TECTONICS, VOL. 16, NO. 6, PAGES 855-878, DECEMBER 1997

Controls on accretion of flysch and mélange belts at convergent margins: Evidence from the Chugach Bay thrust and Iceworm mélange, Chugach accretionary wedge, Alaska

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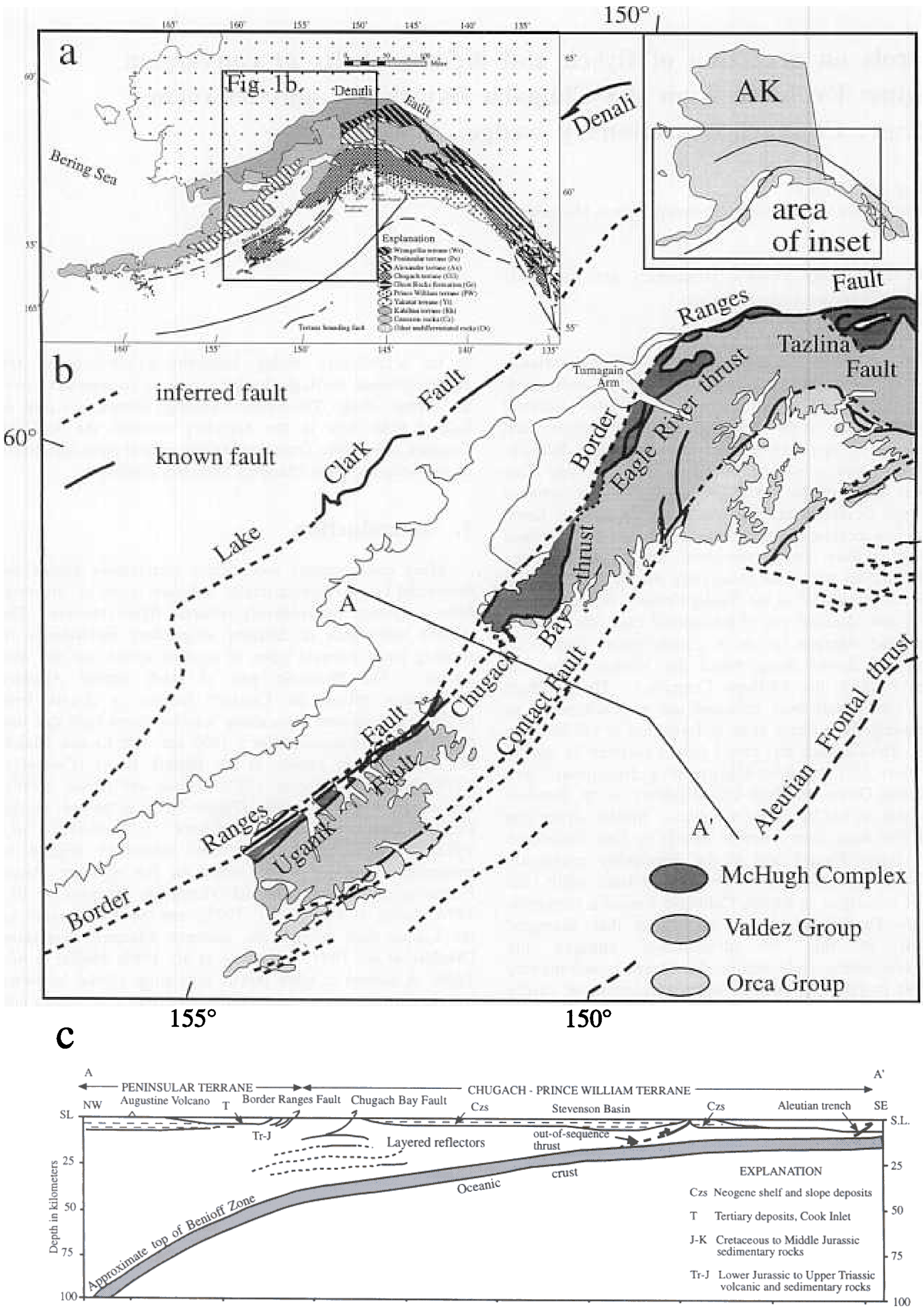
Abstract. Controls on accretion of flysch and mélange terranes at convergent margins are poorly understood. Southern Alaska's Chugach terrane forms the outboard accretionary margin of the Wrangellia composite terrane, and consists of two major lithotectonic units, including Triassic-Cretaceous mélange of the McHugh Complex and Late Cretaceous flysch of the Valdez Group. The contact between the McHugh Complex and the Valdez Group on the Kenai Peninsula is a tectonic boundary between chaotically deformed mélange of argillite, chert, greenstone, and graywacke of the McHugh Complex and a less chaotically deformed mélange of argillite and graywacke of the Valdez Group. We assign the latter to a new, informal unit of formational rank, the Iceworm mélange, and interpret it as a contractional fault zone (Chugach Bay thrust) along which the Valdez Group was emplaced beneath the McHugh Complex. The McHugh Complex had already been deformed and metamorphosed to prehnite-pumpellyite facies prior to formation of the Iceworm mélange. The Chugach Bay thrust formed between 75 and 55 Ma, as shown by Campanian-Maastrichtian depositional ages of the Valdez Group, and fault-related fabrics in the Iceworm mélange that are cut by Paleocene dikes. Motion along the Chugach Bay thrust thus followed Middle to Late Cretaceous collision (circa 90-100 Ma) of the Wrangellia composite terrane with North America. Collision related uplift and erosion of mountains in British Columbia formed a submarine fan on the Farallon plate, and we suggest that attempted subduction of this fan dramatically changed the subduction/accretion style within the Chugach accretionary wedge. We propose a model in which subduction of thinly sedimented plates concentrates shear strains in a narrow zone, generating mélanges like the McHugh in accretionary complexes. Subduction of thickly sedimented plates allows wider distribution of shear strains to accommodate plate convergence, generating a more coherent accretionary style including the fold-thrust structures that dominate the outcrop pattern in the Valdez belt. Rapid underplating and frontal accretion of the Valdez Group caused a critical taper adjustment of the accretionary wedge, including exhumation of the metamorphosed McHugh Complex, and its emplacement over the Valdez Group. The Iceworm mélange formed in a zone of focused fluid flow at the boundary between the McHugh Complex and Valdez Group during this critical taper adjustment of the wedge to these changing boundary conditions.

Paper number 97TC02780.
0278-7407/97/97TC-02780$12.00

1. Introduction

Many contemporary and ancient accretionary prisms are dominated by two fundamentally different types of structural belts – mélange and relatively coherent flysch terrains. The relative importance of different accretionary mechanisms in forming these different types of accreted terrain are not well known. The Mesozoic part of south central Alaska's accretionary prism, the Chugach terrane, is divided into landward and seaward belts along a major thrust fault that can be traced discontinuously for > 1500 km. On Kodiak Island, the thrust fault is known as the Uganik thrust [*Connelly,* 1978; *Sample and Moore,* 1987; *Sample and Fisher,* 1986], and on the Kenai Peninsula (Figure 1), it is known as the Chugach Bay thrust [*Cowan and Boss,* 1978; *Kusky et al.,* 1993]. From there, it continues northward (Figure 1) becoming the Eagle River thrust on the northern Kenai Peninsula and western Chugach Mountains [*Magoon et al.,* 1976; *Pavlis,* 1982; *Winkler,* 1992], and then it continues as the Tazlina fault through the northern Chugach mountains [*Winkler et al.,* 1981; *Nokleberg et al.,* 1989; *Plafker et al.,* 1989]. A number of other thrusts separating similar landward and seaward belts occur discontinuously through SE Alaska and British Columbia [*Plafker et al., 1994*]. These related thrust faults separate units characterized by grossly different rock suites and structural styles. The landward belt consists of a mélange of mafic igneous rocks, Triassic, Jurassic, and Cretaceous chert, graywacke, argillite, plus rare Carboniferous, Permian, and Triassic limestone, and a few massifs of ultramafic igneous rocks, assigned to the McHugh Complex and its correlatives. The seaward belt consists of relatively coherent Late Cretaceous turbidites, assigned to the Valdez Group and its correlatives.

Here we report the results of new geologic mapping on the southern Kenai Peninsula (Figure 2) bearing on the nature, location, and significance of this important fault. In the Seldovia quadrangle, *Magoon et al.* [1976] delineated the



a
Fig. 1b.
Denali
Fault
Bering Sea
Explanation
Terrane bounding fault
150°
AK
area
of inset
Denali
b
inferred fault
known fault
60°
Lake
Clark
Fault
Border
Ranges
Fault
Turnagain
Arm
Eagle River thrust
Tazlina
Fault
Bay
thrust
Chugach
Contact Fault
Uganik
Fault
Aleutian
Frontal
thrust
A
A'
60°
McHugh Complex
Valdez Group
Orca Group
155°
150°
c
A
A'
PENINSULAR TERRANE
CHUGACH - PRINCE WILLIAM TERRANE
NW
Augustine Volcano
T
Border Ranges Fault
Chugach Bay Fault
Czs
Stevenson Basin
Czs
Aleutian trench
SE
SL
S.L.
Tr-J
Layered reflectors
out-of-sequence
thrust
Oceanic
crust
Approximate top of Benioff Zone
Depth in kilometers
25
50
75
100
EXPLANATION
Czs Neogene shelf and slope deposits
T Tertiary deposits, Cook Inlet
J-K Cretaceous to Middle Jurassic sedimentary rocks
Tr-J Lower Jurassic to Upper Triassic volcanic and sedimentary rocks

contact between McHugh Complex and Valdez Group as a seaward directed thrust fault. *Cowan and Boss* [1978] named this structure the Chugach Bay fault and traced it with considerably greater accuracy than *Magoon et al.* [1976]. Our mapping refines the location of the Chugach Bay thrust and shows that the McHugh Complex is far more extensive in the northern part of the quadrangle than was indicated by *Magoon et al.* [1976]. In the southern part of the quadrangle, we have generally confirmed but locally modified the fault trace as mapped by *Cowan and Boss* [1978]. A second purpose of this paper is to describe and discuss the origin of a type I mélange [*Cowan,* 1985] consisting entirely of disrupted Valdez Group along most of the fault trace [*Cowen and Boss,* 1978]. We have found this mélange to be a mappable, regionally extensive unit, and we informally name it the Iceworm mélange after excellent exposures on Iceworm Peak (Seldovia C3 1:64,000 quadrangle). The presence of a thick mélange zone suggests that the fault formed when relatively coherent Valdez Group turbidites were underplated beneath the McHugh Complex between deposition during Campanian-Maastrichtian time and intrusion by Paleocene igneous dikes. A third and final aim of this paper is to consider the tectonic significance of the Chugach Bay and correlative faults with associated type I mélange. We propose a structural model to explain the dramatic change in accretion style from mélange of the McHugh complex to coherent turbidites of the Valdez Group, and we relate this change to specific tectonic events in Mesozoic and Cenozoic Cordilleran tectonics. Mélanges of the McHugh complex were generated during subduction of a thinly sedimented Farallon plate beneath the Chugach terrane, which formed an accretionary wedge outboard of the Wrangellia composite terrane. Rapid sedimentation of the oceanic Farallon plate following collision of Wrangellia with North America led to subduction of a thick sedimentary package beneath the Chugach terrane and a change from accretion of mélanges to accretion of relatively coherent thrust sheets of the Valdez Group. The Chugach Bay thrust and Iceworm mélange mark the contact between previously accreted mélanges of the McHugh Complex and thrust sheets of the Valdez Group accreted during the episode of subduction of a thickly sedimented plate. We suggest that the switch in accretion style may be analogous to similar changes in other accretionary prisms in the current and past plate mosaics.

2. McHugh Complex

The McHugh Complex forms the hanging wall of the Chugach Bay fault in the Seldovia quadrangle. It is equivalent to the Uyak Complex and Cape Current terrane on Kodiak Islands [*Moore and Connelly,* 1977; *Connelly,* 1978] and Kelp Bay Group of southeastern Alaska [*Decker and Plafker,* 1982]. Rock types, which we interpret as the basement and sedimentary cover of a now subducted oceanic plate, include variably disrupted greenstone (basalt and gabbro), chert, argillite, graywacke, conglomerate, outcrop-scale mélange, and rare limestone (Figures 3a and 3b). Several ultramafic complexes, including the large Red Mountain complex, occur as fault-bounded massifs, and have been variously interpreted as accreted ocean floor fragments [*Bradley and Kusky,* 1992; *Kusky,* 1997] or as deep fragments of basement to the Wrangellian arc [*Burns,* 1985]. *Bradley and Kusky* [1992] provided descriptions of each of the component rock types, which are distributed in innumerable strike-parallel belts, bounded by mainly contractional faults, that vary in width from a few centimeters to one or more kilometers. The McHugh Complex has been metamorphosed to prehnite-pumpellyite facies [*Clark,* 1973; *Bradley and Kusky,* 1992]. Stratified oceanic-plate rocks that now comprise the McHugh Complex range in age from Triassic to mid-Cretaceous and were progressively off scraped and (or) underplated to form an accretionary prism seaward of the Wrangellia composite terrane during much of Mesozoic time [*Bradley and Kusky,* 1992]. Some limestone blocks in mélange have yielded Permian Tethyan fusilinids [*Stevens et al., in press,* 1997], but their significance is unclear.

3. Coherent Strata of the Valdez Group

The Valdez Group [*Tysdal and Plafker,* 1978; *Nilsen and Zuffa,* 1982] constitutes the seaward part of the Chugach terrane. Correlatives of the Valdez Group are known as the Kodiak Formation in the Kodiak Islands [*Moore,* 1969], the Shumagin Formation on Shumagin Island [*Burk,* 1965], the Yakutat Group in the Gulf of Alaska and St. Elias Mountains [*Plafker et al.,* 1977], and the Sitka graywacke and the Ford Arm Unit in southeastern Alaska [*Loney et al.,* 1975; *Decker,* 1980]. In the Seldovia quadrangle, we have broken out (and discuss separately) the Iceworm mélange from the main, coherent part of the Valdez Group. Coherent turbidites of the Valdez Group (Figures 3c and 3d) include most of the turbidite facies recognized by *Mutti and Ricci-Lucchi* [1978], which are discussed below in alphabetical order. Massive conglomerates (facies A) have been recognized in several places along the southern coast but are not particularly abundant. The most common conglomerates contain abundant intraformational rip-up clasts of black mudstone (now slate) supported in a graywacke matrix. Less common are conglomerates containing various extraformational clasts, including quartzite and granitic rocks. The conglomerates occur in massive or amalgamated beds up to a few tens of meters thick. Facies A is interpreted as having been deposited in submarine fan channels. Massive, amalgamated graywacke sandstones of facies B also are widespread throughout the quadrangle and are prominent in outcrop because they resist erosion. The sandstones are up to a few tens of meters thick and are interpreted as channel deposits. Facies C, consisting of classical turbidites beginning with the Bouma Ta division, are

Figure 1. (a) Map of southern Alaska showing terranes south of the Denali fault system (inset shows location of map). (b) Map of south-central Alaska [modified after *Plafker et al.,* 1994] showing the distribution of the Uganik-Chugach Bay-Eagle River fault system. A-A' corresponds to line of seismic section shown in Figure 1c. (c) Interpretation of deep crustal structure along section A-A' [modified from *Moore et al.,* 1991] based on EDGE seismic reflection data.

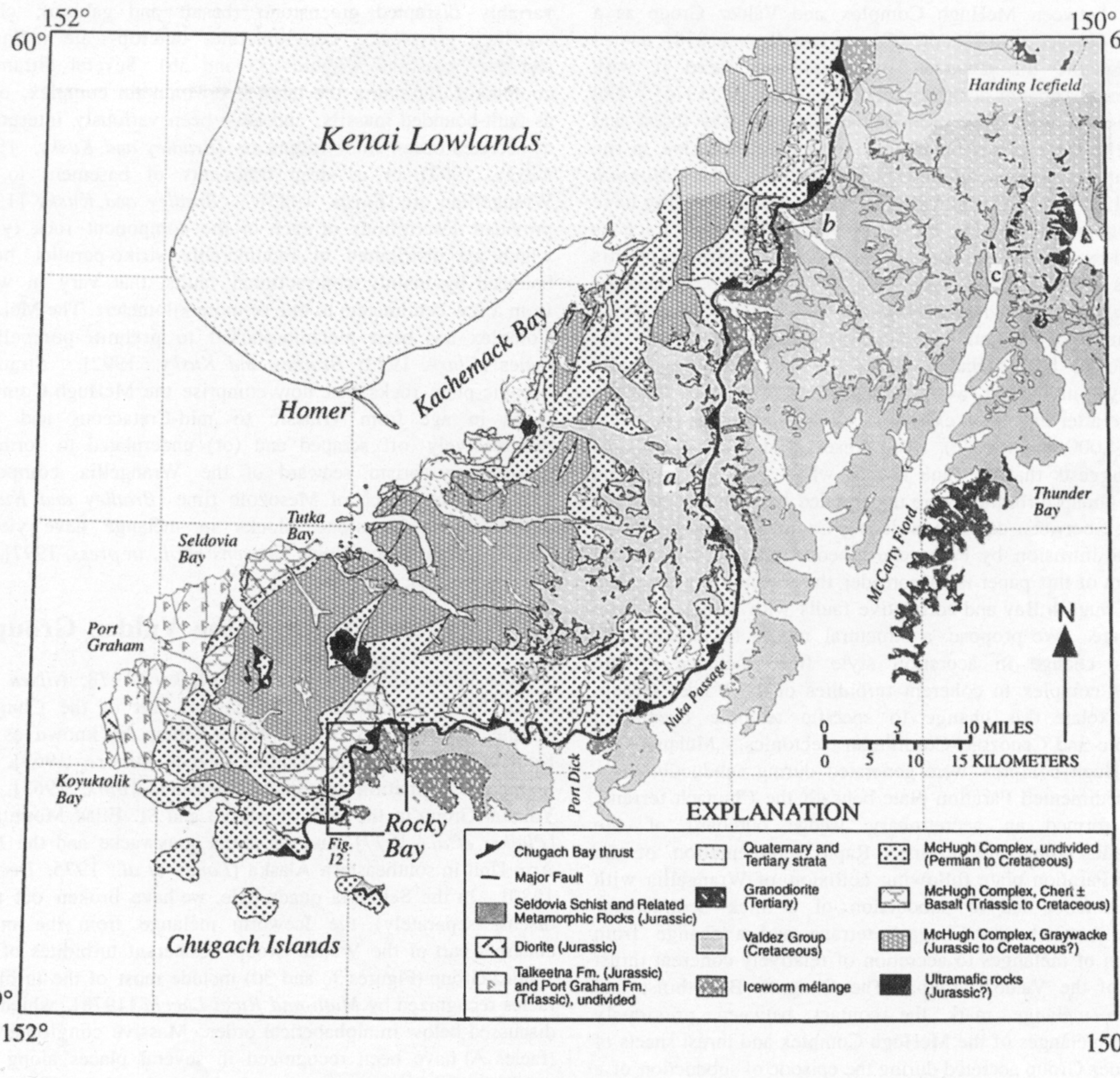


Figure 2. Simplified geologic map of eastern two thirds of Seldovia quadrangle based on mapping by the authors and previous mapping compiled by *Magoon et al.*, [1976].

rare. Thinner-bedded turbidites belonging to facies D (Figure 3c), however, are quite abundant. Thinly interbedded cross-laminated sandstone and slate, in partial Bouma sequences beginning with the Tb or Tc division, are characteristic of this facies. Facies E, consisting of graded sandstone beds of irregular thickness, locally are associated with facies A and B and probably represent levee deposits. Facies F, consisting of chaotically disrupted turbidites resulting from soft-sediment deformation, has not been positively indentified in the southern Kenai Peninsula. Facies G, consisting of pelagic and hemipelagic mudstones, is locally abundant and typically forms evenly cleaved slate. In order of abundance, facies B and D are most common, A, E, and G are somewhat less so, and C and F are rare.

The Valdez Group is regarded as Campanian to Maastrichtian in age, based on the presence of Inoceramids from a few widely separated locations throughout south central Alaska [e.g., *Jones and Clark,* 1973; *Budnick,* 1974; *Plafker et al.*, 1989], including one Inoceramid locality in the Port Dick area of the Seldovia quadrangle [*Tysdal and Plafker, 1978*].

Rocks of the Valdez Group contain abundant chlorite and sericite but no prehnite or pumpellyite, which are common in the McHugh Complex. Hawley [1992] suggested that there has been a large-scale mobilization of many elements because the sericite and chlorite occur in quartz/calcite veins. He suggests a minimum temperature of 200°C for the deformation and alteration since the albite that has precipitated in equilibrium with the sericite is not stable below that temperature [*Liou,* 1971].

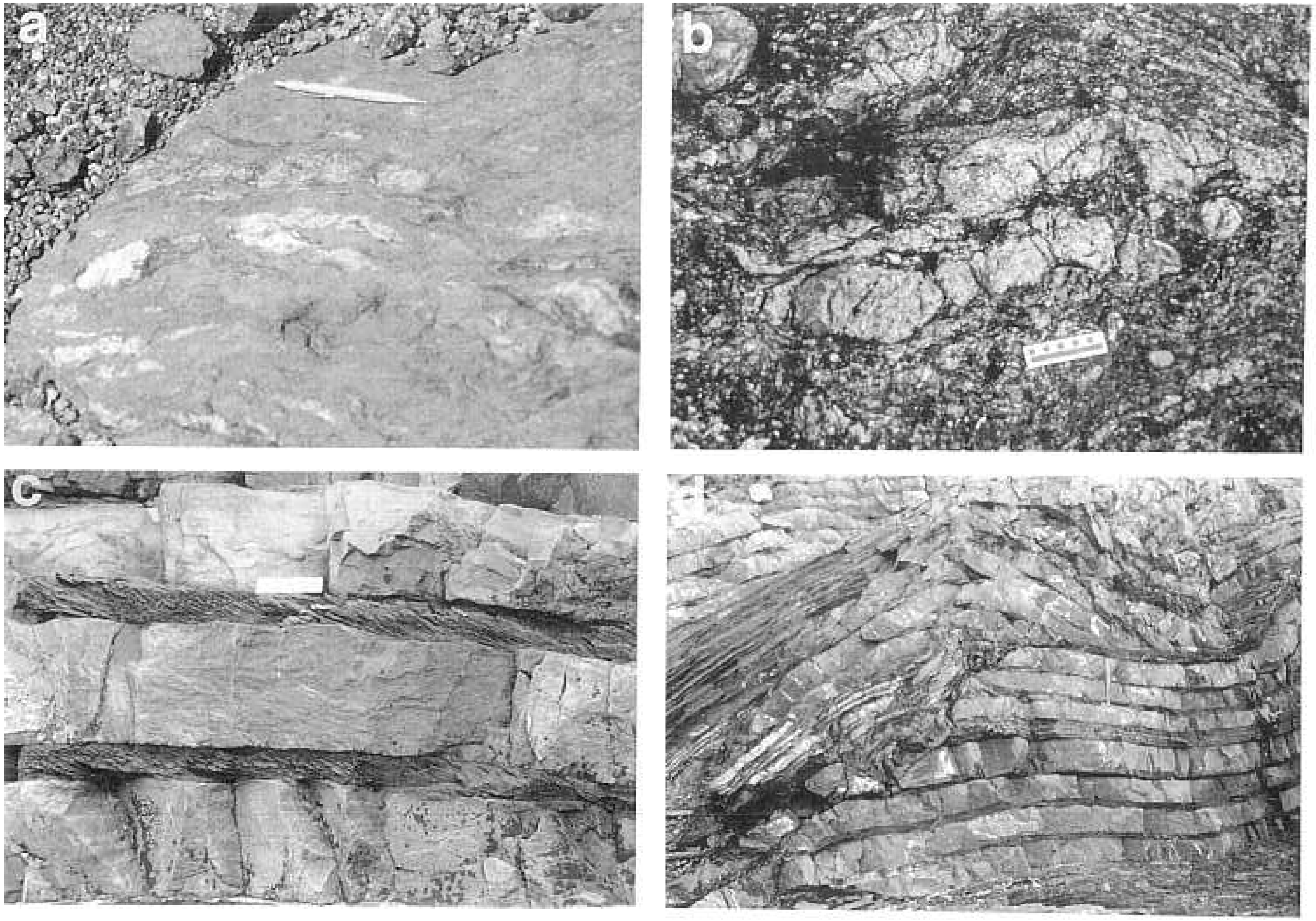


Figure 3. Representative photographs of major rock units on the Kenai Peninsula. (a) Outcrop-scale mélange of McHugh Complex shows partially to completely disrupted beds of graywacke, chert, and greenstone all chaotically mixed together and isoclinally folded. Metamorphic grade is prehnite-pumpellyite. (b) Chert-argillite mélange of the McHugh Complex showing intense stratal extension, forming a block-in-matrix texture. (c) Coherent facies D turbidites of Valdez Group, with bedding and cleavage at moderate angles to each other. (d) Coherent facies D turbidites cut by a thrust and ramp anticline from Rocky Bay.

4. Chugach Bay Fault Zone and Associated Iceworm Mélange

The Chugach Bay fault is a wide zone of type I [*see Cowan*, 1985] mélange; its upper boundary is a tectonic contact with the McHugh Complex, where the mélange is repeated by locally numerous thrust imbricates, and thrust horses are common along some sections of the fault trace (Figure 2). The lower boundary is a gradational structural contact with relatively coherent turbidites of the Valdez Group. This belt of mélange is extensive, distinctive, and significant enough to warrant mapping as a separate unit. We refer to it informally as the Iceworm mélange and treat it as a lithodemic unit of formational rank within the Valdez Group. It takes its name from striking cliff exposures at Iceworm Peak (Seldovia C3 quadrangle, Figure 4a), where its genetic relationship to the Chugach Bay fault zone is clear. A more accessible reference area for the mélange is along the northern shoreline of Rocky Bay (Seldovia A4 quadrangle, Figure 2). Similar belts of mélange occur along the McHugh/Valdez contact along Turnagain Arm, southeast of Anchorage [*Kusky et al.*, 1997], in the western Chugach Mountains north of the Knik River [*Pavlis*, 1982], and also beneath the Uganik thrust on Kodiak Island [*Fisher and Byrne*, 1987]. On the Kenai Peninsula, the mélange occurs in a fairly continuous belt that extends from Chugach Bay and East Chugach Island in the south, to at least as far north as the northern boundary of the Seldovia quadrangle. The outcrop belt varies in width from 0 to 2.5 km. Structural thickness of the mélange zone is up to 1.8 km. Because it is a structurally complex lithodemic unit (Figures 4c and 4d), a type section is not appropriate.

For mapping purposes (Figure 2), we drew the Chugach Bay fault at the contact between the McHugh Complex and either Iceworm mélange or coherent turbidites of the Valdez Group (Figure 4b). Locally, where the transition between McHugh and Iceworm mélange is gradational, we have drawn the fault at the structurally lowest or farthest outboard occurrence of mélange blocks of McHugh aspect (i.e., chert, volcanic, or limestone blocks). The attitude of the fault ranges from gently to steeply west or north dipping, and in several places the fault zone is cut by swarms of late brittle faults. These faults belong to a regional orthorhombic set [e.g., *Kusky et al.*, 1997], which locally reorient fabrics from the earlier mélange forming event.

5. Structural Geology

The regional map pattern and detailed structural analysis together indicate that the Chugach Bay fault originated as a seaward directed thrust fault which was later folded about axes at a high angle to regional strike. The deeply fiord-incised coastline from the Chugach Islands to Rocky Bay mimics the folded fault trace (Figure 2). The fault follows Port Dick, a deep east-west fiord and the major north-south topographic low occupied by Nuka Passage and Yalik Glacier. The fault lacks topographic expression only for short sections where it crosses low mountains between Rocky Bay, Port Dick, and Nuka Passage. From Iceworm Peak (area a on Figure 2) northward, however, the fault bears little relationship to major topographic features, although locally it does correspond to minor saddles and valleys. On the basis of the map pattern and the orientation of fabric elements, we have divided structural data from the fault zone and adjacent rocks into 10 domains, as shown in Figures 5, 6, 7, 8, 10, and 14. The fault has been strongly folded in domains 0 and 1, moderately folded in domain 2, and only weakly folded, if at all, in domain 3.

5.1. McHugh Complex Fabrics

Primary layering within the McHugh Complex, defined by flattened pillow lavas, cumulate layering in mafic-ultramafic complexes (Figure 5a), basalt/chert bedding contacts (Figure 5b), bedding in chert units (Figure 5c), bedding in argillite and graywacke (Figures 5d and 5e), and bedding in massive graywacke (Figure 5f) is variable but shows a preference for northeast strikes. Bedding and other primary fabrics appear to be folded about northeast to north-northwest, gently plunging axes (Figure 5). Macroscopic folds in the McHugh Complex are rare in the field, however, suggesting that the dispersion of layering attitudes may have a different origin and significance, such as warping around large boudin structures, which are common in outcrop. Tectonic layering in the McHugh Complex (Figure 6), defined by clast orientation, extended lithological layers, early tectonic contacts, and phacoidal cleavages, also shows highly variable attitudes, also suggesting boudinage about northeast striking, gently plunging axes (Figure 6). Large-scale pinch and swell structures are visible on the map (e.g., McHugh complex graywacke, Figure 2) and outcrop scale, supporting this interpretation of layer orientation.

In sandstone-rich portions of the McHugh Complex, a complex cataclastic composite fabric disrupts original layering and appears in many cases to have accommodated a large amount of layer-parallel extension, accounting for nearly complete obliteration of all primary textures, forming, in essence, a cataclasite. This "web structure" [*see Cowan*, 1982] is best observed in massive graywacke and greenstone units and may contribute to their characterization as "massive" through total destruction of all primary (S_0) features. Individual cataclastic surfaces are typically less than 1 mm in thickness but occur as an anastomosing network of shear surfaces [*see also Cowan*, 1985; *Byrne*, 1984]. Individual or groups of these shear surfaces typically segment the rock into blocks with similar shapes and sizes to those of inclusions in nearby mélange belts. In thin section, web structures are seen to be zones of grain size reduction through grain breakage (cataclasis), although enhanced concentrations of phyllosilicates along these zones suggests that diffusional mass transfer (pressure solution) was also an important deformation mechanism involved in their genesis [e.g., *Knipe*, 1989]. Web structure typically is the oldest tectonic deformation structure observed in graywacke of the McHugh Compex, and its presence indicates that the graywackes were already lithified when subjected to layer-parallel extension. In unlithified sand, extension would have been accommodated by grain boundary sliding, leaving no petrofabric record.

5.2. Coherent Valdez Group fabrics

Coherent Valdez Group sedimentary rocks crop out only in domains 2, 3, 5, and 6 (Figure 7). Where tops could be

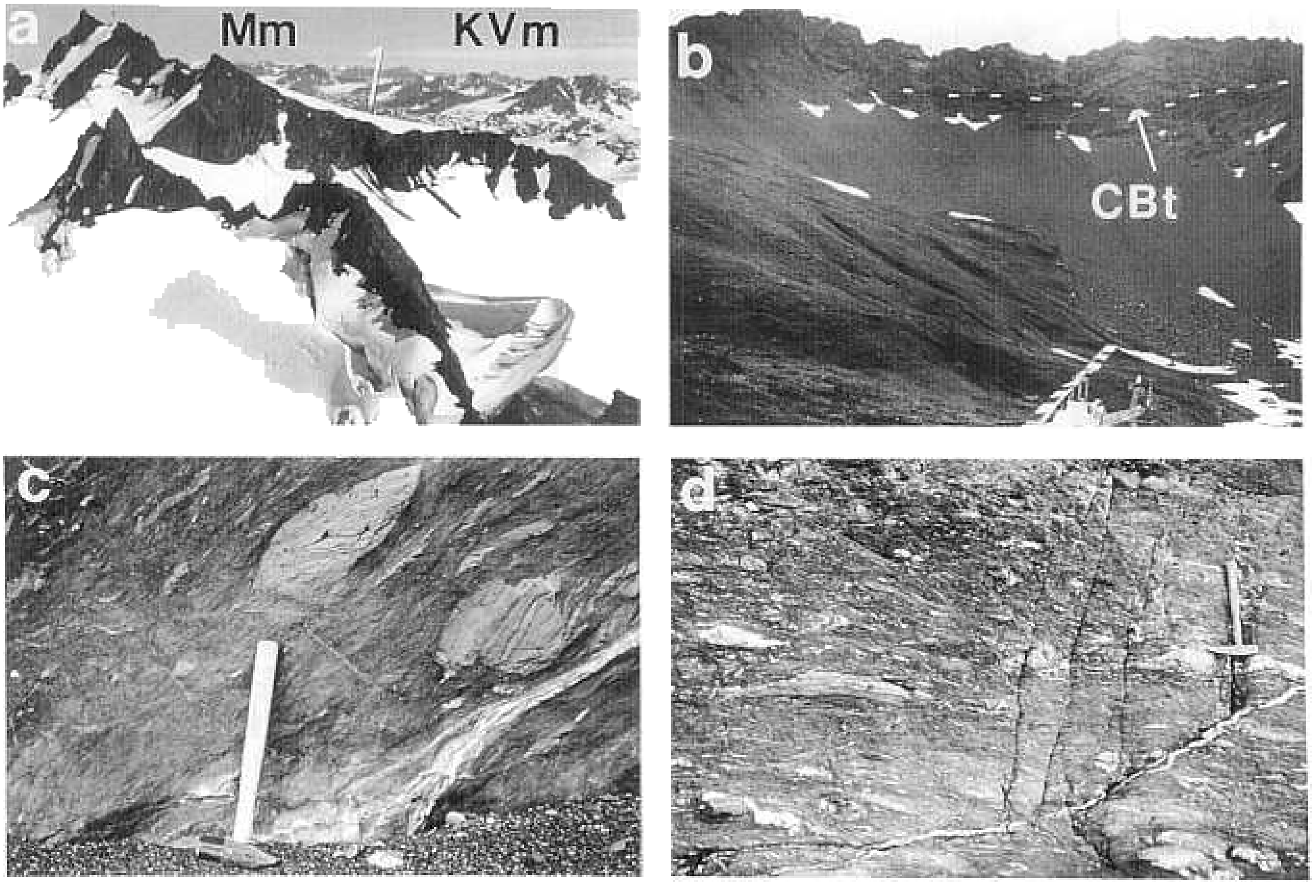
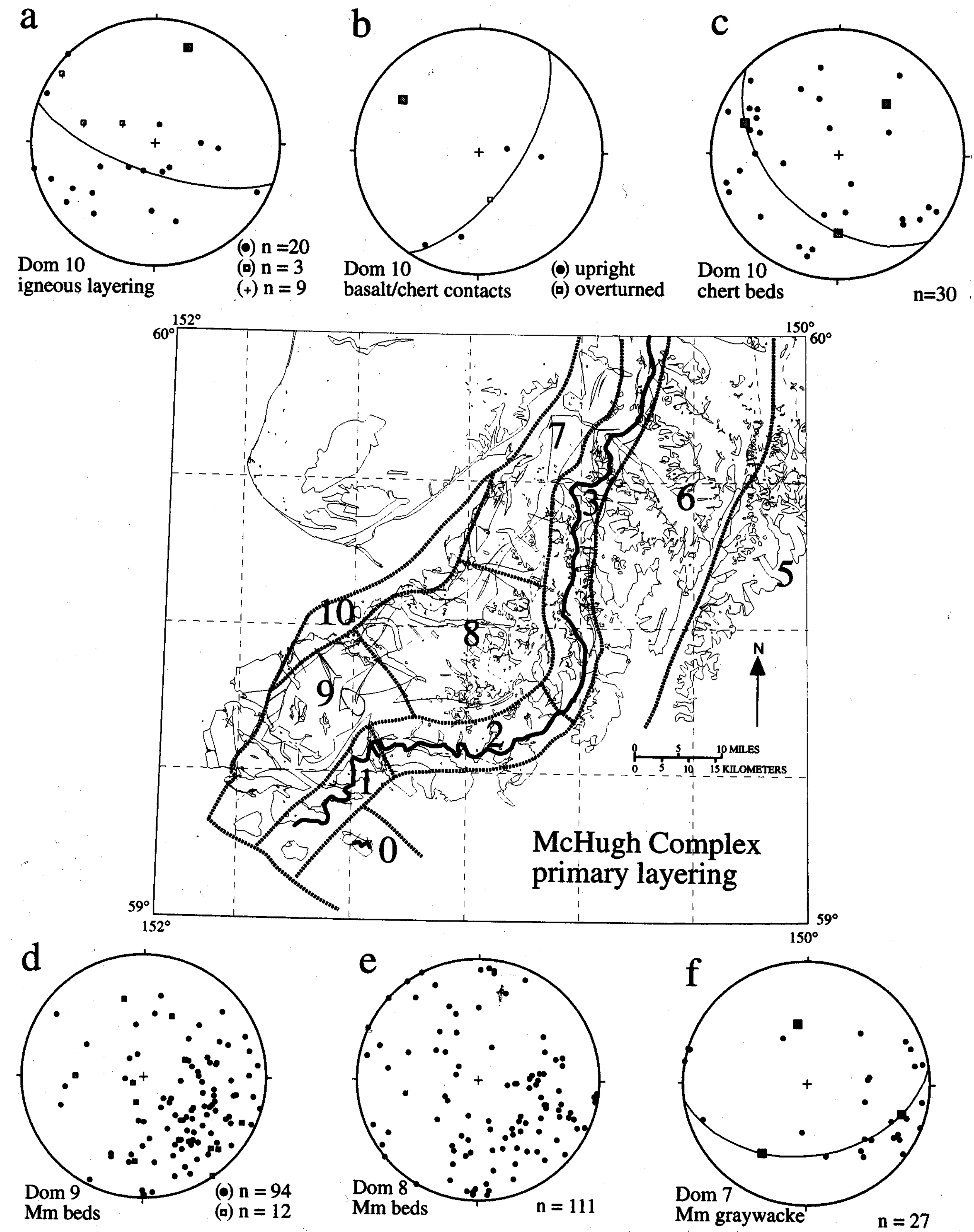


Figure 4. Representative photographs of the Chugach Bay thrust and Iceworm mélange. (a) View of Chugach Bay thrust and Iceworm mélange on the flanks of Iceworm peak (location a on Figure 2). Mm is McHugh Complex, Kvm is Iceworm mélange, arrowhead along Chugach Bay fault. (b) View of Chugach Bay thrust placing McHugh Complex mélange at top of cirque wall over Iceworm mélange, which forms the dark shaley rocks in the lower part of the cirque (from location b on Figure 2). (c) Blocks of semicoherent Valdez turbidites in the Iceworm mélange. (d) Completely disrupted blocks of graywacke in an argillaceous matrix, forming typical Iceworm mélange.

recognized, most beds are upright, dip landward (Figure 7), and are folded about north-northeast trending, gently north plunging fold axes (Figures 7a, 7c and 7f). Structural trends in the Valdez Group are relatively coherent for many kilometers along strike, with individual panels up to several kilometers thick, bounded above and below by thin thrust fault surfaces. Thrust ramps and flats (Figure 3d) are both found in outcrop. Some areas contain numerous coherent panels of Valdez Group turbidites apparently repeated along thrust faults, whereas other areas show tight to isoclinal folds within these panels. Figure 8 shows the orientation of slaty cleavage in domains 0, 2, 3, 5, and 6. In outcrop, bedding/cleavage angles are typically less than 25°, reflecting cleavage fans in tight to isoclinal folds. On a regional scale, bedding and cleavage are parallel, and the cleavage is distributed along great circles compatible with folding about northeast axes but is concentrated in point maxima along these circles suggesting that its regional orientation reflects cleavage fanning within large-scale folds as observed in outcrop (Figure 9) and not folding of the cleavage. The sequence of folding and cleavage development is discussed in section 5.5.

5.3. Iceworm Mélange Fabrics

On an outcrop scale, fabric elements of the Iceworm mélange are dominated by extended bedding and phacoidal to slaty cleavage (Figures 10 and 11). A scaly or phacoidal foliation is present in most of the argillaceous and mudstone-matrix parts of the Iceworm mélange (Figures 4d, 11b, and 11d), and this is generally subparallel to primary layering. Although in detail the cleavage locally anastomoses and cuts across the extended bedding, on an outcrop to regional scale the two fabric elements are statistically parallel (compare Figures 7 and 10). We assign S_1 nomenclature to this layering but recognize that it is truly a composite $S_0 + S_1$ planar fabric. In the rare instances where S_0 (original layering) is recognized, it is described separately from S_1. A linear fabric (L_1) within S_1 is defined by the elongation of inclusions and, more rarely, by a lineation on the scaly shaley units. In cases where the scaly or phacoidal cleavage transects primary layering, it extends these layers parallel to the cleavage. Various stages of disruption from continuous S_0 layering cut by an anastomosing scaly fabric to a scaly anastomosing


a
(•) n =20
(▫) n = 3
(+) n = 9
Dom 10
igneous layering
b
Dom 10
basalt/chert contacts
(•) upright
(▫) overturned
c
Dom 10
chert beds
n=30
152°
60°
150°
60°
7
3
6
5
10
8
9
2
1
0
N
0 5 10 MILES
0 5 10 15 KILOMETERS
McHugh Complex
primary layering
59°
152°
59°
150°
d
Dom 9
Mm beds
(•) n = 94
(▫) n = 12
e
Dom 8
Mm beds
n = 111
f
Dom 7
Mm graywacke
n = 27

fabric with inclusion trains of a different rock type are present (Figure 11). The scaly cleavage typically is a composite planar fabric, with two or more orientations present, but since these tend to anastomose they are not assigned a C-S type of terminology.

Type I mélange consists of originally interbedded sandstones and shales which have experienced layer parallel extension, forming discontinuous blocks of sandstones in an argillite matrix [*Cowan*, 1985]. Figure 11 illustrates four stages in evolution of the Iceworm mélange from the Valdez Group. The Valdez Group grades from nearly continuous to "broken" [*cf. Hsü*, 1968, 1974] sandstone/shale beds (Figure 11a) to a unit (Figures 11b, 11c, and 11d) which has been both extended along brittle faults and ductily thinned by pinch and swell processes to a true type I mélange. Pinching and swelling and breakage is common in boudin necks, and shale is in many cases injected along fractures in the more competent graywacke blocks (arrow in Figure 11d). With continued extensional disaggregation, the broken formation grades into an entirely disrupted rock type we map as the Iceworm mélange. The mélange consists of blocks of graywacke enclosed in a matrix of phacoidally cleaved argillite. Both graywacke and argillite are indistinguishable from comparable rock types within the coherent parts of the Valdez Group. The graywacke blocks are typically lozenge shaped (Figure 11d) and range in length and thickness from a few centimeters to several meters.

Plots of extended bedding (fragment foliation), phacoidal cleavage, and bedding in the Iceworm mélange from domains 1, 2, and 3 are consistent with folding of these fabric elements in the Iceworm mélange about north-northeast trending, gently north plunging fold axes, approximately parallel to the regional strike (Figure 10). In rare cases, the Iceworm mélange shows seaward vergent folds that fold the fragment foliation and the scaly cleavage. In Rocky Bay (Figures 2 and 12), most bedding fragments are elongate parallel to the mélange foliation but are overturned and young trenchward, and several small-scale (parasitic?) fold closures were observed. These F_2 folds deform both the extended graywacke beds and the argillite matrix showing that the folds formed after the mélange was generated. Byrne [1984] described similar swirls and folds in argillite matrix of the Ghost Rocks Formation on Kodiak Island. He interpreted these structures as one of the earliest deformation structures in that location. Our data support Byrne's interpretation that these are early structures, but we can demonstrate that layer-parallel extension at least locally preceeded folding because boudin trains can be traced around fold hinges.

Along Turnagain Arm near Anchorage (Figure 1), a type I mélange structurally below the Eagle River thrust is similar to the Iceworm mélange on the southern Kenai Peninsula [*Kusky et al.*, 1997]. In the mélange along Turnagain Arm, bedding is largely overturned, suggesting that some of the type I mélange may be related to overturning and severe extension of the bedding during overthrusting by more competent rocks of the McHugh complex.

5.4. Mechanisms of Mélange Formation in Iceworm Mélange

We attribute formation of the Iceworm mélange to thrusting of the McHugh Complex over initially coherent but only partly lithified Valdez Group sedimentary rocks because the mélange is located along the contact between the two rock units, and all stages of formation of the mélange, between undisrupted beds, through broken formation, and into true mélange are found in this unit. The presence of boudinage, pinch and swell structures, brittle fractures, and shale injection veins in the graywackes show that they were stronger than the argillites and shales during deformation. This rheological contrast could have been induced by high fluid pressures in the argillites, related to either fluid entrapment when dewatering the accretionary prism sediments that were emplaced beneath the impermeable McHugh hanging wall, or by the incomplete lithification of the argillites at the time of deformation. The structural differences between the argillites and graywackes only tell us the relative competence contrasts not whether one of the rocks was truly "wet" or "soft" at the time of deformation. The presence of rare clastic dikes, including some in Rocky Bay (Figure 12) and another along Turnagain Arm near Anchorage (*Bradley et al.*, 1997) supports the idea that Valdez Group rocks were only partly lithified at the time of deformation.

Pinch and swell as well as boudinage are common manifestations of inferred layer-parallel extension in the Iceworm mélange. Some graywacke boudins show complex structural histories. For example, the boudin in Figure 13 is elongate with the long axis parallel to the L_1 lineation in the argillite matrix. The boudin is cut obliquely by many calcite veins which are perpendicular to faint stylolites, both of which form significant angles with the boudin long axis. The prominent fracture cutting the boudin is a shale injection vein, indicating that some deformation occurred while the shales were relatively "soft" and/or under high fluid pressures. Although not visible on the slabbed sample, the boudin is not

Figure 5. Structural domains of the southern Kenai Peninsula and lower hemisphere equal-area projections of structural data showing primary layering in the McHugh Complex. (a) Igneous layering from domain 10 including pillow lava flattening planes (circles, n=20), overturned pillow lavas (open squares, n=3), and cumulate layering in ultrmafic complexes (crosses, n=9). Layering is folded about axis 029 34° (best fit great circle 119 56°S). (b) Contacts between basalt and chert in domain 10, show folding about axis 304 27° (best fit great circle 034 63° SE). (c) Poles to chert beds in domain 10, which are folded about 043 44° axis (cylindrical best fit 133 46°S). (d) Poles to beds in McHugh complex in domain 9. (e) Poles to beds in McHugh complex in domain 8. (f) Poles to beds in massive graywacke unit of McHugh complex in domain 7. These are folded about axis 351 49° (cylindrical best fit great circle 081 41°S). Mm is McHugh Complex. Large shaded squares in Figures 5a and 5b are poles to visually best fit great circles to data, whereas large shaded squares in Figures 5c and 5f are eigenvectors based on a cylindrical best fit to data.

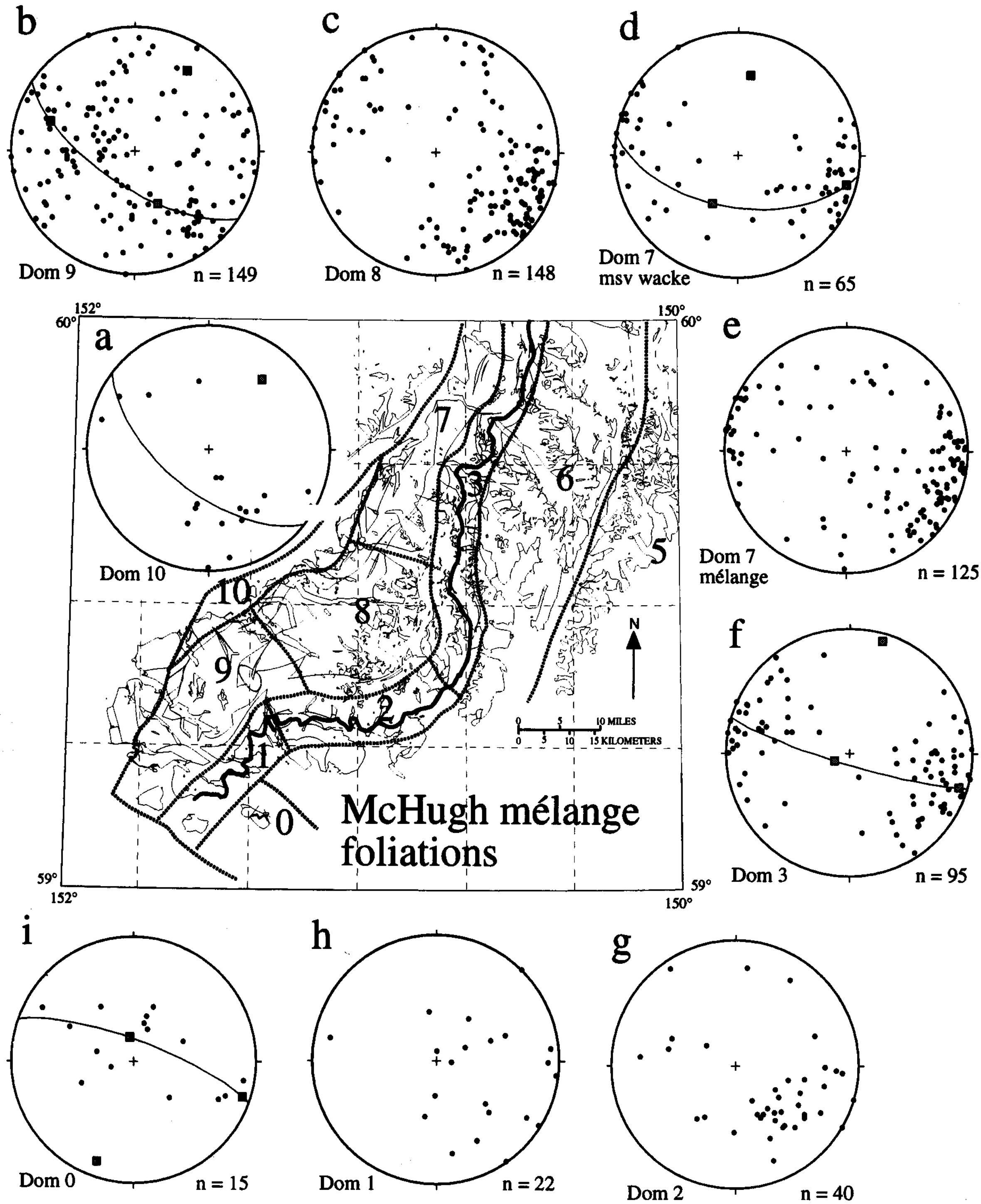


Figure 6. Lower hemisphere equal-area projections of poles to tectonic layering from McHugh Complex. (a) Domain 10 data, folded about axis 038 29° (best fit great circle 128 61°S). (b) Poles to layering from domain 9, folded about axis 033 24° (cylindrical best fit great circle 123 66°S). (c) Poles to foliations from domain 8. (d) Poles to foliations in massive graywacke in domain 7, folded about axis 200 14° (cylindrical best fit great circle 290 76°N). (e) Poles to foliation in mélange from domain 7. (f) Poles to foliations in mélange in domain 3, folded about axis 016 7°(cylindrical best fit 106 83°S). (g) Poles to foliations in domain 2. (h) Poles to foliations in domain 1. (i) Poles to foliation in domain 0, which are folded about 200 14° axis (cylindrical best fit great circle 290 76°N). Large shaded square in Figure 6a is the pole to the visually best fit great circle to data, whereas large shaded squares in Figures 6b, 6d, 6f, and 6i are eigenvectors based on a cylindrical best fit to data.

regularly bedded but is entirely disrupted by a network comprising web structure, cut by the shale injection vein. Thus, for this boudin, we can infer a structural history beginning with cataclastic flow forming web structure, fluid overpressure injecting shales into the boudin, rotation of the boudin with respect to the stress system, then brittle extension accompanied by dissolution along stylolitic surfaces. Many other boudins show curved terminations, indicating that ductile pinching and swelling were also important mechanisms of layer parallel extension at some point prior to brittle extension or that deformation occurred in the brittle-ductile field.

Deformation mechanisms in the Iceworm mélange include pressure solution and cataclasis of quartz, feldspar, and calcite grains along with the development of a planar preferred orientation of chlorite and sericite along the fault zone [*Hawley*, 1992]. Two alternative hypotheses can account for the generation of extensional phacoidal cleavages like that found in the Iceworm mélange. In the first model, cleavages are inferred to form perpendicular to or at a high angle to the maximum principal stress (σ_1). Because σ_1 is presumably subhorizontal in most accretionary wedges, the anastomosing scaly cleavage may have formed after the bedding was rotated into a nearly vertical attitude. In the second model, the cleavage is interpreted to have formed in a wide, downward propagating shear zone at the base of the accretionary prism [e.g., *Silver et al.*, 1985; *Moore and Byrne*, 1987; *Moore et al.*, 1986; *Moore and Lundberg*, 1986]. The second model for the formation of the scaly mélange fabric is favored by the relative timing of fabric development and overprinting relationships as discussed in section 5.5., and by *Bradley and Kusky* (1992).

5.5. Fold Orientation and Overprinting Relationships

The orientation of the fabric elements described above clearly shows folding about north-northeast trending, gently north plunging axes. On stereonet plots of mesoscopically visible fold axial surfaces and planes, most folds belong to this northeast trending set, but several outcrops in domain 2 show northwest to west trending folds refolding the earlier north-northeast trending fold set (Figures 14d and 14e). Northwest trending minor folds are also found in bedded cherts of the McHugh Complex of domain 10 (Figure 14c), and the regional map pattern shows an open, northwest trending curvature that may be a large-scale fold. In addition, the map pattern (Figure 2) indicates that the Chugach Bay thrust is folded about northwest-southeast axes. Folding of the Chugach Bay thrust is most evident on a detailed map of the Windy Bay - Chugach Bay area (Figure 12). Here the thrust is folded about WNW axes, controlling the shape of the coastline in this area. Additionally, the foliation in the McHugh Complex in this area is truncated by the Chugach Bay thrust, but the foliations in the Iceworm mélange closely mimic the trace of the folded thrust. From this, we conclude that the McHugh complex had already been deformed (and metamorphosed) at the time of formation of the Iceworm mélange.

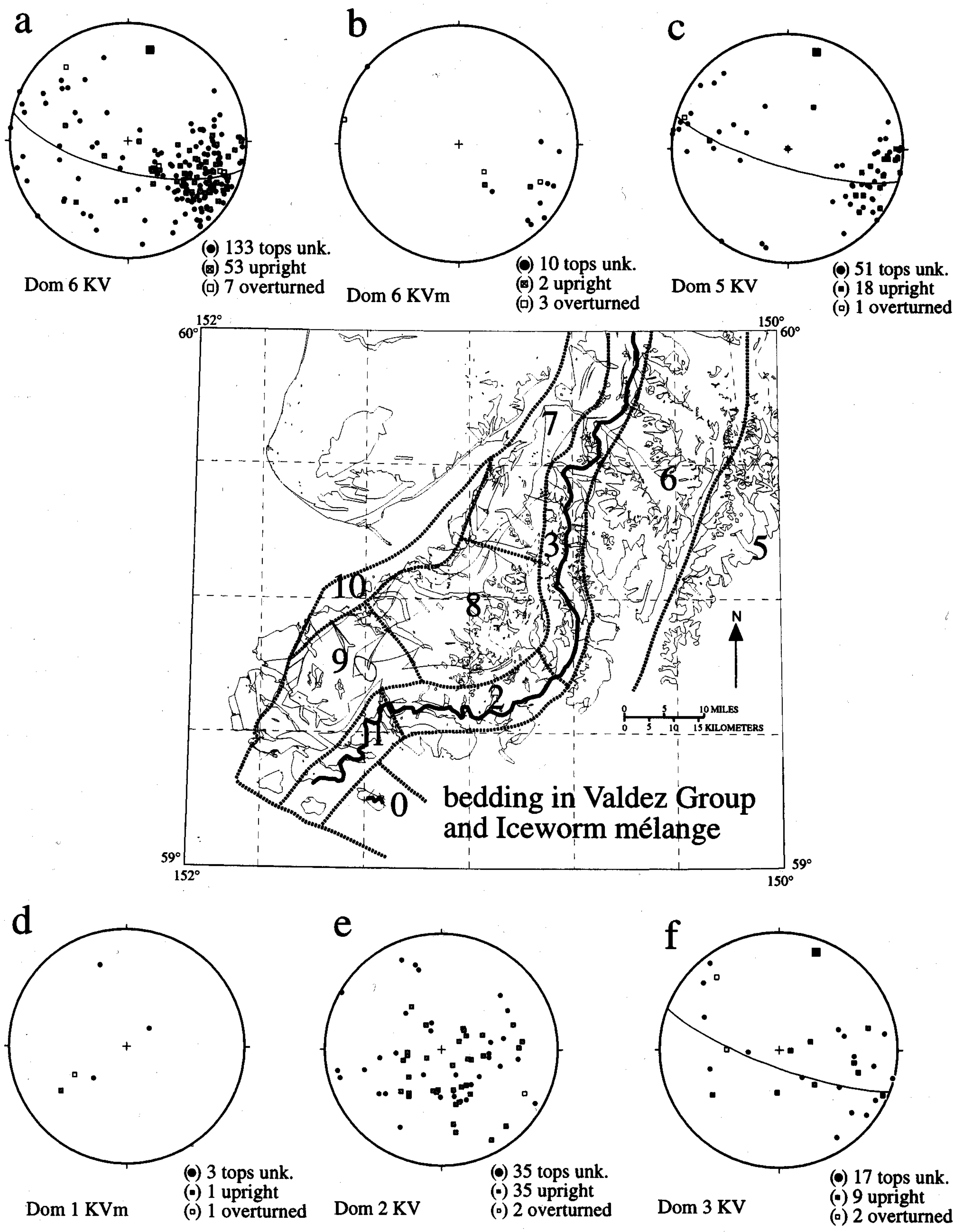
Data bearing on the relative timing of foliation development and successive generations of folds come from outcrop-scale overprinting relationships in the Iceworm mélange. Nearly all of the disruption in the Iceworm mélange appears to be tectonic in origin, although we have evidence for a few early slump folds. These are irregular in appearance, with variably oriented hinges and axial surfaces, and have sedimentary welded contacts with surrounding layers. We assign these folds a D_0 and F_0 nomenclature. The first tectonic deformation appears to be layer-parallel extension via boudinage and structural slicing of bedding within originally coherent or slump-folded Valdez sedimentary rocks. This layer-parallel extension (D_1) is constrained to have occurred prior to north-northeast striking, gently north plunging isoclinal folding (described here as D_2 and F_2), because outcrop-scale isoclinal folds of this generation warp previously extended layering and individual boudin trains can be traced around fold hinges. Cross-folds (F_3) with northwest-southeast to east-west axial surfaces refold the earlier folds on both the outcrop and map scales (Figures 2 and 14). These folds are broad open structures with wide hinge zones. Yet another style group of folds (F_4?) locally present in the Port Dick area includes north-south trending chevron folds with steeply plunging axes associated with thrust faults that transported the hanging walls to both the east and the west. The relative order of F_3 and F_4? could not be determined in the field.

5.6. Late Faults

The entire Seldovia quadrangle, including areas bordering the Chugach Bay thrust and Iceworm mélange, is cut by a myriad of late brittle faults interpreted by *Kusky et al.* [1997] to be a consequence of Paleocene ridge subduction (e.g., Figure 12). These faults do not affect the regional map pattern, and they are not discussed further here. A more complete description of late faults is given by *Bradley and Kusky* [1992] and *Kusky et al.* [1997].

5.7. Age of Displacement on the Chugach Bay Fault

Crosscutting relations bracket the timing of movement on the Chugach Bay fault as Maastrichtian and (or) Paleocene in age. Crosscutting intermediate and silicic dikes truncate mélange fabrics in both the McHugh Complex and Iceworm mélange (Figure 15) and cleavage in the coherent part of the Valdez Group. One such dike has yielded a $^{40}Ar/^{39}Ar$ isochron age of 57.0 ± 0.22 Ma and a plateau age of 55.8 ± 1.4 Ma (Figure 15) [*Clendenin*, cited in *Bradley et al.*, 1994]. The older age limit is established by the fact that the Iceworm mélange is composed of disrupted Valdez Group turbidites of presumed Campanian to Maastrichtian age [e.g., *Jones and Clark*, 1973; *Budnick*, 1974], but as discussed above, fossil ages of the Valdez Group are sparse. Within the Campanian to Paleocene age range, the older end is more consistent with the notion that the Valdez Group was deposited wholly or partly in a trench [*Nilsen and Zuffa*, 1982]. The sedimentary fill of such a trench would have been off scraped and (or) underplated at or beneath the adjacent accretionary prism during sedimentation, and the farthest landward thrust fault would be the oldest.


a
(●) 133 tops unk.
(⊠) 53 upright
(□) 7 overturned
Dom 6 KV
b
(●) 10 tops unk.
(⊠) 2 upright
(□) 3 overturned
Dom 6 KVm
c
(●) 51 tops unk.
(▪) 18 upright
(▫) 1 overturned
Dom 5 KV
152°
60°
150°
60°
7
6
3
5
10
8
9
2
1
0
N
0 5 10 MILES
0 5 10 15 KILOMETERS
bedding in Valdez Group
and Iceworm mélange
59°
152°
59°
150°
d
(●) 3 tops unk.
(▪) 1 upright
(▫) 1 overturned
Dom 1 KVm
e
(●) 35 tops unk.
(▪) 35 upright
(▫) 2 overturned
Dom 2 KV
f
(●) 17 tops unk.
(▪) 9 upright
(▫) 2 overturned
Dom 3 KV

6. DISCUSSION

6.1. Differences in Accretion Style Between the McHugh Complex and Valdez Group

Outcrop-scale mélanges within the McHugh Complex differ in several ways from the Iceworm mélange and, more obviously, from the belts of coherent Valdez Group rocks. Mélanges of the McHugh Complex contain a polymict assemblage of graywacke, chert, greenstone, and limestone set in a phacoidally cleaved argillaceous matrix (Figures 3a and 3b) [*Bradley and Kusky,* 1992]. These are type II mélanges according to the classification of *Cowan* [1985]. The Iceworm mélange, which consists entirely of fragmented graywacke and argillite, is a type I mélange according to the classification of *Cowan* [1985]. Both the McHugh complex and the Iceworm mélange are characterized by intense early stratal disruption with layer-parallel extension but differ in that the McHugh mélanges show significant mixing between individual rock types (presumably initially layers), whereas the Iceworm mélange does not exhibit much interlayer mixing. Cleavage in argillites of the McHugh Complex is weak, probably owing to silicification of matrix argillite. The presence of web structure is characteristic of McHugh Complex sandstones but is very rare in the Iceworm mélange. These differences may be caused by different depths of deformation of the McHugh Complex and Iceworm mélange, by different amounts of simple and pure shear in a general shear environment [*see Simpson and de Paor,* 1993], by relative differences in fluid pressures during deformation, by differences in the amount of lithification or strength contrasts between units, or contrasts in the relative abundances of argillite and sandstone. The McHugh Complex, coherent Valdez Group units, and the Iceworm mélange all show folding about north to NE trending, gently NE plunging axes and a later folding about NW trending axes. All units are cut by late (Paleocene) faults and dikes.

The coherent Valdez Group shows a dramatically different structural style, presumably related to a different mechanism of accretion. Structures are dominantly contractional and include thrust flats and ramps repeating individual sections, and tight to isoclinal folds. The structural style is reminiscent of contemporary accretionary complexes where the subducting plate is thickly sedimented, with kilometer-scale panels of internally coherent beds that are folded about margin-parallel axes [e.g., *McCarthy and Scholl,* 1985; *Scholl et al.,* 1987].

6.2. Significance of Folding Generations

All units show folding about subhorizontal axes roughly parallel to regional strike. These folds are likely related to the off scraping/accretion mechanism, such as incorporation of the accreted packages into duplex structures or tighter folds in thrust and fold nappe packages [e.g., *Sample and Fisher,* 1986; *Sample and Moore,* 1987; *von Huene et al.,* 1997]. The younger cross-folding about NW trending axes does not have such an obvious tectonic explanation, but we suggest that these folds may be related to the post-Paleocene oroclinal rotations described by several authors from southern Alaska [*Bol and Coe,* 1987; *Coe et al.,* 1989; *Packer and Stone,* 1972; *Panuska,* 1987; *Stone,* 1989].

6.3. Broad Tectonic Implications for Alaska

The Chugach terrane was formed on the southern margin of the Wrangellia composite terrane by intermittent off scraping/underplating events, related to the subduction of oceanic plates (including the Izanagi, Kula, and Farallon plates), during the Triassic, Jurassic, and Cretaceous [*Atwater,* 1989; *Plafker and Berg,* 1994]. These events formed the mélange fabrics within the McHugh Complex [*Bradley and Kusky,* 1992] and were the setting for the regional prehnite/pumpellite facies metamorphism (Figures 16a and 17a). Following collision of the Wrangellia composite terrane with cratonic North America in the Middle to Late Cretaceous [*Nokleberg et al.,* 1994; *Plafker and Berg,* 1994; *Pavlis,* 1989], uplift and unroofing in the zone of intense contractional deformation [*Hollister,* 1979, 1982; *Crawford and Hollister,* 1982] deposited large volumes of sedimentary material on the subducting oceanic plates (Figure 16b). It has been suggested that uplift of the Coast Mountains occurred in two major pulses, including one in the Late Cretaceous and one in the Paleocene-Eocene [*Hollister,* 1979; *Crawford and Hollister,* 1982].

The Valdez Group shows a magmatic arc provenance [*Dumoulin,* 1987, 1988; *Gilbert et al.,* 1992; *Farmer et al.,* 1993], consistent with a source in the uplifted Coast Mountains (Kluane arc of *Plafker et al.* [1994] (Figure 16b), although some sediment may have been contributed from uplifted mountains in central Alaska [*Plafker et al.,* 1994]. Sediment transport was dominantly toward the NW (reconstructed Cretaceous coordinates) along the continental

Figure 7. Lower hemisphere equal-area projections of structural data from coherent Valdez Group sedimentary rocks and from well-bedded blocks in Iceworm mélange. Poles to beds with unknown younging directions are plotted as circles, poles to upright beds are plotted as shaded squares, and poles to overturned beds are plotted as open squares. (a) Data from coherent Valdez Group rocks in domain 6, which are folded about an axis 014 21° (cylindrical best fit great circle 104 69°S). (b) Poles to beds from Valdez type 1 mélange in domain 6. (c) Poles to coherent Valdez beds in domain 5, which are folded about an axis 016 11° (best fit great circle 106 79°S). (d) Poles to beds in Iceworm mélange of domain 1. (e) Poles to beds from coherent Valdez Group rocks in domain 2. (f) Poles to coherent Valdez Group beds in domain 3, which are folded about an axis 021 11° (best fit great circle 111 79°S). KV is coherent Valdez Group, Kvm is Iceworm mélange. Large solid squares in Figures 7a, 7c, and 7f are poles to great circles, interpreted as fold axes, based on visual best fit to data.

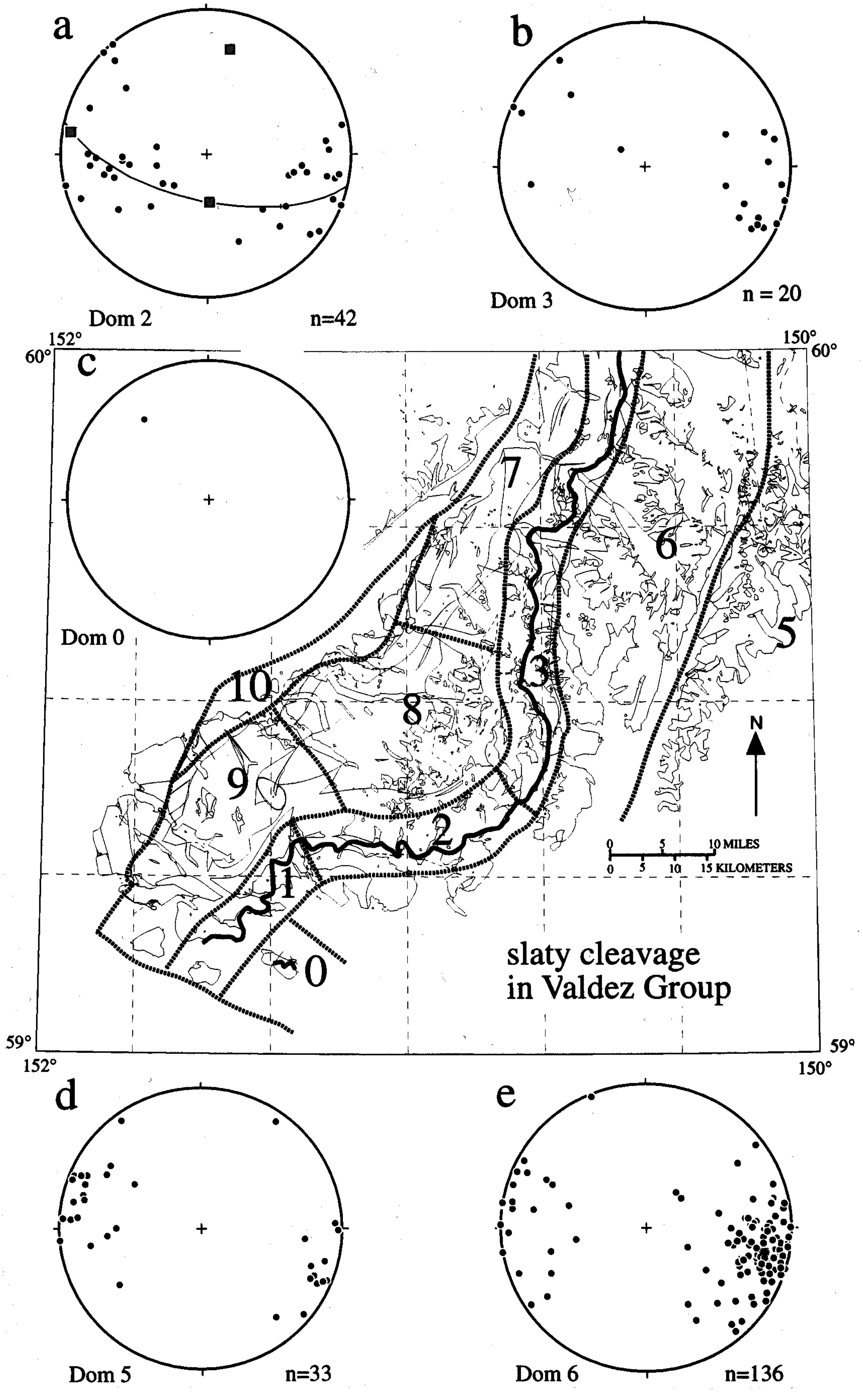

a
Dom 2
n=42
b
Dom 3
n = 20
c
Dom 0
152°
60°
150°
60°
7
6
5
3
10
8
9
2
1
0
N
0 5 10 MILES
0 5 10 15 KILOMETERS
slaty cleavage
in Valdez Group
59°
152°
59°
150°
d
Dom 5
n=33
e
Dom 6
n=136

Figure 9. Map-scale fold in Valdez Group (location c in Figure 2). Axial surface indicated by dashed line.

margin [*Nilsen and Moore,* 1979; *Nilsen and Zuffa,* 1982; *Decker and Plafker,* 1983], but bimodal paleocurrent directions from the Kenai Peninsula (D.C. Bradley and T.M. Kusky, unpublished data, 1994) show that some submarine fans shed turbidites in both directions (Figure 16). Subduction of this thick sedimentary pile is here postulated to have caused the dramatic change in accretion style between the older mélange terranes of the McHugh Complex and the generally coherent turbidite thrust packages of the Valdez Group.

An intriguing but unresolved question is the origin of the age gap between the McHugh Complex and the Valdez Group. The youngest fossils yet found in the McHugh Complex are Albian-Aptian (D.C. Bradley and T.M. Kusky, unpublished data, 1995), yet the oldest fossils found in Valdez Group are Campanian-Maastrichtian, leaving a gap of no reported ages for the early Late Cretaceous. It could be that this corresponds to a period of subduction erosion or that the unfossiliferous protoliths of the Iceworm mélange represent an older, muddier facies of turbidites than preserved in more typical Valdez Group. These could represent the first, distal deposits from uplift and erosion in the Coast Mountains that would have been incorporated into the accretionary wedge before the thicker, more proximal part of the Valdez Group turbidite fan. Attempted subduction of the large amount of buoyant material of the Valdez fan beneath the McHugh Complex would have resulted in rapid frontal accretion [e.g., *Byrne and Fisher,* 1987, *Kimura,* 1994] and may have activated the Chugach Bay and related thrusts, along which the already deformed and metamorphosed McHugh Complex was emplaced over the Valdez Group (Figure 17b).

Another unresolved question relates to the relationship between underplating of the Valdez Group and uplift of the Chugach and Kenai Mountains. Several authors have convincingly shown that some uplift is related to motion on the Border Ranges fault system, but the relative amounts of uplift related to these transpressional events, to underplating of the Valdez Group beneath the McHugh Complex, and to other events such as ridge subduction have not been resolved. Major uplift of the Chugach terrane in southern Alaska occurred in the 60-55 Ma interval but continued with other "localized" events including one between 30 and 35 Ma and another at 15-20 Ma [*Little,* 1988, 1990; *Kveton,* 1989; *Clendenin,* 1991; *Little and Naeser,* 1989; *Plafker et al.,* 1989]. Hawley et al. [1984] determined an apatite fission track age of 65 ± 6 Ma from a granodiorite at 1865 m in the western Chugach Mountains and interpreted it as reflecting the age of underplating and accretion of the Valdez Group along the Eagle River fault. Little [1990] descibed stratigraphic evidence for Paleocene uplift of the northwestern Chugach mountains including Late Cretaceous and Tertiary strata of the Cook Inlet - Matanuska Valley forearc basin sequence resting unconformably on Lower Jurassic rocks of the southern Peninsular terrane. *Little* [1988] also documented a syntectonic alluvial fan sequence– the Paleocene - lower Eocene Chickaloon Formation– that was deposited along north-dipping normal faults associated with uplift of the Chugach terrane to the south. *Little* [1988, 1990] and *Pavlis et al.* [1988] have documented that this sedimentation was related to strike-slip movements along the Border Ranges fault system. *Sisson and Pavlis* [1993], *Bradley et al.* [1994] and

Figure 8. Lower hemisphere equal-area projections of poles to slaty cleavage from Valdez Group rocks in domains 0, 2, 3, 5, and 6. The cleavage poles generally form two point maxima indicating some variation in cleavage orientations about a general north-northeast strike. The cleavage from domain 2 appears folded about an axis 013 27° but may represent cleavage refraction around cleavage fans. Large shaded squares in Figure 8a are eigenvectors based on cylindrical best fit to data.

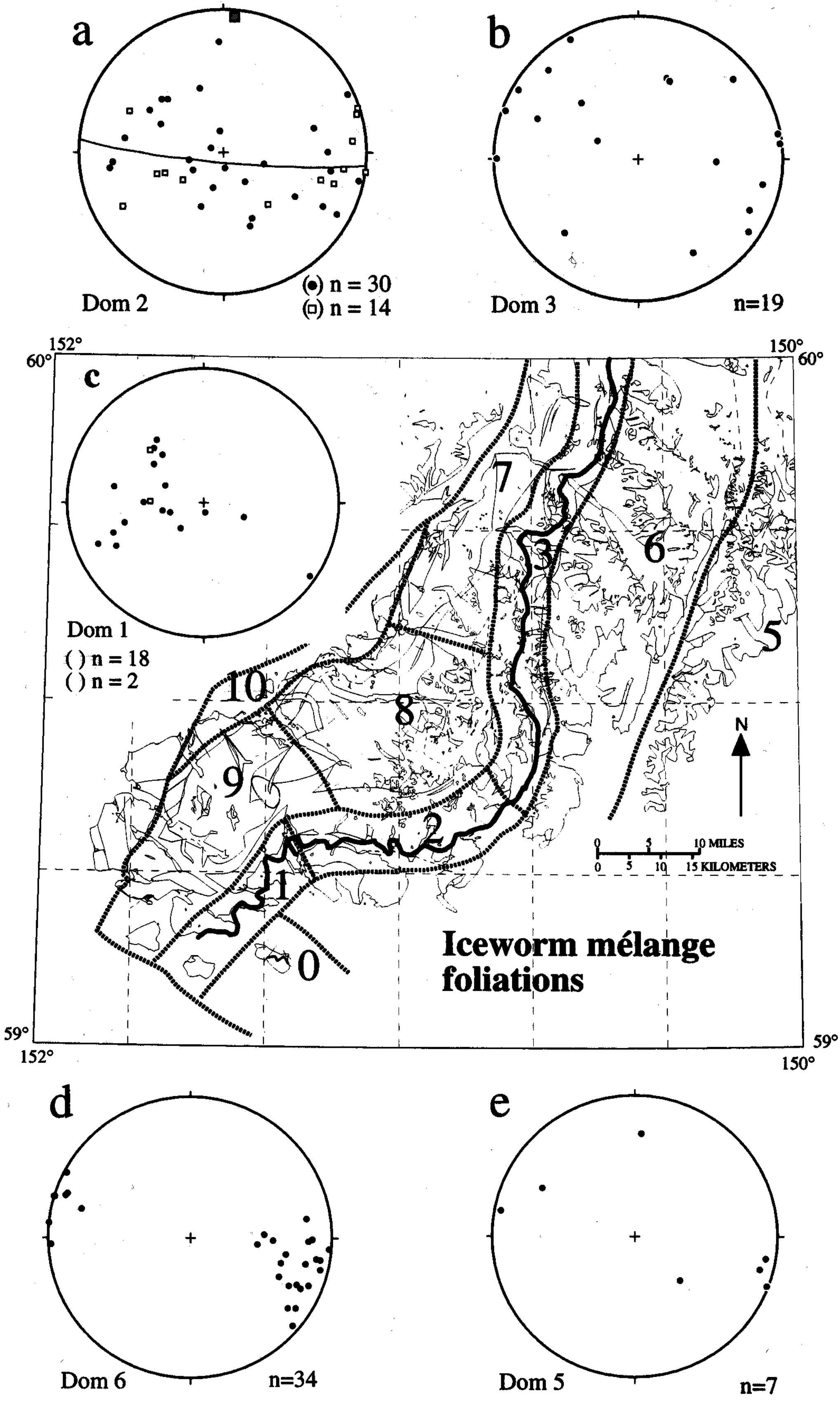


Figure 10. Lower hemisphere equal-area projections of fabric elements in Iceworm mélange. Circles represent poles to mélange foliation (scaly cleavage and fragment foliation), squares represent poles to slaty cleavage. (a) Data from domain 2, which is folded about an axis 004 7° (best fit great circle 094 83°S; large shaded square is pole to visually best fit great circle to data). (b) Data from domain 3. (c) Data from domain 1. (d) Data from domain 6. (e) Data from domain 5.

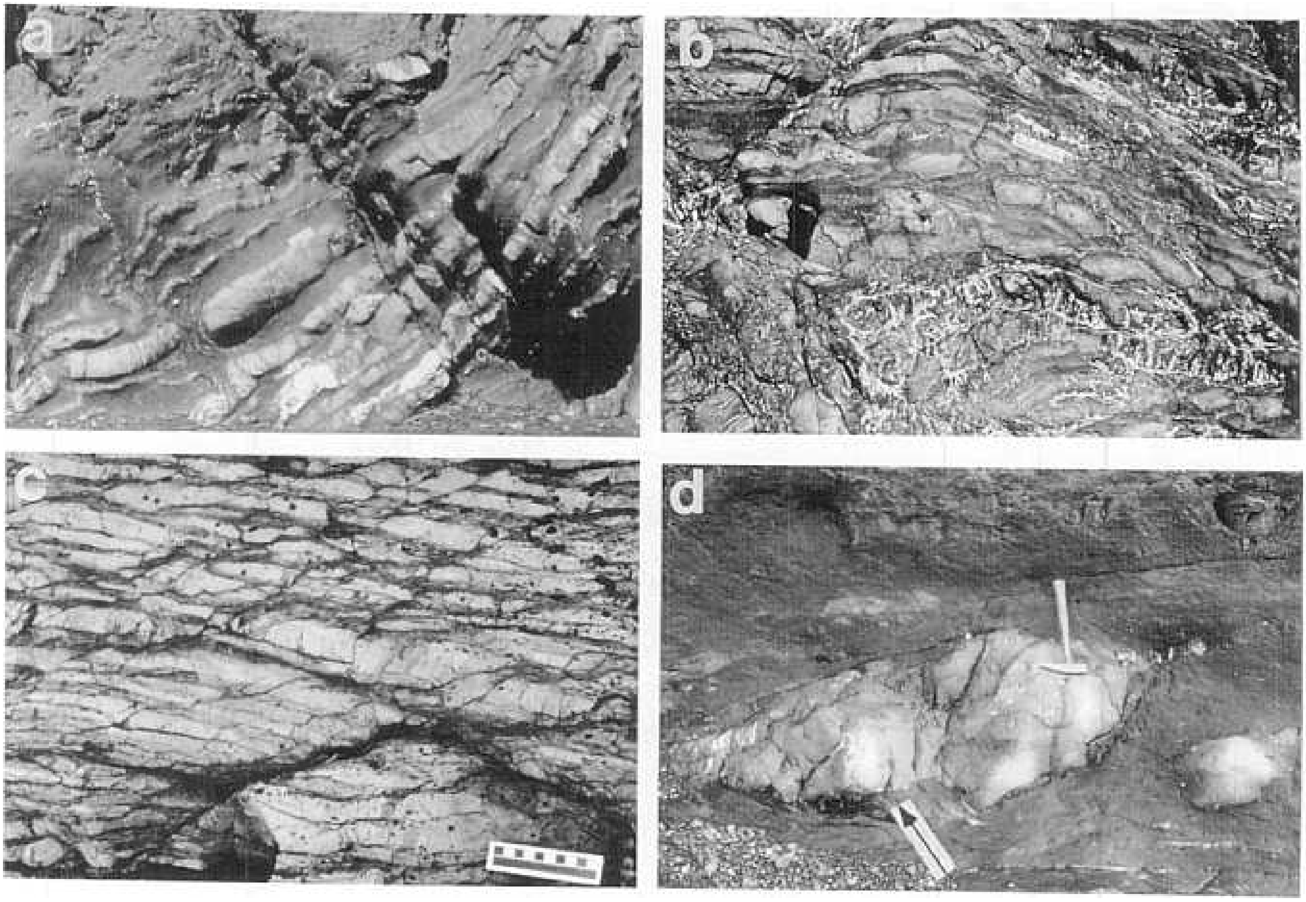


Figure 11. (a) Semicoherent Valdez Group turbidites showing initial stages of disruption by bedding parallel extension. (b) Disrupted Valdez Group turbidites showing asymmetric boudinage, resulting from the principal strains oriented obliquely to layering, and cut by antithetic normal faults. (c) Semicoherent Valdez Group sedimentary rocks cut obliquely by cleavage, small thrust faults, and effected by pinch and swell of the more competent layers. (d) Iceworm Mélange at Rocky Bay showing clasts of graywacke of Valdez Group enclosed in phacoidally cleaved argillite matrix. Arrow points to shale injection vein, showing that a large competence contrast between shale and graywacke existed during deformation, compatible with deformation occurring while graywacke was lithified and argillite was partly lithified to unlithified.

Kusky et al. [1997] have discussed several implications of Paleogene subduction of the Kula-Farallon ridge beneath the Chugach terrane. *Kusky et al.* [1997] presented structural data and discussed a model that predicts that the wedge experienced vertical extension as the triple junction approached any point, but at present there is not enough data to assess the relative importance of ridge subduction, transpression, and underplating in the uplift of the Chugach Mountains.

6.4. Relationship Between Subduction Zone Tectonism and Volume/Rate of Sediment Input: A General Model

We interpret accretion of the mélanges of the McHugh Complex as a normal response to subduction of oceanic crust bearing a thin pelagic sedimentary veneer (Figure 17a), whereas accretion of the coherent thrust packages of the Valdez Group is interpreted as a normal wedge response to subduction of oceanic crust bearing a thick pile of loosely consolidated submarine fan and trench sediments (Figure 17b). Thrusting of the McHugh Complex over the Valdez Group and the formation of the Chugach Bay thrust and Iceworm mélange may represent a dramatic critical taper adjustment to these changing subduction regimes. *Davis et al.* [1983] defined a popular Coloumb wedge model for the mechanics of accretionary prisms in which the stress is everywhere as large as possible, with the wedge thickening toward the rear because of the increased strength of rock in this direction. For a wedge of given strength (determined by rock rheology, basal resistance, pore fluid pressure, etc.), the forces that resist motion of the wedge are balanced by the forces that control the shape of the wedge (e.g., the thickness of the wedge determines the cross-sectional area across which the principal horizontal stress can act). In this way, the combination of surface slope plus basal decollement dip (critical taper) is maintained by deformation of the wedge, as material is added to the toe or base of the wedge. *Platt* [1986] analyzed the dynamics of accretionary wedges with negligible yield strength and demonstrated that underplating can oversteepen the surface slope, causing

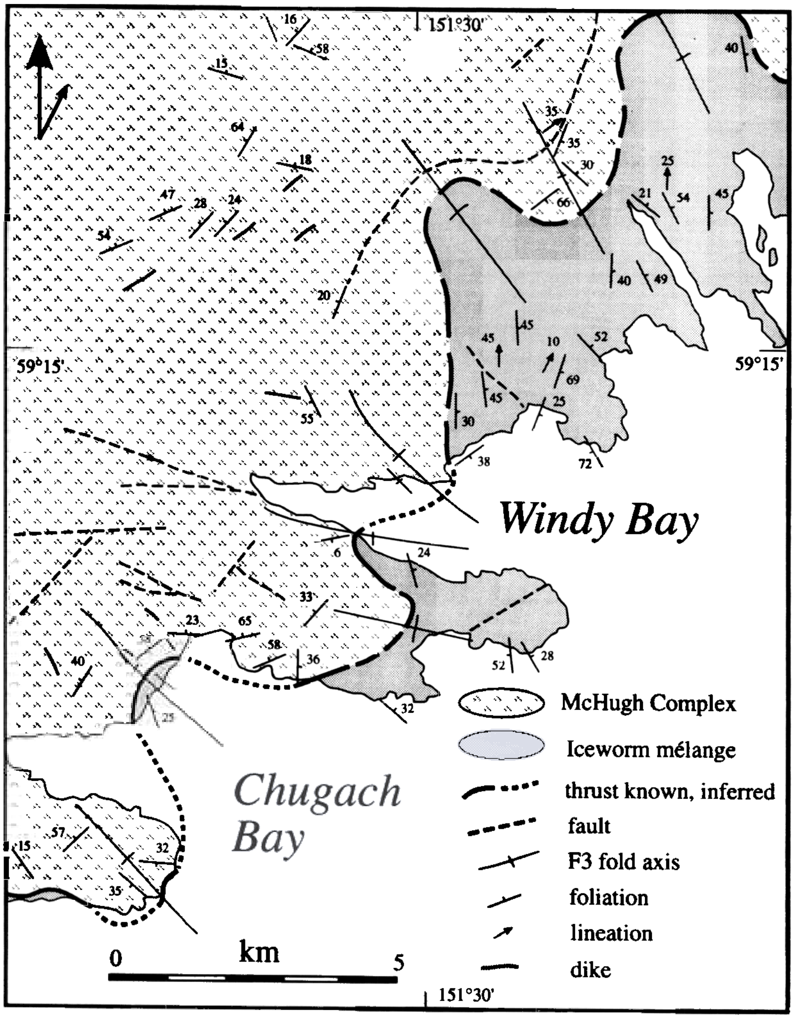


Figure 12. Geologic map of the Chugach Bay - Windy Bay area, showing that the folded Chugach Bay thrust truncates foliations in the McHugh complex and that fabrics in the Iceworm mélange are generally concordant with the trace of the fold. Mapping by D. Bradley, T. Kusky, P. Haeussler, and S. Karl.

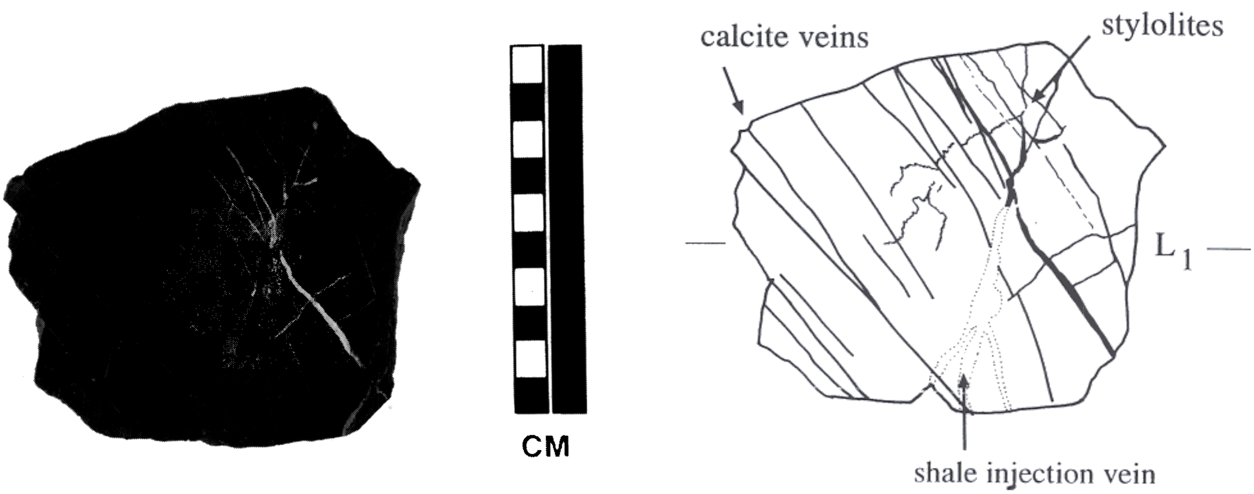


Figure 13. Boudin of graywacke extracted from Iceworm mélange in Windy Bay showing different fabric elements including boudin elongation parallel to L_1 lineation, web structure, calcite veins, and stylolites.

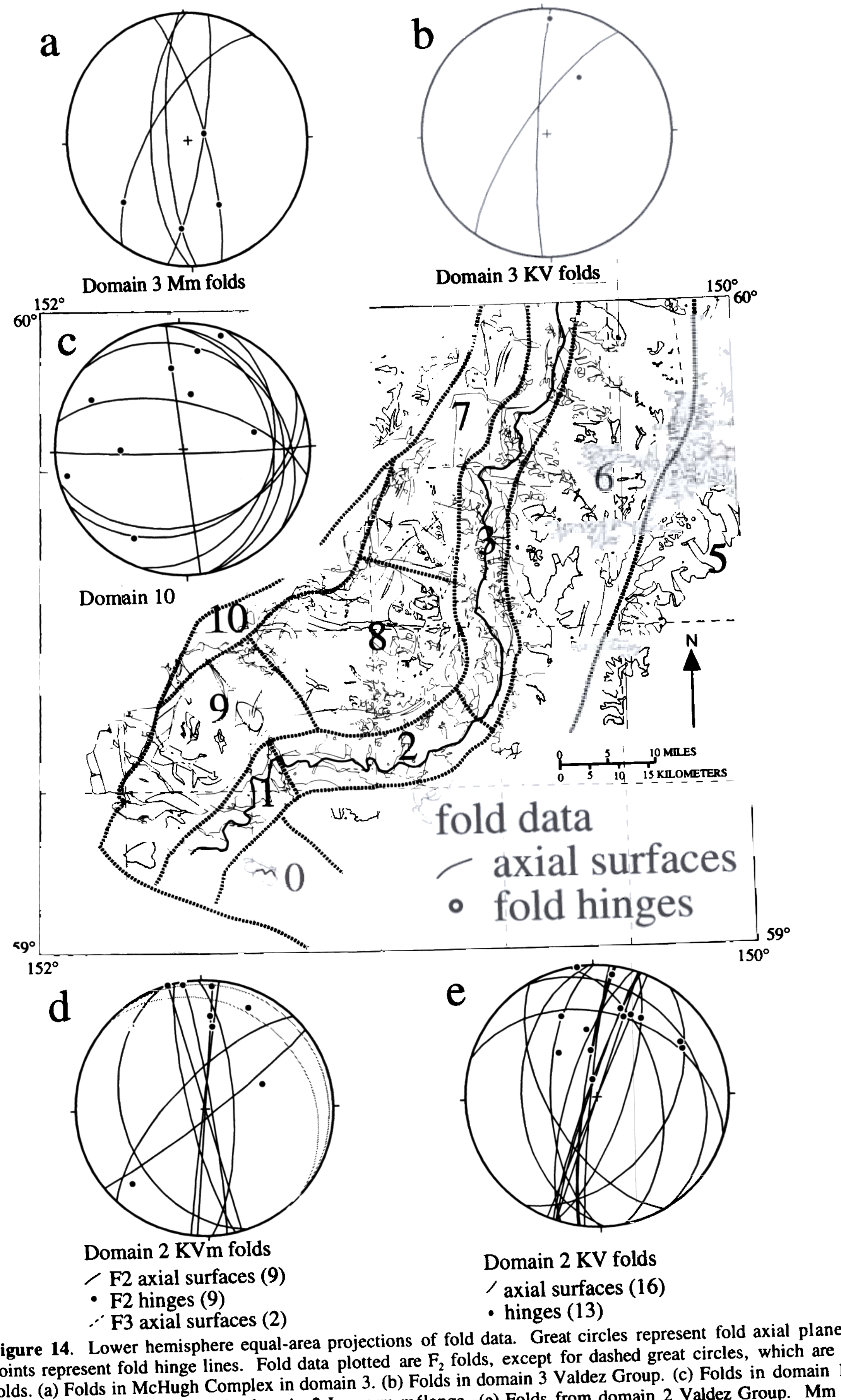


Figure 14. Lower hemisphere equal-area projections of fold data. Great circles represent fold axial planes; points represent fold hinge lines. Fold data plotted are F_2 folds, except for dashed great circles, which are F_3 folds. (a) Folds in McHugh Complex in domain 3. (b) Folds in domain 3 Valdez Group. (c) Folds in domain 10 McHugh Complex. (d) Folds in domain 2 Iceworm mélange. (e) Folds from domain 2 Valdez Group. Mm is McHugh Complex, KV is coherent Valdez Group, and Kvm is Iceworm mélange.

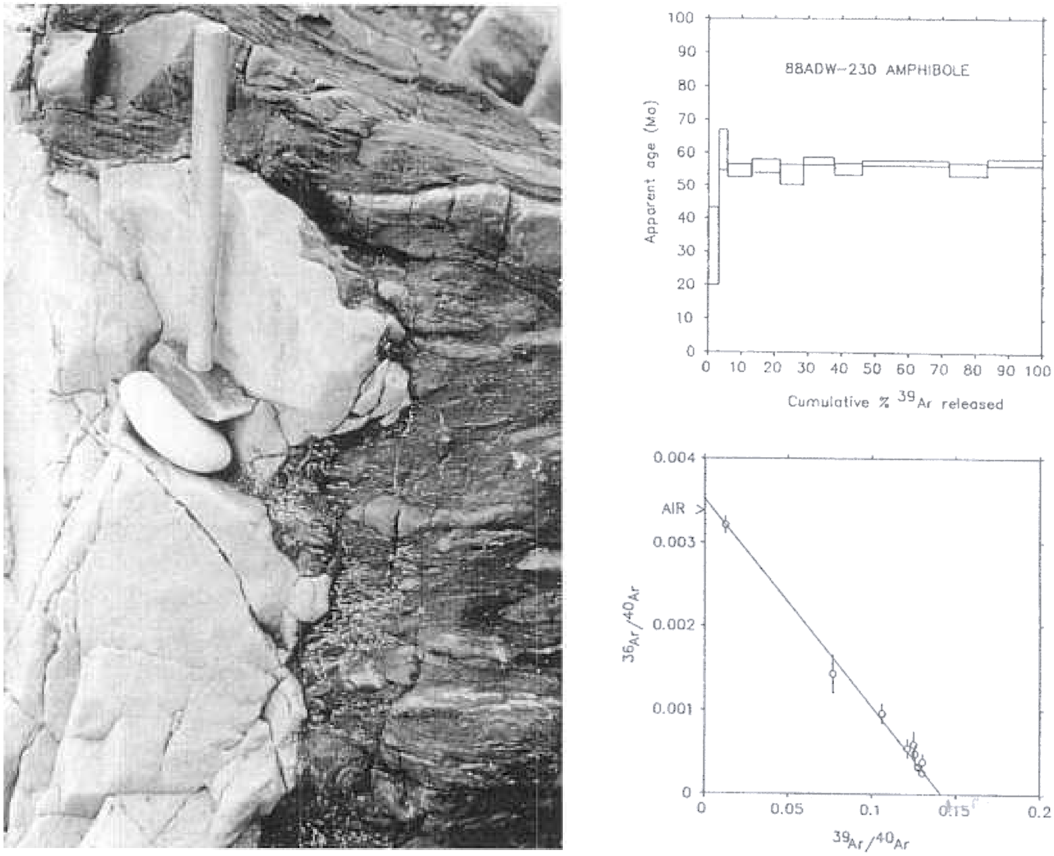


Figure 15. (a) Dike cutting fabrics in Iceworm mélange. Similar dikes belonging to a regional dike swarm have yielded a $^{40}Ar/^{39}Ar$ isochron age of 57.0 ± 0.22 Ma and a plateau age of 55.8 ± 1.4 Ma [W.S. Clendenin, personal communication cited by *Bradley et al.*, 1994], as shown in the (b) age spectra. The dikes are contemporaneous with a suite of near trench plutons that cut much of the Chugach terrane including Iceworm mélange fabrics [*Bradley et al.*, 1994].

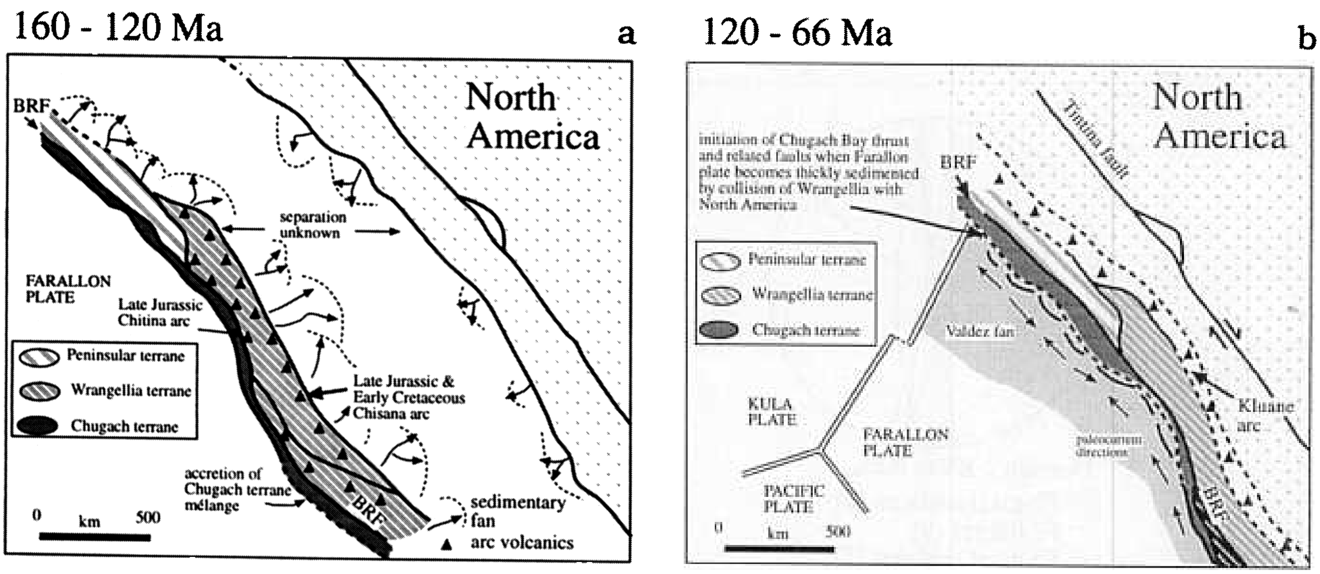


Figure 16. Paleogeographic reconstructions for western North America for (a) 160-120 Ma period, reflecting time of formation of McHugh Complex, and (b) 120-66 Ma, during collision of the Wrangellian composite terrane with North America, and accretion of Valdez Group (modified after *Plafker et al.* [1994]).

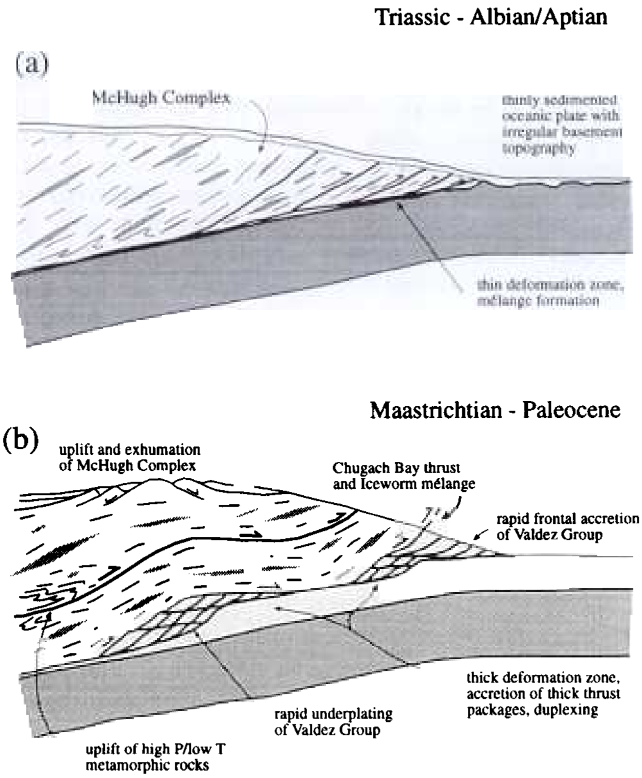


Figure 17. Schematic diagram showing possible different accretion styles for (a) a thinly and a (b) thickly sedimented oceanic plate, corresponding to formation of the McHugh Complex and Valdez Group.

extension in the upper part of the rear of the wedge. This regains the equilibrium critical taper and causes uplift of metamorphic rocks in the rear of the accretionary wedge. These models are directly applicable to the Chugach accretionary wedge in that the McHugh complex is interpreted as material off scraped intermittently during Triassic - Early Cretaceous subduction, with the establishment of a critically tapered wedge (Figure 17a). Attempted subduction of the thick sedimentary veneer of the Valdez Group during Maastrichtian - Paleocene time dramatically upset the critical taper by both rapid frontal accretion and increased underplating (Figure 17b). The wedge's response to this episode of rapid accretion was to deform internally to regain the critical taper. Rapid frontal accretion would cause the wedge to thicken to maintain the critical taper, and in the case of the Chugach terrane much of this thickening was accommodated on the Chugach Bay thrust, emplacing the older part of the wedge (McHugh Complex) over the younger part (Valdez Group). Formation of the Iceworm mélange may have been aided by fluids released from dewatering of the recently accreted Valdez Group escaping upward along the lower boundary of the relatively impermeable McHugh Complex. The Chugach Bay thrust may also have formed where it did because the protoliths of the Iceworm mélange represent a muddy facies of the Valdez Group with considerably more pore fluids that in other parts of the Valdez Group. Elevated pore fluid pressure within part of the accretionary wedge decreases the effective strength of the rock, providing a horizon for enhanced localized deformation. Increased underplating of the wedge during accretion of the Valdez Group caused enhanced uplift of the rear of the accretionary wedge, probably with associated extensional faulting, [e.g., *Platt,* 1986], providing a mechanism for the uplift and exposure of the metamorphosed McHugh Complex, and its emplacement over the Valdez Group on the Chugach Bay thrust (Figure 17b).

Differences in accretion style analogous to the McHugh/Valdez dichotomy are suggested to be characteristic of subduction of thinly versus thickly sedimented oceanic plates, and we cite here a few additional examples to emphasize the generality of this model. Late Cretaceous uplift and erosion of the Mongolia-Okhotsk intracontinental collision zone in Asia shed a large amount of sediments to the south and east [*Klimetz,* 1983; *Nanayama,* 1992], which triggered rapid frontal accretion and growth of accretionary complexes along the northwest Pacific rim [*Kimura,* 1994]. *Kimura* [1994] also documented that rapid underplating by attempted subduction of thick sedimentary caps on the downgoing plates caused uplift of metamorphic rocks of the Kamuikotan complex of Hokkaido and the Susunai complex of Sakhalin. *Taira et al.* [1988] have documented rapid growth of the Nankai accretionary wedge in response to the Izu collision. Tertiary uplift and erosion of the Himalayan mountain range from the India-Asia collision caused rapid growth of the Makran and Sunda accretionary prisms from sediments supplied rapidly to the trench by the Indus and Ghanges Rivers [*Graham et al.,* 1975; *Burbank et al.,* 1996; *Sengor and Natal'in,* 1996]. Similarities are also seen between the model presented here and the ongoing collision of the Yakutat terrane with the southern Alaska margin [R. von Huene, personal communication, 1997]. This collision has caused uplift and erosion of the Chugach and St. Elias Mountains, deposition of a thick sequence of Miocene and younger clastic sediments in the Aleutian trench, and rapid accretion at the toe of the Aleutian accretionary prism [*Plafker et al.,* 1994].

Climate, as well as collisions, may play a significant role in episodic growth and structural style of accretionary prisms [e.g., *Hay,* 1996; *von Huene and Scholl,* 1991]. *Bangs and Cande* [1997] have shown how a thickly sedimented segment of the Chile trench south of the Chile triple junction in the area strongly influenced by glacial climate corresponds to rapid growth and accretion in the accretionary prism. The subducting Chile ridge acts as a topographic barrier to sediments shed into the trench by glacial erosion in the south, and growth of the prism north of the triple junction is less rapid than that to the south of the triple junction. Periods of rapid accretion were also noted during intervals when glaciation extended farther north and erosion accelerated trench sedimentation north of the triple junction. Subduction of the Chile ridge causes significant erosion of the accretionary complex, making the pre-ridge subduction record south of the northward migrating triple junction difficult to interpret.

We suggest that, in general, subduction of slabs with a thin veneer of sedimentary cover may lead to subduction erosion [e.g., *von Huene and Scholl,* 1991] or to the formation of mélanges in accretionary wedges, whereas subduction of thickly sedimented slabs may generally result in large-scale accretion of relatively coherent packages separated by zones of shearing and type I mélange formation. Using a constant slip-rate model, suduction of an oceanic slab with a thin sedimentary veneer will result in significantly higher shear strains in the boundary layer between the upper and lower plates than would subduction of an oceanic slab with a thick sedimentary cover. For example, if we assume 1 km of thrusting per million years and we accommodate this strain in a 100 m thick sedimentary section, then shear strains of 10 will be typical for the sedimentary cover and will likely involve significant mixing between layers. If the subducting oceanic plate has a 1 km thick sedimentary cover, then shear strains will be about 1, and we may expect strains that are lower than in the mélange and perhaps more typical of a foreland fold-thrust belt.

This model may also explain a fundamental temporal change in the style of subduction zone tectonism. Many workers have noted the near absence of subduction mélanges from Archean terranes, even those interpreted as ancient accretionary wedges [e.g., *Kusky*, 1989, 1990, 1991]. Models for Archean plate tectonics predict that the planet may have had a greater plate boundary length, with more, smaller, faster moving plates than at present [e.g., *Pollack*, 1997]. One consequence of such a model is that subducting plates would have tended to be thickly sedimented, with their proximity to active collisions along numerous plate boundaries. Subduction of these thickly sedimented plates would tend to produce Archean accretionary wedges dominated by relatively coherent terranes and few mélanges, consistent with the geological record preserved in Archean granite greenstone terranes [e.g., *de Wit and Ashwal*, 1997].

Acknowledgments. This work was supported by NSF EAR 9304647 and NSF EAR 9706699 awarded to T. Kusky and by the U.S. Geological Survey. Field visits and stimulating discussion with A.B. Till, J. Dumoulin, S. Bloomer, R. Goldfarb, and D. Donley are gratefully acknowledged. Bill Clendenin provided $^{40}Ar/^{39}Ar$ data for a key dike. J. Sink of CalAlaska provided excellent helicopter services. This paper was improved by reviews and comments by Terry Pavlis, Darrel Cowan, Warren Nokleberg, George Plafker, Tim Byrne, Roland von Huene, and Tectonics Editor David Scholl.

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(Received April 29, 1997;
revised September 19, 1997;
accepted September 29, 1997.)