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Thermobarometric Constraints on Mid-Cretaceous to Late Cretaceous Metamorphic Events in the Western Metamorphic Belt of the Coast Mountains Complex near Petersburg, Southeastern Alaska

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Abstract

The western metamorphic belt is part of the Coast Mountains Complex of southeastern Alaska and western Canada. This complex formed as a result of mid-Cretaceous through middle Eocene crustal shortening between the previously amalgamated Wrangellia and Alexander terranes (Insular superterrane) and previously accreted terranes of the North American continental margin (Intermontane superterrane). The western metamorphic belt, which ranges from a few kilometers to several tens of kilometers in width, records a complex sequence of contact-metamorphic and regional metamorphic events, the most significant of which are designated M_1^R, M_2^{C-R}, and M_3^R. The M_1^R regional metamorphic event ranged in grade from subgreenschist to greenschist facies and was overprinted by the M_2^{C-R} and M_3^R metamorphic events. The M_2^{C-R} metamorphic event is recorded in discrete contact-metamorphic aureoles and regional metamorphic-mineral assemblages related to tonalite-granodiorite plutons of the Admiralty-Revillagigedo plutonic belt. The M_3^R metamorphic belt, which is adjacent to the M_2^{C-R} belt, is characterized by regional Barrovian isograds of garnet, staurolite, kyanite, and sillimanite. Using the THERMOCALC program, pressure-temperature (P–T) conditions for the M_2^{C-R} metamorphic event are estimated to be in the ranges 5.3–7.5 kbars and 525–640ºC and for the M_3^R metamorphic event in the ranges 9.4–12.6 kbars and 730–895ºC. The M_2^{C-R} metamorphic event occurred at approximately 90 Ma, but the timing of the M_3^R metamorphic event is poorly documented and uncertain. On the basis of an $^{40}Ar/^{39}Ar$ age on actinolitic amphibole and a Sm–Nd age on garnet core, the timing of metamorphism might be constrained between 90±1 and 80±9 Ma, although the Sm-Nd age of 80±9 m.y. possibly reflects postpeak growth. Thermobarometric data suggest that the two events occurred at different crustal levels and followed different P–T paths. No evidence exists that M_2^{C-R} metamorphic-mineral assemblages were overprinted by the M_3^R metamorphic event, as proposed by some workers. Juxtaposition of the two belts of rocks probably occurred along the Coast shear zone during uplift and exhumation of the Coast Mountains.

Introduction

The plutonic and metamorphic rocks of southeastern Alaska and western Canada constitute part of the Coast Mountains Complex (Brew and others, 1995; referred to as the Coast Plutonic Complex by Stowell and McClelland, 2000). This complex formed as a result of mid-Cretaceous through middle Eocene crustal shortening between the previously amalgamated Wrangellia and Alexander terranes (Insular superterrane) and previously accreted terranes of the North American continental margin (Intermontane superterrane) (Monger and others, 1982). From west to east, the Coast Mountains Complex consists of the western metamorphic belt, the central pluton gneiss belt, and the eastern metamorphic belt (Crawford and others, 1987; Brew and others, 1989, 1995). The central pluton gneiss belt was named the “Coast Range batholith” by Buddington and Chapin (1929), and that designation, or “Coast Mountains batholith,” is still used by some workers.

The magmatic, metamorphic, and deformational history of mid-Cretaceous through middle Eocene crustal contraction is partly recorded in the western metamorphic belt (figs. 1, 2). The sequence of plutonic, metamorphic, and deformational events therein is recognized by most workers in the Coast Mountains, and polymetamorphic overprinting of the M_1^R by the M_2^{C-R} metamorphic event has been documented (Brew and others, 1989; Stowell and Crawford, 2000). However, the temporal and spatial relations of the M_2^{C-R} and M_3^R metamorphic events are poorly understood. Most workers (Douglass and Brew, 1985; Brew and others, 1989; Himmelberg and others, 1991; Stowell and Crawford, 2000; Himmelberg and others, 2004) have assumed that the east side of the belt of rocks affected by the M_2^{C-R} metamorphic event was overprinted by the M_3^R (Barrovian) metamorphic event, but data have not been presented to document polymetamorphism.

In this chapter, we integrate mineral associations and new thermobarometric data with existing geologic mapping and geochronology to evaluate and compare the pressure-temperature (P–T) paths of the M_2^{C-R} and M_3^R metamorphic events and elucidate their implications for the tectonic evolution of the study area (fig. 2). Most of the data are from the Petersburg, Alaska, 1:250,000-scale quadrangle, where numerous M_2^{C-R} contact-metamorphic aureoles occur adjacent to, and in some interpretations spatially overlap with, an extensive belt of M_3^R (Barrovian) metamorphic rocks.

Geologic Setting

The western metamorphic belt (fig. 1) consists of rocks of the Yukon-Tanana and Taku terranes (Gehrels and others, 1990) along its east side, and rocks of the Gravina belt (Berg and others, 1972; Cohen and Lundberg, 1993) along its west side. The Yukon-Tanana terrane, which was originally called the Tracy Arm terrane by Berg and others (1978), is a Proterozoic through Paleozoic continental-margin assemblage (Gehrels and others, 1990). The Taku terrane is a highly faulted Paleozoic through Mesozoic sequence of arc-related rocks (Rubin and Saleeby, 1991), which Brew (2001) interpreted as a structural zone and not as a terrane. The Gravina belt is a Late Jurassic through Early Cretaceous sequence of arc-derived volcanic and sedimentary rocks that was deposited on the eastern margin of the Alexander terrane and on the Taku terrane (Berg and others, 1972; Rubin and Saleeby, 1991; Cohen and Lundberg, 1993).

During mid-Cretaceous time, a major contractional episode occurred between the previously amalgamated Alexander and Wrangellia terranes and previously accreted terranes to the east (Monger and others, 1982; Gehrels and others, 1990; Rubin and others, 1990; Brew and others, 1992; McClelland and Mattinson, 2000). Although closure of the Gravina Basin, which lay between the Alexander terrane and previously accreted parts of North America, also occurred during that time (Berg and others, 1972; McClelland and Gehrels, 1990; Haeussler, 1992), the initial collision between the Alexander terrane and the continental margin occurred earlier (McClelland and Gehrels, 1990; Gehrels, 2001). In the early part of the contractional episode, deformation centered in the western metamorphic belt; and at the latitude of British Columbia, it continued within the central pluton gneiss belt until middle Eocene time (for example, McClelland and Mattinson, 2000; Stowell and Crawford, 2000). In southeastern Alaska, however, deformation had ceased by then, as evidenced by abundant undeformed Eocene plutons (Brew, 1994).

The western metamorphic belt, which ranges from a few kilometers to several tens of kilometers in width, records a complex sequence of contact-metamorphic and regional metamorphic events (Brew and others, 1989; Stowell and Crawford, 2000). In general, the Late Cretaceous through early Tertiary Coast shear zone, a steep, crustal-scale, high-temperature shear zone, separates the western metamorphic belt from the Coast Mountains batholith (McClelland and others, 1992; Brew and Ford, 1998; Klepeis and others, 1998; Brew, 2001), although in some places the Coast shear zone lies entirely within the western metamorphic belt and in other places within plutons of the great tonalite sill on the west side of the Coast Mountain batholith (figs. 1, 2). Brew and Ford (1998) and Brew (2001) considered this zone to be a composite of several structural elements. Metamorphic studies of the western metamorphic belt have been concentrated near Juneau, Alaska (Ford and Brew, 1973, 1977; Himmelberg and others, 1991, 1994a, b, 1995), Petersburg, Alaska (Douglas and Brew, 1985; McClelland and others, 1991; Stowell and others, 2001; Stowell and Tinkham, 2003; Himmelberg and others, 2004), and southern southeastern Alaska and northern British Columbia (Crawford and Hollister, 1982; Crawford and others, 1987; Cook and others, 1991; Cook and Crawford, 1994; Klepeis and others, 1998). In addition, Stowell (1989) reported on the thermobarometry of schists in the Holkham Bay area of Alaska, 80 km south of Juneau. Tectonic studies of the western metamorphic belt were reported by Stowell and Hooper (1990), McClelland and others (1992), Gehrels and others (1992), Haeussler (1992), Rubin and Saleeby (1992), Ingram and Hutton (1994), and Crawford and others (2000).

Regional metamorphism before 110–100 Ma in the western metamorphic belt was dynamothermal and designated M_1 by Brew and others (1989) and M_1^R by Stowell and Crawford (2000). Karl and others (1999) suggested that more than one metamorphic event occurred before 110–100 Ma, but such events have not been documented. Thus, we use M_1^R to indicate all regional metamorphism earlier than 110–100 Ma. The M_1^R metamorphic rocks range from subgreenschist to greenschist facies in grade (Brew and others, 1984, 1989; Himmelberg and others, 1995). Evidence for the M_1^R metamorphic event is best preserved along the western margin of the belt, where this event has not been overprinted by later, higher-grade metamorphic events (fig. 2). The other regionally significant metamorphic events in the western metamorphic belt were (1) contact metamorphism by mid-Cretaceous (101–83 Ma) tonalite-granodiorite plutons of the Admiralty-Revillagigedo plutonic belt (M_4 and M_4' in the notation of Brew and others, 1989; M_2^{C-R} in the notation of Stowell and Crawford, 2000); (2) regional high-pressure Barrovian metamorphism (M_5 in the notation of Brew and others, 1989; M_3^R in the notation of Stowell and Crawford, 2000), and (3) metamorphism superimposed on the east side of the Barrovian metamorphic belt by plutons of the great tonalite sill (M_5 in the notation of Brew and others, 1989; M_4^{C-R} in the notation of Stowell and Crawford, 2000). Henceforth we use the metamorphic-event notation of Stowell and Crawford (2000) without reference to the earlier notation of Brew and others (1989).

Characteristic Mineral Associations and Chemistry

The M_2^{C-R} metamorphic event is recorded in contact-metamorphic aureoles formed around tonalite-granodiorite intrusions of the Admiralty-Revillagigedo plutonic belt that were emplaced in the western metamorphic belt about 101–83 Ma (figs. 1, 2; Douglas and Brew, 1985; Brew and others, 1989; Douglass and others, 1989; Gehrels and others, 1992; McClelland and others, 1992; McClelland and Mattinson, 2000;

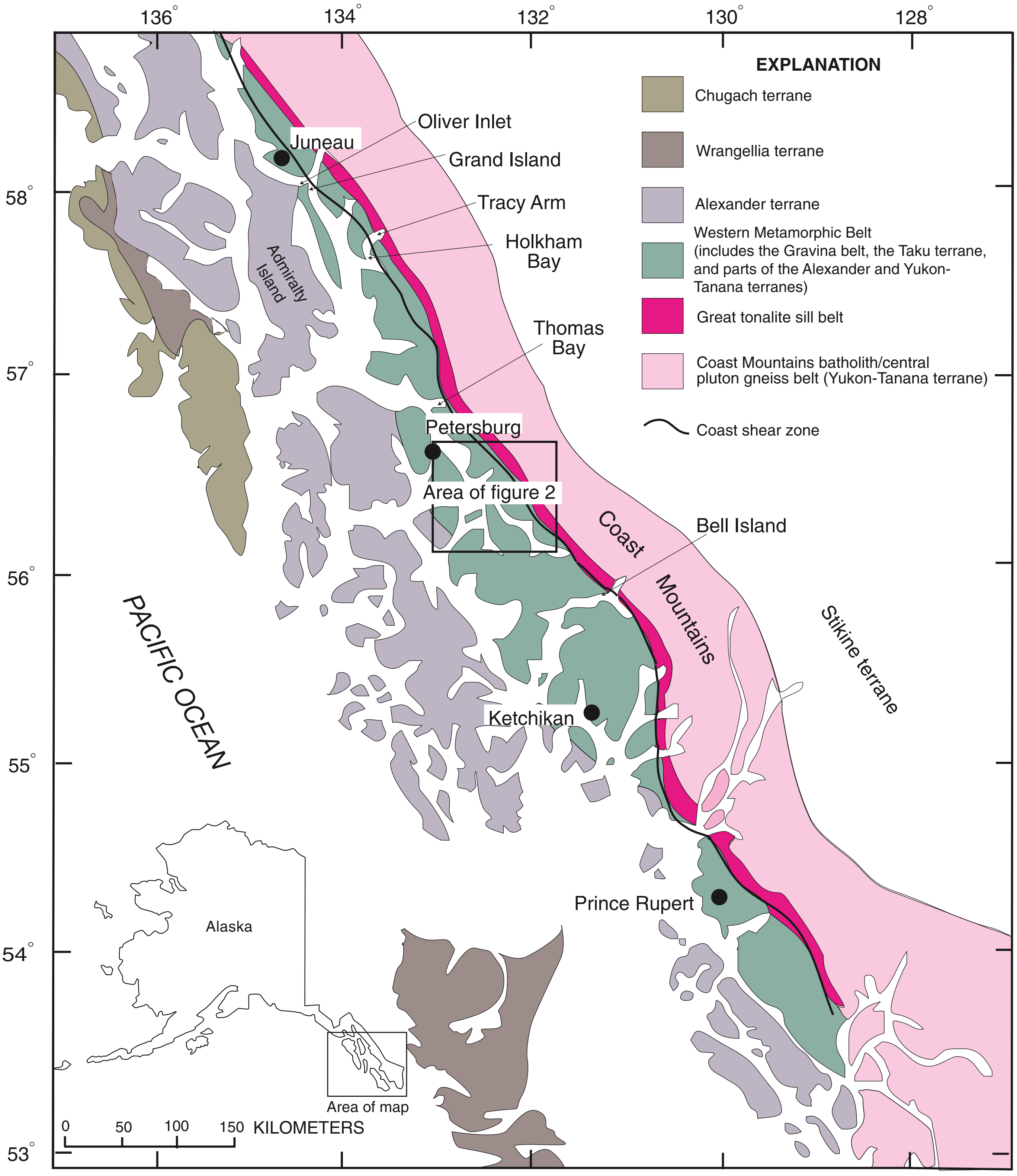

Figure 1. Sketch tectonostratigraphic map of southeastern Alaska, showing locations of the Coast Mountains Complex (Brew and others, 1995), the Coast shear zone (McClelland and others, 1992; Brew and Ford, 1998; Klepeis and others, 1998; Brew, 2001), the western metamorphic belt (Brew and others, 1989; Stowell and Crawford, 2000), the great tonalite sill (Brew, 1994), and the Chugach, Wrangellia, and Alexander terranes (Gehrels and others, 1990; Rubin and Saleeby, 1991).

Table 1. Mineral assemblages in samples of metamorphic rocks selected for thermobarometric calculations.

[Metamorphic minerals: and, andalusite; bt, biotite; cpx, clinopyroxene; grt, garnet; hbl, hornblende; ky, kyanite; ms, muscovite; pl, plagioclase; qtz, quartz; sil, sillimanite; st, staurolite. x, present and stable; [x], relict and metastable]

Sample	Metamorphic event	Metamorphic minerals										
		ms	bt	grt	st	and	sil	ky	hbl	cpx	qtz	pl
20D	M_2^R	x	x	x	– –	– –	– –	– –	– –	– –	x	x
21B	M_2^R	x	x	x	x	– –	– –	– –	– –	– –	x	x
21C	M_2^R	x	x	x	x	– –	– –	x	– –	– –	x	x
21D	M_2^R	x	x	x	x	– –	– –	x	– –	– –	x	x
94A	M_2^R	x	x	x	x	– –	– –	[x]	– –	– –	x	x
95A	M_2^R	x	x	x	– –	– –	– –	[x]	– –	– –	x	x
91A	M_3^R	– –	– –	x	– –	– –	– –	– –	x	x	x	x
112A	M_3^R	– –	– –	x	– –	– –	– –	– –	x	– –	x	x
192A	M_3^R	– –	x	x	– –	– –	– –	– –	x	– –	x	x
202A	M_3^R	– –	x	x	– –	– –	– –	– –	x	– –	x	x
190D	M_3^R	– –	x	x	– –	– –	– –	– –	x	– –	x	x
68A	M_3^R	– –	– –	x	– –	– –	– –	– –	x	– –	x	x
69A	M_3^R	– –	x	x	– –	– –	– –	– –	x	– –	x	x

Stowell and others, 2001; Himmelberg and others, 2004). Where the plutons are widely spaced, these aureoles are well defined and grade from subgreenschist- to greenschist-facies (M_1^R) country rocks to amphibolite-facies (M_2^C) schists adjacent to the plutons. On the mainland south of the Stikine River (fig. 2), however, aureoles cannot be distinguished, a feature that has been attributed to high-grade regional metamorphism (M_2^R) from numerous closely spaced plutons. Several studies interpreted this area to be overprinted by the M_3^R (Barrovian) metamorphic event (Brew and others, 1984; Douglass and Brew, 1985; Stowell and Crawford, 2000; Himmelberg and others, 2004).

M_2^C contact-metamorphic aureole rocks adjacent to the plutons, and regionally affected M_2^R metamorphic rocks on the mainland, are amphibolite-facies grade, characterized by the pelitic assemblage quartz-plagioclase-biotite-garnet-staurolite ±muscovite±kyanite±sillimanite.

Relict andalusite or pseudomorphs of andalusite replaced by one or more of the minerals kyanite, sillimanite, staurolite, muscovite, and biotite are present in some discrete aureole samples (see Douglass and Brew, 1985; Chace and Stowell, 1996; Stowell and Crawford, 2000; Himmelberg and others, 2004). However, neither andalusite nor pseudomorphs of andalusite have been observed in M_2^R metamorphic rocks on the mainland. Relict kyanite enclosed in muscovite occurs in some samples of mainland rocks.

Andalusite replaced by kyanite and (or) sillimanite also has been reported in contact-metamorphic aureoles of the Admiralty-Revillagigedo plutonic belt south of Petersburg about the Eaton Point and Bell Island plutons (Cook and Crawford, 1994). Farther south, in the Ketchikan, Alaska-Prince Rupert, British Columbia, area (Crawford and others, 1987; Cook and Crawford, 1994) and to the north about the Grand Island pluton on the northern part of Admiralty Island (Stowell and Inman, 1991; Inman, 1992), only kyanite or sillimanite is present in aureoles of these plutons.

The M_3^R (Barrovian) metamorphic event in the Petersburg area (fig. 2) is defined by schists on the east side of Frederick Sound that display progressive isograds of garnet, staurolite, kyanite, and sillimanite (Douglass and Brew, 1985). The isograds are best defined on the mainland north of the Stikine River (fig. 2). South of the river, recognition of Barrovian isograds has been complicated by uncertainty as to whether the index minerals were produced by the M_2^R or M_3^R metamorphic event (fig. 2; Brew and others, 1989). Brew and others (1989, 1992) and Himmelberg and others (1991, 1994a, b) attributed the Barrovian regional metamorphism in the Juneau area to heat flow associated with plutons of the great tonalite sill. In other areas, other workers (McClelland and others, 1991; Stowell and Crawford, 2000) attributed the Barrovian regional metamorphism to crustal thickening associated with thrusting before emplacement of the plutons of the great tonalite sill; metamorphism associated with the emplacement of these plutons was interpreted as a later, separate contact-metamorphic (M_4^{C-R}) event superimposed on the Barrovian metamorphic event (Stowell and Crawford, 2000). No andalusite or andalusite pseudomorphs were observed in the Barrovian schists.

The locations of samples selected for mineral analysis and thermobarometric calculations are shown in figure 2, and the metamorphic-mineral assemblages in these samples are summarized in table 1. Sample selection was based on the presence of mineral assemblages useful for thermobarometry, mineralogic and textural indications of equilibrium among the phases used for thermobarometry, and minimum retrograde alteration of any phases.

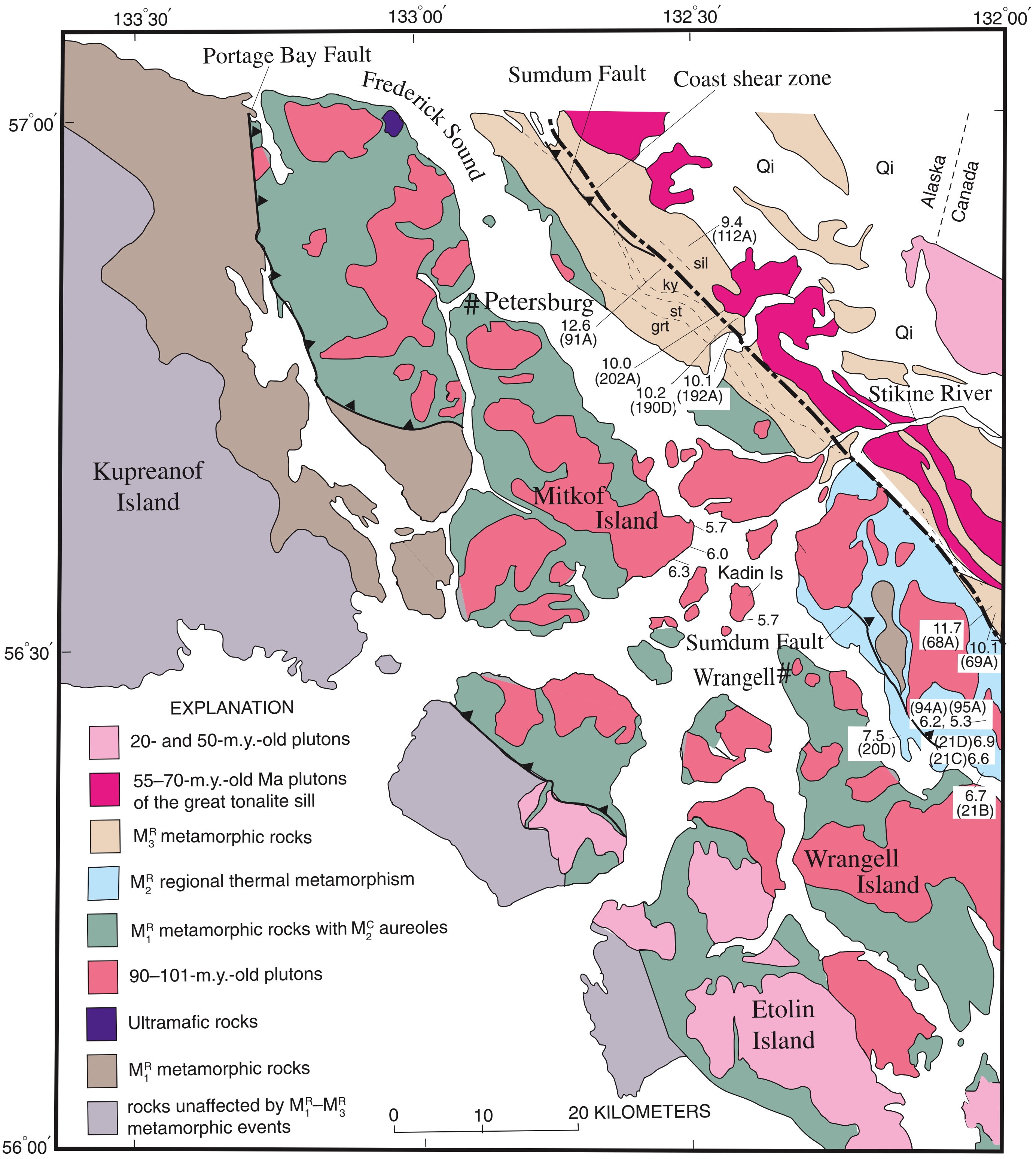

Figure 2. Geologic map of part of the Petersburg 1:250,000-scale quadrangle, southeastern Alaska, showing plutons, metamorphic effects, Barrovian isograds (grt, garnet; ky, kyanite; sil, sillimanite; st, staurolite) and calculated pressures (in kilobars), and samples (numbers in parentheses). Modified from Brew and others (1984) and Karl and others (1999). Calculated pressures on Mitkof and Kadin Islands from Himmelberg and others (2004).

Electron-microprobe analyses of the garnet, biotite, plagioclase, muscovite, hornblende, and clinopyroxene used in thermobarometric calculations are listed in tables 2 through 6. Analyses of plagioclase, hornblende, biotite, muscovite, and clinopyroxene are for matrix grains not in contact with garnet. No significant compositional zoning or intergrain compositional differences were detected in hornblende, biotite, and muscovite; and compositional variation in plagioclase is minor in most samples. The difference in core and rim compositions is generally less than An_1 except for samples 202A, in which the rim is about $An_{1.4}$ greater than the core, and sample 68A, in which the rim is $An_{2.2}$ less than the core. Representative garnet compositional profiles are plotted in figure 3. Most core-to-rim garnet compositional profiles exhibit zoning patterns typical of homogenization by high-temperature intracrystalline diffusion, as illustrated by sample 21C in figure 3. Some samples, however, have bell-shaped spessartine compositional profiles typical of growth zoning, although the pyrope, grossular, and Fe/(Fe+Mg) compositional profiles are essentially flat (sample 95A, fig. 3). Reversal of Fe/(Fe+Mg) compositional profiles near the garnet rim for many samples suggests limited reequilibration during cooling (fig. 3).

Thermobarometry

Thermobarometric calculations (table 7), using the THERMOCALC program (Powell and Holland, 1988), were made with version 3.1 of the program and the internally consistent thermodynamic dataset HP98 (Holland and Powell 1998) updated in 2001. Mineral end-member activities were calculated by using the Ax program provided with THERMOCALC 3.1. Details of the activity models are given in the documentation provided with the THERMOCALC program (see T.J.B. Holland's Web page at URL http://www.esc.cam.as.uk/astaff/holland/), and for some mineral groups by Holland and Powell. The program was run in average P–T mode to give the best-fit pressure and temperature. The THERMOCALC program generates uncertainties based on the propagation of both experimental and analytical errors (table 7). The

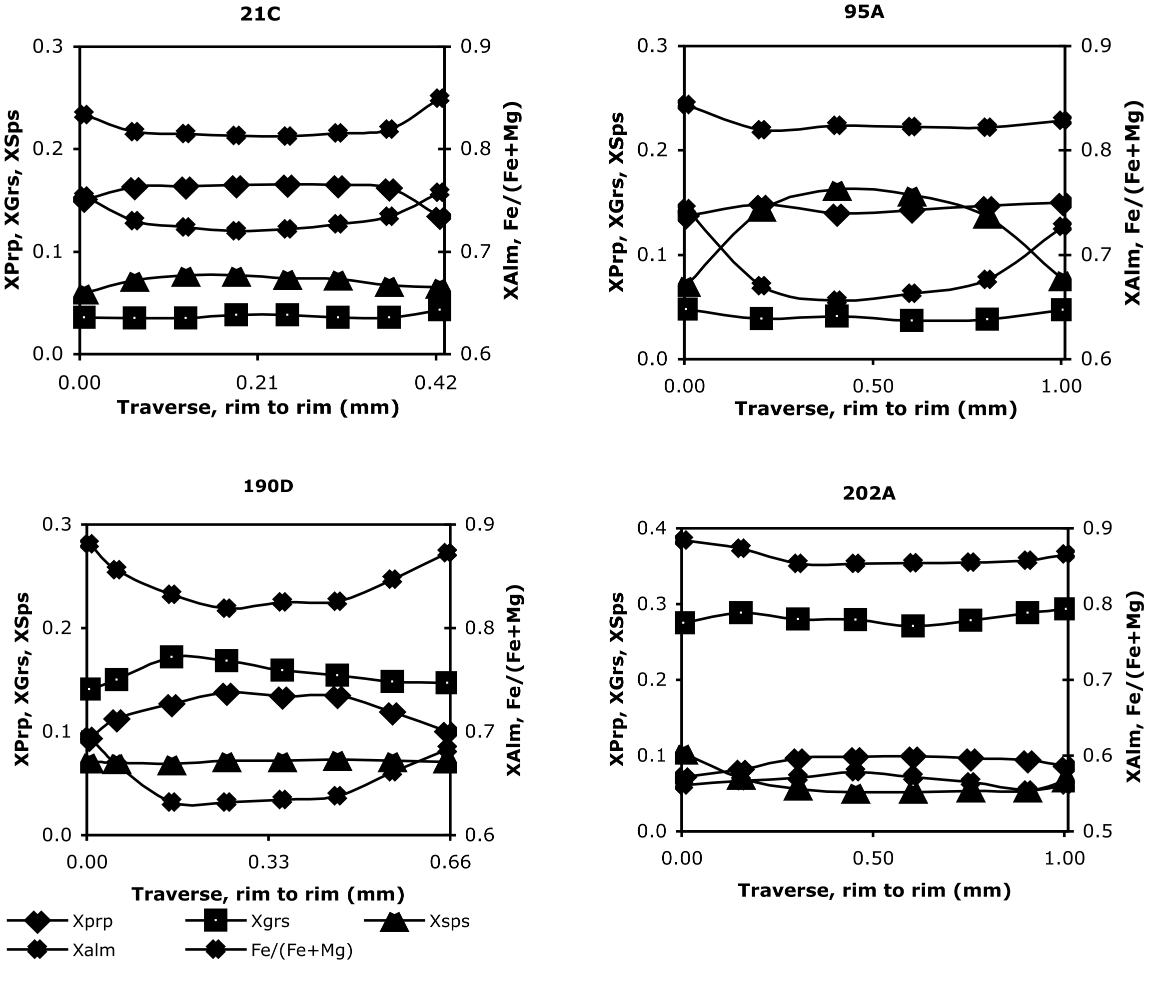

Figure 3. Representative compositional-zoning profiles for analyzed garnet in pelitic samples of M_2^R (21C, 95A, table 1) and M_3^R (190D, 202A) metamorphic rocks of the Petersburg area, southeastern Alaska (see fig. 2 for locations). Normative minerals: Alm, almandine; Grs, grossular; Prp, pyrope; Sps, spessartine.

Table 2. Chemical composition of garnet in samples of metamorphic rocks.

[All results obtained with the JEOL superprobe in the laboratory of Washington University, St. Louis, Mo; matrix corrections made by using a modified CITZAF analytical routine of Armstrong (1988). Total Fe calculated as FeO. Normative minerals: Alm, almondine; Grs, grossular; Prp, pyrope; Sps, spessartine. n.d., not detected]

Sample	20D	21B	21C	21D	94A	95A	91A	112A	192A	202A	190D	68A	69A
Major-element oxides (weight percent)													
SiO_2	36.90	37.72	37.91	36.34	37.85	37.62	38.42	39.82	37.97	38.35	37.35	38.95	38.55
TiO_2	n.d.	0.04	n.d.	0.06	0.08	0.07	0.07	0.04	0.04	0.14	0.02	0.05	0.05
Al_2O_3	21.84	22.17	22.12	21.87	21.87	21.91	21.85	21.76	21.60	21.06	21.32	22.49	21.90
FeO	27.45	31.41	31.79	31.45	29.25	28.75	20.74	27.24	24.48	24.89	27.96	24.67	27.22
MnO	5.68	3.33	3.23	2.88	5.47	6.74	2.06	1.87	3.46	2.95	3.20	0.63	1.49
MgO	3.49	4.18	4.11	4.18	3.52	3.48	2.17	5.21	3.88	2.17	3.46	3.52	3.55
CaO	3.27	1.20	1.29	1.40	1.70	1.24	14.31	5.80	8.05	10.28	5.87	10.89	8.00
Total	98.63	100.05	100.45	98.18	99.74	99.81	99.62	101.74	99.48	99.83	99.19	101.20	100.76
Formula normalized to 12 oxygens													
Si	2.974	2.992	2.998	2.948	3.015	3.003	3.009	3.053	2.998	3.034	2.989	3.000	3.008
Al^{IV}	0.026	0.008	0.002	0.052	0.000	0.000	0.000	0.000	0.002	0.000	0.011	0.000	0.000
Al^{VI}	2.049	2.064	2.059	2.040	2.053	2.061	2.017	1.966	2.007	1.963	1.999	2.041	2.014
Ti	n.d.	0.002	n.d.	0.004	0.005	0.004	0.004	0.002	0.002	0.008	0.001	0.003	0.003
Fe	1.850	2.083	2.102	2.134	1.949	1.919	1.358	1.747	1.616	1.647	1.871	1.589	1.776
Mn	0.388	0.224	0.216	0.198	0.369	0.456	0.137	0.121	0.231	0.198	0.217	0.041	0.098
Mg	0.419	0.494	0.484	0.505	0.418	0.414	0.253	0.595	0.457	0.255	0.413	0.404	0.413
Ca	0.282	0.102	0.109	0.122	0.145	0.106	1.201	0.477	0.681	0.871	0.503	0.899	0.669
Normative minerals (volume percent)													
Prp	14.3	17.0	16.6	17.1	14.5	14.3	8.6	20.2	15.3	8.6	13.8	13.8	14.0
Grs	9.6	3.5	3.8	4.1	5.0	3.7	40.7	16.2	22.8	29.3	16.8	30.6	22.6
Sps	13.2	7.7	7.4	6.7	12.8	15.7	4.6	4.1	7.7	6.7	7.2	1.4	3.3
Alm	62.9	71.8	72.2	72.1	67.6	66.3	46.1	59.4	54.1	55.4	62.3	54.2	60.1

correlated P–T uncertainties allow an error ellipse to be plotted (fig. 4; Powell and Holland, 1988). As a result of using a single method with an internally consistent thermodynamic database, the resulting P–T values are directly comparable to each other.

For those garnets exhibiting growth-zoning patterns, P–T values were calculated by using rim compositions, or near-rim compositions for those garnets that showed rim reequilibration during cooling. For garnet crystals with high-temperature-diffusion homogenized patterns, core compositions were used. Garnet rim points in contact with hornblende or biotite were avoided, and analyses of obvious retrograded garnet points were omitted. Matrix biotite, hornblende, and plagioclase compositions were used in all samples. Rim compositions were used for plagioclase. Although we cannot demonstrate chemical equilibrium of the mineral assemblages used in the thermodynamic calculations, no evidence of nonequilibrium was observed. Textural equilibrium of the prograde mineral assemblages, and the relative chemical homogeneity of matrix grains and garnet near-rim compositions, all argue favorably for an approach to chemical equilibrium.

A significant difference exists between the P–T values calculated for mineral assemblages formed during the M_2^{C-R} and M_3^R metamorphic events, respectively (fig. 4; table 7). Spear (1991) demonstrated that garnets which achieved peak temperatures above about 550ºC are invariably modified by diffusion during cooling. Thus, some of the differences in calculated temperatures and, therefore, pressures between mineral assemblages formed during the same metamorphic event may reflect different degrees of postpeak compositional modification. However, the significant difference in the P–T values calculated for M_2^{C-R} and M_3^R metamorphic-mineral assemblages, with little or no overlap of error ellipses (fig. 4), cannot adequately be explained by this process. Thus, we propose that the P–T values calculated for M_2^{C-R} and M_3^R metamorphic-mineral assemblages reflect near-peak conditions and that the conditions for these two events differed significantly. On that basis, we interpret that the peak or near-peak P–T conditions for M_2^R contact-metamorphic aureoles of the Admiralty-Revillagigedo plutonic belt were in the ranges 5.3–7.5 kbars and 580–640ºC and that the peak or near-peak P–T conditions for M_3^R (Barrovian) metamorphic-mineral assemblages were in or near the ranges 9.4–12.6 kbars and 730–895ºC. The P–T conditions calculated for discrete M2C metamorphic aureoles on Mitkof and Kadin Islands by Himmelberg and others (2004) were in the ranges 5.7–6.3 kbars and 525–635ºC. These data illustrate no significant difference in the peak P–T conditions of discrete M_2^C contact-metamorphic aureoles and regional M_2^R metamorphic rocks caused by intrusion of the Admiralty-Revillagigedo plutonic belt.

Summary of Metamorphic History: P–T Path

Timing of Metamorphic Events

In general, available radiometric ages indicate that the M_2^{C-R} metamorphic event predated the M_3^R (Barrovian) metamorphic event, although the timing of these events may have overlapped in some areas. Plutons of the Admiralty-Revillagigedo plutonic belt were emplaced from 101 to 83 Ma (Douglass and others, 1989; Gehrels and others, 1992; McClelland and Mattinson, 2000). In the study area (figs. 1, 2), the timing of emplacement is constrained by discordant U-Pb zircon ages of about 93 m.y. from southeastern Mitkof Island and about 91 m.y. from LeConte Bay (McClelland and others, 1992). The pluton at Garnet Ledge (fig. 2), which is in the M_2^R metamorphic belt of this study, yields a concordant U-Pb zircon age of 91.6 m.y., and garnet from the aureole of this pluton yields a Sm-Nd isochron age of about 89 m.y. (Stowell and others, 2001). Stowell and others reported that the peak P–T conditions of metamorphism for these rocks were in the ranges 6.1–6.3 kbars and 678–685ºC, consistent with our results for the M_2^R metamorphic belt.

No radiometric ages constrain the timing of the M_3^R metamorphic event in the study area (figs. 1, 2), and overall, the timing of the Barrovian metamorphic event is poorly documented. Sutter and Crawford (1985) cited an ^{40}Ar/^{39}Ar age of 90±1 m.y. for metamorphic actinolitic amphibole from amphibolite-facies rocks near Prince Rupert, British Columbia. Stowell and Crawford (2000) interpreted the actinolite age as the timing of the M_3^R metamorphic event, which would make it later than, or approximately coeval with, emplacement of the Ecstall pluton of the Admiralty-Revillagigedo plutonic belt (U-Pb zircon age, 98±4 m.y.; Sutter and Crawford, 1985; ~91 Ma, G.E. Gehrels, in Stowell and Crawford, 2000). Stowell and Goldberg (1997) obtained Sm-Nd garnet ages of about 80±9 and 77±17 m.y. from M_3^R metamorphic rocks in the areas of Tracy Arm and Taku Inlet, respectively (fig. 1). These ages are younger than the ^{40}Ar/^{39}Ar amphibole age cited above, but considering the large errors associated with the Sm-Nd ages, the difference may not be significant, or, as pointed out by Stowell and Goldberg (1997) the Sm-Nd garnet age of the rocks from Tracy Arm may reflect postpeak garnet growth, and the Sm-Nd age of the rocks from Taku Inlet may reflect reequilibration during the M_4^{C-R} metamorphic event associated with emplacement of the Mount Juneau pluton of the great tonalite sill (71.2±1 Ma; Gehrels and others, 1991). Thus, although the timing of the M_3^R metamorphic event remains uncertain, it may not differ significantly from that of the M_2^{C-R} metamorphic event.

Both the M_2^R and M_3^R metamorphic events apparently postdate the Sumdum Fault (fig. 2), a major mid-Cretaceous thrust fault north and east of Petersburg (fig. 1; McClelland and Mattinson, 2000). Separate mapping of Barrovian isograds by Douglass and Brew (1985) and of the Sumdum Fault by McClelland and Mattinson (2000) suggests that the isograds are continuous across the fault and that the fault is cut by the Admiralty-Revillagigedo plutonic belt. These geologic relations, which are consistent with the ages reported above, indicate that, indeed, an earlier, mid-Cretaceous M_1^R metamorphic event was associated with the Sumdum Fault (McClelland and Mattinson, 2000).

M_2^C and M_2^R Metamorphic Events

Interpreted P–T paths for the various metamorphic events are plotted in figure 5. The common occurrence of andalusite partly replaced by kyanite and (or) sillimanite in the island aureoles suggests near-isobaric heating of M_1^R metamorphic country rocks under low-pressure conditions, followed by crustal thickening and higher-pressure metamorphism (solid gray line, fig. 4). Thermobarometry of these aureole rocks yields pressures ranging from about 5.7 to 6.3 kbars, consistent with the occurrence of kyanite and sillimanite (Himmelberg and others, 2004). Metamorphic-mineral assemblages from other Admiralty-Revillagigedo pluton aureoles south of Petersburg, and pluton-emplacement pressures obtained by using Al in hornblende, are consistent with these determinations (Cook and others, 1991; Cook and Crawford, 1994; Karen Inman, in Stowell and Crawford, 2000; Stowell and Crawford, 2000). On the basis of the parallelism between country-rock fabrics, high-temperature magmatic fabrics, and high- and low-temperature solid-state fabrics of distinct aureoles within and at the margins of the Admiralty-Revillagigedo plutonic belt, Himmelberg and others (2004) argued that crustal thickening was accomplished by thrusting during emplacement and cooling of the plutons. The restriction of high-P–T minerals to the aureoles, and the persistence of low-grade-mineral associations in the country rocks outside the aureoles, indicate that crustal thickening did not cause regional heating to high temperatures.

In contrast to the western M_2^C metamorphic rocks from the islands, samples of M_2^R metamorphic rocks from the mainland contain no evidence of metamorphosis at shallow crustal levels consistent with the andalusite stability field. Neither andalusite nor pseudomorphs of andalusite were observed. Thus, it is unclear whether the P–T path of the M_2^R metamorphic event on the mainland was the same as that of the M_2^C metamorphic event or whether, on the mainland, crustal thickening occurred before emplacement of the plutons, so that the intrusion and associated heating responsible for the M_2^R metamorphic event occurred entirely at depths consistent with kyanite-sillimanite stability (dashed gray path labeled "M_2^R alternative possibility," fig. 5). If the second interpretation is correct, then the plutons on the mainland were emplaced later, and at a deeper crustal level, than those to the west. The available radiometric data are insufficient to confirm this interpretation. The relict kyanite in some samples of M_2^R metamorphic rocks from the mainland may be a result of the prograde transition from kyanite to sillimanite stability fields or of decompression following peak metamorphism.

M_3^R (Barrovian) Metamorphism

The Barrovian metamorphic belt in the Petersburg area (fig. 1) records an eastward increase in grade. Douglass and Brew (1985) mapped garnet, staurolite, kyanite, and sillimanite isograds (fig. 2). No andalusite has been observed in the Barrovian metamorphic belt throughout southeastern Alaska. Our thermobarometry on kyanite- and sillimanite-zone pelitic schists and garnet amphibolites yielded pressures ranging from about 9.1 to 12.6 kbars (table 7). McClelland and others (1991) obtained similarly high pressures for some of the samples in their study, consistent with the pressure obtained for the Barrovian metamorphic belt in the vicinity of Juneau (fig. 1; Himmelberg and others, 1991, 1994a). Stowell (1989) obtained substantially lower pressures (4–5 kbars) for equivalent rocks in the Holkham Bay area between Petersburg and Juneau; however, G.R. Himmelberg (unpub. data, 1994) obtained a pressure of 8.5 kbars for a garnet amphibolite from that area.

Barrovian metamorphism of the western metamorphic belt has been attributed either to regional metamorphism during thrusting or to heat advected during emplacement of plutons of the great tonalite sill. McClelland and others (1991) interpreted the Barrovian metamorphic event through the kyanite zone in the Petersburg area (fig. 1) to be synchronous with movement on the mid-Cretaceous Sumdum-Fanshaw thrust-fault system, one of the major westward-directed thrust faults on the west side of the Coast Mountains. As described

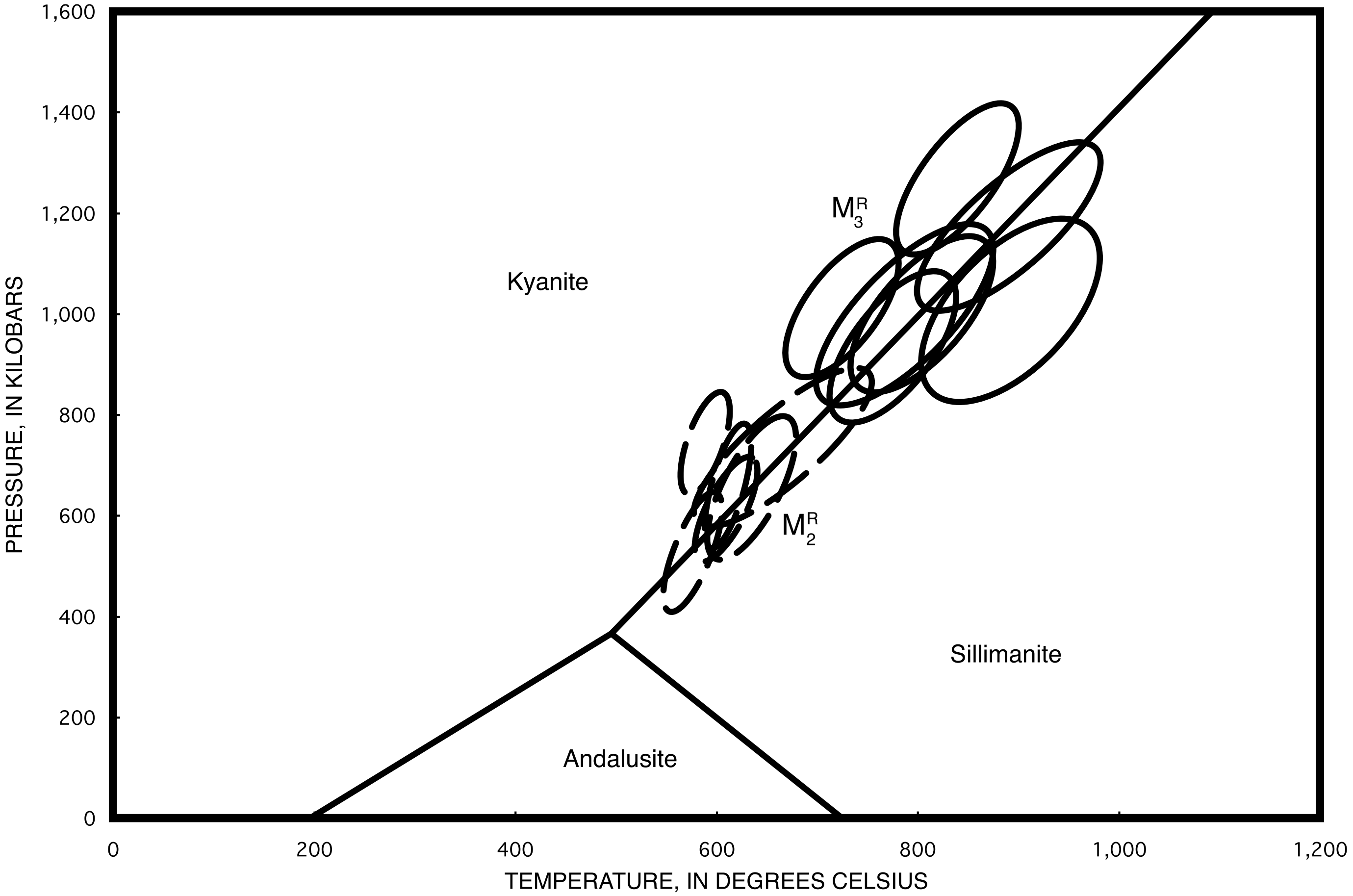

Figure 4. Pressure-temperature estimates for samples of metamorphic rocks, calculated with THERMOCALC software (Powell and Holland, 1988). Error ellipses represent standard deviations: dashed, M_2^R metamorphic rocks; solid, M_3^R metamorphic rocks. Al_2SiO_5 triple point from Holdaway (1971).

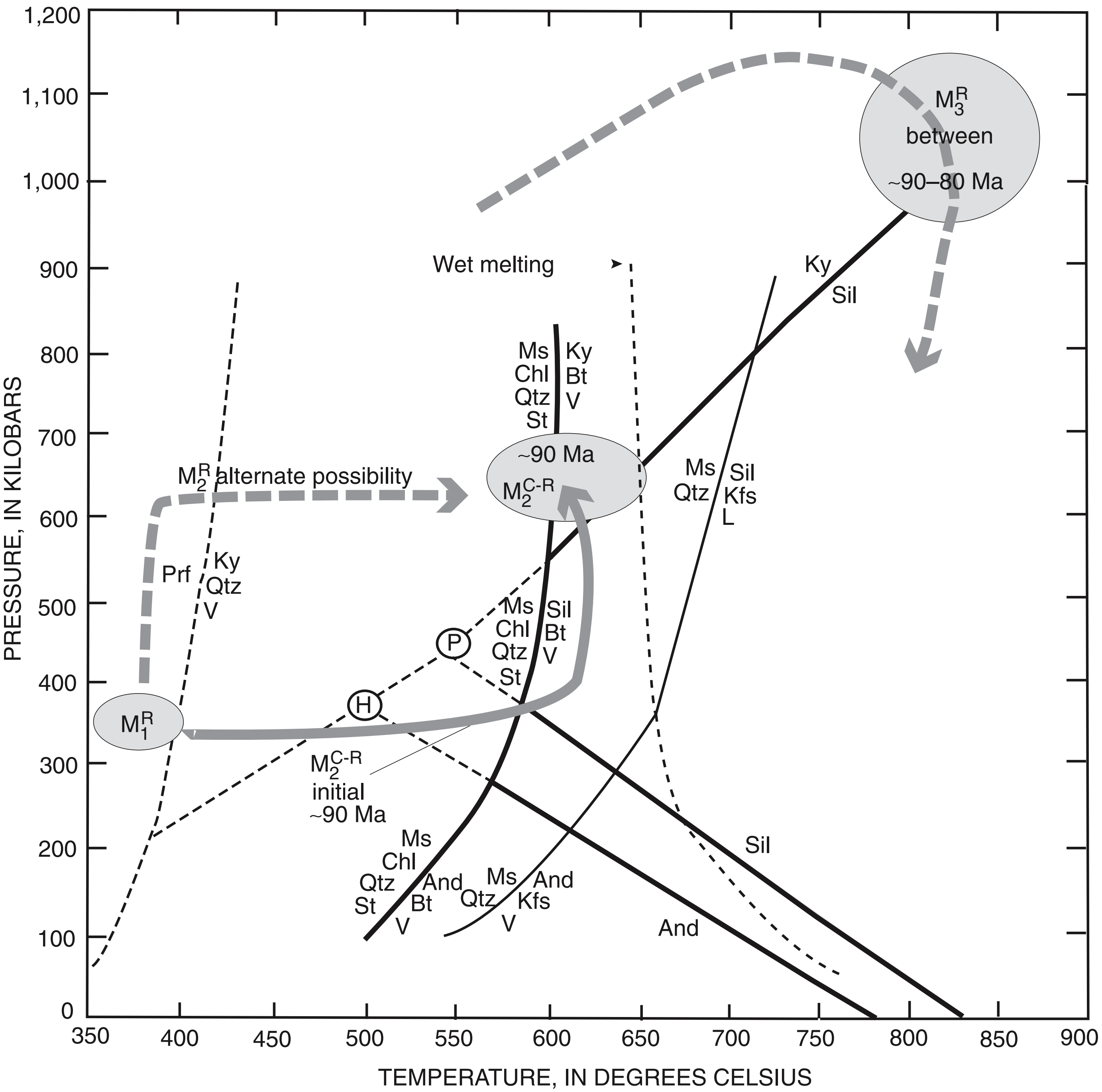

Figure 5. Interpreted pressure-temperature (P–T) paths for M_2^{C-R} metamorphic aureoles (solid gray arrow) and M_3^R (Barrovian) metamorphic rocks (high-pressure dashed gray arrow). Center of M_2^{C-R} and M_3^R ellipses is average P–T value for respective events; radii of ellipses approximately equal standard deviation. See figure 3 for error ellipses of each sample. Alternative P–T path for M_2^{C-R} metamorphic event is also shown (low-pressure dashed gray arrow). P–T path for the M_2^{C-R} metamorphic event modified from Himmelberg and others (2004). P–T conditions for the M1R metamorphic event are approximate and based on mineral assemblages. P–T diagram modified from Pattison (2001). L, liquid; V, vapor. Circled H, Al_2SiO_5 triple point of Holdaway (1971); circled P, Al_2SiO_5 triple point of Pattison (1992). Metamorphic minerals: And, andalusite; Bt, biotite; Chl, chlorite; Kfs, K-feldspar; Ky, kyanite; Ms, muscovite; Prf, pyrophyllite; Qtz, quartz; Sil, sillimanite; St, staurolite. According to Pattison (2001), P–T values to right of Ms+Chl+Qtz+St=Al_2SiO_5+Bt+V equation must be obtained for Al_2SiO_5 polymorphs to occur in Ms+Bt+Qtz-bearing rocks.

Table 3. Chemical composition of biotite in samples of metamorphic rocks.

[All results obtained with the JEOL superprobe in the laboratory of Washington University, St. Louis, Mo; matrix corrections made by using a modified CITZAF analytical routine of Armstrong (1988). Total Fe calculated as FeO; n.d., not detected]

Sample	20D	21B	21C	21D	94A	95A	92A	202A	190D	69A
Major-element oxides (weight percent)										
SiO_2	36.92	36.09	36.07	36.66	36.03	35.89	36.37	35.78	34.37	37.17
TiO_2	1.59	2.11	1.99	1.84	1.83	2.06	3.26	4.82	3.14	2.54
Al_2O_3	19.44	19.90	19.46	20.11	19.74	19.34	15.50	14.31	15.10	16.22
FeO	15.76	18.21	18.63	17.82	17.31	18.60	20.12	23.45	26.35	17.38
MnO	0.10	0.05	0.06	0.04	0.05	0.48	0.18	0.33	0.11	0.15
MgO	12.18	11.01	10.84	11.01	11.00	10.37	11.06	8.28	7.69	12.27
CaO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.01	0.03	0.02	n.d.
Na_2O	0.17	0.15	0.16	0.17	0.22	0.26	0.14	0.16	0.08	0.10
K_2O	8.97	8.78	8.62	8.89	8.79	9.08	9.94	9.08	7.46	9.33
Total	95.13	96.30	95.82	96.55	94.97	96.08	96.57	96.23	94.32	95.16
Formula normalized to 11 oxygens										
Si	2.746	2.683	2.699	2.710	2.706	2.694	2.759	2.765	2.728	2.804
Al^{IV}	1.254	1.317	1.301	1.290	1.294	1.306	1.241	1.235	1.272	1.196
Al^{VI}	0.449	0.427	0.416	0.462	0.454	0.405	0.145	0.069	0.140	0.246
Ti	0.089	0.118	0.112	0.102	0.104	0.116	0.186	0.280	0.187	0.144
Fe	0.980	1.132	1.166	1.102	1.087	1.168	1.277	1.516	1.749	1.096
Mn	0.006	0.003	0.004	0.003	0.003	0.031	0.011	0.021	0.008	0.010
Mg	1.351	1.220	1.209	1.213	1.231	1.160	1.251	0.954	0.910	1.379
Ca	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.001	0.002	0.001	n.d.
Na	0.024	0.021	0.023	0.024	0.032	0.038	0.021	0.024	0.012	0.015
K	0.851	0.832	0.823	0.838	0.842	0.870	0.962	0.895	0.755	0.898
Mg/(Mg+Fe)	0.579	0.519	0.509	0.524	0.531	0.498	0.495	0.386	0.342	0.557

previously, however, movement on this fault system predated the emplacement of plutons of the Admiralty-Revillagigedo plutonic belt and the M_2^{C-R} and M_3^{R} metamorphic events. McClelland and others (1991) attributed sillimanite-zone metamorphism along the east edge of the western metamorphic belt as contact metamorphism (M_4^{C-R}) caused by emplacement of the Late Cretaceous to Paleocene (58–72 m.y. old) plutons of the great tonalite sill. Stowell and Crawford (2000) advanced a similar interpretation in their summary of the history of the western metamorphic belt throughout southeastern Alaska and British Columbia. Brew and others (1989, 1992) and Himmelberg and others (1991) attributed the Barrovian garnet- through sillimanite- grade metamorphism along the east side of the western metamorphic belt in the Juneau area to advection of heat from plutons of the great tonalite sill (58–72 m.y. old). Stowell and Crawford (2000) acknowledged that in the northern part of the belt, regional metamorphism associated with thrusting is difficult to distinguish from contact metamorphism associated with the great tonalite sill. The P–T path for the M_3^{R} metamorphic event plotted in figure 5 (upper dashed gray line) assumes heating as a result of crustal thickening, consistent with the P–T paths created by modeling of orogenic belts (Spear, 1993).

In the Petersburg area (fig. 1), calculated pressures for the kyanite (M_3^{R}) and sillimanite (M_4^{C-R}) zones do not differ significantly (fig. 2; table 7). Thus, if the sillimanite-zone schists and gneisses are a result of contact metamorphism by the great tonalite sill, as advocated by McClelland and others (1991)

Table 4. Chemical composition of plagioclase in samples of metamorphic rocks.

[All results obtained with the JEOL superprobe in the laboratory of Washington University, St. Louis, Mo; matrix corrections made by using a modified CITZAF analytical routine of Armstrong (1988). Total Fe calculated as FeO]

Sample	20D	21B	21C	21D	94A	95A	91A	112A	192A	202A	190D	68A	69A
Major-element oxides (weight percent)													
SiO_2 --------	60.50	61.94	63.02	62.27	61.81	62.46	57.42	60.97	59.47	56.76	61.77	55.83	58.58
Al_2O_3-------	24.96	23.36	23.58	23.99	23.92	23.63	27.26	25.02	25.43	27.31	24.34	28.86	26.51
FeO --------	0.07	0.13	0.18	0.11	0.11	0.07	0.20	0.08	0.10	0.10	0.05	0.06	0.24
CaO --------	5.93	4.18	4.11	4.41	5.66	4.77	9.16	7.12	7.37	9.40	5.87	10.29	7.46
Na_2O -------	8.02	9.05	9.10	8.92	8.46	8.93	6.41	7.90	7.61	6.46	8.39	5.79	7.34
K_2O --------	0.05	0.08	0.07	0.07	0.08	0.09	0.21	0.03	0.07	0.15	0.25	0.14	0.18
Total -------	99.53	98.73	100.04	99.76	100.04	99.95	100.64	101.12	100.05	100.17	100.65	100.97	100.31
Formula normalized to 8 oxygens													
Si -----------	2.699	2.775	2.783	2.761	2.742	2.767	2.561	2.687	2.653	2.547	2.727	2.489	2.612
Al ----------	1.312	1.233	1.227	1.253	1.251	1.234	1.433	1.299	1.337	1.444	1.267	1.516	1.393
Fe ----------	0.003	0.005	0.006	0.004	0.004	0.003	0.007	0.003	0.004	0.004	0.002	0.002	0.009
Ca ----------	0.283	0.201	0.194	0.210	0.269	0.226	0.438	0.336	0.352	0.452	0.278	0.491	0.356
Na ----------	0.693	0.786	0.779	0.766	0.728	0.767	0.554	0.675	0.659	0.562	0.718	0.500	0.634
K -----------	0.003	0.004	0.004	0.004	0.005	0.005	0.012	0.002	0.004	0.009	0.014	0.008	0.010
Normative minerals (volume percent)													
An ----------	28.9	20.2	19.9	21.4	26.9	22.7	43.6	33.2	34.7	44.2	27.5	49.2	35.6
Ab ----------	70.8	79.3	79.7	78.2	72.7	76.8	55.2	66.6	64.9	54.9	71.1	50.1	63.4
Or ----------	0.3	0.4	0.4	0.4	0.5	0.5	1.2	0.2	0.4	0.8	1.4	0.8	1.0

Table 5. Chemical composition of muscovite in samples of metamorphic rocks.

[All results obtained with the JEOL superprobe in the laboratory of Washington University, St. Louis, Mo; matrix corrections made by using a modified CITZAF analytical routine of Armstrong (1988). Total Fe calculated as FeO]

Sample	**20D**	**21B**	**21C**	**21D**	**94A**	**95A**
Major-element oxides (weight percent)						
SiO_2	46.64	46.26	46.10	46.24	44.96	46.36
TiO_2	0.64	0.74	0.83	0.66	0.60	0.66
Al_2O_3	35.91	36.50	36.12	36.14	37.64	36.77
FeO	0.97	1.12	1.20	0.99	0.96	1.02
MgO	0.83	0.66	0.66	0.66	0.61	0.61
Na_2O	1.31	1.44	1.43	1.43	1.38	1.35
K_2O	8.95	8.89	8.74	8.73	8.89	9.22
Total	95.24	95.59	95.08	94.82	95.03	95.99
Formula normalized to 11 oxygens						
Si	3.077	3.045	3.050	3.062	2.978	3.041
Al^{IV}	0.923	0.955	0.950	0.938	1.022	0.959
Al^{VI}	1.869	1.876	1.867	1.883	1.916	1.885
Ti	0.032	0.036	0.041	0.033	0.030	0.033
Fe	0.054	0.061	0.066	0.055	0.053	0.056
Mg	0.081	0.064	0.065	0.065	0.061	0.060
Na	0.168	0.184	0.183	0.183	0.177	0.172
K	0.753	0.746	0.738	0.737	0.751	0.772
Normative minerals (volume percent)						
Ms	81.8	80.2	80.1	80.1	80.9	81.8
Pg	18.2	19.8	19.9	19.9	19.1	18.2

and Stowell and Crawford (2000), then this metamorphic event occurred at essentially the same depth as the kyanite (M_3^R)-zone regional metamorphism in the Petersburg area. Most of the samples of Barrovian metamorphic minerals from the Petersburg area used in thermobarometry, all of which are from schists and gneisses close to the Coast shear zone, yield high pressures (9.1–12.6 kbars).

Discussion and Conclusions

Over much of the Admiralty-Revillagigedo plutonic belt, especially along its western part, the high-temperature, moderate-pressure (M_2^C) metamorphism is largely restricted to discrete aureoles surrounded by low-grade or greenschist-facies (M_1^R) country rocks. No evidence suggests that these aureoles were involved in the M_3^R metamorphic event (Douglass and Brew, 1985; Himmelberg and others, 2004). Although Douglass and Brew (1985) proposed that M_2^R metamorphic rocks, which are related to plutons of the Admiralty-Revillagigedo plutonic belt on the mainland, were subsequently overprinted by the M_3^R (Barrovian) metamorphic event, our thermobarometric data do not support their proposal. The Barrovian metamorphic event occurred under pressures of 9.1 to 12.6 kbars, whereas the metamorphic event (M_2^R) associated with the emplacement of plutons of the Admiralty-Revillagigedo plutonic belt on the mainland yielded pressures of 5.3 to 7.5 kbars, about the same as those determined for discrete aureoles of the Admiralty-Revillagigedo plutonic belt to the

Table 6. Chemical composition of hornblende and clinopyroxene in samples of metamorphic rocks.

[All results obtained with the JEOL superprobe in the laboratory of Washington University, St. Louis, Mo; matrix corrections made by using a modified CITZAF analytical routine of Armstrong (1988). Total Fe calculated as FeO]

	Hornblende							Clino-pyroxene
Sample	**91A**	**112A**	**192A**	**202A**	**190D**	**68A**	**69A**	**91A**
Major-element oxides (weight percent)								
SiO_2	42.01	42.99	43.25	41.67	42.30	43.29	42.45	51.81
TiO_2	0.70	1.27	1.27	2.01	1.37	1.09	1.41	0.00
Al_2O_3	12.78	12.52	12.29	11.71	11.07	11.64	13.33	0.40
FeO	19.04	18.40	16.65	20.50	23.21	18.69	16.31	13.57
MnO	0.34	0.31	0.43	0.51	0.41	0.21	0.25	0.60
MgO	7.93	10.14	9.90	6.96	6.65	8.89	9.79	10.14
CaO	12.25	10.19	11.48	11.77	10.70	11.32	11.05	24.25
Na_2O	1.01	1.96	1.46	1.35	1.71	1.27	1.63	0.11
K_2O	1.56	0.44	0.82	1.70	0.68	0.95	0.93	– –
Total	97.61	98.22	97.53	98.18	98.09	97.34	97.15	100.88
Hornblende formula normalized to 13 cations exclusive of Ca, Na, and K; clinopyroxene formula normalized to 6 oxygens								
Si	6.376	6.244	6.408	6.376	6.389	6.475	6.293	1.975
Al^{IV}	1.624	1.756	1.592	1.624	1.611	1.525	1.707	0.018
Al^{VI}	0.663	0.388	0.554	0.490	0.360	0.528	0.623	0.000
Ti	0.080	0.139	0.142	0.231	0.156	0.123	0.157	0.000
Fe^{3+}	0.213	1.280	0.533	0.070	0.838	0.568	0.608	– –
Fe^{2+}	2.205	0.956	1.531	2.555	2.095	1.772	1.415	– –
Fe_T	2.413	2.236	2.064	2.625	2.933	2.340	2.023	0.433
Mn	0.043	0.038	0.054	0.065	0.052	0.026	0.032	0.019
Mg	1.795	2.198	2.187	1.588	1.499	1.983	2.165	0.576
Ca	1.995	1.588	1.824	1.933	1.734	1.817	1.758	0.991
Na (M4)	0.005	0.412	0.176	0.067	0.266	0.183	0.242	– –
Na (A)	0.291	0.140	0.243	0.335	0.235	0.185	0.228	– –
Na_T	0.296	0.552	0.419	0.402	0.501	0.368	0.470	0.008
K	0.302	0.081	0.156	0.333	0.131	0.181	0.177	– –
Mg	– –	– –	– –	– –	– –	– –	– –	28.8
Fe	– –	– –	– –	– –	– –	– –	– –	21.6
Ca	– –	– –	– –	– –	– –	– –	– –	49.5
$Mg/(Mg+Fe^{2+}+Mn)$	0.444	0.689	0.580	0.377	0.411	0.525	0.599	0.560

Table 7. Thermobarometric data for mineral assemblages in samples of M_2^R and M_3^R metamorphic rocks from the Petersburg area, southeastern Alaska, calculated with the THERMOCALC program.

Sample	Metamorphic event	Temperature (°C)		Pressure (kbars)		Independent reactions		
		Avg	σ	Avg	σ	Fit	c.c.	No.
20D	M_2^R	595	28	7.5	1.1	0.46	0.77	5
21B	M_2^R	640	36	6.7	1.3	0.39	0.77	5
21C	M_2^R	615	22	6.6	1.2	0.44	0.82	6
21D	M_2^R	620	22	6.9	1.1	0.39	0.81	6
94A	M_2^R	610	30	6.2	1.1	0.17	0.75	5
95A	M_2^R	580	26	5.3	1.1	0.65	0.77	5
91A	M_3^R	840	62	12.6	1.5	0.69	0.60	6
112A	M_3^R	785	63	9.4	1.5	0.91	0.63	5
192A	M_3^R	800	77	10.1	1.6	1.12	0.66	7
202A	M_3^R	790	97	10.0	1.6	0.98	0.63	6
190D	M_3^R	895	97	10.2	1.8	0.93	0.67	7
68A	M_3^R	895	93	11.7	1.6	0.70	0.69	5
69A	M_3^R	730	60	10.1	1.4	1.01	0.68	7

west (Himmelberg and others, 2004). If the M_2^R metamorphic rocks had been subjected to the same high temperatures and pressures as those of the Barrovian metamorphic event, the aureoles and interaureole country rocks would probably have more nearly equilibrated to the conditions recorded by schists and gneisses in the Barrovian metamorphic belt, especially along the east side of the M_2^R metamorphic belt adjacent to the Barrovian metamorphic belt.

Thus, we conclude that in the Petersburg area, the M_2^{C-R} metamorphic rocks associated with the Admiralty-Revillagigedo plutonic belt and the Barrovian (M_3^R) metamorphic belt underwent peak metamorphism at significantly different crustal depths and followed different P–T paths. The timing of, and thermobarometric constraints on, the M_2^{C-R}, M_3^R, and M_4^{C-R} metamorphic events indicate that the M_3^R (Barrovian) metamorphic event mostly postdated the emplacement of plutons of the Admiralty-Revillagigedo plutonic belt and, furthermore, that M_2^R metamorphic associations show no evidence of overprinting by M_3^R metamorphic conditions. After metamorphism at different crustal levels, the M_2^R and M_3^R metamorphic belts were juxtaposed as a result of differential uplift and exhumation. In the study area, the boundary between the M_2^R and M_3^R metamorphic belts is near or within the Coast shear zone. Exhumation of the Coast Mountains is believed to have been accommodated along the Coast shear zone, which postdates emplacement of the 90-m.y.-old plutons and was probably active during Late Cretaceous time (McClelland and Mattinson, 2000). Thus, east-side-up differential movement along the Coast shear zone probably is also responsible for juxtaposition of the M_2^R and M_3^R metamorphic belts.

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