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Chapter 15

Metamorphic history of Alaska

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INTRODUCTION

This chapter presents a summary of the major, regionally developed, metamorphic episodes that affected Alaska throughout the evolution and accretion of its many lithotectonic terranes. Plate 4 (map and table showing metamorphic rocks of Alaska, 2 sheets, 1:2,500,000 scale) accompanies this chapter. The metamorphic scheme (Zwart and others, 1967) used for the map (Fig. 1, Table 1) is based on the occurrence of pressure- and temperature-sensitive metamorphic minerals. Regionally metamorphosed rocks are divided into four facies groups, each of which reflects a different grade of metamorphism. In order of increasing temperatures of crystallization, they are: (1) lamontite and prehnite-pumpellyite facies (LPP), shown on Plates 4A and 4B in shades of gray and tan; (2) greenschist facies (GNS), shown in shades of green; (3) epidote-amphibolite and amphibolite facies (AMP), shown in shades of orange and yellow; and (4) two-pyroxene (granulite) facies (2PX), which occurs only on the Seward Peninsula, shown in reddish brown. Where possible, the greenschist-facies and the epidote-amphibolite- and amphibolite-facies groups are further divided on the basis of pressure of crystallization into three facies series: high-, intermediate-, or low-pressure series. These facies series are indicated by an H, I, or L in place of the final letter in the symbol used for the facies group. High-pressure greenschist-(blueschist) facies rocks, and rocks metamorphosed under blueschist-facies conditions that evolved to intermediate- or low-pressure greenschist-facies conditions during a single episode, are shown in shades of blue. The metamorphic facies symbol for each episode is followed by a symbol showing the age of metamorphism or its minimum and maximum age limits. Subscripts are used to differentiate units that have the same metamorphic grade and age but that have different protoliths and are believed to have different metamorphic histories.

Plate 4B gives summary information for each map unit, including the number by which the unit is referred to in this chapter; the facies and age designation of the unit and its color and pattern on the map; the lithotectonic terrane(s) in which the unit occurs; the lithology and age range of the protoliths; the metamorphic rock types and minerals; and the known, minimum, and/or maximum age of metamorphism and the evidence for the three types of ages. Most, but not all, of the units shown on Plates 4A and B are discussed in this chapter. The reader is referred to four more detailed, regional metamorphic reports and accompanying 1:1,000,000-scale metamorphic facies maps on Alaska (Fig. 2) for sources of information and a more complete discussion and listing of references for all the units shown on Plates 4A and B.

Where sufficient data are available, the possible tectonic origin of a given metamorphic episode is discussed. Unless otherwise defined, all lithotectonic terranes are those of Jones and others (1987) west of the 141st meridian and of Monger and Berg (1987) east of it. All radiometric ages cited have been calculated or recalculated using the decay constants of Steiger and Jäger (1977). The Decade of North American Geology time scale (Palmer, 1983) is adopted in relating radiometric ages to geologic time. Abbreviations used in this chapter are explained in Table 2.

DESCRIPTION AND ORIGIN OF METAMORPHIC EPISODES

Brooks Range

Late Proterozoic amphibolite-facies metamorphism. A sequence of polymetamorphosed amphibolite-facies rocks recrystallized to greenschist- and blueschist-facies assemblages (unit 1) crops out in the Baird Mountains of the southwestern Brooks Range. The sequence includes pelitic schist, minor amounts of interlayered quartzite, marble, and metabasite, and crosscutting intermediate to mafic metaplutonic rocks. It makes up the Hub Mountain terrane of Mayfield and others (1982). Mineral assemblages formed duing M_1 include gt, hb, and pl in metabasite, and bt and gt in pelitic schist (A. B. Till, written communication, 1987). A Late Proterozoic age for M_1 is indicated by K-Ar ages on mu and hb between 729 ± 22 and 594 ± 18 Ma (Turner and others, 1979; Mayfield and others, 1982), and by an Rb-Sr mineral-whole rock isochron age of 686 ± 116 Ma (Armstrong and others, 1986). This metamorphic episode is the oldest recorded anywhere in the Brooks Range and is the only documented evidence of Proterozoic metamorphism in the region.

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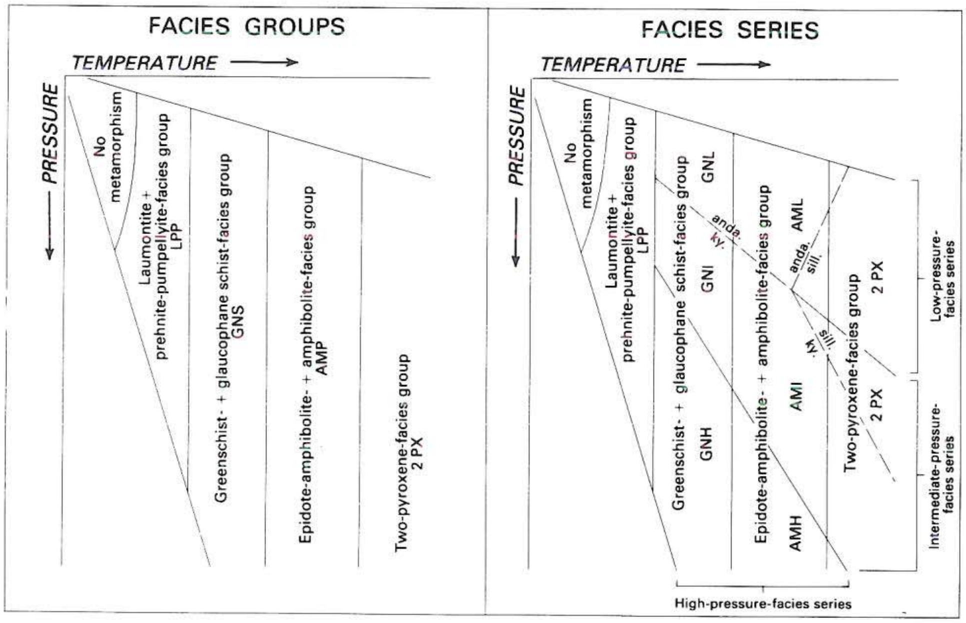

Figure 1. Schematic representation of metamorphic-facies groups and series in P-T space and their letter symbols used on Plates 4A and B (modified from Zwart and others, 1967). Stability fields of Al_2SiO_5 polymorphs andalusite (anda.), kyanite (ky.), and sillimanite (sill.) shown by dashed lines.

Most M_1 assemblages have been partially or, locally, totally recrystallized to greenschist- and blueschist-facies assemblages during subsequent Mesozoic metamorphism (M_2). Common M_2 minerals are ch, ep, wm, ab, sp, bar amph, ac, and bl amph (A. B. Till, written communication, 1987). Recent unpublished mapping indicates that blueschist-facies assemblages are most prevalent in rocks that lie structurally above and below thrust slices of the amphibolite-facies rocks (A. B. Till, written communication, 1987). M_2 is attributed to a high-P evolving to low-P, low-T metamorphic episode that affected the entire southern Brooks Range (unit 3 and M_2 of unit 2) between Middle Jurassic and mid-Cretaceous time (discussed in a later section).

Possible Proterozoic to middle Paleozoic epidote-amphibolite-facies metamorphism. Areas of epidote-amphibolite–facies rocks partly recrystallized to lower grade assemblages crop out in the central Brooks Range (unit 2). By analogy with unit 1, they may also record pre-Mesozoic metamorphism. These areas consist of polymetamorphosed pelitic, feldspathic, and graphitic schist, quartzite, marble, orthogneiss, and metabasite. Protoliths are older than the Middle Devonian granitoids and, between longitudes 151 and 153°, are older than the Proterozoic(?) or pre-middle Paleozoic granitoids (Dillon and others, 1980) that intrude them. It is unclear, however, whether the granitoids, shown with the pattern that denotes a metamorphosed pluton, were metamorphosed prior to the widespread Mesozoic episode that affected the entire southern Brooks Range.

In general, the metamorphic rocks of this unit are distinguished from contiguous rocks of unit 3 by having a coarser crystallinity, relict epidote-amphibolite–facies mineral assemblages, and a more complex structural fabric (Hitzman and others, 1982; Dillon and others, 1987). The structural fabric includes a penetrative fabric that predates that developed in unit 3, as well as one or more younger penetrative fabrics also present in unit 3.

Middle Paleozoic prehnite-pumpellyite- to greenschist-facies metamorphism. Low- to medium-grade metasedimentary, metavolcanic, and metacarbonate rocks of Proterozoic to Middle(?) and Late Devonian protolith age crop out in the Romanzof and Davidson Mountains in the eastern Brooks Range. In the Romanzof Mountains, metamorphic grade increases southward from prehnite-pumpellyite facies (unit 11) to greenschist facies (unit 12). The metamorphic contact between these units was probably gradational, although it has been subsequently modified by thrust faulting (Dusel-Bacon and others, 1989). Metamorphism predates the Mississippian age of unmetamorphosed rocks that unconformably overlie these units and postdates the Middle(?) Devonian protolith age of the youngest metasedimentary rocks (Sable, 1977; Dusel-Bacon and others, 1989).

The indicated range in metamorphic age is similar to the Devonian intrusive age (380 ± 10-Ma U-Pb upper intercept age of zircon; Dillon and Bakke, 1987) of a peraluminous batholith that intrudes units 11 and 12, suggesting that metamorphism and plutonism may have been products of the same tectonic regime. Parts of the batholith are gneissic and mylonitically or cataclastically deformed (Sable, 1977), but the age of this deformation is uncertain. Structural data collected from greenschist-facies rocks in the western end of unit 12 suggest that the pre-Mississippian rocks in that area were transported southeastward during Middle Devonian (Ellesmerian?) thrusting (Oldow and others, 1987). Additional studies are needed to determine the nature and extent

TABLE 1. SCHEME FOR DETERMINING METAMORPHIC FACIES*

Facies symbol	Diagnostic minerals and assemblages	Forbidden minerals and assemblages	Common minerals and assemblages	Remarks
		LAUMONTITE AND PREHNITE-PUMPELLYITE FACIES		
LPP	Laumontite + quartz, prehnite + pumpellyite.	Pyrophyllite, analcime + quartz, heulandite.	"Chlorite," saponite, dolomite + quartz, ankerite + quartz, kaolinite, montmorillonite, albite, K-feldspar, "white mica."	Epidote, actinolite, and "sphene" possible in prehnite-pumpellyite facies.
		GREENSCHIST FACIES		
GNS		Staurolite, andalusite, cordierite, plagioclase (An>10), laumontite + quartz, prehnite + pumpellyite.	Epidote, chlorite, chloritoid, albite, muscovite, calcite, dolomite, actinolite, talc.	
		Low- and intermediate-pressure greenschist facies		
GNL and GNI		Hornblende, glaucophane, crossite, lawsonite, jadeite + quartz, aragonite.		Biotite and manganiferous garnet possible; stilpnomelane mainly restricted to intermediate-pressure greenschist facies.
		High-pressure greenschist (blueschist) facies		
GNH	Glaucophane, crossite, aragonite, jadeite + quartz.		Almandine, paragonite, stilpnomelane.	Subcalcic hornblende (barroisite) may occur in highest temperature part of this facies.
		Low-temperature subfacies of high-pressure greenshist facies		
GNH (with stipple, Plate 4)	Above minerals plus pumpellyite and/or lawsonite.			
		EPIDOTE-AMPHIBOLITE AND AMPHIBOLITE FACIES		
AMP	Staurolite.	Orthopyroxene + clinopyroxene, actinolite + calcic plagioclase + quartz, glaucophane.	Hornblende, plagioclase, garnet, biotite, muscovite, diopside, K-feldspar, rutile, calcite, dolomite, scapolite.	
		Low-pressure amphibolite facies		
AML	Andalusite + staurolite, cordierite + orthoamphibole.	Kyanite.	Cordierite, sillimanite, cummingtonite.	Pyralspite garnet rare in lowest possible pressure part of this facies.
		Intermediate- and high-pressure amphibolite facies		
AMI and AMH	Kyanite + staurolite.	Andalusite.		Sillimanite mainly restricted to intermediate-pressure amphibolite facies.
		TWO-PYROXENE FACIES		
2PX	Orthopyroxene + clinopyroxene.	Staurolite, orthoamphibole, muscovite, epidote, zoisite.	Hypersthene, clinopyroxene, garnet, cordierite, anorthite, K-feldspar, sillimanite,biotite, scapolite, calcite,dolomite, rutile.	Hornblende possible. Kyanite may occur in higher pressure part of this facies and periclase and wollastonite in low-pressure part.

*Modified from Zwart and others (1967).

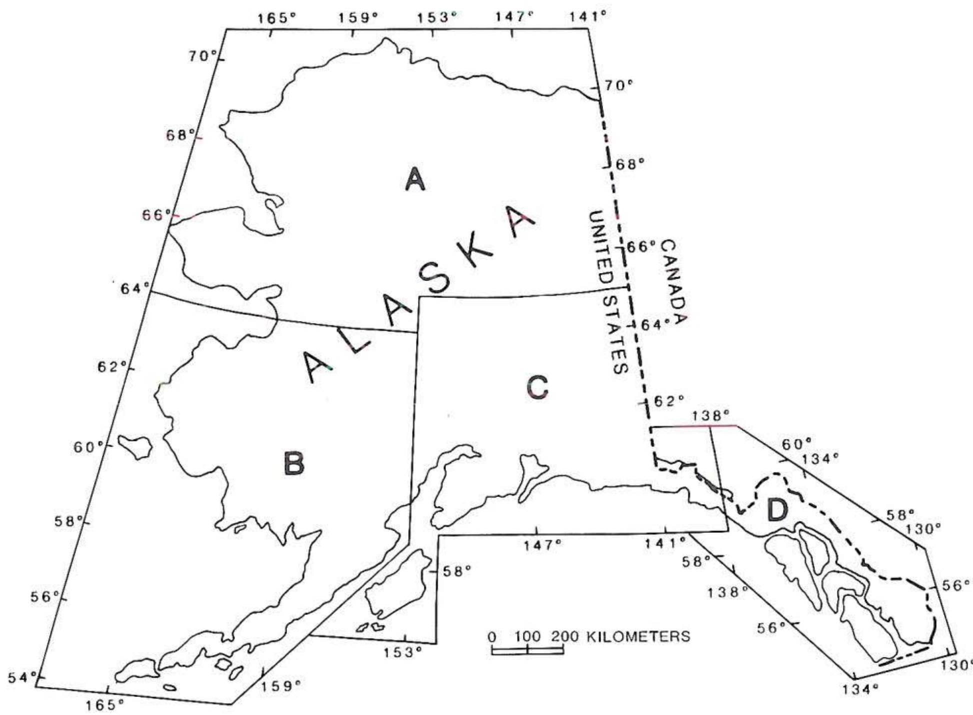

Figure 2. Map showing areas of study in the series of metamorphic facies reports of Alaska. A, Dusel-Bacon and others (1989); B, Dusel-Bacon and others (1991c); C, Dusel-Bacon and others (1991b); D, Dusel-Bacon and others (1991a).

of the proposed southeastward-thrusting event and its temporal relation to the metamorphism.

Isotopic and structural data (Sable, 1977; Dillon, 1987; Oldow and others, 1987) suggest that the rocks of units 11 and 12 and perhaps some parts of the adjacent unmetamorphosed rock unit in the Romanzof Mountains area were subsequently involved in Mesozoic and perhaps early Cenozoic deformation and metamorphism that was part of the widespread Jurassic and Early Cretaceous orogeny that affected the schist belt of the southern Brooks Range (unit 3 and related units).

In the Davidson Mountains, metamorphism of greenschist-facies rocks of unit 13 predated, but was associated with, intrusion of Late Devonian granitoids (Dusel-Bacon and others, 1989). This relation is suggested by an increase in the metamorphic grade from the ch- to the bt-gt-zone with decreasing distance from the crosscutting Late Devonian plutons, and by the closeness in age between the maximum metamorphic age provided by the youngest protolith age (Late Devonian) and the intrusive age of the undeformed crosscutting granitoids.

Jurassic to mid-Cretaceous high evolving to low-P, low-T metamorphism. *Schist belt.* A sequence of polydeformed blueschist- and greenschist-facies rocks (unit 3) crops out across almost the entire width of the southern Brooks Range. This metamorphic sequence, informally called the schist belt, consists of Devonian and older calcareous, pelitic, and graphitic metasedimentary rocks with volumetrically minor metacarbonate rocks, metarhyolite, metabasite, and granitoid orthogneiss (Dillon and others, 1980; Hitzman and others, 1982), and a subordinate amount of upper Paleozoic and locally Triassic metapelite and metacarbonate rocks along its northern margin. The rocks were metamorphosed during a single, prolonged, polyfacial episode and followed a clockwise P-T path that evolved from blueschist- to greenschist-facies conditions. This path reflects tectonic loading followed by decompression. Two phases of penetrative deformation are recognized. Both are characterized by isoclinal folding, and their relation to each other suggests refolding of early formed isoclines during decompression (Gottschalk, 1987). In the Wiseman area, which is probably typical of much of the southern schist belt, lineations and fold axes plunge to the south, and rocks have undergone north-vergent ductile shear deformation concurrent with metamorphism (Gottschalk, 1987).

Most of the rocks in which the high-P minerals gl, lw, and jdpx have been identified occur in a zone within the southern part of this unit (Plate 4A). The restricted occurrence of these minerals may be due to compositional controls (most rocks whose composition favors the development of these minerals are restricted to this zone) or, in part, to structural controls, as proposed by Hitzman (1980). He observed that blueschist assemblages occurred within large nappe-like folds. Glaucophane is by far the most commonly developed high-P mineral and occurs in metabasite, iron-rich metasedimentary rocks, and metatuff (Dusel-Bacon and others, 1989). The assemblage ky+ctd also occurs locally in iron-

TABLE 2. ABBREVIATIONS USED IN TEXT

CAI	conodont alteration index of Epstein and others (1977)	amph	amphibole	kf	potassium feldspar		
		anda	andalusite	ky	kyanite		
M_1	first metamorphic episode of polymetamorphic unit	bar amph	barroisitic amphibole	lw	lawsonite		
		bt	biotite	mu	muscovite		
M_2	second metamorphic episode of polymetamorphic unit	ch	chlorite	pa	paragonite		
		co	cordierite	pl	plagioclase		
S_1	fabric formed during first metamorphic episode	cpx	clinopyroxene	pr	prehnite		
		cr	crossite	pu	pumpellyite		
S_2	fabric formed during second metamorphic episode	ctd	chloritoid	qz	quartz		
		ep	epidote group mineral	sil	sillimanite		
P	pressure	gl	glaucophane	sp	spinel		
T	temperature	gt	garnet	sph	sphene		
		hb	hornblende	st	staurolite		
ab	albite	jd	jadeite	tr	tremolite		
ac	actinolite	jdpx	jadeitic pyroxene	wm	white mica		

rich metasedimentary rocks, but it is not known whether the ky formed during the Jurassic to Cretaceous blueschist-to-greenschist episode or during the possible pre-Devonian episode discussed in the previous section.

The metamorphic grade and overall degree of deformation within unit 3 decreases to the north. The northern limit of this unit is defined, in part, on the basis of a CAI isotherm that delineates the first occurrence of CAI values of less than 5 (corresponding to a temperature of less than 300°C) for Ordovician through Triassic rocks (A. G. Harris, written communication, 1984). It is possible that the northern part of this unit never experienced the high-P episode recorded in the southern part, but available metamorphic and structural data collected by W. P. Brosgé and C. F. Mayfield during reconnaissance mapping of the region did not indicate a discrete change in the metamorphic history across the east-west strike of this unit. Future studies will undoubtedly define a more precise northern limit to the area that experienced early high-P metamorphism.

The high-P phase of the P-T path began in the low-T gl-lw stability field and evolved into the higher T ep-gt-gl stability field. Evidence for this increase in T with time consists of inclusions composed of pseudomorphs of pa and ep after lw within gt from metabasite at several localities across unit 3 (A. B. Till, oral communication, 1987). Jadeite+quartz has been identified in the Ambler River Quadrangle (Gilbert and others, 1977; Turner and others, 1979), and jdpx occurs in eclogite about 200 km to the east near Wiseman (Gottschalk, 1987). Jadeite+quartz probably formed locally during the low-T phase of the high-P metamorphism. Such formation is compatible with mineral assemblage data from the area near the eclogite, which suggest that the earliest phase of metamorphism occurred at $P > 8$ kb and $T \approx 450°C$ and subsequently continued under blueschist- evolving to greenschist-facies conditions at $P < 8$ kb and $T \approx 480°C$ (Gottschalk, 1987).

If much of at least the southern half of unit 3 was originally metamorphosed under blueschist-facies conditions (as suggested by the distribution of gl), then the degree of recrystallization under greenschist-facies conditions is variable, ranging from very little to almost total. Core-to-rim zoning in amphiboles from gl to ac to bar amph (Gottschalk, 1987; A. B. Till, oral communication, 1987) best records the decrease in P and increase in T experienced during this episode. The latest phase of the greenschist-facies part of the metamorphic episode produced a semipenetrative cleavage defined by the presence of aligned flakes of mu and ch and by dislocations in the earlier formed foliation; this was followed by growth of largely postkinematic helicitic ab porphyroblasts and randomly oriented bt, partial to total replacement of early formed gt by ch, and local formation of new idioblastic and unaltered gt porphyroblasts (Gilbert and others, 1977).

Low-grade rocks of the Doonerak window. Prehnite-pumpellyite–facies rocks (unit 4) and greenschist-facies rocks (unit 5), exposed in a structural window in the Mount Doonerak area of the Endicott Mountains, were also metamorphosed, but to a much lesser degree, during the widespread metamorphic episode that affected the schist belt between Middle Jurassic and mid-Cretaceous time (Dusel-Bacon and others, 1989). Both of these units consist of metasedimentary and metavolcanic rocks of Cambrian through Silurian age, and metabasite sills of Ordovician and Devonian age; unit 5 also contains an unconformably overlying sequence of Mississippian through Triassic metacarbonate and metasedimentary rocks along its northern and northeastern border (Dillon and others, 1986).

The angular unconformity between the Mississippian rocks and the underlying Devonian and older rocks in the window has been affected locally by normal faulting in the central part (Dillon and others, 1986) and thrust faulting in the eastern part (Julian and others, 1984). Structural analysis indicates that the schistosity and deformational structures in the Ordovician through Devonian rocks correspond with those in the overlying Mississippian through Triassic rocks (Julian and others, 1984). Thus, rocks both above and below the unconformity were metamorphosed during the same metamorphic episode.

The rocks of the Doonerak window are considered to be an exposure of the basement of the northern Brooks Range, and both areas are included in the North Slope terrane. Units 4 and 5 appear to have the same structures as those in the structurally overlying blueschist- and greenschist-facies rocks of unit 3 outside the window (H. G. Avé Lallemant, oral communication, 1987), suggesting that metamorphism of the basement rocks of the window probably also occurred during Middle Jurassic to mid-Cretaceous time as a result of northward overthrusting. Rocks in the eastern part of the window appear to be part of a duplex structure that formed after the earliest and most pervasive metamorphic foliation and during formation of a second generation of structures, dominated by asymmetric kink folds with northwest-dipping axial planes (Julian and others, 1984). The anomalously low (prehnite-pumpellyite facies) metamorphic grade of the structurally lowest rocks (unit 4), together with the lack of high-P minerals in units 4 and 5, are in accordance with the structural observations of Julian and her coworkers and suggest that the rocks of the window were metamorphosed under low-T and moderate- to low-P conditions late in the metamorphic episode. They were then overthrust, probably from the south, by the more deeply buried blueschist-facies rocks.

Age and tectonic origin of metamorphism. Metamorphism of unit 3 and related units of the southern Brooks Range clearly postdates the Triassic age of the youngest protoliths and probably took place in Jurassic to mid-Cretaceous time as a result of north-vergent tectonic loading. The spatial association between unit 3 and obducted oceanic rocks of the Angayucham terrane (unit 8) along the southern margin of the Brooks Range and Jurassic ultramafic and mafic rocks (Ju) in the northwestern and eastern ends of the range has been used as evidence to suggest that the rocks of the southern Brooks Range were tectonically loaded by north-directed overthrusting of oceanic rocks of Mississippian to Jurassic age along a south-dipping subduction zone (Patton and others, 1977; Roeder and Mull, 1978; Turner and others, 1979). Prior to, and probably closely preceding, its emplacement onto the continental rocks of the schist belt, the oceanic sequence was internally imbricated, and ultramafic rocks were emplaced on top of mafic rocks, becoming the structurally highest part of the sequence (Patton and others, 1977). A Middle to Late Jurassic time for this tectonic mixing is provided by K-Ar ages on hb of about 172 to 154 Ma from gt amphibolite, presumably formed during thrusting, which occurs at the base of the ultramafic sheets (Patton and others, 1977; Boak and others, 1985). Stratigraphic evidence in the western Brooks Range suggests that overthrusting of the oceanic sequence onto the continental rocks in that area began in the Middle Jurassic (Tailleur and Brosgé, 1970; Mayfield and others, 1983).

Dynamothermal metamorphism clearly had ceased by mid-Cretaceous time because Albian and Cenomanian conglomeratic rocks in the Yukon-Koyukuk basin record the uplift and progressive erosional stripping of the oceanic rocks and the underlying metamorphosed continental rocks of unit 3 (Patton, 1973; Dillon and Smiley, 1984). This timing is consistent with Early to mid-Cretaceous (120 to 90 Ma) K-Ar cooling ages on mica from unit 3 (Turner and others, 1979; Turner, 1984; Dillon and Smiley, 1984).

Obduction of the oceanic rocks apparently occurred in response to counterclockwise rotation and oroclinal bending of the lower plate continental rocks of the Arctic Alaska Plate (including the schist belt and Doonerak window) driven by rifting in the Arctic region between Early Jurassic and Early Cretaceous time (Tailleur, 1969; Mayfield and others, 1983; Grantz and May, 1983). Collision of a Jurassic and Cretaceous intraoceanic arc terrane with the southward-facing continental margin adjacent to the Yukon-Koyukuk basin has been proposed as an additional cause of the northward obduction (Box, 1985a).

Structural and metamorphic relations between the high-P schist belt and the structurally overlying, lower T and P, greenschist-facies continental rocks (unit 9) and prehnite-pumpellyite–facies oceanic rocks (unit 8) to the south suggests that post- or late-metamorphic down-to-the-south low-angle extensional faulting has dismembered the upper plate, removing much of the section that originally buried the blueschists. This late extensional phase of the orogeny has been postulated by several workers on the basis of map patterns (Carlson, 1985; Miller, 1987), field observations near Wiseman (Gottschalk and Oldow, 1988), and field and kinematic data from unit 10 in the Cosmos Hills east of Ambler (Box, 1987). Additional evidence in support of late- or post-metamorphic extensional movement between upper and lower plate rocks is found in the Cosmos Hills, where the allochthonous oceanic rocks of unit 8 cut across the metamorphic mineral zones in unit 3 (Hitzman, 1984). Continuation of extensional tectonism into Late Cretaceous, and perhaps early Tertiary, time is recorded in the deformational and metamorphic history of unit 10.

Jurassic to mid-Cretaceous low-grade metamorphism of oceanic thrust sheets. Weakly metamorphosed sedimentary and volcanic oceanic rocks crop out in a narrow V-shaped belt around the margins of the Yukon-Koyukuk basin along the southern margin of the Brooks Range and the northwestern margin of the Ruby geanticline, outboard of metamorphosed continental rocks to the north and southeast, respectively. These rocks make up the Angayucham terrane and consist of an inner and structurally lowest thrust sheet of ocean-continent transition-zone (Patton and others, this volume; W. W. Patton, Jr., and J. M. Murphy, oral communication, 1988) greenschist-facies metagraywacke and phyllite, with minor amounts of metalimestone and metachert, of Devonian to Triassic protolith age (unit 9); and an outer (basinward) overlying sheet of oceanic prehnite-pumpellyite–facies metabasite, metachert, metatuff, metalimestone, and argillite of Mississippian to Jurassic protolith age (unit 8). The structurally highest thrust sheet is of peridotite and gabbro (Ju).

These thrust sheets have been interpreted as components of an allochthonous oceanic complex, rooted in the Yukon-Koyukuk basin, that was thrust onto the Proterozoic and early Paleozoic continental margin during Middle Jurassic to mid-Cretaceous time, causing blueschist- and greenschist-facies metamorphism in the underlying rocks in the southern Brooks Range and possibly along the western margin of the Ruby geanticline (unit 28, discussed below in the section entitled Central Alaska)

(Patton and others, 1977, this volume, Chapter 7; Turner and others, 1979; Patton and Box, 1985). Some or all of the prehnite-pumpellyite–facies metamorphism of unit 8 may have accompanied thrust emplacement (Hitzman, 1983; Dusel-Bacon and others, 1989), as suggested by the following observations. (1) In the Cosmos Hills, prehnite-pumpellyite–facies metamorphism is most intense adjacent to the thrust surface between unit 8 and underlying unit 3 (Hitzman, 1983). (2) In the Ruby geanticline, gl occurs locally in metabasalt of unit 8 near the base of its tectonic contact with underlying unit 28 (Patton and Moll, 1982). The occurrence of gl indicates that some of these rocks were metamorphosed under high-P, low-T conditions and may have been tectonically intermixed with other rocks of this unit, either during the internal imbrication (emplacement of peridotite and gabbro on top of the basaltic thrust sheets) that preceded the obduction of the oceanic complex, or during the obduction itself (Patton and Moll, 1982).

The metamorphic history of unit 9 is less certain. In the Wiseman area of the southern Brooks Range, Dillon and others (1987) consider that the rocks of this unit have a single semipenetrative cleavage, in sharp contrast with the more complexly metamorphosed and deformed rocks of unit 3 to the north. However, mapping in this same sequence of rocks by Gottschalk (1987) in the Wiseman area, and Hitzman and others (1982) in the Cosmos Hills area, suggests that the rocks of this unit shared a common metamorphic history with unit 3.

Seward Peninsula

Jurassic to Early Cretaceous blueschist-evolving to greenschist-facies metamorphism. High-P blueschist-facies rocks that were partly recrystallized under intermediate-P greenschist-facies conditions crop out over a large area, 125 by 150 km (shown as unit 16), across the central Seward Peninsula. These rocks, referred to as the Nome Group, consist of pelitic schist, quartzite, marble, metabasite, mafic schist, and orthogneiss and are thought to have originated in a continental platform environment (Sainsbury and others, 1970; Till, 1983; Forbes and others, 1984). Protoliths of metasedimentary and metavolcanic rocks are Proterozoic and early Paleozoic (largely Ordovician) in age, and crosscutting orthogneiss has a Devonian intrusive age (Till and others, 1986; Armstrong and others, 1986; Till and Dumoulin, this volume).

Metamorphic minerals in the metabasite are gl, ep, gt, ab, sp, ac, ch, wm; pseudomorphs of ep, pa, and locally ab occur after lw (Forbes and others, 1984; Thurston, 1985). Glaucophane is also present in pelitic and mafic schist, and impure marble. Glaucophane-bearing eclogitic rocks have been found just east of the Nome River (Thurston, 1985). Local stabilization of eclogitic rocks is attributed to either outcrop-scale metamorphic conditions marginally different (perhaps lower P_{H_2O}) from those in the surrounding rocks (Thurston, 1985), or to small but complex variations in bulk composition (Evans and others, 1987).

Petrographic, structural, and phase-equilibrium data indicate that crystallization of the blueschist- and greenschist-facies assemblages occurred during a single episode of high-P evolving to intermediate-P, low-T metamorphism, similar to that recorded in the schist belt of the southern Brooks Range. Metamorphic conditions during the high-P phase of this monocyclic polyfacial episode started in the gl-lw-jdpx stability field and, with increasing T, evolved into the ep-gt-gl stability field (Thurston, 1985). The P-T path passed through approximately 9 to 11 kb at 400 to 450°C during the highest P phase of the prograde episode and passed into the ab-ep-bar amph field during initial stages of decompression and thermal relaxation (Forbes and others, 1984). Static retrograde alteration under greenschist-facies conditions occurred during subsequent rapid uplift. The final stages of this metamorphic episode are inferred to have taken place under intermediate-P conditions, because subsequent Cretaceous amphibolite-facies metamorphism (of unit 18), discussed below, that overprints the blueschist-facies fabric began in the ky stability field.

Metamorphism was synkinematic with penetrative ductile deformation, mesoscopic intrafolial isoclinal folding, and development of flat-lying to gently dipping transposition foliation (Thurston, 1985). Stretching lineations and isoclinal fold axes have a north-south trend (Till and others, 1986). The ubiquitous parallelism between stretching lineations and fold axes suggests a highly noncoaxial deformation, during which fold axes rotated toward the stretching direction, as noted by Patrick (1986). Quartz petrofabrics indicate northward vergence during deformation (Patrick, 1986).

Cretaceous amphibolite- and granulite-facies metamorphism. Amphibolite-facies pelitic, calcareous, and quartzofeldspathic schist, marble, quartzite, and amphibolite (unit 18) crop out within the Kigluaik, Bendeleben, and Darby Mountains of the southern Seward Peninsula. Protoliths probably include upgraded lithologic equivalents of the Nome Group—the same protoliths as those of unit 16 (Till and others, 1986). Intermediate-P conditions are indicated by the assemblage ky-st-sil in pelitic schist; T conditions range from those of the bt zone to the sil+kf zone.

On the south flank of the Kigluaik Mountains, isograds that define a northward-increasing prograde metamorphic sequence are closely spaced (Till, 1980; Thurston, 1985), indicating a fairly steep geothermal gradient within the ky stability field. Thurston (1985) proposed that, in this area, the intermediate-P amphibolite-facies minerals were statically superimposed on pelitic rocks whose foliation developed during the widespread Jurassic blueschist-facies metamorphic episode (of unit 16) and that the ky-bearing assemblages were produced during intermediate-P thermal metamorphism associated with Cretaceous plutonism. Work by Patrick and Lieberman (1987) also indicates structural and metamorphic continuity across the contact between units 16 and 18 and supports the hypothesis that the amphibolite-facies assemblages (as well as granulite-facies assemblages, discussed below) were superimposed on (and mostly obliterated) the earlier formed blueschist-facies assemblages.

In the Bendeleben and Darby Mountains, amphibolite-facies metamorphism was more dynamothermal in character and produced ky-bearing assemblages that define a penetrative fabric. These assemblages are overprinted by static, low-P, high-T assemblages that apparently formed as a result of thermal metamorphism associated with Late Cretaceous (80 Ma) plutonism (Till and others, 1986).

In one area of the Kigluiak Mountains, high-T rocks, whose metamorphism is inferred to have been associated with the thermal episode that culminated in the intrusion of 80-Ma plutons (A. B. Till, oral communication, 1987), form an area large enough to show as a separate unit (unit 19). This unit consists of upper amphibolite-facies bt gneiss; granulite-facies marble, pelitic, quartzofeldspathic, and mafic gneiss, and migmatite; and gt lherzolite partially recrystallized to sp lherzolite (Till, 1980, 1983). Protoliths are assumed to include upgraded lithologic equivalents of the Nome Group (Till and others, 1986). Relict ky inclusions within gt formed during granulite-facies metamorphism indicate that granulite-facies metamorphism postdated the intermediate-P amphibolite-facies metamorphism (A. B. Till, oral communication, 1987).

Age and tectonic origin of blueschist-, greenschist-, amphibolite-, and granulite-facies metamorphism. Blueschist-facies metamorphism was apparently caused by rapid tectonic loading of a continental plate (Forbes and others, 1984). Rb-Sr whole-rock-mica isochron ages and K-Ar mineral ages suggest that the high-P metamorphic cycle took place during the Middle or Late Jurassic, before about 160 Ma, followed by decompression and partial reequilibration between about 160 and 100 Ma (Armstrong and others, 1986). Similarities in protoliths, metamorphic grade, structural style, and apparent metamorphic age suggest a correlation between the high-P, low-T metamorphic and tectonic history of unit 16 and the schist belt of the southern Brooks Range (Armstrong and others, 1986; Patrick, 1986; Dusel-Bacon and others, 1989). By analogy with the proposed history of the schist belt, multiple thrust sheets of oceanic rocks (Angayucham terrane) may have once covered the Seward Peninsula (Till, 1983; Forbes and others, 1984). The nearest possible remnant of that oceanic terrane is a sliver of north-south–trending blueschist-facies rocks (unit 17, discussed below) that crops out on the eastern Seward Peninsula; other possible remnants have been proposed by Box (1985a).

A major difference in the subsequent metamorphic histories of the two areas, however, is the subsequent occurrence of moderate- to high-T metamorphism and plutonism on the Seward Peninsula and the absence of these thermal episodes in the schist belt. The rapid change from blueschist metamorphism to intermediate-P amphibolite-facies metamorphism and plutonism is similar to that described in the southern Aegean by Lister and others (1984). Intermediate-P metamorphism in the Aegean was synkinematic with extensional deformation. It was probably driven by gravitational spreading, following the compressional (blueschist) phase of tectonism. An alternative comparison is made by Patrick and Lieberman (1987) who compare the sequence of metamorphic and plutonic episodes on the Seward Peninsula to that observed in the Central Alps. They attribute the thermal overprinting to relaxation of isotherms following subduction, leading to the onset of crustal anatexis. Because no evidence of extensional faulting has been identified on the Seward Peninsula, the tectonic history of the Central Alps appears to be a better analog than does that of the southern Aegean.

The environment of crystallization of the gt lherzolite of unit 19 is unknown. Textural relations indicate that gt was stable in the lherzolite prior to granulite-facies metamorphism, during which time the sp-bearing assemblages apparently formed (Till, 1980; Lieberman and Till, 1987). The gt-bearing assemblage may be a relict of an upper mantle environment or may have been metamorphosed in a deep crustal setting. In the latter case, formation of the gt either occurred during a pre-Mesozoic event, or during the early phases of the Jurassic and Cretaceous metamorphic episode of the schist belt and Seward Peninsula, simultaneous with formation (at shallower levels) of the extensive blueschist-facies terranes (Lieberman and Till, 1987).

Probable Jurassic to Early Cretaceous blueschist-facies metamorphism. Blueschist-facies mylonitic metabasite and minor amounts of serpentinite crop out in a narrow fault-bounded belt (unit 17) along the east side of the Darby Mountains (Till and others, 1986). Protoliths are considered to range in age from middle Paleozoic to Jurassic on the basis of a tentative correlation with the low-grade oceanic rocks of the Angayucham terrane (unit 8) that are present around the margins of the Yukon-Koyukuk basin. Mylonitic metabasite in the northern part of the belt contains the assemblage cr-lw-pu, which is indicative of the low-T subdivision of the blueschist facies; mylonitic metabasite in the southern part of the belt contains the assemblage cr-ep-ac, indicative of the high-T (epidote-bearing) subdivision of the blueschist facies (subdivisions of Taylor and Coleman, 1968; and Evans and Brown, 1987). Relict igneous pyroxene grains are common in mylonitic metabasite in both areas (Till, 1983). The presence of cr and lw in this unit indicates that pressures probably occurred within the lower part of the range of P conditions in the nearby and more extensive unit 16. Somewhat different crystallization and deformational histories for the two units are indicated, however, by the incomplete recrystallization and brittle deformation of this unit compared with the complete recrystallization and ductile deformation of unit 16 (Till and others, 1986).

A middle Jurassic to mid-Cretaceous metamorphic age is assigned to unit 17 on the basis of correlation of its metamorphic history with that of the Angayuchum terrane. Arguing against this correlation is the widespread development of high-P minerals in unit 17 and the general absence of high-P minerals in the Angayucham terrane.

Central Alaska

Pre-middle Paleozoic greenschist- and amphibolite-facies metamorphism. Metamorphic units 22 and 23 crop out southeast of the Susulatna fault and were metamorphosed sometime during Proterozoic to middle Paleozoic time. The more extensive unit (22) consists of greenschist-facies Late Proterozoic felsic metavolcanic rocks (Dillon and others, 1985) and pre-Ordovician schist, quartzite, phyllite, argillite, marble, and mafic metavolcanic rocks (Silberman and others, 1979; Patton and others, 1980 and this volume, Chapter 7). Metamorphic grade is mostly of the ch and bt zones, but locally reaches the gt zone. Pre-Ordovician metamorphic, as well as protolith, ages are indicated for this unit because it is overlain by virtually unmetamorphosed Ordovician through Devonian strata that yield conodont-alteration indices that correspond with very low temperatures—generally less than 200°C (A. G. Harris, written communication, 1984). A minimum metamorphic age of 514 Ma is provided by the oldest of three K-Ar ages on mica from qz-mu-ch schist within this unit (Silberman and others, 1979). K-Ar and U-Pb data suggest that these rocks were not affected by the Late Jurassic and/or Early Cretaceous metamorphic episode that occurred northwest of the Susulatna fault in the Ruby geanticline (Dillon and others, 1985).

The other pre-middle Paleozoic metamorphic unit (23) is limited in area. It consists of polymetamorphosed and locally mylonitic pre-Ordovician schist, sheared grit, quartzite, phyllite, mafic and felsic metavolcanic rocks, and schistose metaplutonic rocks (Dusel-Bacon and others, 1989). Metaigneous rocks give Middle Proterozoic protolith ages (Silberman and others, 1979; Dillon and others, 1985). Polymetamorphism is suggested by replacement textures in pelitic rocks. The M_1 episode (or alternatively, the maximum-T phase of a P-T loop) occurred under amphibolite-facies conditions and produced the assemblage bt + gt ± st ± co in qz-mica schist. Subsequent retrograde metamorphism (M_2, or alternatively, a late phase of M_1) resulted in the almost complete replacement of st by ctd, gt by ch, and co by wm and ch. Textural evidence suggests that retrogressive greenschist-facies metamorphism was accompanied by shearing (Dusel-Bacon and others, 1989).

A maximum metamorphic age for both postulated metamorphic episodes is indicated by the Middle Proterozoic protolith ages; a middle Paleozoic minimum metamorphic age for the episodes is tentatively provided by the U-Pb lower intercept age on zircon (390 ± 40 Ma) from the metavolcanic rocks (Dillon and others, 1985) and by the virtually unmetamorphosed overlying Ordovician through Devonian strata. A Late Proterozoic (663 Ma) K-Ar age on mu from recrystallized mylonite along the border of metaquartz diorite (Silberman and others, 1979) may date the time of uplift and cooling, following retrogressive metamorphism of the country rocks and metamorphism and shearing of the plutonic body.

Pre-Early Cretaceous greenschist- and amphibolite-facies metamorphism. Pre-Early Cretaceous metamorphism affected four monometamorphic units (24, 25, 28, 30) and two polymetamorphic units (26, 27) in or near the Ruby geanticline. All of the units are considered to be part of the Ruby terrane and contain continental sedimentary, volcanic, and plutonic protoliths of Proterozoic and/or Paleozoic age. Intermediate- to high-P metamorphism of unit 28, discussed in a later section, is interpreted (Dusel-Bacon and others, 1989) to have taken place during the Mesozoic obduction of oceanic thrust sheets onto the continental margin. Timing of metamorphism(s) in the other units is more uncertain, and in most areas is known only to predate the intrusion of regionally extensive plutons that have yielded Early Cretaceous (about 110 Ma) K-Ar ages (Silberman and others, 1979; Patton and others, 1987).

Little is known about the metamorphic history of monometamorphic greenschist- and epidote-amphibolite-facies unit 24 and the higher grade areas of amphibolite-facies rocks (unit 25) within it. In the northeastern exposure of unit 25, some of the amphibolite-facies minerals may have been produced by thermal metamorphism caused by the adjacent Early Cretaceous plutons. In the southwestern exposure of unit 25, however, foliation of the amphibolite-facies rocks trends northwestward, subperpendicular to regional trends of thrust fault traces and plutons; metamorphism in this area clearly predates, and is unrelated to, the intrusion of Cretaceous or early Tertiary plutons, most of which are too small to be shown on Plate 4A (G. M. Smith, written communication, 1986).

The third monometamorphic unit (30) consists of lower amphibolite-facies rocks that crop out in a small area north of the Iditarod–Nixon Fork fault. These rocks include amphibolite, orthogneiss, pelitic schist, and quartzite (Miller and Bundtzen, 1985) and were informally designated as the Idono sequence by Gemuts and others (1983). U-Pb data on zircon from orthogneiss indicate an Early Proterozoic age for their granitoid protolith (M. L. Miller and T. W. Stern, unpublished data, 1987). K-Ar dates on hb from amphibolites include both Middle Proterozoic (1.22 and 1.08 Ga) and Early Cretaceous (126 Ma) ages; K-Ar dates on bt from amphibolite are about 324 Ma and 133 Ma (Miller and Bundtzen, 1985; M. L. Miller, written communication, 1986).

Polydeformed and polymetamorphosed metasedimentary and metaigneous rocks (unit 26) crop out in the Ray Mountains (Dover and Miyaoka, 1985a, b). This unit consists of quartzofeldspathic paragneiss, augen gneiss (shown as a metamorphosed pluton), schist, gneiss, marble, quartzite, phyllonite, metabasite, and amphibolite. Only the protolith age of the augen gneiss (Devonian; Patton and others, 1987) is known. Dover and Miyaoka (1985a, b) proposed that the unit experienced at least three deformational episodes and two major metamorphic episodes.

M_1 occurred primarily under amphibolite-facies conditions. It was synkinematic with ductile deformation, and produced blastomylonitic fabrics that are axial planar to isoclinal folds. Isoclines produced during the M_1 episode are overprinted by a second generation of folds that have an axial planar cleavage (S_2) at a low to moderate angle to the older schistosity. S_2 folds are tight and increase in abundance toward cataclastic zones in which a cataclastic foliation is the dominant fabric; this fabric appears to coincide with the S_2 cleavage. S_2 structures are invariably associated with greenschist-facies minerals attributed to a retrogressive metamorphic episode (M_2). Within intensely cataclasized phyllonite zones, M_2 minerals replace gt, bt, and st that were produced during M_1 metamorphism; M_2 minerals also grew synkinematically along shear surfaces. Glaucophane occurs with ctd in an M_2 mineral assemblage at one locality within a phyllonite zone (Dover and Miyaoka, 1985b; Plate 4A).

A similar sequence of polydeformed, polymetamorphosed, and moderately to strongly mylonitized schist, gneiss, quartzite, marble, and amphibolite, and singly metamorphosed granitoid gneiss, including augen gneiss (unit 27), crops out in the Kokrines Hills (Patton and others, 1978). The protolith age of the granitoid gneiss is unknown, but on the basis of lithologic similarity with dated augen gneiss in the Ray Mountains (unit 26) and in the southern Brooks Range (unit 2), a Devonian age is likely. I propose a tentative polymetamorphic history for this unit on the basis of the following field observations and interpretations made by J. T. Dillon (written communication, 1983): (1) metamorphic foliation (S_1) in quartzite and associated schist and gneiss is truncated by the granitoid gneiss whose foliation (S_2) is approximately perpendicular to the intrusive contact and locally to S_1; (2) S_1 foliation formed during an earlier metamorphic episode (M_1), and S_2 foliation and cleavage formed during a later metamorphic episode (M_2); and (3) M_1 produced bt, gt, sil, and locally ky and kf in pelitic rocks, and M_2 produced gt, mu, and bt in granitoid gneiss. Broad structural relations suggest that this unit may form an east-northeast–trending gneiss dome (Patton and others, 1978), but the age and origin of doming or remobilization are unknown.

Age and tectonic origin of pre-Early Cretaceous metamorphic episodes. Proterozoic and/or Paleozoic metamorphism may have occurred in several of the areas. The Idono sequence (unit 30) yields both Middle Proterozoic and Early Cretaceous mineral ages, which may indicate a correlation between its metamorphic history and that proposed for polymetamorphic unit 31 in southwestern Alaska. As discussed in a later section, metamorphism of unit 31 apparently took place during both Early Proterozoic and Jurassic to Cretaceous time. Amphibolite-facies metamorphism (M_1 of unit 27) in the Kokrines Hills may have predated the probable Devonian intrusive age of granitic gneiss, whose presumed metamorphic fabric is reported to crosscut the S_1 fabric of the rest of the unit. Similar orthogneiss, forming the structurally lowest thrust sheets in the Ray Mountains, may also have experienced a pre- or syn-Devonian metamorphic episode (M_1 of unit 26).

Obduction of mafic-ultramafic oceanic rocks onto the Proterozoic and middle Paleozoic continental margin (area of the southern Brooks Range and Ruby geanticline) during Middle Jurassic to mid-Cretaceous time is the most likely cause of the greenschist- and epidote-amphibolite–facies metamorphism of unit 24, and the greenschist-facies M_2 metamorphism of unit 26. The occurrence of gl in an M_2 retrogressive greenschist-facies assemblage, and the increased development of cataclastic fabrics and retrogressive metamorphism in shear zones in the Ray Mountains (unit 26), supports the overthrust origin proposed above. This tectonic model is the same one that is more clearly indicated for unit 28 (discussed below).

Mesozoic low-grade, locally high-P metamorphism. Greenschist-facies continental rocks (unit 28) and prehnite-pumpellyite–facies oceanic rocks (unit 29) were metamorphosed during an Early Cretaceous or older Mesozoic episode that occurred locally under high-P (blueschist-facies) conditions. These units are exposed within and east of both the Kokrines Hills and the Kaiyuh Mountains. The units in both areas are correlative and have been offset by approximately 160 km of right-lateral movement along the Kaltag fault (Patton and others, 1984). The greenschist-facies rocks (unit 28) make up a basement assemblage that consists of schist, quartzite, phyllite, slate, and mafic metavolcanic rocks of Proterozoic(?) and Paleozoic age and recrystallized limestone, dolomite, and chert of early to middle Paleozoic age. This unit is defined by the local presence of gl in pelitic schist (+ wm + qz ± gt ± ch ± ctd) and metabasite (+ ch + ab + ep ± ac). It, like the similar undifferentiated greenschist- and epidote-amphibolite–facies unit (24) that is devoid of gl, is included in the Ruby terrane.

The prehnite-pumpellyite–facies oceanic rocks (unit 29) occur as large thrust sheets (Patton and others, 1977 and this volume, Chapter 21) composed of metabasite, metachert, metasedimentary rocks, metalimestone, and metatuff. Protoliths range in age from Late Devonian to Late Triassic. The northwesternmost thrust sheets are included in the Tozitna terrane, and the southeasternmost thrust sheets in the Innoko terrane. The degree of low-T metamorphism varies considerably within the unit and appears to be a function of the structural position within the thrust sheet (W. W. Patton, Jr., and S. E. Box, oral communication, 1985; Patton and others, this volume, Chapter 21). Glaucophane occurs locally in metabasite near the structural base of the Tozitna terrane (Patton and Moll, 1982) where localized higher P conditions may have existed.

The intermediate- to locally high-P metamorphism of units 28 and 29 resulted presumably from tectonic loading accompanying the obduction of thrust sheets of oceanic rocks onto the Proterozoic and early Paleozoic continental margin. The primary evidence for this model is the occurrence of gl at the base of the oceanic thrust sheets (the northwestern exposures of unit 29, assigned to the Tozitna terrane, and unit 8, assigned to the Angayucham terrane and discussed previously), as well as in the underlying continental greenschist-facies rocks of unit 29. Patton and others (this volume, Chapter 21) present stratigraphic evidence that the obducted oceanic thrust sheets assigned by Jones and others (1987) to the Tozitna and the Angayucham terranes are parts of a single terrane.

The direction from which these oceanic terranes were thrust, and therefore correlation of their metamorphic histories, is a matter of some debate. According to one hypothesis (discussed earlier), the thrust sheets of a (composite) Angayucham-Tozitna terrane were rooted in the Yukon-Koyukuk basin and thrust southeastward over the continentally derived rocks of the Ruby geanticline (Patton and others, 1977 and this volume, Chapter 21; Patton and Moll, 1982; Turner, 1984). According to an alternative hypothesis, based on structural analysis of S-C fabrics (non-coaxial schistosity and shear surfaces) and the sense of rotation of large-scale nappe-like folds (Miyaoka and Dover, 1985; Smith and Puchner, 1985; G. M. Smith, written communication, 1986), the Tozitna terrane was thrust in the opposite direction—from the southeast toward the northwest. Dover and Miyaoka (1985b) attribute the development of cataclastic fabrics and accompanying retrogressive metamorphism within a part of the lower plate rocks (M_2 of unit 26) to the northwestward obduction of the Tozitna terrane that lies to the south.

Middle Jurassic and mid-Cretaceous maximum and minimum metamorphic age constraints for metamorphism caused by southeastward thrusting out of the Yukon-Koyukuk basin are discussed in the Brooks Range section. Metamorphism, if caused by northwestward obduction of the Tozitna terrane, would have to postdate the Triassic age of the youngest protoliths of that terrane. Metamorphism of units 28 and 29, prior to late Early Cretaceous time, is also indicated by K-Ar ages of 134 and 136 Ma on metamorphic mu from gl-bearing schist (unit 28) in the Kaiyuh Mountains (Patton and others, 1984), and by the 111-Ma age of a granitoid pluton that intrudes both the Ruby and Angayucham terranes in the Kokrines Hills (Patton and others, 1977, 1978).

Southwestern Alaska

Early Proterozoic and amphibolite-facies metamorphism. The oldest dated metamorphic episode in Alaska is recorded in a narrow, northeast-trending, fault-bounded belt of continentally derived amphibolite-facies rocks east of Kuskokwim Bay. These rocks, shown as unit 31, form the antiformal (informal) Kanektok metamorphic complex of the Kilbuck terrane and are composed of bt + hb + gt ± cpx gneiss, gt-mica schist, orthogneiss, gt amphibolite, and rare marble (Hoare and Coonrad, 1979; Turner and others, 1983; Decker and others, this volume). Kyanite, indicative of intermediate- to high-P conditions, occurs in gt-mica schist at one locality. Protoliths are Early Proterozoic sedimentary, mafic volcanic, and granitic rocks (Turner and others, 1983). Metamorphic mineral grains generally define a strong lineation and a foliation that is parallel to compositional layering. All of these structural features strike consistently to the northeast, roughly parallel to the trend of the complex (Hoare and Coonrad, 1979; D. L. Turner, written communication, 1982). On the basis of aeromagnetic, gravity, and field data, the structural setting of this metamorphic complex (Kilbuck terrane) has been interpreted as a rootless subhorizontal klippe (Hoare and Coonrad, 1979) or, alternatively, as a block extending to an unknown depth between two southeast-dipping thrust faults (Box, 1985c).

A 1.77-Ga (Early Proterozoic) metamorphic age for amphibolite-facies metamorphism is indicated by a U-Pb age on sph from orthogneiss, by the oldest of five Proterozoic K-Ar hb ages from amphibolite, and possibly also by a whole-rock Rb-Sr "isochron" (Turner and others, 1983). A minimum age for this metamorphic episode is provided by a 1.2-Ga age from $^{40}Ar/^{39}Ar$ incremental heating studies on hb from gt amphibolite (Turner and others, 1983).

On the basis of isotopic data, subsequent greenschist-facies retrogressive metamorphism (M_2) is proposed to have affected the amphibolite-facies rocks during Late Jurassic to Early Cretaceous time. Nearly all of the 58 dated rocks collected throughout the metamorphic complex show a total or partial resetting of K-Ar hb and bt ages and fall in the range of 150 to 120 Ma (D. L. Turner, written communication, 1982; Turner and others, 1983). Because only a limited and cursory petrographic study of the amphibolite-facies rocks has been made, it is not known to what degree, and under what T and P conditions, recrystallization accompanied the Mesozoic thermal episode that is documented by the isotopic dating. A latest Early Cretaceous minimum age for M_2 is indicated because: (1) overlying unmetamorphosed Albian conglomerates contain Kanektok components, and (2) unmetamorphosed Valanginian sediments to the south contain metamorphic gt and ep thought to be derived from the metamorphic complex (Murphy, 1987).

Unit 31 is similar in its lithology, internal structure, structural relation to adjacent mafic complexes, and Mesozoic K-Ar ages to the metamorphic belt that occurs along the southeastern borderland of the Yukon-Koyukuk basin to the north (Ruby terrane) discussed in the previous section (Box, 1985a; Patton and others, this volume, Chapter 7). The part of this belt closest to unit 31 is the informally designated Idono sequence (unit 30) 250 km to the northeast (Miller and Bundtzen, 1985)—a sequence that also gives Proterozoic and Early Cretaceous metamorphic-mineral ages. Several linear northeast-trending faults separate the two metamorphic units. One of these, the Iditarod–Nixon Fork fault, shows evidence of about 110 km of post-Cretaceous right-lateral offset (Grantz, 1966). If the other faults show similar senses of displacement, units 30 and 31 may prove to be right-lateral offset equivalents, making both part of the Ruby terrane (Dusel-Bacon and others, 1994c).

Low-grade, locally high-P Mesozoic metamorphism of oceanic rocks. The predominant period of metamorphism in southwestern Alaska occurred under low-grade conditions during Mesozoic time. Most of the rocks that were metamorphosed are of oceanic affinity; the continentally derived Early Proterozoic metamorphic rocks of unit 31 apparently were retrograded during the Mesozoic. Blueschist-facies rocks occur in two areas (units 33, 34) of the low-grade rocks, suggesting a subduction-related origin for most of the low-grade metamorphism.

One of the areas of blueschist-facies rocks (unit 33) is part of a nappe complex of predominantly schistose metavolcanic and metasedimentary rocks; other rocks in the nappe complex were metamorphosed under pumpellyite-actinolite–facies (facies terminology of Turner, 1981) to greenschist-facies conditions (unit 32). Protoliths are thought to be of Permian and Late Triassic age (Box, 1985b). Recrystallization is generally incomplete and primary textures and minerals are partly preserved. Diagnostic high-P minerals gl (+ ep + ac ± pu) and lw are sparse and poorly developed in unit 33 (Box, 1985b).

Metamorphism of units 32 and 33 is bracketed between the Late Triassic age of the youngest protolith and the Middle Jurassic age of postmetamorphic mafic and ultramafic plutons (Hoare and Coonrad, 1978). A 231 ± 7-Ma K-Ar age on amph (Box, 1985b) from schist of blueschist-facies unit 33 suggests that metamorphism of the nappe complex may have begun during Late Triassic time.

The other area of greenschist- and locally blueschist-facies rocks, shown as unit 34, consists of mafic schist interlayered with metachert, metalimestone, phyllite, and minor amounts of quartzose and calcareous schist (Hoare and Coonrad, 1959). Protolith ages are unknown, but limestone is probably Ordovician, Devonian, or Permian in age, and chert may be as young as latest Jurassic (Tithonian; Box, 1985b). Rocks of this unit have been affected by postmetamorphic, northwest-vergent imbrication (Box, 1985c). Greenschist-facies mafic schist is characterized by ch, ep, and ac, and blueschist-facies mafic schist by gl, ch, ac, and ep.

Actinolite from mafic schist of the northernmost exposure of unit 34 gives a K-Ar age of 146 ± 15 Ma (Box and Murphy, 1987), suggesting a Late Jurassic or Early Cretaceous minimum metamorphic age. The Triassic maximum age of metamorphism of units 32 and 33 is tentatively considered to apply also to unit 34.

The most extensive low-grade metamorphic unit (35) forms a diverse assemblage of prehnite-pumpellyite–facies metabasalt, metagabbro, metavolcaniclastic and metasedimentary rocks, metachert, and metalimestone. Protolith ages range from early or middle Paleozoic to Cretaceous (Silberling and others, this volume; Jones and others, 1987; Dusel-Bacon and others, 1994c). Primary igneous or depositional fabrics are generally well preserved, but locally the rocks are slaty, schistose, or highly sheared and disrupted. The lack of structural fabric, the disrupted character, and the very low grade of this unit make it difficult both to determine which rocks have been metamorphosed and to assess the relation between the timing of metamorphism and the intrusion of crosscutting igneous bodies. A pre-Early Cretaceous age of metamorphism is inferred for all areas of unit 35 because unmetamorphosed Valanginian andesitic volcanic rocks unconformably overlie the northernmost exposure of this unit (Patton and Moll, 1985), and unmetamorphosed Valanginian sedimentary rocks in the southern exposure of the unit contain pr-pu-bearing metavolcanic clasts (Murphy, 1987).

Mesozoic metamorphism is attributed to progressive underthrusting of a composite subduction complex (Goodnews terrane) beneath the northwestern margin of an oceanic arc (Togiak terrane), followed by underthrusting of the Early Proterozoic continental metamorphic complex (Kilbuck terrane) beneath the northwestern margin of Goodnews terrane (Fig. 3) (Box, 1985b, c).

According to this tectonic model, metamorphism of blueschist- and greenschist-facies units 33 and 32, respectively, occurred during the first episode of underthrusting. These two units make up the Cape Peirce subterrane of the Goodnews terrane of Box (1985b, c). Box believes this subterrane structurally underlies the prehnite-pumpellyite–facies rocks of the Togiak terrane and overlies the prehnite-pumpellyite–facies rocks of the Platinum subterrane of the Goodnews terrane (terranes and subterranes are those of Box, 1985c; also see Decker and others, this volume) along low-angle southeast-dipping faults (Fig. 3). Both areas of prehnite-pumpellyite–facies rocks are included in unit 35. Metamorphism of the Cape Peirce subterrane is presumed to have occurred during collision and partial subduction of an oceanic plateau (Platinum subterrane of the Goodnews terrane) beneath an overriding intraoceanic subduction-related volcanic arc (Togiak terrane). Lithologic similarities between the protoliths of the schistose blueschist- and greenschist-facies rocks of the Cape Peirce subterrane and those of the relatively undeformed low-grade overlying and underlying subterranes, suggest that the rocks of the Cape Peirce subterrane are the more tectonized equivalents of the adjacent two subterranes (Box, 1985b). Mafic and ultramafic plutons that intrude the Cape Peirce subterrane, the overlying Togiak terrane, and the underlying Platinum subterrane, provide a Middle Jurassic minimum age for amalgamation of the three subterranes.

Structural data suggest that the overriding arc of the Togiak terrane was originally thrust to the north-northeast over the Goodnews terrane (Box, 1985b). However, the low-angle fault mapped between the upper plate Togiak terrane and the underlying Cape Peirce terrane juxtaposes lower T and P rocks over higher T and P rocks, suggesting that the fault is low-angle normal fault rather than a thrust fault (Box, 1985b). As suggested by Box, a good explanation for the present relation between the plates is that early north-northeastward compressional faulting was followed by extensional (detachment) faulting. This same fault relation (lower grade rocks above higher grade rocks) occurs in the southern Brooks Range and Ruby geanticline (Plate 4A); faulting in all these areas may have the same origin (extensional reactivation of earlier compressional structures).

The greenschist- and blueschist-facies rocks of unit 34 were probably metamorphosed during the second episode of underthrusting. These rocks crop out along the northwestern margin of the Nukluk subterrane of the Goodnews terrane of Box (1985c). Late Jurassic to Early Cretaceous metamorphism of unit 34, and retrograde metamorphism of unit 31, probably took place as the continental Kilbuck terrane (unit 31) was partially thrust beneath the accretionary fore arc (Goodnews terrane) of an intraoceanic volcanic arc (Togiak terrane) (Box, 1985c). The following evidence supports this interpretation of the metamorphic history: (1) unit 34 occurs along the tectonic boundary between the Kilbuck and Goodnews terranes, and (2) the K-Ar age on ac from unit 34 falls in the same range as the Mesozoic K-Ar ages from the Kilbuck terrane.

Yukon-Tanana Upland and Alaska Range north of the McKinley and Denali faults

Overview. The age and origin of metamorphism of many of the units in the Yukon-Tanana upland and northern Alaska Range are poorly known. Metamorphism throughout the Yukon-Tanana upland predates the widespread intrusion of undeformed mid-Cretaceous granitoids. Mylonitic and blastomylonitic textures are common in most rocks, reflecting a history of dynamic metamorphism, followed by varying degrees of more static re-

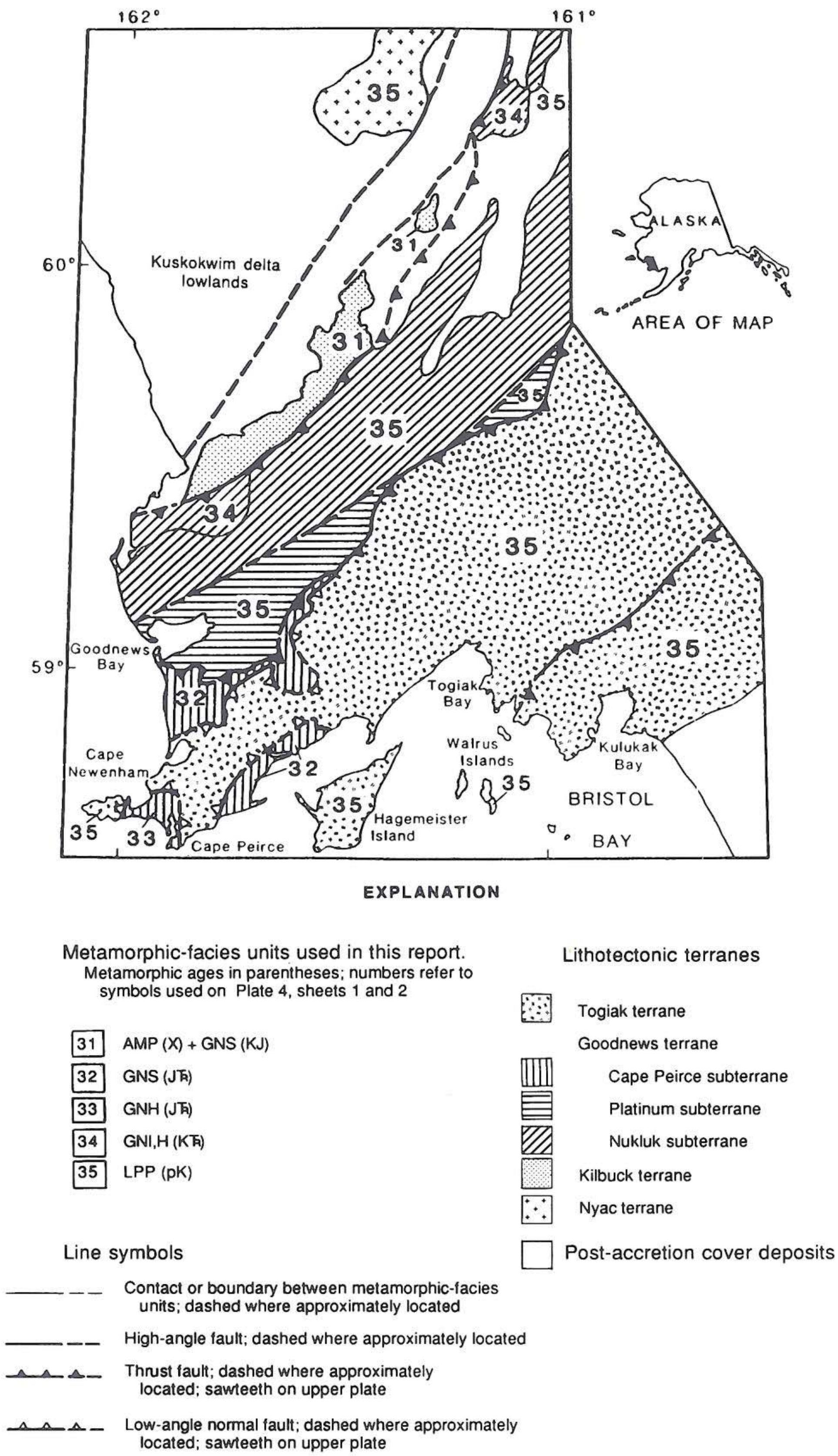

Figure 3. Generalized map showing lithotectonic terranes (modified from Box, 1985c) and metamorphic-facies units in southwestern Alaska.

crystallization. Many metamorphic unit boundaries are also terrane or subterrane boundaries defined by low-angle faults. Metamorphic grade changes abruptly across many of the faults, indicating that major metamorphism predated final emplacement of the fault-bounded units. Some of the low-angle faults place higher grade over lower grade rocks (the relation expected of compressional faulting), whereas others place lower grade over higher grade rocks (the relation expected of extensional faulting), suggesting a complex syn- or post-metamorphic structural evolution. In their regional synthesis, Foster and her co-workers (this volume) interpret the low-angle faults as being south-dipping thrusts. Thrust sheets near the Canadian border were emplaced in Early Jurassic time. Thrusting of other sheets may have occurred throughout a compressional episode that included crustal thickening and metamorphism in either or both Jurassic and/or Cretaceous time. In one area, however, kinematic data indicate that the most recent movement along the low-angle fault that separates greenschist-facies unit 45 of the hanging wall from amphibolite-facies unit 46 of the footwall was extensional, and that the hanging wall moved to the east-southeast (Pavlis and others, 1988b).

Early Paleozoic(?) high-P, high-T metamorphism. The oldest metamorphic episode inferred to have taken place in east-central Alaska produced eclogite and interlayered bands and lenses of mafic, calc-magnesian, quartzitic, pelitic schist, and impure marble. These rocks, shown as unit 36, are thought to be two klippen that form the upper plate of a folded thrust (Brown and Forbes, 1984; Foster and others, 1983). Protoliths are Proterozoic or early Paleozoic in age. Bulk chemistry suggests sedimentary protoliths for the eclogites of the western klippe (Swainback and Forbes, 1975), whereas discordant contacts exhibited by eclogitic rocks in the eastern klippen suggest that they originated as mafic dikes (Laird and others, 1984).

Eclogite within the eastern klippe consists of various combinations of gt, omphacitic cpx, barroisite, phengitic mu, qz, and rutile (Laird and others, 1984). Eclogite within the western klippe consists of combinations of these minerals plus gl, tr, ab, ep, and sph; ky + st + gt occurs in interlayered pelitic schist (Brown and Forbes, 1986). Phase equilibria (excluding that proposed for gl) and thermobarometry suggest P-T conditions of about 15 ± 2 kb and 600 ± 25°C (Laird and others, 1984; Brown and Forbes, 1986). Such temperatures exceed the experimentally determined maximum stability limit of gl (Maresch, 1977) by about 50°C. One explanation for this discrepancy is that the gl formed after the main phase of eclogite crystallization, as was proposed for an eclogitic block along the Tintina fault in Yukon Territory by Erdmer and Helmstaedt (1983). However, textural relations in the gl-bearing rocks of the western klippe show no evidence of such a progression, and the discrepancy is thus far unresolved.

A polymetamorphic history for this unit is suggested, because some eclogitic rocks in both klippen are overprinted by greenschist and epidote-amphibolite assemblages, which are characterized by hb, ab, ep, bt, and ch (Brown and Forbes, 1986; Foster and others, this volume).

An early Paleozoic metamorphic age for the first, and dominant, episode is tentatively suggested by a 470 ± 35-Ma K-Ar age on amph from eclogite in the western klippe (Swainbank and Forbes, 1975). Early isoclinal, recumbent folds about a northwest-trending axis are attributed to this episode. This high-P, high-T metamorphism only affected this group of thrust-bounded rocks and thus predated the time of their emplacement. An Early Cretaceous age for subsequent retrograde metamorphism is proposed on the basis of 115- to 103-Ma K-Ar ages on mica that were determined for associated rocks; the development of folds about a northeast-trending axis is attributed to this metamorphic episode (Swainbank and Forbes, 1975). Early Cretaceous metamorphism, discussed below, was widespread throughout east-central Alaska.

Mineral chemistry and the occurrence of gl indicate that the eclogites are similar to those from alpine-type orogenic environments (Group C of Coleman and others, 1965). The tectonic and metamorphic history of the eclogites may be similar to that of other isolated eclogite occurrences on strike along the Tintina fault in the Yukon Territory, as proposed by Erdmer and Helmstaedt (1983) and Brown and Forbes (1986). Eclogites in central Yukon Territory experienced a subduction-cycle P-T trajectory that included eclogite metamorphism, uplift through the stability field of gl, and finally greenschist-facies metamorphism (Erdmer and Helmstaedt, 1983). The present distribution and geologic position of the eclogite bodies in east-central Alaska and Yukon Territory suggest that rocks in both regions were emplaced as thrust sheets against or onto the cratonic margin of western North America (Erdmer and Helmstaedt, 1983). However, the timing of metamorphism and tectonic emplacement of these eclogite-bearing terranes are not well enough constrained to allow more than a tentative correlation. The early Paleozoic metamorphic age suggested for the Alaskan eclogitic rocks, if valid, would argue against correlation with the Canadian eclogites, which are believed to have middle Paleozoic protoliths and to have been metamorphosed during the late Paleozoic (Erdmer and Armstrong, 1988).

Late Triassic to Early Jurassic metamorphism. Metamorphism during this period was part of an orogenic episode that consisted of metamorphism, plutonism, folding, and thrusting. This episode resulted from the closing of an ocean basin, represented by the weakly metamorphosed rocks of unit 38 and associated ultramafic rocks (MzPzu). Accretion of amphibolite-facies rocks of unit 37 was related to this episode (Foster and others, 1985, this volume).

The earliest phase of this orogenic episode produced intermediate-P amphibolite- and epidote-amphibolite–facies bt gneiss and schist, amphibolite, marble, quartzite, and pelitic schist of unit 37. Rocks are well foliated and multiply deformed; at least some protoliths are of Paleozoic age (Foster and others, 1985). This unit is intruded by latest Triassic to earliest Jurassic granitoids, similar to those in the Stikinia terrane of Yukon Territory, Canada (Tempelman-Kluit, 1976). Unit 37 is in thrust contact with adjacent rocks. It is probably part of the Stikinia terrane or a comparable, but different, part of composite terrane I of Monger and others (1982) that includes the Stikinia terrane and that was accreted to the margin of North America in Jurassic time (Foster and others, this volume).

Amphibolite-facies metamorphism of unit 37 reached its peak about 213 ± 2 Ma ($^{40}Ar/^{39}Ar$ integrated plateau age on amph), followed by synmetamorphic intrusion of the Taylor Mountain batholith (shown as unit J₨g) at about 209 ± 3 Ma (Cushing and others, 1984). Northward thrusting of the amphibolite-facies rocks and low-grade oceanic rocks (unit 38) took place during cooling and was completed by about 185 Ma (Foster and others, this volume). The Early Cretaceous thermal event that strongly affected the adjacent augen gneiss-bearing amphibolite-facies unit 46 to the south (described below) was of only minor intensity in unit 37, as indicated by the Early Cretaceous apparent ages of the low-temperature gas fractions in most of the $^{40}Ar/^{39}Ar$ age spectra (Foster and others, this volume).

Basalt and related oceanic protoliths of unit 38 were metamorphosed under prehnite-pumpellyite– and lower greenschist-facies conditions during the waning stages of the regional metamorphism that accompanied the closing of the ocean basin (Foster and others, this volume). This low-grade oceanic unit makes up the Seventymile terrane and consists of massive and locally pillowed greenstone, argillite, metatuff, qz-wm schist, qz-ac schist, quartzite, metalimestone, metachert, and metagraywacke. Most protolith ages are unknown, but conodonts and radiolarians of Permian age occur in weakly metamorphosed chert in the Big Delta Quadrangle, and radiolarians of Mississippian age, brachiopods of Permian age, and conodonts of Triassic age occur in the northern Eagle Quadrangle (Foster and others, this volume). These rocks are associated with ultramafic and gabbroic rocks. In at least one area, this package of rocks is part of a dismembered ophiolitic assemblage (Keith and others, 1981). Unit 38 consists of a number of isolated thrust remnants, which are themselves broken by internal thrust faults; metamorphic grade differs between individual thrust remnants. Glaucophane (+ep±gt) occurs in one such thrust remnant in a small exposure of metabasalt just south of the Tintina fault (Keith and others, 1981; Plate 4A).

An Early Jurassic age for low-grade metamorphism of unit 38 is indicated by a 201 ± 5-Ma $^{40}Ar/^{39}Ar$ integrated plateau age on ac from greenstone in southeastern Eagle Quadrangle (G. W. Cushing, unpublished data, 1984). Northwestward accretion of the amphibolite-facies unit resulted in thrusting of remnants of the telescoped ocean basin, including this unit and the associated ultramafic rocks, northward onto greenschist-facies unit 44 and southward onto amphibolite-facies unit 37 (Foster and others, this volume). This followed, or was synchronous with, the low-grade metamorphism. The outcrop of gl-bearing greenstone may be part of a fault sliver that was dragged to a greater depth in a subduction zone or a transpressive boundary along the convergent margin.

Metamorphism of greenschist-facies unit 39, included in the Yukon-Tanana terrane, was probably also part of the Late Triassic through Early Jurassic orogenic episode. This unit probably formed part of the continental margin north of the ocean basin onto which the previous two metamorphic units were accreted. Common rock types are qz-wm (±ch±ac) schist, quartzite, phyllite, and metavolcanic rocks; protoliths are probably Paleozoic in age. Foliation is well developed, and rocks are multiply folded and commonly are lineated. This unit is correlated with the Klondike Schist of McConnell (1905) that crops out across the Canadian border (Foster and others, 1985). A Late Triassic to Early Jurassic metamorphic age is suggested by a 175 ± 14-Ma K-Ar age on mu (Tempelman-Kluit and Wanless, 1975) and by a 202 ± 11-Ma Rb-Sr whole-rock age (Metcalfe and Clark, 1983) determined for Klondike Schist in Canada.

Paleozoic or Mesozoic metamorphism of uncertain age and origin. The metamorphic ages of many units in east-central Alaska (units 40 to 45 in the Yukon-Tanana upland, and units 53 and 54, and M_1 of units 47 and 48 in the Alaska Range; Plate 4B) are unknown. Metamorphic ages are bracketed between the known, or probable, Paleozoic age of the youngest protoliths and the Early to mid-Cretaceous age of widespread plutonism that postdates regional metamorphism. Scattered late Early Cretaceous K-Ar mineral and whole-rock ages on schist and a U-Pb age on monazite from orthogneiss (ages given on Plate 4B) tentatively suggest an Early Cretaceous age for latest metamorphism. Unit 47 and its higher grade equivalent, unit 48, crop out south of the Tanana River and consist of metasedimentary, metavolcanic, and metaplutonic rocks of Devonian and older protolith age (Aleinikoff and Nokleberg, 1985; T. K. Bundtzen, oral communication, 1988). M_1 records greenschist-facies conditions in unit 47 but increases in intensity northward; it grades into the amphibolite-facies M_1 of unit 48 in the west (Bundtzen, 1981). M_1 metamorphism in units 47 and 48 postdates the Devonian age of the youngest known protoliths and predates the Early Cretaceous age of the episode that is thought to have caused lower greenschist-facies retrograde metamorphism (M_2) in units 47 and 48 as well as the monometamorphism of unit 49 (discussed in a later section). In unit 48 and the western part of unit 47, Bundtzen and Turner (1979) proposed an Early Jurassic minimum age for M_1 on the basis of the oldest of four K-Ar ages (195, 144, 123, and 104 Ma) on hb from gt amphibolite in unit 48.

Unit 46, characterized by augen gneiss, gives Early Cretaceous ages from a number of isotopic systems and on this basis, its latest, and probably its only, metamorphism is believed to be Early Cretaceous in age. However, limited evidence from U-Pb zircon data from quartzite (Aleinikoff and others, 1984b, 1986) and sillimanite gneiss from unit 46 (Aleinikoff and others, 1984a), and from structural relations between augen gneiss and wall rocks in east-central Alaska and Yukon Territory, suggest that an earlier metamorphic episode may have accompanied the Mississippian intrusion of batholithic sheets of what is now augen gneiss (Dusel-Bacon and Aleinikoff, 1985). These structural relations are: (1) that some areas of augen gneiss coincide with large structural and metamorphic culminations (Mortensen, 1983); and (2) that the concordant contacts of the augen gneiss bodies, and parallelism between lithologic contacts and the gently dipping regional penetrative fabric, suggest the augen gneiss bodies were intruded synkinematically into ductile crust (Dusel-Bacon and Aleinikoff, 1985).

Early Cretaceous metamorphism of augen gneiss-bearing unit. Amphibolite-facies unit 46 is characterized by large bodies of augen gneiss that form a discontinuous belt of metamorphosed Mississippian plutons, believed to have developed beneath, or inland from, a continental magmatic arc of Late Devonian to Early Mississippian age (Dusel-Bacon and Aleinikoff, 1985). Other rock types, interpreted as having been wall rocks to the augen gneiss protolith, are amphibolite-facies qz-mica schist, bt and bt-hb gneiss, quartzite, amphibolite, sillimanite gneiss, and minor amounts of marble, calc-schist, and felsic gneiss. The Mississippian protolith age for the augen gneiss (about 340 Ma, on the basis of a U-Pb lower intercept age of zircon and a Rb-Sr whole-rock isochron; Aleinikoff and others, 1986) establishes a minimum protolith age for the adjacent wall rocks. Protoliths of some metavolcanic rocks are Devonian in age (Aleinikoff and others, 1986).

Transitional low- to intermediate-P conditions are indicated for unit 46 by the local occurrence of ky and/or anda (Plate 4A) in qz-mica ($\pm$ gt $\pm$ st $\pm$ sil) schist. All the rocks of this unit are well foliated; commonly the foliation is multiply folded into isoclinal folds on various scales. Many rocks exhibit a well-developed stretching lineation, and most show some degree of mylonitization followed by varying degrees of recrystallization.

A 600-km^2 body of sillimanite gneiss and flanking pelitic schist crops out in the western part of this unit (shown on Plate 4A by the sillimanite isograd) and has been interpreted as a gneiss dome by Dusel-Bacon and Foster (1983). Metamorphic grade increases across the pelitic schist on the flanks of the dome, where P-T conditions locally were near the Al_2SiO_5 triple point (approximately 3.8 kb and 500°C; Holdaway, 1971), to the gneissic core of the dome, where P-T conditions were near those of the second sillimanite isograd. Garnet-biotite geothermometry (calibration of Ferry and Spear, 1978) indicates an equilibration T of 535 to 600 $\pm$ 30°C for pelitic schist north of the dome and 655 to 705 $\pm$ 30°C for sillimanite gneiss in the core (Dusel-Bacon and Foster, 1983).

Petrographic evidence of a regional retrogressive metamorphic episode is minimal in most of this unit and consists of local, and minor, chloritization of bt and gt, sericitization of pl, kf, and co, and the development of ac from hb. In the southwestern part of unit 46, however, Nokleberg and others (1986a) note that amphibolite-facies rocks are consistently retrograded to greenschist-facies assemblages, and that the degree of retrogression increases to the south. This retrogressive metamorphism is shown on the map as the second greenschist-facies episode in adjacent unit 47 to the south.

Metamorphism of unit 46 postdates the Mississippian intrusive age of the augen gneiss protolith and predates the intrusion of Early and mid-Cretaceous plutons (generally with 105- to 85-Ma K-Ar cooling ages; Wilson and others, 1985). A 115-Ma U-Pb age on zircon from an unmetamorphosed (late metamorphic?) pluton that intrudes the sillimanite gneiss dome (Aleinikoff and others, 1984a) provides the most reliable minimum age of metamorphism. Abundant isotopic data from the metamorphic rocks of this unit suggest that metamorphism occurred between about 135 and 115 Ma: most conventional K-Ar mineral ages fall in the range of about 125 to 110 Ma; a Rb-Sr mineral isochron for augen gneiss is 115 Ma; sph from augen gneiss gives a concordant U-Pb age of 134 Ma; U-rich zircon fractions from sillimanite gneiss and quartzite show Early Cretaceous lead loss (Aleinikoff and others, 1986); and hb from augen gneiss gives a $^{40}Ar/^{39}Ar$ incremental-heating plateau age of 119 Ma (T. M. Harrison, written communication, 1987).

Early to Late Cretaceous metamorphism of other units. Effects of Early Cretaceous metamorphism are believed to be widespread across much of east-central Alaska. The following limited isotopic data suggest an Early Cretaceous age for metamorphism in units 41 and 42 in the northwestern Yukon-Tanana upland: three K-Ar mica ages and one whole-rock age from greenschist-facies unit 41 range from 138 to 100 Ma (Forbes and Weber, 1982), and monazite from orthogneiss of amphibolite-facies unit 42 gives a concordant U-Pb age of 115 Ma (J. N. Aleinikoff, written communication, 1987). As mentioned earlier, retrograde effects on the eclogite-bearing klippen (unit 36) that overlie unit 41 are attributed to this same episode.

Farther south, in the Alaska Range, retrograde metamorphism in polymetamorphic units 47 and 48 is also interpreted as having taken place in the Early Cretaceous. In that area, M_2 metamorphism occurred under ch-grade conditions; its effects are most evident where the metamorphic grade during M_1 was highest, namely in retrograded amphibolite-facies unit 48 and in the northern part of polymetamorphic greenschist-facies unit 47. M_2 assemblages in unit 48 and the adjacent area of unit 47 define a weak metamorphic foliation that is axial planar to broad northeast-trending folds (Bundtzen, 1981). Characteristics of M_2 metamorphism and accompanying deformation in the other parts of unit 47 vary widely, and thus correlation of M_2 episodes throughout the unit is tentative (Dusel-Bacon and others, 1991b). A late Early Cretaceous metamorphic age for M_2 is suggested for unit 48 and the adjacent area of unit 47 by the oldest K-Ar mica age (100 Ma) determined for those rocks (Bundtzen and Turner, 1979). A similar late Early Cretaceous age is suggested by a 107-Ma K-Ar age on mu from phyllite of unit 47 in the central Alaska Range (Sherwood, 1979). Nokleberg and others (1986a; this volume, Chapter 10) report that mid-Cretaceous plutons in the northern part of unit 47 in the Mt. Hayes Quadrangle appear to have been weakly metamorphosed under lower greenschist-facies conditions together with their polymetamorphosed wall rocks, suggesting that metamorphism in that area continued longer, perhaps into Late Cretaceous time.

Low-grade regional metamorphism of monometamorphic unit 49 was synkinematic with the development of northeast-trending folds and has been correlated with the M_2 of adjacent units 47 and 48 (Bundtzen and Turner, 1979). Mylonitic textures are common throughout this unit and indicate a large dynamic component to the regional metamorphic episode. An Early Cretaceous age for this deformational and metamorphic episode is proposed on the basis of a whole-rock K-Ar age of 108 ± 3 Ma on metafelsite (Bundtzen and Turner, 1979).

An eastward-increasing metamorphic sequence developed in Early(?) to Late Cretaceous time within units 50 (at least in that part east of longitude 151°), 51, and 52—units that are bounded to the south by the McKinley fault. Low- to intermediate-P conditions are indicated for the amphibolite-facies part of the sequence (unit 52) and are inferred for the lower grade part of the sequence to the west. Evidence for this P range consists of the sparse occurrence of relict anda, indicating low P, and the presence of gt in both metabasic and metapelitic rocks, suggesting intermediate P. Metamorphism may have begun earlier in the highest grade, eastern, part of the sequence. Geologic relations in the Healy Quadrangle indicate that metamorphism preceded, and continued during, intrusion of an Early Cretaceous pluton (105-Ma $^{40}Ar/^{39}Ar$ hb incremental-heating plateau age) into unit 52. The pluton generally crosscuts the metamorphic fabric but, locally, igneous contacts are migmatitic, and in places the pluton is foliated (Csejtey and others, 1986). Weak metamorphic effects also have been noted in plutonic rocks of Late Cretaceous (70 Ma) age farther east within unit 52 (Nokleberg and others, 1991). Metamorphism of this sequence may have been part of the M_2 metamorphic episode that affected unit 47 to the north. A similar eastward increase in metamorphic grade occurs in M_2 assemblages within the adjacent part of unit 47 south of the Hines Creek fault (Dusel-Bacon and others, 1991b).

Problematic tectonic origin of Cretaceous metamorphism and an alternative interpretation of Early Cretaceous isotopic ages. The assumption that much of east-central Alaska was metamorphosed during Cretaceous time is based on the interpretation that isotopic ages from throughout the region record uplift and cooling (to blocking temperatures of about 500°C in hb and about 300°C in bt) that followed (by not more than 20 to 40 m.y.) an initial episode of crustal thickening and metamorphism. Northward migration and accretion of the Wrangellia terrane against the North American margin, which would have included the rocks of east-central Alaska north of the McKinley and Denali faults, might be a possible cause of Cretaceous crustal thickening, but the timing of the accretion appears to be too late to explain the widespread Early Cretaceous (110 to 135 Ma) isotopic ages. As discussed in a subsequent section, accretion of the Wrangellia terrane is believed to have postdated the early Late Cretaceous (Cenomanian: 98 to 91 Ma) age of the youngest flysch in a basin that separated the Wrangellia terrane from North America, and to have resulted in intermediate-P metamorphism and synkinematic plutonism within the flysch basin at about 70 to 56 Ma. The mid- to Late Cretaceous metamorphism of units 50 to 52 that crop out just north of the McKinley fault probably overlapped with accretion of the Wrangellia terrane.

Given the problem of identifying the cause of a compressional episode in Early Cretaceous time, an alternative possibility is that the Early Cretaceous ages may not date the time of crustal thickening and heating but instead date uplift and cooling, perhaps brought about by extension, that followed the latest Triassic to Early Jurassic compressional episode (discussed above) that affected units 37 and 39 near the United States–Canada boundary. The original western extent of this episode is unknown. It is possible that metamorphism of other units in the Yukon-Tanana upland, whose metamorphic age is either given as Early Cretaceous or is bracketed between Paleozoic and Early Cretaceous time, may have been initially heated during the latest Triassic to Early Jurassic episode.

An argument in favor of this interpretation is the fact that oceanic rocks of unit 38 and associated ultramafic rocks (MzPz u), both of which are interpreted as having been part of the ocean basin that separated North America from a composite terrane that included the Stikinia terrane (Foster and others, this volume), occur far west of units 37 and 39, suggesting a greater original extent of the accreted composite terrane than is now recognized. Moreover, extensional faulting recently has been proposed for several areas in the Yukon-Tanana upland (Pavlis and others, 1988b; Duke and others, 1988; Hansen, 1989). Structural data collected near the fault contact between the flanks of the sillimanite gneiss dome of unit 46 and the structurally overlying mylonitic greenschist-facies rocks of unit 45 indicate that the latest fault movement was extensional (east to southeast movement of the hanging wall; Pavlis and others, 1988b). Other low-angle faults that place lower grade rocks over higher grade rocks (such as the fault that separates units 41 and 42 from units 43 and 44), the relation common in extended terranes, are possible candidates for extensional faulting. A correspondence between the age of extension and the Early Cretaceous isotopic ages remains to be proven, but it appears to be a reasonable supposition because augen gneiss and associated rocks of unit 46 are wall rocks to 90-Ma calderas (Bacon and others, 1990) and therefore were virtually at the surface by that time.

Arguing against latest Triassic to Early Jurassic accretion-related metamorphism throughout much of the Yukon-Tanana terrane time is the fact that latest Triassic to Early Jurassic plutons only occur in association with unit 37 (of possible Stikinia terrane affinity) in the eastern part of the Yukon-Tanana upland, and isotopic ages from upper greenschist- and amphibolite-facies metamorphic rocks in the rest of the upland and adjacent parts of the Alaska Range are predominantly late Early Cretaceous.

Area of southern Alaska between the McKinley and Denali faults and the Border Ranges fault system

Jurassic metamorphism in the Peninsular and Wrangellia terranes. Several areas of amphibolite- and greenschist-facies metaigneous rocks and associated metasedimentary rocks crop out in the Alaska Peninsula, the Talkeetna Mountains, the Gulkana area northeast of the Talkeetna Mountains, and the eastern Chugach Mountains (Nokleberg and others, this volume, Chapter 10; Plafker and others, this volume, Chapter 12). Lithologic assemblages in all areas (units 55 to 60) are similar and include varying amounts of most of the following rock types: amphibolite and other amphibolite-facies rocks including mafic, calcareous, and pelitic schist, bt gneiss, marble, and quartzite or metachert; greenschist-facies rocks including greenschist, greenstone, metavolcaniclastic rocks, phyllite, argillite, and slate; and admixtures of the above rock types with massive to schistose intermediate to mafic plutonic rocks that are variably altered, sheared, and foliated. The association of protoliths (mafic to intermediate extrusive and intrusive rocks, siliciclastic rocks, calcareous rocks, and chert) suggests an oceanic affinity for most rocks. Unit 55 (Kakhonak Complex; see Detterman and Reed, 1980), and unnamed wall rocks to Jurassic plutons mapped in the Talkeetna Mountains (see Csejtey and others, 1978), and unit 56 (retrograded schist at the southern edge of the Talkeetna Mountains; Csejtey and others, 1978) are included in the Peninsular terrane. Unit 57 (informally designated metamorphic complex of Gulkana River; see Nokleberg and others, 1986b) crops out along the contact between the Peninsular and Wrangellia terranes. Unit 58 (informally designated Haley Creek metamorphic assemblage; see Plafker and others, 1989b), unit 59 (part of the Strelna metamorphics of Plafker and others, 1989b), and unit 60 (informally designated Dadina River metamorphic assemblage; see Winkler and others, 1981; Aleinikoff and others, 1988; Plafker and others, 1989b) are included by the cited workers in the Wrangellia terrane.

I interpret metamorphism in all the areas to have been part of the same metamorphic episode that was early tectonic or syntectonic with the intrusion of Jurassic batholiths. Assumed protolith ages in the Peninsular terrane differ from those known or assumed in the Wrangellia terrane (Plate 4B), however, and the widespread metamorphic episode probably was imposed on different protolith assemblages. Evidence for a Jurassic metamorphic age differs in the various areas and is summarized in Plate 4B; the reader is referred to the appropriate regional report (Fig. 2) for a detailed discussion of these units.

Following the model of Plafker and others (1989b), metamorphism and synkinematic plutonism probably took place within a magmatic arc(s) that developed as a result of left-oblique subduction of the Farallon Plate beneath a composite terrane composed of the Peninsular, Wrangellia, and Alexander terranes.

Possible correlatives of Jurassic metamorphism of the Peninsular and Wrangellia terranes in southern and southeastern Alaska. Unit 61 consists of a diverse sequence of greenschist- and epidote-amphibolite-facies tectonized metaplutonic, metasedimentary, and metavolcanic oceanic rocks. They have been informally called the "Knik River schist" by Carden and Decker (1977) and are described in detail by Pavlis (1983) and Pavlis and others (1988a). This unit is spatially associated with both Jurassic mafic and ultramafic plutons that form part of the Border Ranges ultramafic and mafic complex of Burns (1985; shown on Plate 4A as unit Jmu) and with Early Cretaceous trondhjemite. Pavlis and others (1988a) suggest that metamorphism of this unit accompanied intrusion of the Early Cretaceous (135 to 110 Ma) tonalitic to trondhjemitic plutons. K-Ar ages on rocks from this unit include a 177-Ma age on ac (Carden and Decker, 1977) and three younger ages on hb of 135, 121, and 107 Ma (Pavlis, 1983). These ages are compatible with either a model in which metamorphism took place during Jurassic time (in which case the younger ages were partly or totally reset during Early Cretaceous intrusion), or in which some or all the rocks were metamorphosed twice, each time in association with nearby plutonism.

The metamorphic history of unit 62 is difficult to assess because this heterogeneous assemblage of metaplutonic and metasedimentary rocks, referred to informally as the Cottonwood Creek complex of Richter and others (1975) and Richter (1976), occurs as a narrow slice within the Denali fault zone that is widely separated from the rest of the complex (probably the Alexander or Wrangellia terrane) from which it was derived.

Unit 63, informally referred to as the metamorphic complex of Tlikakila River, crops out as a northeast-trending belt within the Late Cretaceous and early Tertiary plutons of the Alaska–Aleutian Range batholith (Carlson and Wallace, 1983; Nelson and others, 1983). Metamorphism is known to postdate the Late Triassic protolith age of the youngest rocks. The spatial association between the metamorphic rocks of this unit and the adjacent Late Cretaceous and Tertiary plutons suggests that metamorphism may have been related to either one or both of the plutonic episodes. However, similarities in metamorphic rock types between this unit and unit 55 (discussed above), suggest that at least some of the rocks of the metamorphic complex of Tlikakila River may have been metamorphosed during the widespread episode of metamorphism and tectonism that slightly preceded or accompanied Middle to Late Jurassic plutonism in the Alaska-Aleutian Range and Talkeetna Mountains area.

Unit 94 crops out on Chichagof and Baranof Islands in southeastern Alaska and is also included in the Wrangellia terrane. This unit consists of amphibolite-facies mafic metavolcanic rocks and marine metasedimentary rocks whose protoliths predate the intrusion of Middle to Late Jurassic (168- to 155-Ma K-Ar ages on bt and hb) diorite plutons (Loney and others, 1967). R. A. Loney (oral communication, 1985) considers that the metamorphism of this unit is unrelated to the intrusion of the Jurassic plutons, because the direction of increase in metamorphic grade bears no relation to the distance from the plutons. However, Johnson and Karl (1985) report that rocks of this unit grade into the dioritic rocks of Jurassic, and Jurassic or Cretaceous, age and become more migmatitic close to the plutons, implying a genetic connection between plutonism and metamorphism. Because of the uncertainty in the metamorphic history of this unit, the age of metamorphism is widely bracketed between Paleozoic and Early Cretaceous time, allowing for the possibilities that metamorphism occurred long before plutonism, assuming the oldest possible protolith age for the rocks; or that metamorphism was associated with plutonism, as appears to be the case in other parts of the Wrangellia terrane basement, as described above.

Medium-grade metamorphism in the adjacent northern Alexander terrane. The greenschist-facies marble, phyllite, greenschist, mica schist, and weakly metamorphosed late Paleozoic plutons (shown with a diagonal dash overprint) of unit 64 crop out in the Wrangell and Saint Elias Mountains area (MacKevett, 1978; Hudson and others, 1977b; Campbell and Dodds, 1978; Miller, this volume). Marble is, in part, Devonian in age and may be as old as Cambrian (Gardner and others, 1988).

In the Saint Elias Mountains, the late Paleozoic plutons have been altered to greenschist-facies assemblages. Relations between the metamorphic rocks and the late Paleozoic plutons may indicate that metamorphism in that area was synkinematic with plutonism. These relations, reported by Hudson and others (1977a, b) consist of: (1) limited data that suggest that slightly higher grade metamorphic mineral assemblages are developed adjacent to the plutons; and (2) the fact that the plutons are dominantly foliate and commonly altered, and that contact relations between plutons and country rocks are locally complex, sometimes being sharp and crosscutting and sometimes gradational.

In the southeastern McCarthy Quadrangle, a pluton of Middle Pennsylvanian age (shown as a weakly metamorphosed pluton of unit 65, discussed below) intrudes both the Alexander and Wrangellia terranes, thereby indicating that the two terranes have been sutured since late Paleozoic time (MacKevett and others, 1986; Gardner and others, 1986). Because of this Middle Pennsylvanian minimum age for the juxtaposition of the two terranes, low-grade metamorphism in much of the Alexander terrane (this unit), like the slightly higher grade M_1 metamorphism in the Strelna Metamorphics of the Wrangellia terrane (unit 59) may have been associated with the intrusion of Late Jurassic plutons. Although Late Jurassic plutons have not been mapped within the Alexander terrane in Alaska, Late Jurassic to Early Cretaceous (160 to 130 Ma) plutons make up a major intrusive suite within the continuation of these terranes in Canada (Dodds and Campbell, 1988). Geologic evidence from this unit in Canada suggests that regional metamorphism and deformation may have occurred during latest Jurassic to earliest Cretaceous time (about 160 to 130 Ma) and been associated with plutonism of that age (R. B. Campbell and C. J. Dodds, written communication, 1986). Evidence on which Campbell and Dodds base this interpretation consists of: (1) metamorphism and deformation appear to postdate the deposition of Upper Triassic strata that probably rest unconformably on Paleozoic rocks but nevertheless appear to be equally deformed and metamorphosed; (2) the younger plutons within the belt of 160- to 130-Ma plutons seem clearly to postdate the metamorphism and deformation in the northeast where they produce distinct contact metamorphic aureoles; and (3) the older plutons of this group to the southwest may have been intruded during the metamorphism and deformation, because they are commonly elongate parallel to the regional structural grain, but they clearly have local crosscutting contacts and probably in part postdate those events.

The late Paleozoic to Early Cretaceous age constraints given for this unit reflect the possibility that one or both metamorphic episodes discussed above may have affected different parts of this unit.

Post–Early Jurassic to pre–mid-Cretaceous(?) low-grade metamorphism of the Wrangellia terrane. Weakly metamorphosed oceanic oceanic rocks of the Wrangellia terrane crop out south of the Talkeetna thrust and Denali fault, and north of faults that separate them from the belt of greenschist- and amphibolite-facies rocks that constitute the basement of the Peninsular and Wrangellia terranes (Nokleberg and others, this volume, Chapter 10; Plafker and others, this volume, Chapter 12). These weakly metamorphosed rocks, shown as unit 65, include upper Paleozoic arc-related metavolcanic and metaplutonic rocks, metalimestone, argillite, and metachert; overlying Middle Triassic argillite, Upper Triassic metabasalt (Nikolai Greenstone), and Upper Triassic and Lower Jurassic metasedimentary rocks of the McCarthy Formation; and, north of latitude 62°, small areas of overlying Triassic metalimestone, and Mesozoic marine metasedimentary rocks.

Most rocks have not been penetratively deformed (except near major faults) and exhibit well-preserved volcanic, sedimentary, or plutonic textures (MacKevett, 1978; Richter, 1976; W. J. Nokleberg, oral communication, 1984; Beard and Barker, 1989). Locally, however, in the general area that is proposed to be the leading edge along which the Wrangellia terrane was accreted (Csejtey and others, 1982), rocks are weakly phyllitic or schistose in the central Alaska Range (Smith, 1981; Nokleberg and others, 1985) and intensely folded and sheared in the Talkeetna Mountains (Csejtey and others, 1978).

Triassic greenstone in most areas contains the assemblage ch-pr-pu-ab-ep, indicating prehnite-pumpellyite–facies conditions (Richter, 1976; MacKevett, 1978; Csejtey and others, 1978; Smith, 1981; Nokleberg and others, 1985). CAI values of 5.5 to 6.0 from Upper Triassic conodonts collected the McCarthy Quadrangle from the Nizina and Chitistone Limestones and the lower part of the McCarthy Formation suggest metamorphic temperatures of about 350 to 450°C (M. W. Mullen, oral communication, 1989). Locally, in the more deformed northern areas of this unit, greenstone may contain the assemblage ac-ch-ep-ab, indicating lower greenschist-facies conditions.

The metamorphic grade of these late Paleozoic metavolcanic and metaplutonic rocks is generally comparable to that of the low-grade Mesozoic rocks. In the northeastern Gulkana Quadrangle, the Ahtell pluton contains metamorphic wm, ch, ab, and qz (W. J. Nokleberg, written communication, 1988). Metamorphic minerals developed in the correlative diorite complex of Richter (1976) consist of ac, ch, ep, and wm (Barker and Stern, 1986). Late Paleozoic metavolcanic rocks in the northwestern Nabesna Quadrangle generally contain the low-grade assemblage ch-ep-pu, except near the diorite complex where it has been crystallized to massive, fine-grained assemblages of hb, ep, ch, and feldspar (Richter, 1976). In the southeastern McCarthy Quadrangle, the (informal) Barnard Glacier pluton of Middle Pennsylvanian age (309 ± 5-Ma U-Pb age on zircon; Gardner and others, 1988) is generally unfoliated, but locally, it is cataclastically deformed (MacKevett, 1978). It is this pluton, mentioned in the previous section, that is intrusive into both the low-grade rocks of unit 65 to the west, included in the Wrangellia terrane, and the greenschist-facies rocks of unit 64 to the east, included in the Alexander terrane, thereby indicating that the two terranes were sutured together by Middle Pennsylvanian time (MacKevett and others, 1986; Gardner and others, 1988). Although the data are inconclusive, the pluton is tentatively shown on Plate 4A to have been weakly metamorphosed along with the Wrangellia terrane wall rocks on the west, although numerous other possible correlations of its metamorphic history are possible given the uncertainty of the timing of metamorphism in this region.

The age and cause of metamorphism may be different in other parts of unit 65. Because the metamorphic grade is so low, it is difficult to determine with certainty whether some associated rocks have been metamorphosed. In the southern part of this unit, the CAI values from the Late Triassic conodonts indicate that metamorphism is post–Late Triassic in age. The minimum metamorphic age in that area is uncertain, but I also assume that it postdates the Lower Jurassic part of the McCarthy Formation. A tentative Middle or Late Jurassic minimum age of metamorphism for at least some areas of this unit is suggested by the apparent lack of metamorphism in the Upper Jurassic and Lower Cretaceous Nutzotin Mountains sequence in the Nabesna Quadrangle (Richter, 1976) and in the Jurassic and Cretaceous sedimentary rocks that overlie the McCarthy Formation in the Valdez and McCarthy Quadrangles (Winkler and others, 1981; MacKevett, 1978).

Hornblende and biotite from the diorite complex in the northeastern part of unit 65 yield Early Jurassic K-Ar ages (Richter and others, 1975), but it is uncertain whether these ages (1) date the predominant period of metamorphism in that area, (2) provide a minimum age for a late Paleozoic or early Mesozoic episode, or (3) represent a partial resetting of the Pennsylvanian protolith age by a possible Cretaceous metamorphic episode, described below.

Metamorphism in some areas along the southern margin of unit 65 may have been associated with the intrusion of the Jurassic plutons that I propose occurred during the greenschist- to amphibolite-facies metamorphism of the Strelna Metamorphics (unit 59) to the south. Although the two units that may grade into each other are separated by a thrust fault of Cretaceous age (Chitina fault: Gardner and others, 1986), an overall proximity of the units during the Late Jurassic intrusive and metamorphic episode is suggested by the facts that (1) a Late Jurassic pluton also intrudes unit 65 in one area in the western McCarthy Quadrangle, (2) higher grade unit 59 includes a minor component of Upper Triassic rocks that are correlated with those of unit 65, and (3) metamorphic temperatures, as determined from Late Triassic conodonts, are comparable across the Chitina fault (that is, about 350 to 450°C to the north and about 350°C to the south: M. W. Mullen, written communication, 1989).

Some data suggest an alternative or, perhaps, additional, mid-Cretaceous metamorphic age for at least the northern part of unit 65. Field and petrographic observations in the Talkeetna Mountains and the eastern Alaska Range suggest that Jurassic and Cretaceous rocks that overlie the Triassic Nikolai Greenstone also have undergone low-grade metamorphism (B. Csejtey, Jr., written communication, 1984; Nokleberg and others, 1985). Three K-Ar whole-rock ages from samples of the Nikolai Greenstone from the southern part of this unit in the central McCarthy Quadrangle fall on a 112 ± 11-Ma isochron (Silberman and others, 1981).

Silberman and his co-workers (1981) propose that the late Early Cretaceous K-Ar ages from the McCarthy Quadrangle date an episode of low-grade metamorphism that was caused by frictional heating that accompanied the accretion of the Wrangellia terrane to the North American margin. Arguing against this hypothesis for at least the McCarthy Quadrangle, however, is the fact that the Upper Triassic rocks show no sign of being deformed (although they have been heated to about 350 to 450°C since the Late Triassic). Assuming that the late Early Cretaceous K-Ar ages do in fact date the timing of low-grade metamorphism in the central McCarthy Quadrangle, an alternative interpretation is that metamorphism may have been coeval with the northeast-directed, Early Cretaceous movement along the nearby Chitina fault (Gardner and others, 1986) that placed the medium-grade metamorphic rocks (unit 59) and synkinematic Jurassic plutonic rocks of the Wrangellia terrane on top of the low-grade rocks of unit 65.

The localized development of a penetrative fabric and higher-T ac-bearing mineral assemblages in the central Alaska Range and the Talkeetna Mountains suggests that metamorphism, at least in these areas, occurred during late Mesozoic accretion. Both areas were near the leading edge along which this terrane is thought to have been accreted in mid-Cretaceous time (Csejtey and others, 1982; Nokleberg and others, 1985).

Similar low-grade oceanic rocks crop out in southeastern Alaska where they are shown as units 91 and 99. Unit 91 is included in the northern part of the Taku terrane by Monger and Berg (1987), but subsequently has been reinterpreted as part of the Wrangellia terrane by Plafker and others (1989a); unit 99 is included in the Wrangellia terrane by Monger and Berg (1987). The age and tectonic origin of their metamorphism are also uncertain.

Mid-Cretaceous to early Tertiary metamorphism. *Low-grade metamorphism within a compressed flysch basin.* Very weakly metamorphosed and highly deformed flyschoid rocks, primarily metagraywacke, semischist, and argillite, and rocks from several tectonically interleaved fragments within the flysch, crop out as a northeastward-tapering wedge (shown as unit 67) in the central Alaska Range between the low-grade rocks of the Wrangellia terrane to the southeast, and the unmetamorphosed to moderately metamorphosed rocks of the continental margin to the northwest. Flyschoid rocks are Late Jurassic to mid-Cretaceous (Cenomanian) in protolith age (Csejtey and others, 1986). Tectonic fragments include protoliths that range in age from Late Devonian to Late Jurassic age and include a variety of sedimentary, volcanic, and ophiolitic rocks (Jones and others, 1980; Silberling and others, this volume). The tectonic juxtaposition of the disparate fragments (terranes) included within this unit is considered to have taken place during mid-Cretaceous time (Csejtey and others, 1978, 1982; Jones and others, 1980). According to Csejtey and others (1982), the flyschoid rocks were deposited in a basin between the North American craton and the approaching Talkeetna superterrane (equivalent to the composite Peninsular-Wrangellia terrane) to the south, and the small terranes within the flysch were transported in front of the superterrane by northward plate movement. Because the Wrangellia and Alexander terranes are stitched together by a Pennsylvanian pluton, as mentioned in a previous section, the superterrane also must have included the Alexander terrane as its southeasternmost component (Plafker and others, this volume, Chapter 12).

The dominant structural style of this metamorphic unit is compression and attendant thrust faulting that has juxtaposed fragments of what were parts of extensive coherent terranes (Csejtey and others, 1978; Jones and others, 1980). Deformation and recrystallization within the flysch terrane is most intense along zones of concentrated shear; rocks in these zones are commonly phyllitic, semischistose, or protomylonitic. The degree of metamorphism may vary within unit 67, but this aspect of the terranes has not been studied in detail. Metamorphic minerals developed in flyschoid rocks indicate metamorphic conditions characteristic of the prehnite-pumpellyite facies (Dusel-Bacon and others, 1994b).

Metamorphism is bracketed between the mid-Cretaceous age of the youngest metamorphosed rocks and the latest Paleocene and Eocene age of the overlying unmetamorphosed sedimentary and volcanic rocks, and the early Tertiary age of postmetamorphic granitoids that intrude the flyschoid rocks (Csejtey and others, 1982, 1986). The apparent increase in metamorphic grade toward zones of shearing, together with age brackets for accretion that are approximately the same as those for low-grade metamorphism, suggest that much of the metamorphism probably accompanied northward migration and accretion. Low-grade metamorphism of some of the elements of the tectonic fragments may have occurred even earlier.

Intermediate-P metamorphism of the Maclaren metamorphic belt. The Maclaren metamorphic belt consists of a largely fault-bounded, 140-km-long, roughly symmetrical, intermediate-P (Barrovian) sequence of: (1) prehnite-pumpellyite–facies metasedimentary rocks and metagabbro (unit 68); (2) greenschist-facies phyllite, metagraywacke, marble, quartzite, metapelite, and greenstone (unit 69); and (3) amphibolite-facies schist, gneiss, and amphibolite (unit 70) intruded by foliated, synkinematic plutons of intermediate composition, shown as unit TKg with a cross pattern (Smith, 1981; Csejtey and others, 1982, 1986; Nokleberg and others, 1985). Protoliths are Triassic to Cretaceous in age.

Intermediate-P conditions for the sequence are indicated by the presence of ky (+ sil + gt + st) in pelitic schist and gneiss of unit 70 (Smith, 1981), and sil pseudomorphs after ky (L. S. Hollister, written communication, 1985). Kyanite is also reported to occur in amphibolite (Smith, 1981)—further evidence of intermediate- or even high-P conditions. Andalusite has been reported from two localities, one near the western and one near the eastern boundary of unit 70 (Dusel-Bacon and others, 1994b). These reported occurrences of anda warrant further investigation, but they may simply indicate that higher structural levels are exposed on the ends of the metamorphic belt, relative to deeper level exposure in the central part of it.

Where not affected by tectonic shortening, metamorphic grade increases gradually from the flanks of the sequence toward its core. Along the southern limb of the belt, lower grade rocks dip northward under higher grade rocks to form an inverted metamorphic sequence (Smith, 1981). East of longitude 147°, there is an abrupt, rather than gradational, contact between greenschist- and amphibolite-facies rocks due to tectonic shortening along steep north-dipping faults (Nokleberg and others, 1985). A similarly sharp change in metamorphic grade occurs on either side of a north-dipping thrust (overturned to the south along its eastern end) that forms the southern margin of the foliated plutonic body, referred to as the East Susitna batholith (Nokleberg and others, 1985; Smith, 1981). Deeper level rocks are exposed north of the thrust, as indicated by the first appearance of sil and, with one exception, ky in upper plate rocks adjacent to the thrust (Smith, 1981).

Metamorphic recrystallization occurred during and after two dynamic phases of a prolonged metamorphic episode (Smith, 1981). The concordancy between intrusive contacts and metamorphic foliations in the granitoids and in the metamorphosed wall rocks, together with an increase in metamorphic grade toward the East Susitna batholith, indicates that the foliated granitoids intruded during the early part of the metamorphic episode (Smith, 1981; Nokleberg and others, 1985). This may have been toward the end of an early shearing phase or interkinematically before a final phase of shearing (Smith, 1981). U-Pb data on zircon from schistose quartz diorite indicate a 70 ± 7-Ma intrusive age of the East Susitna batholith (Aleinikoff and others, 1982). U-Pb data on sphene and K-Ar data on biotite from the same rock indicate a 56-Ma metamorphic age (Aleinikoff and others, 1982), which apparently marks the end of the prolonged Late Cretaceous to early Tertiary metamorphic episode. Biotite from pelitic schist gives a similar K-Ar age of 57 Ma (Smith and Lanphere, 1971). Rapid uplift and cooling during metamorphism is indicated by the fact that approximately the same age is given by sphene, whose closure temperature is greater than 600°C (Mattinson, 1978), and biotite, whose closure temperature is about 280°C (Harrison and others, 1985).

Metamorphism and tectonic shortening of the Maclaren metamorphic belt apparently resulted from the accretion of the previously amalgamated Peninsular and Wrangellia terranes to the Yukon-Tanana and Nixon Fork terranes of the ancient North American continent (Csejtey and others, 1982) and the synorogenic intrusion of the East Susitna batholith (Nokleberg and others, 1985). The flyschoid protoliths of the Maclaren metamorphic belt, as well as those of unit 67, were deposited mostly in the narrowing and subsequently collapsed ocean basin between the converging terranes (Csejtey and others, 1982; Nokleberg and others, 1985).

The location in which the convergence, deformation, plutonism, and metamorphism took place is disputed, however. Multiple lines of field and isotopic evidence suggest that the Maclaren metamorphic belt and East Susitna batholith are the offset equivalents of the Kluane Schist and Ruby Range batholith in Yukon Territory, displaced 400 km by right-lateral Cenozoic movement along the Denali and McKinley faults (summary of evidence given in Nokleberg and others, 1985; see also Aleinikoff and others, 1987). Nokleberg and his co-workers (1985) postulate that intense deformation and prograde metamorphism of the belt began during mid- to Late Cretaceous time as a result of the accretion of the Wrangellia terrane onto the North American margin further to the south and continued during early Tertiary time as a result of the northward migration of the flyschoid (Maclaren) terrane and the Wrangellia terrane along the North American margin. Csejtey and others (1982) dispute the correlation between the two metamorphic-plutonic complexes and propose instead that regional metamorphism of the Maclaren metamorphic belt occurred in place, extends across the McKinley fault, and is only slightly offset by it. Although there is an apparent similarity in metamorphic grade and a similar eastward increase in metamorphic grade on either side of the McKinley fault in the east-central part of the Healy Quadrangle, metamorphic data are insufficient to document continuity of metamorphic history across the fault. Arguing against continuity of metamorphic history on either side of the McKinley fault is the occurrence of a fault-bounded block of unit 54 (Windy terrane) between the areas of amphibolite-facies rocks that Csejtey would correlate across the fault (units 52 and 70).

Area of southern and southeastern Alaska that lies south of the Border Ranges fault system

Jurassic blueschist- to greenschist-facies metamorphism. A belt of transitional, and tectonically intermixed high-P blueschist-facies to intermediate-P greenschist-facies metabasalt, metachert, mica schist, marble, and fine-grained clastic rocks, derived from oceanic protoliths, crops out immediately south of the Border Ranges fault system, at the northern margin of the Chugach terrane (Plafker and others, this volume, Chapter 12). The belt, shown as unit 71, extends discontinuously for about 750 km from Kodiak Island on the west to the Copper River on the east. This unit consists of fault-bounded, commonly internally imbricated blocks, and includes, from southwest to northeast, the Raspberry Schist of Roeske (1986) on Kodiak and Afognak Islands, the informally designated schist of Seldovia on the Kenai Peninsula (Forbes and Lanphere, 1973; Carden and others, 1977), the informally designated schist of Iceberg Lake near Tazlina Glacier (Winkler and others, 1981; Sisson and Onstott, 1986), and the informally designated schist of Liberty Creek just west of the Copper River (Metz, 1976; Winkler and others, 1981; Plafker and others, 1989b). Protolith ages are unknown.

In most areas, greenschists that contain ch + ac commonly are finely intercalated with blue-amph–bearing schists that contain cr + ep (Forbes and Lanphere, 1973; Carden and others, 1977; Carden, 1978; Winkler and others, 1981). Glaucophane (+ ep) has been identified only in the Raspberry Schist on Afognak Island, and the assemblage gt + cr + ep is present in the schist of Iceberg Lake near Tazlina Glacier (Winkler and others, 1981). Lawsonite coexists with blue amph at scattered localities along the belt (Plate 4A).

The coexistence of blue amphibole with ep, and in one area with gt, is indicative of the high-T subdivision of the blueschist facies (Taylor and Coleman, 1968; Evans and Brown, 1987). However, the sporadic occurrence of lw, which is diagnostic of the low-T subdivision of the blueschist-facies, indicates that temperatures during metamorphism were probably near the boundary bedtween the two subdivisions. Phase equilibria that involve the breakdown of pu to form ep (Nitsch, 1971), and the breakdown of lw to form zo (Franz and Althaus, 1977), suggest temperatures between about 350 and 400°C. Phase equilibria and cr composition indicate crystallization at about 6 ± 2 kb for the schists of Iceberg Lake and Liberty Creek (Sisson and Onstott, 1986). This P-T range is consistent with the hypothesis of Carden and others (1977) that the finely developed intercalation of ac-ch-bearing layers and cr-bearing layers in the Raspberry Schist (equivalent to the Kodiak schist unit of Carden and others, 1977) and the schist of Seldovia are probably due to minor variations in original chemistry of layers that were metamorphosed under conditions close to the boundary between the greenschist and blueschist facies (Turner, 1981).

Detailed mapping in the area of Kodiak Island indicates that postmetamorphic faults separate blocks ranging from meters to hundreds of meters wide, and that overall the metamorphic grade of the blocks increases from southeast to northwest (Roeske, 1986). To the north, the schist of Seldovia also occurs as fault-bounded blocks of varying metamorphic grade (S. M. Roeske, oral communication, 1984).

The schist of Iceberg Lake makes up an elongate, 40- by 4-km, fault-bounded belt enclosed by the low-grade McHugh Complex (unit 72) near the Tazlina Glacier. Several small elongate blocks of this unit (too small to show on Plate 4A) also occur in melange along the Border Ranges fault system to the north (Winkler and others, 1981). Similar metamorphic mineral assemblages (primarily those of the greenschist-facies) are developed in the schist of Liberty Creek and the schist of Iceberg Lake, but rocks are noticeably finer grained (generally less than 3 mm) in the former than in the latter (Plafker and others, 1989b). Crossite-bearing rocks in the schist of Iceberg Lake locally contain gt and those in the schist of Liberty Creek, hematite.

Data for several isotopic systems suggest a Jurassic (primarily Early to early Middle Jurassic) age for the intermediate- to high-P greenschist-facies episode. K-Ar ages on wm and cr (as well as on ac from the schist of Seldovia) from unsheared rocks in all units except the schist of Liberty Creek range from Early to Late Jurassic, from 190 to about 152 Ma (Forbes and Lanphere, 1973; Carden and others, 1977; Winkler and others, 1981). Crossite-bearing rocks from the Raspberry Schist give an Early

Jurassic age of 196 Ma for a Rb-Sr whole rock-ph isochron and 204 ± 8 Ma for a U-Pb isochron of sph, wm, ab, and amph (Roeske and Mattinson, 1986). Near the eastern end of the belt, cr and ph from unsheared rocks of the schist of Iceberg Lake yield $^{40}Ar/^{39}Ar$ plateau ages of about 185 Ma (Sisson and Onstott, 1986).

Strongly sheared rocks from the schist of Iceberg Lake yield Early Cretaceous (138 to 113 Ma) K-Ar mineral ages (Winkler and others, 1981), indicating partial resetting subsequent to the well-dated Jurassic metamorphic episode. Resetting of the isotopic ages may have taken place during the emplacement of the schistose rocks of the McHugh Complex, the adjacent seaward subduction complex (unit 72) that was primarily accreted between Early Cretaceous and early Tertiary time (Winkler and others, 1981).

Early Cretaceous (123 to 107 Ma) K-Ar whole-rock ages have been determined for three samples of sheared rock from the schist of Liberty Creek (Plafker and others, 1989b), but interpretation of these ages is uncertain. Because of the very fine grain size of the unit, no minerals suitable for isotopic dating have been successfully separated. If the schist of Liberty Creek, like the rest of the belt, was originally metamorphosed during a Jurassic subduction-related transitional greenschist- to blueschist-facies episode, then its Early Cretaceous ages probably represent the same resetting event, attributed to emplacement of the McHugh Complex, that was proposed for the nearby schist of Iceberg Lake. Alternatively, the Early Cretaceous whole-rock ages may in fact date the timing of subduction-related metamorphism of the schist of Liberty Creek. In this case, a better analog for its metamorphic history would be that of the sparse blue-amph–bearing schist within the prehnite-pumpellyite- to greenschist-facies melange of unit 73 (Kelp Bay Group) of the Chugach terrane on Chichagof Island, over 600 km to the southeast (discussed below). Arguing against the analogy with the rocks on Chichagof Island is the fact that blue amphibole has only been found at one locality on Chichagof Island, whereas it occurs across a much larger area and in more abundance in the schist of Liberty Creek.

Similarities in lithology, mineralogy, and isotopic ages suggest that all parts of this unit, with the possible exception of the schist of Liberty Creek, are segments of a formerly continuous belt of accreted, subduction-related rocks. Metamorphism of the Raspberry Schist and schist of Seldovia is thought to have occurred as a result of northwest-directed subduction, which was coeval with magmatism in the nearby Alaska–Aleutian Range during Early Jurassic time (Carden and others, 1977; Connelly, 1978). Plafker and others (1989b) concur with this general hypothesis and propose that northward to eastward subduction beneath the (composite) Peninsular-Wrangellia terrane began in Late Triassic time and continued to Middle(?) Jurassic time as a result of left-oblique subduction of the Farallon plate. As pointed out by Plafker and his co-workers, the juxtaposition across the Border Ranges fault system of the low-T, high-P rocks of unit 71 with the approximately coeval high-T plutonic and volcanic rocks of the Triassic to Jurassic arc (including unit Jmu and the Talkeetna Formation that forms part of unit N) implies structural disruption of the seaward margin of the arc. On the basis of the separation between the inner margins of accretionary prisms and magmatic belts in modern arcs, Plafker and others (1989b) proposed that the observed juxtaposition indicates relative underthrusting, on the order of 50 km, of the high- to intermediate-P rocks beneath the plutonic rocks.

Jurassic to early Tertiary low-grade metamorphism of Chugach and Yakutat terranes melange. Tectonic melange, included in the melange facies of the Chugach terrane (Plafker and others, 1977 and this volume, Chapter 12), occurs immediately outboard of the Border Ranges fault or, in a few areas in southern Alaska, separated from it by the high- to intermediate-P subduction complex discussed above. The melange makes up all of unit 72 and the inboard parts of units 73 to 75. It consists of disrupted, deformed, and weakly metamorphosed blocks, ranging from tens of meters to several kilometers in longest dimension, of greenstone, mafic schist, metatuff, metagraywacke, metaargillite, metachert, metalimestone, phyllite, quartzite, serpentinite, and mafic plutonic rocks. Blocks are aligned in a sheared matrix of argillite, metatuff, and metachert.

Unit 72 crops out around the Gulf of Alaska and records primarily prehnite-pumpellyite–facies conditions; exotic metamorphic blocks in the melange locally record blueschist-facies conditions. This unit makes up the McHugh Complex in the Chugach Mountains (Clark, 1973; Tysdal and Case, 1979; Winkler and others, 1981), the Seldovia Bay complex in the Kenai Mountains (Cowan and Boss, 1978), and the Uyak Complex in the Kodiak Island area (Connelly, 1978). Near Seldovia, a small area of this unit is included in the Kachemak terrane by Jones and others (1987). Paleontologic ages of radiolarians from the melange matrix of this unit range from Late Triassic to mid-Cretaceous (Albian to Cenomanian), the bulk of the fossil ages being Late Jurassic to Early Cretaceous (Plafker and others, 1977; Connelly, 1978; Nelson and others, 1987). Fossils from blocks within the melange are as old as late Paleozoic.

Unit 73 crops out in southeastern Alaska and is made up primarily of melange (revised Kelp Bay Group of Johnson and Karl, 1985) that records prehnite-pumpellyite–facies, lower greenschist-facies, and rare blueschist-facies conditions (Decker, 1980). Along its western margin, unit 73 also includes a less extensive sequence of moderately deformed and disrupted bedded turbiditic metasedimentary and metavolcanic rocks (Sitka Graywacke) metamorphosed under prehnite-pumpellyite– and greenschist-facies conditions; these rocks are included in the flysch facies of the Chugach terrane (Plafker and others, 1977). Blocks within the melange are Triassic or Jurassic, Late Jurassic (Tithonian), and Early Cretaceous (Valanginian) in age (Loney and others, 1975; Decker and others, 1980; Johnson and Karl, 1985; Brew and others, 1988). Deposition of the melange matrix took place, in part, during the Late Jurassic (Tithonian; Brew and others, 1988) and presumably continued during at least the Early Cretaceous (age of the youngest blocks; Decker, 1980; Johnson and Karl, 1985; Brew and others, 1988). The depositional age of the bedded rocks is unknown but is considered to be Cretaceous on the basis of correlation with lithologically similar rocks in the Valdez Group and Yakutat Group to the northwest (Plafker and others, 1977; Brew and Morrell, 1979).

Around the Gulf of Alaska, rocks of the flysch facies of the Chugach terrane (units 77 and 78, discussed below) have been shown to have a younger depositional, and presumably, metamorphic age than that of the inboard melange facies of the Chugach terrane (unit 72). In southeastern Alaska, however, the depositional age of the flysch facies is unknown, and separate metamorphic histories have not, as yet, been demonstrated for the two tectonic facies. For this reason, both of these tectonic facies are included in unit 73 and in two related polymetamorphic units (units 74 and 75) in which the early low-grade metamorphic episode was overprinted by regionally extensive, low-P, thermal metamorphism associated with Eocene plutonism (Loney and others, 1975; Loney and Brew, 1987).

The melange of both areas is considered to be a subduction complex consisting of oceanic sedimentary and igneous rocks, offscraped fragments of continental margin, or older subduction assemblages (Clark, 1973; Moore and Connelly, 1979; Plafker and others, 1977; Cowan and Boss, 1978; Decker, 1980; Winkler and others, 1981). The relation of crystallization to deformation observed on Kodiak and Afognak Islands suggests that metamorphism occurred during active underthrusting, continued after accretion of the subduction complex onto the overthrust plate, and was followed by late fracturing and cataclasis during uplift of the complex (Connelly, 1978). This evolution is a reasonable hypothesis for the other areas of melange as well. As pointed out by Connelly (1978), a similar progression of deformation has been proposed for the Franciscan Complex (subduction complex; Glassley and Cowan, 1975).

Accretion of the melange facies may have taken place over a long time span that extended throughout the Jurassic and Cretaceous. This prolonged period of accretion is suggested by Plafker and others (1989b) because of an apparent southward decrease in age from Late Triassic to mid-Cretaceous noted in the western Valdez Quadrangle (Winkler and others, 1981), and the probable convergent plate motion that is indicated along the southern margin of the (composite) Peninsula-Wrangellia-Alexander terrane during much or all of Jurassic and Cretaceous time (Engebretsen and others, 1985). As suggested by Plafker and others (1989b), the earliest accretion of Chugach terrane rocks is probably represented by the Jurassic intermediate- to high-P greenschist-facies metamorphism of unit 71.

Although the innermost parts of the melange complex of the Chugach terrane may have been accreted as early as Jurassic time, accretion and metamorphism of much of units 72 to 75 probably occurred in Early to mid-Cretaceous time, following accumulation of the youngest matrix material. Low-grade metamorphic minerals that were interpreted by Decker and his coworkers (1980) to have formed during subduction and accretion of unit 73 on Chichagof Island give Cretaceous K-Ar ages (106 to 91 Ma; Decker and others, 1980). Early Cretaceous (135 to 110 Ma) plutons that intrude unit 72 northeast of Anchorage are interpreted to be the result of near-trench plutonism that occurred during underthrusting of the melange complex (Pavlis, 1982; Pavlis and others, 1988a). An early Tertiary minimum metamorphic age is indicated by the facts that: (1) emplacement and metamorphism of the melange complex preceded the probable latest Cretaceous or early Tertiary emplacement and metamorphism of the tectonically underthrust flysch facies of the Chugach terrane that occurs outboard of unit 72; and (2) metamorphic assemblages within flysch and melange on Baranof Island in southeastern Alaska (units 74 and 75) are overprinted by thermal metamorphism associated with Eocene plutons (Loney and others, 1975).

Lithologically similar melange composed of structurally disrupted lenses of Upper Jurassic to Lower Cretaceous chert, argillite, conglomerate, mafic volcanic rocks, and rare blocks of exotic lithologies (Hudson and others, 1977b) also occurs within units 79 to 81 of the Yakutat terrane. The Yakutat terrane lies outboard of the Chugach terrane and has been correlated with it by Plafker and others (1977, 1989b). Melange of the Yakutat terrane occurs tectonically interleaved with flysch that makes up the dominant part of units 79 to 81 (discussed below); tectonic mixing is on a scale too small to allow delineation of the melange. As with the Chugach terrane melange, metamorphism of parts of the Yakutat terrane melange may have occurred in the Jurassic or Early Cretaceous. At one locality within unit 79, deformed melange is crosscut by a tonalite pluton (unit Kg) that gives discordant K-Ar ages of 96 Ma on hb and 84 Ma on bt (G. Plafker, unpublished data, 1978). It is also likely that, as is the case with the Chugach terrane melange, blueschist-facies metamorphism affected some of these rocks because glacial erratics of crossite-bearing metabasalt occur locally along Russell Fiord and Yakutat Bay (G. Plafker, unpublished data, 1987). The lithology and occurrence of these erratics are most compatible with a source in the ice-covered parts of the Yakutat terrane.

Late Cretaceous to early Tertiary low-P metamorphism of Chugach and Yakutat terranes flysch. A low-P facies series of low- to medium- (and locally high-) T metamorphosed flysch of the Chugach terrane (units 76 to 78) and Yakutat terrane (units 79 to 81) forms an arcuate belt of rocks that extends from the Sanak and Shumagin Islands off the southeast coast of the Alaska Peninsula in the west to the Saint Elias Mountains area south of Yakutat Bay in the east. Protoliths of the Chugach terrane (western and central parts of the belt) consist of a steeply dipping Upper Cretaceous (Maastrichtian) turbidite sequence of graywacke, slate, and locally intercalated conglomerate and volcanic rocks (Moore, 1973; Jones and Clark, 1973; Nilsen and Moore, 1979). Protoliths of the Yakutat terrane (eastern part of the belt) include these rock types, in addition to small amounts of the structurally interleaved melange (undifferentiated on Plate 4A) discussed above.

The flysch of the Chugach terrane forms a north-dipping accretionary prism that was underthrust beneath either the melange facies of that terrane or beneath the combined Peninsular and Wrangellia terranes to the north. Metamorphic grade within the accretionary prism increases progressively to the east around the Gulf of Alaska where it culminates in the polymetamorphic rocks of the (informal) Chugach metamorphic complex (unit 78) of Hudson and Plafker (1982), which crops out in the eastern Chugach Mountains and the Saint Elias Mountains. Flysch on Sanak and Shumagin Islands underwent laumontite-facies metamorphism that was ascribed by Moore (1973) to burial. Within the rest of the prism, flysch and related rocks underwent prehnite-pumpellyite–facies (unit 76) to lower greenschist-facies (unit 77 and M_1 of unit 78) low-P metamorphism that probably accompanied north-directed underthrusting of the Chugach terrane beneath the (composite) Peninsular-Wrangellia terrane, and the development of south-vergent folds, during latest Cretaceous to early Tertiary time (Moore and others, 1983; Sample and Moore, 1987; Nokleberg and others, 1989). Metamorphism during this low-grade episode postdates the Maastrichtian age of the protoliths and predates the intrusion of crosscutting tonalitic plutons that give K-Ar ages of 63 Ma on Kodiak Island (Byrne, 1982) and approximately 60 to 50 Ma (data summarized by Plafker and others, 1989b; and Sisson and others, 1989) in the Chugach Mountains.

The Chugach metamorphic complex (unit 78), forms an elongate, 200-km-long and less than 50-km-wide, east-west–trending belt made up of anda- and co-bearing schist and gneiss, and a core zone of sil-bearing migmatite. These rocks represent the deepest parts of the accretionary prism that makes up the Chugach terrane. They were initially metamorphosed during the greenschist-facies episode that affected the adjacent rocks of unit 77 and further heated under low-pressure amphibolite-facies conditions that developed during the widespread Eocene intrusion of tonalitic plutons. Metamorphic grade generally increases from the edges toward the elongate core of the metamorphic complex. This overall increase is independent of the exposed distribution of major plutons, and as Sisson and others (1989) point out, this progression is not solely a product of contact-metamorphic effects. In addition to the overall distribution of metamorphic grades, local contact metamorphism has produced high-grade rocks near the contacts of large felsic intrusions (Sisson and Hollister, 1988). Amphibolite-facies metamorphism and partial melting in the core of the metamorphic complex overlapped in time with the development of second-generation north-vergent folds, steeply dipping cleavage and schistosity, and near horizontal east-west–trending fold axes and lineations (Sisson and Hollister, 1988).

Intrusion and M_2 metamorphism of unit 78 postdated the accretion of the upper Paleocene to middle Eocene Orca Group of the Prince William terrane against the southern margin of the Chugach terrane (south of the Contact fault). This relation is indicated by the fact that an elongate 51-Ma tonalite pluton (Winkler and Plafker, 1981) and the metamorphic effects associated with it (M_2 of unit 85; Miller and others, 1984; Sisson and others, 1989) crosscut the Chugach/Prince William terrane boundary near Miles Glacier.

Metamorphic P throughout the metamorphic complex (unit 78) was between 2 and 3 kb (about 10 km) and T between 500°C near the edge of the complex to about 650°C in its migmatitic core (Sisson and others, 1989). These P-T estimates, together with those from the adjacent greenschist-facies unit 77, suggest a nearly isobaric P-T-time path in which the rocks of unit 78, already heated to greenschist-facies conditions at a depth of about 10 km during M_1, were further heated to amphibolite-facies conditions during M_2.

The tectonic origin of the heat that produced both the amphibolite-facies Chugach metamorphic complex and the widespread belt of early Tertiary plutons that crops out within the Chugach terrane and the outboard Prince William terrane is problematic. Marshak and Karig (1977) pointed out that in a normal subduction setting, the temperatures within an accretionary prism, such as the Chugach and Prince William terranes, are much too low to cause partial melting. They proposed that the anomalous near-trench plutonism was the result of eastward migration of a ridge-trench-trench triple junction along the continental margin, and subduction of the Kula-Farallon spreading ridge. A second but related hypothesis proposed by Plafker and others (1989b; see also Plafker and Berg, this volume) suggests that the anomalous heating during the early Tertiary metamorphic and plutonic episode resulted from the opening of a high-T oceanic-slab–free mantle window beneath the continental margin, as the subducting Kula Plate pulled away from the Farallon-Pacific Plate, in a manner analogous to one described along the San Andreas transform fault system by Dickinson and Snyder (1979). According to a third hypothesis, the high temperatures that produced the Chugach metamorphic complex resulted from a combination of heat introduced by extensive horizontal, as well as vertical, transport of fluids (beginning during initial greenschist-facies metamorphism) followed by felsic melts, both of which were generated from downdip in the subduction zone and involved either subduction of young hot oceanic crust at a high rate and a low angle, or subduction of a spreading ridge (Sisson and Hollister, 1988; Sisson and others, 1989).

A low-P facies series, similar to and probably correlative with the series that developed within the Chugach terrane flysch, also was formed within Late Cretaceous flysch and the structurally interleaved melange of the Yakutat terrane (Hudson and others, 1977b). The flysch and melange of the Yakutat Group are correlative with the flysch and melange of the Chugach terrane (Plafker and others, 1989b). The Yakutat Group, like the Chugach terrane in south-central and southeastern Alaska, is extensively intruded by Eocene granitoid plutons. Yakutat terrane rocks affected by the low-P metamorphic episode include: (1) laumontite- and prehnite-pumpellyite–facies rocks of unit 79; (2) a narrow fault-bounded sliver of greenschist-facies rocks of unit 80; and (3) epidote-amphibolite– and amphibolite-facies rocks of unit 81 (Hudson and others, 1977b). A steep thermal gradient is indicated by a rapid progressive increase in metamorphic grade from prehnite-pumpellyite–facies rocks to an area (oval in plan view) of amphibolite-facies rocks, with only a narrow interval of intervening greenschist-facies rocks (not shown on Plate 4A). Within the oval outcrop area of amphibolite-facies rocks, anda porphyroblasts are developed locally, and rocks are characterized by semigranoblastic textures, providing evidence that metamorphism of these rocks was dominantly thermal in nature. The oval outline suggests a buried pluton.

The rest of epidote-amphibolite– and amphibolite-facies unit 81 occurs as an elongate fault-bounded sliver that is separated from the amphibolite-facies rocks of the Chugach terrane (unit 83, described below) by the Fairweather fault to the northeast, and from the prehnite-pumpellyite–facies rocks of the Yakutat terrane by another major fault to the southwest. Tectonic shortening, by thrust faulting or strike-slip faulting with a significant dip-slip component, is suggested by the juxtaposition of high- and low-grade rocks along the southwestern fault contact, and by the absence of intervening greenschist-facies rocks.

Major metamorphism is considered to be latest Cretaceous to early Tertiary in age, based on: (1) the latest Cretaceous protolith age of the youngest rocks; (2) K-Ar ages on hb of about 65 Ma, determined for amphibolites (Hudson and others, 1977b), and (3) the interpretation that this unit shared a common metamorphic history with that of the adjacent Chugach terrane discussed above.

Late Cretaceous to mid-Tertiary intermediate(?)-P metamorphism of Chugach terrane flysch. A sequence of transitional greenschist- to amphibolite-facies rocks (unit 82) and amphibolite-facies rocks (unit 83) crops out along the eastern margin of the Gulf of Alaska in the Saint Elias Mountains and Fairweather Range (Brew, 1978; Hudson and others, 1977b; Hudson and Plafker, 1982). Protoliths are interpreted as being turbidites and tholeiite of Late Cretaceous age because of lithologic similarity with the flysch facies of the Chugach terrane (Plafker and others, 1977 and this volume, Chapter 12; Barker and others, 1985). Most boundaries of the sequences are faults. The two fault blocks that make up the higher grade part of the sequence are presumed to have shared the same metamorphic history and to have subsequently been separated by right-lateral displacement along the Fairweather fault (Dusel-Bacon and others, 1994b).

The timing and number of metamorphic episodes that affected units 82 and 83 are unknown. A Cretaceous maximum age of metamorphism is proposed on the basis of the probable age of the protoliths. At least some of the metamorphism is known to have occurred prior to the intrusion of crosscutting plutons of intermediate composition that have K-Ar ages on hb of 61 ± 2 Ma in the southeastern Yakutat Quadrangle (Hudson and others, 1977a) and K-Ar ages of about 52 Ma in the southwestern Skagway Quadrangle (George Plafker, unpublished data, 1978). A K-Ar age on hb of 67 Ma from amphibolite in the Nunatak Fiord area, 55 km northeast of Yakutat, suggests a latest Cretaceous metamorphic age (Barker and others, 1985). In the same area, however, K-Ar ages on hb and bt from metamorphic rocks between Nunatak Fiord and the southwestern Skagway Quadrangle range from about 23 to 19 Ma, which suggests an additional, or alternative, Miocene metamorphic age; these K-Ar ages fall close to or within the 37- to 21-Ma range of K-Ar ages from widespread felsic intrusive rocks (Hudson and others, 1977b; George Plafker, unpublished data, 1978). Farther to the south, in the area northwest of Cross Sound, metamorphism appears to predate and to be unrelated to the intrusion of Oligocene (28 ± 8-Ma $^{40}Ar/^{39}Ar$ age on hb; Loney and Himmelberg, 1983) gabbroic plutons (Dusel-Bacon and others, 1994a).

The origin of the metamorphic episode(s) that affected units 82 and 83 is unknown. In the northern and central part of the area made up of these units, the spatial relation of the higher grade metamorphic rocks and Tertiary plutons suggests a genetic link. Unlike the Chugach metamorphic complex (unit 78, and adjacent parts of unit 77), described above, the thermal history of at least some parts of units 82 and 83 appears to be complicated by the occurrence of multiple periods of plutonism (and perhaps metamorphism) in the Tertiary and also probably by a much younger uplift history, as indicated by the exposure of the Miocene plutonic rocks and discordant biotite-hornblende pairs. Another difference between these two metamorphic sequences is the fact that ky, indicative of intermediate-P conditions, occurs at one locality in unit 83, whereas anda, indicative of low-pressure conditions, is present in unit 78.

Retrograde effects in overlying units corresponding with metamorphism and underthrusting of Chugach terrane flsych. North-directed underthrusting of Chugach terrane flysch beneath the southern margin of the (composite) Peninsular-Wrangellia-Alexander terrane, which is thought to have occurred during latest Cretaceous to early Tertiary time, may be responsible for (1) greenschist-facies retrograde metamorphism (M_2) of overlying unit 58 (Haley Creek metamorphic assemblage; Wallace, 1981, 1984; Nokleberg and others, 1989); (2) prehnite-pumpellyite–facies retrograde metamorphism (M_2) of overlying unit 59 (part of the Strelna metamorphics of Plafker and others, 1989b); and (3) a low-grade overprint in the Jurassic plutons that intrude unit 59 (Dusel-Bacon and others, 1994b). Characteristic M_2 minerals in unit 59 are pr (which occurs most commonly as lenses that bow apart the cleavage planes of metamorphic and igneous bt, and less commonly as veins), ep, ch, and rare pu or lau (Dusel-Bacon and others, 1994b). Calcium-rich fluids which formed veins of pr, and probably played a part in crystallization of M_2 phases, may have been derived from the underlying graywackes of the Valdez Group (Chugach terrane flysch). Lower plate rocks belonging to the Valdez Group may underlie unit 59 at a fairly shallow level, as is the case with the correlative Haley Creek metamorphic assemblage (unit 58), where the Valdez Group occurs at a depth of only 1 km (Page and others, 1986). Fracturing and fluid migration probably occurred during extension of upper plate rocks belonging to the Strelna metamorphics as they were underthrust by rocks of the Valdez Group. A possible analog to the proposed formation of pr in this unit is provided by the study of pr in plutonic and metamorphic rocks of the Salinian block of California. Ross (1976) proposed that hydrous solutions, derived from a "substratum" of Franciscan(?) graywackes, migrated through fractured rocks of the tectonically thinned margin of the Salinian block near the Sur fault zone, causing widespread crystallization of Ca-Al silicates.

Early Tertiary low-grade metamorphism of Prince William and Ghost Rocks terranes. A weakly metamorphosed and strongly deformed subduction complex of flysch and tholeiite, shown as prehnite-pumpellyite–facies unit 84 and related polymetamorphosed unit 85, crops out seaward of the slightly older Chugach terrane subduction complex. This complex is separated from the Chugach terrane by the landward-dipping Contact fault system (Plafker and others, this volume, Chapter 12). In the northern Gulf of Alaska, units 84 and 85 make up the Orca Group of the Prince William terrane (Tysdal and Case, 1979; Winkler, 1976; Winkler and Plafker, 1981; Helwig and Emmet, 1981). On Kodiak Island, unit 84 constitutes the Ghost Rocks Formation of Byrne (1982) of the Ghost Rocks terrane (Connelly, 1978; Byrne, 1986). The depositional age of the Orca Group is late Paleocene to middle Eocene (Plafker and others, 1985). Eocene fossils are reported from the Ghost Rocks Formation (Connelly, 1978), but the bulk of the formation accumulated during earliest Paleocene time with melange units including some Late Cretaceous material (Moore and others, 1983). Units 84 and 85 are generally isoclinally folded and include metagraywacke, argillite, metalimestone, greenstone, and mafic schist. Intense localized shearing has produced many zones of tectonic melange on Kodiak Island (Byrne, 1984) and in the southwestern part of Prince William Sound. In general, rocks of the Orca Group of unit 84 show a gradual increase in metamorphic grade from south to north (Goldfarb and others, 1986).

Low-grade metamorphism and deformation within both the Ghost Rocks and Prince William terranes took place during early Tertiary time and predated, perhaps by very little, the intrusion of the early Tertiary plutons that stitch them to the Chugach terrane. On Kodiak Island, these plutons, dated at 62 Ma, contact metamorphosed the Upper Cretaceous and Paleocene Ghost Rocks Formation and cut its structural fabric (Moore and others, 1983). Eocene and younger rocks in the Kodiak Islands are only slightly altered—further supporting a Paleocene metamorphic age for that area (Moore and others, 1983). Intrusion and metamorphism of the upper Paleocene to middle Eocene Orca Group occurred slightly later than did metamorphism of the Ghost Rocks Formation. From Prince William Sound to the east, 53- to 48-Ma plutons crosscut and contact metamorphosed already deformed and weakly metamorphosed rocks of the Orca Group (Winkler and Plafker, 1981; Miller and others, 1984). If the timing of metamorphism parallels that of plutonism, metamorphism began earlier in the west than in the east.

Low-grade metamorphism was probably associated with accretion of the terranes. Asymmetric north-dipping south-verging folds, which developed within unit 84 and the adjacent greenschist-facies rocks of the Chugach terrane (unit 77) near the Contact fault zone west of the Copper River, are interpreted as being synaccretionary structures, developed during oblique thrust convergence (Plafker and others, 1986). Similarly, Byrne (1986) proposed that the development of conjugate folds and spaced cleavage within the Ghost Rocks Formation occurred as a result of subhorizontal shortening of the accretionary complex during underthrusting.

East of the Copper River within unit 85, the low-grade mineral assemblages and associated structures, presumed to have formed during accretion, are overprinted by gt-co-bearing, low-P, amphibolite-facies assemblages. These higher grade assemblages were produced during the regionally extensive, predominantly thermal, metamorphism that accompanied the intrusion of Eocene plutons in this area of the Prince William and adjacent Chugach terranes (Miller and others, 1984; Sisson and others, 1989). The metamorphic effects of this episode extend across the Contact fault zone and correspond to the M_2 episode of unit 78 (Chugach metamorphic complex), as discussed in a previous section.

Southeastern Alaska

Middle Cambrian to Early Ordovician metamorphism. The oldest metamorphic episode in southeastern Alaska occurred under dominantly greenschist-facies conditions (M_1 of unit 86) on southern Prince of Wales Island (Gehrels and Saleeby, 1987b), in small areas (not shown on Plate 4A) on the southern tip of Gravina Island and adjacent islands (Gehrels and others, 1987), and under amphibolite-facies conditions (M_1 of unit 87) on southern Dall Island to the west (G. E. Gehrels, oral communication, 1987; Gehrels and Berg, this volume). Both of these units consist of metavolcanic and metasedimentary rocks. They have been described as the Wales Group (Buddington and Chapin, 1929; Herreid and others, 1978; Eberlein and others, 1983) and most recently as the informally designated Wales metamorphic suite (Gehrels and Saleeby, 1987b). Unit 86 consists of greenschist-facies mafic schist, greenstone, pelitic schist, phyllite, and marble, and small areas of amphibolite-facies schist and metaplutonic rocks. Unit 87 contains amphibolite-facies equivalents of unit 86. Preliminary U-Pb ages on zircon indicate Middle and Late Cambrian protolith ages for interlayered metaplutonic bodies, and thus Late Proterozoic and/or Cambrian protolith ages for the associated metasedimentary and metavolcanic rocks of these two units (Gehrels and Saleeby, 1987b).

In most areas, protolith features are obscured by penetrative metamorphic recrystallization and a high degree of flattening (Gehrels and Saleeby, 1987b). Mineral lineations are common in the amphibolite-facies rocks, and are present locally in mafic schist (Herreid and others, 1978; Eberlein and others, 1983).

A Late Cambrian and Early Ordovician age is indicated for M_1 metamorphism because: (1) metaplutonic rocks of Middle and/or Late Cambrian age are metamorphosed and deformed (Gehrels and Saleeby, 1987b), but uppermost Lower and Middle Ordovician strata of unit 88 that occur nearby and probably overlie unit 86 are only weakly metamorphosed and lack the penetrative metamorphic fabric characteristic of unit 86 (Eberlein and others, 1983; Gehrels and Saleeby, 1987b); and (2) rocks from unit 86 yield K-Ar ages of about 483 Ma (Turner and others, 1977). This metamorphic episode is part of the Wales orogeny of Gehrels and Saleeby (1987a, b). Although retrograde metamorphic effects have not been reported for units 86 and 87, geologic relations indicate that they were probably affected by the same low-grade metamorphic episode during Silurian and earliest Devonian time (shown as M_2) that is recorded in adjacent unit 88.

Silurian to earliest Devonian low- to medium-grade metamorphism. A weakly to moderately developed, Silurian to earliest Devonian metamorphic episode is recorded in the prehnite-pumpellyite–facies rocks of unit 88; in the lower greenschist-facies rocks of unit 89; and in the M_1 episode of the polymetamorphosed greenschist- and locally epidote-amphibolite-facies rocks of unit 90. Included in these units are basaltic to rhyolitic metavolcanic rocks, metasedimentary rocks, metachert, and metalimestone of late Early Ordovician to Early Silurian protolith age, and quartz dioritic plutons of Middle Ordovician to Early Silurian age (Eberlein and others, 1983; Gehrels and Berg, 1992; this volume).

The metamorphic grade is lowest on southern Prince of Wales Island and increases westward and eastward. Unit 88 is not penetratively deformed, and relict sedimentary and volcanic textures are widespread. Crosscutting plutonic rocks, also assumed to have been weakly metamorphosed, are locally brecciated. Metamorphism in the westernmost exposure of unit 88 increases southward into semischistose rocks of unit 89. East of Prince of Wales Island, the polymetamorphosed rocks of unit 90 generally are cataclastically deformed and show no pronounced foliation; locally rocks are schistose (Berg and others, 1988; Gehrels and others, 1983). Minor retrogressive metamorphism, apparent in the higher grade rocks of unit 90, is believed to have occurred during one or more of the Cretaceous metamorphic episodes, described below.

A Silurian to earliest Devonian metamorphic age is indicated for the following reasons: (1) strata of Early Silurian age are metamorphosed, but overlying strata of middle Early Devonian age and younger are either unmetamorphosed, as on Prince of Wales Island, or only affected by the Cretaceous metamorphic episode, as on the islands to the east (Gehrels and others, 1983); (2) metamorphosed Silurian rocks of unit 87 are cut by an undeformed latest Silurian to earliest Devonian (408 ± 10 Ma) pyroxenite (Eberlein and others, 1983; G. E. Gehrels, written communication, 1984); and (3) Late Silurian trondhjemite dikes crosscut the foliation of metadioritic rocks of Late Ordovician to Early Silurian protolith age, but have the same post-metamorphic deformational features as their wall rocks, indicating that the trondhjemite dikes and plutons were intruded before the final deformation that occurred during the latter stages of the episode (Gehrels and others, 1983; G. E. Gehrels, oral communication, 1985). Metamorphism of this unit is considered to have been part of an orogenic event referred to as the Klakas orogeny (Gehrels and others, 1983; Gehrels and Saleeby, 1987b).

Early Cretaceous metamorphism. Metamorphism in units 95 to 98 was apparently associated with the intrusion of elongate bodies of highly foliated tonalite and diorite of Early Cretaceous age (120 to 110 Ma; Loney and others, 1967; Decker and Plafker, 1982; Dusel-Bacon and others, 1994a; Brew, this volume). These units are included in the Alexander terrane.

Unit 95 crops out near Glacier Bay and on Chicagof Island and consists of a diverse assemblage of amphibolite-facies and hornblende-hornfels facies pelitic and semipelitic schist and gneiss, marble, and amphibolite, and minor amounts of lower grade greenstone and greenschist; protoliths are sedimentary and volcanic rocks of Silurian to Devonian age (Loney and others, 1975; Brew, 1978). On Chichagof Island, rocks are intensely folded, and there is a complete gradation in metamorphic textures between hornfels and foliated rocks (Loney and others, 1975). Structural trends in metamorphic rocks parallel those of the Cretaceous plutons. The general parallelism between the foliate fabric of the plutons, pluton/wall-rock contacts, and structures in the wall rocks, suggests that plutonism, folding, and thermal and dynamothermal metamorphism all took place as part of a continuum that occurred under roughly the same stress conditions.

Units 96 to 98 crop out on Admiralty Island and the adjacent mainland and form a sequence of metasedimentary, metavolcanic, and metaplutonic rocks that range in grade from prehnite-pumpellyite facies (unit 96), to greenschist (or albite-epidote-hornfels) facies (unit 97), and finally to undifferentiated greenschist (or albite-epidote-hornfels) facies and amphibolite (or hornblende-hornfels) facies (unit 98). Protoliths range in age from Ordovician to Early Cretaceous (references given in Dusel-Bacon and others, 1994a). Most medium and higher grade rocks are penetratively deformed. Intrusive rocks of the largest batholith on Admiralty Island are poorly to well foliated, but the trend of the foliation relative to that of the country rocks has not been studied in detail (Lathram and others, 1965). Evidence that metamorphism was associated with late Early Cretaceous plutonism consists of an apparent progressive increase in metamorphic grade toward the plutons, and a merging of contact aureoles with large areas of dynamothermally metamorphosed phyllite, schist, and gneiss of unit 98 (Loney and others, 1967).

The age and origin of metamorphism of greenschist- and, very locally, amphibolite-facies rocks of unit 92 is unknown. This unit crops out northeast of Glacier Bay and is bounded on the east by the Denali fault. Protoliths include mafic volcanic rocks, sedimentary rocks, and limestone, and have been correlated with rocks of Silurian to Permian age (MacKevett and others, 1974). Unit 92 also is intruded by a pluton of the belt of 120- to 110-Ma plutons that are thought to have been associated with metamorphism of units 95 to 98 to the south; therefore, metamorphism of unit 92 may have had a similar origin. An alternative and slightly older metamorphic history is suggested by geologic evidence from the apparent continuation of this unit about 100 km to the northwest in Canada. In that area, regional metamorphism and deformation appear to have occurred between Late Triassic and Early Cretaceous time and may have been associated with latest Jurassic to earliest Cretaceous (150 to 130 Ma) plutonism (R. B. Campbell and C. J. Dodds, written communication, 1986). This possible metamorphic episode is analogous to that discussed for unit 64 in the previous section (area of southern Alaska between the McKinley and Denali faults and the Border Ranges fault system).

Mid-Cretaceous low-grade metamorphism. Prehnite-pumpellyite– to lower greenschist-facies metasedimentary rocks, intermediate to mafic metavolcanic rocks, metalimestone, and metachert (unit 100 and related polymetamorphic unit 102) crop out in a 150-km-long southeast-trending belt from Kupreanof Island to Cleveland Peninsula. Protoliths of rocks correlated with the protoliths range in age from Late Triassic to mid-Cretaceous–Albian or Cenomanian (Berg and others, 1972; Brew and others, 1984; Gehrels and Berg, 1992). Rocks have been weakly metamorphosed (ch-, ac-, and rarely bt-zone assemblages) and locally are intensely folded and faulted. Metasedimentary rocks are generally poorly foliated, but fine-grained variants have good cleavage. Greenschist and greenstone locally contain abundant relict pyroxene phenocrysts (Brew and others, 1984).

Regional low-grade metamorphism is known to predate the intrusion of Alaskan-type mafic-ultramafic bodies that have yielded K-Ar ages of 110 to 100 Ma (Lanphere and Eberlein, 1966; Clark and Greenwood, 1972; Brew and others, 1984; Douglass and Brew, 1985). The late Early Cretaceous minimum metamorphic age indicated by these dates is close to the Albian or Cenomanian protolith age of the youngest rocks included in this unit. The geographic limits of the area affected by this episode are not known with certainty; they may have extended into the area shown as unit 101, discussed below.

Early Late Cretaceous intermediate-P metamorphism associated with the intrusion of 90-Ma plutons. Amphibolite-facies pelitic schist, quartzofeldspathic schist and gneiss, amph schist and gneiss, and minor amounts of marble, calc-schist, migmatite, and metaplutonic rocks (Berg and others, 1988; Brew and others, 1984) of unit 103 crop out from near Wrangell to Revillagigedo Island adjacent to and extending some distance from 90-Ma plutons. Protoliths of unit 103 are considered to include Jurassic and/or Cretaceous flysch, Permian and Triassic limestone, and intrusive rocks of probable Jurassic to Cretaceous age. Rocks are sufficiently recrystallized so that neither the original textures nor the original structures remain.

Kyanite, indicative of intermediate-P metamorphic conditions, is common in the st + gt ± sil–bearing pelitic schist of unit 103 (Berg and others, 1988; Douglass and Brew, 1985) and in aureoles developed around the 90-Ma plutons that intrude unit 102. In the northern part of unit 103 and within adjacent unit 102, relict anda also has been observed in pelitic schist from the aureoles of 90-Ma plutons (Plate 4A). In these areas, relict porphyroblasts of statically formed anda have been replaced by static (radial) ky or in some locations by mineral aggregates of intergrown ky and st (Dusel-Bacon and others, 1994a). This crystallization sequence of the Al_2SiO_5 polymorphs appears to indicate an increase from low- to intermediate-P conditions in the northern part of this unit during intrusion and metamorphism.

Most of the 90-Ma plutons referred to above are of intermediate composition and contain primary gt and epidote; they are part of a plutonic belt that extends from southern Revillagigedo Island north to the vicinity of Haines (Zen and Hammarstrom, 1984a; Brew, this volume). Sillimanite and ky isograds are located around the large 90-Ma plutons in the areas of Wrangell and northern Revillagigedo Islands, and metamorphic grade increases toward the plutons (Dusel-Bacon and others, 1994b), providing evidence that metamorphism was associated with plutonism. These plutons (shown as Kg with a "+" overprint on Plate 4A) are interpreted as having been emplaced during the waning stages of metamorphism and deformation (Brew and others, 1984; Douglass and Brew, 1985; Berg and others, 1988).

Geothermometric and geobarometric data from two samples of gt-ky schist in the southern part of unit 103 indicate a final equilibration T and P of 600°C, 7.5 to 8.5 kb, and 575 to 600°C, 8.5 to 9.2 kb for mineral rims (M. L. Crawford, written communication, 1983; Dusel-Bacon and others, 1994a). A similar, moderately high, P of final crystallization has been proposed for the primary gt- and epidote-bearing 90-Ma plutons that intruded this unit late in, or immediately following, the metamorphic episode. Zen and Hammarstrom (1984b), citing experimental data on the composition of magmatic gt and on the P required to crystallize magmatic epidote, propose that the magma began to crystallize at a minimum P of 13 to 15 kb (about 40 to 50 km) and finally crystallized at about 6 to 10 kb (about 20 to 30 km). The combination of the high- to intermediate-P magmatic and crystallization history inferred for the plutons, and the occurrence of relict anda, indicative of low-P conditions (less than 3.8 kb; Holdaway, 1971), in their aureoles in the Wrangell Island area, is indeed problematic.

Greenschist-facies unit 101 crops out south of amphibolite-facies unit 103 in the area of Revillagigedo Island and consists of metasedimentary and metavolcanic rocks, and minor amounts of marble and metaplutonic rocks (Berg and others, 1988). Protolith ages range from Devonian to Early Cretaceous (Berg and others, 1988; Gehrels and others, 1987). On Revillagigedo Island and the peninsula to the northwest, metamorphic foliation dips to the northeast, and the metamorphic sequence is cut by southwest-vergent thrust faults (Berg and others, 1988; Rubin and Saleeby, 1987).

Metamorphism of unit 101 also may have been part of the same thermal episode that culminated in the intrusion of early Late Cretaceous (approximately 90 Ma) plutons, as was the case for unit 103. This relation is suggested by the observation made by Berg and others (1988) that metamorphic mineral assemblages show an apparent gradational increase in grade from the southwest to the northeast, beginning in the greenschist-facies rocks of unit 101 and continuing into the amphibolite-facies unit 103. An argument against this interpretation is the recent detailed mapping by M. L. Crawford (oral communication, 1988), which indicates an abrupt, rather than gradational, increase in metamorphic grade at the boundary between units 101 and 103. An alternative, but not necessarily mutually exclusive, interpretation is that regional greenschist-facies metamorphism is a higher grade equivalent of the mid-Cretaceous episode that affected unit 100

(Dusel-Bacon and others, 1991a). This hypothesis is based on an extension of the interpretation of the metamorphic history of unit 100 to the northwest (Brew and others, 1984; Douglass and Brew, 1985) and on similarities noted during a reconnaissance of northern Revillagigedo Island by D. A. Brew (unpublished data, 1983).

K-Ar age determinations on amphibolite- and greenschist-facies rocks on Revillagigedo Island show a decrease in maximum apparent ages northward and eastward (Smith and Diggles, 1981; Berg and others, 1988). $^{40}Ar/^{39}Ar$ plateau ages on hb from plutonic and metamorphic rocks on Revillagigedo Island and from similar rocks to the south in British Columbia, show a similar age pattern, ranging from greater than 90 Ma in the west to about 56 Ma near the eastern boundary of unit 103 (Sutter and Crawford, 1985). Uplift of this block of rocks was greatest and occurred latest in the eastern part of the block. The eastern boundary of the block is spatially related to the Coast Range megalineament (Brew and Ford, 1978)—a topographic, structural, and geophysical feature that appears to have been near the western limit of large-scale regional uplift of southeastern Alaska and adjacent parts of British Columbia beginning in early Tertiary time (Crawford and Hollister, 1982, 1983).

Late Cretaceous to early Tertiary synkinematic metamorphism and plutonism. An intermediate-P (Barrovian) metamorphic sequence consisting of prehnite-pumpellyite–facies rocks (unit 105), greenschist-facies rocks (unit 106), and amphibolite-facies rocks (unit 107) crops out as an elongate, northwest-trending belt along the mainland of southeastern Alaska from Skagway to the area east of Wrangell. The Barrovian sequence increases in metamorphic grade to the northeast (Dusel-Bacon and others, 1994a, and references contained therein). Protoliths are thought to be clastic sedimentary rocks, mafic to intermediate volcanic, intrusive, and volcanogenic sedimentary rocks, limestone, and chert. Few fossils have been found in these rocks, but protolith ages are considered to be Permian, Triassic, and Jurassic to Cretaceous (Brew and Ford, 1984).

An early foliation, presumably formed during either or both of the low-grade episodes recorded in adjacent units 93 and 96, is locally detectable in unit 105 and the lowest grade part of unit 106 (Brew and others, 1984). With increasing metamorphic grade, rocks develop well-defined crenulation cleavage and transposition layering. Higher grade rocks in unit 106 and all those in unit 107 are well foliated and lineated. Foliation in gneissic rocks is locally anastamosing or lenticular. Mineral isograds marking the first appearance of bt, gt, st, ky, and sil trend north-northwest, generally parallel with elongate quartz dioritic plutons referred to as a tonalite sill complex by Brew and Ford (1981; also see Brew, this volume). It is shown on Plate 4A as the 600-km-long synkinematic intrusive unit TKg, just east of the Coast Range megalineament. Isogradic surfaces dip moderately to steeply northeast (Ford and Brew, 1973, 1977a; Brew and Ford, 1977), and hence are inverted. In the area east of Kupreanof Island, isogradic surfaces appear to steepen northeastward toward the Coast Range megalineament (Brew and others, 1984).

Garnet-biotite geothermometry for the sil-zone rocks of unit 107 (Himmelberg and others, 1984) indicates an equilibration T of about 690°C (calibration of Thompson, 1976) or 750°C (calibration of Ferry and Spear, 1978). The absence of anda and the abundance of ky indicates a minimum equilibration P of about 3.8 kb (Holdaway, 1971). Preliminary sphalerite geobarometry of three massive-sulfide deposits within the megalineament zone on the mainland east of central Admiralty Island indicates a general P range that is consistent with values of 3.8 to 4.5 kb at 575°C, calculated from silicate mineral equilibria of st-zone rocks in the same general area (Stowell, 1985). Geobarometry calculated by several methods indicates a P of about 9 kb for rocks to the north, but the data exhibit large scatter (G. R. Himmelberg, unpublished data, 1987; Brew and others, 1987).

Amphibolite-facies rocks on the mainland east and southeast of Wrangell Island (unit 108) contain lithologies similar to those in the amphibolite-facies part of the Barrovian metamorphic sequence (unit 107) to the north. Although they occur on strike, they are differentiated on the basis of possible P differences during final equilibration of the rocks. Unit 108 is a heterogeneous complex of migmatite, massive to foliated or gneissic batholiths, and smaller plutons that enclose metamorphic screens and roof pendants of paragneiss (Berg and others, 1988). Protolith ages are not generally known, but those of paragneiss are probably Paleozoic or Mesozoic (Brew and Ford, 1984; Berg and others, 1988), and at least some of those of orthogneiss are Early Cretaceous (Barker and Arth, 1984; Hill, 1984).

Garnet and sil are common constituents of the paragneiss and pelitic schist of unit 108; co occurs locally in the pelitic schist. Intermediate- to low-P conditions are suggested by mineral assemblages, and by thermobarometric data that indicate P-T conditions of 3.5 to 4.5 kb and 650°C (calibration of Ferry and Spear, 1978) for a sample of sil-gt-bt-qz-pl schist in northeastern Ketchikan Quadrangle (M. L. Crawford, written communication, 1983; Dusel-Bacon and others, 1994a). In many areas, paragneiss grades downward and laterally into gneissic granodiorite; elsewhere it is in sharp contact with plutonic rocks, or passes gradually into them through a zone of migmatite (Berg and others, 1988). Quartz diorite of the tonalite sill is commonly at least weakly foliated, and in the extreme case, is gneissic. Its foliation generally strikes north or northwest and is parallel to the outcrop trend and to the internal structure of the adjoining metamorphic rocks of unit 108. Much of the quartz diorite also has mylonitic or cataclastic textures, such as undulose quartz and granulated grain boundaries (Berg and others, 1988).

Metamorphism of units 105 to 108 (and M_2 of unit 104) is considered to be slightly pre- and synkinematic with the latest Cretaceous and early Tertiary mesozonal intrusion of the tonalite sill. Intrusion of the sill has been dated by U-Pb zircon methods of about 69 and 62 Ma in the north (Gehrels and others, 1984) and at about 58 to 55 Ma in the south (Berg and others, 1988). Evidence for the association of metamorphism and plutonism consists of the increase in metamorphic grade toward the sill; general parallelism between the sill and isograds that define the

Barrovian metamorphic sequence; and parallelism of foliation, contacts, and locally developed lineation in the sill with structural elements in the adjacent metamorphic rocks. In the Juneau area, truncation of metamorphic isograds by the sill, and parallelism between foliation in the sill and that in the metamorphosed wall rocks, suggest that intrusion of the sill accompanied a late stage of the regional metamorphism—a stage occurring after the thermal maximum but before the end of penetrative deformation (Ford and Brew, 1977b). Epizonal plutons (Tg) intruded the eastern part of the amphibolite-facies units during Eocene time. These Eocene plutons are surrounded by low-P high-T metamorphic rocks and by migmatites. The original eastern limit of the Barrovian metamorphism is obscured by the Eocene intrusions, but limited evidence indicates that the low-P metamorphism around the Eocene plutons was superimposed over the previous intermediate-P metamorphism.

A P-T-time path has been determined for the plutonic and metamorphic sequence that crops out near Prince Rupert, British Columbia, across the international boundary from unit 108. Many aspects of that path may also apply to the metamorphic history of unit 108 and perhaps also of units 105 to 107. Near Prince Rupert, metamorphic reactions, thermobarometric data, and isotopic data indicate that rocks correlative with those of unit 108 were uplifted and eroded at a rate of about 1 mm/yr between about 60 and 48 Ma, beginning at a depth of about 20 km and terminating at about 5 km (Hollister, 1982; revised in Crawford and others, 1987). The emplacement of the elongate 60-Ma Quotoon pluton, which is the continuation of the Alaskan tonalite sill, apparently occurred at deep levels during the early stages of uplift. Emplacement of intermediate and felsic plutons along the eastern margin of the complex occurred at high levels during the end stages of uplift. According to the Canadian work, metamorphism continued throughout the period of uplift under evolving P-T conditions (Hollister, 1982; Crawford and Hollister, 1982, 1983). Because of similarities in style and conditions of metamorphism between rocks west of the megalineament in British Columbia (correlative with unit 101) and early metamorphic relicts found in rocks east of the megalineament (correlative with unit 108), Crawford and Hollister (1982, 1983) suggest that high-grade rocks east of the megalineament were also metamorphosed during the episode associated with the intrusion of the 90-Ma plutons, discussed above. The high-grade crustal block east of the megalineament is thought to have remained at depth until it was displaced by rapid vertical uplift as a result of the weakening of the crust by anatexis and the development of melt-lubricated shear zones—particularly the one represented by the tonalite sill, along which rapid vertical movement was concentrated (Hollister and Crawford, 1986; Crawford and others, 1987).

The tectonic environment of the widespread plutonometamorphic episode that occurred along the western edge of the Coast Mountains in early Late Cretaceous and early Tertiary time was dominated by crustal thickening due to the accretion of an outboard terrane to the west (Plafker and Berg, this volume, Chapter 33). Monger and others (1982, 1983) proposed that the plutonometamorphic belt of the Coast Mountains of southeastern Alaska and British Columbia developed as a welt resulting from the accretion of the amalgamated Wrangellia and Alexander terranes against the previously accreted Stikinia and other terranes in Cretaceous and Tertiary time. Brew and Ford (1983) interpret the stratigraphic and paleomagnetic evidence to suggest that the Alexander and Stikinia terranes are one and the same and that a rift developed in the megaterrane as it migrated northward. According to their model, that rift was filled with the flysch and volcanic rocks of the Gravina belt (Berg and others, 1972) during Late Jurassic and Early Cretaceous time. They propose that the plutonometamorphic belt formed as a result of the closure of the rift and the resultant crustal thickening during accretion of the Chugach terrane—a terrane that lies to the west and southwest of the Alexander and Wrangellia terranes.

Workers in the southern extension of this metamorphic belt near Prince Rupert, British Columbia, concur with the terrane accretion model of Monger and others (1982). They propose that the crustal thickening resulted from west-directed tectonic stacking of crustal slabs along east-dipping thrusts. In places the thrusts were possibly lubricated by the intrusion of melt (parent magma of intermediate epidote-bearing plutons and sills) generated at the base of the crust (Hollister and Crawford, 1986; Crawford and others, 1987). These thrust faults, which were synchronous with 100- to 90-Ma plutonism near Prince Rupert, may be correlative with thrusts identified on Revillagigedo Island in Alaska (M. L. Crawford, oral communication, 1987).

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NOTES ADDED IN PROOF

Significant additions to our understanding of the metamorphic history of Alaska have been made since this chapter was written five years ago. More up-to-date coverage of metamorphic data for much of Alaska is presented in the regional-scale treatments of the topic in U.S. Geological Survey Professional Papers 1497-C, published in 1993, and 1497-B and 1497-D planned for publication in 1994. Detailed metamorphic studies in three areas—the Yukon-Tanana upland, the Seward Peninsula, and the southern Brooks Range—conducted since this chapter was written have yielded important new constraints, which are outlined briefly below.

Recent geothermobarometric data from the Yukon-Tanana Upland of east-central Alaska (Dusel-Bacon and Hansen, 1992) indicate that high- to intermediate-pressure/medium-temperature metamorphism affected both the ductilely deformed amphibolite-facies rocks of unit 37 (Taylor Mountain terrane of Dusel-Bacon and Hansen [1992]) and those of the adjacent, eastern part of unit 46 (Lake George subterrane of the Yukon-Tanana terrane of Dusel-Bacon and Hansen [1992]). Rocks of unit 37 give latest Triassic to Middle Jurassic metamorphic cooling ages, whereas those of unit 46 give Early Cretaceous metamorphic cooling ages (Hansen and others, 1991). On the basis of geothermometric, kinematic, thermochronologic, and lithologic data, Hansen and others (1991) and Dusel-Bacon and Hansen (1992) proposed that high-pressure metamorphism of both units 37 and 46 took place during different phases of the latest Paleozoic through early Mesozoic shortening episode, resulting from closure of an ocean basin now represented by klippen of the Seventymile–Slide Mountain terrane (units 38 and MzPz u). According to their model, high-pressure metamorphism of unit 37 took place within a southwest-dipping (present-day coordinates) subduction system, whereas high-pressure metamorphism of unit 46 occurred during continentward overthrusting of the Taylor Mountain and Seventymile–Slide Mountain terranes and imbrication of the continental margin in Jurassic time. Hansen and others (1991) and Dusel-Bacon and Hansen (1992) propose that the difference in metamorphic cooling ages between the Taylor Mountain terrane and adjacent parts of the Lake George subterrane is best explained by Early Cretaceous unroofing of the Lake George subterrane caused by crustal extension, recorded in a younger top-to-the-southeast fabric. Unequivocal evidence for widespread mid-Cretaceous extension within the Yukon-Tanana terrane, discussed briefly in this chapter under the subheading "Problematic tectonic origin of Cretaceous metamorphism . . . ," is presented in detail by Pavlis and others (1993) in connection with their important kinematic study of mylonites within the footwall of the sillimanite gneiss dome southeast of Fairbanks, shown on Plate 4.

Important geophysical constraints on the tectonic history of the Yukon-Tanana terrane of east-central Alaska have been provided by seismic refraction/wide-angle reflection and magnetotelluric experiments conducted as part of the Trans-Alaska Crustal Transect program (TACT). Major crustal features identified by these studies are an anomalously thin crust, approximately 30 km thick (Beaudoin and others, 1992), a highly conductive zone in the middle crust interpreted as underthrust Mesozoic flysch (Stanley and others, 1990), and a basal crustal section that Beaudoin and others (1992) interpreted as the underthrust basement of the composite Peninsular-Alexander-Wrangellia superterrane. Largely on the basis of the above interpretations of the present makeup of the crust along the TACT line, Nokleberg and others (1991) interpret the Early Cretaceous metamorphic cooling ages in unit 46 to record regional metamorphism and deformation associated with underplating of Mesozoic flysch and the Gravina arc and oblique collision of the Peninsular-Alexander-Wrangellia superterrane with the Yukon-Tanana terrane, rather than to record cooling related to metamorphism during an extensional event. However, as mentioned in this chapter under the subheading "Problematic tectonic origin of Cretaceous metamorphism . . . ," problems remain with the relative timing of events inherent in the underplating model.

Additional data on the evolution of the blueschist belt on the Seward Peninsula (unit 16, Plate 4) published since this chapter was written are presented in papers by Evans and Patrick (1987) and Patrick and Evans (1989). Recent work in the Kigluaik Mountains in the southwestern Seward Peninsula has shown that Cretaceous magmatism was synchronous with amphibolite- to granulite-facies metamorphism (of units 18 and 19, Plate 4) (Amato and others, 1992). Two different interpretations of the tectonic setting of the high-grade metamorphic episode have been made. Patrick (1988) and Patrick and Lieberman (1988) proposed that the high-grade episode overprinted the earlier widespread blueschist-facies metamorphism (of unit 16, Plate 4) and was a natural consequence of crustal telescoping followed by thermal relaxation and anatexis. According to Amato and others (1992) and Miller and others (1992), however, high-grade metamorphism probably occurred as a result of mafic magmatism associated with regional extension within the Cretaceous magmatic belt.

Important additional metamorphic, structural, and thermochronologic studies have also been made that relate to the evolution of the widespread blueschist facies belt in the southern Brooks Range (units 1-3, Plate 4). Till and others (1988) delineated two temporally and structurally distinct high-pressure/low-temperature metamorphic belts in the southern Brooks Range: the schist belt, penetratively and ductilely deformed in the Jurassic, and the central belt, inhomogeneously deformed during mid-Cretaceous time. An inverted metamorphic gradient overprinted schist-belt blueschists in the Walker Lake area at 110 Ma (Patrick and others, 1991; Till and Patrick, 1991). The schist belt was exhumed by mid-Albian, based on deposition of detritus from the belt in the foreland basin at that time (Till, 1992).

Structural fabrics in the schist belt have been attributed to a ductile event related to contractional tectonism and a later less penetrative event related to extension (Gottschalk and Oldow, 1988; Gottschalk, 1990) or to a ductile event related to extension (Miller and others, 1990a, b). The ductile extension proposed by Miller and her coworkers for the schist belt is just one of many lines of evidence used by Miller and Hudson (1991) to postulate that the crust of northern and central Alaska was thinned by lithospheric-scale extension during the mid-Cretaceous. This theory remains controversial and has been discussed by Till and others (1993) and Miller and Hudson (1993).

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