereas elsewhere, dikes intrude along fault traces (for example, near both small bays on the southwestern side of the island in fig. 4*A*). Protoclastic textures in some dike margins near the fault zones indicate that deformation occurred while the dikes were still hot.

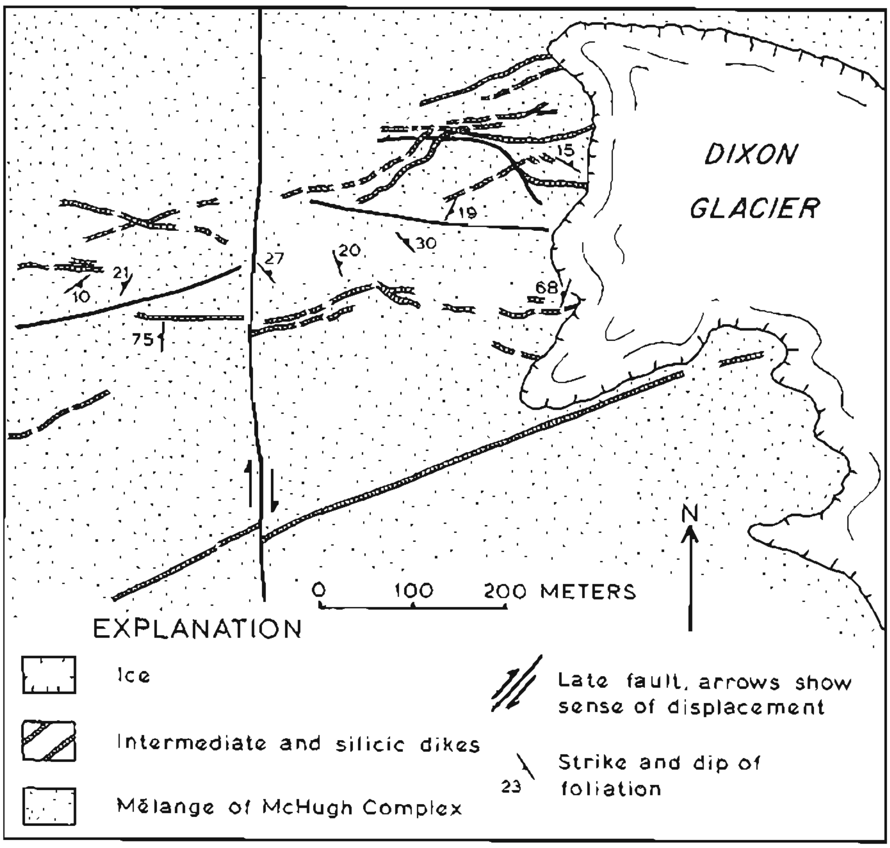
Although none of the dikes mapped in the present study have been dated, we believe that they are probably early Eocene on the basis of isotopic ages of compositionally similar intrusive rocks elsewhere in the Seldovia quadrangle. Biotites from the Nuka pluton (biotite granite; fig. 2) yielded a $^{40}Ar/^{39}Ar$ plateau age of 54.2± 0.08 Ma; monazite from the same sample yielded a U-Pb age of 56.0± 0.5 Ma. Amphiboles from an intermediate dike at the head of Seldovia Bay yielded a $^{40}Ar/^{39}Ar$ isochron age of 57.0± 0.22 Ma (W. Clendenen, written commun., 1989).

INTERPRETATION

Early Structures

Whereas the map pattern at Grewingk Glacier is complicated by offsets on late cross-faults, we interpret the primary repetition of elongate belts of greenstone, chert, graywacke, and mesoscale mélange as the product of motion on myriad early seaward-directed thrust faults (fig. 4*A*). This interpretation is consistent with the map pattern, the inferred oceanic-plate stratigraphy (fig. 3*A*), and the few available way-up indicators. Both in-sequence and out-of-sequence thrusting would seem to be necessary to account for the thinness of fault-bounded map units that are likely to have been many times thicker originally. In the McHugh Complex in the Trans-Alaska Crustal Transect transect area, about 450 km along strike to the northeast, Nokleberg and others (1989) attributed the earliest generation of structures to subduction-accretion. Similarly, we suggest that previously subhorizontal rocks of a downgoing oceanic plate were imbricated along subduction-zone thrusts.

A less compelling explanation for the repetition of rock types is by contractional soft-sediment deformation



B

Figure 8. Continued.

(for example, at the base of a slope where slump sheets accumulate). However, some of the imbricated rocks at Grewingk Glacier, such as pillow basalt, could not conceivably have been soft when deformed. A similar argument applies to the origin of the pebbly mudstone. Two key relations are that the pebbly mudstone grades into broken formation consisting of pulled apart beds of graywacke and argillite, and that broken formation grades into coherently bedded turbidites (fig. 6*A*; fig. 4*B*, loc. A). Thin-section evidence of cataclastic grain-size reduction during disruption of bedding, mentioned previously, requires that disruption occurred in already lithified graywacke. Accordingly, we suggest that both broken formation and pebbly mudstone formed in zones of particularly intense tectonic disruption of already lithified rocks, rather than as a result of soft-sediment deformation. Clear evidence for soft-sediment deformation is lacking at Grewingk Glacier.

Early ductile shear bands are widespread but enigmatic structures in the McHugh Complex. The sense of motion presents an interesting problem in structural analysis. Some shear bands offset steeply dipping markers in

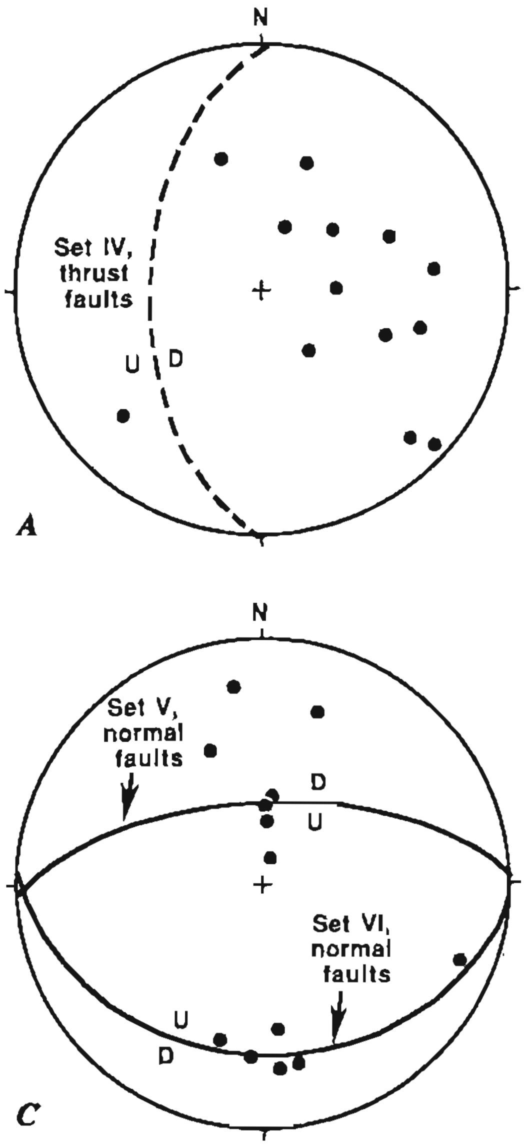


Figure 9. Lower-hemisphere equal-area projections from McHugh Complex at Grewingk Glacier. *A*, Poles to thrust-fault surfaces. *B*, Thrust-fault slickenlines. *C*, Poles to normal-fault surfaces. *D*, Normal-fault slickenlines. *E*, Poles to dextral-fault surfaces. *F*, Dextral-fault slickenlines. *G*, Poles to sinistral-fault surfaces. *H*, Sinistral slickenlines. Solid great circles represent average fault attitudes from tightly clustered poles to faults; dashed great circles are rough approximate averages from poorly clustered poles to faults.

an apparent thrust sense (in the present reference frame), whereas a number of otherwise identical shear bands offset moderately dipping markers in an apparent normal sense (fig. 6*B*, *C*). In all cases, however, the shear bands cause extension of layering. This is clearly seen by comparing stereoplots of the shear bands in their present orientation (fig. 7*A*) with the same data subject to simple strike rotation of host layering to correct for tilt [fig. 7*B*; see Bradley (1989) for methodology and rationale]. After tilt correction, data that had been scattered and inconsistent all plot as down-to-east normal faults. Accordingly, we suggest a simple scenario wherein the shear bands formed in a single tectonic regime at a time when layering (bedding, early tectonic contacts, and mélange foliation) were still subhorizontal. Subsequent, mainly landward rotation of layering also affected the shear bands, and in some cases rotation was sufficient to transform the normal faults into apparent thrust faults (Bradley, 1989). Fisher and Byrne (1987, p. 778) recognized comparable early faults on Afognak Island, which cut accreted trench deposits of the Kodiak Formation. The faults on Afognak Island occur in a variety of orientations, but all extend bedding and, subject to restoration of bedding to horizontal, most have a seaside-down sense of displacement. Because their effect is opposite that commonly thought to be associated with subduction (that is, extension in the inferred direction of plate convergence), the significance of the early extension faults is unclear.

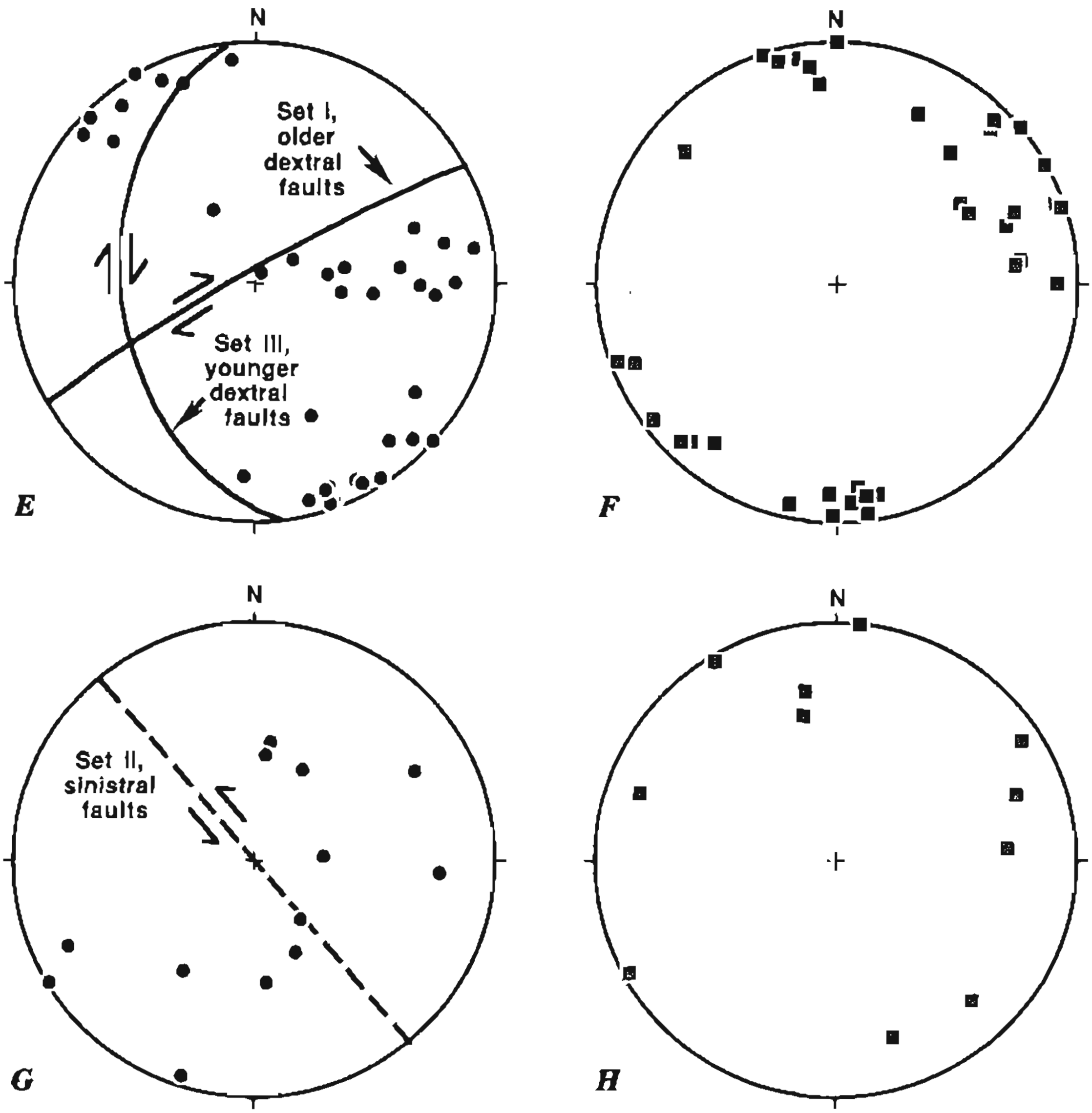


Figure 9. Continued.

Late Faults and Dikes

Of the various late structures in the study area, the dikes and apparently coeval dextral faults are most readily interpreted in terms of regional tectonic events. Intermediate to silicic dikes pervade the Chugach terrane in the Seldovia quadrangle and are part of the Sanak-Baranof magmatic belt (Hudson, 1983; also called the Gulf of Alaska belt by Wallace and Engebretson, 1984), which intrudes the Chugach terrane along a strike length of more than 2,000 km. Intrusions lie anomalously close to the trench, far from the coeval axis of the magmatic arc (Hill and others, 1981). Existing isotopic ages tend to progress systematically along strike around the southern Alaska orocline, being older at Sanak (62 Ma) and younger at Baranof (47 Ma). Isotopic ages of 57–54 Ma from the Seldovia quadrangle fit this overall pattern.

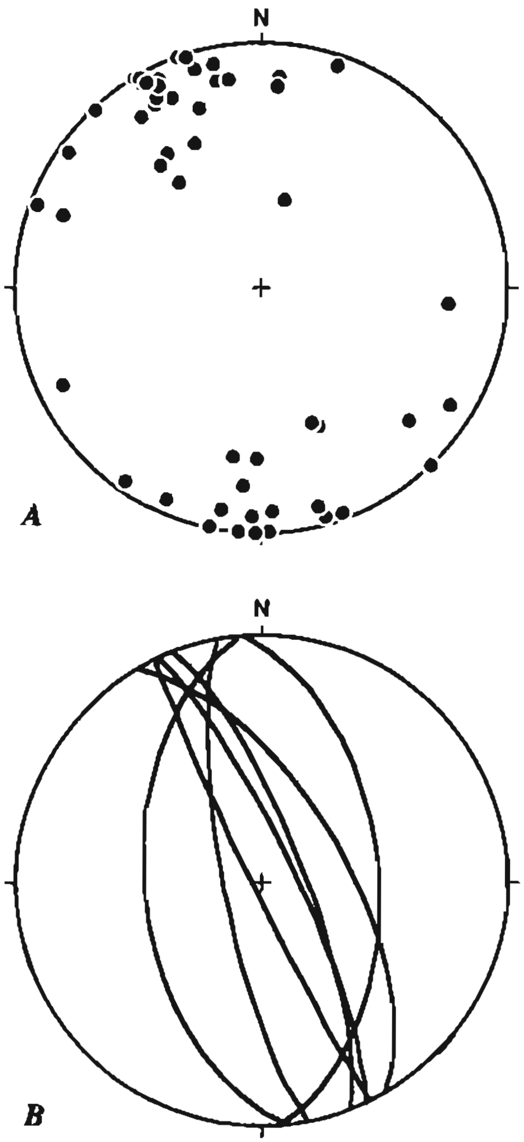


Figure 10. Lower-hemisphere equal-area projections from McHugh Complex and Valdez Group in Seldovia quadrangle. *A*, Poles to dike margins, which plunge in approximate direction of dike opening. *B*, Dike-opening transform faults, plotted as great circles rather than as poles because true opening direction is constrained to lie on transform plane but could have any orientation on it. Taken together with population of poles to dike margins, mean dike opening direction is about 345°.

Two findings from the present study bear on conditions within the accretionary wedge during near-trench magmatism. Dike injection was accompanied by extension at a high angle to tectonic strike (dike opening direction was about 345° and tectonic strike at Grewingk Glacier is about 020°). Dike injection at Grewingk Glacier was coeval with motion on 070° dextral faults. Bradley and Kusky (1990) showed that dextral faults of comparable orientation are widespread from Kodiak Island to Turnagain Arm, and that motion on these and conjugate sinistral faults resulted in orogen-parallel extension.

We interpret the near-trench magmatism and associated orogen-parallel extension as the products of subduction of an oceanic spreading center: either the Kula-Farallon ridge (Marshak and Karig, 1977; Hill and others, 1981; Plafker and others, 1989, p. 4287) or, conceivably, another ridge farther to the north. The former existence of a Kula-Farallon ridge during the Late Cretaceous and Paleogene is a fundamental, irrefutable feature of all modern plate reconstructions of the Pacific realm (for example, Engebretson and others, 1985). Because the Kula and Farallon plates have all but disappeared, most details of the plate-motion history are limited to what can be reconstructed from the half-spreading history of the Pacific plate (Atwater, 1989). One unknown parameter is the location, through time, of the Kula–Farallon–North America triple junction; a related unknown is the position along the continental margin of the Chugach terrane (Moore and others, 1983; Plafker and others, 1989). The along-strike progression of igneous ages along the Sanak-Baranof belt implies that the triple junction migrated west to east along the continental margin. This would mean that, for the part of the Chugach terrane now in the Seldovia quadrangle, the Farallon plate was subducted prior to about 57–54 Ma, and that the Kula plate was subducted between about 54 and 42 Ma. After about 42 Ma, the Kula-Pacific ridge became extinct and the two plates became one (Lonsdale, 1988); presumably, the Pacific plate has been subducted since then.

An important, unknown parameter that geologic data may ultimately yield is the Kula-Farallon spreading direction. This might simply be the dike opening direction, but it seems unlikely that there is such a close relationship between spreading direction in the two underriding plates and any structures produced in the overriding plate. Foremost among the possible complications is that subduction of a high-standing spreading axis is likely to upset the critical taper of the accretionary wedge, creating compressional or tensional body forces of unknown orientations [a qualitative solution will require that the critical taper equations of Platt (1986) be recast in three dimensions].

Late structures in the three detailed map areas do not bear conclusively on the long-standing hypothesis that the Chugach terrane slid northward to its present location along one or more coast-parallel strike-slip faults (for example, Plumey and others, 1983). Strike of early contractional structures is about the same as would be produced at the Benioff Zone today. We are led to conclude that if the McHugh Complex *did* undergo major coastwise strike-slip, it must have done so without experiencing any of the internal block rotations that are so prevalent in active strike-slip settings, and without being cut by major splays such as typify the San Andreas fault system.

Late structures in the three detailed map areas also have little bearing on Carey's (1955) hypothesis that the southern Alaska orocline formed by bending of belts, such as the Chugach terrane, that were originally straight (see, for example, Coe and others, 1985; Plafker and others, 1989). If such bending did occur, it would have been accompanied by shortening parallel to strike on the inner side of the arc. Instead, we observe three structural elements (conjugate fault sets I and II, dikes, and conjugate fault sets V and VI) that had the opposite effect: extension parallel or nearly parallel with the orogen. The only late structures in the study areas of suitable orientation are north-striking dextral faults of set III, which might be related either to the southward escape of material being squeezed out of the tightening hinge of the orocline or to coastwise motion around an existing bend. Whatever the case, cross-cutting relations require that events related to fault set III followed those related to the dikes and fault sets I and II.

SUMMARY

At Grewingk Glacier, the McHugh Complex consists of multiple fault slices of relatively coherent basalt, chert, and graywacke, each up to a few tens of meters thick, bounded by zones of mesoscale mélange. We interpret the mesoscale mélanges as having formed in thrust zones, and the map pattern as the result of thrust repetition of an originally simple oceanic-plate stratigraphy, the lower part of which constitutes the Kachemak "terrane" of Jones and others (1987). Throughout the Seldovia quadrangle, intermediate to silicic dikes were injected into already deformed rocks of the McHugh Complex and Valdez Group during early Eocene time. Dike emplacement was coeval with motion on dextral strike-slip faults, which are prominent at Grewingk, Dixon, and Wosnesenski Glaciers, and are part of a conjugate pair whose acute bisector trends about east-west. Diking and conjugate strike-slip faulting together resulted in approximately orogen-parallel extension. We interpret both phenomena as the consequence of subduction of the Kula-Farallon Ridge. A younger set of north-striking dextral faults offsets the older strike-slip faults and dikes; these may be related to formation of the southern Alaska orocline and (or) to movement of the Chugach terrane around the oroclinal bend.

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