Evolution of the western part of the Coast plutonic–metamorphic complex, south-eastern Alaska, USA: a summary

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The western Cordillera of North America extends for over 6000 km from the tip of Baja California to the Alaska Range. It includes a wide variety of metamorphic and plutonic terrains, but none is more spectacular scenically or geologically than the Coast plutonic–metamorphic complex (Brew & Ford 1984) of western Canada and south-eastern Alaska. This report briefly describes the evolution of the western part of the complex, integrating information from the deformational, plutonic and metamorphic events. Most of the original studies are reported by the authors in U.S. Geological Survey Circular numbers 733, 751, 823-B, 868, 939, 945, 967 and 978, and are not cited specifically here. This summary does not contain either a comprehensive bibliography or a comparison of the metamorphic histories of south-eastern Alaska with the adjacent parts of British Columbia.

The Coast plutonic–metamorphic complex is here divided into three major elements: the western metamorphic, the central granitic and the eastern metamorphic zones (Fig. 1). The western metamorphic belt is extremely long (900 km), and narrow (7–25 km). It consists of regional dynamothermally and regional thermally metamorphosed rocks with mineral assemblages ranging from prehnite–pumpellyite to upper amphibolite facies, scattered mesozonal to epizonal granitic bodies, and a few concentrically zoned mafic–ultramafic masses. The metamorphic grade and the amount of deformation increase from south-west to north-east, culminating at, or slightly to the north-east of, the 'great tonalite sill': a remarkable 700-km-long, 3- to 25-km-wide vertical to northeast-dipping belt of mostly syntectonic plutons of approximately the same age, composition and structural habit (Fig. 1).

Fossils indicate that the protoliths of the western metamorphic belt range in age from Permian to early Late Cretaceous. With the exception of the Upper Jurassic and Lower Cretaceous rocks, which were originally a flysch wedge with associated volcanic flows and breccia, the protoliths are dominantly volcanic with minor, almost equal, amounts of fine-grained clastic rock and minor discontinuous beds of limestone.

Magmatism and deformation

The plutonic rocks serve to bracket the deformational and metamorphic episodes. The regional distribution, characteristics and age relations of the plutonic rocks have been synthesized elsewhere (Brew & Morrell 1983, Brew 1988). In the western metamorphic belt, six closely spaced intrusive episodes (Table 1) all post-date the earliest deformation. The episodes are: a 110 Ma event (P_1) that produced a linear belt of widely separated mafic–ultramafic plutons; a 105–100 Ma event (P_2) that produced only scattered quartz diorite and granodiorite plutons; a 90 Ma event (P_3) that produced a linear belt of alternately widely separated and concentrated diorite and quartz–diorite plutons containing magmatic epidote; a 70–55 Ma event (P_4) that produced the great tonalite sill (Fig. 1); a 60 Ma event (P_5) that give rise to a relatively short belt of stubby vertical granodiorite sills adjacent to the great tonalite sill on its north-east side; and a 50 Ma event (P_6) that generated a large volume of granodiorite and quartz monzonite in a broad belt of composite plutons along the USA–Canada boundary.

Deformation in the western metamorphic belt started almost immediately after the deposition of the Upper Jurassic and Lower Cretaceous turbidites and their asssociated volcanic flows and breccias. Those rocks were isoclinally folded about gently to moderately northwest- and southeast-plunging axes with northeast-dipping axial planes (D_1), and were subjected to low-grade regional metamorphism (M_1) before the earliest (P_1) intrusions (Table 1). The next two intrusive events (P_2 and P_3) followed apparently without any intervening deformation; the later (P_3) itself deformed (D_2) pre-existing structural elements, bringing axial planes and S-surfaces locally parallel to the pluton contacts during forceful emplacement. Major regional deformation (D_3) affected some of the 90 Ma (P_3) bodies and just preceded the intrusion of the

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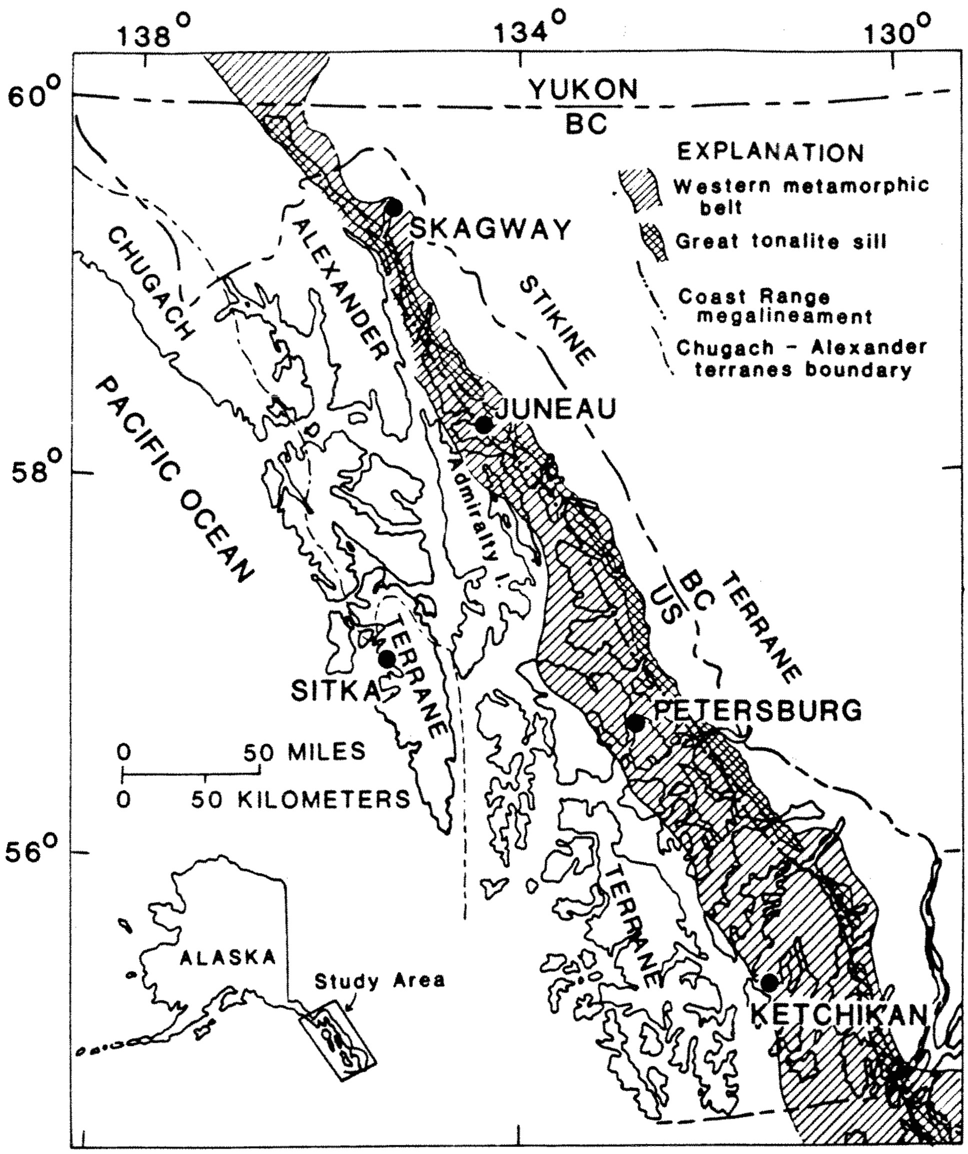

FIG. 1. Map of south-eastern Alaska, showing locations of the western metamorphic belt of the Coast plutonic–metamorphic complex (Brew & Ford 1984), the great tonalite sill and the Coast Range megalineament.

TABLE 1. *Approximate time relations of plutonic, deformational and metamorphic events in the western metamorphic belt of the Coast plutonic–metamorphic complex*

	Time (Ma)							
	120	110	100	90	80	70	60	50
Plutonic events		P1	P2	P3		P4	P5	P6
Deformational events	D1			D2		D3 D4 D5	D4? D5?	D6?
Metamorphic events	M1	M2	M3	M4 M4′		M5	M5?	M6

great tonalite sill (P_4). The D_3 deformation was also characterized by northeast-dipping axial planes and northwest- and southeast-plunging axes; it intensified the D_1 elements, refolded D_1 folds, and locally preserved D_1 fabric elements in S-C tectonites. The last folding event (D_4) was localized close to the great tonalite sill: the steep north-plunging small Z-folds with northeast-dipping axial planes have the same orientation as the pronounced stretching lineations in the sill. Subsequent deformation produced a persistent mylonite zone (D_5) that commonly forms the south-west contact of the great tonalite sill, and the locally ductile fault zone (D_6) known as the Coast Range megalineament zone (Brew & Ford 1978) close to the great tonalite sill for its whole length (Fig. 1).

The recurrent southwest-vergent Late Cretaceous fold history indicates a long duration of northeast-over-southwest movement that resulted in the collapse of the Cretaceous flysch and volcanic wedge between the Alexander Terrane to the west and the Stikine Terrane to the east (Fig. 1). It also caused the development of a thickened prism of rock in the site of the Late Jurassic and Early Cretaceous trough. The upward-, southwest-directed movement of the great tonalite sill resulted in the addition of a large volume of granitic rock to the thickened prism. The later (50 Ma) intrusion of large volumes of granodioritic material north-east of the great tonalite sill also established that the Coast plutonic–metamorphic complex was a large, thick and relatively light element of the earth's crust.

The origin of the Coast Range megalineament is obscure, but it is probably related to a profound structural discontinuity and to the contrast in the volume of granitic rock at depth on its opposite sides. Quantitative studies of the uplift of the Coast plutonic–metamorphic complex in adjacent parts of British Columbia (Hollister 1982, Parrish 1983) indicate a rate of 1–2 mm $year^{-1}$ for the east side of the megalineament. Preliminary results suggest a similar uplift history in south-eastern Alaska.

At a few localities, the Coast Range megalineament and the mylonitic south-west boundary of the great tonalite sill are coincident or nearly so. In those places the combined D_5 and D_6 strain is concentrated in a narrow zone.

Metamorphism

Metamorphism in the western belt is intimately related to its deformational and plutonic history. The earliest documented regional dynamothermal metamorphism (M_1) affected rocks as young as the lower Upper Cretaceous flysch and volcanic rocks; it pre-dates the 110 Ma mafic–ultramafic (P_1) event. The extent of the area affected and the metamorphic grade (probably up to greenschist facies) of M_1 are not well known because of the M_5 (70 Ma) metamorphic overprinting. Rare relict riebeckite in parts of the M_5 metamorphic belt suggest that higher pressure assemblages were developed locally in the M_1 episode.

M_2 is limited to the thermal aureoles of the P_1 (110 Ma) mafic–ultramafic bodies. The aureoles are up to a few hundred metres wide and contain hornblende-hornfels assemblages. M_3 is a poorly understood thermal event associated with the P_2 (105 to 100 Ma) granitic rocks.

M_4 is a regional thermal metamorphism associated with the P_3 (90 Ma) intrusives. Aureoles around the smaller plutons are generally only a few tens of metres wide, and the thermal effects on the previously folded rocks give rise to small areas of garnet–staurolite–biotite schists of dynamothermal aspect. Andalusite–biotite hornfels are common, and in a few aureoles the andalusite has been replaced by kyanite late in M_4.

Around the larger P_3 plutons, 10-km-wide belts of Barrovian metamorphic rocks occur; facies range from prehnite–pumpellyite through upper amphibolite with well-developed garnet, staurolite, kyanite and sillimanite isograds that can be mapped for tens of kilometres.

The M_5 metamorphic belt is associated with the P_4 (70 to 55 Ma) great tonalite sill. Some of the P_3 (90 Ma) plutons are in the M_5 belt, some are not. This allows use of isotopic ages of both granitic events in constructing the composite $P-T-t$ curve (Fig. 2). The M_5 belt is consistently narrow and reaches its maximum width of about 12 km to the south-west of the great tonalite sill (P_4) plutons at the latitude of Juneau. The extent of the M_5 metamorphism to the north-east of the sill is unclear.

In a single transect across the belt, west of the great tonalite sill near Juneau, Forbes (1959) identified the first appearances of biotite, garnet, staurolite, kyanite and sillimanite successively to the north-east. Our subsequent studies have confirmed and refined Forbes' work and have extended the belt to its now-recognized 400 km length. In addition, we have mapped the pumpellyite-out, green-biotite-in, brown-biotite-in, chlorite-out, kyanite-out, and local 'melting isograd' surfaces (Ford & Brew 1973, 1977, Brew & Ford 1977, 1986). We have also established the presence of reaction isograds

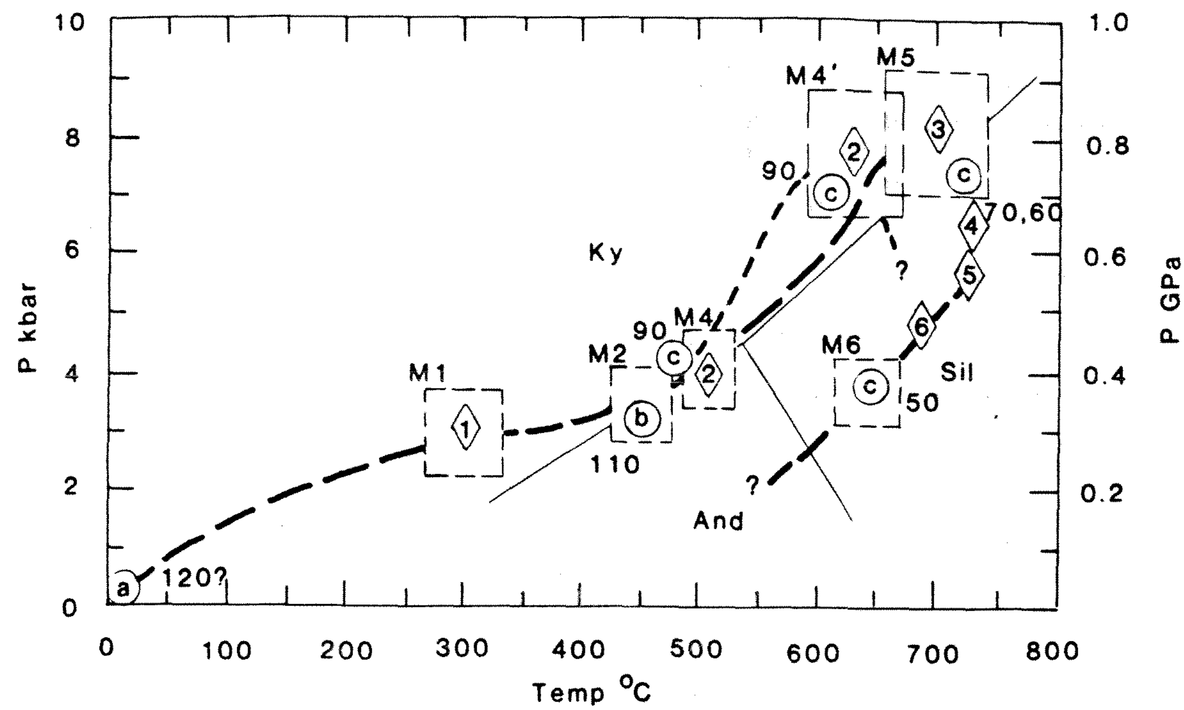

FIG. 2. Inferred $P-T-t$ paths for the western metamorphic belt in general, combining information from the Juneau–Taku River–Tracy Arm and Petersburg transects. Short-dashed line represents path associated with syntectonic 90 Ma intrusions. Deformation events D_1-D_6 and metamorphic events M_1-M_6 are described in the text. Geochronological data (ages in Ma) are based on: a = fossils; b = K–Ar on Bt and Hbl; c = U–Pb on Zrn. Except for M_5, the error boxes for metamorphic conditions are estimated from mineral assemblages. Aluminium silicate polymorph curve from Salje, curve b (1986).

and the following details concerning specific mineral assemblages.

Using AFM topologies, model reactions forming biotite, garnet, staurolite, kyanite and sillimanite correspond to isograds mapped on the basis of the first appearance of these minerals. The isograds are inverted, with the isogradic surfaces dipping to the north-east, which is the direction of progression from lower to higher grade. There are no significant discontinuities in the progression from lower to higher facies.

In the low-grade western part of the M_5 belt, on Douglas, Admiralty and other nearby smaller islands, mineral assemblages are in the prehnite–pumpellyite facies. The disappearance to the north-east of pumpellyite and prehnite marks the transition into the greenschist facies.

Biotite may have formed by several bulk composition-controlled reactions, including:

$$\text{Stp + phengite = Chl + Bt + Qtz + } H_2O \quad (1)$$

Chloritoid occurs in the biotite zone of the greenschist facies just below the garnet isograd. Garnet was formed by the continuous reaction:

$$\text{Chl + Ms + Qtz = Grt + Bt + } H_2O \quad (2)$$

and its first appearance was controlled by bulk composition also. Common assemblages in the garnet zone are: Chl–Bt–Ms–Qtz, Bt–Grt–Ms–Qtz and Chl–Bt–Grt–Ms–Qtz.

The formation of staurolite is modelled by the discontinuous reaction:

$$\text{Chl + Ms + Grt = St + Bt + Qtz + } H_2O \quad (3)$$

and the formation of kyanite is modelled by the reactions:

$$\text{Chl + St + Ms + Qtz = Ky + Bt + } H_2O \quad (4)$$

$$\text{St + Ms + Qtz = Grt + Ky + Bt + } H_2O \quad (5)$$

The kyanite zone is divided into lower, middle and upper parts. The boundary between the lower and middle zones, which represents reaction (4) going to completion, was mapped as the 'chlorite-out' isograd. The boundary between the middle and upper kyanite zones, which represents reaction (5) going to completion, was mapped as the 'staurolite-out' isograd.

The sillimanite isograd is based on the reaction:

$$\text{Ky = Sil} \quad (6)$$

The absence of staurolite in sillimanite-bearing samples indicates that reaction (5) is completed before reaction (6). The 'melting isograd' in pelitic rocks near Juneau appears to be consistently above the kyanite-out surface.

Geothermometry and geobarometry for the M_5 metamorphic event are limited. Biotite–garnet geothermometry (using the method of Ferry & Spear 1978) indicates maximum temperatures of 535°C for the lower part of the garnet zone, 565°C for the staurolite zone, 645°C for the kyanite zone and 735°C for the sillimanite zone. The determinations show a considerable scatter, and further analyses are in progress. Our geobarometric results also have a large amount of scatter, but a maximum of 0.9 GPa is indicated for the sillimanite zone and possibly for the kyanite zone.

Not all of the Barrovian surfaces are recognized everywhere in the M_5 belt. They are truncated to the north-west of the Juneau–Taku River–Tracy Arm transect by the south-west contact of the great tonalite sill, probably because of the late movement (D_5) along that contact. Elsewhere it appears that the $P-T$ conditions required for kyanite and sillimanite were not attained near the sill. In some localities, where the south-west margin of the great tonalite sill and the Coast Range megalineament are coincident, evidence of the Barrovian M_5 metamorphism is missing entirely.

The metamorphism (M_6) that is inferred to be associated with the extensive P_6 (50 Ma) plutons is superposed on the high-grade mineral assemblages of the M_5 event and we have not been able to map it consistently. In southern south-eastern Alaska, rare occurrences of sillimanite and cordierite (R. L. Elliott pers. comm. 1979) on the north-east side of the great tonalite sill are interpreted by us as belonging to the M_6 event.

Although our data base is limited, we believe that the available quantitative geobarometry and geothermometry and estimates of pressure–temperature conditions from mineral assemblages justify construction of a composite hypothetical $P-T-t$ curve for this sequence of metamorphic episodes (Fig. 2).

Tectonic setting

Large-scale tectonic models involving the accretion of several tectonostratigraphic terranes have been proposed for south-eastern Alaska. Monger & Ross (1971) recognized that the Cache Creek Terrane (an extensive Palaeozoic oceanic crustal unit in British Columbia adjacent to the North American craton) contained Permian fusulinids of Tethyan origin. This terrane is part of composite Terrane I of Monger *et al.* (1982). West of the Cache Creek and extending almost to the present continental margin were both Palaeozoic and Mesozoic rocks that included Permian strata with fusulinids of cosmopolitan or North American affinity. These western rocks have been called the Stikine, Alexander and Wrangellia Terranes by Berg *et al.* (1978). The Stikine is part of composite Terrane I and the others are part of composite Terrane II of Monger *et al.* (1982). Along the continental margin is the Chugach Terrane of Berg *et al.* (1972), a flysch and melange unit of Cretaceous age that may not be as exotic as are the two large terranes to the east. Thus three large tectonostratigraphic units are present outboard of the North American craton: (1) the Cache Creek terrane; (2) the Stikine, Wrangellia and Alexander terranes; and (3) the Chugach terrane.

This tectonic setting is fundamental to the evolution of the western metamorphic belt. As described by Monger *et al.* (1982), it, as part of the Coast plutonic–metamorphic complex, is a product of the collision of composite Terrane II from the west with composite Terrane I to the east. Brew & Ford (1983) interpret the evidence as indicating that the collision was between two large fragments (now the Alexander and Stikine terranes) of a larger terrane that rifted apart during the northward migration. In both interpretations, the rocks that were deformed, metamorphosed and intruded in the western metamorphic belt consists of (1) the Upper Jurassic and Lower Cretaceous flysch and associated volcanic rocks that occupied the space between the two colliding terranes, and (2) the Palaeozoic and lower Mesozoic rocks that were adjacent to those units.

Most of the intrusive, metamorphic, deformational and tectonic events described above are concentrated and superposed in a narrow linear zone, termed the 'south-eastern Alaska coincident zone' by Brew & Ford (1985), that extends the length of south-eastern Alaska and beyond. The origin of this zone and the juxta- and superposition of the different features within it, is perhaps the single most intriguing question in northern Cordilleran geology.

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