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Terrane assembly and structural relationships in the eastern Prince Rupert quadrangle, British Columbia

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ABSTRACT

The eastern part of the Prince Rupert quadrangle, British Columbia, is subdivided into two regions: the western metamorphic belt and the central belt. The western metamorphic belt is underlain by five distinct mappable rock sequences. From west to east these are the Digby, Venn, Delusion Bay, Kaien, and Tsimpsean sequences. Rocks of the Digby sequence seem to correlate with Triassic and upper Paleozoic rocks of the Alexander terrane; the overlying Venn sequence contains rocks of the same age as parts of the Gravina belt. The Tsimpsean sequence is considered to be part of the Yukon-Tanana terrane, a continental margin assemblage. Correlation of the two intervening sequences, Kaien and Delusion Bay, is uncertain; they may belong either to the Taku terrane or to the Yukon-Tanana terrane. We tend to favor the latter interpretation. North- to northwest-striking thrust faults approximately bisect the belt and separate the Digby and Venn sequences on the west from the structurally overlying units to the east. Near Prince Rupert, west-directed, probably mid-Cretaceous, thrusting accompanied emplacement of tonalite and basalt dikes and sills. These thrusts and others to the north juxtapose upper amphibolite facies rocks over greenschist facies schist. The northern thrusts appear to postdate the regional metamorphism. Above and below the thrusts the rocks show intense ductile deformation. The Prince Rupert shear zone, east of the thrusts, records a strong flattening deformation, possibly due to overthrusting by the 91 Ma Ecstall pluton and associated high-grade gneiss. This tectonic emplacement of hot rocks and the associated igneous activity represented by syntectonic tonalite sills emplaced in the shear zone are inferred to be the cause of the 90 Ma amphibolite facies metamorphism that underlies the Prince Rupert shear zone.

The western metamorphic belt is bounded on the east by the Coast shear zone, which separates the western belt from the central belt. This shear zone evolved during emplacement of 65–52 Ma plutons of the Paleogene Coast Mountains batholith that underlie much of the central belt. As the Coast Mountains batholith was emplaced, strain within the arc changed from dominantly contractional normal to the batholith and to the orogen, to extensional parallel to the length of the batholith. The latter stages of batholith emplacement apparently accompanied batholith exhumation. The youngest part of the Coast shear zone is a 1–2-km-wide zone of vertical fabric along the western side of the shear zone and is at the westernmost extent of 85–50 Ma plutons. This Work-Behm shear zone formed during the late stages of uplift of the western metamorphic belt by westward tilting about a northwest-trending hinge. After a hiatus with no identified tectonic activity other than gradual exhumation, Miocene and younger felsic and mafic dikes and young brittle faults cut the rocks throughout the eastern part of the quadrangle.

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INTRODUCTION

The northwest-southeast trending Coast Mountains orogen of British Columbia and Alaska extends from the Washington–British Columbia border to the Yukon-Alaska border at ~60° N. This paper focuses on the Prince Rupert quadrangle in the central part of the orogen adjacent to the British Columbia–Alaska border at 54°45′ N (Fig. 1). The main features of the Coast Mountains orogen in this area have been described in earlier studies from the Prince Rupert and Ketchikan quadrangles (Hutchison, 1982; Woodsworth et al., 1983a; Crawford et al., 1987; Arth et al., 1988; Berg et al., 1988; Rubin and Saleeby, 1992a). The central Coast Mountains underwent a period of westward-vergent ductile thrust faulting, syntectonic pluton emplacement, and greenschist to amphibolite facies metamorphism between mid-Cretaceous and Eocene time (e.g., Berg et al., 1978; Monger et al., 1982; Crawford et al., 1987; Gehrels and Saleeby, 1987; McClelland and Gehrels, 1990; Crawford and Crawford, 1991; Rubin and Saleeby, 1992a). This activity accompanied the accretion of a series of tectonostratigraphic terranes onto the western margin of North America (Monger et al., 1982; Crawford et al., 1987; Rubin and Saleeby, 1992a; Klepeis et al., 1998). By the end of the Cretaceous this convergence and accretion had created a major crustal welt between the Alexander-Wrangellia and Stikine terranes (Monger et al., 1982). Between ca. 80 Ma and 50 Ma, during continued convergence, the plutons of the central Coast Mountains Paleogene batholith were emplaced along the eastern margin of the accreted terrane complex (Hutchison, 1982; Crawford and Hollister, 1982). This resulted in additional crustal thickening, and formation of major structures including the Coast shear zone (Klepeis et al., 1998). The end of the orogenic cycle is marked by exhumation resulting from orogen-parallel extensional faulting in the central belt and dip-slip movement along shear zones and faults on the western and eastern sides of the central belt (Klepeis and Crawford, 1999). Cooling ages obtained from the plutons and gneiss (Hollister, 1982; Wood et al., 1991) and the metamorphic assemblages in this central belt suggest rapid cooling during uplift at ca. 50 Ma (Hollister, 1982, 1993; Hutchison, 1982; Crawford et al., 1987).

The rocks in the Prince Rupert quadrangle are in four longitudinal belts characterized by features that result from the tectonic history summarized here. These belts are distinguished by (1) the metamorphic conditions preserved in the supracrustal rocks; (2) the age and general character of the associated plutonic rocks; and (3) the style of deformation. From west to east (Fig. 1) they are (1) rocks of the Alexander terrane that show little evidence of the mid-Mesozoic to Cenozoic igneous and metamorphic events resulting from the accretion that produced the Coast Mountains orogen; (2) the western metamorphic belt characterized by 100–89 Ma plutons and associated regional and contact metamorphic rocks; (3) the central belt with 80–49 Ma plutons of the Paleogene batholith and associated high-grade metamorphic rocks; and (4) the eastern belt with low-temperature metamorphism and shallow-level plutons formed during the mid-Cretaceous to Eocene orogenic events.

Our aim is to describe the lithologic sequences that we have identified along the western side of the orogen in this quadrangle, the structural features recorded in these rocks and in the rocks of the central belt to the east, and to summarize the metamorphic conditions described in more detail elsewhere. This chapter summarizes the results of detailed mapping along all shorelines as well as along roads, including logging roads. Away from shorelines and roads dense forest cover and muskeg preclude geological observations. Ages reported in this chapter, unless otherwise indicated, are preliminary ages obtained by G. Gehrels.

In the Prince Rupert quadrangle, and in the Ketchikan quadrangle to the north, the western metamorphic belt is distinguished by a greater proportion of high-grade metamorphic supracrustal rock relative to plutonic igneous rocks than in areas to the north and to the south. To the north the western metamorphic belt narrows and many of the rocks are of lower grade than in the Prince Rupert and Ketchikan quadrangles (Stowell and Crawford, this volume), whereas to the south the metamorphic rocks occur as scattered screens and pendants in a dominantly plutonic terrain. In addition, the central belt in the Prince Rupert quadrangle contains a relatively larger proportion of the gneissic country rocks that host the Paleogene Coast Mountains batholith than areas to the north and south. As a consequence the Prince Rupert and Ketchikan quadrangles provide the best segment of the orogen in which to study the processes of orogen formation and the attendant record of crustal deformation and thermal events associated with pluton emplacement and crustal exhumation from as deep as 30 km. However, here it is more difficult to identify the stratigraphic relationships of the supracrustal protoliths of the metamorphic rocks than in areas of lower grade rocks.

REGIONAL GEOLOGY

In this chapter we concentrate on the western metamorphic belt and the adjacent parts of the central belt exposed in the eastern part of the Prince Rupert quadrangle. In this area the rocks of the western metamorphic belt preserve a record of mid-Cretaceous (ca. 100–90 Ma) thick-skinned thrusting, coeval pluton emplacement, and associated high- to moderate-pressure metamorphism not extensively overprinted by younger events. Stacking of thick crustal slabs produced an inverted metamorphic gradient with higher pressure and temperature rocks at the structurally highest (eastern) levels of the currently exposed crust of the western metamorphic belt. The western boundary of the western metamorphic belt between the Skeena River on the south and Bradfield Canal on the north (Fig. 1) coincides with faults and/or shear zones that separate greenschist facies and higher grade rocks to the east and northeast from lower grade to unmetamorphosed rocks, mainly of the Alexander terrane, to the west (Gehrels et al., 1987; Cook et al., 1991; Rubin and Saleeby, 1992a). In the Prince Rupert quadrangle, this boundary is underwater in Chatham Sound. It emerges onto land north of the British Columbia–Alaska border where it turns northwest to follow the southern shore of

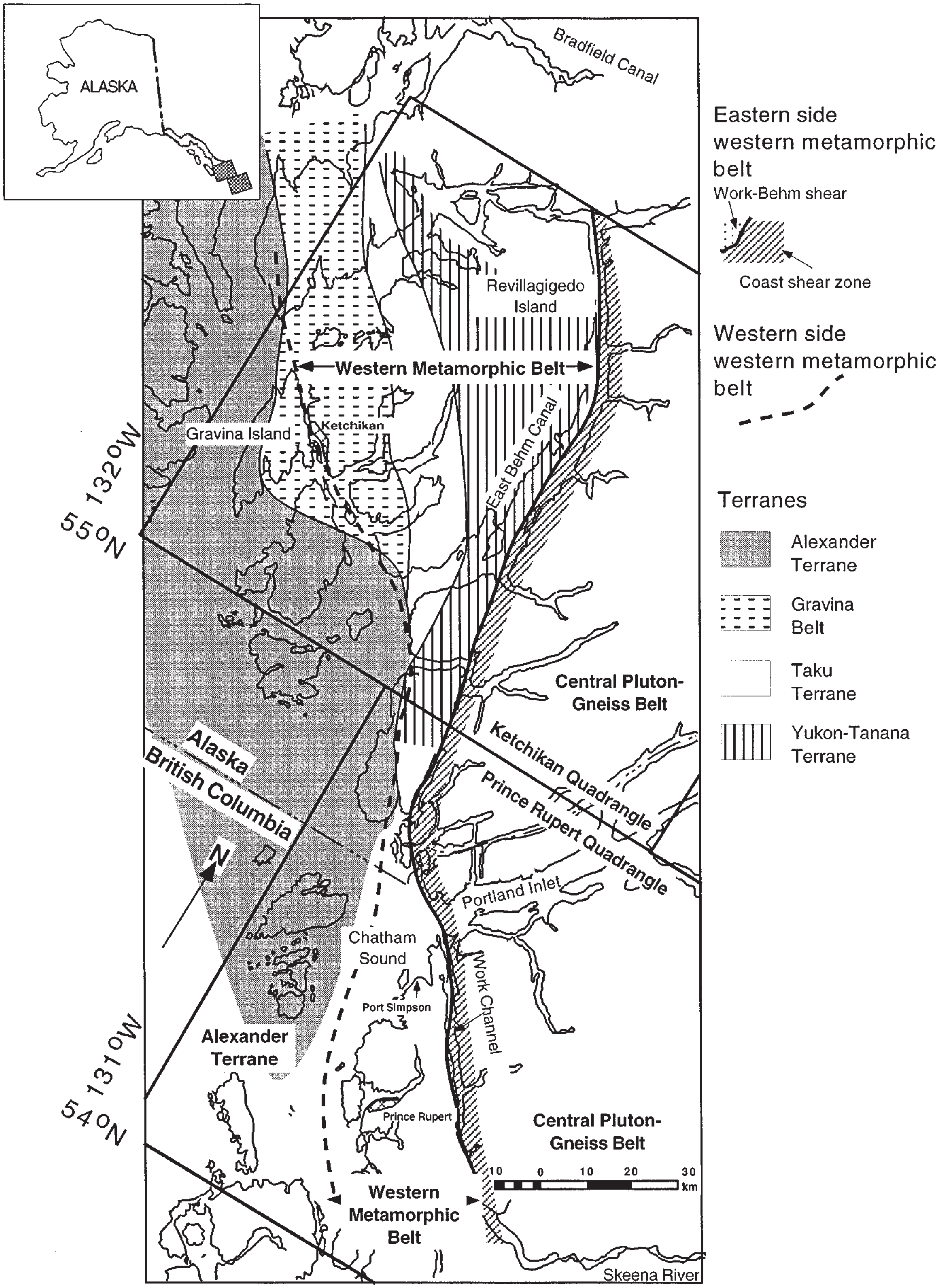

Figure 1. Ketchikan and Prince Rupert quadrangles, southeastern Alaska and British Columbia. Mapped the location of the Alexander, Taku, and Yukon-Tanana terranes and of Gravina belt, from Rubin and Saleeby (1992a), are shown in Ketchikan quadrangle.

Revillagigedo Island in the Ketchikan quadrangle (Cook et al., 1991; Rubin and Saleeby, 1992b).

The central belt includes the 80–50 Ma plutons of the Paleogene Coast Mountains batholith emplaced into high-temperature and moderate- to low-pressure metamorphic country rocks. Westward-vergent thrusts along the eastern side of the western metamorphic belt may, in part, be coeval with penetrative moderately to steeply dipping west-vergent displacements that deform 65–63 Ma plutons along the western side of the central belt. The two belts are separated by the Coast shear zone (Crawford and Crawford, 1990; McClelland et al., 1992b; Klepeis et al., 1998), a zone of intense ductile deformation that, among other things, marks the western limit of Paleogene plutonism. Along the Coast shear zone mid-Cretaceous kyanite-grade schist of the western metamorphic belt is juxtaposed against Paleocene-Eocene plutonic rocks and the upper amphibolite facies migmatitic gneiss that forms the host rock of these plutons. The shear zone is along Work Channel (Work Channel lineament, Crawford and Hollister, 1982) and extends north along east Behm Canal to the northern border of the Ketchikan quadrangle (Fig. 1) where it coincides with the physiographic feature called the Coast Range megalineament (Brew and Ford, 1978).

The two bounding sets of faults that define the eastern and western sides of the western metamorphic belt converge at the border between the Prince Rupert and the Ketchikan quadrangles. Here, at the British Columbia–Alaska boundary, the western metamorphic belt is narrowest (~5 km wide). To the south, at the latitude of Prince Rupert it widens to 30 km or more; in the Ketchikan quadrangle it widens to about 65 km.

LITHOLOGIC UNITS

In the western metamorphic belt of both the Prince Rupert and the Ketchikan quadrangles thrusts juxtapose lithologically distinct groups of rocks. In the Ketchikan quadrangle, Rubin and Saleeby (1992a) assigned these groups of rocks to the eastern edge of the Alexander terrane; metamorphosed turbidite and volcanic rocks of the Gravina belt; the Taku terrane; and the Yukon-Tanana continental margin assemblage (Fig. 1). Narrowing of the western metamorphic belt and the lack of outcrop across the mouth of Portland Inlet (Fig. 2) makes it difficult to trace these lithostratigraphic terranes from the Ketchikan into the Prince Rupert quadrangle.

The most complete section across the western metamorphic belt in the Prince Rupert quadrangle is along a transect through the city of Prince Rupert from Chatham Sound in the west to Work Channel in the east (Figs. 2 and 3). Five lithologic sequences are recognized along this transect. A description of these rocks must be prefaced by noting that they are metamorphosed at greenschist facies on the west and grade to upper amphibolite facies on the east. A summary of the metamorphic features of the western metamorphic belt is given by Stowell and Crawford (this volume); metamorphism in the Prince Rupert quadrangle has been described by Crawford et al. (1979, 1987), and Woodsworth et al. (1983a). This metamorphism and the accompanying deformation obliterate many of the features commonly used for stratigraphic correlation. Bedding transposition and numerous faults make estimates of original thickness impossible. Despite these difficulties we provide our best estimate of a correlation with less intensely metamorphosed units to the north in southeastern Alaska.

Digby sequence (Alexander terrane)

The westernmost group of rocks east of Chatham Sound is the Digby sequence, named for exposures along the western side of Digby Island (Figs. 2, 3, and 4). The Digby sequence comprises predominantly siliceous volcanic rocks, interlayered calcareous felsic and chlorite-rich phyllite, and marble that crop out in three segments up the east coast of Chatham Sound. From south to north these are (1) along the western side of Digby Island; (2) on Tsimpsean peninsula on the shores of Big Bay; and (3) on the western side of Kanaganut Island just north of the British Columbia–Alaska border. On western Digby Island a calcareous muscovite and chlorite phyllite with thin marble layers is interpreted to represent a limy fragmental metavolcanic or tuffaceous sequence. Overlying this phyllite is massive rhyolite and associated marble that can be traced along the western shore of Digby Island north to Straith Point (Fig. 2). West of Straith Point, on Devastation Island, the marble contains a poorly preserved brachiopod and coral hash of indeterminate age (Woodsworth and Orchard, 1985). At this locality, between the marble and overlying rhyolite, is a several-meter-thick clast-supported conglomerate containing fine-grained felsic clasts to 0.5 m in diameter. Most of the clasts appear to be siliceous metavolcanic rocks; some are porphyritic. The conglomerate grades upward into the marble as the amount of carbonate matrix increases. The eastern contact of the Digby sequence is exposed at Straith Point. Here a massive, locally fragmental, rhyolite unit, ~150 m thick, is structurally overlain by black phyllite with conglomerate layers and lenses assigned to the Venn sequence (see following). The Big Bay segment of the Digby sequence also consists of rhyolite, marble, and calcareous tuff. In Alaska, similar rocks are found on Kanaganut Island (Fig. 2) and along the shores of Tongass Island and Harry Bay just north of the map area. Rhyolite that appears very similar to that on Devastation Island also underlies small islands and rocks in Chatham Sound east of Dundas Island. Scarce biotite flakes and, in some places, garnet in addition to quartz, sodic plagioclase, calcite/dolomite, and muscovite, demonstrate that these rocks are everywhere metamorphosed at low to middle greenschist facies conditions.

U-Pb dates on zircon from two of these rhyolite units yield ages of 472 Ma on western Digby Island and 354 Ma on western Tongass Island (Fig. 5). These ages support the suggestion by Berg (1973), Gehrels et al. (1987), and Woodsworth and Orchard (1985), based on units exposed on Randall and Dunira Islands west of Chatham Sound and on Gravina Island in the Ketchikan quadrangle (Fig. 1), that the Digby Island portions of this unit

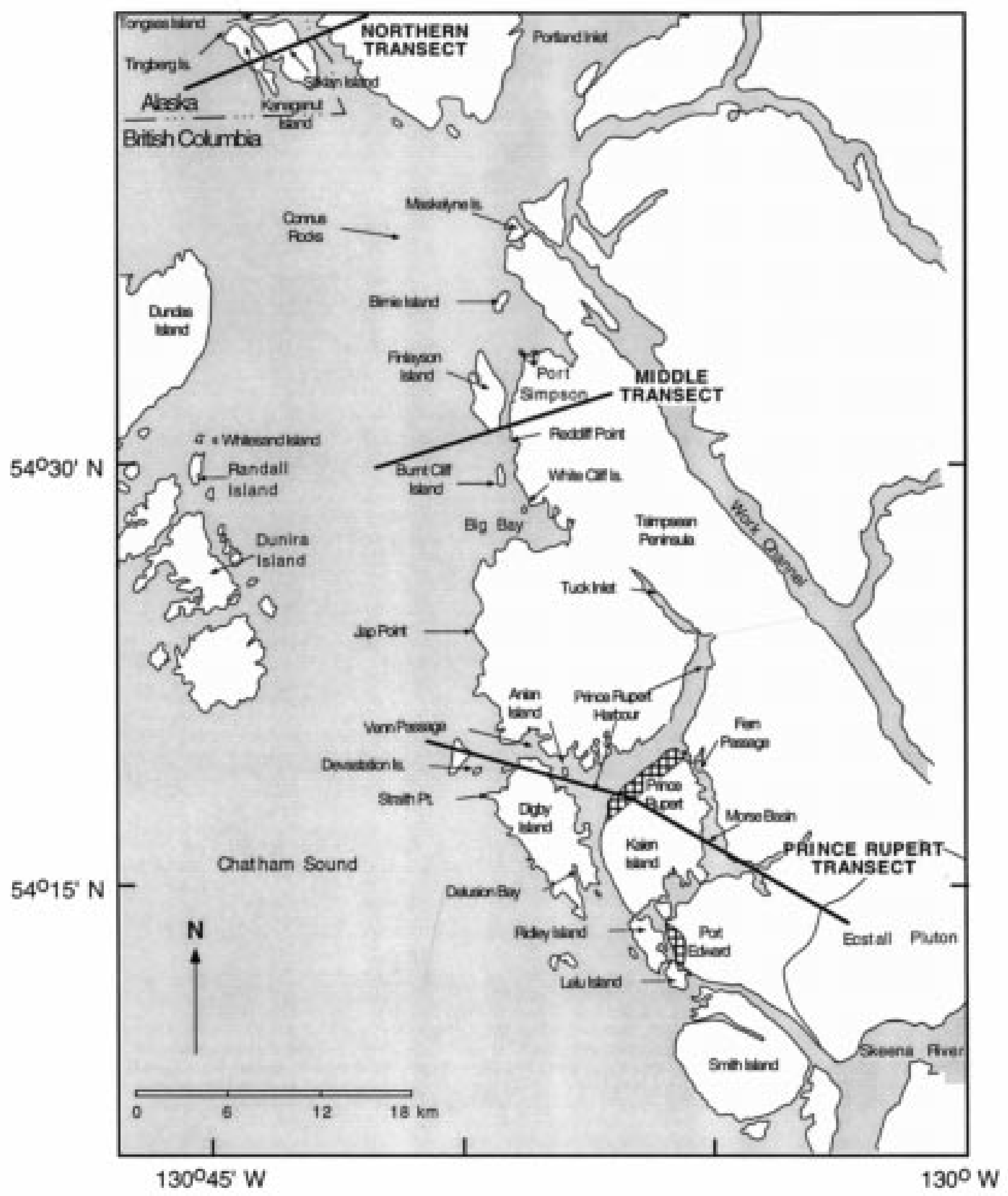

Figure 2. Location map including sites mentioned in text for eastern part of Prince Rupert quadrangle, British Columbia.

correlate with upper Paleozoic and Triassic portions of the Alexander terrane. In Alaska, immediately north of the study area, the units we assign to the Digby sequence are directly east of the Alexander terrane rocks at Cape Fox.

Venn sequence (Gravina belt?)

At the mouth of Venn passage the Digby sequence is overlain by the Venn sequence (Figs. 3 and 4). The Venn sequence consists of carbonaceous muscovite and calcareous muscovite-chlorite phyllite and schist that commonly show graded bedding and contain numerous metaconglomerate layers as well as local rhyolite layers. In the phyllite and schist dark gray to black carbonaceous units predominate. As a result of metamorphic recrystallization and deformation that increase in intensity eastward, few primary sedimentary structures other than bedding survive. Locally in the west there are features that appear to be soft-sediment slumps or rip-up and possibly flame structures. A similar graded-bed metaargillite and siltstone unit, with rhyolite but lacking the conglomerate layers, overlies the Digby sequence on

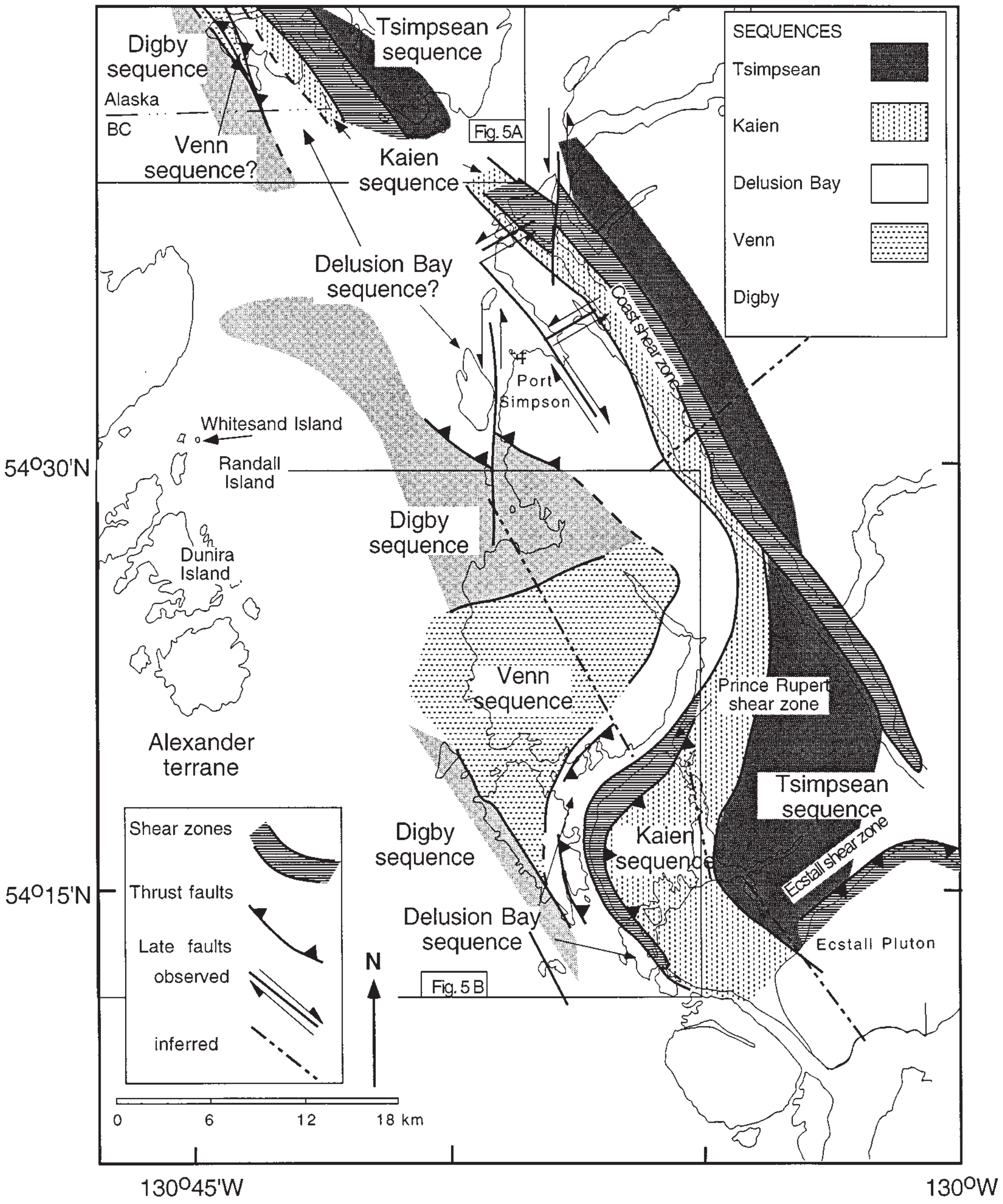

Figure 3. Generalized stratigraphic and structural features of Prince Rupert quadrangle, British Columbia. Mid-Cretaceous to Eocene structures include thrust faults (heavy lines with barbs on upper plate) and ductile shear zones (ruled). Post-Eocene structures include steep strike-slip faults (heavy lines with arrows) and possible faults along lineaments (dashed lines).

Kanaganut Island (Fig. 3).

The Venn sequence carbonaceous phyllite is characterized by fine-grained quartz and muscovite and, at many localities, by randomly oriented plates of ilmenite several millimeters in diameter. All the mineral grains are coated by fine carbonaceous material that makes the rock black even in thin section. The less abundant greenish muscovite-chlorite phyllite, commonly with calcite and dolomite, superficially resembles phyllite units of the Digby sequence. In higher grade rocks to the east actinolite and hornblende occur in calcareous layers; biotite and garnet are found in the carbonaceous muscovite phyllite. Chloritoid is found in a few aluminous samples. Ilmenite plates replaced by rutile are found in the highest grade rocks along the western side of Prince Rupert Harbour, and the carbonaceous material appears as discrete graphite flakes. The rhyolite is massive and virtually indistinguishable from the Digby Island sequence rhyolite, except for the absence of associated limestone or calcareous tuff. Assignment of rhyolite to the Venn sequence is based on U-Pb zircon ages of 168 Ma from

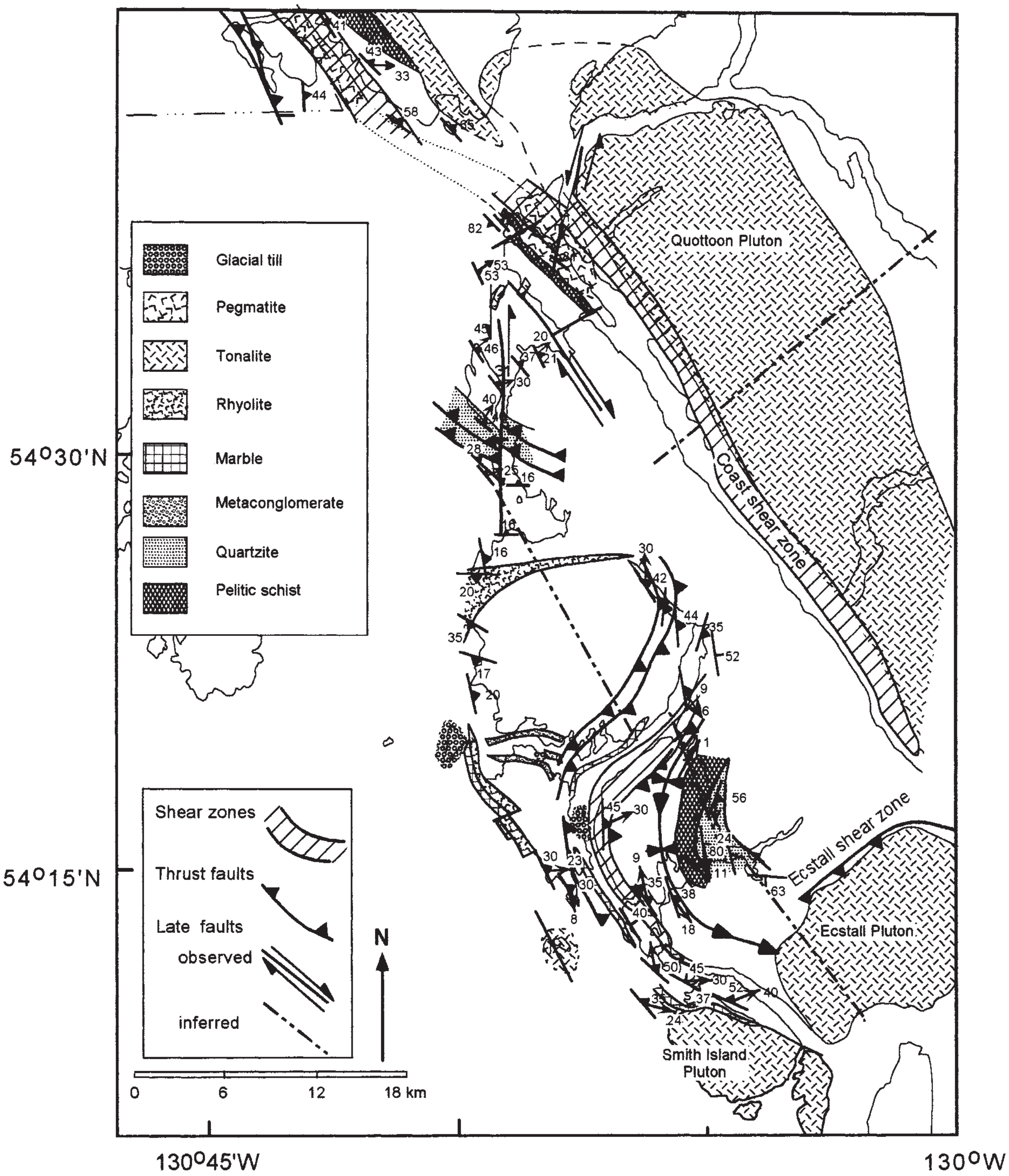

Figure 4. Generalized geologic map of Prince Rupert quadrangle. Selected distinctive map units that can be traced for some distance are shown as well as selected attitudes of bedding and foliation. All non-coastal areas of map area west of Coast shear zone are densely forested.

Jap Point and of 177 Ma from Tingberg Island (Fig. 5A) as well as an age of 170 Ma from rhyolite on Tongass Island, just north of Tingberg Island. On Randall and Dunira Islands Mississippian limestone and Pennsylvanian calcareous siltstone, shale, and shaley limestone are overlain by Upper Triassic rocks that include massive limestone and dolomite, green phyllite, and the Moffat rhyolite. The latter was tentatively dated as Jurassic (U-Pb zircon; Woodsworth and Orchard, 1985), subsequently confirmed by a U-Pb age of 177 Ma (Fig. 5B). The Venn sequence rhyolite everywhere crops out close to the contact with the Digby sequence rhyolite and marble. As a consequence it is possible that rhyolite units for which we have no ages may be misassigned.

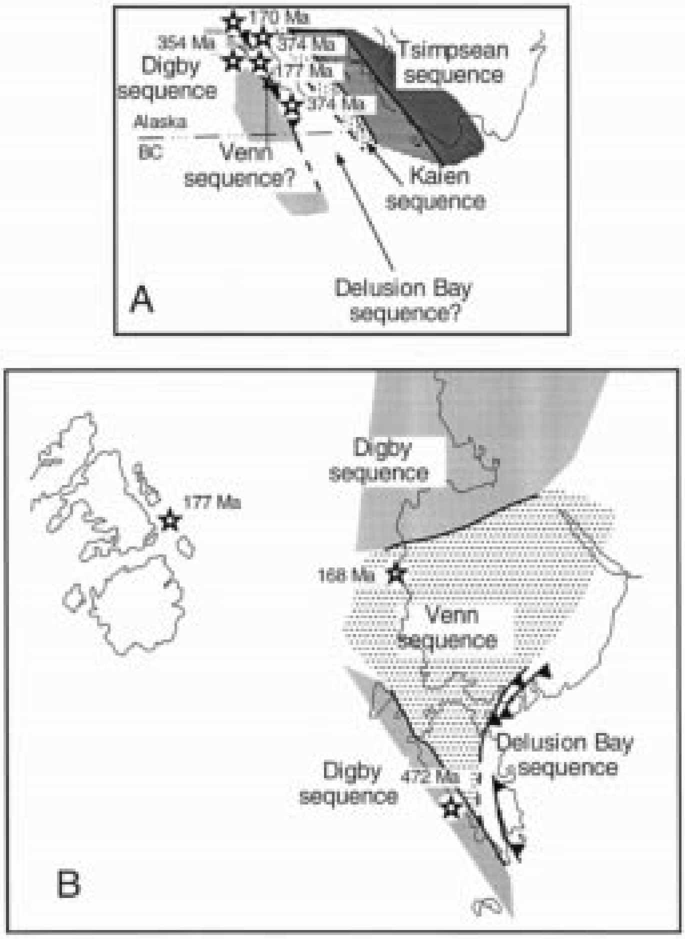

Figure 5. Maps showing locations of samples yielding U-Pb zircon ages (see Fig. 3).

The thickness of the conglomerate layers varies from several meters to a few centimeters. The thicker conglomerate layers, to 10 m thick, occur in a band that extends eastward along the southern shores of Venn Passage (Fig. 4), close to the rhyolite layers and to the contact with the Digby sequence. Ovoid to subangular cobbles to 1 m in diameter occur in these clast-supported conglomerate layers. Cobble lithologies include fine-grained felsic igneous rocks, some of which are porphyritic, a few red clastic sedimentary rocks, and a few crinoid-bearing marbles. In the rest of the Venn sequence conglomerate layers are a few to tens of centimeters thick. Clasts in these layers (2–15 cm diameter) are flattened and elongated in the plane of the foliation; some stretched clasts reach 50 cm in length. The most common pebbles are recrystallized felsic metavolcanic rocks and white equigranular quartzite (recrystallized chert?). Some of the fine volcanic fragments have relict euhedral plagioclase phenocrysts; others have a well-developed texture defined by feathery laths of alkali feldspar. These clasts probably originate in the adjacent rhyolite units. Other clasts include dark gray flattened metasiltstone and metaargillite pebbles that resemble the nonconglomerate lithologies in this unit and scarce limestone pebbles. The clastic pebbles may have been derived from underlying layers during deposition of the conglomerate. The matrix of the conglomerate, associated metasandstone and metasiltstone, and the sand- to silt-size portions of graded beds contain 0.1–0.2 mm angular plagioclase grains surrounded by fine quartz-muscovite ± carbonate groundmass.

The presence of volcanic clasts in the conglomerate layers, the abundance of plagioclase and of chlorite relative to muscovite in some parts of the unit, and the high Ti content reflected by the ilmenite, all bespeak a volcanogenic origin for the Venn sequence. The presence of graded bedding, conglomerate, and rip-up clasts in the conglomerate points to an origin as a series of turbidite and debris flows. These characteristics, as well as the fact that these rocks overlie the presumed Alexander terrane units of the Digby sequence, suggest that the Venn sequence may correlate with Gravina sequence rocks, originally described by Berg et al. (1972). Throughout their extent, Gravina belt rocks have been interpreted to depositionally overlie the Alexander terrane (Berg et al., 1972; Cohen and Lundberg, 1993). West of Prince Rupert, as is also true in southeastern Alaska, contacts are either faulted or unexposed (Brew and Karl, 1988). At the northern end of our map, on Kanaganut Island, the contact is well exposed and there is no detectable structural break between the rocks we have correlated with the Venn sequence and the underlying Digby sequence rocks. However, the contact is between rhyolite and marble and the marble has abundant small doubly plunging and sheath folds and so has clearly been strongly deformed. If, in fact, this exposure represents the Alexander terrane–Gravina belt transition, the field relations might be interpreted to suggest that the two sequences are depositionally conformable, albeit strongly transposed.

In the Ketchikan quadrangle, the Gravina sequence consists of Upper Jurassic andesite and basaltic metavolcanic and volcaniclastic rocks overlain by graded bedded metagraywacke of unknown age; farther north metagraywacke units have fossils with ages as young as Cenomanian (Cohen and Lundberg, 1993). Plagioclase, hornblende, and biotite dominate the mineral assemblage in the Gravina metagraywacke of the Ketchikan quadrangle. On the basis of this mineralogy we suggest that the detritus had a mafic to intermediate volcanic source. In addition, the metagraywacke units are interlayered with fragmental to massive mafic volcanic layers. The Venn sequence differs from the Gravina sequence of the Ketchikan quadrangle in having rhyolite layers as well as numerous conglomerate layers with abundant feldspathic volcanic clasts, and quartzite and marble pebbles; in the paucity of plutonic rock pebbles in the conglomerate layers; and in the presence of phyllite possibly derived from felsic tuffs. However, Berg (1973) described a conglomerate with clasts of metarhyolite, leucotrondhjemite, basic volcanic rocks, siltstone, argillite, and metachert, and an overlying unit comprising siltstone and argillite from western Gravina Island. McClelland et al. (1992a) described clasts of argillite, chert, limestone and volcanic rocks in conglomerate from the lower part of the Gravina sequence in the vicinity of Petersburg. They conclude that the clasts were derived from the underlying Alexander terrane. These observations support our correlation of the Venn sequence with the Gravina belt.

Rocks lithologically similar to those in the Venn sequence occur on Whitesand Island west of Chatham Sound. These turbidites are less deformed and recrystallized and better preserve sedimentary structures. The location of these rocks, displaced northward relative to the outcrop area of Venn sequence rocks to the east, suggests that one or more faults may underlie Chatham Sound.

Delusion Bay sequence (Taku terrane? Yukon-Tanana terrane?)

East of and structurally above the Venn sequence, separated from it by thrust faults, is the Delusion Bay sequence (Fig. 3). This group of metamorphic rocks includes limestone and dolomite marble, clastic metasedimentary rocks dominated by quartz-rich schist and calc-schist, and interlayered felsic and mafic metavolcanic rocks, locally including pillow lava. These amphibolite facies rocks are exposed from Smith Island in the south to Tuck Inlet at the northern end of Prince Rupert Harbour (Figs. 2 and 3). The structurally lower part of the section on the west consists of interlayered mafic and felsic metavolcanic rocks interlayered with marble. The thickest and most continuous marble unit can be traced from Smith Island up the western shore of Prince Rupert Harbour (Fig. 4). The only fossils found thus far are poorly preserved crinoids in marble on Anian Island in western Venn Passage (Hutchison, 1982). Overlying the marble is micaceous and calcareous schist, some with garbenschiefer texture, interlayered with amphibolite. On the basis of the composition of the calc-schist and the association with amphibolite, probably derived by metamorphism of mafic volcanic rocks, we suggest that it originated as calcareous tuffs. Along the western side of Prince Rupert Harbour, just east of Melville Arm, a massive quartz-plagioclase body with minor biotite, apparently a trondhjemite or keratophyre stock or plug, intrudes the calc-schist and amphibolite.

Scattered throughout the Delusion Bay sequence, within and east of (structurally above) the marble-rich part of the section, are aluminous, muscovite-poor layers with mineral assemblages that record an increase in metamorphic temperatures from west to east. The westernmost samples contain chloritoid; a central band has garnet + staurolite; the easternmost assemblages in the Delusion Bay sequence are kyanite bearing. The low muscovite and plagioclase content of the aluminous schist and the close association with mafic metavolcanic rocks identified by textures such as plagioclase phenocrysts in a chloritic matrix and pillow structures suggest that the aluminous schist was derived from low-K volcanic rocks through weathering or leaching by hot seawater, not from pelitic metasedimentary rocks.

The easternmost units of the Delusion Bay sequence, exposed along the western shore of the northern end of Prince Rupert Harbour, are quartz-rich schist. Quartz schist and quartzite also crop out on Finlayson Island and on the shoreline to the east (Fig. 4). The siliceous rocks on Finlayson Island and on the mainland to the east are thrust over muscovite and chlorite-rich phyllite assigned to the Digby sequence. Overlying the siliceous metasedimentary rocks on Finlayson Island and east as far as Maskelyne Island, are clastic, calcareous, and possibly metavolcanic rocks metamorphosed to garnet + hornblende + biotite + chlorite + calcite and garnet + hornblende + muscovite + biotite + calcite assemblages. Garbenschiefer textures with radiating hornblende prisms associated with garnet in a matrix of felsic minerals characterize parts of this sequence. Similar lithologies can be traced into Alaska along the eastern side of Kanaganut Island and on Sitklan Island to the east. These alternating bands of micaceous and moderately calcareous schist are similar in composition and appearance to the calcareous schist that is along the western side of the northern shore of Prince Rupert Harbour, although the sequence appears inverted relative to that near Prince Rupert.

Correlation of the Delusion Bay sequence with rocks to the north based on lithologic similarities suggests three possibilities: the sequence may belong to the Taku terrane, to the Yukon-Tanana continental margin assemblage (Mortensen, 1992), or to the Alexander terrane. In the northern part of the map area two rocks that we correlate with the Delusion Bay sequence gave U-Pb zircon ages of 374 Ma (Fig. 5A). These Devonian ages apparently rule out correlation with the Taku terrane, originally defined by Berg et al. (1978) for rocks of late Paleozoic through Triassic age that extend northward from the Ketchikan quadrangle along the eastern side of the western metamorphic belt. Nevertheless there are lithologic similarities with the lower part of the Alava sequence in the Ketchikan quadrangle (Berg et al., 1988; Cook et al., 1991; assigned to the Taku terrane by Rubin and Saleeby, 1992a), as well as with the upper Paleozoic portion of the Taku terrane in northern southeast Alaska (Gehrels et al., 1992). Another possibility is to correlate the Delusion Bay sequence with the mid-Paleozoic Endicott Arm assemblage of the Yukon-Tanana terrane, described by Gehrels et al. (1992) from localities in northern southeastern Alaska and the correlative Ruth assemblage of McClelland et al. (1992a) exposed in Thomas Bay east of Petersburg. The Endicott Arm assemblage includes felsic rocks with interpreted crystallization ages of 375 ± 15 Ma, 367 ± 10 Ma, and 345 ± 1 Ma (Gehrels et al., 1992; McClelland et al., 1992a). It is characterized by mafic and quartzo-feldspathic schist derived from volcanic rocks, by biotite schist, quartzite, and marble. Although we consider this unlikely, the Delusion Bay sequence may belong to the upper Paleozoic section of the Alexander terrane (Gehrels et al., 1987).

Kaien sequence (affiliation unknown)

The Kaien sequence is in the city of Prince Rupert and elsewhere on Kaien Island, as well as along the eastern shores of the northern part of Prince Rupert Harbour. On the basis of their chemical composition as deduced from their mineralogy, these dominantly quartz-biotite, biotite-hornblende, and hornblende schists are inferred to have graywacke and mafic volcanic protoliths. Some of the hornblende schist shows textures reminiscent of lava flows, such as small (<1 cm) felsic clots that may represent recrystallized amygdules. Scattered aluminous layers, more abundant in the eastern part of the sequence, have recrystallized to kyanite-garnet or staurolite-garnet assemblages. Intense deformation and extensive recrystallization associated with amphibolite facies metamorphism have obliterated other evidence for the origin of these rocks. The contact between this sequence and the Delusion Bay sequence to the west for the most part is under water in Prince Rupert Harbour. As described in the following, the Prince Rupert shear zone deforms the rocks of the Kaien sequence, and it is tempting to suggest that the rocks of the sequence are faulted against the structurally underlying Delusion Bay sequence. Where the contact is exposed at the northern end of Prince Rupert Harbour, however, there is no discernible structural break between the two sequences.

We also assign hornblende-biotite gneiss, hornblende gneiss, and biotite gneiss along Work Channel north and east of Port Simpson (Figs. 2, and 4), informally named the Work Channel amphibolite (Hutchison, 1982), to the Kaien sequence on the basis of compositional similarity with the rocks to the south and their position overlying and east of the Delusion Bay sequence. This unit can be traced down both sides of Work Channel. South of the Skeena River, in the Scotia-Quaal metamorphic belt, Gareau (1991) mapped and described a Paleozoic(?) metavolcanic unit lithologically similar to the Kaien sequence and to the Work Channel amphibolite. This unit consists of amphibole and biotite quartzofeldspathic semischist; minor quartzite, pelite, and marble. Gareau tentatively correlated the metavolcanic unit with mid-Paleozoic rocks of the Yukon-Tanana terrane from northern British Columbia described by Currie (1990, 1991).

Tsimpsean sequence (Yukon-Tanana terrane?)

On the mainland, east of Kaien Island, a series of rocks comprises quartzite, pelitic schist, subordinate marble, siliceous and quartzo-feldspathic schist, and orthogneiss. The contact with the Kaien sequence appears to be conformable, although the metamorphic recrystallization and deformation probably obliterated pretectonic stratigraphic relationships. The quartzite in this sequence is thicker and cleaner than the quartz schist of the Delusion Bay sequence. Similar siliceous gneiss and associated thin marble layers crop out at the northern end of Work Channel east of the Work Channel amphibolite and to the north, across the Alaska border (Fig. 3). The quartzite and marble at this locality are associated with sillimanite-bearing pelitic gneiss and biotite-hornblende gneiss of possible metavolcanic origin. This association is diagnostic of the Yukon-Tanana continental margin assemblage (Gehrels et al., 1990, 1991; Samson et al., 1991; Wheeler and McFeely, 1991; Mortensen, 1992). Similar quartzite, minor marble, and pelite units interlayered with mafic metavolcanic rocks form the gneissic host rocks of the Paleogene batholith in the central belt east of the Coast shear zone. Although the degree of disruption and recrystallization is even greater east of the Coast shear zone, we also assign these rocks to the Tsimpsean sequence.

In the Ketchikan quadrangle Rubin and Saleeby (1992a) assigned quartzite units with Precambrian detrital zircon and associated marble to the Kah Shakes sequence and, following the work of Gehrels to the north, correlated this sequence with rocks of the Yukon-Tanana terrane. Lithologic similarities and its position east of the other groups of rocks suggest that the Tsimpsean sequence can be correlated with the continental margin Kah Shakes sequence of Rubin and Saleeby (1992a), and with the Tracy Arm assemblage of Gehrels et al. (1992). However, definitive correlation remains to be demonstrated. To the south Gareau identified a quartzite unit east of her Paleozoic(?) metavolcanic unit, separated from that metavolcanic unit by a clastic metasedimentary sequence that we have not found in the Prince-Rupert area.

Summary

The metamorphic recrystallization and tectonic disruption of the rocks of the western metamorphic belt in the Prince Rupert quadrangle, the absence of diagnostic identifiable fossils, and the current lack of other stratigraphic information, make correlation of these sequences on the northern British Columbia coast with those in adjacent southeastern Alaska difficult. Our preferred correlation relates the Digby sequence to Triassic and possibly upper Paleozoic Alexander terrane rocks to the west on Dunira and Randall Islands. The correlation of the Venn sequence with Gravina sequence rocks and the Tsimpsean sequence with the Kah Shakes sequence and the Tracy Arm assemblage of the Yukon-Tanana terrane are reasonably well supported, but farther work is required before they can be confirmed. Other suggested correlations are more tenuous but would agree with the succession of units defined to the north. In the Ketchikan quadrangle, as well as farther north, Taku terrane rocks structurally overlie the Gravina belt units and, in turn, are structurally overlain by rocks assigned to the Yukon-Tanana terrane. It remains to be seen whether the Delusion Bay sequence is part of the Taku or of the Yukon-Tanana terrane. In the latter case, which we somewhat prefer, the Kaien sequence is probably also a Yukon-Tanana terrane assemblage.

DEFORMATION AND METAMORPHISM IN THE WESTERN METAMORPHIC BELT

In the western metamorphic belt of the Prince Rupert quadrangle, westward-vergent moderately dipping thrust faults and ductile shear zones juxtapose the stacked lithologic packages described here. Three transects with the most continuous exposures across strike of these thrust stacked sequences are east and west of the city of Prince Rupert; in the vicinity of Port Simpson between Finlayson Island and Work Channel; and on the north side of Portland Inlet along the British Columbia–Alaska border. The rocks along all three transects are characterized by regional foliation that resulted from ductile simple shear deformation; locally this deformation was partitioned into discrete more intensely deformed shear zones or thrust faults. In addition, along all transects higher grade metamorphic rocks are thrust westward over lower grade rocks, which results in inverted metamorphic gradients. Greenschist facies rocks compose the structurally lower units to the west; metamorphic conditions increase to upper amphibolite facies in the structurally higher units along the eastern side of the belt (Crawford et al., 1987; Stowell and Crawford, this volume). Along the Prince Rupert transect the evidence suggests that metamorphism of the western rocks accompanied thrusting and hence was related to emplacement of the upper slabs. To the north thrusting juxtaposed previously metamorphosed rocks; there is no evidence that the overthrust units were hotter than the lower plate rocks at the time of thrust emplacement.

Prince Rupert area structures

This transect is along the axis of a regional west-directed salient outlined by an arcuate pattern of west-vergent thrust faults and shear zones, including the 1.5-km-thick Prince Rupert shear zone (Fig. 4). At the western end of the transect the structurally lowest rocks beneath the thrusts are deformed by simple shear into a regional-scale sheath fold with a hinge zone that coincides with the northwest-trending axis of the salient. In these schists parallel flakes of muscovite and chlorite flakes and, in carbon-rich samples, of fine-grained graphitic material, define an early metamorphic foliation (S_1) in the low-grade rocks of the Digby and Venn sequences. Bedding (S_0) has been transposed parallel to this foliation. On the southwestern shores of Digby Island D_1 isoclinal folds are refolded about hinges that trend northwest (C, Fig. 6). This D_2 folding is accompanied by an axial planar crenulation foliation spaced several millimeters apart in the phyllite. Discrete northwest-striking and moderately dipping (30°–50°) thrust faults and a few normal faults, with offsets of less than a few meters, are common. Porphyritic greenstone dikes of basaltic composition with a weakly developed fabric are parallel to the S_2 foliation. These dikes lack the penetrative fabric of the country rocks. The absence of deformation in the dikes and their orientation parallel to S_2 suggest that these dikes were intruded during

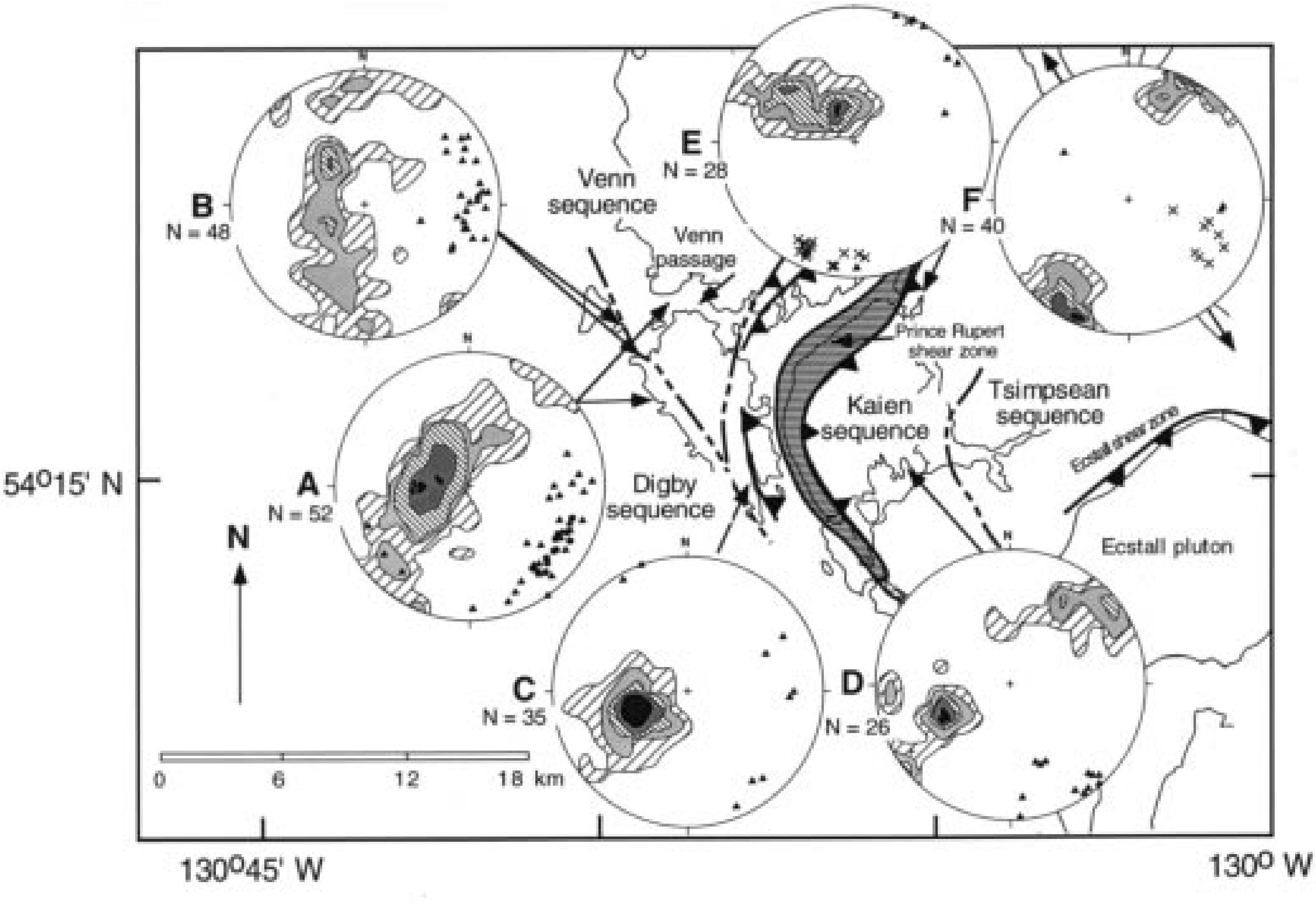

Figure 6. Equal-area nets summarizing structural relationships along east-west transect across Prince Rupert area. Poles to layers and foliation are contoured. Filled triangles are fold axes; filled circles are axes of elongated pebbles; X are intersection and mineral lineations; N is number of points contoured; contour intervals are: 4%, 8%, 12%, and 16%. Ruled map pattern = Prince Rupert shear zone.

D_2. A group of quartz veins that strike perpendicular to both foliation and fold axes suggests northwest-southeast extension. Similar relations are seen along the shore between Venn Passage and Big Bay. North of Jap Point and in Big Bay S_1 foliation dips gently; southerly dips are common. At many localities this foliation is folded and a second (S_2) crenulation cleavage dips moderately to the east. This is interpreted to be the same crenulation cleavage that formed during D_2 on Digby Island.

Along Venn Passage and Digby Island D_2 deformation is more intense. The S_0 bedding and parallel S_1 foliation in the schist are folded into reclined tight to isoclinal folds on a scale of 1 mm to tens of meters; the folds have axial planes that dip eastward, parallel to the plunge of the fold axes and intersection lineations (A, Fig. 6). This folding is accompanied by development of an S_2 axial planar foliation formed by crenulation of the S_1 fabric and by growth of new phyllosilicate minerals. Fold hinges plunge southeast except adjacent to the massive rhyolite layers on Devastation Island and immediately to the east at Straith Point where plunges are easterly (B, Fig. 6). Our observations suggest that the outcrop-scale reclined isoclinal folds form part of a thick zone of penetrative ductile shearing (D_2) characterized by sheath folds. Equal-area plots of fold axes (A, B in Fig. 6) show that they are dispersed along an arc. There is no evidence for a second folding event, hence we interpret this pattern to suggest that, on a regional scale, the folding is noncylindrical. Stretched pebbles and cobbles are common in conglomerate units of the Venn sequence; in a few cases the aspect ratio of the pebbles reaches 15:1. The long axes of the pebbles define a discrete cluster within the spread of fold axes and at several localities the pebble long axes are at a small but distinct angle to fold hinges and to bedding-cleavage intersections. The folds have been flattened and fold hinges have been rotated toward the transport direction defined by the stretched pebbles.

The outcrop pattern of the Venn sequence can best be explained as representing a regional scale tubular or sheath fold (Fig. 7). The contact between the Venn sequence and the underlying Digby sequence at Straith Point as well as conglomerate units within the Venn sequence strike east, at a high angle to the dominantly northwesterly regional strike of layers and foliation. Units near the southern contact at Straith Point dip steeply to the north, whereas dips on the northern side of the Venn sequence near Jap point are to the south (Fig. 4).

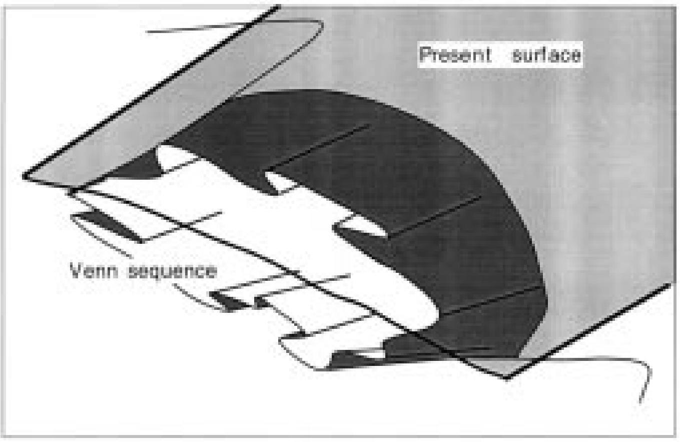

Figure 7. Proposed sheath fold invoked to explain observed relations of Venn sequence.

Within the Venn sequence along Venn passage the metamorphism increases and deformation intensifies to the east. The S_1 foliation is progressively transposed and becomes indistinguishable from S_2 as metamorphic grade increases. Metamorphic recrystallization of the fine-grained phyllosilicates and destruction of relict clastic grains and aggregates of plagioclase and quartz eradicate the early fabric. However, oriented graphite flakes derived from the fine-grained carbonaceous material of the lowest grade phyllite commonly preserves the S_1 foliation even in the higher grade rocks. At the eastern end of Venn Passage the S_2 foliation is gently warped into large pinch and swell structures. Discontinuous limestone layers record large-scale (tens of meters) boudinage. Incipient crenulation cleavage shows a conjugate normal geometry; the obtuse angle between the crenulation cleavages is perpendicular to the foliation. This geometry supports the evidence from the pinch and swell and boudinage for shortening normal to the foliation.

In eastern Venn Passage and along the western shores of Prince Rupert Harbour, thrust faults trend approximately parallel to the regional foliation (Figs. 3 and 4). These are inferred from a lack of continuity of strata along strike and from local repetition of strata. The boundary between the Venn sequence and the overlying Delusion Bay sequence is marked by these faults. Where the fault contact is not exposed, a distinct topographic break is inferred to be the northerly extension of this fault contact, a reflection of the greater resistance to erosion of the metavolcanic and siliceous rocks of the Delusion Bay compared with the Venn sequence phyllite and schist.

Farther east, on the western side of Kaien Island and extending up the eastern shore of Prince Rupert Harbour, is the ~2-km-thick Prince Rupert shear zone, which has a north-south arcuate shape (Figs. 3 and 6). This shear zone differs from others in the western metamorphic belt because it appears to have formed in a pure shear regime. This deformation resulted in distortion of preexisting fabric by “chocolate tablet” boudins (Wegmann, cited *in* Ramsay, 1967), which record flattening strain. The boudins range from <1 m to tens of meters in length both along strike and downdip. On the basis of the greater separation of the boudins parallel to strike, stretching parallel to the strike direction appears to have been more intense than stretching in the downdip direction. No stretching lineations are observed in the rocks of this shear zone. The zone of most extensive boudinage occupies the lower 1 km of the shear zone in the center of the arc. To the south, on and east of Ridley and Lelu Islands (Fig. 2), boudinage is less strongly developed than in the arc center. The northern extension of the shear zone is not exposed because it is under northern Prince Rupert Harbour. In the upper part of the shear zone, asymmetric west- and northwest-vergent folds (E, Fig. 6) and southeast-dipping discrete thrust faults replace flattening deformation.

Locally within the Prince Rupert shear zone on western Kaien Island, 5–10-m-thick tonalite sills are parallel to the foliation (Fig. 8). These sills are characterized by flattened angular autoliths of tonalite in a fine-grained felsic matrix. One sill also has angular xenoliths of metasedimentary rocks. Above the shear zone, intermediate to felsic sills and dikes intrude the schist in the zone between the Kaien and the Tsimpsean sequence rocks. Dikes are oriented perpendicular to the fold axes, whereas sills parallel the foliation and are stretched into boudins. These observations suggest that these sills and dikes were syntectonic, emplaced during the D_2 ductile deformation, and subsequently disrupted as deformation continued during and following crystallization. In Port Edward (Fig. 8) a poorly exposed but extensive tonalite body may also be one of these syntectonic intrusions.

Structurally above the Prince Rupert shear zone on eastern Kaien island is a zone of upright to overturned tight to isoclinal folds that plunge gently southwest in the north and southeast in the south (D, Fig. 6). The trends of these folds and of others to the east follow the arc of the Prince Rupert shear zone. These folds are in the core of a regional asymmetric synclinorial fold (Fig. 4) of foliation between the Prince Rupert shear zone and the Ecstall pluton. The western limb of this fold dips gently east to northeast and the eastern limb dips steeply west to south. Tight folds in the core of the fold are upright. Extensional boudinage parallel to the hinges of minor folds in the core occurred during kyanite-grade metamorphism, as demonstrated by kyanite-quartz segregations in boudin necks (Crawford et al., 1979). East of Prince Rupert the northern margin of the Ecstall pluton is at the Ecstall shear zone (Figs. 3 and 6). Foliation in the country-rock gneiss along this northern margin dips to the south and southeast, under the pluton; shear structures and outcrop-scale thrust faults suggest that the Ecstall pluton was thrust over the surrounding country rocks. Hutchison (1982) inferred that emplacement of the Ecstall pluton was responsible for the arcuate pattern and generally south-dipping foliation in the area north of the pluton. Our mapping suggests that this part of the Ecstall pluton is in the core of the regional synclinorial fold described here and may be folded. If this interpretation is correct, then the Ecstall pluton was emplaced prior to the formation of the Prince Rupert shear zone and to the folding of the rocks above the shear zone.

Timing of thrusting is constrained to about 90 Ma by the relationship between shear-zone development and the metamorphic and igneous events that affected the rocks. The Ecstall pluton in the structurally highest thrust slabs is about 91 Ma (90.8 ± 1 Ma and 91.5 ± 1.0 Ma; G. Gehrels, 1999, personal commun.). Evidence cited herein suggests that westward thrusting of this pluton and the hot country rocks that underlie the Ecstall shear zone resulted in the syntectonic metamorphism dated as ca. 90 Ma ($^{40}Ar/^{39}Ar$ hornblende; Sutter and Crawford, 1985) recorded in the underlying thrust slices.

Prince Rupert area metamorphism

The metamorphic isograds in the Prince Rupert area are structurally inverted. The structurally lower units on the west are in the greenschist facies; metamorphic conditions increase to upper amphibolite facies in the structurally higher units along the eastern end of the transect. In addition, metamorphism of the rocks along the western part of the transect appears to be syntectonic. Biotite and garnet isograds cut through the Venn sequence along Venn passage and through the Digby sequence along the

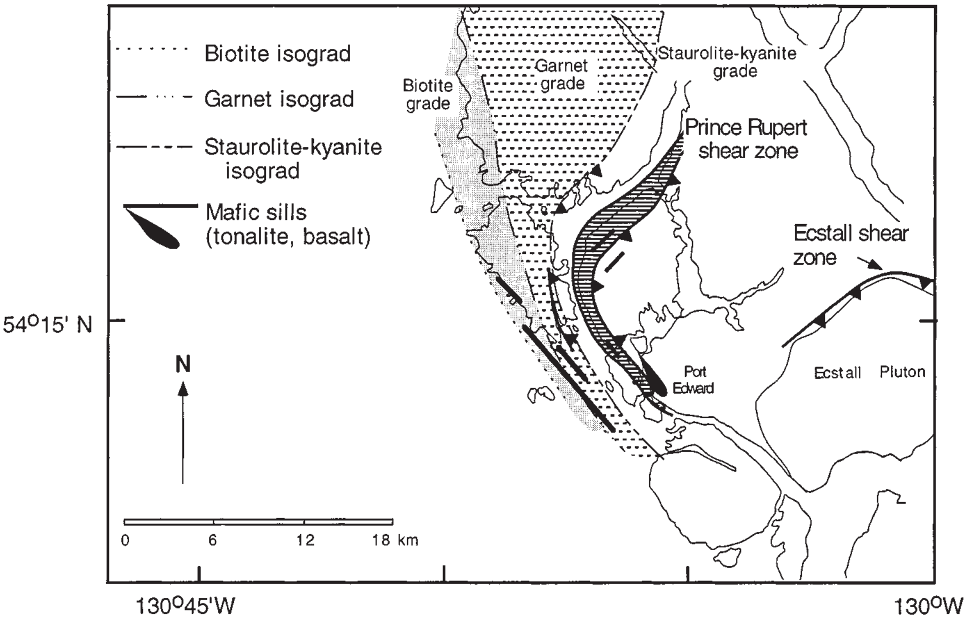

Figure 8. Detail of Prince Rupert area showing biotite, garnet, and staurolite-kyanite metamorphic zones and location of syntectonic mafic dikes.

southwestern shore of Digby Island (Fig. 8). In the Venn sequence, biotite crystallized in small kink folds in intensely foliated phyllite. These biotite flakes are fractured, apparently in response to continuing deformation of the type that produced the kinks. Elsewhere in the Venn sequence and in the Digby sequence on southwestern Digby Island, randomly oriented biotite grows over the S_1 foliation or is parallel to the S_2 crenulation foliation. These features indicate that biotite growth accompanied D_2 deformation. Garnet appears in higher grade rocks. In most rocks close to the garnet isograd garnet grows statically over the S_1 foliation. In some outcrops, however, deformation outlasted garnet growth, as demonstrated by crenulations that nucleate on garnet grains.

The staurolite-kyanite isograd coincides with the boundary between the Venn and Delusion Bay sequences (Fig. 8). In the amphibolite facies rocks of the Delusion Bay sequence, biotite, staurolite, and plagioclase grow over a folded foliation, assumed to be S_1, marked by carbonaceous material. Garnet and staurolite locally show helicitic textures. Staurolite, biotite, and kyanite grains parallel to S_2 are stretched and broken; the cracks are healed by quartz. These features indicate that the metamorphic index minerals grew during D_2. There is no evidence of a discontinuity in metamorphic conditions at the thrust faults that separate the Venn and Delusion Bay sequences; however, the rapid increase in metamorphic grade over a relatively narrow zone (1–2 km) in the lower western part of the Delusion Bay sequence suggests that thrusting may have compressed the metamorphic gradient.

The rocks above the Prince Rupert shear zone are in the kyanite zone of the upper amphibolite facies. Staurolite is not found in these highest grade rocks. Kyanite occurs aligned parallel to fold axes and in quartz pods in the necks of boudins in the limbs of those folds (Crawford et al., 1979). Pressures of 8–9 kbar inferred from the assemblages in these kyanite-bearing upper plate rocks are higher than those obtained from kyanite-bearing samples within and under the Prince Rupert shear zone (5–6 kbar, Crawford et al., 1987). The pressures in these upper plate rocks are in the range expected for crystallization of the Ecstall pluton, which intruded these rocks and contains primary igneous epidote (Zen and Hammarstrom, 1984). This pressure difference requires that the metamorphic rocks above the Prince Rupert shear zone were transported from deeper crustal levels and that they did not equilibrate to lower pressures after thrusting.

The distribution and textures of syntectonic metamorphic minerals and pressure-temperature estimates on rocks with kyanite-bearing assemblages suggest that the west to east inverted metamorphic gradient formed as a result of westward thrusting. Metamorphic recrystallization of rocks under the Prince Rupert shear zone was over 90 Ma, based on the basis of an $^{40}Ar/^{39}Ar$ age of hornblende that crystallized during deformation (Sutter and Crawford, 1985). Heat transfer from the gneissic upper plate, which includes the ca. 91 Ma Ecstall pluton, into the underlying colder rocks probably served as a heat source for this metamorphism. The failure of the uppermost metamorphic assemblages to recrystallize may be due to cooling upon emplacement. Following the syntectonic metamorphism, additional west-directed deformation may have telescoped the metamorphic units to produce the relatively narrow metamorphic field gradient.

Prince Rupert area summary

The structures observed along this transect document west-vergent thrust deformation characterized by contractional, shearing, and flattening strains. The spatial distribution of strain is not uniform. In particular the Prince Rupert shear zone primarily records flattening, whereas the rocks of the underlying Venn sequence are pervasively foliated and transposed. This led to formation of a regional sheath fold in the structurally lowest part of the Venn sequence. The distribution and textures of syntectonic metamorphic minerals and pressure-temperature estimates on rocks with kyanite-bearing assemblages suggest that the west to east inverted metamorphic gradient formed as a result of westward thrusting. Originally deep-seated hot rocks were emplaced over colder rocks to the west. The hot upper plate, which includes the ca. 91 Ma Ecstall pluton, probably served as a heat source for this metamorphism. Hutchison (1982) proposed that the gneiss north of the Ecstall pluton was deformed through continuous overriding associated with northward emplacement of that pluton: we extend this model to suggest that the Ecstall pluton and associated country rocks were also thrust westward over the rocks now exposed on Kaien Island. In this interpretation the flattening associated with the Prince Rupert shear zone resulted from crustal loading due to thrusting of this slab of hot rocks. This would explain the local extent and arcuate pattern of the Prince Rupert shear zone as well as provide a heat source for the syntectonic inverted metamorphic gradient. The tonalitic to basaltic sills emplaced into and west of the Prince Rupert shear zone during D_2 could also have played a role in heat transfer into the lower plate rocks. Continued deformation folded the rocks overlying the Prince Rupert shear zone, probably including the Ecstall pluton.

Middle transect

Along this transect, in contrast to the Prince Rupert transect, major structural features are southwest-vergent thrust faults that disrupt the metamorphic isograds and thus are later than the ca. 90 Ma metamorphism. In Big Bay (Fig. 2) a nearly horizontal foliation characterizes phyllite of the Digby sequence. Throughout the Big Bay area and to the south, a later low-angle southeast-dipping crenulation foliation is associated with meter-scale northwest-vergent folds. Axes of these folds trend northeast and are approximately horizontal. In the northwestern part of Big Bay, on Burnt Cliff Island and on the mainland to the northeast, this phyllite is structurally overlain by quartz-rich schist of the Delusion Bay sequence emplaced along east- to northeast-dipping low-angle thrust faults (Fig. 4). Adjacent to the thrust faults, metamorphic minerals in schist are deformed and replaced by lower grade assemblages. This is particularly evident at Redcliff Point, east of the southern end of Finlayson Island, where staurolite has been replaced by biotite-quartz pseudomorphs. In addition, garnet and staurolite are restricted to rocks above the faults; structurally lower rocks contain chlorite and biotite. These observations suggest that thrusting at the base of the Delusion Bay sequence north of Big Bay was later than the peak of metamorphism.

Folds in the units above the thrust fault zone are reclined, just as they are in the Digby and Venn sequences west of the Prince Rupert shear zone to the south. Here, however, the dominant plunge of the hinges is northeast (B, Fig. 9), in contrast to Prince Rupert transect where fold hinges plunge southeast to east. A strong mineral lineation, especially well shown by hornblende in calcareous units, is parallel to hinges of the reclined folds; hence these folds are synmetamorphic.

Northern transect

On Kanaganut Island, Alaska, just north of the British Columbia–Alaska border, structural relations document progressively more intense deformation upward (from west to east). As in the middle transect, the schists are cut by faults that postdate the metamorphism. On the western side of Kanaganut Island, layering in Digby sequence rocks is folded into tight to isoclinal west-vergent D_1 folds. Outcrop-scale folds of this generation with strongly curved hinges are well preserved in a marble layer. The hinges lie along a great circle that strikes west-northwest (C, Fig. 9). Rocks assigned to the Venn sequence overlie these Digby sequence rocks. West of the Digby-Venn contact, a thrust

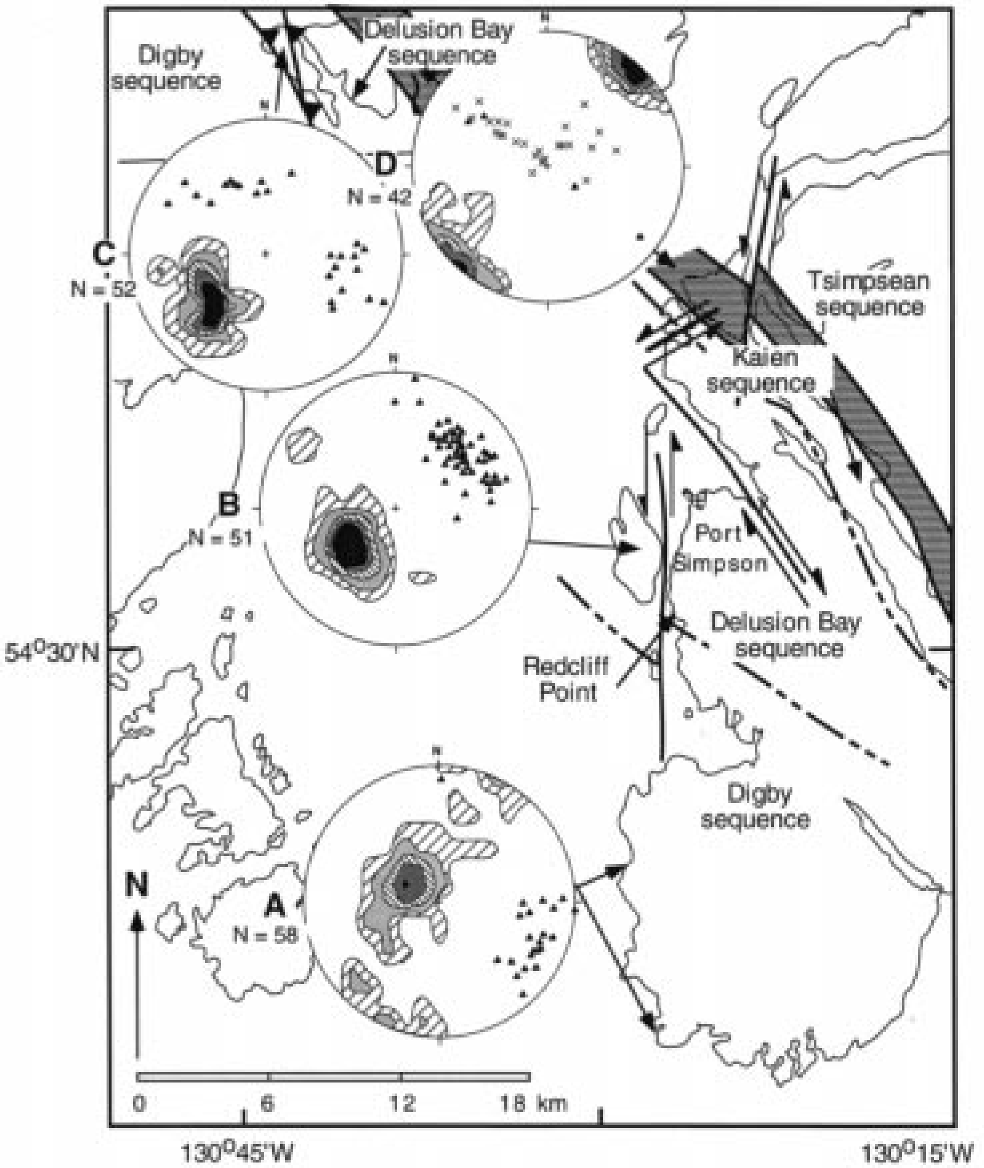

Figure 9. Equal-area nets summarizing structural relationships in northern part of study area. Poles to layers and foliation are contoured. Filled triangles are fold axes; Xs are intersection and mineral lineations; N is number of points contoured; contour intervals are: 4%, 8%, 12%, and 16%. Ruled area is Coast shear zone.

fault is mapped on the basis of a metamorphic discontinuity and a change in the style and intensity of deformation. This change is marked by appearance of tight to isoclinal D_2 fold hinges that fold a preexisting foliation, and transposition of layering to lie parallel to the F_2 foliation, parallel to the axial planes of these folds in the rocks above (east of) the thrust fault. The folds are reclined; stretching lineations plunge to the east, parallel to fold axes. Sigma-shaped tails on garnets and asymmetric boudinage of quartz veins document an east over west transport parallel to the lineation. In the Digby sequence and in the Venn sequence below this thrust fault, the metamorphism is biotite grade or lower; above the thrust metamorphic grade is garnet grade on the west and increases to staurolite grade on the eastern side of the island. Additional east-dipping faults and shear zones parallel the F_2 foliation in the eastern part of the island. East of and above the faults, Delusion Bay and Kaien sequence rocks are kyanite bearing. Mineral fabrics show that the dominant foliation in the garnet-grade and higher grade rocks wraps around the metamorphic-index mineral porphyroblasts. Garnet shows a well-developed internal fabric that is clearly discordant with the foliation in the matrix. In addition, as on the north side of Big Bay, retrograde metamorphism affects the most intensely sheared rocks in which lower temperature phases replace higher grade minerals. Thus, in contrast to the Prince Rupert transect, thrusting followed the peak of metamorphism in the northern and middle transects.

There are no ages for the thrust faults of the two northern transects. However, the lower temperatures during thrust faulting, inferred from the presence of retrograde metamorphism in the middle and northern areas, suggest that thrust deformation lasted later in the north.

COAST SHEAR ZONE

The Coast shear zone, a band of intense deformation that ranges from 2 to 6 km in width, forms the eastern boundary of the western metamorphic belt. This shear zone is a prominent structural feature of the Coast Mountains orogen that can be traced northward through southeastern Alaska to north of Juneau; its regional significance is a matter of ongoing study. In the map area the Coast shear zone consists of two distinct elements: (1) a 1–5 km-wide, moderately northeast dipping flattening and shear fabric, with top to the west transport sense and a well-developed down dip stretching lineation; and (2) a superimposed narrow (~1 km), vertical shear fabric with steep to vertical stretching lineation, vertical sheath fold hinges, and west-side-up sense of displacement (Klepeis et al., 1998). This latter zone forms the western side of the Coast shear zone. Fabrics elsewhere along the length of the shear zone are similar: dominated by west- to southwest-vergent reverse shear with local near vertical normal shear (McClelland et al., 1992b; Ingram and Hutton, 1994; Stowell and Hooper, 1990; Gehrels et al., 1992).

The eastern part of the Coast shear zone is well exposed along Portland Inlet and waterways to the north in the northern parts of the Prince Rupert quadrangle (Klepeis et al., 1998). Here hornblende and coarse prismatic sillimanite define a north- to northeast-plunging stretching lineation parallel to hinges of reclined folds. Top to the southwest and west transport is documented by asymmetric boudinage and scattered s and d clasts. The shear fabric deforms plutons as young as 65 Ma (Klepeis et al., 1998). South of Portland Inlet, however, the main phase of the 58.6 ± 0.8 Ma (Gehrels et al., 1991) to 55 Ma (J. Thomas, 1999, personal commun.) Quottoon pluton shows no evidence of this fabric. On the basis this we infer that the eastern Coast shear-zone fabric is older than ca. 58 Ma.

The narrow zone with steep west-side-up fabrics along the western side of the Coast shear zone is referred to here as the Work-Behm shear from its location along Work Channel in the Prince Rupert quadrangle and, in the Ketchikan quadrangle to the north, along East Behm Canal (Fig. 1). Kinematic indicators that document west-side-up shear sense include shear bands, asymmetric boudins, and scattered σ and δ clasts (Klepeis et al., 1998). Where overprinting of Work-Behm shear fabrics onto structures of the western metamorphic belt is best exposed, in the Port Simpson and Kanaganut Island areas, both foliations and lineations in the western metamorphic belt steepen as the shear zone is approached from the west (Figs 6F, 9D, and 10). East of Port Simpson, the more competent units in this transition zone show short subhorizontal gash veins, nearly perpendicular to the steep lineation, filled with quartz, carbonate, and muscovite. The veins suggest semibrittle behavior of the western metamorphic belt rocks during shear-zone formation. In addition to vertical foliation and lineation, numerous vertical trondhjemite pegmatite

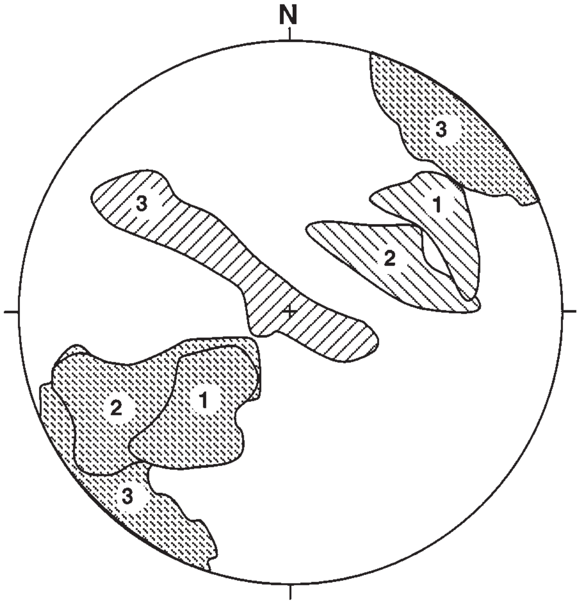

Figure 10. Equal-area net summarizing steepening of attitudes of foliation and lineation from west (1) to east (3) between Port Simpson and Work Channel. Poles to foliation plot within areas identified with short dashes; fold axes and related lineations plot within areas marked by diagonal lines.

dikes not reported outside this western part of the Coast shear zone characterize the Work-Behm shear. Some of these pegmatite dikes are deformed, whereas others cut the shear-zone fabric.

Saleeby (this volume) presents U-Pb ages from three pegmatite samples in Boca de Quadra that yield poorly defined lower intercepts between 65 and 50 Ma. Klepeis et al. (1998) documented that the Work-Behm shear zone deforms 55 Ma dikes. These ages, combined with the observation that the Work-Behm shear deforms the youngest phase of the Quottoon pluton, dated as 55 Ma (J. Thomas, 1999, personal commun.), establish the age of the Work-Behm shear as 55 to ≤52 Ma. It is coeval with emplacement of the youngest igneous rocks in the central belt east of the Coast shear zone and accompanied or is slightly older than the rapid uplift and exhumation of central belt rocks that resulted in K-Ar and $^{40}Ar/^{39}Ar$ cooling ages of hornblende and biotite of ≤50 Ma (Hutchison, 1982; Smith and Diggles, 1981; Hollister, 1993).

Evidence from the metamorphic rocks also suggests both normal and reverse offset across the Coast shear zone. A band of kyanite-bearing metamorphic assemblages abuts the western side of the Coast shear zone. On the basis of observations in the northern part of the Ketchikan quadrangle, Cook and Crawford (1994) concluded that this band of kyanite schist along the eastern side of the western metamorphic belt resulted from 7 km of uplift by west-side-up tilting and exhumation of deep-seated rocks of the western metamorphic belt. The tilting resulted from displacement along the Work-Behm shear zone ca. 55 Ma. The Coast shear zone separates these kyanite-bearing metamorphic rocks and the 100–88 Ma plutons in the western metamorphic belt from the sillimanite and cordierite-bearing gneiss of the central belt that are the country rocks for the Quottoon and other plutons of the Paleogene batholith on the east. Any estimate of the significance of the juxtaposed kyanite-sillimanite-cordierite assemblages across the Coast shear zone must be tempered by the observation that the eastern central belt metamorphic assemblages reflect thermal input by the voluminous plutons of the Paleogene batholith, whereas, in the western metamorphic belt, the main thermal event ceased ca. 90 Ma (Stowell and Crawford, this volume).

CENTRAL BELT

In the Prince Rupert quadrangle, rocks east of the Coast shear zone comprise the 10–15-km-wide Quottoon tonalite pluton, other plutons of the Paleogene batholith, and gneiss that hosts the plutons. The transition from the western metamorphic belt across the Coast shear zone into the central belt is most clearly observed north of Portland Inlet, at the northern margin of the Prince Rupert quadrangle (Figs. 1 and 4). In this area and to the north, the Quottoon pluton is thin and there are outcrops of gneissic rocks on either side of the Coast shear zone.

Structural features and metamorphic assemblages observed in this part of the central belt can be related to similar features across the Coast shear zone in the western metamorphic belt. Foliation in migmatitic paragneiss- and orthogneiss east of the Coast shear zone mostly dips north and contains north-plunging downdip mineral lineations. Recumbent folds of quartzite layers, on a scale of 1 m to tens of meters seen in a few places, are the oldest structures. Fold limbs and foliation parallel to the axial surfaces of these folds are folded into upright folds. Both sets of folds have gently north plunging hinges. West of the Coast shear zone, both along Boca de Quadra in the Ketchikan quadrangle, and south of the Skeena River in the Scotia belt west of the Quottoon pluton are similar recumbent folds refolded into upright folds, both with gently north plunging hinges. As noted here, the metamorphic grade in country rocks of the central belt reflects high temperatures and moderate pressures (see also Stowell and Crawford, this volume). Sillimanite is the only aluminum-silicate mineral in the gneiss of the central belt in the Prince Rupert quadrangle. In a number of places, however, the sillimanite clearly replaces earlier minerals. Both thick-bladed sillimanite aggregate with shapes characteristic of kyanite and prismatic aggregates that in places show the habit of staurolite twins can be found throughout pelitic gneiss. In some localities the sillimanite pseudomorphs of kyanite even show a bluish color similar to that of kyanite grains. The high-temperature metamorphic overprint on the older kyanite- and staurolite-bearing assemblages probably resulted from the emplacement of the plutons of the Paleogene batholith in the central belt. In addition, we interpret that the Tsimpsean sequence crosses the Coast shear zone (Fig. 3) and note that Gareau (1991) was not able to identify the Coast shear zone south of the Skeena River. We suggest that these findings, supported by the age data cited herein, document that the Coast shear zone is younger than 65 Ma and was superimposed on rocks that once extended from the western metamorphic belt into the central belt. Along and south of the Skeena River it is a much less significant feature than in the northern Prince Rupert quadrangle and farther north.

A distinctive feature of the central belt is the presence of numerous shear zones ranging from several meters long and 1 m wide to 1 km long and tens to hundreds of meters wide (Klepeis and Crawford, 1999) that cut the older fabrics. East of the Coast shear zone in the northern part of the Prince Rupert quadrangle, most of these shear zones are steep to vertical and show down-to-the-north displacements. Offset on these shear zones is dominantly sinistral, as documented by moderately to steeply northwest plunging mineral stretching lineations, S-C fabrics, and σ and δ clasts. Some outcrops also show gently south to southwest dipping shears with top to-the-south displacements that we interpret as conjugate to the steeply north dipping set. The orientation of these shear zones, which are everywhere the youngest ductile features, suggests that they result from north to northwest orogen-parallel extension. Their timing is inferred from the fact that they cut plutons older than 54 Ma and the age of a felsic dike in one of the shear zones gave an age of 51 Ma. This coincides with the cooling ages cited here, hence the shears are also interpreted as related to exhumation (Klepeis and Crawford, 1999). In places where the eastern margin of the Quottoon pluton is well exposed, the country rocks adjacent to the pluton contact have sinistral shear fabrics similar to those in the shear zones. From this we propose that emplacement of the younger phases of the Quottoon pluton may have been facilitated and controlled by the north-directed extensional deformation (Crawford et al., in press).

YOUNGER IGNEOUS BODIES AND FAULTS

U-Pb zircon ages of plutons (Woodsworth et al., 1983b; Arth et al., 1988; Gehrels et al., 1991; Rubin and Saleeby, 1992a, 1992b) and K-Ar and ^{40}Ar/^{39}Ar cooling ages (Hutchison, 1982; Smith and Diggles, 1981; Cook et al., 1991; Hollister, 1993) show that tectonic and igneous activity shifted eastward from the western metamorphic belt rocks to the central plutonic-gneiss belt. All of the rocks were then rapidly cooled between 50 and 45 Ma. However, small-scale igneous activity persisted across both parts of the orogen, manifest in postorogenic Oligocene and Miocene plutons and dikes as well as younger dikes and lava flows, some of which are postglacial in age.

In the western metamorphic belt in the vicinity of Port Simpson, a suite of felsic plugs and dikes intruded in two clusters. One cluster is located on the north side of Big Bay and on Burnt Cliff and adjacent islands. The other is north of Port Simpson, on Birnie Island and on the shore to the east. Chemical analyses for three of these bodies are presented in Table 1. No ages are available for this igneous activity; it is tentatively correlated with similar felsic plugs and stocks that give early Miocene (ca. 20 Ma) dates in the Ketchikan and Petersburg quadrangles to the north. Contact metamorphism adjacent to the ~150-m-thick felsic dike on Birnie Island suggests burial depths of about 10 km (Stowell and Crawford, this volume). The two felsic complexes are at the intersection of a north-trending and two southeast-trending topographic lineaments (Fig. 3). Snyder (1980) mapped a fault along the waterway that, on the basis of offset of units on opposite shorelines, is along the north-trending lineament. The southeast-trending lineaments are marked by zones of brittle deformation exposed in road cuts along the southern shore of Morse Basin south of Prince Rupert and along the shore east of Port Simpson.

Other regionally significant sets of igneous bodies are swarms of young lamprophyric dikes. Dikes similar to these in southeastern Alaska were described by Smith (1972) and Lull and Plafker (1988). Smith (1972) suggested that the mafic dikes may correlate with Miocene basalt in British Columbia. Clinopyroxene and brown amphibole with rare olivine compose the phenocrysts, and the typical ground mass is made up of plagioclase, brown amphibole, clinopyroxene, apatite, and magnetite. Altered rocks may contain sericite, epidote, carbonate, talc, chlorite, and pyrite. Lamprophyric dikes of similar mineralogy occur on the islands in Big Bay and farther north along the coast of British Columbia to the border with Alaska. The major element chemistry of these rocks (Table 1) shows them to be broadly alkalic basalt. The dikes in southeastern Alaska strike N60°E ± 20°, dip within 10° of vertical, and, where they are abundant, appear to define the topographic grain. Northeast of Port Simpson a set of steep brittle faults that strikes N60°E, parallel to the trends of the Alaska mafic dikes, shows offsets of a few meters. In British

TABLE 1. CHEMICAL ANALYSES OF YOUNG (MIOCENE OR YOUNGER?) IGNEOUS BODIES, NORTHERN PRINCE RUPERT QUADRANGLE

	Stocks and plugs			Lamprophyre dikes				
	A	B	C	4	5	6	7	8
SiO_2	57.00	52.70	69.80	48.00	47.50	48.80	48.50	49.00
TiO_2	0.69	0.86	0.23	1.65	1.69	1.52	2.14	1.34
Al_2O_3	17.40	18.30	14.80	15.70	16.40	16.20	15.00	16.80
Fe_2O_3T	6.13	7.52	2.31	11.70	10.70	9.68	13.00	10.50
MnO	0.12	0.15	0.03	0.16	0.15	0.15	0.09	0.15
MgO	2.91	2.64	0.78	4.13	6.85	5.49	6.14	6.53
CaO	4.50	5.98	2.47	7.78	7.95	9.18	8.06	9.42
Na_2O	4.39	4.77	4.14	4.14	3.91	3.84	2.80	2.93
K_2O	2.01	1.52	3.32	3.76	1.20	1.33	0.89	0.70
P_2O_5	0.44	0.53	0.08	0.70	0.64	0.46	0.27	0.24
LOI	n.d.	n.d.	n.d.	2.08	2.39	3.70	2.47	2.62
TOTAL	95.59	94.97	97.96	99.80	99.38	100.35	99.36	100.23

(A) White Cliff Island, B.C.; (B) Burnt Cliff Island, B.C.; (C) Birnie Island, B.C.; (4) plagioclase, clinopyroxene, hornblende, opaque mineral, Nakat Inlet, Southeast Alaska; (5) plagioclase, clinopyroxene, hornblende, opaque mineral, Mainland near Slim Island, Southeast Alaska; (6) plagioclase, clinopyroxene, hornblende, opaque mineral, Mainland near Slim Island, Southeast Alaska; (7) plagioclase, clinopyroxene, opaque mineral, Southern Tongass Island, Southeast Alaska; (8) plagioclase, clinopyroxene, opaque mineral, Southwestern Shore, Sitklan Passage, Southeast Alaska.

Analysis: X-ray fluorescence by XRAL Laboratories.

Columbia, although a few dikes have the same trend as the Alaska dikes, most strike N10°E ± 20° and dip 75° E ± 15°. The north-south trend of the felsic plutons on Burnt Cliff and Birnie Islands matches that of the majority of the mafic dikes in the vicinity. Topographic lineaments that follow both trends are found between Prince Rupert and the border to the north. Many of the linear topographic features (Fig. 3) are fjords, such as Portland Canal, or heavily forested valleys. Thus it is difficult to determine the underlying cause of these linear features.

DISCUSSION

The western metamorphic belt in the Prince Rupert quadrangle shares many features with its extension to the north in southeastern Alaska. These include the following. (1) Westward- or southwestward-directed reverse faults and shear zones of mid-Cretaceous age involve Gravina belt and overlying rock sequences and affect rocks of the eastern edge of the Alexander terrane. In both areas these faults and shear zones produced a thick-skinned stack of thrust slabs capped by units assigned to the continental margin Yukon-Tanana terrane. (2) There is an increase in metamorphic grade eastward into structurally overlying units. (3) The eastern side of the western metamorphic belt is truncated by the Coast shear zone. (4) These are felsic and mafic postorogenic stocks and dikes. In detail, however, the relationships in the Prince Rupert quadrangle permit us to choose among several models that have been proposed for the tectonic evolution of the western metamorphic belt.

A group of thrust faults approximately bisects the belt and separates the greenschist facies Digby and Venn sequences from the higher grade metamorphic rocks to the east. Our favored interpretation of the stratigraphic relations, strongly influenced by studies to the north along the belt, holds that the thrusts juxtapose continental margin assemblage rocks of the Yukon-Tanana terrane (Delusion Bay, Kaien, and Tsimpsean sequences) over rocks of the Gravina belt and the Alexander terrane (the Venn and Digby sequences). Similar relations are observed in southeastern Alaska where thrust faults separate Yukon-Tanana rocks from underlying units. The nature of the footwall rocks varies along strike of the belt; they may belong to the Taku or Alexander terrane or to the Gravina belt (McClelland et al., 1992a; Gehrels et al., 1992). Rocks above and below the thrust faults show intense ductile deformation. Beneath the thrust faults intense westward-vergent simple shear has deformed the Venn sequence into a regional tubular or sheath fold. The intensity of this deformation decreases downward and westward. No evidence for transcurrent faults was found in the western metamorphic belt. Our data therefore support the interpretation that juxtaposition of the Alexander terrane with continental margin strata to the east was accomplished primarily by convergent tectonics. Any earlier structures related to terrane movements have been obliterated by this mid-Cretaceous convergent event in the area of our study.

Thrust stacking of the several terranes influenced the thermal history of the rocks as recorded by the distribution of metamorphic assemblages. The kyanite-staurolite isograd is east of the thrust faults and structurally above them and the greenschist facies rocks. We attribute both the regional metamorphism and the inverted metamorphic gradient in the Prince Rupert transect to thrust emplacement of hotter rocks above the Prince Rupert shear zone over the cooler rocks to the west. To the north, in Alaska, staurolite-kyanite–grade metamorphism along the eastern side of the belt has been ascribed (1) to contact metamorphism around 100–90 Ma plutons (Cook and Crawford, 1994; Stowell and Inman, 1991; Stowell and Crawford, this volume) and (2) to emplacement of the foliated tonalite plutons of the Great Tonalite Sill of Brew (1988) (Himmelberg et al., 1991, 1994). Neither of these mechanisms can be invoked for the Prince Rupert area. Age relations constrain the amphibolite facies metamorphism in the rocks beneath the Prince Rupert shear zone to ca. 90 Ma (^{40}Ar/^{39}Ar age of hornblende in staurolite-kyanite schist, Sutter and Crawford, 1985, approximately the same age as the Ecstall pluton (90.8 ± 1 Ma and 91.5 ± 1.0 Ma, G. Gehrels, 1999, personal commun.). The relationship of the metamorphic index minerals to fabrics formed during regional ductile deformation, and the fact that the kyanite-grade metamorphism extends 20 km west from the currently exposed margin of the Ecstall pluton, rules out a simple thermal contact-metamorphism interpretation for this event. The Quottoon pluton (part of the Great Tonalite Sill) is 20 km or more east of the staurolite-kyanite isograd and is much younger (58–55 Ma) than the metamorphism. Consequently we suggest that a combination of mid-Cretaceous pluton emplacement, crustal thickening by thrusting, and associated westward transport of hot upper plate rocks provides the model most consistent with the observed data for the metamorphic relations observed near Prince Rupert. In contrast, in the northern part of the quadrangle, retrograde metamorphism in overthrust units suggests that the metamorphic inversion postdated the regional metamorphism and thus is due to thrust stacking of previously metamorphosed and cooled units. It could be difficult to distinguish metamorphism due to crustal thickening that produces an inverted thermal gradient from inversion by thrusting of previously metamorphosed rocks, especially if both processes have operated on the same group of rocks, as may be the case toward the northern end of the western metamorphic belt in the vicinity of Juneau.

Ingram and Hutton (1994) proposed that the Coast shear zone marks a plate boundary separating the Insular superterrane, including the Alexander terrane, from the Intermontane superterrane, presumably including the Yukon-Tanana terrane. A similar idea was put forward by Brew and Ford (1978). Whereas this interpretation seems reasonable in northern southeastern Alaska because of the close spatial relationship between the Coast shear zone and the western boundary of the rocks assigned to the Yukon-Tanana terrane by Gehrels et al. (1992), this coincidence does not extend to southeastern Alaska and to the Prince Rupert area if our stratigraphic correlations are correct. In much of southeastern Alaska, Yukon-Tanana rocks are also a considerable distance west of the Coast shear zone. In the Ketchikan quadrangle, according to Rubin and Saleeby (1992a), rocks assigned to the Yukon-Tanana terrane extend 50 km west of the Coast shear zone and are truncated by that shear zone. In the Prince Rupert quadrangle, rocks we correlate with the Yukon-Tanana terrane are also a considerable distance west of the Coast shear zone. Our work suggests that one of the sequences assigned to the Yukon-Tanana terrane, the Tsimpsean sequence, crosses the Coast shear zone (Fig. 3). We also suggest that the early metamorphism of the central belt gneiss in the Prince Rupert quadrangle is the same as the metamorphism of the western metamorphic belt rocks and that structures on either side of the Coast shear zone may be correlated across that shear zone, especially where there are few Paleocene plutons along the eastern side of the Coast shear zone. All of these observations suggest that the Coast shear zone is not directly controlled by a major tectonic suture. Instead we propose that the Coast shear zone formed at a significant thermal discontinuity along the western side of the Paleocene batholith. The early phase of the Coast shear zone separates western metamorphic belt rocks from crust of the central belt to the east thickened by pluton emplacement. The late part of the Coast shear zone, the Work-Behm shear, formed in response to decoupling and uplift of the western metamorphic belt crustal block followed by rapid uplift and exhumation of the central belt ca. 50 Ma.

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