Regionally extensive mid-Cretaceous west-vergent thrust system in the northwestern Cordillera: Implications for continent-margin tectonism

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ABSTRACT

The Intermontane-Insular superterrane boundary zone represents a fundamental crustal boundary separating the two largest allochthonous crustal fragments in the North American Cordillera. Structural, stratigraphic, and geochronologic relations along this boundary indicate that substantial west-vergent compression and concomitant crustal thickening occurred there in mid-Cretaceous time. This orogenic zone extends for more than 1200 km along strike length, between southern southeast Alaska and northern Washington. In southern southeast Alaska and northwest British Columbia, rocks of the Insular superterrane were imbricated along a series of west- to southwest-vergent thrust faults. In northern Washington and southwestern British Columbia, a wide zone encompassing the margins of the two superterranes, as well as numerous intervening smaller fragments, was shortened principally along west-vergent thrusts. Known geologic relations do not discriminate among existing tectonic models that explain the origin of the mid-Cretaceous thrust system.

INTRODUCTION

Mesozoic high-grade metamorphism and magmatism have long been documented in the northwestern Cordillera and were accompanied by thrust faulting. We propose that a mid-Cretaceous thrust system extends for more than 1200 km along strike, between southern southeast Alaska and northern Washington. Deformation affected rocks that range in age from early Paleozoic to mid-Cretaceous. Collectively, these rocks mostly belong to the Intermontane and Insular superterranes (terranes I and II of Monger et al., 1982; Fig. 1). We review structural, stratigraphic, and geochronologic relations that suggest a west-vergent fold and thrust system developed along the boundary between the two superterranes from about 100 to 85 Ma and involved both crystalline basement and supracrustal rocks.

TECTONIC FRAMEWORK

Many of the lithotectonic elements constituting the western Cordillera between lat 40° and 60°N can be grouped into the Intermontane and Insular superterranes (Fig. 1). The composite Intermontane superterrane consists of Stikine, Cache Creek, and Quesnel terranes and was accreted to North America in Middle Jurassic time (Monger et al., 1982); it thus formed the western margin of the continent during the Cretaceous. The Insular superterrane consists of the Wrangellia and Alexander terranes and is parallel to and west of the Intermontane superterrane. North of 49°N, the boundary between the two is largely obscured by the Coast Plutonic Complex, whereas to the south, the superterranes are separated partly by the crystalline core of the north Cascades, including the Skagit metamorphic suite.

Together with earlier work (Misch, 1966; Crawford et al., 1987), our geologic field studies in southern southeast Alaska and northern Washington show that contemporaneous mid- to Late Cretaceous west-vergent thrust faulting occurred locally along parts of the superterrane boundary (Fig. 1). In southern southeast Alaska, the thrust belt is localized along the eastern edge of the Alexander terrane and consists of an imbricate series of west-vergent thrust sheets that have a total structural thickness of more than 20 km (Fig. 2A; Rubin and Saleeby, 1987a). West-vergent folds and thrust faults are present along the inner boundary zone of the Alexander terrane, near Prince Rupert, British Columbia (Fig. 2B; Crawford et al., 1987). In the San Juan Islands and northwest Cascades, an imbricate west-vergent thrust system (Fig. 2C; Brandon et al., 1988) affects a variety of terranes, including some probably derived from the two superterranes. Compressional deformation and regional metamorphism that affected the two superterranes are complex and vary in detail along strike of the boundary; however, the similarities in structural styles and timing of thrusting are remarkable.

SOUTHERN SOUTHEAST ALASKA

The Insular superterrane in southern southeast Alaska consists of the lower Paleozoic to lower Mesozoic Alexander terrane, the Upper Jurassic–Lower Cretaceous Gravina sequence, and the upper Paleozoic and lower Mesozoic Alava sequence, which includes metavolcanic rocks, marble, and argillite formerly assigned to parts of the Taku terrane (Monger and Berg, 1987; Berg et al., 1988). In most areas, rocks of the Alexander terrane are only slightly deformed and are not highly metamorphosed (Gehrels and Saleeby, 1987a), except along the eastern margin where they are overprinted by mid-Cretaceous compressional structures (Saleeby et al., 1985; Rubin and Saleeby, 1987a). East of and depositionally overlying the Alexander terrane is the Upper Jurassic to Lower Cretaceous Gravina sequence, which consists of marine pyroclastic and volcaniclastic debris and epiclastic rocks

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(C. Rubin and J. Saleeby, unpub. mapping), although the depositional nature of the contact has been questioned by Brew and Karl (1987). The youngest fossils obtained from the Gravina sequence in the Ketchikan region are Albian in age (Berg et al., 1972). Structurally overlying the Alexander terrane and the Gravina sequence is the Alava sequence. The Alava sequence is also depositionally overlain by the Gravina sequence; however, in most places the contact is an east-dipping thrust fault in southern southeastern Alaska (C. Rubin and J. Saleeby, unpub. mapping).

The Alexander terrane and the Gravina and Alava sequences were intruded by mafic-ultramafic complexes, epidote-bearing tonalite, quartz diorite, and granodiorite plutons. The plutons, sills, and dikes range in age from 101 to 89 Ma (Pb-U ages on zircon; Rubin and Saleeby, 1987a, 1987b; Arth et al., 1988). All these plutons crosscut the earlier regional metamorphic fabric; 95–101 Ma plutons are cut by thrust faults, and 90 Ma plutons crosscut thrust faults. A belt of Late Cretaceous to early Paleocene plutons is east of the thrust belt (Smith and Diggles, 1981); fabrics in the younger rocks reflect Tertiary deformation. Mesozoic and Tertiary fabrics are differentiated by orientation and their relations to radiometrically dated plutons.

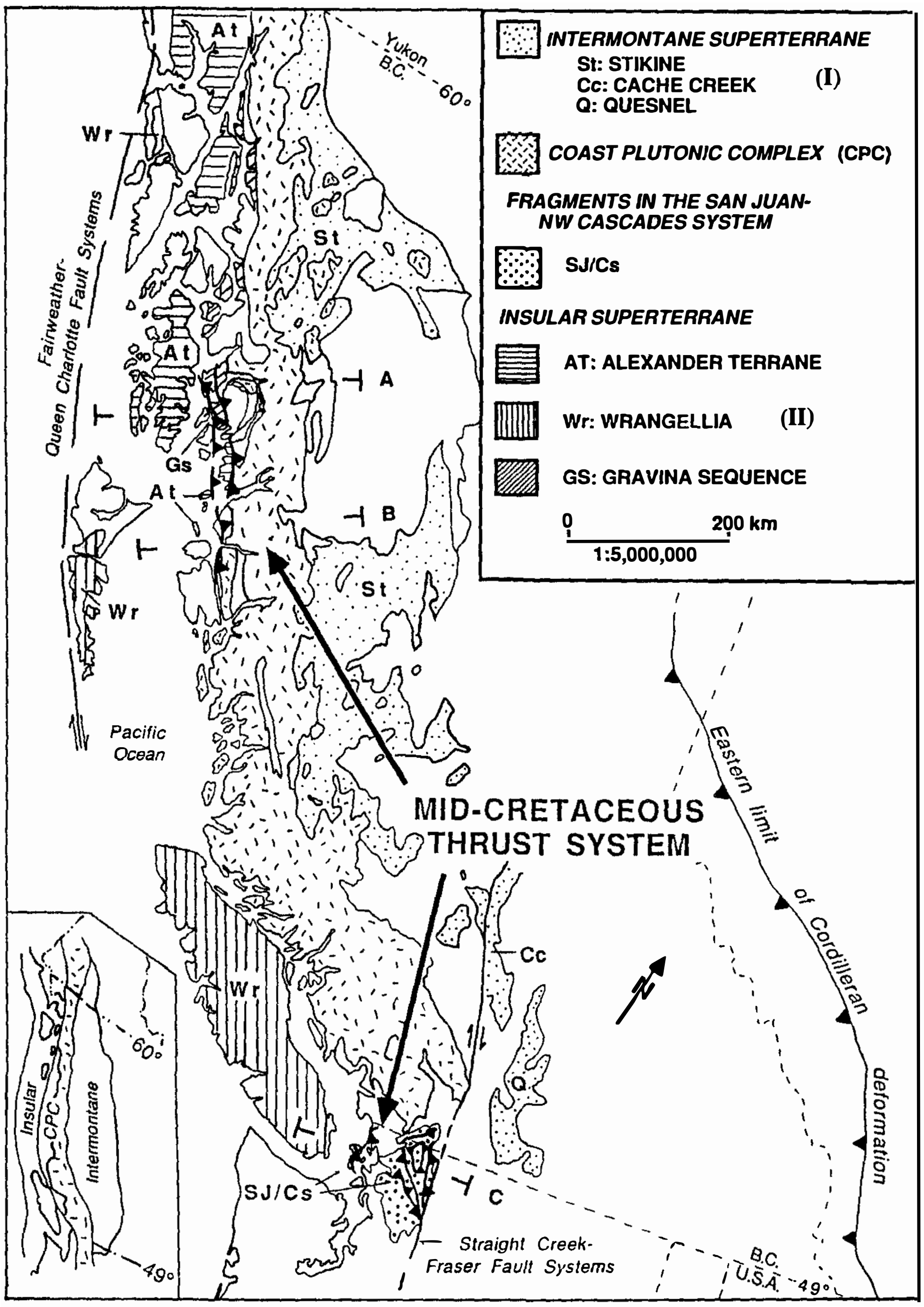

Figure 1. Distribution of mid-Cretaceous thrust system in northwestern Cordillera (after Brandon et al., 1988; Brandon, 1989; Crawford et al., 1987; Rubin and Saleeby, 1987a, 1987b). Terranes I and II of Monger et al. (1982).

Our regional studies in the Ketchikan area indicate that rocks of the Alexander terrane and the Gravina and Alava sequences were imbricated along a series of west-vergent thrust sheets (Fig. 2A; Berg et al., 1988). The structurally lowest thrust sheets consist of lower Paleozoic schist, marble, and meta-igneous rocks of the Alexander terrane. Low to medium greenschist facies rocks of the Gravina sequence structurally overlie the Alexander terrane; the sequence consists of six separate east-dipping thrust sheets. Higher grade Alava sequence schist and imbricated Gravina sequence occupy higher structural positions. Mesoscopic deformation is characterized by folding, cleavage formation, and thrust faulting. Mesoscopic asymmetric folds are related to a northeast-dipping axial planar cleavage. The mesoscopic folds are associated with moderately dipping ductile thrust faults. Together, these structures and fabrics record widespread compressional deformation and a protracted history of crustal shortening. Syntectonic metamorphism ranges from lower greenschist to amphibolite facies. Increasing strain and metamorphic grade occur structurally upward.

Age constraints for the timing of deformation come from the relation between plutons and regional structural fabrics. Locally, mylonitic tonalite and granodiorite crosscut metamorphic fabrics associated with folding and are, in turn, cut by thrust faults. These plutons yield ages from 95 to 101 Ma (Pb-U ages on zircon; Arth et al., 1988; Rubin and Saleeby, 1987a, 1987b). Granodiorite plutons that crosscut thrust faults yield Pb-U zircon ages of 89 to 91 Ma (Arth et al., 1988; Rubin and Saleeby, 1987a). Thus, thrust faulting was still active during or after 95 Ma and terminated by 90 Ma. On the basis of our geochronologic constraints, the age of the youngest strata involved in deformation (Berg et al., 1972), and the geologic time scale of Harland et al. (1982), thrust faulting must have begun between Albian and early Cenomanian time and ceased by the Turonian. Geochemical and isotopic data indicate that all the intrusive rocks have continental-arc-related magmatic affinities (Arth et al., 1988), suggesting an intra-arc setting for the mid-Cretaceous deformation.

WESTERN BRITISH COLUMBIA

Two of the lithotectonic assemblages described above from southern southeast Alaska are also represented in the mountains west of Prince Rupert, British Columbia. Low-grade metamorphic rocks of the westernmost western metamorphic belt are correlated with the Alexander terrane (Fig. 1; Woodsworth et al., 1983; Woodsworth and Orchard, 1985). These rocks are overlain by carbonaceous argillite and conglomerate that are similar to rocks of the Gravina sequence exposed in the Ketchikan area (Crawford et al., 1987). All these rocks are affected by thrust faults and associated west-vergent folds (Fig. 2B; Crawford and Hollister, 1982; Crawford et al., 1987). Metamorphic grade increases from west to east; the highest grade rocks occupy the highest structural levels (Crawford and Hollister, 1982). The mid-Cretaceous Ecstall pluton is intruded into kyanite-bearing schist and migmatitic gneisses that form the structurally highest thrust sheets (Crawford et al., 1987). Magmatic flow lineation and oriented mafic inclusions within the Ecstall pluton are parallel to both the pluton margin and the regional foliation of the surrounding country rock and are thought to be syntectonic fabrics (Crawford and Hollister, 1982; Crawford et al., 1987).

Constraints for the timing of deformation come from mid- to Late Cretaceous plutons. The Ecstall pluton was generated and emplaced during thrust faulting and associated deformation (Crawford et al., 1987) and yields a Pb-U zircon age of 98 ±4 Ma (Woodsworth et al., 1983). K/Ar biotite cooling ages of 96 and 84 Ma from nondeformed plutons (Hutchison, 1982) give a minimum age for the cessation of deformation and metamorphism in the westernmost part of the thrust belt.

To the west, in the Queen Charlotte Islands, the mid- to Upper Cretaceous rocks of the Queen Charlotte Group consist of marine and nonmarine sandstone, conglomerate, and shale (Sutherland-Brown, 1968). Provenance and paleocurrent indicators suggest an eastern source made up of volcaniclastic and plutonic debris shed off the flanks from an active magmatic arc and its basement complex (Sutherland-Brown, 1968; Yagishita, 1985). The Upper Cretaceous foredeep deposits of the Queen Charlotte Group probably represent late orogenic sediments that were derived from the thrust system.

In both southern southeast Alaska and western British Columbia, mid-Cretaceous regional-scale deformation affected rocks of the Insular superterrane. Emplacement of mid-Cretaceous arc-related quartz-diorite, tonalite, and granodiorite plutons was broadly synchronous with this deformation, suggesting an intra-arc setting for the mid-Cretaceous deformation. Thrust-related deformation in southeast Alaska is constrained as pre-Turonian and in western British Columbia as pre-Cenomanian.

NORTHWESTERN WASHINGTON AND SOUTHERN BRITISH COLUMBIA

In northern Washington and southern British Columbia, the San Juan–northwest Cascades thrust system consists of thrust sheets west of the steeply dipping Straight Creek–Fraser fault (Fig. 1; Misch, 1966; Brown, 1987; Brandon et al., 1988; Brandon, 1989; Journeay, 1989). Thrust

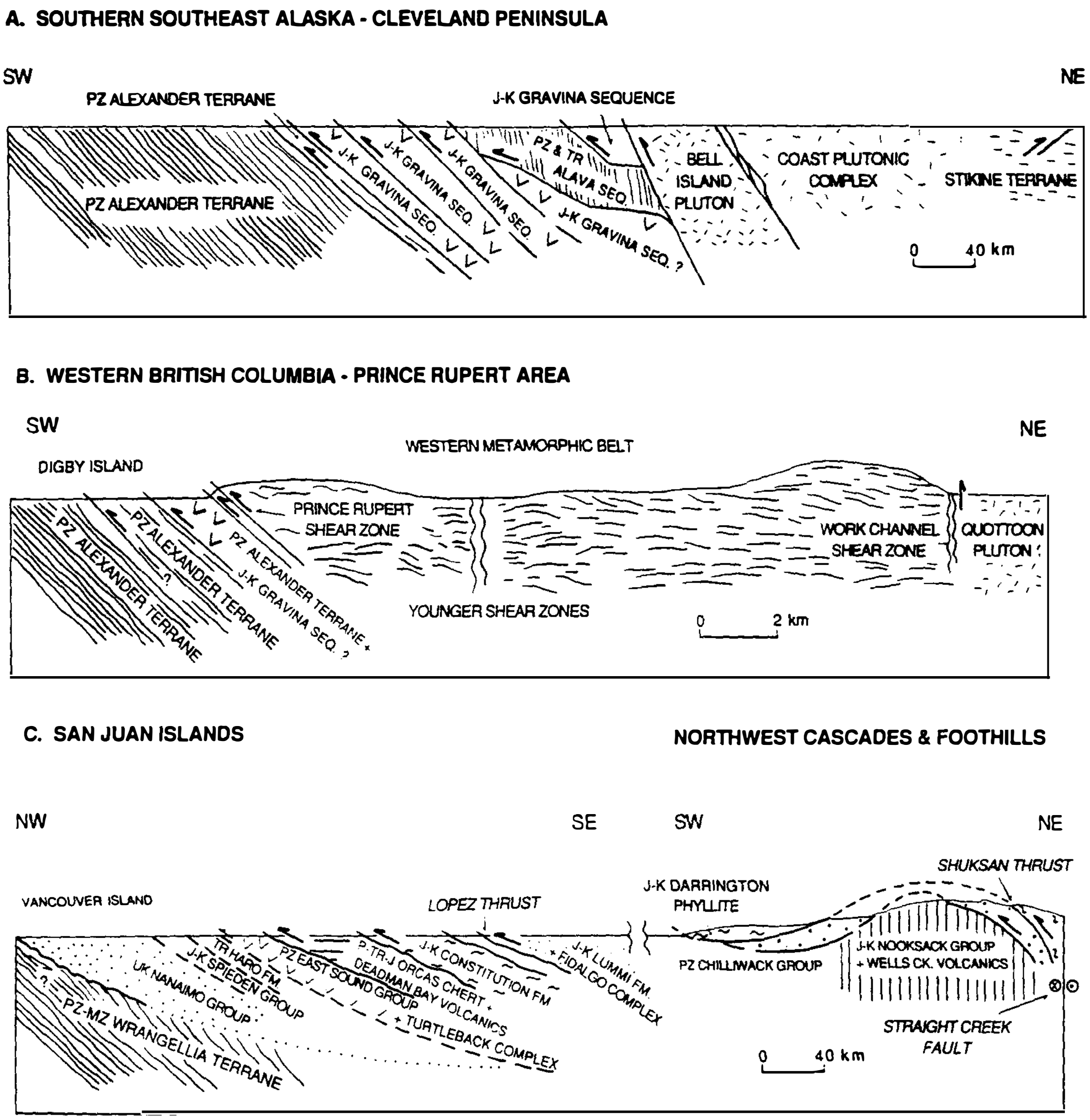

Figure 2. Structural transects across mid-Cretaceous thrust system. PZ = Paleozoic; P = Permian; MZ = Mesozoic; TR = Triassic; J = Jurassic; K = Cretaceous; UK = Upper Cretaceous. A: After Rubin and Saleeby (1987a, 1987b) and unpublished mapping by Rubin and Saleeby. B: After work of Crawford et al. (1987). C: After Brandon et al. (1988) and Brandon (1989). Locations of cross sections are shown in Figure 1.

sheets contain diverse rock units ranging in age from early Paleozoic to latest Early Cretaceous. In the San Juan Islands, the stacking order, from structurally lowest to highest, is as follows: lower to upper Paleozoic tonalite, gabbro, and volcanogenic rocks of the Turtleback terrane; Permian to Lower Jurassic chert, basalt, and limestone of the Deadman terrane; Upper Jurassic to Lower Cretaceous volcaniclastic sedimentary rocks and interbedded chert and basalt of the Constitution Formation; and the Decatur terrane, including the Middle to Late Jurassic Fidalgo ophiolite and its upper Mesozoic clastic cover (Fig. 2C; Brandon et al., 1988). Thrust sheets in the northwest Cascades include (Fig. 2C) Middle Jurassic(?) Wells Creek Volcanics and their volcaniclastic cover of Upper Jurassic and Lower Cretaceous Nooksack Group; upper Paleozoic and Triassic Chilliwack Group and overlying strata; and structurally highest, the Shuksan Metamorphic Suite, comprising Jurassic(?) metasedimentary and metabasaltic rocks that were metamorphosed to greenschist or blueschist facies during the Late Jurassic and Early Cretaceous (Misch, 1966; McGroder and Miller, 1989). Most of the rocks in the thrust system record high-*P*/low-*T* metamorphism, which resulted from tectonic burial that accompanied contractional imbrication and crustal thickening.

The age of thrusting is based on several lines of evidence. In the San Juan Islands, the youngest rocks involved in the deformation are late Albian age (99–101 Ma; time scale of Harland et al., 1982). Santonian (ca. 84 Ma) strata of the Nanaimo Group, which mostly postdate thrusting, contain clasts derived from some of the metamorphosed units in the thrust sheets (Brandon et al., 1988). In the Cascades, east of the Straight Creek fault, the 88 Ma Mount Stuart batholith (Pb-U zircon; J. Maglouglin, 1988, personal commun.; analyzed by P. Van der Heyden) intruded a post-96 Ma thrust fault (Miller, 1985). All available evidence suggests that the major episode of thrusting occurred between 90 and 100 Ma.

The San Juan–northwest Cascades thrust system formed a wedge that was emplaced westward over the Wrangellia terrane (Insular superterrane) in mid-Cretaceous time. This interpretation concurs with that of Misch (1966), in that the overall vergence of the system was toward the west; in contrast, Brown (1987) proposed north-northwestward tectonic transport. The Intermontane superterrane sensu stricto is about 100 km east of the easternmost preserved remnants of the thrust system. The Intermontane superterrane, however, is thought to have formed the hanging wall to the thrust system (Brandon et al., 1988). The Intermontane superterrane and the thrust system are now separated by the uplifted core of the North Cascades (Skagit Metamorphic Suite of Misch, 1966; Fig. 2). Viewed broadly, the San Juan–northwest Cascades system constitutes a wide, internally imbricated, lithologically diverse zone separating the two superterranes. Some pre-Cretaceous lithotectonic units in the thrust system (e.g., the Chilliwack Group and the Deadman Bay terrane) have tectonic affinity to rocks of the Intermontane superterrane (Brandon et al., 1988). During the mid-Cretaceous, they were imbricated with non-Intermontane rock types. The Mount Stuart and related 80–90 Ma plutons represent a magmatic arc that was constructed across the newly formed contractional orogen.

DISCUSSION

Similarities in structural style, vergence, and age of deformation among thrust systems in southeast Alaska, western British Columbia, and northwestern Washington–southwestern British Columbia suggest that they are parts of a mid-Cretaceous orogenic zone that spanned at least 1200 km. Coeval east-vergent thrusting and folding are now documented in a parallel belt, east of the orogen, from north-central British Columbia (Tipper, 1969; Rusmore and Woodsworth, 1988) to north-central Washington (McGroder and Miller, 1989).

Mid-Cretaceous fold development and thrust faulting were broadly coeval with arc magmatism, in that calc-alkalic plutonism occurred shortly before, perhaps during, and shortly after the structures were developed; however, older fabrics are locally present. Mid-Cretaceous plutons that are coeval with thrust faulting occur in western British Columbia (Crawford et al., 1987) and in southern southeast Alaska (Rubin and Saleeby, 1987a, 1987b). Younger plutons are more widespread. Calc-alkalic plutons that crosscut the deformational fabrics are present within both superterranes. Such magmatism persisted intermittently until at least the Eocene (Armstrong, 1988).

Two models that incorporate existing ideas explain the origin of the mid-Cretaceous thrust belt and are compatible with our current understanding of the magmatic history of the northwestern Cordillera (Fig. 3). Model 1 implies the existence of an intervening subduction zone and marginal basin between the Insular superterrane and the western margin of North America (Fig. 3). Evidence of a pre-Cretaceous subduction zone within the intervening marginal basin is not preserved, perhaps because of extensive crustal shortening. The closure along this postulated subduction zone marks the collision of the two superterranes. In this context, deformation can be viewed as a result of a collisional orogeny involving the collapse of a marginal basin system that separated the Insular superterrane from the western margin of North America. In light of the synchroneity of deformation along strike, a collisional origin implies that (1) prior to mid-Cretaceous time, the two superterranes must have been roughly parallel and had nearly linear edges, and (2) an ocean basin existed that was small and elongate parallel to the superterranes.

Model 2 implies that mid-Cretaceous crustal shortening and magmatism occurred in an intra-arc setting, above a single, east-dipping subduction zone (Fig. 3). Arc magmatism and deformation involved the collapse of a series of marginal basins and a magmatic arc. This model implies that the intervening basins were small and their collapse was not necessarily accommodated by a separate subduction zone. Deformation may have been related to changes in velocity and direction of plate motions and was a direct consequence of subduction beneath the edge of the continental margin. In this context, the thrust system overprinted the older tectonic boundary between the Insular superterrane and the North American margin. Compressional deformation was broadly coeval with arc magmatism, and thus reflects intra-arc tectonism.

In either model, subsequent to mid-Cretaceous deformation, the locus of arc magmatism migrated to the east (Armstrong, 1988) and was superimposed along the boundary between the two superterranes. The Coast Plutonic Complex

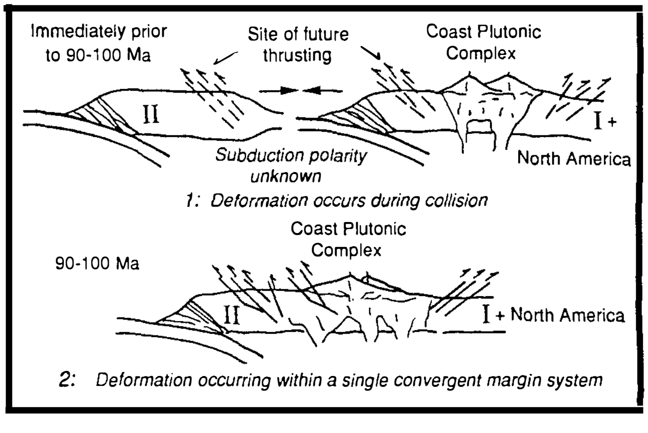

Figure 3. Tectonic models for origin of mid-Cretaceous deformation within Coast Plutonic Complex. I = Intermontane superterrane; II = Insular superterrane. Model 1 adapted from Goodwin (1975) and Monger et al. (1982). Model 2 adapted from Berg et al. (1972), Monger et al. (1972), Armstrong (1988), and Van der Heyden and Woodsworth (1988).

was intruded along this boundary zone in response to ongoing east-dipping subduction. Synorogenic to post-orogenic marine and nonmarine foredeep sequences, represented by the Upper Cretaceous Queen Charlotte and Nanaimo Groups, record westward dispersal of sediments derived from the uplifted thrust belt.

CONCLUSIONS

Structural, stratigraphic, and geochronologic relations along the Insular-Intermontane superterrane boundary suggest that a predominantly west-vergent fold and thrust belt affected the tectonic boundary between two large crustal fragments in southeast Alaska, western British Columbia, and northern Washington. This west-vergent thrust belt spans at least 1200 km in strike length. Radiometric and stratigraphic age constraints bracket thrust faulting between 101 and 88 Ma. A major continental arc subsequently formed just east of the locus of the thrust system. This arc is represented by the mid-Cretaceous to Eocene component of the Coast Plutonic Complex. Two existing models may explain this deformation: (1) crustal shortening is attributed to the collision of the Insular superterrane to the western North American margin (e.g., Intermontane superterrane), and (2) crustal shortening occurred in an intra-arc setting following the accretion of the Insular superterrane.

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